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Petroleum and natural gas industries — Specific requirements for offshore structures —

Part 1: Metocean design and operating considerations

Industries du pétrole et du gaz naturel — Exigences spécifiques relatives aux structures en mer —

Partie 1: Dispositions océano-météorologiques pour la conception et l'exploitation

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 19901-1 was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 7, *Offshore structures*.

ISO 19901 consists of the following parts, under the general title *Petroleum and natural gas industries — Specific requirements for offshore structures*:

— *Part 1: Metocean design and operating considerations*

— *Part 2: Seismic design procedures and criteria*

— *Part 4: Geotechnical and foundation design considerations*

— *Part 5: Weight control during engineering and construction*

— *Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units*

The following parts are under preparation:

— *Part 3: Topsides structure*

— *Part 6: Marine operations*

ISO 19901 is one of a series of standards for offshore structures. The full series consists of the following International Standards.

— ISO 19900, *Petroleum and natural gas industries — General requirements for offshore structures*

— ISO 19901 (all parts), *Petroleum and natural gas industries — Specific requirements for offshore structures*

— ISO 19902, *Petroleum and natural gas industries — Fixed steel offshore structures*[1)]

— ISO 19903, *Petroleum and natural gas industries — Fixed concrete offshore structures*[1)]

1) To be published.

— ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*[2)]

— ISO 19904-2, *Petroleum and natural gas industries — Floating offshore structures — Part 2: Tension leg platforms*[3)]

— ISO 19905-1, *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 1: Jack-ups*[3)]

— ISO/TR 19905-2, *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 2: Jack-ups commentary*[3)]

— ISO 19906, *Petroleum and natural gas industries — Arctic offshore structures*[3)]

2) To be published.

3) Under preparation.

Introduction

The series of International Standards applicable to types of offshore structure, ISO 19900 to ISO 19906, constitutes a common basis covering those aspects that address design requirements and assessments of all offshore structures used by the petroleum and natural gas industries worldwide. Through their application the intention is to achieve reliability levels appropriate for manned and unmanned offshore structures, whatever the type of structure and the nature or combination of the materials used.

It is important to recognize that structural integrity is an overall concept comprising models for describing actions, structural analyses, design rules, safety elements, workmanship, quality control procedures and national requirements, all of which are mutually dependent. The modification of one aspect of design in isolation can disturb the balance of reliability inherent in the overall concept or structural system. The implications involved in modifications, therefore, need to be considered in relation to the overall reliability of all offshore structural systems.

The series of International Standards applicable to types of offshore structure is intended to provide a wide latitude in the choice of structural configurations, materials and techniques without hindering innovation. Sound engineering judgement is therefore necessary in the use of these International Standards.

The overall concept of structural integrity is described above. Some additional considerations apply for metocean design and operating conditions. The term “metocean” is short for “meteorological and oceanographic” and refers to the discipline concerned with the establishment of relevant environmental conditions for the design and operation of offshore structures. A major consideration in the design and operation of such a structure is the determination of actions on, and the behaviour of, the structure as a result of winds, waves and currents.

Environmental conditions vary widely around the world. For the majority of offshore locations there are little numerical data from historic conditions; comprehensive data often only start being collected when there is a specific need, for example, when exploration for hydrocarbons is being considered. Despite the usually short duration for which data are available, designers of offshore structures need estimates of extreme and abnormal environmental conditions (with an individual or joint probability of the order of 1×10^{-2} / year and 1×10^{-3} to 1×10^{-4} / year, respectively).

Even for areas like the Gulf of Mexico, offshore Indonesia and the North Sea, where there are up to 30 years of fairly reliable measurements available, the data are insufficient for rigorous statistical determination of appropriate extreme and abnormal environmental conditions. The determination of relevant design parameters has therefore to rely on the interpretation of the available data by specialists, together with an assessment of any other information, such as prevailing weather systems, ocean wave creation and regional and local bathymetry, coupled with consideration of data from comparable locations. It is hence important to employ specialists from both the metocean and structural communities in the determination of design parameters for offshore structures, particularly since setting of appropriate environmental conditions depends on the chosen option for the offshore structure.

This part of ISO 19901 provides procedures and guidance for the determination of environmental conditions and their relevant parameters. Requirements for the determination of the actions on, and the behaviour of, a structure in these environmental conditions are given in ISO 19901-3, ISO 19901-6, ISO 19901-7, ISO 19902, ISO 19903, ISO 19904, ISO 19905 and ISO 19906.

Some background to, and guidance on, the use of this part of ISO 19901 is provided in informative Annex A. The clause numbering in Annex A is the same as in the normative text to facilitate cross-referencing.

A discussion on wave spectra is provided in informative Annex B.

Regional information, where available, is provided in informative Annex C.

Petroleum and natural gas industries — Specific requirements for offshore structures —

Part 1: Metocean design and operating considerations

1 Scope

This part of ISO 19901 gives general requirements for the determination and use of meteorological and oceanographic (metocean) conditions for the design, construction and operation of offshore structures of all types used in the petroleum and natural gas industries.

The requirements are divided into two broad types:

a) those that relate to the determination of environmental conditions in general, together with the metocean parameters that are required to adequately describe them;

b) those that relate to the characterization and use of metocean parameters for the design, the construction activities or the operation of offshore structures.

The environmental conditions and metocean parameters discussed comprise

— extreme and abnormal values of metocean parameters that recur with given return periods that are considerably longer than the design service life of the structure,

— long-term distributions of metocean parameters, in the form of cumulative, conditional, marginal or joint statistics of metocean parameters, and

— normal environmental conditions that are expected to occur frequently during the design service life of the structure.

Metocean parameters are applicable to

— the determination of actions and action effects for the design of new structures,

— the determination of actions and action effects for the assessment of existing structures,

— the site-specific assessment of mobile offshore units,

— the determination of limiting environmental conditions, weather windows, actions and action effects for pre-service and post-service situations (i.e. fabrication, transportation and installation or decommissioning and removal of a structure), and

— the operation of the platform, where appropriate.

NOTE Specific metocean requirements for tension leg platforms are to be contained in ISO 19904-2[1], for site-specific assessment of jack-ups in ISO 19905-1[2], for arctic structures in ISO 19906[3] and for topsides structures in ISO 19901-3[4].

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 19900, *Petroleum and natural gas industries — General requirements for offshore structures*

ISO 19902, *Petroleum and natural gas industries — Fixed steel offshore structures* [4)]

ISO 19903, *Petroleum and natural gas industries — Fixed concrete offshore structures*

ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*

3 Terms and definitions

For the purpose of this document, the terms and definitions given in ISO 19900 and the following apply.

3.1
abnormal value
design value of a parameter of abnormal severity used in accidental limit state checks in which a structure is intended not to suffer complete loss of integrity

NOTE Abnormal events have probabilities of the order of 10^{-3} to 10^{-4} per annum. In the limit state checks, some or all of the partial factors are set to 1,0.

3.2
chart datum
local datum used to fix water depths on a chart or tidal heights over an area

NOTE Chart datum is usually an approximation to the level of the lowest astronomical tide.

3.3
conditional distribution
conditional probability
statistical distribution (probability) of the occurrence of a variable A, given that other variables B, C, … have certain assigned values

NOTE The conditional probability of A given that B, C, … occur is written as $P(A|B,C,\ldots)$. The concept is applicable to metocean parameters, as well as to actions and action effects.

EXAMPLE When considering wave parameters, A can be the individual crest elevation, B the water depth and C the significant wave height, and so on.

3.4
design crest elevation
extreme crest elevation measured relative to still water level

NOTE The design crest elevation is used in combination with information on astronomical tide, storm surge, platform settlement, reservoir subsidence and water depth uncertainty and is derived from an extreme value analysis. Because of the simplified nature of the models used to estimate the kinematics of the design wave, the design crest elevation can be different from, usually somewhat greater than, the crest elevation of the design wave used to calculate actions on the structure.

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4) To be published.

3.5
design wave
deterministic wave used for the design of an offshore structure

NOTE 1 The design wave is an engineering abstract. Most often it is a periodic wave with suitable characteristics (e.g. height H, period T, steepness, crest elevation). The choice of a design wave depends on

— the design purpose(s) considered,

— the wave environment,

— the geometry of the structure,

— the type of action(s) or action effect(s) pursued.

NOTE 2 Normally, a design wave is only compatible with design situations in which the action effect(s) are quasi-statically related to the associated wave actions on the structure.

3.6
extreme value
design value of a parameter used in ultimate limit state checks, in which a structure's global behaviour is intended to stay in the elastic range

NOTE Extreme events have probabilities of the order of 10^{-2} per annum.

3.7
gust
brief rise and fall in wind speed lasting less than 1 min

NOTE In some countries, gusts are reported in meteorological observations if the maximum wind speed exceeds approximately 8 m/s.

3.8
gust wind speed
maximum value of the wind speed of a gust averaged over a short (3 s to 60 s) specified duration within a longer (1 min to 1 h) specified duration

NOTE 1 For design purposes, the specified duration depends on the dimensions and natural period of the (part of the) structure being designed such that the structure is designed for the most onerous conditions; thus, a small part of a structure is designed for a shorter gust wind speed duration (and hence a higher gust wind speed) than a larger (part of a) structure.

NOTE 2 In practice, for design purposes, the gust wind speeds for different durations (e.g. 3 s, 5 s, 15 s, 60 s) are derived from the wind spectrum.

3.9
highest astronomical tide
HAT
level of high tide when all harmonic components causing the tides are in phase

NOTE The harmonic components are in phase approximately once every 19 years, but these conditions are approached several times each year.

3.10
hindcasting
method of simulating historical (metocean) data for a region through numerical modelling

3.11
long-term distribution
probability distribution of a variable over a long time scale

NOTE The time scale exceeds the duration of a sea state, in which the statistics are assumed constant (see short-term distribution in 3.29). The time scale is hence comparable to a season or to the design service life of a structure.

EXAMPLE Long-term distributions of

— significant wave height,
— significant wave height in the months May to September,
— individual wave heights,
— current speeds (such as for the vortex induced vibrations of drilling risers),
— scatter diagrams with the joint distribution of significant wave height and wave period (such as for a fatigue analysis), or
— a particular action effect.

3.12
lowest astronomical tide
LAT
level of low tide when all harmonic components causing the tides are in phase

NOTE The harmonic components are in phase approximately once every 19 years, but these conditions are approached several times each year.

3.13
marginal distribution
marginal probability
statistical distribution (probability) of the occurrence of a variable A that is obtained by integrating over all values of the other variables B, C, …

NOTE The marginal probability of A for all values of B, C, … is written as $P(A)$. The concept is applicable to metocean parameters, as well as to actions and action effects.

EXAMPLE When considering wave conditions, A can be the individual crest elevation for all mean zero-crossing periods B and all significant wave heights C, occurring at a particular site.

3.14
marine growth
living organisms attached to an offshore structure

3.15
mean sea level
MSL
arithmetic mean of all sea levels measured at hourly intervals over a long period, ideally 19 years

NOTE Seasonal changes in mean level can be expected in some regions and over many years the mean sea level can change.

3.16
mean wind speed
time-averaged wind speed, averaged over a specified time interval

NOTE The mean wind speed varies with elevation above mean sea level and the averaging time interval; a standard reference elevation is 10 m and a standard time interval is 1 h. See also sustained wind speed (3.37) and gust wind speed (3.8).

3.17
mean zero-crossing period
average period of the (up or down) zero-crossing waves in a sea state

NOTE In practice the mean zero-crossing period is often estimated from the zeroth and second moments of the wave spectrum as $T_z = T_2 = \sqrt{m_0(f)/m_2(f)} = 2\pi\sqrt{m_0(\omega)/m_2(\omega)}$.

3.18
monsoon
wind which blows for several months approximately from one direction

NOTE The term was first applied to the winds over the Arabian Sea which blow for six months from north-east and for six months from south-west, but it has been extended to similar winds in other parts of the world.

3.19
most probable maximum
value of the maximum of a variable with the highest probability of occurring

NOTE The most probable maximum is the value for which the probability density function of the maxima of the variable has its peak. It is also called the mode or modus of the statistical distribution.

3.20
operating conditions
most severe combination of environmental conditions under which a given operation will be permitted to proceed

NOTE Operating conditions are determined for operations that exert a significant action on the structure. Operating conditions are usually a compromise: they are sufficiently severe that the operation can generally be performed without excessive downtime, but they are not so severe that they have an undue impact on design.

3.21
polar low
depression that forms in polar air, often near a boundary between ice and sea

3.22
residual current
part of the total current that is not constituted from harmonic tidal components (i.e. the tidal stream)

NOTE Residual currents are caused by a variety of physical mechanisms and comprise a large range of natural frequencies and magnitudes in different parts of the world.

3.23
return period
average period between occurrences of an event or of a particular value being exceeded

NOTE The offshore industry commonly uses a return period measured in years for environmental events. The return period in years is equal to the reciprocal of the annual probability of exceedance of the event.

3.24
scatter diagram
joint probability of two or more (metocean) parameters

NOTE A scatter diagram is especially used with wave parameters in the metocean context, see A.5.8. The wave scatter diagram is commonly understood to be the probability of the joint occurrence of the significant wave height (H_s) and a representative period (T_z or T_p).

3.25
sea floor
interface between the sea and the seabed

[ISO 19901-4:2003]

3.26
sea state
condition of the sea during a period in which its statistics remain approximately constant

NOTE In a statistical sense the sea state does not change markedly within the period. The period during which this condition exists is usually assumed to be three hours, although it depends on the particular weather situation at any given time.

3.27
seabed
materials below the sea in which a structure is founded, whether of soils such as sand, silt or clay, cemented material or of rock

NOTE The seabed can be considered as the half-space below the sea floor.

[ISO 19901-4:2003]

3.28
seiche
oscillation of a body of water at its natural period

3.29
short-term distribution
probability distribution of a variable within a short interval of time during which conditions are assumed to be statistically constant

NOTE The interval chosen is most often the duration of a sea state.

3.30
significant wave height
statistical measure of the height of waves in a sea state

NOTE The significant wave height was originally defined as the mean height of the highest one-third of the zero up-crossing waves in a sea state. In most offshore data acquisition systems the significant wave height is currently taken as $4\sqrt{m_0}$ (where m_0 is the zeroth spectral moment, see 3.31) or 4σ, where σ is the standard deviation of the time series of water surface elevation over the duration of the measurement, typically a period of approximately 30 min.

3.31
spectral moment
n^th^ **spectral moment**
integral over frequency of the spectral density function multiplied by the nth power of the frequency, either expressed in hertz (cycles per second) as $m_n(f) = \int_0^\infty f^n S(f) df$ or expressed in circular frequency (radians/second) as $m_n(\omega) = \int_0^\infty \omega^n S(\omega) d\omega$

NOTE 1 As $\omega = 2\pi f$, the relationship between the two moment expressions is: $m_n(\omega) = (2\pi)^n m_n(f)$.

NOTE 2 The integration extends over the entire frequency range from zero to infinity. In practice the integration is often truncated at a frequency beyond which the contribution to the integral is negligible and/or the sensor no longer responds accurately.

3.32
spectral peak period
period of the maximum (peak) energy density in the spectrum

NOTE In practice there is often more than one peak in a spectrum.

3.33
spectral density function
energy density function
spectrum
measure of the variance associated with a time-varying variable per unit frequency band and per unit directional sector

NOTE 1 Spectrum is a shorthand expression for the full and formal name of spectral density function or energy density function.

NOTE 2 The spectral density function is the variance (the mean square) of the time-varying variable concerned in each frequency band and directional sector. Therefore the spectrum is in general written with two arguments: one for the frequency variable and one for a direction variable.

NOTE 3 Within this document the concept of a spectrum applies to waves, wind turbulence and action effects (responses) that are caused by waves or wind turbulence. For waves, the spectrum is a measure of the energy traversing a given space.

3.34
squall
strong wind event characterized by a sudden onset, a duration of the order of minutes and a rather sudden decrease in speed

NOTE 1 A squall is often accompanied by a change in wind direction, a drop in air temperature and by heavy precipitation.

NOTE 2 To be classed as a squall the wind speed would typically be greater than about 8 m/s and last for longer than 2 min (thereby distinguishing it from a gust).

3.35
still water level
abstract water level typically used for the calculation of wave kinematics for global actions and wave crest elevation for minimum deck elevations

NOTE Still water level is an engineering abstract calculated by adding the effects of tides and storm surge to the water depth but excluding variations due to waves (see Figure 1). It can be above or below mean sea level.

3.36
storm surge
change in sea level (either positive or negative) that is due to meteorological (rather than tidal) forcing

3.37
sustained wind speed
time-averaged wind speed with an averaging duration of 10 min or longer

3.38
swell
sea state in which waves generated by winds remote from the site have travelled to the site, rather than being locally generated

3.39
tropical cyclone
closed atmospheric or oceanic circulation around a zone of low pressure that originates over the tropical oceans

NOTE 1 The circulation is counter-clockwise in the northern hemisphere and clockwise in the southern hemisphere.

NOTE 2 At maturity, the tropical cyclone can be one of the most intense storms in the world, with wind speeds exceeding 90 m/s and accompanied by torrential rain.

NOTE 3 In some areas, local terms for tropical cyclones are used. For example, tropical cyclones are typically referred to as hurricanes in the Gulf of Mexico and North Atlantic, while in the South China Sea and NW Pacific they are called typhoons. In the South Pacific and South Indian Ocean, however, they are commonly referred to as cyclones.

NOTE 4 The term cyclone is also used to refer to a tropical storm with sustained wind speeds in excess of 32 m/s (Beaufort Force 12).

3.40
tsunami
long period sea waves caused by rapid vertical movements of the sea floor

NOTE The vertical movement of the sea floor is often associated with fault rupture during earthquakes or with seabed mud slides.

3.41
water depth
vertical distance between the sea floor and still water level

NOTE 1 As there are several options for the still water level (see 3.35), there can be several water depth values. Generally, design water depth is determined to LAT or to mean sea level.

NOTE 2 The water depth used for calculating wave kinematics varies between the maximum water depth of the highest astronomical tide plus a positive storm surge, and the minimum water depth of the lowest astronomical tide less a negative storm surge, where applicable. The same maximum and minimum water depths are applicable to bottom founded and floating structures, although water depth is usually a much less important parameter for floating structures. Water depth is, however, important for the design and analysis of the mooring system and risers for floating structures.

3.42
wave spectrum
measure of the amount of energy associated with the fluctuation of the sea surface elevation per unit frequency band and per unit directional sector

NOTE 1 The wave frequency spectrum (integrated over all directions) is often described by use of some parametric form such as the Pierson-Moskowitz or JONSWAP wave spectrum.

NOTE 2 The area under the wave spectrum is the zeroth spectral moment m_0, which is a measure of the total energy in the sea state; m_0 is used in contemporary definitions of the significant wave height.

3.43
wave steepness
characteristic of individual waves calculated as wave height divided by wave length

NOTE For periodic waves, the concept is straightforward as H / λ. For random waves, the definition is used with the significant wave height (H_s) and the wave length that corresponds with the peak period (T_p) of the wave spectrum in deep water. The significant wave steepness is then defined as $H_s / \lambda_p = H_s / [(g/2\pi)\ T_p2]$ and is typically in the range of 1/16 to 1/20 for severe sea states.

3.44
wind spectrum
measure of the variance associated with the fluctuating wind speed per unit frequency band

NOTE 1 The wind spectrum is an expression of the dynamic properties of the wind (turbulence). It reflects the fluctuations about and in the same direction as a certain mean wind speed, usually the 1 h sustained wind speed. There is hence no direction variable associated with the wind spectrum within this document.

NOTE 2 As the sustained wind speed varies with elevation, the wind spectrum is a function of elevation.

4 Symbols and abbreviated terms

4.1 Main symbols

A	parameter in the Pierson-Moskowitz spectrum
B	parameter in the Pierson-Moskowitz spectrum
c	wave celerity (wave phase speed)
$D(\theta)$	wave directional spreading function
$D(\omega,\theta)$	general form of the wave directional spreading function
d	water depth
$F_{\text{coh}}(f;P1,P2)$	coherence function between turbulence fluctuations at $P_1(x_1, y_1, z_1)$ and at $P_2(x_2, y_2, z_2)$
F_{n}	normalizing (scaling) factor for the JONSWAP spectrum
$F_{\text{n,sw}}$	normalizing (scaling) factor for the swell spectrum
F_{s}	stretching factor
f	frequency in cycles per second (hertz)
g	acceleration due to gravity
H	height of an individual wave
H_{b}	breaking wave height
H_{N}	maximum height of an individual wave having a return period of N years
H_{s}	significant wave height
$I_{\text{u}}(z)$	wind turbulence intensity at z m above mean sea level, see Equation (A.4)
k	wave number = $2\,\pi\,/\,\lambda$
m_{n}	n^{th} spectral moment (either in terms of f or ω). In particular, m_0 is the zeroth spectral moment and is equivalent to σ^2, the variance of the corresponding time series
S	spectral density function, energy density function
$S(f)$, $S(\omega)$	wave frequency spectrum
$S(f,\ \theta)$, $S(\omega,\ \theta)$	directional wave spectrum
S_{gen}	general formulation of the spectrum for a sea state
S_{JS}	JONSWAP spectrum for a sea state
S_{PM}	Pierson-Moskowitz spectrum for a sea state
S_{OH}	Ochi-Hubble spectrum for a total sea state consisting of a combination of two sea states with a general formulation (see Annex B)
$S_{\text{sw}}(f)$, $S_{\text{sw}}(\omega)$	swell spectrum

T	wave period; also period in general
T_0	standard reference time-averaging interval for wind speed of 1 h = 3 600 s
T_a	apparent period of a periodic wave (to an observer in an earth bound reference frame)
T_e	encounter period of a periodic wave (to an observer in a reference frame that moves with respect to earth as well as the wave; the frame is usually fixed to a moving vessel)
T_i	intrinsic period of a periodic wave (in a reference frame that is stationary with respect to the wave, i.e. with no current present)
T_p	modal or peak period of the spectrum
T_z	mean zero-crossing period of the water surface elevation in a sea state
T_1	mean period of the water surface elevation in a sea state, defined by the zero and first order spectral moments
t	time
U_c	free stream current velocity
U_{c0}	surface current speed at z = 0
U_{ref}	reference wind speed, U_{ref} = 10 m/s
$U_c(z)$	current speed at elevation z ($z \leqslant 0$)
$U_w(z,t)$	spatially and temporally varying wind speed at elevation z above mean sea level and at time instant t
$U_w(z)$	mean wind speed at elevation z above mean sea level averaged over a specified time interval
$U_{w,1h}(z)$	1 h sustained wind speed at elevation z above mean sea level
$U_{w,T}(z)$	sustained wind speed at elevation z above mean sea level, averaged over time interval $T < 1$ h
U_{w0}	1 h sustained wind speed at 10 m above mean sea level (the standard reference speed for sustained winds)
$u_w(z,t)$	fluctuating wind speed at elevation z around $U_w(z)$ and in the same direction as the mean wind
$V_{in\text{-}line}$	component of the current velocity in-line with the direction of wave propagation
x,y,z	coordinates of a right-handed orthogonal coordinate system with the xy-plane in the undisturbed still water level (for waves and currents) or mean sea level (for winds) and the z-axis positive upwards
z	vertical coordinate [measured upwards from the still water level (for waves and currents) or mean sea level (for winds)]
z_r	reference elevation for winds above the mean sea level, z_r = 10 m
z_s	stretched vertical coordinate for waves and currents (measured upwards from the still water level)
γ	shape parameter of the peak enhancement factor in the JONSWAP spectrum

η	water surface elevation as a function of time and location
θ	wave direction angle
$\overline{\theta}$	mean wave direction
θ_c	direction of the current velocity with respect to the wave direction
λ	wave length
σ	standard deviation of the water surface elevation in a sea state
σ_a, σ_b	parameters in the peak enhancement factor of the JONSWAP spectrum
σ_{sw}	parameter defining the width of the symmetric swell spectrum (equals the standard deviation of the Gaussian function)
ϕ	directional spreading factor
ω	wave frequency; also circular frequency in general (radians per second $\omega = 2\pi f$)
ω_1	mean wave frequency of the wave spectrum ($\omega_1 = 2\pi / T_1$)
ω_a	apparent wave frequency
ω_e	encounter wave frequency
ω_i	intrinsic wave frequency
ω_m	modal frequency at the peak of the spectrum ($\omega_m = 2\pi f_m = 2\pi / T_p$)
ω_z	average zero-crossing frequency of the water surface elevation ($\omega_z = 2\pi / T_z$)

4.2 Abbreviated terms

HAT	highest astronomical tide
LAT	lowest astronomical tide
MSL	mean sea level
PSU	practical salinity units

5 Determining the relevant metocean parameters

5.1 General

The owner of a platform is responsible for selecting the appropriate environmental conditions applicable to particular design and operating situations. The selection shall take regulatory requirements into account, where these exist.

General guidelines on metocean information are given in ISO 19900. Information about the following shall be determined.

a) Extreme and abnormal metocean parameters, which are required to develop extreme and abnormal environmental actions and/or action effects. These parameters are used to define design situation(s) and to perform design checks for ultimate limit states and accidental limit states.

b) Long-term distributions of metocean parameters, in the form of cumulative conditional or marginal statistics. These parameters are used

— to define design situation(s) and to perform design checks for the fatigue limit state, or

— to make evaluations of downtime/workability/operability during a certain period of time, for the structure or for associated items of equipment.

c) Normal environmental conditions, which are required

— for carrying out checks for serviceability limit states,

— for developing actions and action effects to determine when particular operations can safely take place, and

— for planning construction activities (fabrication, transportation or installation) or field operations (e.g. drilling, production, offloading, underwater activities).

Depending on the geographical region and the offshore operations involved, other environmental conditions can be required for specific design situations or for particular operations.

5.2 Expert interpretation of the metocean database

Reliable estimates of (very) low probability environmental events can be made using a number of different approaches, including analysis of all data values, annual or monthly maxima, peak-over-threshold events. Implicit in the use of each approach are assumptions about the data used, the statistical procedures applied, and the interpretation of the results.

The appropriate design parameters are also dependent on the structural form chosen, for example, different design parameters can be appropriate to fixed and floating structures.

Experts in meteorology and oceanography, familiar with the considerations, are needed to obtain reliable and appropriate design parameters. The experts shall be involved with the analysis of the data and its interpretation into the appropriate design criteria.

5.3 Selecting appropriate parameters for determining design actions or action effects

Environmental actions and associated action effects for the design of offshore structures are usually, but not always, dominated by wave conditions.

The wave condition(s) to be considered for a particular design situation can be specified through either a), b) or c), as follows.

a) Long-term statistical distributions of the oceanographic parameters describing the wave climate at the location of interest over many years. Where adequate data are available, the statistical distributions may reflect the joint occurrence of the oceanographic parameters. Alternatively, the distributions can be marginal distributions for separate parameters. From these long-term distributions appropriate oceanographic design parameters shall be derived that are commensurate with the design situation involved.

b) Short-term descriptions of one or a number of different design sea states, in conjunction with one or more design currents. A design sea state shall be described by a wave spectrum together with the significant wave height, a representative frequency or period, and a mean wave direction. Where appropriate, the wave spectrum may be supplemented with a directional spreading function, see 8.7. A design current is specified by a surface velocity and its velocity profile over the water column, including its direction, see Clause 9.

c) One or a number of individual design waves, in conjunction with one or more design currents. A design wave shall be specified by its height and period, together with an appropriate wave theory from which the wave kinematics can be derived, as well as (an) associated direction(s), see Clause 8. A design current is specified by a surface velocity and its velocity profile over the water column including its direction, see Clause 9.

The above descriptions shall be supplemented by associated meteorological conditions (including wind) that are relevant for the particular design situation considered.

The selection of the most appropriate specification a), b) or c) above depends on the data that are available for the location of interest, the type of structure concerned, the design situation involved and the limit state considered. It is entirely appropriate that a different selection is made to suit different structure types, different design situations and different limit states.

If the current is known to dominate design actions on the structure, the selection of an associated wave height for a given current velocity should be considered. Where environmental actions for structural design are not dominated by wave or current conditions (but, for example, by wind or earthquakes), special consideration shall be given to the selection of the relevant metocean parameters in combination with those other events.

5.4 The metocean database

A site-specific metocean database shall be established containing information on

— significant wave heights, periods and directions,

— current speeds and directions at a number of depths throughout the water column,

— wind speeds and directions,

— sea ice, icebergs, snow and ice accretion,

— water levels, and

— other relevant metocean parameters (air and water temperatures, water salinity, etc.).

The database may either be established by site-specific measurements over a period of years or as an alternative by numerical modelling (hindcasts) of historical events. If numerical simulations are used, the simulated results shall be calibrated (or verified) against measurements from a nearby location from which measurements exist. If such measurements do not exist, the hindcast model may be calibrated or verified against measurements from an analogous site with a similar metocean climate in a different ocean basin.

If measurements or hindcasts exist from a nearby location, the database from this location may be used, provided that conditions at the two sites are similar in water depth, fetch limits and overall climate.

For more detailed advice on sea ice, icebergs, snow and ice accretion, see ISO 19906[3].

When conducting metocean surveys at sea, safe practices should be followed.

5.5 Storm types in a region

General information on the various types of storms which can affect the structure shall be used to supplement available data.

When determining the appropriate environmental conditions it is important to separate storms of different types, for example, monsoons and typhoons, before performing an extreme value analysis. Furthermore, it can be necessary to set operating limits for a particular platform for particular storm types and seasons.

5.6 Directionality

In some locations, representative storm tracks and topographic features can provide fetch limitations on wave heights from specific directions, or tidal or general circulation currents can be in a predominant direction. For design in such situations, different wave, wind, and/or current magnitudes may be used for different approach directions, provided that sufficient reliable data are available to derive them. However, the owner of the structure shall ensure that the overall reliability of the structure is not compromised by the use of such lower directional environmental conditions.

The possibility of the structure's orientation deviating from the design orientation shall be considered. Deviations can result from installation tolerances and from movements of floating structures. In locations where reliable directional data are not available, the directions of the wind, wave and current shall be assumed to coincide for determining extreme and abnormal actions and action effects.

For some structures, in particular floating structures, action effects can be greater with non-collinear wave, current and wind. In such cases special consideration shall be given to the selection of the most appropriate directions or combination of directions.

5.7 Extrapolation to rare conditions

Designers require metocean parameters at (very) low probabilities or recurrence rates, e.g. with a return period of 100, 1 000 or 10 000 years. Since data covering such long periods are rarely available, an extrapolation of existing data is necessary. Many extrapolation methods have been used and, while some methods are clearly better than others, no single method is theoretically superior. In general, the longer a data set the more accurate the extrapolation will be. In some relatively homogeneous areas, hindcasts can be used to extend the time basis for estimating return period values at a particular site, thereby reducing the amount of extrapolation needed. However, even with long data sets, estimates of (very) low probability parameters can still depend to a considerable degree on the extrapolation method.

5.8 Metocean parameters for fatigue assessments

The fatigue limit state can govern the design of individual structural components in fixed and in floating offshore structures in several parts of the world.

Fatigue is an accumulation of damage caused by the repeated application of time-varying stresses. The predominant cause of these time-varying stresses is the environment of the structure, particularly the wave environment for offshore structures. For some components and types of structures, cyclic stresses due to vortex induced vibrations (VIV) in steady currents or winds should also be considered.

Fatigue limit state assessment of a structure requires specification of all environmental conditions that are expected to occur during the entire period of the structure's exposure, i.e. its construction phase, including transportation, and its design service life. The specification of the environment is given by the long-term distribution(s) of one or more metocean parameters. The metocean parameters relevant for the fatigue assessment depend on the type of structure and the location under consideration. The distribution(s) of the relevant parameter(s) shall be determined from the metocean database, taking due account of the requirements for the structure being considered, see A.5.8.

5.9 Metocean parameters for short-term activities

Transportation, installation, maintenance and removal of a structure are scheduled activities that are weather-sensitive. Operation of a platform includes regular and routine activities that are also weather-sensitive. Some of these activities are sensitive to high winds, while others are sensitive to currents, swell, wave heights, wave periods, wave directions or combinations thereof.

Examples of weather-sensitive scheduled short-term activities are

— transportation of the structure, particularly when involving long exposed tows,

— installation of fixed steel offshore structures, including

  1) lifting, launching, upending and placement on the seabed,

  2) the period following placement but prior to and during piling, and

  3) the period following piling but prior to and during pile grouting and until grout setting,

— installation of fixed concrete offshore structures including

  1) placement on the seabed, and

  2) the period following placement but prior to and during any grouting and until grout setting,

— establishment/re-establishment of a floating structure at the operating location, including the setting of mooring systems,

— installation and foundation pre-loading for jack-ups,

— topsides installation,

— underwater operations, including inspection and repair, and

— removal for decommissioning or reuse.

As well as being critical and expensive, these activities usually require a weather window with low environmental conditions for significant durations, e.g. sufficient to allow for all piling and pile fixing. Consequently, the accuracy of short-term forecasting can be as important as the values of the metocean parameters.

Examples of routine activities that are weather-sensitive:

— use of cranes for lifting to and from supply boats;

— use of cranes for moving items around decks;

— under-deck access;

— use of drilling derrick, particularly derrick movements;

— helicopter movements;

— personnel transfer operations by boat.

These activities generally have different weather sensitivities. Limiting criteria shall be established for each activity. In many cases the limitations are established by considering the safety of personnel.

It is useful in the planning of a development or the planning of a specific activity to know that the probability of the metocean parameters exceeding the criteria for particular activities is sufficiently low for sufficient time to complete these activities. The probability of sufficiently calm conditions varies considerably through the year, usually with longer calmer periods occurring during the summer months.

Predictions of the variation of the relevant metocean parameters should be made from the metocean database. Predictions should provide either the proportion of time and the durations for which metocean parameters are expected to remain within limiting criteria, or the probability of the values of certain metocean parameters being exceeded. Seasonal variations (by month or by quarter) should be reported if these are significant.

6 Water depth, tides and storm surges

6.1 General

The water depth at the site, including variations of the water depth, shall be determined where significant for the type of structure being considered.

The range of water depths at a particular site is important for the design of structures as it affects several parameters, including

— the environmental actions on the structure,

— the elevations of boat landings, fenders, and cellar deck on bottom founded structures,

— the riser length/stroke on floating structures, and

— mooring forces for taut or vertically moored floating structures.

For the purpose of design or assessment, the water depth can be considered to consist of a more or less stationary component, this being the water depth to a reference datum (e.g. LAT or MSL), and variations with time relative to this level, see Figure 1. The variations are due to the astronomical tide (see 6.2) and to the wind and atmospheric pressure, which can create storm surges (which may be positive or negative) (see 6.3). Other variations in water level can result from long-term climatic variations, sea floor subsidence or episodic events such as tsunamis. Water level variations have a relatively minor impact in deep water, but can be considerably more important in shallow water.

It is important for the design of all structures (and in particular bottom founded structures in shallow water) to have a good knowledge of the joint distribution of the tide, the storm surge height and the crest and trough elevations of the waves.

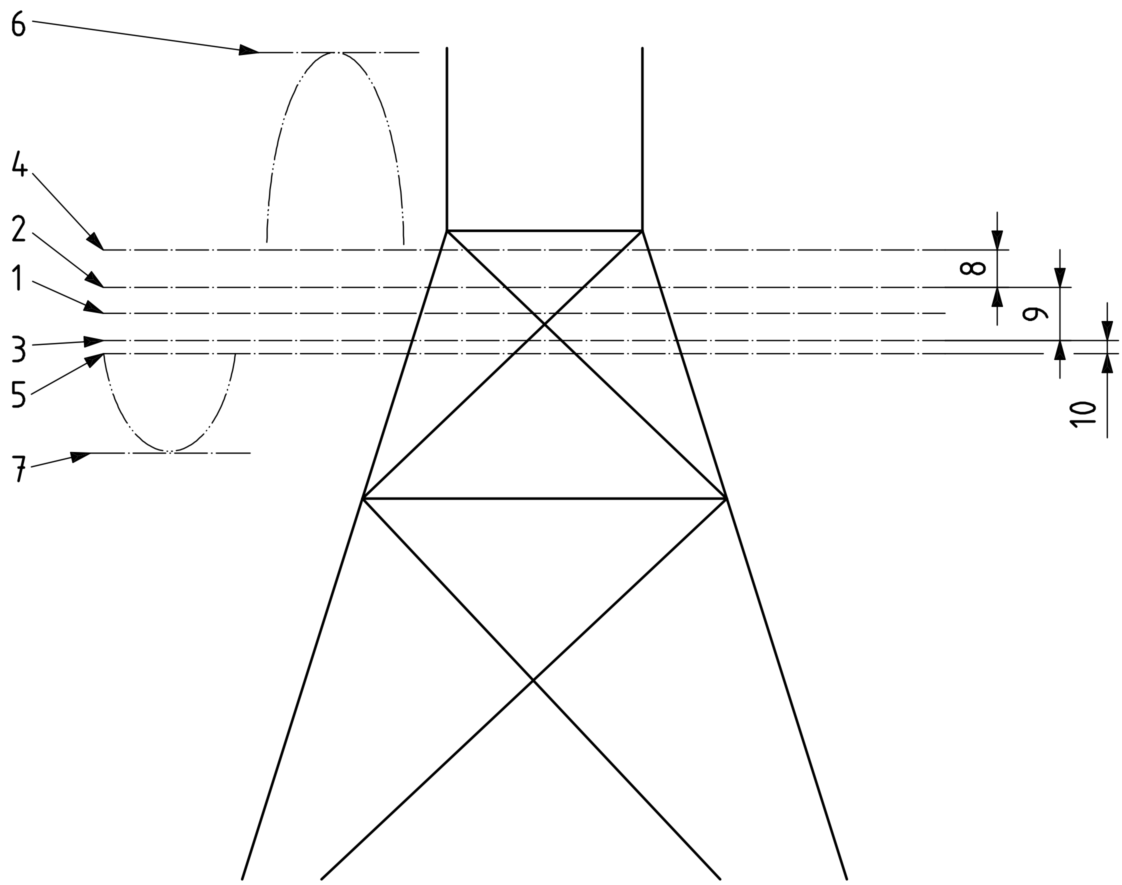
6.2 Tides

Tidal variations are the result of the gravitational and rotational interaction between the sun, moon and earth and are regular and largely predictable; they are bounded by the highest astronomical tide (HAT) and the lowest astronomical tide (LAT) at the site.

The variations in elevation of the daily astronomical tides determine the elevations of boat landings, fenders, splash-zone treatment, conductors and risers, and the upper limits of marine growth for bottom founded structures.

6.3 Storm surge

Storm surges, which are meteorologically generated and hence essentially random, are superimposed on the tidal variations, such that total still water levels above HAT and below LAT can occur.



Key

1 mean sea level
2 highest astronomical tide (HAT)
3 lowest astronomical tide (LAT)
4 highest still water level
5 lowest still water level
6 maximum crest elevation
7 minimum trough elevation
8 positive storm surge
9 tidal range
10 negative storm surge

Figure 1 — Water depth, tides and storm surges

7 Wind

7.1 General

Wind speed and direction vary in space and time. There are normally insufficient data available to describe the spatial and time variations in great detail, while for most applications this is also unnecessary. Therefore, descriptions of the wind field are usually substantially simplified in that wind parameters are described in statistical terms, such as the mean and the standard deviation of the speed, as well as the mean direction. For the definition of such statistical parameters, both length scales and time scales are required.

On length scales typical of even the largest offshore structures, the mean and standard deviation of the wind speed, averaged over durations of the order of an hour, do not vary horizontally, but they do change with elevation (wind profile). For averaging durations shorter than an hour, there will be periods with higher mean speeds, while also the spatial variations will increase. Therefore, a wind speed value is only meaningful if it is qualified by its elevation as well as the duration over which it is averaged, and hence both elevation and averaging time interval should be specified. An elevation of 10 m above mean sea level is used as a standard reference height.

Wind speeds are classified as either

— sustained wind speeds, or

— gust wind speeds.

The elevation, duration and measurement period of a gust should always be reported.

Extreme gusts occur due to a variety of phenomena. These include squalls, thunderstorms, downbursts, tornados, water spouts, all of which are relatively short-lived. The ratio of maximum gust wind speed to hourly mean wind speed at any one location in these examples can be large.

However, gusts also occur during periods of high hourly mean wind speed due simply to turbulence, but in this case the ratio of maximum gust wind speed to hourly mean wind speed over the sea is typically less than about 1,5.

Wind conditions shall be determined by proper analysis of wind data. Guidance on collecting wind data is given in A.7.1.

To determine appropriate design situations for offshore structures with regard to wind, the extreme, abnormal and normal wind conditions shall be specified in accordance with the type of structure and the nature of the structure's response. Wind turbulence in gusts has three-dimensional spatial scales related to the durations. For example, 3 s gusts are coherent over shorter distances and therefore affect smaller components of a structure than 15 s gusts. For structures (structural components) that are subject to appreciable dynamic response, it can be necessary to take the time variation of actions caused by wind into account. Further guidance is provided below, while procedures for determining actions and action effects caused by wind for different types of structure shall be in accordance with ISO 19902 for fixed steel structures, ISO 19903 for fixed concrete structures and ISO 19904-1 for floating structures (monohulls, semi-submersibles and spars). See ISO 19904-2[1] for those relating to tension leg platforms, ISO 19905-1[2] for site-specific assessments of jack-ups, ISO 19906[3] for arctic structures and ISO 19901-3[4] for topsides structures.

7.2 Wind actions and action effects

Wind acts on the topsides and that portion of the structure that is above the water, as well as upon any equipment, deck houses, bridges, flare-booms, and derricks that are located on the topsides. As the wind speed varies with elevation, the height of the component shall be taken into account. A vertical wind profile that can be used is discussed in 7.3 and provided by A.7.3.

For the design of offshore structures that respond globally in a nearly static fashion, global actions caused by wind are generally much less important than those caused by waves and currents. However, for the local response of certain parts or of individual components of these structures, the action effects caused by wind can be significant. Global actions on structures shall be determined using a time-averaged design speed in the form of a sustained wind speed. For the design of individual structural components, a time-averaged wind speed can also be adequate, but the averaging duration shall be reduced to allow for the smaller turbulence scale that can affect individual components. Local actions on individual components shall therefore be determined using a gust wind speed. Guidance on the selection of appropriate averaging times is given in A.7.2.

For the design of offshore structures (structural components) that are subject to appreciable dynamic response, the time and spatial variation of the wind speed needs to be accounted for. A dynamic analysis of a structure (structural components) is generally necessary when the wind field contains energy at frequencies near the natural frequencies of the structure (structural components). Such analyses require detailed knowledge of the wind turbulence intensity, the wind frequency spectrum and its spatial coherence, see 7.4.

A special case of dynamic response is vortex induced vibration (VIV) of relatively slender structures subjected to steady winds in which alternate vortex shedding excites components. Components of fixed steel offshore structures can be exposed to VIV during construction and transportation. Flare structures and telecommunication towers can also be susceptible to VIV throughout their lives.

Wind should be considered in detail for compliant bottom founded structures and floating structures.

7.3 Wind profile and time-averaged wind speed

The vertical profile of the mean wind speed in storms is usually expressed by a logarithmic function. Adjustments to the wind profile at a particular location or under certain conditions may be made when specific appropriate measured data from an offshore location are available (i.e. measured data for the kind of event used in design).

7.4 Wind spectra

If a structure (a structural component) is subject to appreciable dynamic response due to wind action, the time and spatial variation of the wind speed shall be considered. Turbulent wind may be viewed as an evolving field of vortices being swept past the structure. Additional turbulence is generated by the structure itself. The most accurate wind actions are derived from physical testing in a boundary layer wind tunnel, or by using computational fluid dynamics. Useable results may be obtained from a time series of wind velocity generated by adding spectral frequency components (mathematically as described below for waves) to the mean wind speed. In the absence of three-dimensional wind modelling, only the speed fluctuations in the mean wind direction may be described. An appropriate form of the frequency spectrum for wind speeds in the mean direction is given in A.7.4. The spatial variation of the wind speed in the mean direction between two points in space is expressed by means of a coherence function, see A.7.4.

The concept of a wind spectrum is only applicable to steady wind conditions. As squalls are not steady, the time and spatial variation of the wind speed in a squall cannot be described by a wind spectrum. Analysis of actions and action effects caused by squalls requires the specification of a time series of wind velocity.

8 Waves

8.1 General

Ocean waves are irregular in shape, vary in height, length and speed of propagation, and approach a structure from one or more directions simultaneously. These features of a real sea are best reflected by describing a sea state by means of a random wave model. The linear random wave model views the sea as the superimposition of many small individual frequency components, each of which is a periodic wave with its own amplitude, frequency and direction of propagation; the components have random phase relationships with respect to each other.

The wave conditions existing in a sea state can be distinguished into two broad classes: wind seas and swells. Wind seas are generated by the local wind in the area, while swells have no relationship with the local wind. Swells consist of wind-driven waves that have travelled out of the area in which they were generated.

In some applications, periodic or regular waves can be used as an adequate abstract of a real sea for design purposes. Periodic waves are also the building blocks for the linear random wave model.

For most geographical areas, waves are the major source of environmental actions on all offshore structures. The intensity and distribution of the actions caused by waves are usually the most important contribution to the action effects that govern the design of a structure. Actions caused by waves depend on combinations of several environmental parameters. The type, magnitude and interactions of these parameters are difficult to determine with any precision. For these reasons, the relevant wave conditions, the parameters to adequately describe these and the resulting actions and action effects shall be determined with great care. Procedures for determining actions and action effects caused by waves for different types of structure shall be in accordance with ISO 19902 for fixed steel structures, ISO 19903 for fixed concrete structures, ISO 19904-1 for floating structures (monohulls, semi-submersibles and spars), ISO 19904-2[1] for tension leg platforms, ISO 19905-1[2] for site-specific assessments of jack-ups, ISO 19906[3] for arctic structures and ISO 19901-3[4] for topsides structures.

For structures that only respond in a quasi-static mode, it can be sufficient to use individual periodic waves. The most important wave parameters required to describe a single, periodic design wave are its height, crest elevation above still water level, period and direction of travel. The wave kinematics properties can then be estimated using the local still water depth. The distribution of individual waves in a given sea state can be estimated from statistical wave parameters, such as the significant wave height and the mean zero-crossing period.

Structures with significant dynamic response require wave energy spectra or time series of the surface elevation for their analysis. These may be specified in a number of ways; a common approach is to use a sea state defined by a standard wave frequency spectrum, with a given significant wave height, a representative frequency/period, a mean wave direction and, sometimes, a directional spreading function.

The description of a sea state should include its duration; this is normally assumed to be 3 h but depends on the particular weather situation and how the design situation and associated criteria have been derived.

8.2 Wave actions and action effects

Waves shall be specified in an appropriate way for the type of structure under consideration, for extreme, for abnormal and for normal conditions (see 8.1).

Important features of periodic waves and their use are given in 8.3 to 8.5. Details of the linear random wave model are presented in 8.6 and 8.7. The height of the highest wave crests in extreme and abnormal environmental conditions can be of special significance in certain situations, see 8.8.

8.3 Intrinsic, apparent and encounter wave periods

Wave periods appear to be different depending on the relative velocities of wave propagation and the reference frame of an observer. This is due to the Doppler effect. For example, an observer moving against the direction of the waves encounters successive wave crests more quickly than an observer travelling in the same direction as the waves.

All wave theories are developed using a reference frame which is a right-handed orthogonal coordinate system on a body of water without current. The horizontal xy-plane is the still water surface and the vertical z-axis points upward from the still water level. The wave direction is measured (in the horizontal plane) from the positive x-axis using the right-hand rule. This is the intrinsic reference frame for the waves.

When waves are superimposed on a (uniform) current, the intrinsic reference frame for the waves travels at the speed and in the direction of the underlying current.

Three particular situations are the following.

- An observer travelling at the same speed and in the same direction as the current is stationary with respect to the intrinsic reference frame and will therefore measure the intrinsic wave period T_i.
- An observer on a fixed structure is stationary relative to the seabed and measures the apparent wave period, T_a. If the waves are travelling in the same direction as the current, approaching wave crests pass the platform more quickly than if there was no current and consequently the apparent period is shorter than the intrinsic period. Similarly, if the waves are travelling against the current the apparent period is longer than the intrinsic period. If there is no current, the fixed structure is stationary with respect to the intrinsic reference frame and hence $T_a = T_i$.
- An observer on a moving vessel (having a velocity relative to the seabed) measures the encounter wave period, T_e. The difference between T_e and T_i depends on the relative speeds and directions of the moving vessel and of the current. If the moving vessel is travelling at the same speed and in the same direction as the current, then $T_e = T_i$.

See A.8.3 for the relationship between T_i, T_a and T_e.

Wave kinematics for the calculation of actions caused by waves shall be derived from the intrinsic wave period (or the intrinsic wave frequency).

8.4 Two-dimensional wave kinematics

For an intrinsic wave period (T_i), a specified wave height (H) and water depth (d), two-dimensional regular wave kinematics can be calculated using an appropriate periodic wave theory. Discussion on the wave theories, their applicability and references is given in A.8.4.

Linear (or Airy) theory is the basic periodic wave theory for all applications. However, as this is based on linearization of the physical process, the free surface boundary condition coincides with the still water level. The main drawback of Airy theory is therefore that it cannot describe the wave kinematics between the wave crest and the still water level. Moreover, it can be inaccurate in relatively steep wave conditions.

Where linearization can be justified, or if it is to be adopted in connection with overriding modelling assumptions (see 8.1), Airy theory may be used. If time series analysis is used, the kinematics should be stretched to the instantaneous free surface elevation using either linear stretching (also known as Wheeler stretching, see A.9.4.1) or delta stretching (see A.8.4).

For design waves and the determination of actions caused by waves on structures containing predominantly slender tubular components, such as fixed steel space frame structures, a non-linear periodic wave theory such as a suitable order of stream function theory is normally used. In many cases, Stokes 5th order wave theory will produce acceptable accuracy, while in some cases linear (or Airy) wave theory will even be adequate. Other wave theories, such as Extended Velocity Potential and Chappelear theory, may also be used if an appropriate order of solution is selected. As an alternative to periodic wave theories, representative waves from a random sea derived with wave theories such as New-wave theory may be used. New-wave theory is a linear representation of the most probable maximum waveform in a (severe) random sea. To ensure approximate parity of actions caused by different design waves, the crest elevation in New-wave shall then be taken as 5/9 times the wave height used in Stokes 5th order or stream function theory. Delta stretching should be used with New-wave.

8.5 Maximum height of an individual wave for long return periods

If regular (periodic) waves are adequate for use as a design wave for an offshore structure, the maximum height of an individual wave with the specified return period, H_N, (e.g. H_{100} for 100 year return period and 0,01 annual probability of exceedance) is the single most important wave parameter to be determined. The data provided by measurement programmes or hindcasts are time series of significant wave height and mean zero-crossing period (or spectral peak period). The required long-term, individual wave height, H_N, shall be established by convolution of long-term distributions derived from the data with a short-term distribution that accounts for the distribution of individual wave heights in a sea state.

8.6 Wave spectra

It is often useful or necessary to describe a sea state in terms of the linear random wave model by specifying a wave spectrum, which determines the energy in different frequency and/or direction bands. Parameters required for defining a wave spectrum are the significant wave height and a representative frequency or period. For many applications, wave direction, wave spreading and peakedness of the wave spectrum are also required.

There are several standard wave frequency spectra in use; the most appropriate spectral form depends on the geographical area, the severity of the sea state to be modelled and the application concerned.

Further discussion and guidance on wave spectra and the most common parametric forms for the wave frequency spectrum are given in A.8.6 and Annex B.

8.7 Wave directional spreading function and spreading factor

As the water surface elevation in a sea state is in reality three-dimensional (short-crested), the wave frequency spectrum may be supplemented by a directional spreading function. Parametric forms for the wave directional spreading function are given in A.8.7.

Two-dimensional regular wave theories do not account in their kinematics for irregularity in the wave profile shape nor for wave directional spreading. Where appropriate, directional spreading can be approximately modelled in periodic wave analyses by multiplying the horizontal velocities and accelerations from the two-dimensional periodic wave solution by a wave directional spreading factor ϕ, see A.8.7.

The wave directional spreading factor may be modified, if justified, to account for spatial effects.

8.8 Wave crest elevation

Knowledge of the distribution of extreme and abnormal crest elevations is required for setting minimum deck heights on bottom founded structures and for assessing the probability of green water intruding onto the topsides of all types of structures and decks and hulls which are intended to be kept above the waves.

For structures where there can be significant wave-structure interaction (e.g. for structures with a caisson or with very large diameter legs), the possible enhancement of the crest elevation due to the presence of the structure shall be considered. This enhancement often does not lead to large increases in the global actions on the structure, but can impose significant local pressures on the underside of the topsides. It can also impede offshore (particularly under-deck) operations, and local measures to reduce its effect can be necessary.

9 Currents

9.1 General

Currents affect the design, construction and operation of offshore structures in various ways. In addition to their impact on the environmental actions and action effects on the structure, they affect the location and orientation of boat landings and fenders, can create sea floor scouring, and often have an adverse effect on operating practices. All of these factors can influence the structure's design.

The current velocity generally varies through the water column. Information on the vertical profile is given in 9.3. Where currents co-exist with waves, the current profile is stretched and compressed with the water surface elevation; guidance on current profile stretching is provided in 9.4. Currents can also be modified by partly transparent structures, see 9.5.

9.2 Current velocities

Like wind, current speeds also vary in space and time but at much lower rates. Therefore, currents may generally be considered as a steady flow field in which velocity is only a function of depth.

The total current velocity is the vector-sum of the tidal and residual currents. The components of the residual current can include circulation and storm-generated currents, as well as short- and long period currents generated by various phenomena, such as density gradients, wind stress and internal waves. Residual currents are often irregular, but at many locations the largest component of the residual current to be considered is the wind driven current.

Tidal currents are regular and predictable and the maximum tidal current precedes or follows the highest and lowest astronomical tides, HAT and LAT. They are generally weak in deep water outside the continental shelves, and generally stronger on broad continental shelves than on steep shelves. Tidal currents can, however, be strengthened by shoreline or sea floor configurations; strong tidal currents exist in many inlets and coastal regions, e.g. surface values of approximately 3 m/s occur in Alaska's Cook Inlet.

Circulation currents are relatively steady, large-scale features of the general oceanic circulation. Examples include the Gulf Stream in the Atlantic Ocean and the Loop Current in the Gulf of Mexico, where surface velocities can be in the range of approximately 1 to 2 m/s. While relatively steady, these circulation features can meander and intermittently break off from the main circulation feature to become large-scale eddies or rings, which then drift at a speed of a few kilometres per day. Velocities in such eddies or rings can approach or exceed that of the main circulation feature. These circulation features and associated eddies occur in deep water beyond the shelf break, but in some areas of the world they can affect shallow water sites.

Storm-generated currents are caused by the wind stress and atmospheric pressure gradient throughout a storm. Storm current velocities are a complex function of the storm strength and meteorological characteristics, bathymetry and shoreline configuration, and water density profile. In deep water along open coastlines, surface storm currents can be roughly estimated to have velocities up to 3 % of the 1 h sustained wind speed during storms. As a storm approaches the coastline and shallower water, the storm surge and current can increase, and after a storm has passed inertial currents can persist for some time.

Sources of information about the statistical distribution of currents and their variation with depth through the water column are generally scarce in most areas of the world. To avoid encountering problems during early phases such as exploration drilling, concerted measurement campaigns are required to acquire the data, particularly in remote, deep water areas near the edges of continental shelves. In deep water areas (water depths greater than typically 200 m) such as in the Gulf of Mexico and along the northern and eastern coasts of South America, the effect of currents on offshore operations and the design of structures can be more important than the effect of waves.

The variation of current velocity and direction with depth shall be determined by an experienced metocean expert.

9.3 Current profile

The variation of current speeds and directions through the water column shall be determined for the specific location of the structure, taking account of all available information. For situations in which the direction of the current velocities over the full water column is the same and simple profiles are appropriate, guidance is provided in A.9.3.

9.4 Current profile stretching

Current speeds and current profiles are determined for still water conditions, although in some conditions they are applicable to storm conditions. The current profile is modified by the presence of waves, with a component of the current being present throughout the water column from sea floor to free water surface (between wave crest and wave trough).

Wave kinematics, adjusted for directional spreading where appropriate, shall be vectorially combined with the current velocities, adjusted for blockage where appropriate (see 9.5). As the current profile in design environmental conditions is specified only up to the storm still water level, the profile to the local instantaneous wave surface shall be modified by some means, see A.9.4.

9.5 Current blockage

The current velocity around and through a structure is modified by blockage. The presence of the structure causes the incident flow to diverge, with some of the flow going around the structure rather than through it. For structures that are more or less transparent, the current velocities within the structure are reduced from the free stream values.

The degree of blockage depends on the type of structure. For dense, fixed space frame structures it will be large, while for some types of transparent floaters it will be very small. More specific advice for the treatment of current blockage for different types of structure is given in ISO 19902 for fixed steel structures, ISO 19903 for fixed concrete structures and ISO 19904-1 for floating structures (monohulls, semi-submersibles and spars). See ISO 19904-2[1] for procedures relating to tension leg platforms, ISO 19905-1[2] for site-specific assessments of jack-ups, ISO 19906[3] for arctic structures and ISO 19901-3[4] for topsides structures.

10 Other environmental factors

10.1 Marine growth

The thickness and type of marine growth depends on location, the age of the structure and the maintenance regime. Experience in one area of the world cannot necessarily be applied to another. Where necessary, site-specific studies shall be conducted to establish the likely thickness and its depth dependence.

Marine growth on submerged structural components and other parts of a structure shall be considered. Due consideration shall be given to the influence of marine growth on hydrodynamic actions during its design service life, as well as to the increased mass and its influence on dynamic response and the associated mass inertial forces.

Marine growth thickness and type vary with depth. The influence of marine growth on hydrodynamic actions is due to increased dimensions and increased drag coefficients due to roughness. Structural components, conductors, risers and appurtenances shall be increased in cross-sectional area to account for marine growth thickness as appropriate. Components with circular cross-sections should be classed as either “smooth” or “rough”, depending on the thickness and type of marine growth expected to accumulate on them.

Structural components can be considered hydrodynamically smooth if they are either above HAT or sufficiently deep such that marine growth is sparse enough to ignore the effect of roughness. However, caution should be exercised, as a small increase in roughness can cause an increase of the drag coefficient corresponding to those of rough surfaces. Site-specific data should be used to establish the extent of the hydrodynamically rough zones. Otherwise, structural components should be considered as being rough down to the sea floor.

More specific advice for the different types of structure is given in ISO 19902 for fixed steel structures, ISO 19903 for fixed concrete structures, ISO 19904-1 for floating structures (monohulls, semi-submersibles and spars), ISO 19904-2[1] for tension leg platforms, ISO 19905-1[2] for site-specific assessments of jack-ups, ISO 19906[3] for arctic structures and ISO 19901-3[4] for topsides structures.

10.2 Tsunamis

Tsunamis are water waves caused by impulsive disturbances that displace a large water mass in the sea. The main disturbances causing tsunamis are earthquakes, but they can also be generated by seabed subsidence, landslides, underwater volcanoes, nuclear explosions, and even impacts from objects from outer space (meteorites, asteroids, and comets). Their wavelength is several tens of kilometres and they have periods in the range of 5 to 100 min. Their speed of propagation across the ocean is a function primarily of water depth; in the deepest oceans the tsunami waves can travel at speeds of several hundred kilometres per hour.

In deep water, tsunamis have a low height and very long period and pose little hazard to floating or fixed offshore structures. Tsunamis contain more energy when they are generated in deeper water, and can be extremely destructive when they impact on the coast. When they reach shallow water, the wave form pushes upward from the bottom to create a rise and fall of water that can break in shallow water and wash inland with great power.

The greatest hazard to offshore structures from tsunamis results from inflow and outflow of water in the form of waves and currents. These waves can be significant in shallow water, causing substantial actions on structures. Currents caused by the inflow and outflow of water can cause excessive scour problems.

Tsunamis travel great distances very quickly and can affect regions that are not normally associated with the disturbances that cause them. The likelihood of tsunamis affecting the location of the platform shall be considered.

10.3 Seiches

Coastal measurements of sea level in semi-enclosed bodies of water often show seiches with amplitudes of a few centimetres and periods of a few minutes due to oscillations of the local harbour, estuary or bay, superimposed on the normal tidal changes. Normally, variations are small enough offshore that they can be ignored, but if a platform is located in shallow, partly enclosed seas, the effect of seiches should be considered.

10.4 Sea ice and icebergs

Sea ice and icebergs can affect the design and operation of platforms. Before commencing design for, construction of, or operations on, platforms in areas that are likely to be affected by sea ice and icebergs, adequate data shall be collected. In vulnerable areas the data shall include

- the seasonal distribution of sea ice,
- the distribution and probability of ice floes, pressure ridges and/or icebergs,
- the effect of ice-gouges on the seabed from icebergs or ice ridges,
- the type, thickness and representative features of sea ice,
- drift speed, direction, shape and mass of ice floes, pressure ridges and/or icebergs, and
- strength and other mechanical properties of the ice.

These data shall be used to determine design characteristics of the installation as well as possible evacuation procedures.

For more specific advice on sea ice and icebergs, see ISO 19906[3].

10.5 Snow and ice accretion

Where relevant, snow accumulation (e.g. on the roofs of buildings) and ice accretion (e.g. on lattice structures) shall be considered in the design of structures.

An estimate shall be made of the extent to which snow can accumulate on the structure and topsides and of its possible effect on the structure.

Topsides icing can increase the diameter of structural components and can lead to a substantial increase of actions caused by wind and gravity, particularly for long, slender structures such as flares. Icing from sea spray, freezing rain or drizzle, freezing fog, or cloud droplets shall be considered in the design.

For more specific advice on snow and ice accretion, see ISO 19906[3].

10.6 Miscellaneous

Depending on circumstances, other environmental factors can affect operations and can consequently influence the design of structures. Appropriate data shall be compiled, including, where appropriate, records and/or predictions of

- air and sea temperatures,
- precipitation,
- humidity,
- fog,
- wind chill,
- salinity,
- the oxygen content of the sea water, and
- guano accumulations.

Annex A
(informative)

Additional information and guidance

NOTE The clauses in this annex provide additional information and guidance on clauses in the body of this part of ISO 19901. The same numbering system and heading titles have been used for ease in identifying the subclause in the body of this part of ISO 19901 to which it relates.

A.1 Scope

Environmental conditions generally have a significant influence on the design and the construction of offshore structures of all types. In some areas of the world, the prevailing environmental conditions can also have an influence on the operational aspects of a platform, which in turn can affect the design of the structure.

The environmental conditions and metocean parameters discussed herein relate to the pre-service, the in-service and the removal phases of structures.

It is beyond the scope of this document to provide detailed instructions that can be followed to produce reliable estimates of extreme or abnormal conditions in all areas and in all cases.

Requirements for the calculation of environmental actions on offshore structures and the resulting action effects are given in ISO 19902 for fixed steel structures, ISO 19903 for fixed concrete structures, ISO 19904-1 for floating structures (monohulls, semi-submersibles and spars), ISO 19904-2[1] for tension leg platforms, ISO 19905-1[2] for site-specific assessments of jack-ups, ISO 19906[3] for arctic structures and ISO 19901-3[4] for topsides structures.

A.2 Normative references

No guidance is offered.

A.3 Terms and definitions

No guidance is offered.

A.4 Symbols and abbreviations

No guidance is offered.

A.5 Determining the relevant metocean parameters

A.5.1 General

The design parameters should be chosen after considering all of the relevant service and operating requirements for the particular type of structure.

Selection of environmental conditions and the values of the associated parameters should be made after consultation with both the platform designer and appropriate specialists in oceanography, meteorology and related fields. The sources of all data should be noted. The methods used to develop available data into the desired metocean parameters and their values should be defined.

General information on the various types of environmental conditions that can affect the site of the structure should be used to supplement data developed for normal conditions. Statistics can be compiled giving the expected occurrence of metocean parameters by season, direction of approach, etc.

Of special interest for the planning of construction activities, platform operations and evacuation are the duration, the speed of development, the speed of movement and the extent of storm conditions. The ability to forecast storms in the vicinity of a structure is very significant.

If the amount of metocean data available is very limited (particularly in the early phases of a project), the extreme and abnormal metocean conditions should be derived conservatively. If, in the judgement of the metocean expert, there is considerable uncertainty in the data, the extremes should be set too high rather than too low. A subsequent increase in extreme values later in a project can have both safety and economic consequences[5].

A.5.2 Expert interpretation of the metocean database

It is important to select a metocean expert with experience in all facets of the process; this includes the hardware and software associated with data gathering (*in-situ* or remote sensing), hindcasting procedures, data sampling and analysis procedures, and extreme statistical analysis techniques.

The approach used to determine metocean parameters will often be dictated by the available data itself (measured, continuous, storm hindcasts, ship's visual observations, satellite, radar, etc.). Understanding of the methods used to record and analyse the data is critical; as is knowledge of how these methods and data can influence the selection of an analysis approach or possibly bias the result. A sound understanding of the data techniques is necessary in order to be able to account for them during interpretation of the data sets and to apply any corrections that could be necessary to the final estimates.

Given a suitable database of measured and/or hindcast data, it is important to investigate the sensitivity of estimates to the use of different data sets (measured or hindcast) and statistical analysis procedures. It is important that the design engineer who will use the metocean parameters is aware of the uncertainty (preferably by a quantitative assessment) in the parameters provided. Relatively small changes in estimates of the design wave height (in particular) can affect the reliability of a fixed structure by an order of magnitude. However, given reliable long-term data sets, the various statistical approaches should tend to similar results.

It is recommended that the metocean experts are integral members of design teams, particularly when the environmental conditions and associated metocean parameters used for the design of proposed structures are based on design criteria for actions (action effects) with long return periods.

A.5.3 to A.5.9 provide brief general descriptions of the principal considerations for deriving safe, reliable metocean parameters to support the design of different types of offshore structures and associated operations.

A.5.3 Selecting appropriate parameters for determining design actions or action effects

The design of structures is often governed by extreme actions or extreme action effects caused by the environment. The design conditions are quantified in terms of a parameter (e.g. wave height) or action effect (e.g. global bending moment on a hull). Thus, the term “100 year storm” has no meaning except as an informal description of a set of conditions that introduce the parameter or action effect.

The return period in years, for larger values of return period, can be taken as the inverse of the annual probability of exceedance of a parameter (e.g. a wave height or wind speed).

Three methods are discussed below for defining an environment that generates the extreme direct action and, generally, also the extreme action effect, caused by the combined extreme wind, wave and current conditions. Other methods are possible.

a) Specified return period wave height (significant or individual) with "associated" wave period, wind and current velocities.

This has been the established practice for deriving wind and current extremes occurring simultaneously with the wave height in some areas (e.g. USA). The specified return period is usually 100 years. It has also been used for deriving secondary parameters (such as wave periods) in the North Sea. The "associated" wave period, current, or wind is the value expected to co-exist with the specified return period wave height. The method is applicable if

— there is a statistically significant correlation between the associated value and the specified return period wave height, and

— the extreme global environmental action on the structure is dominated by waves.

Wave dominance will apply to the majority of the structures covered by this document. However, the correlation between current velocity and wave height is not significant in many geographical areas (e.g. areas where the current is dominated by tide).

One way of developing the associated value of a particular parameter is to find a (positive) correlation between the parameter and the wave height. For example, assume a model hindcast has been made in a region dominated by tropical storms. To find the associated current, one can develop a regression plot of the modelled significant wave height versus current velocity at or near the peak of each storm. To account for directionality, the current component in line with the significant wave height can be used. Assuming this plot shows that the current is statistically correlated with the wave, an equation can be developed for the in-line current as a function of significant wave height. The associated current is then the value given from the equation using the specified return period significant wave height.

If there is not a strong correlation between waves and current or if the global environmental action is not wave-dominated, then there is no explicit confirmation in this method that the combination of the primary metocean parameter (here, wave height) and its associated parameters (here, current and wind velocities) will approximate to the return period global environmental action on a structure. By contrast, method c) below, when correctly applied, will always provide a good estimate of the specified return period global environmental action.

When the present method is used for structures that are sensitive to wave period, the most onerous combination of wave height and period can be at a different period from that associated with the maximum specified return period wave height. Consequently, a reasonable range of variations in both period and wave height should be investigated to determine the most onerous combination of wave height and period with the same, or higher, probability of occurrence than the specified return period.

b) Specified return period wave height combined with the wind speed and the current velocity with the same specified return period, all determined by extrapolation of the individual parameters considered independently.

This method has been used in the North Sea and many other areas of the world, normally with a return period of 50 or 100 years. A modified version, using the 100 year wave height and the 100 year wind speed combined with the 10 year current velocity, has been used in Norway.

The method is simple, independent of the structure, and can be determined from separate (marginal) statistics of waves, currents and wind. It will always yield results that are conservative compared to either of the two other methods for the same specified return period when used to determine design actions for fixed structures, but is not appropriate for floating and other types of structure with significant dynamic response.

c) Any “reasonable” combination of wave height and period, wind speed and current velocity that results in

— the global extreme environmental action on the structure with the specified return period, or

— a relevant action effect (global response) of the structure (base shear, overturning moment, floater displacement, etc.) with the specified return period.

This method involves calculating an associated current and wind speed using the wave height and one or several critical structural response functions (action effects), such as base shear or overturning moment on a fixed structure or horizontal displacement of a floating structure[6], [7], [8]. Directional effects of wind, wave and current, and water depth fluctuation due to tide and surge, are fully accounted for. Storms are treated as independent events and short-term uncertainty is taken into account. The long-term distribution of the structural response is then determined and from this its extreme and abnormal values. The same structural response function can be used to determine combinations of metocean parameters leading to the desired return period extreme and abnormal responses. It should be noted that a set of parameters is not unique: several other related sets will produce the same result. In addition, the statistics can be used in the development of partial factors for environmental actions (action effects) as described below. Reference [6] describes the procedure in some detail.

Although this method can involve time and cost in developing software, it can provide a realistic set of design parameters — even if there is little correlation between waves, winds and currents. Thus, defining the specified return period action or action effect has a significant advantage over defining the specified return period wave height, either with associated or with specified return period values of wind and current. The definition of the action or action effect should not use an arbitrary set of related wave, wind and current values that satisfies the specified return period global environmental action or action effect, but should make a “reasonable” (expected) choice so as to correctly model the probable spatial distribution of global hydrodynamic actions over the structure. Reasonably accurate combinations of metocean parameters can be deduced from observing the combinations that cause the greatest responses in the storms used in developing response statistics.

Additional consideration should be given to obtaining extreme direct actions (action effects) for locations where there are strong currents that are not driven by local storms. Such currents can be driven by tides or deep water currents, such as the Loop Current in the Gulf of Mexico or the Gulf Stream. In this case, method a) can be acceptable if the storm-generated conditions are the predominant contributors to the extreme global environmental action (action effect) and if the appropriate “associated” value of tidal and circulation current can be determined. However, method c) is conceptually more straightforward and preferable. Method b) is the simplest method and ensures an adequate design environmental action (action effect); however, this can be very conservative compared to the true global environmental action (action effect) of the required return period.

For some areas, substantial databases are becoming available with which it is possible to establish statistics of joint occurrence of wind, wave and current magnitudes and directions. When sufficient data are available, method c) above should be used. The corresponding partial factors to be used in conjunction with the global environmental action (action effect) should be determined using reliability analysis principles, in order to ensure that an appropriate safety level is achieved. This approach provides more consistent reliability (safety) for different geographic areas than has been achieved by the practice of using separate (marginal) statistics of winds, currents, and waves.

Reference [9] contains an example of selecting appropriate wind factors for jack-ups.

A.5.4 The metocean database

There are various circumstances in which site-specific data from measurements or hindcasts should be analysed in order to produce metocean parameters, including the following:

— where regulatory requirements insist on the use of site-specific data;

— where the operator has field data in addition to the data used in producing the environmental conditions presented in standard guidance documents;

- where environmental conditions are not provided in standard guidance documents or are otherwise deemed by an operator to be inappropriate;
- where an operator may wish to produce metocean parameters for return periods other than those available in standard guidance documents.

A well-controlled series of measurements at the location of an offshore structure is a valuable reference source for establishing design situations as well as operating conditions and associated criteria, although measurements taken over a short duration may give misleading estimates of long-term extremes. Extremes derived from short-term, site-specific measurements should only be used in preference to any indicative values presented in standard guidance documents if care is taken to adjust the records to reflect long-term variability, e.g. by analysing the record together with several years of measurements or hindcasts from a nearby site.

Where there are known or expected long-term climate cycles, the database should be long enough to include at least one full cycle.

Site-specific measurements should be taken consistently throughout the period considered and, when required, in a manner suitable for estimating climatological extremes. It should also be recognized that measurements made during a climatologically anomalous period can dominate a data set, and the data can therefore be atypical of the long-term climate at the location.

Climatic variations during the design service life of structures can result in changes to

- the water level (mean, tide, and/or surge),
- the frequency of severe storms,
- the intensity of severe storms, and
- associated changes in the magnitude and frequency of extreme winds, waves and currents.

Wave height depends on wind speed, direction and fetch, all of which are potentially affected by changes in intensity, frequency and track of weather systems. The analysis of meteorological observations is affected by homogeneity problems in historical weather maps; to date, it has not been possible to be definite about changes in wind or wave statistics or storm tendencies in general.

The various application(s) for the database should be considered when determining the type(s) of wave hindcast model calibrations which are most appropriate. For example, if a primary concern is to derive downtime estimates for tanker-offloading operations in a mild climate (e.g. through the use of persistence analyses), it is important to verify the accuracy of the database for low sea states with a broad range of wave periods and directions. If the database will also be used for deriving fatigue estimates on deep water fixed or on bottom founded compliant structures, the database should be verified for the full dynamic range of significant wave heights (H_s) and wave periods (T_p or T_z), in order to derive representative directional wave scatter diagrams — perhaps together with estimates of directional associated current profiles.

If the database will be used for establishing extreme design parameters, it is important to establish that the database is as long and as accurate as possible. A judgement should be made on the suitability of the design parameters that have been developed, e.g. with respect to how climatologically representative the available database is. Factors that need to be considered include the time over which the data have been collected, and whether this time was climatologically normal in terms of the frequency and strength of storms.

When extrapolating metocean databases to small probabilities of exceedance, it is assumed that the database is representative of long-term conditions. This hypothesis should continue to be tested and, if necessary, suitable allowances should be made to incorporate any residual uncertainty.

Reference [10] contains guidelines for safe practice for undertaking metocean surveys.

A.5.5 Storm types in a region

The definition of environmental conditions and the associated metocean parameters that can occur in different storm types is an important part of understanding the workability of various offshore operations, as well as determining the process that will be needed to define the extreme and abnormal metocean parameters. For some areas, the definition of storm types is problematic, in particular in regions where tropical cyclones lose their identity and metamorphose into extratropical storms. Such storms can become very severe and their characteristics during the transition are not yet well understood[11]; the derivation of extreme and abnormal metocean parameters in such areas requires additional care.

A.5.6 Directionality

Where directional variations of parameters are used, the sectors should generally not be smaller than 45°. In addition, the environmental conditions should be scaled up such that the combined event from all sectors has the same probability of exceedance as the target return period, see Reference [12].

A.5.7 Extrapolation to rare conditions

The problem of determining low probability values of metocean parameters has become even more important because of the recent trend to use very rare events to directly calculate the failure probability of a structure. It is becoming increasingly common for owners and regulators to require consideration of the 1 000 to 10 000 year events, i.e. the 10^{-3} and 10^{-4} annual non-exceedance probability, respectively. Great caution should be used in extrapolating data to such extremely low probabilities.

There are two basic methods for calculating low probability values: the historical and the deductive methods.

The historical method takes data, either from measurements or model hindcasts, and fits the tail (low probability region) of the probability distribution with an appropriate extreme distribution such as Gumbel or Weibull. This historical method is the overwhelming favourite in the oil industry and is well documented in Reference [13].

The deductive method breaks a storm into a series of simplified sub-models with specified probabilities. The sub-models are eventually combined using probabilistic laws to develop events with much lower overall probabilities. Deductive models have been used to estimate extremes of earthquakes, storm surges and, to a lesser degree, winds and waves[14]. The method has recently received renewed interest because it can potentially provide more accurate extreme estimates than the historical method for very rare events having return periods from about 1 000 to 10 000 years.

Both methods have their strengths and weaknesses. The historical method is easy to apply. It requires simply using a curve-fitting routine (e.g. least squares or maximum likelihood) to fit an analytical expression (e.g. Gumbel, Weibull) to data originating from measurements or from a hindcast model. A disadvantage is that the statistical confidence in the extrapolated value rapidly decreases for return periods greater than two or three times the length of the database. It follows that extrapolations to very rare recurrence intervals of 1 000 years or greater are speculative given the length of commonly available data sets.

The deductive method begins by breaking the regional storm type into parameters whose probability can be determined from historical data, e.g. in the case of a hurricane this could be the radius to maximum wind, pressure deficit and forward speed. Synthetic storms are generated by combining the parameters accounting for their joint probability of occurrence. In the simplest case, where the parameters are statistically independent, the probability of a synthetic storm simply becomes the product of the probabilities of each of the storm's parameters. In this way very rare synthetic storms can be constructed using storm parameters with relatively high and statistically confident probabilities. Parameters that are statistically correlated complicate the analysis, but can be handled provided that the joint probability distributions can be deduced from the historical data. The main disadvantage of the deductive method is that it is time-consuming to apply, and in regions where storms are physically complicated it can be impossible to derive parameters that adequately describe the storms. The deductive method is applicable only if the extreme event is due to a rare combination of parameters which occur reasonably frequently within their individual distributions. Modelling such regions is a topic of ongoing research in the oil industry.

Since the deductive method is relatively uncommon and its application in the oil industry is still in its infancy, the remainder of this subclause relates to the historical method. Reference [13] provides a detailed discussion of how to apply the historical method.

When extrapolating data sets, the following recommendations and considerations are relevant.

- It has been argued that some distributions are theoretically superior to others. However, experience has shown that the most robust extreme estimates are obtained by finding the distribution that fits a subset of a reasonable number of the more extreme data points most closely using an error-minimizing algorithm (e.g. maximum likelihood method).

- When fitting data, care should be taken not to mix data from one type of storm event (e.g. winter storms) with data from another type of storm event (e.g. hurricanes). The probability distributions of the two types of extreme event are often a strong function of the storm physics (storm type) and mixing storm types can lead to non-conservative estimates of the extremes; each storm type should be fitted separately and then the combined statistics computed.

- Fitting should include a sufficient number of storms to achieve statistical confidence in the fit.

- Care should be taken not to extrapolate too far beyond the length of the data set. A good rule of thumb is not to derive metocean parameters with return periods more than a factor of four beyond the length of the data set. For example, at least a 25 year data set should be used to estimate the 100 year storm parameters.

- Bias should be removed from the data, whether the data are from measurements or from hindcast modelling. Biased data can lead to substantial offsets in the estimates of rare events which can be non-conservative because of the extrapolation process. Scatter (noise) increases the confidence limits on the extrapolations and can introduce positive bias. The bias tends to increase as one extrapolates further beyond the data.

- It is preferable to extrapolate a noisy data set of longer duration rather than a shorter-duration cleaner data set. For example, a 50 year model hindcast data set to estimate the 100 year storm is preferred to a few years of measurements, even though the hindcast results may have more scatter than the measurements. This assumes that bias has been removed from both data sources. It is emphasized that any model used to extrapolate data should be carefully validated against available measurements.

- A variety of different techniques should be considered before deciding on an extreme value, e.g. the use of different thresholds, different distributions, annual maxima, peak-over-threshold (POT) and cumulative frequency distribution analyses.

- Estimates of rare events should be checked to make sure they do not exceed some limiting state imposed by physical constraints, e.g. the wave breaking limit in shallow water.

- Confidence in estimates of rare events can often be substantially improved by pooling data from nearby sites, especially in places where storms are sparse. Pooling is straightforward if the data source is a gridded hindcast model. There are other methods of reducing statistical uncertainty, such as averaging extreme estimates from adjacent sites, but research suggests that these can introduce bias and are inferior to pooling. Regardless of the method used, one should take great care to exclude sites that can be expected to be different from the site of interest because of a differing physical environment. For example, wave data from shallow water sites should not be pooled with wave data from a substantially different water depth.

A.5.8 Metocean parameters for fatigue assessments

A.5.8.1 General

Time-varying stresses in an offshore structure are due to time-varying actions caused by waves (with or without currents), gust winds and combinations thereof. Time-varying stresses for a fatigue assessment are characterized by the number of occurrences of various magnitudes of stress range (maximum stress minus preceding or following minimum stress), in some cases supplemented by the mean value of the stress range.

Determination of the relevant metocean parameters should take due account of the required characterization for each case.

A.5.8.2 Fixed structures

Variable stresses during the in-place situation of fixed structures (either steel or concrete) are due to gust winds and waves, with or without the simultaneous presence of a current. The variable stresses caused by gust winds are normally small and, except for the design of some topsides components, can be neglected. The effect of current is normally not taken into account, for the following reasons:

- current velocities co-existing with waves in other than extreme or abnormal environmental conditions are usually small and not in the same direction as the waves;
- the influence of current on stress ranges is generally much smaller than the influence on the maximum stress experienced.

The minimum requirement for the fatigue assessment of a fixed structure during the in-place situation is therefore an appropriate description of the site-specific wave environment during its design service life. This is ideally provided by the long-term joint distribution of the significant wave height (H_s), a representative wave period (T_z or T_p), the mean wave direction ($\bar{\theta}$) and the directional spreading around the mean wave direction. However, adequate information on the joint occurrence of these four parameters is usually not available. The availability of data usually limits the options to providing a two-parameter wave scatter diagram. The wave scatter diagram gives the probability density $p(H_s, T_z)$ or $p(H_s, T_p)$ of the joint occurrence of H_s and T_z or T_p. Where adequate data exist, this can sometimes be extended to the three-parameter wave scatter diagram $p(H_s, T_z, \bar{\theta})$ or $p(H_s, T_p, \bar{\theta})$; otherwise, the mean wave direction $\bar{\theta}$ is specified by its long-term marginal distribution independent of H_s and T_z or T_p. Wave directional spreading is usually neglected or accounted for by a standard spreading function independent of the other three parameters, see A.8.7.

The long-term distribution should either cover the full duration of the design service life or the duration of a typical year. If annual distributions are used, it is assumed that the conditions during the typical year repeat themselves each year during the design service life. Seasonal distributions are not appropriate for fatigue assessments.

Where a deterministic fatigue assessment can be used for quasi-statically responding structures, the site-specific wave environment during the structure's design service life may be specified by the long-term marginal distribution of individual wave heights. This distribution can be derived from the wave scatter diagram.

Where vortex induced vibrations (VIV) due to currents in the in-place situation are important, the long-term marginal distribution of site-specific current speeds should also be determined.

For vortex induced vibrations due to wind action in the pre-service condition, the long-term marginal distribution of sustained wind speeds during the construction period should be made available.

Where variable stresses due to gust winds cannot be disregarded (e.g. for separate support structures for vent stacks or flare towers), the two- or three-parameter wave scatter diagram should be replaced by a three- or four-parameter scatter diagram of the joint occurrence of waves and winds. In such special cases the waves are as usual specified by H_s and T_z or T_p, supplemented if possible by $\bar{\theta}$, while the wind is normally specified by the sustained wind speed U_{w0} as being the representative parameter of gust winds, see A.7.4.

For slender structural components above water (e.g. drilling derricks, flare towers), the long-term marginal distribution of sustained wind speeds should suffice for a fatigue assessment due to excitation by both gust winds and vortex induced vibrations.

Requirements and guidance for the fatigue assessment of fixed steel and concrete structures are given in ISO 19902 and ISO 19903, respectively.

A.5.8.3 Floating structures

In principle, the specification of all environmental conditions that are expected to occur during the floating structure's period of exposure is along similar lines as that for fixed structures. However, the behaviour of a floating structure under environmental actions is normally more complex than that of a fixed structure. Therefore, the long-term joint distribution of relevant metocean parameters should ideally comprise more parameters than for fixed structures.

Floating structures experience oscillatory motions in six degrees-of-freedom due to wave action. Additionally, floating structures are subjected to slow variations in their position and their orientation as a result of the simultaneous effects of wind, current and waves. These phenomena are not fully understood and can not often be reliably predicted in advance. This makes the determination of variable stresses in floating structures at the design stage very difficult. Consequently, a fatigue assessment of a floating structure normally uses pragmatic and experience-based procedures. The relevant metocean parameters and the way in which these are specified should suit the procedure being used. For requirements and guidance for the fatigue assessment of floating structures, see ISO 19904-1 for monohulls, semi-submersibles and spars, and ISO 19904-2[1] for tension leg platforms.

A.5.8.4 Jack-ups

The principal differences between jack-ups in their elevated condition and fixed structures regarding fatigue are

— that they are deployed at different sites during their working lives,

— that their period of exposure at one particular site is usually considerably shorter,

— at different sites at which the jack-up is deployed, the fatigue sensitive locations differ (primarily due to water depth variations),

— there are frequent opportunities to carry out non-destructive examinations of fatigue sensitive components, and

— periodic examinations are required by classification societies and coastal state authorities.

For requirements and guidance for the fatigue assessment of a jack-up during a site-specific application, see ISO 19905-1[2].

A.5.9 Metocean parameters for short-term activities

Almost all short-term offshore operations, and some offshore-related aviation operations, are sensitive to the accuracy, reliability and timeliness of weather forecasts. Planning prior to the operation is essential to enable safety plans to be properly completed, cost estimates to be accurately determined and any capacity limits on accommodation or transport to be defined.

The most common technique used in such planning exercises is the so-called “persistence” or “weather-window” analysis. This analysis is typically applied to a long time series (e.g. with a duration of 10 years) of a metocean variable such as significant wave height, mean wind speed or current speed. More sophisticated analyses of multiple parameters (including wave period) can be necessary, in particular for operations involving floating systems.

EXAMPLE In order to plan a required operation at an installation safely, the average number of occasions in the months June to August when the significant wave height at a specific location can be expected to be below 1,5 m for a period of 36 h or more, when at the same time the wind speed should be less than 10 m/s, and the spectral peak wave period is less than 9 s, can be evaluated. It could be necessary to modify an operation to allow the limiting criteria to be relaxed.

In all cases, weather forecasts are likely to be needed both before and during the operations and it is often worthwhile to collect real-time data on critical metocean parameters (such as wind speed and wave height/period) during the operation in order to assist with the accuracy and timing of the forecasts.

References [5] and [15] provide examples of applications of operations requiring metocean data, and Reference [16] describes the types of metocean analyses which are often needed in studies to support the planning of floating systems operations.

A.6 Water depth, tides and storm surges

A.6.1 General

Changes in relative still water level comprise several components, including atmospheric tides, storm surge effects, changes in mean sea level, vertical movement of the earth's crust, settlement and subsidence. Records in areas such as northern Europe over the last 100 years show a downward trend in relative still water level because the crust in this area is lifting at a faster rate than the rise in actual sea level. Apart from sudden tectonic movements, such as earthquakes, changes in relative sea level from tectonics and isostasy are unlikely to be significant during the design service life of a structure. However, there can be significant local crustal movements over periods of decades or so caused by local effects, such as sediment compaction and subsidence, including the effects of reservoir compaction.

At present, the consensus of opinion for the rate of change of still water level due to climate change for the next century is about 5 mm per year[17]. However, this estimate is likely to change as knowledge increases. Any change in actual still water level is not expected to be uniform over the globe.

Changes in water depth due to changes in still water level will cause little change in tide and surge elevations unless depths are modified by many metres.

A.6.2 Tides

The best estimates of the water depth and of the fluctuations in water level (HAT, LAT, extreme surge elevation, and extreme total still water level) are derived from site-specific measurements with an offshore tide gauge measuring pressure from the sea floor. If the tidal signal is dominant, adequate estimates of the tidal range at a given site can be obtained from one month of measured data. However, accurate estimates of extreme tides, including HAT and LAT, require at least one complete year of high-quality data from one location. A method of analysing water level data requires

- conversion of pressure measurements to equivalent depths, using density/temperature/atmospheric pressure corrections,
- harmonic tidal analysis, giving values of all significant tidal constants and the mean water level,
- prediction of tides over 19 years (the harmonic constituent with the longest period) and extraction of HAT and LAT,
- subtraction of predicted tides from measured levels, giving time series of hourly storm surge elevations,
- separate statistical analyses of the tidal and storm surge elevations, and
- combination of the frequency distribution of tidal and surge elevations to give the required probabilities of total still water level.

When tide gauge measurements have not been made and water depth has been determined by local soundings, corrections should be made for the state of the tide by reference to published tide tables, co-tidal charts or the nearest available tide gauge.

A.6.3 Storm surge

Accurate estimates of the storm surge require a long data set (approximately 10 years), but if long-term measurements or hindcasts are available from an adjacent site, spatial techniques can be used and one to two years of data can provide workable estimates.

A.7 Wind

A.7.1 General

When making wind measurements, the following is recommended.

— The height of the wind measurement above mean sea level should be known and should be sufficiently high to be clear of disturbances to the airflow from the wave surface or from the structure.

— The averaging time of the wind speed measurement should be known.

— The air and sea temperatures should be measured to enable an evaluation of the atmospheric stability which can affect the wind profile and the wind spectrum (see A.7.3 and A.7.4) in low wind conditions.

— The anemometer should not be aerodynamically shielded.

Reference [18] contains guidance on measuring instruments and their use.

Measurements at a location away from the site of interest can be misleading, e.g. because of a sharp gradient in wind speed near a coastline. If it is decided to use such measurements because site-specific measurements are not available, allowance should be made (e.g. by the use of numerical models) for such effects. Wind measurements made over land should be corrected to reflect over-water conditions.

Wind data should be adjusted to a standard elevation of 10 m above mean sea level (the reference elevation z_r) with a specified averaging time such as 1 h. Wind data can be adjusted to any specified elevation different from the base value using the wind profile given in A.7.3[19].

A.7.2 Wind actions and action effects

When determining appropriate design wind speeds for extreme and abnormal conditions, the projected extreme wind speeds in specified directions and with specified averaging times should be developed as a function of their recurrence interval. Data should be recorded for the following:

— the measurement site, date of occurrence, magnitude of measured sustained wind speeds, wind directions and gust wind speeds for the recorded data that were used during the development of extreme and abnormal winds;

— the projected number of occasions during the specified design service life of the structure when sustained wind speeds from specified directions are expected to exceed a specific threshold;

— the type of storm causing high winds, which is significant when more than one type of storm can be present in the region.

When determining appropriate design wind speeds for normal and short-term conditions, data should be recorded for the following:

— the frequency of occurrence of specified sustained wind speeds from various directions for each month or season;

— the persistence of sustained wind speeds above specified thresholds for each month or season;

— the probable gust wind speed associated with sustained wind speeds.

In some instances the spectrum of wind speed fluctuations about the mean should be specified. For example, floating and other compliant structures in deep water can have natural sway periods in the range of a minute or more, a period at which there is significant energy in the wind speed fluctuations. Data on wind spectra are given in A.7.4.

For most purposes a relatively simple wind model consisting of the following scalar equation in the mean wind direction θ_w suffices:

$$U_w(z,t) = U_w(z) + u_w(z,t) \quad (A.1)$$

where

$U_w(z,t)$ is the spatially and temporally varying wind speed at elevation z above mean sea level and at time instant t;

$U_w(z)$ is the mean wind speed at elevation z above mean sea level, averaged over a specified time interval;

$u_w(z,t)$ is the fluctuating wind speed at elevation z around $U_w(z)$ and in the same direction as the mean wind.

The wind speed in a 3 s gust is appropriate for determining the maximum quasi-static local actions caused by wind on individual components of the structure, whereas 5 s gusts are appropriate for maximum quasi-static local or global actions on structures whose maximum horizontal dimension is less than 50 m, and 15 s gusts are appropriate for the maximum quasi-static global actions on larger structures.

When design actions due to wind need to be combined with actions due to waves and current, the following is appropriate:

- for structures with negligible dynamic response, the 1 h sustained wind can be used to determine quasi-static global actions caused by wind in conjunction with extreme or abnormal quasi-static actions due to waves and currents;
- for structures that are moderately dynamically sensitive, but do not require a full dynamic analysis, the 1 min mean wind can be used to determine quasi-static global actions caused by wind, again for wind in conjunction with extreme or abnormal quasi-static actions due to waves and currents;
- for structures with significant dynamic response to excitation with periods longer than 20 s, a full dynamic response analysis to fluctuating winds should be considered.

A.7.3 Wind profile and time-averaged wind speed

Measurements of representative offshore conditions, in strong, nearly neutrally stable atmospheric wind conditions, suggest that the mean wind speed profile $U_w(z)$ in storm conditions can be more accurately described by a logarithmic profile as given in Equation (A.2) than by the power law profile traditionally used:

$$U_{w,1h}(z) = U_{w0}\,[1 + C \ln(z/z_r)] \quad (A.2)$$

where

$U_{w,1h}(z)$ is the 1 h sustained wind speed at a height z above mean sea level;

U_{w0} is the 1 h sustained wind speed at the reference elevation z_r and is the standard reference speed for sustained winds;

C is a dimensionally dependent coefficient, the value of which is dependent on the reference elevation and the wind speed, U_{w0}. For z_r = 10 m, $C = (0{,}0573)\,(1 + 0{,}15\,U_{w0})^{1/2}$ where U_{w0} is in units of metres per second (m/s);

z is the height above mean sea level;

z_r is the reference elevation above mean sea level (z_r = 10 m).

For the same storm conditions, the mean wind speed for averaging times shorter than 1 h may be expressed by Equation (A.3) using the 1 h sustained wind speed $U_{w,1h}(z)$ of Equation (A.2):

$$U_{w,T}(z) = U_{w,1h}(z)\,[1-0{,}41\, I_u(z)\, \ln(T/T_0)] \qquad (A.3)$$

where additionally

$U_{w,T}(z)$ is the sustained wind speed at height z above mean sea level, averaged over a time interval $T < 3600$ s;

$U_{w,1h}(z)$ is the 1 h sustained wind speed at height z above mean sea level, see Equation (A.2);

T is the time averaging interval with $T < T_0 = 3\,600$ s;

T_0 is the standard reference time averaging interval for wind speed of 1 h = 3 600 s;

$I_u(z)$ is the dimensionally dependent wind turbulence intensity at a height z above mean sea level, given by Equation (A.4), where U_{w0} is in units of metres per second (m/s):

$$I_u(z) = (0{,}06)\left[1 + 0{,}043\, U_{w0}\right]\left(\frac{z}{z_r}\right)^{-0{,}22} \qquad (A.4)$$

The equations in this subclause are typical engineering equations derived from curve fitting through available data[19] and contain numerical constants that are only valid in the SI units of metres and seconds.

NOTE 1 Approximations to Equations (A.2) and (A.3) using a power law can be adequate.

NOTE 2 In the absence of further information on tropical storm winds in the region of interest, these equations may also be applied to this storm type.

NOTE 3 The above equations are not valid for the description of squall winds, since the duration of the squall is often less than 1 h. The description of squall wind statistics is a topic of ongoing research.

A.7.4 Wind spectra

Wind turbulence, i.e. the dynamic properties of the wind, depend on the stability of the atmospheric boundary layer. Stability, in turn, depends on the temperature difference between air and sea and on the mean wind speed. The equations in this subclause for the dynamic wind properties are appropriate for nearly neutral (slightly unstable) atmospheric stability in storm conditions[19]. For general atmospheric conditions where (in)stability is important, and for weaker wind conditions, a more complex formulation that allows deviations from neutral stability is more appropriate.

The fluctuating wind speed $u_w(z,t)$ (turbulence) can be described in the frequency domain by a wind spectrum, analogous to the way in which the wave spectrum describes the water surface elevation (see A.8.6). The spectral density function of the longitudinal wind speed fluctuations at a particular point in space can be described by the one-point turbulence spectrum of Equation (A.5):

$$S(f,z) = \frac{(320\ \mathrm{m^2/s}) \cdot \left(\dfrac{U_{w0}}{U_{ref}}\right)^2 \cdot \left(\dfrac{z}{z_r}\right)^{0{,}45}}{\left(1 + \tilde{f}^{\,n}\right)^{5/(3n)}} \qquad (A.5)$$

where

$S(f,z)$ is the wind spectrum (spectral or energy density function) at frequency f and elevation z;

U_{w0} is the 1 h sustained wind speed at the reference elevation z_r (the standard reference speed for sustained winds);

U_{ref} is the reference wind speed, U_{ref} = 10 m/s;

f is the frequency in cycles per second (hertz) over the range 0,001 67 Hz $\leqslant f \leqslant$ 0,5 Hz;

z is the height above mean sea level;

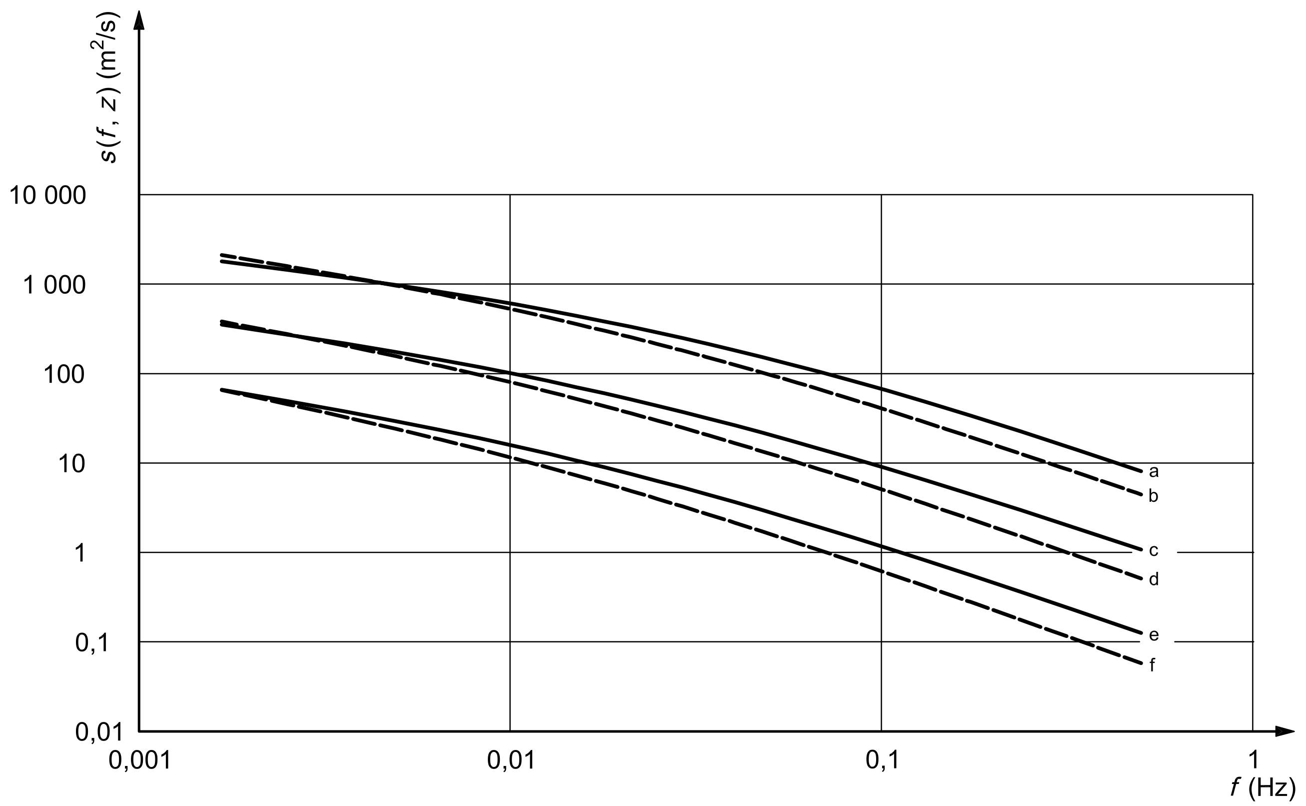
z_r is the reference elevation above mean sea level (z_r = 10 m);

$\tilde{f}$ is a non-dimensional frequency defined by Equation (A.6) where the numerical factor 172 has the dimension of seconds (s)

$$\tilde{f} = (172\ \mathrm{s})\ f \left(\frac{z}{z_r}\right)^{2/3} \left(\frac{U_{w0}}{U_{ref}}\right)^{-0,75} \tag{A.6}$$

n is a coefficient equal to 0,468.

Figure A.1 shows wind spectra for 1 h sustained wind speeds of 10, 20 and 40 m/s and elevations of z = 10 m and z = 40 m.



a z = 10 m, U_{w0} = 40 m/s.

b z = 40 m, U_{w0} = 40 m/s.

c z = 10 m, U_{w0} = 20 m/s.

d z = 40 m, U_{w0} = 20 m/s.

e z = 10 m, U_{w0} = 10 m/s.

f z = 40 m, U_{w0} = 10 m/s.

Figure A.1 — Examples of wind spectra

The variance (i.e. the square of the standard deviation) of the wind speed fluctuations about the mean wind speed is by definition equal to the integral of the spectral density function over the entire frequency range from f equals zero to infinity. However, the data from Reference [19], from which the spectral formulation in Equations (A.5) and (A.6) has been derived, extend from f = 1/ 600 = 0,001 67 Hz to f = 0,43 Hz ≈ 0,50 Hz. The integral of the spectrum over frequency can thus only reflect wind speed fluctuations within this frequency range. Therefore, the integral of the spectrum will only correspond with a part of the total variance of the wind speed and so caution should be exercised when relating the integral to available measurements to ensure that comparable frequency ranges are compared. It should further be noted that $S(f, z)$ from Equation (A.5) does not go to zero below the lowest frequency of f = 1/600 Hz considered in the measurements, as should be expected from the notion of a spectral gap.

For practical applications, the wind spectrum at a point needs to be supplemented by a description of the spatial coherence of the fluctuating longitudinal wind speeds over the exposed surface of the structure or the structural component. In frequency domain analyses, it can be conservatively assumed that all scales of turbulence are fully coherent over the entire topsides. However, for some structures, it can be advantageous to account in the dynamic analysis for the less-than-full coherence at higher frequencies. The correlation between the spectral energy densities of the longitudinal wind speed fluctuations at frequency f between two points in space can be described in terms of the two-point coherence function. The recommended coherence function between two points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$, with along-wind positions x_1 and x_2, across-wind positions y_1 and y_2, and elevations z_1 and z_2, is given by

$$F_{\text{Coh}}(f, P_1, P_2) = \exp\left\{ -\frac{1}{U_{\text{w0}}} \left[\sum_{i=1}^{3} (A_i)^2 \right]^{1/2} \right\} \qquad \text{(A.7)}$$

where

$F_{\text{Coh}}(f, P_1, P_2)$ is the coherence function between turbulence fluctuations at $P_1(x_1, y_1, z_1)$ and at $P_2(x_2, y_2, z_2)$;

U_{w0} is the 1 h sustained wind speed at 10 m above mean sea level in metres per second (m/s);

A_i is a function of frequency and the position of the two points P_1 and P_2.

A_i is calculated from Equation (A.8):

$$A_i = \alpha_i \, f^{r_i} \, (D_i)^{q_i} \left(\frac{z_{\text{g}}}{z_{\text{r}}} \right)^{-p_i} \text{ in metres per second (m/s)} \qquad \text{(A.8)}$$

where

f is the frequency in hertz (Hz);

D_i is the distance, measured in metres (m), between points P_1 and P_2 in the x, y and z directions for i = 1, 2 and 3 respectively, see Table A.1;

z_{g} is the geometrical mean height of the two points, $z_{\text{g}} = (z_1 \cdot z_2)^{1/2}$;

z_{r} is the reference elevation above mean sea level, z_{r} = 10 m;

α_i, p_i, q_i and r_i are coefficients given in Table A.1.

Table A.1 — Coefficients in Equation (A.8) for points P_1 and P_2

i	D_i	α_i	p_i	q_i	r_i
1	$\|x_1 - x_2\|$	2,9	0,4	1,00	0,92
2	$\|y_1 - y_2\|$	45,0	0,4	1,00	0,92
3	$\|z_1 - z_2\|$	13,0	0,5	1,25	0,85

A.8 Waves

A.8.1 General

The main factors to be considered when assessing the properties of waves at a particular site and their influence on the design, construction and operation of structures are described below.

— **Fetch limitations**

Wave growth is restricted by fetch length and width if the waves are generated by local winds. Reference [20] provides simple parametric expressions quantifying these effects, while more complete numerical models referenced below include these processes for much more general geometries.

— **Non-linear wave effects**

In extreme storms, even in deep water, individual waves exhibit non-linear behaviour. In shallow water, even under normal conditions, waves also exhibit non-linear behaviour, as they are affected by the sea floor. In deep water, for waves that are not too high or too steep, linear wave theory (Airy) is adequate for describing the kinematics of the waves, but for higher or steeper waves in deep water and in shallow water, higher order theories are more appropriate to describe wave properties, such as the crest elevation and kinematics. Water can be taken as shallow when the water depth/deep water wave length of the spectral peak frequency is less than approximately 0,13[13].

— **Refraction**

As waves propagate into shallow water, their speed (which depends on their period and the local water depth) is reduced and they are refracted. For simple bathymetry and single wave periods, refraction can be estimated using Snell's Law or by ray plotting techniques as described in Reference [20]. For more complex bathymetry and short-crested waves, a numerical method is more appropriate. Refraction can result in both increases and decreases in wave energy/heights as well as in changes in direction between adjacent sites within a shallow water area, depending on the bathymetric configuration. Currents can also cause refraction and should be considered, particularly where tides or rivers create strong currents.

— **Diffraction and reflection**

These processes can be important when waves encounter a protruding object, such as a breakwater or an island. The potential for focal points of wave energy occurring behind nearby islands or sea-mounts should be considered.

— **Shoaling and wave breaking**

As a periodic wave propagates into shallower water, its length is reduced but its period remains the same. For random waves it may be assumed that the spectral peak period remains the same. This process is known as shoaling. As the wave continues to propagate into shallow water, the wave steepens until the particle velocity at the crest exceeds the speed of the wave and breaking results. In shallow water the empirical limit of the wave height is approximately 0,78 times the local water depth for waves that are long-crested. The wave height of short-crested waves can approach 0,9 times the local water depth. The breaker height also depends on beach slope. In deep water, waves can break with a theoretical limiting steepness of 1/7.

— **Crest elevations**

An accurate description of the distribution of extreme crest elevations at the site is needed to establish the minimum deck elevation of bottom founded structures. Shoaling and non-linear processes affect crest elevations as waves move into shallow water. The proportion of the wave height above nominal still water increases as the water becomes shallower.

— **Bottom dissipation**

  As waves move into shallow water, the horizontal oscillatory velocities at the bottom become large and turbulent dissipation results. This process can be modelled in present day hindcast models as shown in Reference [21].

— **Wave-wave interaction**

  Detailed directional wave spectra at several sites were examined in Reference [22]. It was found that the evolution of the wave spectrum could be parameterized as a function of local water depth. It was proposed that this was due to the non-linear wave-wave interactions between different wave frequency components.

In view of the complexity of shallow water processes, the best method of calculating wave height will usually be through a comprehensive numerical wave model that includes the relevant processes outlined above. Reference [23] shows how accurate wave models have become.

Estimates from many locations around the world indicate that the following accuracies can be achieved with hindcast models in either deep or shallow water:

— mean error (bias) in H_s of 0,1 m;

— coefficient of variation of 10 % to 15 % for storm peak H_s;

— coefficient of variation of approximately 20 % for all H_s over long continuous periods (e.g. 10 year hindcasts).

No wave sensor or wave model is ideal in its ability to accurately measure waves or reproduce still water level as a reference base. For example, operating constraints on bottom founded offshore structures frequently mean that platform-mounted sensors do not measure the undisturbed sea surface. Similarly, wave buoys do not respond ideally in high sea states. Wave models are only as good as the physics that are incorporated in them. The strengths and weaknesses of any particular data set should be recognized throughout the process of its analysis and interpretation.

When using hindcast data, care should be taken to ensure that hindcast waves are consistent with site-specific and reliable measured data recorded over the same period. In particular, the spatially and temporally averaged nature of hindcast data and the sampling noise inherent in many measurement data sets should be taken into account and one or both data sets should be factored if necessary.

Reference [24] provides a description of a recording philosophy for waves. A description of methods for analysing wave data and calculating extremes can be found in References [13] and [6].

Experienced specialists, knowledgeable in the fields of meteorology, oceanography and hydrodynamics, should be consulted when developing wave-dependent environmental conditions and associated metocean parameters. In those areas where prior knowledge of oceanographic conditions is insufficient, the development of wave-dependent metocean parameters should include the following steps towards developing a hindcast database:

— development of all necessary meteorological data;

— projection of surface wind fields;

— prediction of deep water general sea states along storm tracks using a mathematical model;

— definition of maximum possible sea states consistent with geographical limitations;

— delineation of bathymetric effects on deep water sea states;

— introduction of probabilistic techniques to predict sea state occurrences at the structure's site against various time bases;

— development of design wave parameters (through physical and economic risk evaluation) to produce design environmental actions.

In areas where considerable previous knowledge of, and experience with, oceanographic conditions exist, the foregoing sequence may be shortened.

In developing sea state data, either in the form of statistical parameters characterizing the sea state or in the form of representative individual waves occurring within the sea state, consideration should be given to the following.

a) For normal conditions and short-term activities (for both seas and swells):

   1) the probability of occurrence and the average persistence of various sea states for each month and/or season (e.g. environmental conditions with waves higher than 3 m from specified directions in terms of general sea state parameters, such as the significant wave height and the mean zero-crossing wave period);

   2) the wind speeds, tides and currents occurring simultaneously with the above sea states;

   3) the percentage of significant or individual wave heights, directions, and periods within specified ranges (e.g. 3 m to 4 m high waves from the SE quadrant during each month and/or season).

b) For extreme and abnormal conditions

   Estimated extreme and abnormal wave heights from specified directions should be developed and presented as a function of their return periods. Other data that should be developed include

   1) the probable range and distribution of wave periods associated with extreme and abnormal wave heights, for the specification of individual design waves,

   2) the distribution of maximum crest elevations, and the wave energy spectrum in the sea state producing extreme and abnormal wave heights,

   3) the tides, currents, winds and marine growth likely to occur simultaneously with the sea state producing the extreme and abnormal waves,

   4) the nature, date and place of the event that produced the historical sea states (e.g. Hurricane Camille, August 1969, Gulf of Mexico) that are used in the development of the estimated values.

A.8.2 Wave actions and action effects

When considering extreme and abnormal conditions for design situations, the following points should be considered.

— The maximum height of an individual wave with a given return period is, in general, higher than the most probable extreme or abnormal wave height of a one-hour or three-hour sea state with the same return period.

— The highest action on, or the largest action effect in, a structure is not necessarily induced by the highest sea state or the highest wave in a sea state. This is due to the nature of wave action, the sensitivity of structures to the frequency content of waves in a sea state, and the geometric particulars of the structure concerned.

— Waves and currents can create seabed scour around objects on or near the sea floor that obstruct free flow conditions. Examples of where scour can occur are around the legs of structures and jack-ups, around subsea templates and underneath pipelines.

A.8.3 Intrinsic, apparent and encounter wave periods

The correct period to be used in all periodic wave theories to determine the wave length and all wave kinematics is the intrinsic period. If the wave period is derived from measurements taken by fixed (rather than drifting) instruments, the measurements are of the apparent wave period. If the wave period is based on hindcasts of waves with a model that is calibrated to measurements taken by fixed instruments, and no adjustments are made to the model to account for the presence of current, then again the wave period represents the apparent wave period. In both cases the intrinsic wave period should be calculated from the apparent wave period. These are the usual cases for offshore structures covered by this document. If the wave hindcast model already accounts for the Doppler effect on the wave periods due to currents, no adjustment is required.

In calculating wave particle kinematics, some computer programs adjust the wave period/length internally to account for currents. Other programs require the user to manually adjust the wave period before using it to compute kinematics. The user should ensure that the correct procedure is applied.

For a uniform current profile over the water depth, the basic problem is formulated by the relationship between speeds in the apparent and the intrinsic coordinate systems that are given by Equations (A.9):

$$\begin{aligned} c_{\text{a}} &= c_{\text{i}} + V_{\text{in-line}} \\ c_{\text{a}} &= \frac{\lambda}{T_{\text{a}}} \\ c_{\text{i}} &= \frac{\lambda}{T_{\text{i}}} \\ V_{\text{in-line}} &= U_{\text{c}} \cos\theta_{\text{c}} \end{aligned} \tag{A.9}$$

where

a	is a subscript for an apparent property;
i	is a subscript for an intrinsic property;
c	is the wave celerity (the wave phase speed);
λ	is the wave length;
T	is the wave period;
$V_{\text{in-line}}$	is the component of the current velocity in-line with the direction of wave propagation;
U_{c}	is the free stream steady current velocity, not reduced by structure blockage;
θ_{c}	is the direction of the current velocity with respect to the direction of wave propagation.

This results in the relationship between the apparent and intrinsic periods given by Equation (A.10):

$$\frac{\lambda}{T_{\text{a}}} = \frac{\lambda}{T_{\text{i}}} + V_{\text{in-line}} \tag{A.10}$$

Through multiplication by the wave number $k = 2\pi / \lambda$, Equation (A.10) can be rewritten in terms of the apparent and intrinsic frequencies as:

$$\omega_{\text{a}} = \omega_{\text{i}} + k\, V_{\text{in-line}} \tag{A.11}$$

where ω is the wave circular frequency, $\omega = 2\pi / T$.

The wave length, which is unaffected by the frame of reference, and the intrinsic period are coupled through the dispersion equation, which for first and second order waves is

$$T_i^2 = \frac{2\pi\lambda}{g\tanh(2\pi d/\lambda)} = \frac{4\pi^2}{kg\tanh(kd)} \tag{A.12}$$

where

d is the water depth;

g is the acceleration due to gravity.

For higher order waves, the dispersion relationship is determined through numerical simulations.

$V_{\text{in-line}}$ is positive when wave propagation and the in-line component of the current velocity are in the same direction ($-90° < \theta_c < +90°$); in these cases the apparent frequency is higher than the intrinsic frequency.

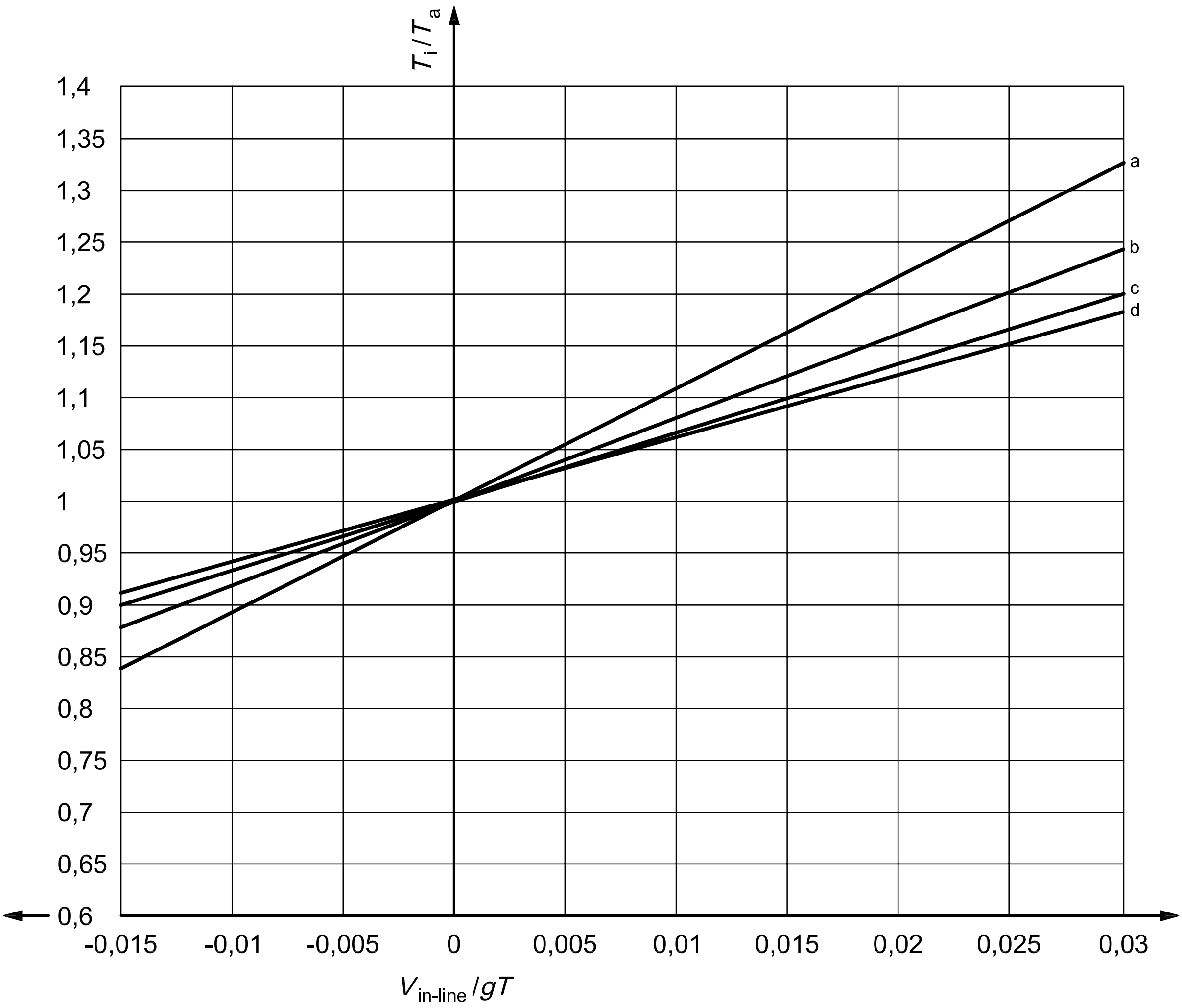
Conversely, $V_{\text{in-line}}$ is negative when wave propagation and the in-line component of the current velocity are in opposite directions ($\theta_c > +90°$ or $\theta_c < -90°$) and the apparent frequency is lower than the intrinsic frequency. For negative values of $V_{\text{in-line}}$ (opposing currents), the condition $c_i + V_{\text{in-line}} > 0$ should be satisfied — otherwise, the waves move faster downstream by the current than they can propagate forward. For the special case of $c_i + V_{\text{in-line}} = 0$ and $\theta_c = 0$, standing waves occur.

When the intrinsic period T_i [or frequency ω_i] is known, the wave length λ and the wave number k are also known [see Equation (A.12)], and there is a unique apparent period T_a [or frequency ω_a] associated with T_i [ω_i] for each current velocity. When the apparent wave period T_a [ω_a] is known, there is only a unique intrinsic period T_i [ω_i] associated with T_a [ω_a] when the current velocity is in the direction of wave propagation ($V_{\text{in-line}} > 0$). For opposing current velocities, i.e. $-c_i < V_{\text{in-line}} < 0$, there are in principle two values of T_i [ω_i] that correspond with each T_a [ω_a]. However, the second solution is associated with excessively short, unrealistic waves and can be ignored.

Equations (A.9) to (A.12) directly provide T_a from a given T_i, but should be solved iteratively to determine T_i from a given T_a. For the special case of a uniform current profile, the solution to these equations is provided in non-dimensional form in Figure A.2. This figure gives the ratio of T_i to T_a as a function of $V_{\text{in-line}}/gT$ for constant values of $d/gT^2 > 0{,}01$. The figure may be used with $T = T_a$ to determine T_i or with $T = T_i$ to determine T_a. For smaller values of d/gT^2, shallow water depth approximations apply and the equation $T_i / T_a = 1 + V_{\text{in-line}} / \sqrt{gd}$ can be used.

While strictly applicable only to a current that is uniform over the full water depth, Figure A.2 provides acceptable estimates of T_i/T_a for "slab" current profiles that are uniform over the top 50 m or more of the water column. For non-uniform current profiles a weighted, depth-averaged in-line current speed may be used, as shown in Reference [25]:

$$V_{\text{in-line}} = \frac{2k}{\sinh(2kd)} \int_{-d}^{0} U_c(z)\cos\theta(z)\cosh\left[2k(z+d)\right]dz \tag{A.13}$$



[a] $d/(gT^2) = 0{,}01$

[b] $d/(gT^2) = 0{,}02$

[c] $d/(gT^2) = 0{,}04$

[d] $d/(gT^2) = 0{,}10$

NOTE Either $T = T_a$ or $T = T_i$ can be used to calculate $d/(gT^2)$ and $V_{in\text{-}line} / gT$.

Figure A.2 — Doppler shift in wave period due to steady current — Relationship between intrinsic and apparent periods

Spatial relationships change in a similar manner as the temporal relationships. The relationship between the coordinates in the direction of wave propagation in the apparent reference frame and the intrinsic reference frame is

$$x_a = x_i + V_{in\text{-}line}\, t \qquad \text{(A.14)}$$

So that the space- and time-dependent argument ($kx_i - \omega_i$) of the harmonic function in all wave equations transforms, using Equations (A.14) and (A.11), into:

$$kx_i - \omega_i t = kx_a - (\omega_i + kV_{in\text{-}line})\, t = kx_a - \omega_a t \qquad \text{(A.15)}$$

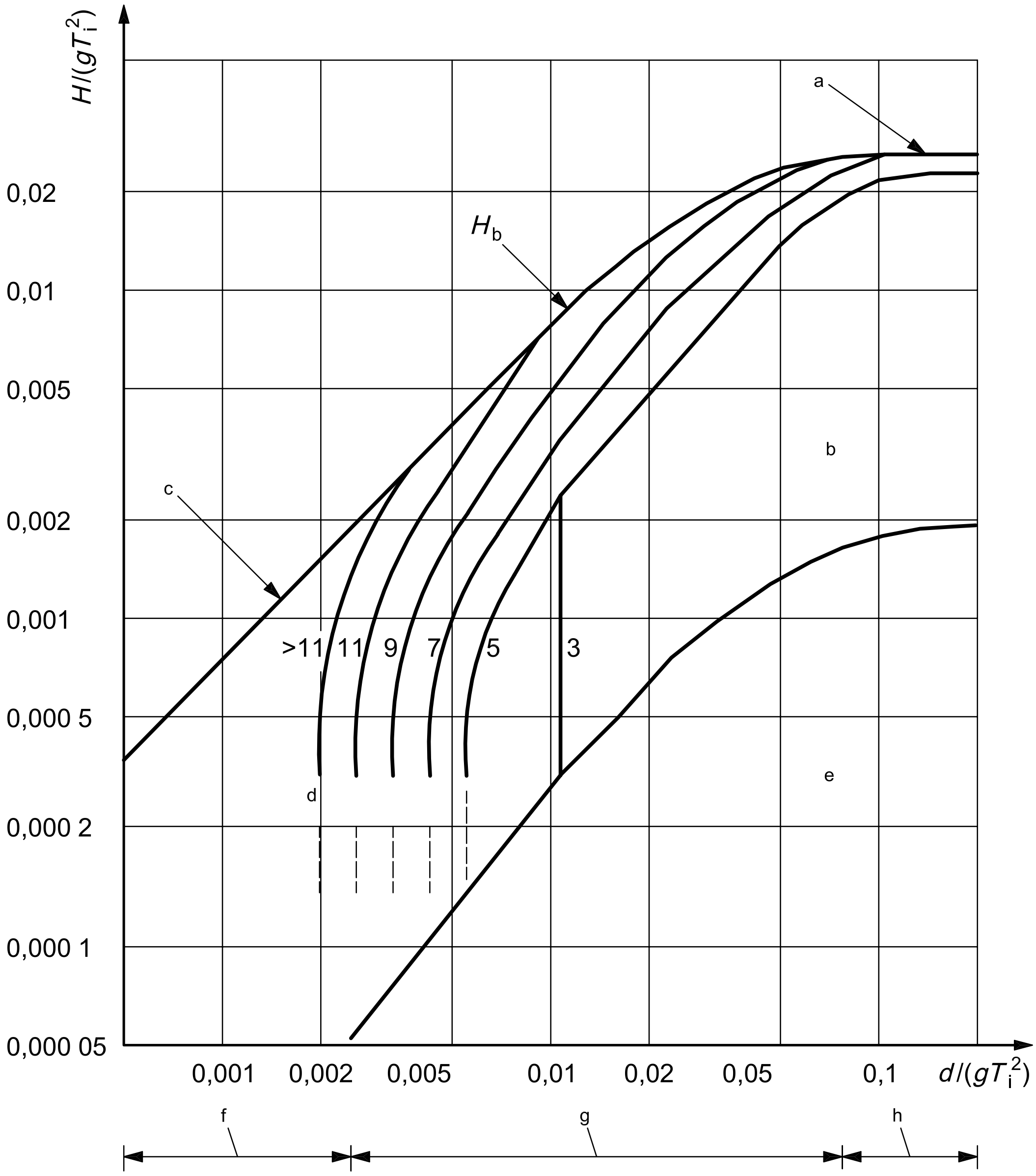
The transformation between encounter periods as measured from a moving vessel and intrinsic periods follows similar principles but does not need to be described here.

In wave spectra formulations (see A.8.6), the frequency parameter is the intrinsic frequency. However, a stationary structure (fixed or floating) in a wave field with current responds to the apparent frequency. To be able to perform the response calculations, the wave frequency spectrum formulation should therefore be transformed into the apparent frequency. As the wave energy per frequency band is independent of the reference frame, $S(\omega_i)d\omega_i = S(\omega_a)d\omega_a$ and hence the wave spectrum in the apparent frequency becomes $S(\omega_a) = S(\omega_i)d\omega_i / d\omega_a$. The coordinate transformations are carried out using Equation (A.11), taking due account of the fact that the wave number k is a function of the intrinsic wave frequency ω_i through Equation (A.12).

A.8.4 Two-dimensional wave kinematics

Several periodic wave theories can be used to predict the kinematics of two-dimensional regular waves. The different theories all provide approximate solutions to the same differential equations with appropriate boundary conditions. All compute a waveform that is symmetric about the crest and propagates without changing shape. The theories differ in their functional formulation and in the degree to which they satisfy the non-linear kinematic and dynamic boundary conditions at the wave surface.

Linear wave theory[13] is applicable only when the linearization of the free surface boundary conditions is reasonable, i.e. strictly speaking only when the wave amplitude and steepness are infinitesimally small. Stokes' fifth order theory[26] is a fifth order expansion in the wave steepness about mean water level that satisfies the free surface boundary conditions with acceptable accuracy over a fairly broad range of applications, as shown in Figure A.3, which is adapted from Reference [16]. Chappelear's theory[27] is similar to Stokes' fifth order theory, but determines the coefficients in the expansion numerically through a least squares minimization of errors in the free surface boundary conditions, rather than analytically. Extended velocity potential theory (EXVP-D)[28] satisfies the dynamic boundary condition exactly and minimizes the errors in the kinematic boundary condition. Stream function theory[29] satisfies the kinematic boundary condition exactly and minimizes the errors in the dynamic boundary condition.



a Deep water breaking limit H / λ = 0,14.

b Stokes' fifth order, New-wave or third order stream function.

c Shallow water breaking limit H / d = 0,78.

d Stream function (showing order number).

e Linear/Airy or third order stream function.

f Shallow water.

g Intermediate depth.

h Deep water.

Figure A.3 — Regions of applicability of alternative wave theories

When Stokes' fifth order theory is not applicable, stream function theory can be used. Selection of the appropriate solution order can be based on either the percentage error in the dynamic and kinematic boundary conditions, or on the percentage error in the velocity or acceleration compared with the next higher order. These two methods provide comparable solution orders over most of the feasible domain, but differ in the extremes for $H > 0,9\ H_b$ (where H_b is the breaking wave height) and $d / gT_i 2 < 0,003$. In these extremes, the theories have not been well substantiated with laboratory measurements and should therefore be used with caution. In particular, the curve for long-crested breaking wave height H_b shown in Figure A.3 is not universally accepted.

New-wave theory — see, for example, Reference [30] — is based on a mathematical derivation of the characteristics of the most probable maximum wave in a sea state. The New-wave surface has the shape of the autocorrelation function. New-wave includes the continuous spectrum of wave frequencies in a random sea; it is not based on discrete harmonics of the fundamental frequency. The kinematics of each wave frequency are computed using linear wave theory, summed and subsequently delta-stretched.

Delta stretching[31] provides a simple empirical correction to extend the kinematics obtained from linear theory into the wave crest above the still water level. When the local water surface elevation is above still water level and the vertical coordinate being considered, z, is above the stretching depth, d_s (the distance below the still water level at which the stretching process begins), then z in the equations for linear wave kinematics should be replaced by the stretched vertical coordinate z_s:

$$z_s = F_s\,(d_s + z) - d_s = (F_s - 1)\,d_s + F_s\,z \tag{A.16}$$

where

z is defined as the vertical coordinate with $z = 0$ at the still water level;

F_s is a stretching factor defined by Equation (A.17):

$$F_s = \frac{d_s + a\eta}{d_s + \eta} \tag{A.17}$$

where

a is a stretching parameter ($0 < a < 1{,}0$);

η is the water surface elevation at the horizontal location of interest.

The stretching depth (d_s) is typically set to one half of the significant wave height or half of the crest elevation, and the stretching parameter a typically equals 0,3. The stretching factor F_s is always smaller than 1,0 and consequently $z_s < z$.

In the use of New-wave theory, the kinematics are evaluated at only one instant during the wave evolution and then frozen as the wave propagates through the structure. New-wave is compatible with random directional wave models and produces results for global direct actions on fixed steel structures similar to those calculated by time domain simulations.

Another form of stretching is linear or Wheeler stretching, see A.9.4.1.

A.8.5 Maximum height of an individual wave for long return periods

The long-term maximum height H_N of an individual wave with a return period of N years can be estimated in several ways. The method used should account for the long-term uncertainty in the severity of the environment and the short-term uncertainty in the severity of the maximum wave of a given sea state or storm.

The statistically correct methods are based on storms. Storms are obtained from a time series of significant wave height by breaking it into events that have a peak significant wave height (H_{sp}) above some threshold.

The long-term uncertainty in the severity of the environment is treated using the probability distribution of the severity of the storm, measured either in terms of its peak significant wave height or the most probable maximum value of the individual waves in the storm (H_{mp}). The uncertainty in the height of the maximum wave of any storm is estimated as a probability distribution conditional on H_{sp} or H_{mp}. Convolution of the two distributions gives the distribution for any random storm and, thereby, the complete long-term distribution for the heights of individual waves. For further information, see Reference [6].

A similar method has been applied using sea states rather than storms as the independent variable. It is recognized that this method is not statistically robust because successive sea states are not independent. It involves analysis of many sea states that do not contribute to the final result and can give a false confidence in the results as the amount of independent input data is much less than it appears. Despite these known flaws, this method often provides a useful first estimate of conditions in an area when only a short (e.g. 1 to 2 years) measured dataset of H_s is available — see, for example, Reference [32].

An approximation that is sometimes used to generate H_N is to multiply H_{sN}, an estimate of the N year return period H_s, by a factor that relates to the ratio of the most-probable highest wave in a sea state to the significant wave height H_{sN}. However, this method underestimates H_N because it ignores the contribution from sea states that are lower but more frequent than H_{sN}, as well as sea states that are higher but less frequent than H_{sN}. The accuracy of the method also depends on the mutual cancellation of errors in all the steps leading to the final answer. When this method is used, the individual wave heights are generally assumed to obey a Rayleigh or Forristall[33] distribution, see below, and the sea state is assumed to have a duration of 3 h. Although the method has been applied in the past with some success, its use demands extreme care and should be avoided as better methods are now available — see, for example, References [6] and [13] for a discussion of various methods.

The classical description of the distribution of crest to trough heights (H) in narrow-banded seas is the Rayleigh distribution[34], which in its cumulative probability form is given by

$$P\left(H \leqslant H^*\right) = 1 - \exp\left[-2\left(H^*\right)^2 / \left(H_s\right)^2\right] \tag{A.18}$$

where H^* is any desired value of the significant wave height.

In practice, most seas are not narrow-banded and using the Rayleigh distribution would tend to overpredict the height of waves. To take account of the finite bandwidth, a number of empirically derived distributions have been proposed. The distribution proposed by Forristall[33], which was empirically derived using hurricane wave data from the Gulf of Mexico, is often used:

$$P\left(H \leqslant H^*\right) = 1 - \exp\left(-(4H^*/H_s)^\alpha / \beta\right) \tag{A.19}$$

where

α = 2,126

β = 8,42

NOTE When α = 2 and β = 8, the Forristall distribution reverts to the Rayleigh form.

The probability distributions for the maximum individual wave height in a stationary sea state can be established by raising Equation (A.18) or Equation (A.19) to a power equal to the number of waves in the interval. The probability distribution for the maximum individual wave height conditional on H_{sp} or H_{mp} can be determined by combining the distributions for each of the stationary sea states of which the storm is composed.

A.8.6 Wave spectra

A.8.6.1 General

A real sea is the product of a random process. It may be viewed as the superposition of many small individual frequency components, each of which is a periodic wave with its own amplitude, frequency and direction of propagation, and having random phase relationships with respect to each other. A unidirectional random sea, where all frequency components propagate in the same direction, is a special case of this. The surface of a unidirectional sea is long-crested, whereas the surface of a real or directional sea is short-crested. In the linear random wave model, the sea state is completely described by the directional wave spectrum $S(\omega,\theta)$ of the water surface elevation, which specifies the distribution of wave energy over frequencies and directions.

The directional characteristics are often assumed to be independent of frequency, allowing a separation of variables so that the directional wave spectrum can be expressed as the product of a wave directional spreading function $D(\theta)$ (see A.8.7), independent of frequency, and a wave frequency spectrum $S(\omega)$, which is independent of direction. The general relationship:

$$S(\omega,\theta) = D(\omega,\theta) \cdot S(\omega) \quad \text{(A.20)}$$

is then replaced by

$$S(\omega,\theta) = D(\theta) \cdot S(\omega) \quad \text{(A.21)}$$

where the directional spreading function by definition satisfies the relationship:

$$\int_{-\pi}^{\pi} D(\theta) d\theta = 1 \quad \text{(A.22)}$$

See A.8.7 for a discussion of $D(\theta)$.

A.8.6.2 Definition of frequency

The wave frequency may either be expressed in terms of ω in radians per second (rad/s) or in terms of f in cycles per second or hertz (Hz). The relationship between these two frequencies is

$$\omega = 2\pi f = \frac{2\pi}{T} \quad \text{(A.23)}$$

Since the energy per frequency band remains the same, i.e.

$$S(\omega) d\omega = S(f) df$$

the relationship between the two alternative expressions of the wave frequency spectrum is

$$S(f) = 2\pi \cdot S(\omega) \quad \text{(A.24)}$$

The formulations in Clause 8 and Annex B are given in terms of ω.

A.8.6.3 The wave frequency spectrum

The shape of wave spectra varies widely with the wave conditions actually experienced. Two broad classes of wave conditions can be distinguished: wind seas and swells. Wind seas are generated by the local wind; the corresponding shape of the wave spectrum will thus depend on the wind speed, the fetch length of the wind over open water and the duration during which the wind has been blowing. Waves from a wind-driven sea that travel out of the area can appear as swell in another area, far from where the waves were generated. For swells, there is thus no direct connection with the local wind regime. Spectra for swells and wind seas should hence be clearly distinguished. Within wind seas there is a further distinction between wave conditions that are fully developed and wave conditions that are still developing. In the first case, the sea is in a state of equilibrium: the energy input by the wind and the energy dissipation in the wave processes are in balance. In the second case, there is net energy input and the waves are consequently still growing.

Most parametric spectral forms developed by oceanographers relate to wind seas, and most of these to fully developed seas. They express the wave frequency spectrum in terms of the steady state local wind speed only (a one-parameter spectral formulation). For offshore engineering applications, the use of such spectra is generally avoided in favour of a two-parameter spectral formulation; these express the wave frequency spectrum by means of two representative parameters of the sea state existing at the site, regardless of the wind. The parameters used are the significant wave height H_s and a representative frequency, for which can be chosen

— the peak or modal frequency ω_m of the wave frequency spectrum,

— the average zero-crossing frequency ω_z of the water surface elevation, or

— an alternative mean frequency ω_1 of the wave spectrum.

Both the significant wave height and the representative frequency are usually obtained from site measurements.

The two most frequently used standard formulations of the wave frequency spectrum $S(\omega)$ in marine applications are the Pierson-Moskowitz spectrum for a fully developed sea and the JONSWAP spectrum for a developing sea.

In wave spectra formulations (see A.8.6), the frequency parameter is the intrinsic frequency. However, a stationary structure (fixed or floating) in a wave field with current responds to the apparent frequency. To be able to perform the response calculations, the wave frequency spectrum formulation should therefore be transformed into the apparent frequency. As the wave energy per frequency band is independent of the reference frame, $S(\omega_I)d\omega_I = S(\omega_a)d\omega_a$ and hence the wave spectrum in the apparent frequency becomes $S(\omega_a) = S(\omega_I)d\omega_I / d\omega_a$. The coordinate transformations are carried out using Equation (A.11), taking due account of the fact that the wave number k is a function of the intrinsic wave frequency ω_I through Equation (A.12).

A.8.6.4 The Pierson-Moskowitz spectrum

The general form of the Pierson-Moskowitz wave frequency spectrum[13] for a fully developed wind sea can be written as

$$S_{PM}(\omega) = \frac{A}{\omega^5} \exp\left(-\frac{B}{\omega^4}\right) \tag{A.25}$$

where A and B are two parameters that are determined in accordance with the significant wave height (H_s) and a representative frequency (or period) of the sea state. The exact forms of the parameters A and B depend on which representative frequency (ω_m, ω_z or ω_1) of the sea state is chosen. See Reference [13] and Annex B for further discussion and explanation.

A.8.6.5 The JONSWAP spectrum

The JONSWAP (joint North Sea wave project) wave frequency spectrum is a modification of the Pierson-Moskowitz spectrum for a developing wind sea in a fetch limited situation:

$$S_{JS}(\omega) = F_n \cdot S_{PM}(\omega) \left\langle \gamma^{\exp\left\{-\frac{1}{2}\left[(\omega-\omega_m)/(\sigma\,\omega_m)\right]^2\right\}} \right\rangle \tag{A.26}$$

where

γ is a non-dimensional peak shape parameter;

σ is a numerical parameter

$\sigma = \sigma_a$ for $\omega \leqslant \omega_m$

$\sigma = \sigma_b$ for $\omega > \omega_m$

F_n is a normalizing or scaling factor used to ensure that S_{JS} and S_{PM} have the same H_s.

See Annex B for further discussion and explanation.

Default values for γ and σ that are often used are $\gamma = 3{,}3$, $\sigma_a = 0{,}07$ and $\sigma_b = 0{,}09$; the corresponding normalizing factor is $F_n = 0{,}66$. These values for γ and σ are the mean values from the data of the original JONSWAP project in relatively deep water. When fitting measured data to the JONSWAP spectrum, the values derived for γ and σ vary widely between different times during the development of the sea and between different sites around the world. However, a central value of $\gamma \sim 2$ seems to be appropriate for very severe storms.

If the behaviour of an offshore structure is considered to be sensitive to the energy levels around the spectral peak, a range of γ values should be used.

Wave spectral shapes in shallow water do not generally conform to either the Pierson-Moskowitz or the JONSWAP forms, although a modified version of the JONSWAP spectrum is sometimes used, see Reference [22].

NOTE For $\gamma = 1$, the JONSWAP spectrum reverts to the Pierson-Moskowitz spectrum.

A.8.6.6 The high frequency tail of the wave frequency spectrum for wind seas

The high frequency tails of the Pierson-Moskowitz and JONSWAP spectra decrease with frequency as ω^{-5}. However, there is evidence that this is not entirely correct and that a power ω^{-4} is, at least partially, more appropriate[35]. Broadly speaking, there is wide support for ω^{-4} in the frequency range of approximately $1{,}5\ \omega_m < \omega < 3\ \omega_m$ and for ω^{-5} in the frequency range $\omega > 3\ \omega_m$[36].

A.8.6.7 Swell spectra

Wave frequency spectra for swells are generally much narrower than spectra for wind seas. Long period swells from distant storms are more or less symmetrical in shape around a dominant modal frequency. Even so, the swell spectrum is frequently described with a JONSWAP function with a large peak enhancement factor. Use of the JONSWAP function has the advantage that the spectral shape of shorter period swells — which tend to have broader spectra particularly above the modal frequency — can be described well. Nevertheless, the symmetric normal or Gaussian function is generally considered to be a better descriptor of swell, particularly long period swell.

A symmetric swell spectrum can be defined in complete analogy with the normal or Gaussian probability density function by letting the basic variable be the wave frequency, setting the mean to be equal to the modal frequency of the swell and the standard deviation to be a suitable function of the mean zero-crossing and modal frequencies of the swell. This provides the following formulation of the wave frequency spectrum for swell:

$$S_{sw}(\omega) = F_{n,sw} \frac{1}{\sigma_{sw}\sqrt{2\pi}} \exp\left[\frac{-\left(\omega - \omega_{m,sw}\right)^2}{2\left(\sigma_{sw}\right)^2}\right] \quad \text{(A.27)}$$

where

$S_{sw}(\omega)$ is the swell spectrum;

$F_{n,sw}$ is a scaling factor used to ensure that the spectrum will have the correct $H_{s,sw}$,

$$F_{n,sw} = \frac{H_s^{\,2}}{16}$$

ω is the wave frequency;

$\omega_{m,sw}$ is the peak or modal frequency of the swell spectrum, $\omega_{m,sw} = 2\pi/T_p$;

σ_{sw} is a parameter defining the width of the symmetric swell spectrum (equals the standard deviation of the Gaussian function)

$$\sigma_{sw} = \sqrt{\left(\omega_{z,sw}\right)^2 - \left(\omega_{m,sw}\right)^2}$$

where

$\omega_{z,sw}$ is the mean zero-crossing frequency of the swell;

$\omega_{z,sw} = 2\pi/T_z = \omega_{2,sw} = 2\pi/T_2$.

Low frequency, narrow-band swells have $T_z = T_2$ values that are nearly equal to, but always somewhat smaller than, T_p.

A.8.6.8 Applications

The most appropriate form of the wave frequency spectrum for an offshore structure depends on the geographical area, the severity of the sea state, whether the sea state is fully developed or is still growing, and the application concerned. For example, for a short-term North Sea design storm condition, a unidirectional JONSWAP spectrum can be most appropriate, whereas for the modelling of a series of sea states for a long-term fatigue analysis directionally spread, Pierson-Moskowitz spectra are often more appropriate. Similarly, for vessel downtime studies offshore West Africa, the use of a bimodal spectrum composed of a low frequency swell spectrum from one direction and a high frequency wind sea spectrum from a different direction can be appropriate.

A review of a number of double-peaked spectrum parameterizations can be found in Reference [13]. For tropical areas, the Ochi-Hubble[37] parameterization (see Annex B) tends to be used.

A.8.7 Wave directional spreading function and spreading factor

A.8.7.1 Directional spreading function

The directional spreading function $D(\theta)$ is used with the wave spectra, see A.8.6.1.

Standard formulations for the directional spreading function can be found in the literature, for example in Reference [13]. However, directional wave information is difficult to measure and data for validating directional spreading functions are hence scarce. In practical applications, unidirectional sea states are therefore often assumed. If the influence of directional wave spreading is expected to be significant, sensitivity analyses should be performed to investigate the effect. In such cases, one of the distributions shown in Equation (A.28) can be used.

The directional spreading function $D(\theta)$ from A.8.6.1 is a symmetric function around the mean direction $\bar{\theta}$. In the absence of information to the contrary, the mean wave direction can be assumed to coincide with the mean wind direction. There are three expressions for $D(\theta)$ in common use:

$$
\begin{aligned}
&D_1(\theta) = C_1(n)\cdot\left(\cos(\theta-\bar{\theta})\right)^n && \text{for } -\tfrac{1}{2}\pi \leqslant \left(\theta-\bar{\theta}\right) \leqslant +\tfrac{1}{2}\pi \\
&D_2(\theta) = C_2(s)\cdot\left[\cos\left(\frac{\theta-\bar{\theta}}{2}\right)\right]^{2s} && \text{for } -\pi \leqslant \left(\theta-\bar{\theta}\right) \leqslant +\pi \\
&D_3(\theta) = C_3(\sigma)\cdot\frac{1}{\sigma\sqrt{2\pi}}\cdot\exp\left[-\frac{\left(\theta-\bar{\theta}\right)^2}{2\sigma^2}\right] && \text{for } -\tfrac{1}{2}\pi \leqslant \left(\theta-\bar{\theta}\right) \leqslant +\tfrac{1}{2}\pi \\
&D_1(\theta) = D_2(\theta) = D_3(\theta) = 0 && \text{for all other } \left(\theta-\bar{\theta}\right)
\end{aligned}
\qquad \text{(A.28)}
$$

where

$$C_1(n) = \frac{\Gamma(n/2+1)}{\sqrt{\pi}\,\Gamma(n/2+1/2)}$$

$$C_2(s) = \frac{\Gamma(s+1)}{2\sqrt{\pi}\,\Gamma(s+1/2)}$$

$$C_3(\sigma) = 1$$

The functions all have a peak at $\theta = \bar{\theta}$, the sharpness of which depends on the exponent n in $D_1(\theta)$ or s in $D_2(\theta)$, or the standard deviation σ of the normal distribution $D_3(\theta)$. The coefficients C are normalizing factors dependent on n, s or σ, which are determined such that the integral of $D(\theta)$ over all θ is equal to 1,0. For appropriately chosen values of the parameters, the functions $D_1(\theta)$ and $D_2(\theta)$ are virtually indistinguishable.

In engineering applications, $D_1(\theta)$ is often used with $n = 2$ to $n = 4$ for wind seas; for $n = 2$, the corresponding factor $C_1(2) = 2 / \pi$. For swells, the value $n = 6$ or higher is more appropriate.

If $D_2(\theta)$ is used, typical values of s are $s = 6$ to 15 for wind seas and $s = 15$ to 75 for swells.

A.8.7.2 Directional spreading factor

The directional spreading factor ϕ is used to modify unidirectional regular wave theories.

For engineering applications, the sea is often represented by a deterministic design wave, assuming periodic waves that propagate in a particular direction. This is an abstract of a real sea, used for design purposes only.

Deterministic design wave procedures can, for example, be used to determine global actions caused by waves on fixed structures. This is especially common practice for the static design of fixed steel structures of space frame configuration. The directional spreading of the frequency components then tends to result in peak global actions that are somewhat smaller than those predicted for unidirectional seas. For such purposes, the reduction in global hydrodynamic actions due to directional spreading can be included in deterministic design wave procedures by reducing the horizontal velocity and acceleration, which are obtained from a two-dimensional periodic wave theory, by a “spreading factor”.

Only the wave energy that travels in the principal wave direction contributes to the wave kinematics in that direction. The ratio of the in-line energy to the total wave energy is the “in-line variance ratio”. Since the kinematics are proportional to the square root of the wave energy, the directional spreading reduces the in-line kinematics under the highest point of the crest by a spreading factor that is equal to the square root of the in-line variance ratio. All of the energy in the wave spectrum contributes to the kinematics so that the spreading factor is calculated by integrating the entire wave spectrum over frequency and direction.

The directional spreading factor ϕ is dependent on the type of storm in the area concerned and the distance of the site of interest from the storm centre. Though reference may be made to site-specific directional spreading data where these are available, caution should be exercised since such data are difficult to interpret. In addition, it should be noted that spreading data derived from hindcasts will often lead to an underestimate of ϕ. In general, the values in Table A.2 from Reference [38] are appropriate for open water, where refraction and diffraction effects do not modify spreading.

Table A.2 — Directional spreading factors for open water conditions

Type of storm or region	Directional spreading factor ϕ
Low-latitude monsoons typically $\lvert\psi\rvert < 15$ °	0,88
Tropical cyclones below approximately 40 °	0,87
Extratropical storms for the range of latitudes 36 ° $< \lvert\psi\rvert <$ 72 °	1,019 3 – 0,002 08$\lvert\psi\rvert$
NOTE ψ is the geographical latitude in degrees	

The wave directional spreading factor may be used with any of the two-dimensional wave theories discussed in A.8.4.

The relationship between the spreading factor ϕ and the exponents n and s in the two formulations $D_1(\theta)$ and $D_2(\theta)$ in Equation (A.28) is given in Table A.3.

Table A.3 — Relationship between spreading factor ϕ and exponents n and s for directional spreading functions $D_1(\theta)$ and $D_2(\theta)$

Variable	$D_1(\theta)$	$D_2(\theta)$
Directional spreading factor ϕ in terms of n or s	$\phi^2 = \left[\frac{(n+1)}{(n+2)}\right]$	$\phi^2 = 0{,}5\left[1 + \frac{s(s-1)}{(s+1)(s+2)}\right]$
Exponent n or s in terms of directional spreading factor ϕ	$n = \frac{2\phi^2 - 1}{1 - \phi^2}$	$s = \frac{\left[3\phi^2 - 1 + \sqrt{\left(\phi^4 + 6\phi^2 - 3\right)}\right]}{\left(2 - 2\phi^2\right)}$

The spreading factor for low-latitude monsoons of ϕ = 0,88 in Table A.2 corresponds with n = 2,43 and s = 6,25. The factor given in Table A.2 for tropical cyclones of ϕ = 0,87 similarly corresponds with n = 2,11 and s = 5,60. For extratropical storms at a latitude $\lvert\psi\rvert$ = 60 °, Table A.2 provides a spreading factor of ϕ = 0,895 which corresponds with n = 3,00 and s = 7,41.

A.8.8 Wave crest elevation

The long-term distribution of extreme and abnormal crest elevations can be established from a long time series of significant wave heights (H_s) and a short-term distribution of crest elevations conditional on H_s, $P(\eta > \eta^* \mid H_s)$. The statistically correct approach would use storms as the independent variable[6]. The methods described in A.8.5. for wave height are equally useful for obtaining design values of crest elevation and total surface elevation.

Recent research suggests that crest elevations for seas with typical directional spreading of wave energy are satisfactorily predicted by second order, random, directional wave theory. The short-term distribution of $P(\eta > \eta^* \mid H_s)$ can be obtained directly from theory or from a model distribution calibrated to fit the results of the theory. In Reference [39] a Weibull model has been matched to the theory over a range of water depths and wave steepnesses. The Weibull expression is

$$P(\eta > \eta^* \mid H_s) = \exp\left[-(\eta / \alpha H_s)^{\beta}\right] \quad \text{(A.29)}$$

where α and β are empirical functions of the wave steepness (S_1) and the Ursell number (U_r). S_1 and U_r are given by Equations (A.30) and (A.31):

$$S_1 = 2 \pi H_s / g T_1^2 \quad \text{(A.30)}$$

$$U_r = H_s / (k_1^2 d^3) \quad \text{(A.31)}$$

where

T_1 is the mean wave period calculated from the ratio of the first two moments of the wave spectrum, m_0 / m_1;

k_1 is the wave number for a wave frequency $2 \pi / T_1$;

d is the water depth.

For a spread sea, the expressions for α and β are given by Equations (A.32) and (A.33):

$$\alpha = 0{,}3536 + 0{,}2568\, S_1 + 0{,}0800\, U_r \quad \text{(A.32)}$$

$$\beta = 2 - 1{,}7912\, S_1 - 0{,}5302\, U_r + 0{,}284\, U_r^2 \quad \text{(A.33)}$$

A.9 Currents

A.9.1 General

For bottom founded structures, the total current profile associated with the sea state producing extreme or abnormal waves should be specified for the design of the structure. For floating structures, the selection of an appropriate combination of currents, waves and winds is often less obvious and needs careful consideration.

A.9.2 Current velocities

The current flow at a particular site varies both in time and with depth below the mean sea surface. The characteristics of the extreme or abnormal current profile that need to be estimated for the design of offshore structures are particularly difficult to determine since current measurement surveys are relatively expensive and consequently it is unlikely that any measurement programme will be sufficiently long to capture a representative number of severe events. Furthermore, current (hindcast) modelling is not as advanced as wind and wave modelling in terms of being able to provide the parameters needed. Also, extrapolation of any data set demands that account is taken of the three-dimensional nature of the flow.

Site-specific measurements of currents at the location of a structure can be used either as the basis for independent estimates of likely extremes or to check the indicative values of the various components of the total current.

Information on the frequency of occurrence of total current speed and direction at different depths for each month and/or each season is normally useful for planning operations. Boat landings and fenders should be located, where possible, to allow the boat to engage the structure, with the boat moving against the current.

Any changes in tidal currents away from locally resonant areas are unlikely to be significant. However, residual currents are affected by changes in the wind-driven or thermohaline driven circulations of the ocean and sea basins.

For most design situations in which waves are dominant, estimates of the extreme or abnormal residual current and total current can be obtained from high-quality site-specific measurements; these should extend over the water profile and over a period that captures several major storm events that generated large sea states. Current models may be used in lieu of site-specific measured data. The period over which the current model is run should be adequate to allow tidal decomposition to be carried out and the residual current to be separated out of the total current. Consideration should be given to long period, large-scale environmental fluctuations, which can affect the residual current climate. Efforts should be made to ensure that the output of a current model is validated against nearby measured data.

A.9.3 Current profile

The characteristics of the current profile over depth in different parts of the world depend on the regional oceanographic climate, in particular the vertical density distribution and the flow of water into or out of the area. Both of these controlling aspects vary from season to season. Typically, shallow water current profiles in which tides are dominant can often be characterized by simple power laws of velocity versus depth, whereas deep water profiles are more complex and can even show reversals of the current direction with depth. Such characteristics of the current flow can be particularly important to consider in the design of deep water structures and parts of the system such as risers and mooring systems.

The power law current profile given in Equation (A.34) can be used where appropriate (e.g. in areas dominated by tidal currents in relatively shallow water such as the southern North Sea):

$$U_{\mathrm{c}}(z) = U_{\mathrm{c0}}\left(\frac{z+d}{d}\right)^{\alpha} \quad \text{(A.34)}$$

where

$U_{\mathrm{c}}(z)$ is the current speed at elevation $z(\leqslant 0)$;

U_{c0} is the surface current speed (at $z = 0$);

z is the vertical coordinate, measured positively upwards from still water level;

d is the still water depth;

α is an exponent (typically 1/7).

Other current profiles in common use are

— a linear distribution between the surface current U_{c0} and a bottom current of half the surface current ($U_{\mathrm{c0}}/2$),

— a bilinear distribution with parameters that are determined for the location concerned, and

— a slab profile [see Figure A.4 b)] where a uniform current occurs over the upper part of the water column with zero current over the lower part.

For deep water, more accurate design current profiles can be derived from long-term measured current profile data sets through a two-stage process. In the first stage, the data are parameterized using empirical orthogonal functions; in the second stage, the design current profile with the required return period is selected through a process involving an inverse first order reliability method (FORM) procedure. The method is described in Reference [40].

For some applications, an approach using a response function such as the integrated drag loading on a vertical cylinder can be used as described in A.5.3 c).

A.9.4 Current profile stretching

A.9.4.1 General

References [41] and [42] show that waves alternately stretch and compress the current profile under crests and troughs, respectively. Stretching means that, in the presence of waves, the instantaneous current speed $U_c(z)$ of a water particle calculated at depth z (measured positively upwards from still water level for $-d \leqslant z \leqslant 0$) is effective at a stretched vertical coordinate z_s. In the design data, the current profile $U_c(z)$ is specified over the full water column between the sea floor at $z = -d$ and the still water level at $z = 0$. Both linear and non-linear stretching methods are used.

In linear stretching, the relationship between z_s and z is proportional to the ratio of the instantaneous height of the water surface elevation and the still water depth. A stretching factor F_s can be introduced, in an analogous manner to the delta stretching procedure for wave kinematics. For current stretching F_s is defined as

$$F_s = \frac{d + \eta}{d} \tag{A.35}$$

where

η is the water surface elevation directly above the water particle (measured upwards from still water level);

d is the still water depth.

The stretched vertical coordinate can then be expressed as

$$z_s = F_s\,(d + z) - d \tag{A.36}$$

where

z_s is the stretched elevation (measured upwards from still water level);

z is the original elevation (measured upwards from still water level).

For current stretching, the stretching factor F_s is larger than 1,0 and consequently $z_s > z$.

In non-linear stretching, the elevations z_s and z are related through linear (Airy) wave theory as:

$$z_s = z + \eta\,\frac{\sinh\left(k_{nl}\,(z + d)\right)}{\sinh\left(k_{nl} d\right)} \tag{A.37}$$

where, additionally,

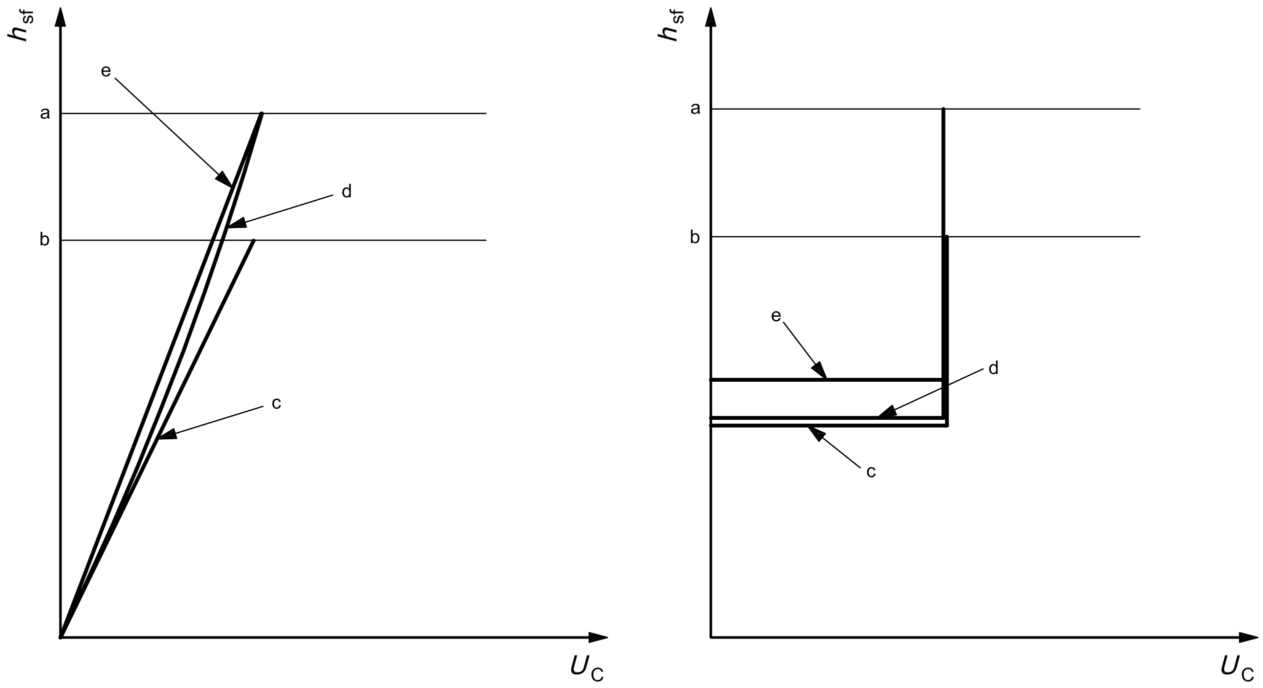
k_{nl} is the non-linear wave number

$$k_{nl} = \frac{2\pi}{\lambda_{nl}}$$

λ_{nl} is the wave length for the regular wave under consideration for water depth d and wave height H (calculated using non-linear wave theory and the intrinsic wave period).

Equation (A.37) provides a non-linear stretching of the current, with the greatest stretching occurring high in the water column, where the particle orbits have the greatest radii. Figure A.4 illustrates a comparison of linear and non-linear stretching for a sheared and a slab current profile.

Non-linear stretching is the preferred method. For slab or power-law current profiles, simple vertical extension of the current profile from the still water level to the instantaneous wave surface is a good approximation to non-linear stretching. For other current profiles, linear stretching is an acceptable approximation.



a) **Shear profile**

b) **Slab profile**

Key

h_{sf} height above sea floor

U_c current speed

a Wave crest.

b Still water level.

c Input current profile.

d Non-linear stretch current profile.

e Linear stretch current profile.

Figure A.4 — Linear and non-linear stretching of current profiles

Another approximate model is the linearly stretched model described by Equation (A.37), adjusted such that the total momentum in the stretched profile from the sea floor to the wave surface equals that in the specified profile from the sea floor to the still water level. However, this procedure is not supported by the theoretical analyses in References [41] and [42].

If the current is not in the same direction as the wave, the methods discussed above can still be used, with one modification: both the in-line and the normal components of the current would need to be stretched, but only the in-line component used to estimate T_i for the Doppler-shifted wave.

While no exact solution has been developed for irregular waves, the wave/current solution for regular waves can be logically extended. In the two approximations described above for regular waves, the period and length of the regular wave would be replaced by the period and length corresponding to the spectral peak frequency.

A linearly stretched current profile is an acceptable approximate model for many applications. The method is exactly analogous to the stretching of linear wave kinematics as applied by Wheeler[43].

A.9.4.2 Effect of current profile stretching on hydrodynamic actions

Reference [41] reports that a model that combined Doppler-shifted wave kinematics with a non-linearly stretched current profile gave the best estimate of global hydrodynamic actions on a space frame structure. These are within a few percent of those produced by the exact solution on a typical drag-dominant fixed structure subjected to representative waves and current profiles.

In most cases, simple vertical extrapolation of the input current profile above mean water level produces reasonably accurate estimates of global hydrodynamic actions on drag-dominated fixed structures. In particular, for a slab profile thicker than approximately 50 m, vertical extrapolation produces nearly the same result as non-linear stretching, as illustrated in Figure A.4. However, if the specified profile $U_c(z)$ has a very high speed at the still water level, sheared to much lower speeds just below still water level, the global action can be overestimated (by approximately 8 % in a typical application).

A.9.5 Current blockage

Current blockage refers to the global distortion of the current field in and around non-solid structures. These are structures with a configuration that is to some extent transparent to the current and which thus allow partial flow at a reduced velocity through the structure. Taking account of current blockage can be of interest for the design of space frame type structures, both fixed and floating (e.g. semi-submersibles and TLPs), especially when they accommodate a large number of conductors or risers.

For fixed steel structures, reference should be made to ISO 19902.

A.10 Other environmental factors

A.10.1 Marine growth

No guidance is offered.

A.10.2 Tsunamis

A preliminary assessment of the risk of tsunamis in a region can be obtained from atlas sources such as References [44] or [45].

Detailed procedures for seismic design are described in ISO 19901-2, which provides guidance and methods for determining the magnitude and probability of earthquake events.

For a given location, the frequency of earthquake events is generally very low and in particular the frequency of occurrence of a tsunami at a site is even lower, since only a very few earthquakes give rise to tsunamis. In comparison to earthquake data, the data on tsunamis are limited, in part because a global tsunami monitoring/forecasting system does not exist. Historical records should be examined to see if any tsunamis have occurred at or near a particular location, and consideration should also be given to possible source events and possible magnitudes. Tsunami waves undergo strong refraction, so consideration should be given to the exposure of a site to the possible directions of tsunami wave approach and the associated currents from possible earthquake sources.

For the majority of offshore structures, the environmental actions are dominated by extreme wind waves. Most structures are effectively in deep water with regard to tsunami wave physics which are at most a few tens of centimetres in height. While tsunami waves do not generally govern the design of fixed offshore structures, their very long periods can result in substantial actions on moored floating structures in water shallower than 100 m. It is prudent to be aware of the potential impact of tsunamis on moored floating structures that form part of an offshore field development.

Tsunami heights can radically increase due to shoaling and refraction, so special care should be taken at shallow water sites near complicated bathymetry that can lead to a caustic (focal point for wave energy) or near semi-enclosed features like bays. Coastal facilities are likely to be at the greatest risk due to the run-up of the tsunami and the potential for inundation of the facility and processing plant. Historical run-up data are available from Reference [45]. Tsunamis approaching the coastline often scour the seabed, transporting large amounts of sediment shoreward and dumping it onshore, thereby increasing their destructiveness. It is prudent to perform an inspection if a tsunami passes over a pipeline.

Where tsunamis have a high probability of occurrence and significance (exceeding the generally accepted risk level in the design), the effects on installations should be assessed. Where possible, offshore structures should be designed against potential tsunamis or they should be located to minimize the consequences of impact.

A.10.3 Seiches

The effect of seiches can be important to consider for the design of loading and offloading facilities as well as for operations (e.g. of tankers) in relatively shallow water locations.

A.10.4 Sea ice and icebergs

Where data are being collected on sea ice and icebergs, the following should be considered.

- The type of sea ice expected to occur is a measure of its age, whether first-year, multi-year or of glacial origin. Distribution statistics reflect the variations that occur in the thickness, consolidation and concentration of ice types during a season, both seasonally and from year to year.

- Sea ice keels can create gouges in the seabed in relatively shallow or intermediate water depths (typically less than 25 m water depth).

- Characterization of year-round regional ice cover includes the occurrence and distribution of ice concentrations, thicknesses, floe sizes and types present during freeze-up, winter, break-up and open water seasons.

- Probability of occurrence of specific ice features, such as multi-year hummock fields and ice islands. In areas where ice of glacial origin is to be expected, the annual and seasonal variation in the flux, concentration and size of icebergs is relevant.

- The probability distributions or extreme values of the velocity of pack ice, ice floes, and discrete ice features (such as icebergs, “bergy bits”, “growlers” and ice islands) and seasonal variations of these distributions are relevant.

Where sea ice or icebergs are possible and could be in excess of that which can be accommodated in a structure's design, an emergency preparedness system should be established. Solutions based on the relocation of the structure or the towing away of the ice feature may be chosen; in such cases the emergency preparedness should be reliable and planned in relation to the time required to relocate the structure or to tow the ice feature away.

A.10.5 Snow and ice accretion

Snow can settle on both horizontal surfaces and, if the snow is sufficiently wet, on non-horizontal windward parts of a platform. On vertical surfaces, it is only likely to stay in position as snow for a few hours, although it can freeze and remain as ice. It can therefore affect all exposed areas above the splash-zone. On horizontal surfaces, dry snow is blown off as soon as any thickness accumulates, while wet snow can remain in position for several hours.

In areas that are affected by icing, consideration should be given to the possibility of topsides icing from freezing sea-spray and freezing atmospheric vapour.

Ice can form on the topsides of a platform through a number of mechanisms:

- freezing of old wet snow;

— freezing sea spray;

— freezing fog and super-cooled cloud droplets;

— freezing rain.

The effect of topsides icing on the stability of floating structures and on the operation of emergency equipment are particular aspects that should be considered when designing for operations in cold climates.

In the absence of specific information, new snow can be assumed to have a density of 100 kg/m^3 and the average density of ice formed on the structure can be taken to be 900 kg/m^3.

A.10.6 Miscellaneous

No guidance is offered.

Annex B
(informative)

Discussion of wave frequency spectra

B.1 The Pierson-Moskowitz spectrum

As noted in A.8.6.3, most parametric spectral formulations developed by oceanographers relate to wind seas, and most of them to fully developed seas. These formulations express the fully developed wave frequency spectrum in terms of the steady state local wind speed only (one-parameter spectrum). Pierson and Moskowitz developed their spectral formulation in 1964 from measured wave data in the North Atlantic in the following form[46]:

$$S_{\text{PM}}(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\beta\left(\frac{g}{\omega U}\right)^4\right] \tag{B.1}$$

where

α is a numerical constant, $\alpha = 0{,}0081$;

β is another numerical constant, $\beta = 0{,}74$;

g is the acceleration of gravity;

U is the wind speed at 19,4 m above the sea surface.

The factor ω^{-5} controls the high frequency flank of the spectrum, whereas the exponential function controls the low frequency flank. The modal frequency ω_{m} at the peak of the spectrum is defined by $dS(\omega) / d\omega = 0$. This results in

$$\omega_{\text{m}}^4 = \frac{4\beta}{5} \cdot \left(\frac{g}{U}\right)^4$$

or

$$\left(\frac{g}{U}\right)^4 = \frac{5}{4} \cdot \frac{\omega_{\text{m}}{}^4}{\beta} \tag{B.2}$$

Substitution of $(g / U)^4$ from Equation (B.2) into Equation (B.1) results in the Pierson-Moskowitz spectrum as it is usually cited in the literature:

$$S_{\text{PM}}(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\frac{5}{4}\left(\frac{\omega_m}{\omega}\right)^4\right] \tag{B.3}$$

Equation (B.1) may be generalized by releasing the constraints associated with the numerical constants and the dependency on the wind speed by writing it as

$$S_{\text{PM}}(\omega) = \frac{A}{\omega^5} \exp\left(-\frac{B}{\omega^4}\right) \tag{B.4}$$

This transforms the one-parameter Pierson-Moskowitz spectrum (as a function of wind speed) into the two-parameter Pierson-Moskowitz spectrum (as a function of the parameters A and B). The moments of the spectrum (Equation (B.5)) are related to the statistical parameters of the water surface elevation as given by the Equations (B.6). Using these relationships the parameters A and B can be expressed in the significant wave height and a representative frequency or period of the sea state.

The moments of the spectrum and their relationships with A and B in Equation (B.4) are

$$
\begin{aligned}
m_n &= \int_0^\infty \omega^n S(\omega) d\omega \\
m_0 &= \frac{A}{4B} \\
m_1 &= \frac{\Gamma(3/4)}{4} \cdot \frac{A}{B^{3/4}} \\
m_2 &= \frac{\sqrt{\pi}}{4} \cdot \frac{A}{\sqrt{B}} \\
m_4 &= \infty
\end{aligned}
\tag{B.5}
$$

where $\Gamma(3/4)$ is the gamma function $\Gamma(x)$ for x = 3/4, and $\Gamma(3/4)$ = 1,225 4.

The statistical parameters of the water surface elevation of a random sea and their relationships with the moments of the spectrum are

$$
\begin{aligned}
H_s &= 4\sqrt{m_0} = 2\sqrt{\frac{A}{B}} \\
\omega_1 &= \frac{2\pi}{T_1} = \frac{m_1}{m_0} = B^{1/4}\Gamma(3/4) \\
\omega_z &= \frac{2\pi}{T_2} = \frac{2\pi}{T_z} = \sqrt{\frac{m_2}{m_0}} = (\pi B)^{1/4} \\
\omega_m &= \frac{2\pi}{T_p} = \left(\frac{4}{5}B\right)^{1/4} \\
\varepsilon &= \sqrt{1 - \frac{m_2^2}{m_0 m_4}}
\end{aligned}
\tag{B.6}
$$

where

T_1 is a mean period of the water surface elevation, defined by the zeroth- and first order spectral moments;

T_2 and T_z are the average zero-crossing period of the water surface elevation, defined by the zeroth- and second order spectral moments, (T_2 = T_z);

T_p is the modal or peak spectral period;

ε is the spectral width parameter with $0 \leqslant \varepsilon \leqslant 1{,}0$.

NOTE The modal frequency ω_m is denoted by the subscript m. However, the modal or peak period T_p is denoted by the subscript p rather than m to avoid an erroneous interpretation as the mean period.

The fourth spectral moment m_4 of the Pierson-Moskowitz spectrum [see Equation (B.5)] is infinitely large when the spectrum is integrated from ω = 0 to infinity. This means that ε = 1,0 and that the spectrum is broad-banded. In numerical calculations the Pierson-Moskowitz spectrum should always be truncated at a sufficiently high frequency, resulting in a finite m_4 and a (relatively high) value of the spectral width parameter ε < 1,0.

Using the Equations (B.6), the parameters A and B can be expressed through H_s and one of the three period options, T_p or $T_z = T_2$ or T_1, all three of which can be found in the literature. All equations can be used with any internally consistent system of units. In SI units, the dimensions of A and B are $m^2(rad/s)^4$ and $(rad/s)^4$, respectively.

Choosing H_s and T_p, the parameters A and B become

$$B = \frac{5}{4}\omega_m^4 = \frac{5}{4}\cdot\left(\frac{2\pi}{T_p}\right)^4 = \frac{20\pi^4}{T_p^4}$$
$$A = \frac{BH_s^2}{4} = 5\pi^4 \cdot \frac{H_s^2}{T_p^4} \tag{B.7}$$

The spectral formulation in Equation (B.4) then becomes

$$S_{PM}(\omega) = 5\pi^4 \cdot \frac{H_s^2}{T_p^4}\cdot\frac{1}{\omega^5}\cdot\exp\left(-\frac{20\pi^4}{T_p^4}\cdot\frac{1}{\omega^4}\right) \tag{B.8}$$

Choosing H_s and T_z, the parameters A and B become

$$B = \frac{1}{\pi}\omega_z^4 = \frac{1}{\pi}\cdot\left(\frac{2\pi}{T_z}\right)^4 = \frac{16\pi^3}{T_z^4}$$
$$A = \frac{BH_s^2}{4} = 4\pi^3 \cdot \frac{H_s^2}{T_z^4} \tag{B.9}$$

and the spectral formulation in Equation (B.4) becomes

$$S_{PM}(\omega) = 4\pi^3 \cdot \frac{H_s^2}{T_z^4}\cdot\frac{1}{\omega^5}\cdot\exp\left(-\frac{16\pi^3}{T_z^4}\cdot\frac{1}{\omega^4}\right) \tag{B.10}$$

Finally, choosing H_s and T_1 the parameters A and B become

$$B = \left(\frac{1}{\Gamma(3/4)}\right)^4 \cdot \omega_1^4 = \left(\frac{1}{\Gamma(3/4)}\right)^4 \cdot \left(\frac{2\pi}{T_1}\right)^4 = 7{,}096\cdot\frac{\pi^4}{T_1^4}$$
$$A = \frac{BH_s^2}{4} = 1{,}774\,\pi^4 \cdot \frac{H_s^2}{T_1^4} \tag{B.11}$$

and the spectral formulation in Equation (B.4) becomes

$$S_{PM}(\omega) = 1{,}774\,\pi^4 \cdot \frac{H_s^2}{T_1^4}\cdot\frac{1}{\omega^5}\cdot\exp\left(-\frac{7{,}096\,\pi^4}{T_1^4}\cdot\frac{1}{\omega^4}\right) \tag{B.12}$$

Considering the differences between the Equations (B.8), (B.10) and (B.12), care should be taken to combine the correct formulation of the spectrum with the period chosen to represent the sea state. The choice usually depends on the type of available data and user preference. Equating the expressions for the parameter B from the Equations (B.7), (B.9) and (B.11) the relationships between the peak (the modal) period T_p, the average zero-crossing period $T_z = T_2$ and the mean period T_1 for a Pierson-Moskowitz spectrum are found to be

$$\begin{aligned} T_1 &= 1{,}086\ T_z = 0{,}772\ T_p \\ 0{,}920\ T_1 &= T_z = 0{,}710\ T_p \\ 1{,}296\ T_1 &= 1{,}408\ T_z = T_p \end{aligned} \tag{B.13}$$

B.2 The JONSWAP spectrum

The JONSWAP wave frequency spectrum resulted from extensive measurements taken off the coast of the German island of Sylt[47]. The JONSWAP spectrum is formulated as a modification of the Pierson-Moskowitz spectrum for a developing sea state in a fetch limited situation:

$$S_{JS}(\omega) = F_n\ S_{PM}(\omega) \left\langle \gamma^{\exp\left\{-\frac{1}{2}\left[(\omega-\omega_m)/(\sigma\,\omega_m)\right]^2\right\}} \right\rangle \tag{B.14}$$

where

γ is a non-dimensional peak shape parameter;

σ is a numerical parameter

$\sigma = \sigma_a$ for $\omega \leqslant \omega_m$

$\sigma = \sigma_b$ for $\omega > \omega_m$

F_n is a normalizing factor used to ensure that both spectral forms have the same H_s.

For $\gamma = 1$ the JONSWAP spectrum reduces to the Pierson-Moskowitz spectrum. The factor in the large brackets in Equation (B.14) is a peak enhancement factor, which is a function of the three parameters γ, σ_a and σ_b. These parameters were not constant in the North Sea data obtained in the project but showed appreciable scatter. Average values from the JONSWAP data were

$$\begin{aligned} \gamma &= 3{,}3, \\ \sigma_a &= 0{,}07, \\ \sigma_b &= 0{,}09. \end{aligned} \tag{B.15}$$

The peak shape parameter γ varied between about 1 and 6 and was approximately normally distributed with a mean of 3,3 and a standard deviation of 0,79. The JONSWAP spectral form also appears to be capable of representing the observations rather well in different geographical areas, provided that the parameters γ, σ_a and σ_b are chosen in accordance with the local data, see Reference [36]. The values in other areas are likely to be very different from the JONSWAP data.

For $\gamma > 1{,}0$ the peak enhancement factor is always larger than 1,0 for all ω; therefore $S_{JS}(\omega) \geqslant S_{PM}(\omega)$ for all ω. Without the normalizing factor F_n, the JONSWAP spectrum would hence have a larger energy content (a larger H_s) than the corresponding Pierson-Moskowitz spectrum; its modal frequency is also larger: $\omega_{m,JS} \geqslant \omega_{m,PM}$. To ensure that H_s is the same for both spectra, the normalizing factor should be

$$F_n = \frac{\int_0^\infty S_{PM}(\omega)\,d\omega}{\int_0^\infty S_{PM}(\omega)\left\langle \gamma^{\exp\left\{-\frac{1}{2}\left[(\omega-\omega_m)/(\sigma\,\omega_m)\right]^2\right\}}\right\rangle d\omega} \tag{B.16}$$

As the JONSWAP spectrum cannot be integrated analytically, the normalizing factor can only be calculated numerically. Based on curve fitting through the results of a number of numerical exercises for different peak shape parameter values, but always using σ_a = 0,07 and σ_b = 0,09, the expressions for the normalizing factor shown in Equation (B.17) were developed:

$$\begin{aligned} F_n(1) &= \left[0{,}78 + 0{,}22\gamma\right]^{-1} && \text{for } 1 \leqslant \gamma \leqslant 6 \\ F_n(2) &= \left[\,5\left(0{,}065\gamma^{0{,}803} + 0{,}135\right)\right]^{-1} && \text{for } 1 \leqslant \gamma \leqslant 10 \end{aligned} \tag{B.17}$$

$F_n(1)$ was obtained by Ewing[48] and $F_n(2)$ by Yamaguchi[49].

By way of example, for different values of γ the expression $F_n(2)$ results in

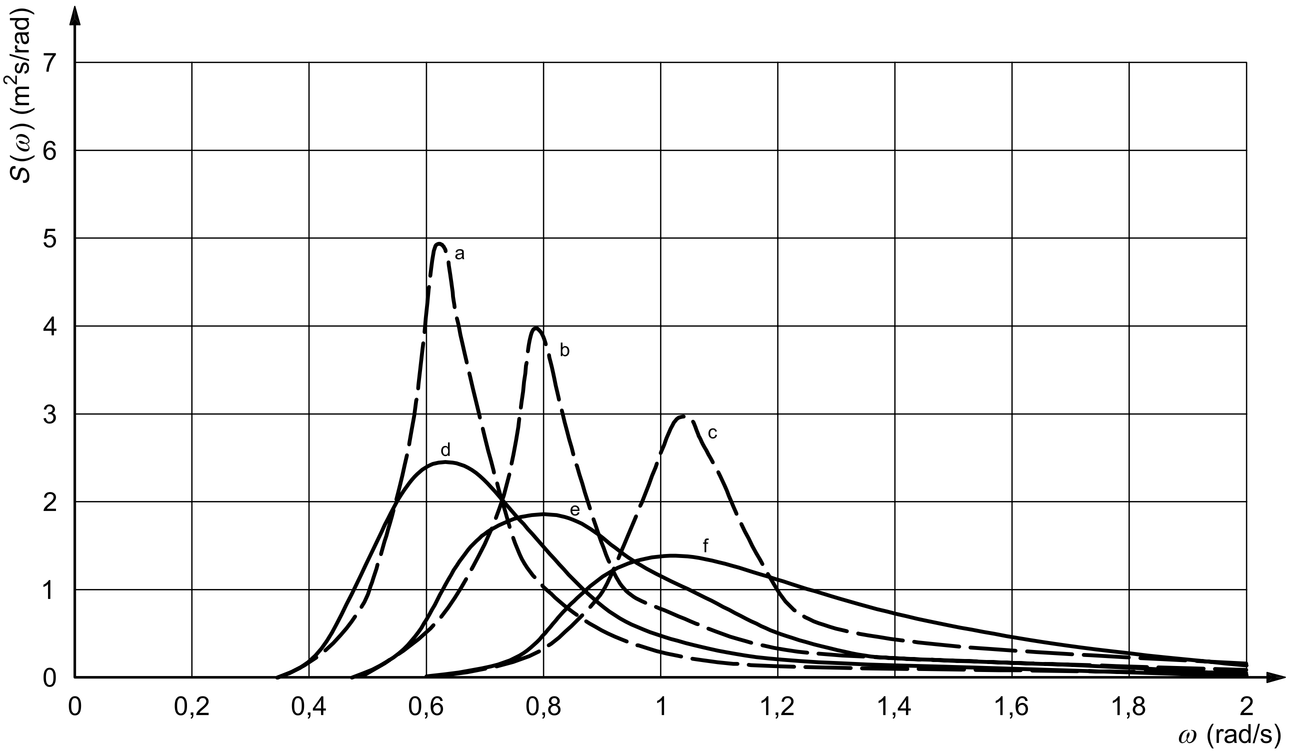
$$\begin{aligned} \gamma &= 1 && F_n(2) = 1{,}00 \\ &= 2 && F_n(2) = 0{,}81 \\ &= 3 && F_n(2) = 0{,}68 \\ &= 5 && F_n(2) = 0{,}54 \\ &= 10 && F_n(2) = 0{,}36 \end{aligned} \tag{B.18}$$

Numerical integration of the JONSWAP spectrum for the average values of γ = 3,3; σ_a = 0,07 and σ_b = 0,09 results in the following ratios between T_p, $T_z = T_2$ and T_1:

$$\begin{aligned} & T_1 &&= 1{,}073\ T_z &&= 0{,}834\ T_p \\ 0{,}933\ & T_1 &&= T_z &&= 0{,}777\ T_p \\ 1{,}199\ & T_1 &&= 1{,}287\ T_z &&= T_p \end{aligned} \tag{B.19}$$

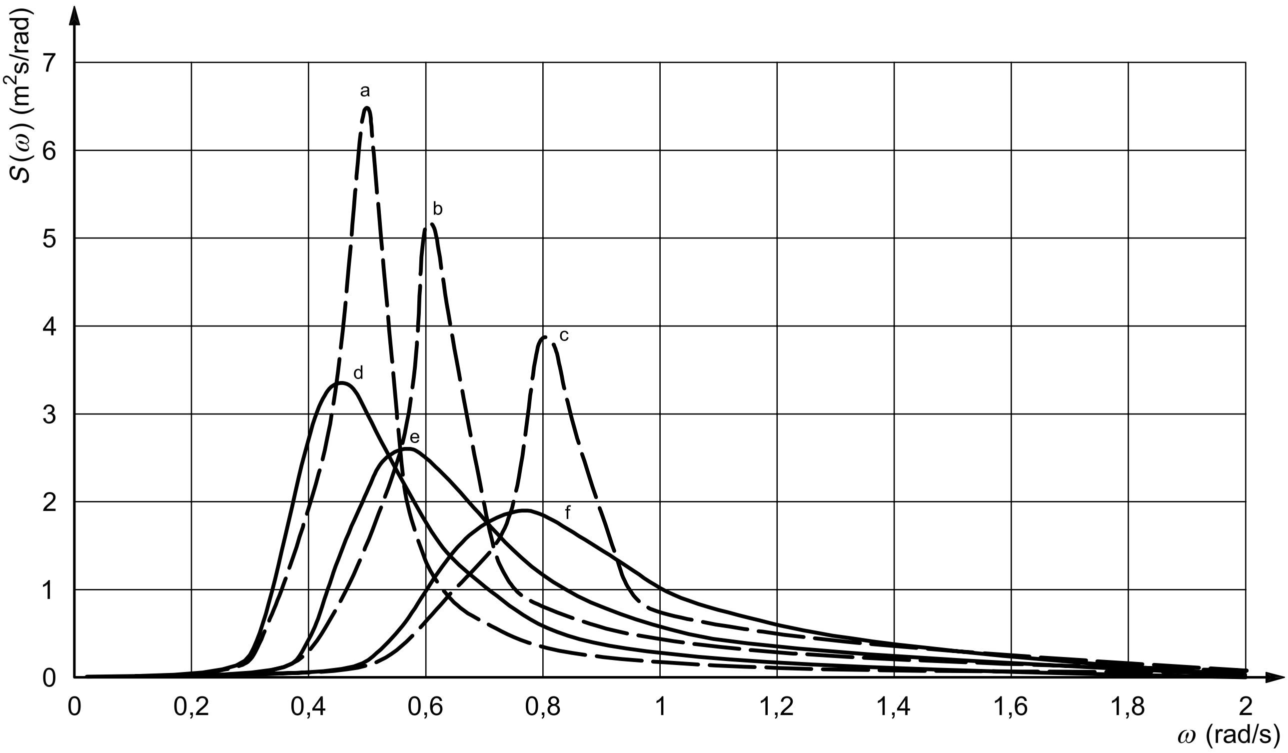
B.3 Comparison of Pierson-Moskowitz and JONSWAP spectra

For illustration, Figures B.1 and B.2 show a comparison of the Pierson-Moskowitz and JONSWAP spectral formulations for three different sea states each. The JONSWAP spectra are based on the average project data of γ = 3,3; σ_a =0,07; σ_b = 0,09; F_n = 0,66. The significant wave height is H_s = 4,0 m for all sea states. In Figure B.1 the spectral peak periods of both formulations are the same (T_p = 6 s, 8 s and 10 s respectively). In Figure B.2 the mean zero-crossing periods of both formulations are the same (T_z = 6 s, 8 s and 10 s respectively); the relationship between mean zero-crossing period and peak period for the JONSWAP spectrum is T_p = 1,287 T_z, in accordance with Equation B.19. Note the different distribution of wave energy over frequency for corresponding Pierson-Moskowitz and JONSWAP spectra, as well as the shift in position of the spectra between the figures.



a JONSWAP, T_p = 10 s
b JONSWAP, T_p = 8 s
c JONSWAP, T_p = 6 s
d Pierson-Moskowitz, T_p = 10 s
e Pierson-Moskowitz, T_p = 8 s
f Pierson-Moskowitz, T_p = 6 s

Figure B.1 — Pierson-Moskowitz and JONSWAP spectra — H_s = 4,0 m **— Equal peak periods:** T_p = 6 s, 8 s, 10 s



a JONSWAP, T_z = 10 s

b JONSWAP, T_z = 8 s

c JONSWAP, T_z = 6 s

d Pierson-Moskowitz, T_z = 10 s

e Pierson-Moskowitz, T_z = 8 s

f Pierson-Moskowitz, T_z = 6 s

Figure B.2 — Pierson-Moskowitz and JONSWAP spectra — H_s = 4,0 m **— Equal mean zero-crossing periods:** T_z = 6 s, 8 s, 10 s

B.4 Ochi-Hubble spectra

Ochi-Hubble spectra[37] are a general spectral formulation to describe seas which consist of a combination of two different sea states, each of which is in turn described by a further generalization of the Pierson-Moskowitz spectrum including three instead of two parameters. Ochi-Hubble spectra thus have six parameters in total. The discussion below is based on Reference [36].

The Pierson-Moskowitz spectrum can be normalized by dividing it by its zeroth moment, which results in

$$S_{\text{PM,n}}(\omega) = \frac{S_{\text{PM}}(\omega)}{m_0(\omega)} = \frac{4}{\omega^5}\left[B\exp\left(-\frac{B}{\omega^4}\right)\right] \quad \text{(B.20)}$$

where

$S_{\text{PM,n}}(\omega)$ is the normalized Pierson-Moskowitz spectrum;

$S_{\text{PM}}(\omega)$ is the Pierson-Moskowitz spectrum of Equation (B.4);

$m_0(\omega)$ is the zeroth moment of the Pierson-Moskowitz spectrum of Equation (B.5).

As $S_{\mathrm{PM,n}}(\omega)$ has unit area, Equation (B.20) may be considered as if it were a probability density function. The factor within the square brackets has the form of the probability density function of the exponential distribution:

$$f_{\exp}(x) = \alpha \exp(-\alpha x) \tag{B.21}$$

$x \geqslant 0$

$\alpha > 0$

with $\alpha = B$ and $x = \omega^{-4}$. The exponential distribution is a special case of the more general gamma distribution with the probability density function:

$$f_{\mathrm{gam}}(x) = \frac{1}{\Gamma(\lambda)} x^{\lambda-1} \alpha^{\lambda} \exp(-\alpha x) \tag{B.22}$$

$x \geqslant 0$

$\alpha > 0$

$\lambda > 0$

For $\lambda = 1$, the gamma distribution reduces to the exponential distribution. The normalized Pierson-Moskowitz spectrum $S_{\mathrm{PM,n}}(\omega)$ may hence be generalized to become $S_{\mathrm{gen,n}}(\omega)$ by substituting the gamma probability density function for the exponential probability density function in Equation (B.20), which results in

$$S_{\mathrm{gen,n}}(\omega) = \frac{4}{\omega^5}\left[\frac{1}{\Gamma(\lambda)} \omega^{-4(\lambda-1)} B^{\lambda} \exp\left(-\frac{B}{\omega^4}\right)\right] = \frac{4}{\Gamma(\lambda)} \frac{B^{\lambda}}{\omega^{4\lambda+1}} \exp\left(-\frac{B}{\omega^4}\right) \tag{B.23}$$

The parameter B can be determined by observing that the spectrum has a horizontal tangent at the spectral peak, i.e. $d(S_{\mathrm{gen,n}}(\omega)) / d\omega = 0$ for $\omega = \omega_{\mathrm{m}}$. This provides the one and only solution:

$$B = \frac{4\lambda+1}{4} \omega_{\mathrm{m}}^4 \tag{B.24}$$

This is the equivalent of Equation (B.6) for the Pierson-Moskowitz spectrum. Substitution of B from Equation (B.24) into Equation (B.23) gives the generalized spectral formulation as

$$S_{\mathrm{gen,n}}(\omega) = \frac{4}{\Gamma(\lambda)}\left(\frac{4\lambda+1}{4}\omega_{\mathrm{m}}^4\right)^{\lambda} \frac{1}{\omega^{4\lambda+1}} \exp\left[-\frac{4\lambda+1}{4}\left(\frac{\omega_{\mathrm{m}}}{\omega}\right)^4\right] \tag{B.25}$$

$S_{\mathrm{gen,n}}(\omega)$ is still normalized with unit area. To describe a sea state with a significant wave height H_{s}, it should be multiplied by $H_{\mathrm{s}}^2 / 16$, see Equation (B.6), finally resulting in

$$S_{\mathrm{gen}}(\omega) = \frac{H_{\mathrm{s}}^2}{4\Gamma(\lambda)}\left(\frac{4\lambda+1}{4}\omega_{\mathrm{m}}^4\right)^{\lambda} \frac{1}{\omega^{4\lambda+1}} \exp\left[-\frac{4\lambda+1}{4}\left(\frac{\omega_{\mathrm{m}}}{\omega}\right)^4\right] \tag{B.26}$$

$S_{\mathrm{gen}}(\omega)$ is a more general spectral formulation than the Pierson-Moskowitz spectrum, having three instead of two parameters, i.e. H_{s}, $\omega_{\mathrm{m}} = 2\pi / T_{\mathrm{p}}$ and λ. It is easily verified that for $\lambda = 1$, the spectrum $S_{\mathrm{gen}}(\omega)$ reduces to the Pierson-Moskowitz spectrum.

The Ochi-Hubble spectra are obtained by combining two spectra of the form of Equation (B.26), one for the low frequency components (usually a swell) and one for the high frequency components of the wave energy (usually a wind sea), see Figure B.3. The spectral formulation of the Ochi-Hubble spectra is accordingly

$$S_{\text{OH}}(\omega) = S_{\text{gen},1}(\omega) + S_{\text{gen},2}(\omega) = \sum_{j=1,2} \left\{ \frac{H_{\text{s},j}^4}{4\Gamma(\lambda_j)} \left(\frac{4\lambda_j + 1}{4} \omega_{\text{m},j}^4 \right)^{\lambda_j} \frac{1}{\omega^{4\lambda_j+1}} \exp\left[-\frac{4\lambda_j + 1}{4} \left(\frac{\omega_{\text{m},j}}{\omega} \right)^4 \right] \right\} \quad \text{(B.27)}$$

It should be noted that each of the two general spectra has one peak only [i.e. unimodal, see Equation (B.24)]. However, Ochi-Hubble spectra are combinations of two spectra and can obviously have two peaks (i.e. bimodal). This is not necessarily always the case; while there will clearly be a “hump” in the total spectrum at the location of $\omega_{\text{m},2}$, the sum of the spectral ordinates between $\omega_{\text{m},1}$ and $\omega_{\text{m},2}$ might well be larger than the peak value of the high frequency spectrum at $\omega_{\text{m},2}$ so that the tangent at $\omega_{\text{m},2}$ not need be horizontal.

Another property of the combination of two spectra is

$$m_{\text{n,OH}}(\omega) = \int_0^\infty \omega^n S_{\text{OH}}(\omega)\, \text{d}\omega = \int_0^\infty \omega^n \left[S_{\text{gen},1}(\omega) + S_{\text{gen},2}(\omega) \right] \text{d}\omega = m_{\text{n},1}(\omega) + m_{\text{n},2}(\omega) \quad \text{(B.28)}$$

From which it follows that

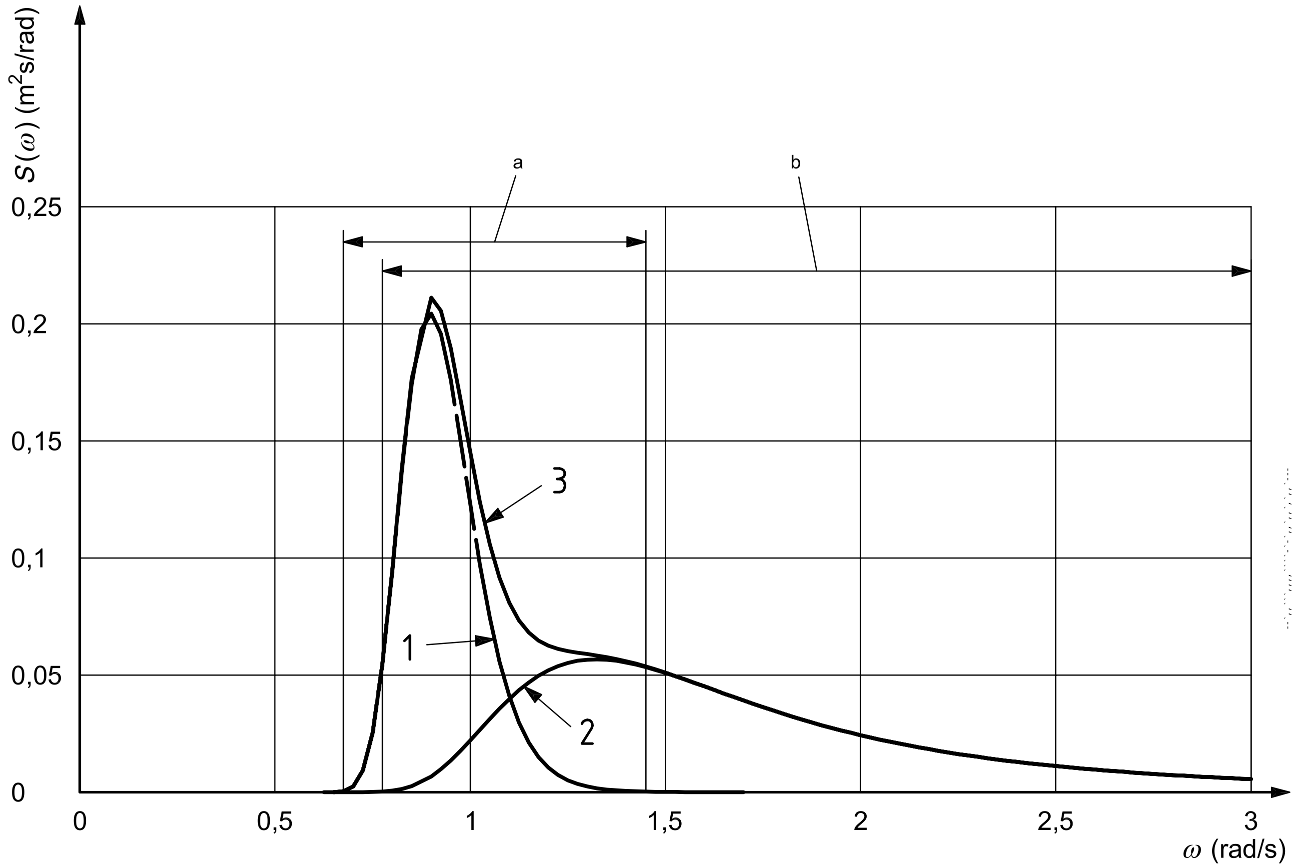
$$H_{\text{s}}^2 = H_{\text{s},1}^2 + H_{\text{s},2}^2 \quad \text{(B.29)}$$

where

H_{s} is the total significant wave height of the combined sea state;

$H_{\text{s},1}$ is the significant wave height of the low frequency part of the sea state;

$H_{\text{s},2}$ is the significant wave height of the high frequency part of the sea state.



Key

ω	frequency
$S(\omega)$	spectrum
1	swell spectrum
2	wind sea spectrum
3	total spectrum

[a] Frequency range of swell spectrum.

[b] Frequency range of wind sea spectrum.

Figure B.3 — Ochi-Hubble spectrum — Swell parameters: $H_{s,1}$ = 0,875 m, $T_{p,1}$ = 7 s, λ_1 = 6 **— Wind sea parameters:** $H_{s,2}$ = 1,0 m, $T_{p,2}$ = 4,75 s, λ_2 = 0,75

Annex C
(informative)

Regional information

C.1 General

This annex presents an overview of various regions of the world for which information has been developed by experts on each region, and is intended to supplement the provisions, information and guidance given in the main body and Annexes A and B of this part of ISO 19901. It also provides some guidance relating to the particular region dealt with in each of its clauses, as well as some indicative values for metocean parameters which can be suitable for conceptual studies. However, site- or project-specific shall be developed for structural design and/or assessment.

C.2 North-west Europe

C.2.1 Description of region

The geographical extent of the region of north-west Europe is bounded by the continental shelf margins of Europe as shown in Figure C.1. The region is diverse, stretching from the sub-arctic waters off Norway and Iceland to the Atlantic seaboard of France and Ireland in the south, and includes

- the waters off Norway, part of which are within the Arctic Circle,
- the Baltic Sea,
- the North Sea,
- the Irish Sea,
- the English Channel,
- the northern half of the Bay of Biscay,
- the waters off the west coasts of Ireland and Scotland, and
- the waters off the Faeroes Islands.

C.2.2 Data sources

Measured data are available from many stations throughout the area. Sources for measured data may be identified through the International Oceanographic Data and Information Exchange[50], which is part of UNESCO[1)]. Links will be found to national oceanographic data centres, which in turn provide links to specialist institutes and other organizations within each country. Data may also be obtained from commercial organizations. In addition to measured data, in recent years a number of joint, industry-sponsored hindcast studies have been performed — see for example, References [51] and [52]. These have resulted in extensive (but usually proprietary) data sets for the companies involved; however, a recently published report[53] provides useful information derived from the NEXT hindcast study[51].

1) United Nations Educational, Scientific and Cultural Organization.

C.2.3 Overview of regional climatology

The conditions experienced within the region vary from arctic to temperate. The north of Norway experiences very cold winters with low temperatures and associated ice in various forms. However, ice occurs very rarely in the south-west of the region.

In all parts of the region, extremes of wind and wave are most likely to occur during the passage of a vigorous frontal depression. Depressions are areas of low atmospheric pressure and cyclonic airflow; they vary from nebulous, with light winds, to intense and stormy with a large area of strong winds. Together with associated frontal systems, they cross the area throughout the year, generally from west to east. They can move rapidly, with speeds of translation of 5 m/s to 15 m/s, and a wide range of conditions can be experienced at any one site. Depressions are larger than tropical cyclonic storms such as hurricanes. Another type of depression is called a “polar low”. Such depressions do not have fronts and are less common than frontal depressions and generally less intense.

C.2.4 Water depth, tides and storm surges

Water depths in the area are shown in Figure C.2. Much of the water around the British Isles and in the North Sea and Baltic Sea is less than 200 m deep. However, there is a deep trench adjacent to the southern coast of Norway where water depths in excess of 1 000 m occur. Off the continental shelf, the Norwegian Sea is deep water while the Barents Sea is approximately 500 m deep. The Faeroes-Shetland Channel is approximately 1 000 m deep.

Tides in the region are semi-diurnal with two high and two low tides per day. Largest tidal ranges occur on the eastern side of the Irish Sea, the east coast of the UK, in the English Channel and around the Brest Peninsula.

The highest storm surges occur in the south-eastern part of the North Sea. Storm surge also affects the areas with large tidal range.

C.2.5 Winds

The airflow in depressions is cyclonic, which is anti-clockwise in the northern hemisphere. The fronts associated with depressions occur in troughs of low pressure within the depression and are often marked by a change of wind direction and/or speed.

Intense depressions generate sustained winds with speeds in excess of 33 m/s, which is hurricane force. The strongest winds tend to blow from between south-west and north-west, with the lightest winds being those from the north-east. Topography and unstable atmospheric conditions can modify wind speed and direction. A warmer sea overlain with cooler air produces unstable atmospheric conditions conducive to squalls and turbulent airflow.

C.2.6 Waves

The region includes semi-enclosed seas, i.e. the Irish Sea, the English Channel, the North Sea and the Baltic Sea, as well as areas of ocean. While strong winds can occur over the whole region, the nature of waves varies according to the water depth and fetch over which they have been generated. Where fetch is restricted, storm waves are shorter, steeper and lower than in the deep ocean. The oceanic area is subject to swell waves that have moved out of the area in which they were generated. These swell waves can occur without any wind and can have wave periods of 20 s or more. Swell can penetrate to all but the most sheltered locations.

C.2.7 Currents

The seas of the region contain extensive areas of shallow water, channels and headlands that experience strong tidal currents on a daily basis.

Periodically, strong currents may also occur in association with storm surge. This is water flow induced by meteorological forcing such as wind and atmospheric pressure.

Significant eddies occur in a permanent current along the coast of Norway.

In the oceans, the continental shelf edge is subject to particularly complex processes that have only recently been the subject of extensive study. The area west of the Shetland Islands experiences strong currents at all depths due to the topography of the sea floor and the interaction of water masses with differing characteristics. Other sections of the continental shelf edge have yet to be studied in detail. A comparison of the area to the West of Shetland with the northern North Sea, together with a discussion of the background to the complex current regime in the area, can be found in Reference [54].

C.2.8 Other environmental factors

C.2.8.1 Marine growth

Marine growth, or fouling, occurs in both hard and soft forms and also as seaweed or kelp. Hard fouling consists of mussels, barnacles and tubeworms; soft fouling consists of organisms such as hydroids, anemones and coral. Different types of marine growth occur at different water depths and in different parts of the region. An anti-fouling coating can delay marine growth but significant fouling is likely within 2 to 4 years.

Estimates of marine growth on offshore structures in UK waters are given in Reference [55]; the information is summarized in Table C.1.

Table C.1 — Terminal thickness of marine growth — UK sector

Depth	Type of growth		
	Hard	Soft	Algae/Kelps
0 m to 15 m	0,2 m	0,07 m	3,0 m
15 m to 30 m	0,2 m	0,3 m	unknown
30 m to sea floor	0,01 m	0,3 m	No growth

Unless more accurate data are available, or if regular cleaning is not planned, the thickness of marine growth for areas offshore Norway may be assumed to be those shown on Table C.2 (Reference [56]). The thickness of marine growth may be assumed to increase linearly over a period of two years after the structure has been placed offshore.

Table C.2 — Estimated maximum thickness of marine growth — Areas offshore Norway

Depth below mean water level m	Latitude	
	56° to 59° N	59° to 72° N
Above +2	0,00 m	0,00 m
+2 to −40	0,10 m	0,06 m
Below −40	0,05 m	0,03 m

C.2.8.2 Sea ice and icebergs

The Barents Sea is the most northerly sea in the region and there is a large variation of ice conditions from year to year. The ice reaches its maximum extension usually in April; in the eastern part it reaches the Russian mainland. The minimum extension is usually in August, when an ice border can typically be seen at 80° N. The icebergs that drift in the Barents Sea originate from the glaciers at Svalbard and Franz Joseph Land and Novaya Zemlya. Reference [57] provides a good general overview of the meteorological and oceanographic conditions pertaining to the Barents Sea area.

Actions from sea ice and icebergs should be taken into account when structures are located in areas nearshore, in Skagerrak, in the northern and western parts of the Norwegian Sea and in parts of the Barents Sea.

Figure C.3 shows the occurrence of first-year ice in the region, based on satellite observations, with an annual probability of exceedance of 10^{-2}. For planning of operations, the monthly extreme ice limit with annual probability of exceedance of 10^{-2} may be used; however, these data should be used with caution and allowance made for ice concentrations below some 10 % to 20 %, which cannot be detected by satellite. Monthly values for the extreme ice limit with an annual probability of exceedance of 10^{-2} can be found in Reference [57]. These values may be used in evaluations during an early phase of exploration.

To calculate the actions caused by ice, values for thickness and size of ice floes that are representative of the area should be selected. The mechanical properties of the ice can be assumed to be similar to those in other Arctic areas.

Regions where collision between icebergs and a structure can occur with an annual probability of exceedance of 10^{-2} and 10^{-4} in the Barents Sea are shown in Figure C.4. Icebergs were observed in considerable numbers off the East Finnmark coast in 1881 and in 1929.

C.2.8.3 Snow and ice accretion

The incidence of snow and ice varies considerably between the south-western and north-eastern limits of north-west Europe. In the south-west, snow and ice occur infrequently, while in the north-east, snow and ice are important design parameters.

Estimates of extreme snow accumulations on offshore structures in UK waters are given in Reference [55]; typical values are given in Table C.3. The pressure due to wet snow has been calculated as being in the range of 0,15 kPa to 0,24 kPa.

Table C.3 — Accumulation of ice — Offshore structures in UK sector

Cause of ice	Thickness mm	Density kg/m3
Wet snow	10 to 30	900
Sea spray	5 to 25	850

Useful information about the occurrence of snow and ice accretion off Norway can be found in Reference [56]. For areas on the Norwegian continental shelf where more accurate meteorological observations have not been made, the characteristic pressure due to snow may be assumed to be 0,5 kPa.

In the absence of a more detailed assessment, values for the thickness of ice accretion caused by sea spray and precipitation may be taken from Table C.4. The thicknesses and densities should be calculated separately for ice created from sea spray and ice created from precipitation and both should be applied. When calculating wind, wave and current actions, increases in dimensions and changes in the shape and surface roughness of the structure as a result of ice accretion should be considered by assuming that

— ice from sea spray covers the whole circumference of the element, and

— ice from precipitation covers all surfaces facing upwards or against the wind (for tubular structures it can be assumed that ice covers half the circumference).

An uneven distribution of ice should be considered for buoyancy-stabilized structures. The effects of ballast water, firewater, etc., which can freeze, should also be taken into account.

Table C.4 — Ice accretions — Annual probability of exceedance of 10^{-2}

Height above sea level m	Ice created from precipitation			Ice created from sea spray	
	Thickness mm		Density kg/m³	Thickness mm	Density kg/m³
	56° N to 68° N	North of 68° N			
5 to 10	80	150	850	10	900
10 to 25	Linear reduction from 80 to 0	Linear reduction from 150 to 0	Linear reduction from 850 to 500	10	900
Above 25	0	0	—	10	900

C.2.8.4 Air temperature, humidity, and visibility

In winter, typical air temperatures range from –4 °C in the Barents Sea to +10 °C south of Ireland. Absolute minima are considerably lower. In summer, typical air temperatures range from 6 °C in the Barents Sea to 18 °C south of Ireland. Absolute maxima are considerably higher.

High humidity occurs when relatively warm air is cooled by the sea. This leads to reduced visibility or fog. Fog is more common in winter than in summer, with the North Sea experiencing more fog than most other areas.

Details of the meteorology of all sea areas are found in navigational publications such as *Pilots*. Such documents are published in many countries.

C.2.8.5 Sea water temperature and salinity

In winter, sea surface temperature ranges from about 0 °C in the Barents Sea to 12 °C south of Ireland. In summer the corresponding range is from about 8 °C to 18 °C. Both lower temperatures in winter and higher temperatures in summer are regularly attained locally.

Mean salinity is fairly constant at 35 PSU (practical salinity units) but lower salinity occurs around the coasts of Norway and in particular in the Baltic Sea where the surface water is much less saline.

C.2.9 Estimates of metocean parameters

C.2.9.1 Extreme metocean parameters

In the north-west European region there is a high (but not perfect) correlation between severe wind and wave events. Storm surge events are also associated with strong winds as well as with low atmospheric pressure. Tides are forced by astronomical influences and as such are independent of meteorology.

Actions on a structure are due to the combined action of wind, waves and current. However all structures react differently, and without detailed knowledge of a structure it is not possible to define how wind, waves and current should be characterized and combined to generate actions.

Metocean parameters for several locations in the region are provided in Tables C.5 to C.12. The wind, wave and current values are independently derived marginal parameters; no account has been taken of conditional probability. This information should not replace detailed, site-specific parameters, which should be obtained for the design or assessment of a particular structure that is to be constructed for, or to be operated at, a particular site.

Table C.5 — Indicative values of metocean parameters — Sites in Celtic Sea

Metocean parameter	Return period no. years				
	1	5	10	50	100
10 min mean wind speed (m/s)	27	31	32	35	37
Significant wave height (m)	9,4	11,8	12,8	15,4	16,8
Spectral peak period [a] (s)	13,9	15,6	16,3	17,9	18,7
Surface current speed (m/s)	0,89	0,92	0,94	0,98	1,00

[a] Assume the spectral peak period can vary by ±10 % around these central estimates.

Table C.6 — Indicative values of metocean parameters — Sites in southern North Sea

Metocean parameter	Return period no. years				
	1	5	10	50	100
10 min mean wind speed (m/s)	27	31	32	35	36
Significant wave height (m)	6,0	7,1	7,5	8,6	9,0
Spectral peak period [a] (s)	11,3	12,3	12,6	13,6	13,9
Surface current speed (m/s)	1,17	1,23	1,25	1,31	1,33

[a] Assume the spectral peak period can vary by ±10 % around these central estimates.

Table C.7 — Indicative values of metocean parameters — Sites in central North Sea

Metocean parameter	Return period no. years				
	1	5	10	50	100
10 min mean wind speed (m/s)	31	33	34	36	39
Significant wave height (m)	9,8	11,2	11,8	13,1	13,6
Spectral peak period [a] (s)	13,6	14,6	15,0	15,7	16,0
Surface current speed (m/s)	0,88	0,90	1,00	1,00	1,00

[a] Assume the spectral peak period can vary by ±10 % around these central estimates.

Table C.8 — Indicative values of metocean parameters — Sites in northern North Sea

Metocean parameter	Return period no. years				
	1	5	10	50	100
10 min mean wind speed (m/s)	35	39	40	43	45
Significant wave height (m)	12,0	13,6	14,3	15,7	16,4
Spectral peak period [a] (s)	14,6	15,5	15,9	16,7	17,0
Surface current speed (m/s)	0,60	0,65	0,70	0,85	0,90

[a] Assume the spectral peak period can vary by ±10 % around these central estimates.

Table C.9 — Indicative values of metocean parameters — Sites west of Shetland

Metocean parameter	Return period no. years				
	1	5	10	50	100
10 min mean wind speed (m/s)	35	39	40	43	45
Significant wave height (m)	13,2	15,0	15,7	17,3	18,0
Spectral peak period [a] (s)	16,2	17,1	17,4	17,9	18,2
Surface current speed (m/s)	1,64	1,78	1,80	1,95	2,00

[a] Assume the spectral peak period can vary by ±10 % around these central estimates.

Table C.10 — Indicative values of metocean parameters — Sites at the Haltenbank

Metocean parameter	Return period no. years				
	1	5	10	50	100
10 min mean wind speed (m/s)	32	35	34	36	37
Significant wave height (m)	11,6	13,3	13,9	15,7	16,4
Spectral peak period [a] (s)	15,9	16,8	17,2	17,9	18,2
Surface current speed (m/s)	0,80	0,85	0,95	1,00	1,05

[a] Assume the spectral peak period can vary by ±10 % around these central estimates.

Table C.11 — Indicative values of metocean parameters — Sites in Barents Sea

Metocean parameter	Return period no. years				
	1	5	10	50	100
10 min mean wind speed (m/s)	33	35	36	39	40
Significant wave height (m)	10,0	11,9	12,2	14,0	14,5
Spectral peak period [a] (s)	14,7	15,9	16,0	17,1	17,4
Surface current speed (m/s)	0,90	0,95	0,97	1,00	1,05

[a] Assume the spectral peak period can vary by ±10 % around these central estimates.

Table C.12 — Temperature ranges — Sites in North Sea, eastern North Atlantic and Norwegian Sea

Area	Air temperature	Sea surface temperature	Sea floor temperature
	°C		
Celtic Sea	–4 to +27	–4 to +22	—
Southern North Sea	–6 to +26	0 to +22	+4 to +15
Central North Sea	–6 to +24	+1 to +21	+4 to +11
Northern North Sea	–7 to +22	+2 to +19	+3 to +13
West of Shetland	–5 to +22	+3 to +19	–2 to +12
Haltenbank	–9 to +18	+5 to +17	+5 to +9
Barents Sea	–18 to +18	+2 to +14	–1 to +7

C.2.9.2 Long-term distributions of metocean parameters

Scatter diagrams of significant wave height versus zero-crossing period for sites in the North Sea, eastern North Atlantic and Norwegian Sea are available for UK operating areas from Reference [53].

Figure C.1 — Map of North-west Europe region

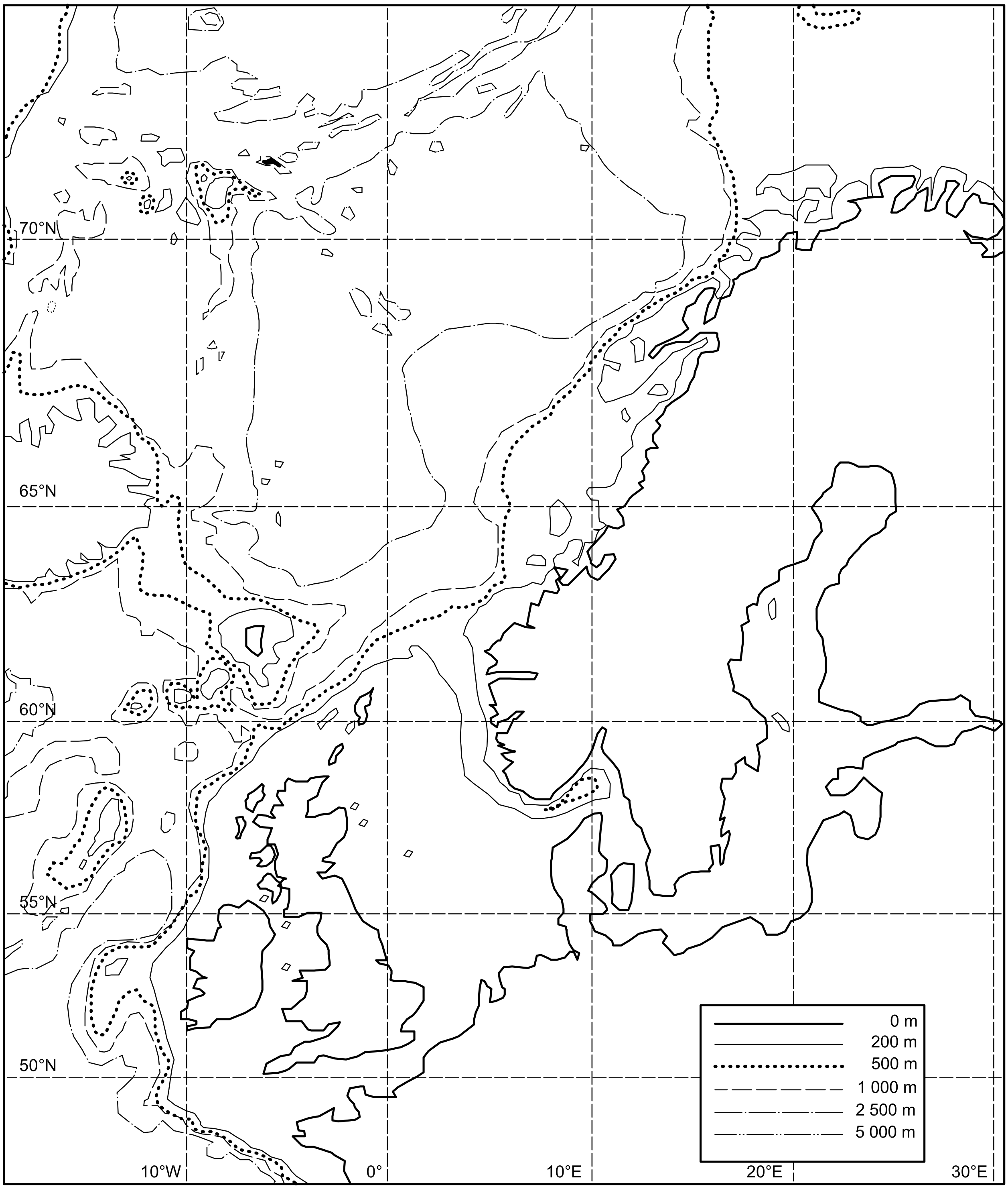


Figure C.2 — Water depths — North-west Europe region

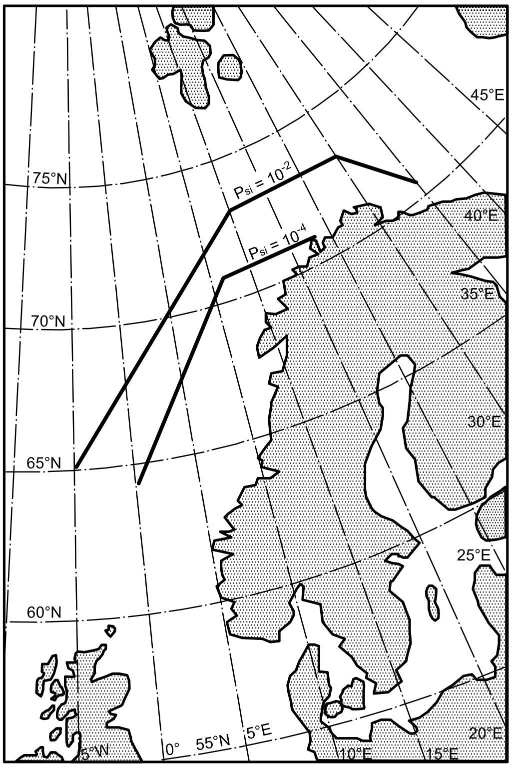


Figure C.3 — Limit of sea ice — North-west Europe region — Annual probabilities of exceedance of 10^{-2} and 10^{-4}

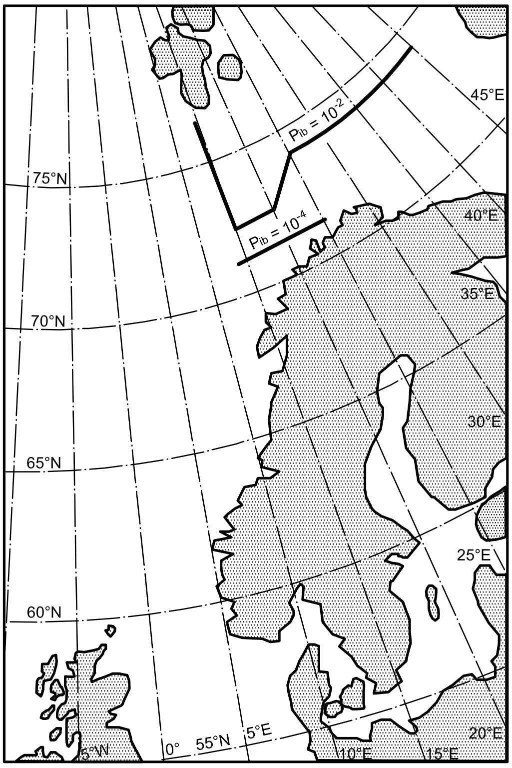


Figure C.4 — Limit for collision with icebergs — North-west Europe region — Probabilities of exceedance of 10^{-2} and 10^{-4}

C.3 West coast of Africa

C.3.1 Description of region

The geographical extent of this region are the waters off West Africa from the Ivory Coast to Namibia, see Figure C.5. Insufficient data are available to provide guidance for other waters off West Africa.

The continental shelf is relatively narrow throughout most of the region, with a distance from the coast to the 200 m depth contour generally less than 100 km. The continental shelf is generally narrower near the equator (e.g. offshore the Ivory Coast to Nigeria) and wider in the south (e.g. offshore Namibia), although there are fluctuations along the entire coast.

A large number of rivers discharge into the area, the most significant being the Congo and the Niger.

C.3.2 Data sources

Publicly available measured and modelled data are generally scarce across the region. The principal metocean hindcast data set for the region is WANE (West Africa normals and extremes)[58]. The WANE hindcast model does not represent squalls, which dominate the extreme wind conditions. Detailed squall criteria have so far been derived from a small number of proprietary measured data sets. Strategic measurement programmes that provide improved measurement of squalls are likely to be a focus of future joint industry projects.

A description of the environmental conditions offshore West Africa is available in Reference [59]. Much of the information in this clause has been derived from this source and from the Admiralty Pilots[60].

C.3.3 Overview of regional climatology

The northern hemisphere summer is defined as July through to September, while the southern hemisphere summer is defined as November to February.

Compared to regions such as the Gulf of Mexico and West of Shetlands, the climate offshore West Africa is often considered benign. The persistent south-easterly trades dominate the normal wind regime, while extreme winds are caused by squall events. Normal and extreme wave conditions are dominated by two sources of swell: those coming from the south-east and those from the south-west sectors. The long periods associated with some of the swell have specific consequences for design. A distinct sea wave component is usually also present.

The long-term current conditions are dominated by large-scale circulation patterns. On shorter time scales a wide range of oceanographic processes, including mesoscale activity, river outflow, inertial currents and internal waves, complicate the current regime.

Hot and humid conditions prevail across the region, particularly near the equator. The region encounters a wide geographical variation in rainfall, with the most intense rainfall being caused by thunderstorms and squalls near the equator. Visibility is reduced by a variety of factors across the region.

C.3.4 Water depth, tides and storm surges

There are three major deep ocean basins in the region, all over 5 000 m deep: the Guinea basin, the Angola basin and the Cape basin. The Guinea and Angola basins are separated by a gently sloping ridge along which exist numerous seamounts and, further inshore, an island chain. The much steeper Walvis Ridge separates the Angola and Cape basins. Between these ridges the continental slope (from the 200 m to 5 000 m depth contours) varies in width from approximately 100 km offshore Ghana to over 600 km offshore Angola.

Equatorial and south-west Africa experiences a semi-diurnal tidal regime. Tidal ranges are relatively small at the coast with spring tidal ranges around 2 m and neap tidal ranges less than 1 m. The tidal range decreases rapidly further away from the shore, with a spring tidal range usually less than 1 m in deep water. Storm surges are small throughout the region.

C.3.5 Winds

The normal wind regime is dominated by persistent southerly trade winds, driven by large-scale atmospheric pressure systems. The trade winds are strongest in southern parts of the region where they typically range from 5,5 m/s to 7,5 m/s, and weakest in the north where they vary between 2,5 m/s to 5,0 m/s. The strongest winds generally occur during the northern hemisphere summer and the weakest winds generally occur in the northern hemisphere winter. These seasonal variations follow fluctuations in the latitude of the northernmost boundary of the "south-easterly trade wind regime", from about 15° N in the northern hemisphere summer to about 7° N in the northern hemisphere winter.

In the southern part of the region, the trade winds blow predominately form the south-east, but the direction slowly shifts until it reaches south-westerly off Nigeria.

Apart from the seasonal changes the strength of the trade winds is fairly constant. However, there can be a significant diurnal variation in wind speed in nearshore locations influenced by sea breezes. This diurnal variation is reduced further from the shore.

Fully developed tropical or extratropical revolving storms (e.g. tropical cyclones) are very rare or non-existent in the region and extreme winds are caused by squall events. Squalls are associated with the leading edge of multi-cell thunderstorms. Thunderstorms and squalls are most frequent in equatorial West Africa, and typically stronger offshore Nigeria than offshore Angola, with around 15 to 30 significant events per year. Depending on location, there are clearly defined squall seasons that can be explained by the seasonal migration of the inter-tropical convergence zone (ITCZ). Squall activity is observed when the ITCZ and associated cumulonimbus formation are in the region. There is one clearly defined squall season in Angola during the northern hemisphere winter. There are two peak squall seasons offshore Nigeria due to two passages of the ITCZ: on the way north in northern hemisphere spring, then again on the way south in the northern hemisphere autumn. Squalls clearly occur for a much larger part of the year in Nigeria than in the other regions, with only a brief minimum around August.

The rapidly varying wind and direction associated with squalls, and large variations between the characteristics of different squalls, can lead to considerable variations in vessel or offshore structure response. Further measurements are required to better define squall characteristics, including spatial variations in the wind field, rates of increase and decay, variations in wind direction, and improved extreme value estimates. These are likely to be considered as part of a future joint industry project.

Thunderstorms and squalls are responsible for the strongest winds, but are thought to generate only weak currents and low wave heights due to the limited fetch and duration.

C.3.6 Waves

The wave climate offshore West Africa is dominated by swell from two distinct sources:

— high-latitude extratropical storms in the South Atlantic generate swell from the south-west;

— episodic increases in the trade winds offshore South Africa generates swell from the south-east.

Wind seas are driven by the local winds.

The swell is greatest in southern parts of the region, where extreme significant wave heights can be about 9 m[61]. Wave heights decrease further north due to dissipation, where extreme values of about 3 m to 4 m are more typical. It is in these more northern regions that locally-generated wind seas can become just as important as the swell component — at least for structural designs that are governed by drag.

Swell waves from distant storms can be associated with long peak periods, sometimes in excess of 20 s. Such long period waves can be critical for the operability of some vessels. Longer period swells are generally encountered in northern parts of the region, due to the longer propagation distance from the source.

The wave spectrum is often characterized by at least two peaks, a swell component and a locally-generated wind seas component, the latter having significant wave heights of about 1 m[62]. Owing to the presence of both sea and swell, it is not appropriate to represent the sea state offshore West Africa using a spectral model with just one peak. At the time of publication of this part of ISO 19901, the bimodal Ochi-Hubble spectra (see Annex B) are recommended; however, the latest results from ongoing research into appropriate spectral models of the wave climate offshore West Africa under the joint-industry West Africa squall project (WASP) should be considered.

As swell approaches the coast in some parts of the region, particularly along the coast of South-West Africa, it can be transformed into a phenomenon called rollers. These are large steep waves that are likely to affect both floating structures in nearshore regions and coastal infrastructure.

C.3.7 Currents

The long-term current conditions offshore West Africa are controlled by large-scale anti-clockwise surface circulations of the South Atlantic Ocean. These currents undergo seasonal variations in intensity and extent, but are generally less than 0,5 m/s. Although they usually only impact the deep ocean, the key characteristics are described here, mostly derived from an excellent review conducted as part of the WAX project[63].

The Benguela Current flows northwards along the coast of Namibia and separates from the coast to form part of the South Equatorial Current that turns westwards near the equator to flow across the Atlantic Ocean. The Benguela Current only affects the southern-most deep water parts of Namibia.

The other energetic (peaks of order 0,50 m/s) current system in the region, the Guinea Current, flows eastward along the Ivory Coast to Nigeria in the upper part of the water column, below which the Guinea Undercurrent flows towards the west.

Other current systems in the region are weak (0,1 m/s) but can be persistent. The Equatorial Undercurrent flows eastwards along the equator underneath the South Equatorial Current, and splits into two branches when it reaches the West African coast. The northern branch enters the Gulf of Guinea and the southern branch feeds the southward flowing Gabon-Congo Undercurrent and surfaces to form part of the southward flowing Angola Current. Throughout most of the region the current direction often reverses, through a vertical section, leading to complex current profiles with strong shear.

The large-scale circulation patterns described above are characterized by significant meanders, and numerous eddies are formed either side of the main flow. This mesoscale activity is found throughout the region and can be associated with stronger-than-average currents flowing in different directions to that of the larger scale flow.

Strong currents have been encountered near the Congo River and these can extend perhaps 50 km north of the mouth of the river. These strong currents are confined to the uppermost few metres of the water column, but can be responsible for extreme current conditions.

Perhaps of wider impact is the effect of the major rivers on the near-surface salinity. Significantly fresher water can be observed several hundred kilometres from the mouths of the Congo and Niger. The stratification means that strong (1 m/s) inertial currents can be generated in the upper water column (approximately the top 30 m) by local winds.

Tidal currents are generally less than 0,1 m/s throughout the region, although local intensification will exist in some areas due to seabed features. In such regions the tidal currents are likely to generate internal waves at the tidal period, called internal tides. These manifest themselves as currents that vary in time at the semi-diurnal tidal period, but flow in opposite directions in different depths of the water column. Shorter-period internal waves (solitons) have been reported in some parts of West Africa. Although the currents associated with these internal waves are unlikely to be much higher than 0,5 m/s in the region, they cause rapid changes in current speed and direction over periods as short as half an hour, so can be significant for design and operation of marine equipment.

Strong inertial currents have been observed in some deep water areas offshore West Africa. The direction of these currents rotates through 360° once every inertial period (the natural period of large scale oscillations in the ocean). The inertial period is infinite at the equator and decreases with latitude. Inertial currents are particularly notable offshore southern Namibia where the inertial period is close to 24 h, allowing a near-resonant response to diurnal variations in wind forcing. The vertical structure of inertial currents can be complex, with one or more peaks in the current speed that move vertically through the water column with time.

The description given in this subclause only provides a very general overview of current conditions likely to be experienced offshore West Africa. The processes that drive ocean currents are considerably more numerous and complex than those that drive wind and waves, and site-specific measurements can be required to derive criteria for engineering design, particularly in deeper waters.

C.3.8 Other environmental factors

C.3.8.1 Marine growth

Warm water conditions coupled with an abundance of nutrients are likely to lead to extensive marine growth. The rate of growth and the particular marine species are likely to vary considerably over the region, but a typical thickness of about 0,1 m can be expected in the upper 50 m of the water column and up to about 0,3 m above mean sea level in the splash zone.

C.3.8.2 Tsunamis

West Africa is not considered one of the high-risk areas for tsunami activity, although future events can never be completely discounted. An online tsunami database[45] contains details of only two distinct tsunami events anywhere in the region, both of which affected the coastal regions of Ghana. The first event in 1911 was associated with a wave of height 1,5 m, and the second event in 1939 with a height of 0,6 m.

C.3.8.3 Sea ice and icebergs

Sea ice does not develop within the region and iceberg drift is not a design consideration. Icebergs have been sighted as far north as 35° S, and are possible around the Cape of Good Hope[60].

C.3.8.4 Snow and ice accretion

As with sea ice, snowfall and ice accumulation on structures are not design considerations.

C.3.8.5 Air temperature, humidity, pressure and visibility

High air temperatures are encountered throughout the region, particularly close to the equator. In equatorial West Africa, daily temperatures range between 23 °C and 33 °C in the northern hemisphere summer and 20 °C to 25 °C in the northern hemisphere winter. In southwest Africa, daily temperatures range between 26 °C and 31 °C in the southern hemisphere summer and 20 °C to 27 °C in the southern hemisphere winter. These figures were derived from a climate summary[64] containing data from onshore meteorological stations and some offshore measurements.

The amount of rainfall varies considerably over the region, with very high values near the equator (annual total up to about 4 000 mm) and low rates in the south (annual total as low as 40 mm). The most intense rainfall is usually associated with thunderstorms and squalls.

The relative humidity is highest in equatorial regions, where values often exceed 90 %, and generally decreases towards the south. Warm air temperatures combined with high humidity represent a potential hazard to personnel. The humidity varies throughout the day, with a maximum generally occurring in the morning and a minimum during the afternoon. Seasonal variations also exist in many parts of the region, with a maximum in the southern hemisphere summer and a minimum in the southern hemisphere winter. Large fluctuations in humidity can be caused locally by changes in the wind direction, with much lower values associated with dry winds blowing from the interior.

A high pressure system is usually located in the south-east Atlantic close to 30 °S 10 °W, driving the south-easterly trade winds that prevail over the region. The position of this high leads to generally higher atmospheric pressures in the south and lower pressures in equatorial regions. Seasonal variations in mean atmospheric pressure are typically between 1 010 mbar and 1 014 mbar near the equator and between 1 014 mbar and 1 022 mbar in the south. The atmospheric pressure is higher over the entire region during the southern hemisphere summer than during the southern hemisphere winter. Atmospheric pressure undergoes significant diurnal variations in many parts of the region.

Air temperatures, humidity and pressure all undergo rapid changes during the passage of thunderstorms and squalls.

Visibility is reduced by fog along many parts of the coast, particularly in areas to the south influenced by the cold water of the Benguela Current. Low visibility is also caused by dust (windborne sand) or heavy rain, particularly near the equator, offshore Namibia and most notably in the Bight of Biafra.

C.3.8.6 Sea water temperature and salinity

Sea surface temperatures are warmest near the equator where they typically range between 24 °C and 28 °C over the year, and cooler in the south where seasonal variations between about 13 °C and 16 °C occur. Temperatures across the region are warmer during the southern hemisphere summer and cooler during the southern hemisphere winter.

Cold water transported into the region by the Benguela Current is a major influence on sea surface temperature in southern regions. Localized decreases in surface temperatures occur along several areas of the continental slope, throughout West Africa, due to upwelling of cooler deep waters. The water column is generally stratified throughout the year with temperatures less than 15 °C at 200 m depth.

Sea surface salinities in the open ocean are generally between 35 PSU and 36 PSU, but there are very significant reductions in salinity in areas influenced by river discharge, where salinity can be as low as 28 PSU. The Congo River provides one of the largest inputs of fresh water into an ocean anywhere in the world.

C.3.9 Estimates of metocean parameters

C.3.9.1 Extreme metocean parameters

Indicative extreme values of wind, wave and current parameters are provided in Tables C.13 to C.16 for various return periods and for four locations offshore West Africa. The wind, wave and current values are independently derived marginal parameters; no account has been taken of conditional probability. Table C.17 gives extreme values for other metocean parameters. As for all indicative values provided within Annex C, these figures are provided to assist preliminary engineering concept selection; they are not suitable for design of offshore structures.

Extreme wave conditions offshore Nigeria are caused by swell from distant storms, and Nigerian wave spectra tend to be more narrow-banded compared to most extreme conditions in other parts of the world. The Rayleigh distribution assumes narrow-band conditions, whereas the Forristall distribution is a modified Rayleigh distribution which takes account of the wider-band conditions within storms. The Rayleigh distribution leads to a higher ratio of H_{max}/H_s, typically by about 10 % [38]. Calculations of the short-term statistics from offshore Nigeria hindcast spectra [38] show that their distribution is close to halfway between Rayleigh and Forristall — increasing the individual wave height by around 5 %. In addition, account is made of short-term variability, i.e. the possibility that the maximum individual wave could occur in a sea state other than the maximum sea state. The net result of the computations is that the ratio H_{max}/H_s tends to a value of 2,0 rather than 1,9.

Structures can be sensitive to different combinations of sea and swell heights as well as spectral peak periods and spectral widths. A representative combination of wave/swell parameters should be defined for the location of interest and the largest action effects for the component being designed should be determined. A combination of 100 % wind waves with no swell and, separately, 100 % swell with no wind waves is a useful combination to test on structures. For swell, the longer T_p range should be used, and for wind waves the shorter T_p range.

Table C.13 — Indicative wind, wave and current parameters — Shallow water sites off Nigeria

Metocean parameter		Return period no. years				
		1	5	10	50	100
Nominal water depth		30 m				
Wind speed at 10 m above MSL (m/s)						
	10 min mean	19	23	25	29	31
	3 s gust	24	29	32	37	39
Wave height (m)						
	Maximum	4,8	5,5	5,8	6,5	6,8
	Significant	2,3	2,7	2,8	3,2	3,3
Wave direction (from)		SSW				
Spectral peak period (s)						
	For swell	15 to 17	15 to 17	15 to 17	15 to 17	15 to 17
	For wind seas	7 to 8	7 to 8	7 to 8	7 to 8	7 to 8
Current speed (m/s)						
	Surface [a]	0,9	1,0	1,0	1,1	1,1
	Mid-depth	0,8	0,9	0,9	1,0	1,0
	1 m above sea floor	0,5	0,6	0,6	0,7	0,7

[a] These extreme values exclude any effect from river plumes.

Table C.14 — Indicative wind, wave and current parameters — Deep water sites off Nigeria

Metocean parameter		Return period no. years				
		1	5	10	50	100
Nominal water depth		1 000 m				
Wind speed at 10 m above MSL (m/s)						
	10 min mean	19	23	25	29	31
	3 s gust	24	29	32	37	39
Wave height (m)						
	Maximum	5,7	6,4	6,8	7,5	7,7
	Significant	2,7	3,2	3,4	3,7	3,8
Wave direction (from)		SSW				
Spectral peak period (s)						
	For swell	14 to 16	15 to 17	16 to 18	17 to 19	17 to 19
	For wind seas	7 to 8	7 to 8	7 to 8	7 to 8	7 to 8
Current speed (m/s)						
	Surface [a]	1,1	1,2	1,2	1,3	1,4
	Mid-depth	0,3	0,3	0,3	0,3	0,4
	1 m above sea floor	0,2	0,2	0,2	0,2	0,2

[a] These extreme values exclude any effect from river plumes.

Table C.15 — Indicative wind, wave and current parameters — Sites off northern Angola

Metocean parameter		Return period no. years				
		1	5	10	50	100
Nominal water depth		1 400 m				
Wind speed at 10 m above MSL (m/s)						
	10 min mean	16	20	21	25	26
	3 s gust	19	23	25	29	31
Wave height (m)						
	Maximum	7,9	8,6	8,8	9,5	9,9
	Significant	4,0	4,3	4,4	4,7	4,9
Wave direction (from)		SSW				
Spectral peak period (s)						
	For swell	13 to 17	13 to 17	13 to 17	13 to 17	13 to 17
	For wind-seas	7 to 8	7 to 8	7 to 8	7 to 8	7 to 8
Current speed (m/s)						
	Surface [a]	0,9	1,0	1,0	1,2	1,2
	Mid-depth	0,2	0,3	0,3	0,3	0,3
	1 m above sea floor	0,2	0,3	0,3	0,3	0,3

[a] These extreme values exclude any effect from river plumes.

Table C.16 — Indicative wind, wave and current parameters — Sites off southern Namibia

Metocean parameter		Return period no. years				
		1	5	10	50	100
Nominal water depth		200 m				
Wind speed at 10 m above MSL (m/s)						
	10 min mean	20	20	26	29	31
	3 s gust	25	27	32	36	39
Wave height (m)						
	Maximum	12,7	13,7	16,0	19,0	20,0
	Significant	6,8	7,4	8,7	10,0	10,6
Wave direction (from)		SSE/SW				
Spectral peak period (s)						
	For swell	11 to 14	12 to 15	13 to 16	14 to 17	14 to 17
	For wind-seas	7 to 8	7 to 8	7 to 8	7 to 8	7 to 8
Current speed (m/s)						
	Surface [a]	1,1	1,2	1,2	1,3	1,4
	Mid-depth [b]	0,3	0,3	0,3	0,3	0,5
	1 m above sea floor	0,3	0,3	0,3	0,4	0,5

[a] These extreme values exclude any effect from river plumes.

[b] Mid-depth currents off southern Namibia are below the seasonal thermocline where currents can be stronger.

Table C.17 — Indicative extreme values for other metocean parameters

Metocean parameter	Nigeria		Northern Angola	Southern Namibia
	Shallow water	Deep water		
Mean spring tidal range (m)	1,9	1,5	1,4	2,0
Sea water temperature (°C)				
Minimum near surface	22	25	17	9
Maximum near surface	32	31	28	28
Minimum near bottom	20	4	4	4
Maximum near bottom	30	4	4	—
Air temperature (°C)				
Minimum	18	20	17	8
Maximum	33	33	35	26

C.3.9.2 Long-term distributions of metocean parameters

Recorded wave spectra offshore West Africa are complex and present simultaneous long period swell components, with various peak periods and directions, generated by storms in different parts of the Atlantic Ocean. *In-situ* wave measurements also indicate that mixed swell and wind sea conditions are quasi-permanent. As a minimum for design purposes, one swell component shall be superimposed on a wind-sea component. A refinement considers two swell partitions superimposed on a wind sea.

Wave scatter diagrams for two areas offshore West Africa are provided in Tables C.18 and C.19, showing combinations of total significant wave height and associated spectral peak wave periods of combined wind seas and swell conditions. The information in these tables was generated from the WANE hindcast model[58], [61]. It should be noted that a significant proportion of the wave energy in any given sea state offshore West Africa consists of long period swell. These tables are not always conservative for certain applications to dynamically responding structures, therefore designers should also test against the appropriate dual-peaked cases such as those given in Table C.20.

Table C.18 — Percentage occurrence of total significant wave height versus spectral peak period — Offshore Nigeria location

Significant wave height m	Peak period s													
	0 to 1,99	**2 to 3,99**	**4 to 5,99**	**6 to 7,99**	**8 to 9,99**	**10 to 11,99**	**12 to 13,99**	**14 to 15,99**	**16 to 17,99**	**18 to 19,99**	**20 to 21,99**	**22 to 23,99**	**>24**	**Total**
0,00 to 0,49				0,02		0,03	0,02	0,03						0,10
0,50 to 0,99			0,50	5,37	2,55	3,48	3,14	2,46	0,64	0,13	0,05	0,02		18,34
1,00 to 1,49			0,34	11,01	16,65	9,40	11,01	8,76	2,74	0,88	0,24	0,04		61,07
1,50 to 1,99				0,08	5,85	4,67	2,76	2,95	1,19	0,33	0,09	0,03		17,95
2,00 to 2,49					0,17	0,79	0,58	0,41	0,19	0,07	0,03			2,24
2,50 to 2,99						0,06	0,08	0,04	0,05	0,02				0,25
>3,00							0,02	0,03						0,05
Total			0,84	16,48	25,22	18,43	17,61	14,68	4,81	1,43	0,41	0,09	0	100,00

Table C.19 — Percentage occurrence of total significant wave height versus spectral peak period — Offshore Angola location

Significant wave height m	**Peak period** s													
	0 to 1,99	**2 to 3,99**	**4 to 5,99**	**6 to 7,99**	**8 to 9,99**	**10 to 11,99**	**12 to 13,99**	**14 to 15,99**	**16 to 17,99**	**18 to 19,99**	**20 to 21,99**	**22 to 23,99**	>**24**	**Total**
0,00 to 0,49				0,01	0,03	0,04	0,06	0,06						0,20
0,50 to 0,99		0,01	1,00	3,98	1,82	5,17	5,52	3,70	1,17	0,34	0,13	0,01	0,00	22,85
1,00 to 1,49			0,60	6,28	10,48	11,49	11,38	9,19	2,87	0,83	0,19	0,06	0,00	53,37
1,50 to 1,99			0,01	0,06	2,86	5,78	4,76	3,52	1,51	0,54	0,12	0,01		19,17
2,00 to 2,49					0,07	0,94	1,33	1,05	0,34	0,10	0,01			3,84
2,50 to 2,99					0,00	0,04	0,14	0,23	0,10	0,03				0,54
3,00 to 3,49								0,02	0,01					0,03
>3,50								0,00						0,00
Total	0,00	0,01	1,61	10,33	15,26	23,46	23,19	17,77	6,00	1,84	0,45	0,08	0,00	100,00

Wind seas and swell conditions are considered as independent phenomena. In principle, any combination of wind seas and swell H_s-T_p classes is possible, and all permutations, with their joint frequency of occurrence, shall be considered for engineering purposes.

Sea states offshore West Africa can be represented by the dual-peaked Ochi Hubble spectra (see Annex B). Table C.20 provides an example of a scatter diagram for offshore Angola.

For the purposes of defining bimodal spectra representing combined swell and wind sea conditions, the total significant wave height H_s and the associated spectral peak period T_p should be divided into a swell part and a wind sea part. This can be achieved by inspection of a frequency table of the joint occurrences of H_s and T_p. The low wave heights associated with the wind sea component permit selection of relatively few significant wave height classes for wind seas. The frequency of occurrence of swell H_s with associated T_p should be calculated, conditional on the value of the wind sea H_s with its associated T_p, to determine the frequency of occurrence of each combined wind sea/swell bimodal sea state. The resolution of the swell H_s class will determine the number of combinations of wind sea and swell H_s and T_p available for engineering purposes.

The example in Table C.20 provides information on the joint frequency of occurrence of swell and wind sea conditions, giving the significant wave height, the peak period, the associated parameter γ and the direction of swell (θ_1) and wind sea (θ_2) for a site offshore Angola.

For the example data in Table C.20, the values from any row can be used to construct a bimodal Ochi-Hubble spectrum (see Annex B). Sea states should be assumed to be representative of a duration of 3 h. The values of percentage occurrence in Table C.20 can be used to define the fatigue wave climate.

Table C.20 — Example of wind sea states used for combined wind sea/swell bimodal sea states — Offshore Angola

No.	% occurrence	H_{s1} m	T_{p1} s	H_{s2} m	T_{p2} s	γ_1	γ_1	θ_1 (towards)	θ_2 (towards)
291	15,3	0,91	12	0,76	7,7	7,0	2,1	27	21
231	12,1	0,61	11	0,70	7,2	7,3	1,6	25	23
208	10,9	0,61	12	0,70	7,7	7,3	1,8	29	19
154	8,1	0,91	11	0,76	7,2	7,1	1,8	22	23
117	6,1	1,22	12	0,82	8,1	7,4	2,9	27	22
103	5,4	0,61	10	0,73	6,3	5,4	1,4	21	27
94	4,9	0,91	13	0,76	8,4	7,5	2,3	30	18
90	4,7	1,22	13	0,85	8,2	7,2	2,2	32	21
72	3,8	0,61	13	0,79	7,9	7,1	2,2	33	19
65	3,4	0,91	14	0,88	8,7	7,5	2,4	33	17
63	3,3	0,61	14	0,79	8,9	7,7	2,3	35	18
52	2,7	1,52	13	0,91	8,7	8,1	2,4	29	22
47	2,5	1,22	14	0,98	9,4	8,3	2,7	31	21
37	1,9	1,52	14	0,98	9,4	7,3	3,1	32	19
36	1,9	1,22	11	0,88	7,7	7,5	2,0	21	22
35	1,8	0,91	10	0,76	5,9	4,0	1,4	21	31
32	1,7	0,61	15	0,91	9,6	8,4	2,4	32	22
29	1,5	0,91	15	0,88	9,4	8,7	2,9	34	17
28	1,5	0,30	12	0,61	8,6	8,7	3,3	32	15
27	1,4	1,52	12	0,82	8,6	7,5	5,0	27	21
26	1,4	0,30	11	0,76	7,0	8,1	1,9	28	18
24	1,3	1,52	15	1,01	9,8	8,1	2,5	31	20
23	1,2	1,83	14	0,88	8,7	7,0	1,7	32	18
20	1,1	0,61	17	1,04	10,2	9,0	2,8	31	23

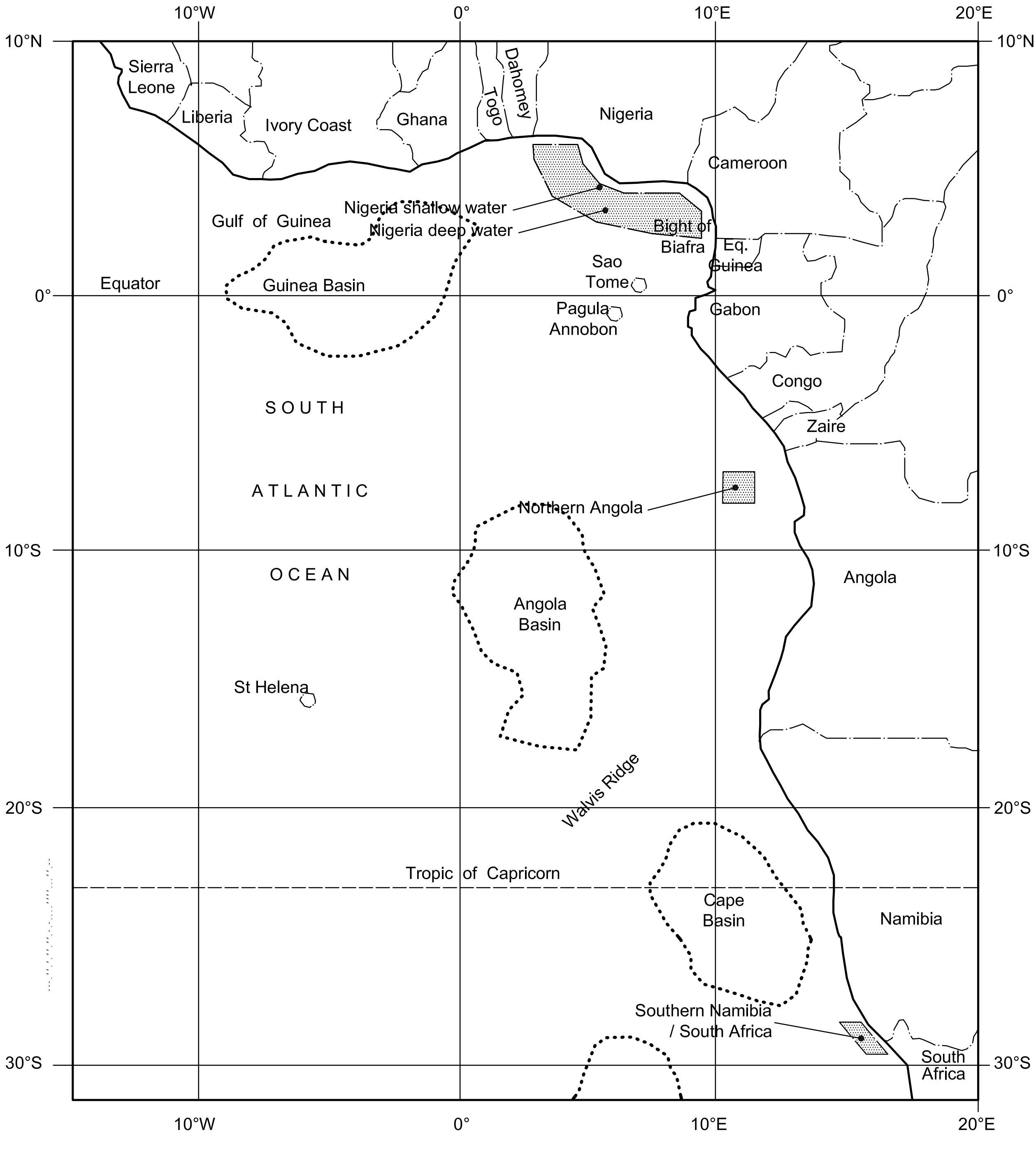


Figure C.5 — Map of west coast of Africa region — Locations of example metocean parameters

C.4 US Gulf of Mexico

C.4.1 Description of region

The geographical extent of the region are the waters of the Gulf of Mexico that fall within the United States exclusive economic zone (EEZ), which is generally the portion of the Gulf of Mexico north of 26 °N, as shown on Figure C.6, and which includes the lease blocks shown on Figures C.6 and C.7.

The Gulf of Mexico has a total area of 1 587 000 km^2. The US Gulf coast is 2 625 km long and comprises the coasts of the following US states (from west to east with coastline lengths):

— Texas 591 km;

— Louisiana 639 km;

— Mississippi 71 km;

— Alabama 85 km;

— Florida 1 239 km (Gulf coastline only).

Offshore Florida, Alabama and Mississippi, the width of the continental shelf varies between 25 km and 125 km wide, with water depths at the shelf break of between 60 m and 100 m. Further west, off the Mississippi River delta, the continental shelf width is less than 20 km and increases to 200 km offshore central and western Louisiana and Texas. Waters along the shelf are generally less than 100 m deep. Water depths off the shelf can exceed 3 000 m.

The main hydrocarbon-bearing area is offshore Texas and Louisiana in the north-western Gulf. Here the continental shelf is composed of sand and sediments from the Mississippi and other rivers. Two-thirds of the United States' freshwater runoff empties into the northern Gulf, and the sediments of the Mississippi Fan are derived from soil erosion and runoff from the central United States.

C.4.2 Data sources

The northern offshore area of the Gulf of Mexico is one of the most studied regions in terms of its meteorology and physical oceanography. Wind, wave and meteorological measurements have been made at many stations throughout the area over the past 30 years, both on and off the continental shelf. Much of this data has been recorded under sponsorship of the US government[65].

In addition, various industry-sponsored measurement programs have been conducted, and data are generally available for purchase or trade. In addition to measured wind and wave data, several important industry-sponsored numerical hindcast studies of both extreme and operational winds and waves have been performed, e.g. References [66], [67] and [68].

A number of current and water quality measurements (temperature, salinity, chemical composition) have also been made in the region over the years. Many of these studies have been sponsored by the U. S. minerals management service (MMS)[69], [70], [71]. In 1982, MMS began a series of data collection programmes starting in the eastern Gulf[72] and culminating in 1985 with the LATEX study of the central northern Gulf. The LATEX study results have been archived with the national oceanographic data centre (NODC)[70]. The MMS contracted with Texas A&M University to reanalyse and synthesize all available data (including some industry data) on the Gulf. The results of this comprehensive study were published in 2001[73].

The industry has also taken an active role in collecting measurements[74]. The Eddy joint industry project (EJIP), an industry collaborative effort, has sponsored measurements in the deeper waters of the region since 1983. The Climatology and Simulation of Eddies JIP (CASE), another industry effort, used the EJIP data to develop numerical models for use in estimating design currents in deep water associated with the Loop Current and warm eddies. Eddy tracking with satellite data and drifting buoys is now routine in the Gulf. Recent MMS-sponsored measurements along the Sigsbee Escarpment provide data on topographic Rossby waves. Several industry data sets of rare but intense subsurface jets, believed to be cold core eddies, also exist.

C.4.3 Overview of regional climatology

The climate in the Gulf of Mexico ranges from tropical to temperate. Summer wind and wave conditions are generally benign, with warm temperatures and high relative humidity. There are occasional light squalls and thunderstorms. The extreme wind and wave climate in the Gulf is dominated by hurricanes in the summer season and the passage of non-tropical frontal systems in the winter season. Swell is not a major factor except when associated with a hurricane. Waves tend to be correlated with winds (either hurricane or winter storm) and temporarily strong currents can be associated with storm systems, although there are also prevailing circulation currents even in the shallow Gulf.

The hurricane season officially runs from May to end of November, and on average three tropical storms can be expected to form in or enter the region each year. These storms can originate in the Gulf of Mexico, the Caribbean Sea or in the North Atlantic Ocean.

Temperatures are generally mild, with occasional freezes in the coastal areas. Some coastal areas are periodically affected by fog.

An important oceanographic feature of the deep water Gulf is the Loop Current (see Figure C.11). The Loop Current is a warm-water current that enters the Gulf through the Yucatan Strait, flows generally northwards in the eastern Gulf, then turns southward along the west Florida coast, and exits through the Florida Strait as the Florida Current. It is detectable to around 800 m below the surface. A characteristic of the Loop Current is its periodic northward intrusion into the eastern Gulf; these intrusions occur every 4 to 16 months. The northward penetration of the Loop usually reaches about 28 to 29 °N and is followed by the shedding of a large eddy (a Loop Current eddy) with a diameter ranging from 150 to 450 km with clockwise rotation. After an eddy is shed, the Loop Current retracts to the south, usually below 26 °N, and starts the cycle again.

After separating, a Loop Current eddy can attach and detach several times. Eventually, the eddy moves to the west or southwest at an average translation speed of about 3 km/day. The energy of the eddy slowly decays to about half its original strength by the time it gets to the western Gulf. There, the Loop Current eddy usually slowly breaks down into a series of smaller cyclonic and anti-cyclonic eddies. The dissipation process can take more than a year.

C.4.4 Water depth, tides and storm surges

Tides in the Gulf of Mexico are semi-diurnal with little phase lag throughout the Gulf. Tide range is generally less than 1,0 m in near shore areas, and decreases rapidly offshore to about 0,3 m in deep water. Tidal currents in most of the Gulf are negligible compared to the other current processes described and are noticeable only in areas where the flow is constrained by the topography, such as river mouths, passes between islands, and near the Florida panhandle.

Storm surge in the Gulf results primarily from the passage of hurricanes, and can exceed 7 m along the low-lying coastal areas. Surge decreases offshore, but can still reach levels of 1,0 m in deep water[75].

C.4.5 Winds

The mean background wind flow in the northern portion of the Gulf of Mexico is governed by the mid-latitude westerlies, while in the southern portion, south of 26 °N, it is dominated by the easterly Trades. The general circulation is controlled by the North Atlantic subtropical high (known as the Bermuda High). Flow along the southern edge of the Bermuda High produces the Trade winds, which are weakest during the winter and strongest during the summer.

Tropical storms and hurricanes occasionally affect the region during the period between May and November. In addition to generating surface winds in excess of 30 m/s, the passage of a hurricane is associated with high seas (see below), heavy rain, high storm surges along the coast and strong currents in the upper layer of the ocean. The direction of the wind at a particular site depends on the direction of hurricane travel, and its position relative to the site. Tropical storms and hurricanes are relatively localized events. The most severe winds are generally within 100 km of the storm track and typically cause severe conditions at a site for 24 h or less.

Hurricanes initially move west at around 5 m/s, then tend to follow a parabolic path toward the northwest as they accelerate to 10 m/s. As a result, many do not affect the southern US coast. The number of hurricanes varies from year to year, and is possibly linked to *El-Niño* and summer sea surface temperatures in the Gulf.

During autumn and winter (mid-September to mid-February), winds are mainly north to north-easterly with speeds of less than 15 m/s. In the late spring and summer (May to mid-August), tropical weather prevails in the northern Gulf with winds from the southeast and speeds of typically less than 10 m/s.

Extratropical storms and frontal systems affect the region from October to March inclusive, and can generate winds in excess of 15 m/s. Storm conditions of gusty winds and rain associated with the passage of fronts can last for several days.

Northers occur when cold air from the Rocky Mountains moves south and out over the Gulf[76]. This unstable air is heated from below by the warm Gulf waters and produces strong (7,5 to 12,5 m/s) gusty winds and frequent showers. The *northers* occur between October and February, with the more severe events from December onward. Occasionally, *northers* can produce winds reaching gale force (17 m/s to 23,5 m/s) that can last for up to three days, with resulting wave heights of over 9 m in the central and southern areas of the Gulf[76].

Typical wind roses for a summer and a winter month for the north west Gulf, are shown on Figure C.8. Examples of tropical storm and hurricane tracks are shown on Figure C.9.

For additional information on wind events in the Gulf see References [76], [77] and [78].

C.4.6 Waves

The Gulf of Mexico is effectively a semi-enclosed sea. While strong winds can occur over the whole region, the wave characteristics vary according to the water depth and fetch over which they are generated.

Most of the waves in the northern Gulf are less than 3 m in height. Summer wave heights are typically 1,5 m or less. Wave periods are usually below 8 s. There are occasional episodes of long period swell propagating into the region during the summer months.

Severe winter storms can produce individual waves in excess of 9 m in height, with high sea states persisting for several days. The largest waves encountered in the Gulf are generated by tropical cyclones, or hurricanes. In deep water, individual waves produced by hurricanes can be in excess of 30 m. Hurricane waves on the continental shelf are reduced somewhat by shoaling and refraction effects, and are depth-limited in the shallowest areas. Hurricane-generated sea states tend to be fairly confused, and exhibit more directional spreading than those generated by extratropical storms and fronts[38]. Hurricanes that originate outside, and move into, the Gulf are stronger than those that originate in the Gulf itself.

As with the winds, there is a wave height gradient across the Gulf: typical heights in the east are about 1 m less than those in the west. Long period swell originates in the Atlantic and can enter the Gulf from the south and east in summer months, but is not a significant design consideration. Swell is less noticeable in winter.

Indicative independent wave heights are presented in Table C.21. A single value is presented for each parameter, for each return interval. The values were developed by a group of oil industry metocean specialists from the proprietary studies GUMSHOE[66], WINX[67] and GOMOS[68]. These studies used state-of-the-art, calibrated wind and wave models to hindcast a large number of hurricanes and winter storms. The hurricane wave heights include consideration of Hurricane Ivan (September 2004), a very large, severe storm that caused much damage to offshore facilities. Spatial variability was considered when deriving the values presented in Table C.21.

These values are only indicative, and while expected to prove conservative for most deep water locations in the central and western Gulf, could prove non-conservative for some locations in the extreme eastern and western production areas. The services of a qualified metocean specialist should be obtained to provide site-specific criteria for any development in the Gulf of Mexico.

The values of the parameters for return intervals of 10, 50, and 100 years are based on hurricanes. The criteria for 1 and 5 year return intervals are based on winter storms, which can be more severe than hurricanes for these short return periods.

C.4.7 Currents

C.4.7.1 General

Currents in the Gulf vary substantially according to location. On the continental shelf (less than 200 m depth), currents are primarily driven by the local wind, although the Mississippi River can have a substantial influence at sites up to 100 km away. Tides are weak, with amplitudes of about 1 m, generating tidal current speeds of less than 0,1 m/s. Hurricanes drive the extremes in shallow water, generating currents in excess of 2,0 m/s.

C.4.7.2 Loop Current

In the deep waters of most of the Gulf, currents are dominated by the Loop Current and its associated eddies (see Figure C.11). The Loop Current either directly or indirectly influences the deep water circulation of the entire northern Gulf. In the eastern and central Gulf, Loop Current intrusions and Loop Current eddies can generate surface currents with speeds in the order of 2,5 m/s, and moderate (0,7 m/s) speeds over a substantial portion of the water column (300 m). Loop Current eddy currents are somewhat weaker in the western Gulf. The variation of eddy current strength in different parts of the Gulf is shown on Figure C.14. Eddies do not intrude onto the continental shelf, so eddy currents are shown as zero in Area I of Figure C.14. Beyond the shelf, eddies are strongest in the east, 2,5 m/s in Area II, and decay to approximately 2,0 m/s in Area III. The Loop Current or one of its eddies can affect a site for weeks. See Reference [79] for additional information.

C.4.7.3 Hurricane-driven currents

Atmospheric events such as hurricanes and *northers* can generate strong episodic currents to considerable depths. Hurricane-driven surface currents of 1,0 to 1,5 m/s are not unknown[80] and the resulting flows can be traced as deep as 700 m or more over the continental slope. The decay of these events shows in the water column as a series of inertial oscillations that propagate downward (and horizontally) over several days. The time slice plot in Figure C.12 shows one such series measured in the western Gulf in 2001[75], which produced currents of 0,6 m/s at 700 m depth. Hurricane inertial currents usually dissipate over three to five days. In open water, the current direction typically appears to rotate every 24 h, while in deep water areas close to a steep slope, the direction appears fairly uniform and the flow is parallel to the bathymetry from east to west.

On the slope, currents tend to be complicated and weakly correlated to local wind. Mean currents are weak, although substantial shelf waves are often seen. Extremes are dominated by hurricanes, and perhaps by the Loop Current in the eastern and east-central Gulf.

C.4.7.4 Submerged currents

Strong submerged currents thought to be caused by cold eddies have been observed on several occasions in the Gulf of Mexico in waters deeper than 500 m. Though these events appear to be rare and possibly have some geographical dependence, the cold eddies are potentially critical factors for the design of risers and should be considered. Estimated values of parameters for a cold eddy have been included in Table C.24. Joint industry efforts are underway to reduce uncertainty in the values presented in the table, which are the best estimates currently available.

C.4.8 Other environmental factors

C.4.8.1 Sea temperature

The annual range of western Gulf of Mexico sea temperatures is shown in Figure C.13, taken from Reference [81]. In general, there is little variation across the Gulf, although typically in winter the surface temperature is around 21 °C in the north and 25 °C in the southern part.

C.4.8.2 Marine growth

Marine growth thickness may be taken as 38 mm between LAT +3 m and –50 m, unless site-specific studies are conducted to determine more appropriate values.

C.4.8.3 Snow and ice accretion

Design of structures for the Gulf of Mexico need not consider snow or ice accumulations.

C.4.9 Estimates of metocean parameters

C.4.9.1 Applicability of estimates

This annex provides some indicative values for metocean parameters which can be suitable for conceptual studies. Site- or project-specific criteria shall be developed for structural design and/or assessment.

C.4.9.2 Extreme metocean parameters

The extreme metocean environment in the Gulf of Mexico is governed primarily by two phenomena: hurricanes (winds and waves) and the Loop Current and eddies (currents). These two phenomena are uncoupled, therefore criteria may be based on their combined probabilities of occurrence if adequate data are available.

Table C.21 provides indicative independent extreme values of characteristic parameters for winds, waves and hurricane-driven currents for those portions of Areas II and III deeper than 300 m, as shown in Figure C.14. This area extends from the water depth of 300 m to the longitude of 86 °W in the east, and to the limits of the US EEZ (approximately 26 °N) in the south. The area east of 86 °W is omitted because there are no exploration activities in that area. As already stated, the indicative values in Table C.21 are applicable only to the deep water areas of the northern Gulf, and can be non-conservative for other portions of Areas II and III. Furthermore, these values can be unduly conservative for some areas, particularly in the central Gulf. Qualified specialists in oceanography and meteorology should be consulted to select the appropriate values of the environmental parameters for design criteria.

For Area I and for those portions of Areas II and III (see Figure C.14) with depths less than 300 m, wave heights decrease from the values given in Table C.21 to much lower values as the depth reduces and the shoreline is approached. Figure C.10 gives an indication of the variation of extreme maximum (rather than significant) wave height as a function of water depth. This curve is normalized to the deep water maximum wave height for the appropriate return interval, to provide representative wave heights for water depths less than 300 m. The effects of storm surge and wave breaking have been considered in Figure C.10. The wave heights specified for depths less than 20 m are actually breaking waves (based on water depth plus storm surge).

The data in Figure C.10 can be used to calculate maximum wave heights in water depths less than 300 m as follows.

a) Determine the site storm water depth (still water depth plus storm surge).

b) Enter abscissa of Figure C.10 with this depth value.

c) Read ratio of shallow water maximum wave height to deep water maximum wave height ($H'_{\text{max,s}}/H'_{\text{max,d}}$) from the ordinate of Figure C.10.

d) Multiply the deep water wave height for appropriate return period (from Table C.21) to obtain maximum wave height for that return period and water depth.

Extreme values for other metocean parameters are largely independent of the geographical area or return period, and are included in Table C.22. The values are to be used with all return periods of the parameters listed in Table C.21.

Examples of extreme combined values (100 years only) are presented in Table C.24 (loop current/eddies and bottom currents).

Independent extreme values for the Loop Current and eddy current parameters are presented in Table C.23 for Areas II and III in Figure C.14. The Loop Current rarely penetrates onto the Continental Shelf, so values are not presented for Area I. For a site near the seaward edge of Area I (i.e. water depth slightly less than 200 m), the value for Area II or III, as appropriate, should be used if representative Loop Current criteria are required.

C.4.9.3 Long-term distributions of metocean parameters

A wave scatter diagram for the deep water areas of the northern Gulf of Mexico, comprising total significant wave height and associated spectral peak periods, is provided in Table C.25. This table is applicable to exposed deep water areas. For shallower areas, there can be site- and depth-dependent effects in the long-term distributions as well as in the extreme criteria. The information in the table was generated from data from National Data Buoy Center (NDBC) Buoy No. 42001. This buoy is located in the central Gulf at 25,92 °N, 89,68 °W. The data cover a 10 year period.

Table C.21 — Indicative independent extreme values for winds, waves, and storm-generated currents — Areas II and III of Gulf of Mexico (see Figure C.14) **— Water depths greater than 300 m**

Metocean parameter [a]	**Return period** no. years				
	1 [b]	**5** [b]	**10** [c]	**50** [c]	**100** [c]
Wind speed (m/s)					
10 min mean wind speed	17,6	25,5	28,4	40,9	46,1
3 s gust wind speed	22,1	32,0	35,6	51,3	57,8
Waves [d]					
Maximum wave height (m)	9,4	13,0	15,0	22,8	25,8
Significant wave height (m)	4,9	7,3	8,5	12,9	14,6
Spectral peak period [e] (s)	10,3	11,7	12,3	14,3	14,9
Current speed — Storm-generated (m/s) [f]					
Surface	0,4	0,6	1,3	2,0	2,3
20 m depth	0,4	0,6	1,1	1,8	2,0
30 m depth	0,4	0,6	0,8	1,7	1,9
40 m depth	0,4	0,6	0,1	1,4	1,8
50 m depth	0,4	0,6	0,1	0,9	1,4
60 m depth	0,4	0,6	0,1	0,3	0,8
70 m depth	0,4	0,6	0,1	0,1	0,1
90 m depth	0,1	0,1	0,1	0,1	0,1
1 m above sea floor	0,1	0,1	0,1	0,1	0,1

[a] This annex provides some indicative values for metocean parameters which can be suitable for conceptual studies. Site- or project-specific criteria shall be developed for structural design and/or assessment.

[b] Winter storm.

[c] Hurricane.

[d] Wave heights in this table for each return period are identical for all deep water areas of the Gulf of Mexico. This is not necessarily conservative for some areas, and can be overly conservative for some areas in the central Gulf.

[e] Assume that the spectral peak period can vary by ±10 % around these central estimates.

[f] The peak hurricane wind and wave and the peak hurricane current do not generally occur together. To estimate the current associated with the peak hurricane wind and wave, factor the current speed and depth scale by 0,9. To estimate the wind and wave associated with the peak hurricane current, factor the peak wind and wave by 0,9.

Table C.22 — Indicative extreme values for other metocean parameters — Gulf of Mexico north of 26 °N and west of 86 °W (see Figure C.14)

Mean spring tidal range (m)		0,5
Sea water temperature (°C)		
	Min. near surface	8,5
	Max. near surface	32,5
	Min. near bottom (2 000 m)	3,2
	Max. near bottom (2 000 m)	4,8
Air temperature (°C)		
	Min.	0,0
	Max.	39,0
This annex provides some indicative values for metocean parameters which can be suitable for conceptual studies. Site- or project-specific criteria shall be developed for structural design and/or assessment.		

Table C.23 — Indicative independent extreme values for Loop Current and eddies — Gulf of Mexico north of 26 °N and west of 86 °W (see Figure C.14) **— Water depths greater than 200 m**

Depth	**Current speed** m/s	
	Area II	**Area III**
Surface	2,5	2,0
55 m depth	2,5	2,0
160 m depth	1,75	1,4
300 m depth	1,0	0,8
500 m depth	0,75	0,6
⩾1 000 m depth	0,25	0,2
This annex provides some indicative values for metocean parameters which can be suitable for conceptual studies. Site- or project-specific criteria shall be developed for structural design and/or assessment.		

Table C.24 — Indicative combined extreme (100 year return period) for Loop Current/eddies and bottom currents — Gulf of Mexico north of 26 °N and west of 86 °W (see Figure C.14) — Water depths greater than 200 m

Metocean Parameter [a]	Area II (see Figure C.14)		Area III (see Figure C.14)		Cold eddy	Bottom currents [b]
	Eddy or Loop max.	**Eddy or Loop and max. wave**	**Eddy or Loop** max.	**Eddy or Loop and max. wave**		
Wind: 10 min mean speed (m/s) [c]	7,4	19	7,4	19	7,4	7,4
Wave height (m) [d, e]						
Maximum	3	11	3	11	3	3
Significant	2	6	2	6	2	2
Spectral peak period (s) [f]	6	11	6	11	6	6
Surge: Distance above MLLW (m)	0 to 0,2	0 to 0,6	0 to 0,2	0 to 0,6	0 to 0,2	0 to 0,2
Current speed (m/s) at depth (m) [g]	2,5 at 0	2,25 at 0	2,0 at 0	1,8 at 0	0,2 at 0	
	2,5 at 55	2,25 at 55	2,0 at 55	1,8 at 55	0,2 at 100	
	1,75 at 160	1,5 at 160	1,4 at 160	1,2 at 160	2,4 at 200	
	1,0 at 300	1,0 at 300	0,8 at 300	0,8 at 300	1,8 at 400	
	0,75 at 500	0,75 at 500	0,6 at 500	0,6 at 500	0,2 at 550	
	0,25 at ⩾1 000	0,25 at ⩾1 000	0,2 at ⩾1 000	0,2 at ⩾1 000	0,1 at seabed	0,8 at seabed

[a] This annex provides some indicative values for metocean parameters which can be suitable for conceptual studies. Site- or project-specific criteria shall be developed for structural design and/or assessment.

[b] The “bottom current case”, applies to all bottom founded components like pipelines and subsea trees. Note that currents can significantly exceed these values at sites within a few km of sharp topographic gradients like the Sigsbee Escarpment. For these locations, site-specific data should be used to characterize bottom currents.

[c] For structures that have wind sensitivity, different wind-averaging periods should be used, and dynamic wind analysis should be performed.

[d] Use the JONSWAP spectra and wave spreading of the form $\cos^n$.

[e] Kinematics for the deterministic wave are given by stream function theory and for random waves by Wheeler. Maximum crest elevation is found by multiplying the wave height from stream function theory by 1,07.

[f] Assume that the spectral peak period may vary by ±10 % around these central estimates.

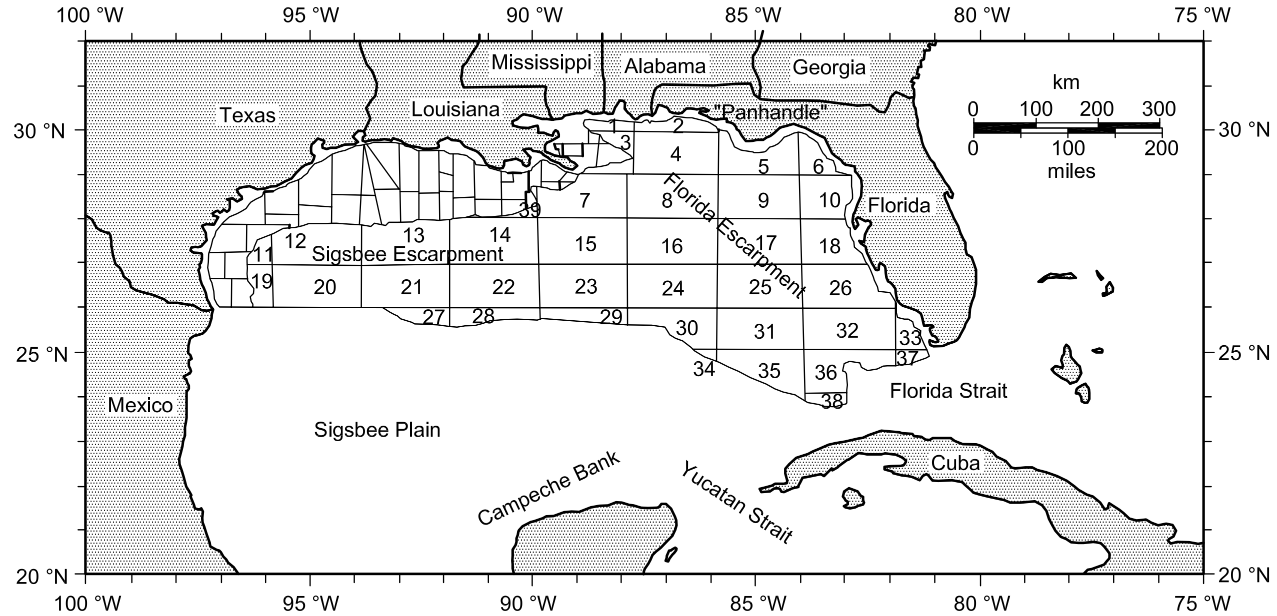
[g] Event durations for currents should be taken as the following.

- Eddy/Loop Durations:
  1) ramp up to 85 % of 100 year profile from background current over 7 days;
  2) 85 % 100 year profile for 7 days;
  3) 100 year profile for 24 hours;
  4) 85 % 100 year profile for 7 days;
  5) Ramp back down to background current over 7 days.
- Bottom Current: full strength for 7 days.

Table C.25 — Percentage occurrence of total significant wave height and spectral peak period combinations — Deep water location — Gulf of Mexico

Wave height m	Peak period [a] s											
	0,5 to 1,5	1,5 to 2,5	2,5 to 3,5	3,5 to 4,5	4,5 to 5,5	5,5 to 6,5	6,5 to 7,5	7,5 to 8,5	8,5 to 9,5	9,5 to 10,5	10,5 to 11,5	11,5 to 12,5	Total for 0,5 to 12,5
0,2 to 0,5	0	0,16	1,99	4,26	5,67	2,74	1,05	0,67	0,05	0,01	0,02	0	16,62
0,5 to 0,8	0	0,04	1,22	3,39	7,78	6,62	1,84	0,53	0,13	0,01	0,00	0	21,56
0,8 to 1,1	0	0,01	0,35	1,41	4,80	7,84	3,14	0,61	0,08	0,03	0,00	0	18,27
1,1 to 1,4	0	0	0,07	0,27	1,97	5,89	4,78	1,50	0,08	0,01	0,01	0	14,58
1,4 to 1,7	0	0	0,01	0,05	0,49	3,02	4,28	2,32	0,14	0,03	0,01	0	10,35
1,7 to 2,0	0	0	0	0	0,13	1,16	2,87	2,37	0,23	0,03	0,01	0	6,80
2,0 to 2,3	0	0	0	0	0,03	0,36	1,54	2,05	0,39	0,08	0,02	0	4,47
2,3 to 2,6	0	0	0	0	0	0,11	0,62	1,46	0,39	0,10	0,02	0	2,70
2,6 to 2,9	0	0	0	0	0	0,02	0,20	0,88	0,37	0,11	0,02	0	1,60
2,9 to 3,2	0	0	0	0	0	0	0,06	0,46	0,42	0,08	0,02	0	1,04
3,2 to 3,5	0	0	0	0	0	0	0,02	0,20	0,25	0,10	0,03	0	0,60
3,5 to 3,8	0	0	0	0	0	0	0,01	0,12	0,17	0,13	0,03	0	0,46
3,8 to 4,1	0	0	0	0	0	0	0	0,08	0,12	0,13	0,04	0	0,37
4,1 to 4,4	0	0	0	0	0	0	0	0,02	0,05	0,08	0,03	0	0,18
4,4 to 4,7	0	0	0	0	0	0	0	0,01	0,03	0,04	0,05	0	0,13
4,7 to 5,0	0	0	0	0	0	0	0	0	0,01	0,03	0,05	0	0,09
5,0 to 5,3	0	0	0	0	0	0	0	0	0	0,01	0,05	0	0,06
5,3 to 5,6	0	0	0	0	0	0	0	0	0	0,00	0,04	0	0,04
5,6 to 5,9	0	0	0	0	0	0	0	0	0	0,01	0,04	0	0,05
5,9 to 6,3	0	0	0	0	0	0	0	0	0	0,01	0,02	0	0,03
Total for 0,2 to 6,3	0	0,21	3,64	9,38	20,87	27,76	20,41	13,28	2,91	1,03	0,51	0	100,00

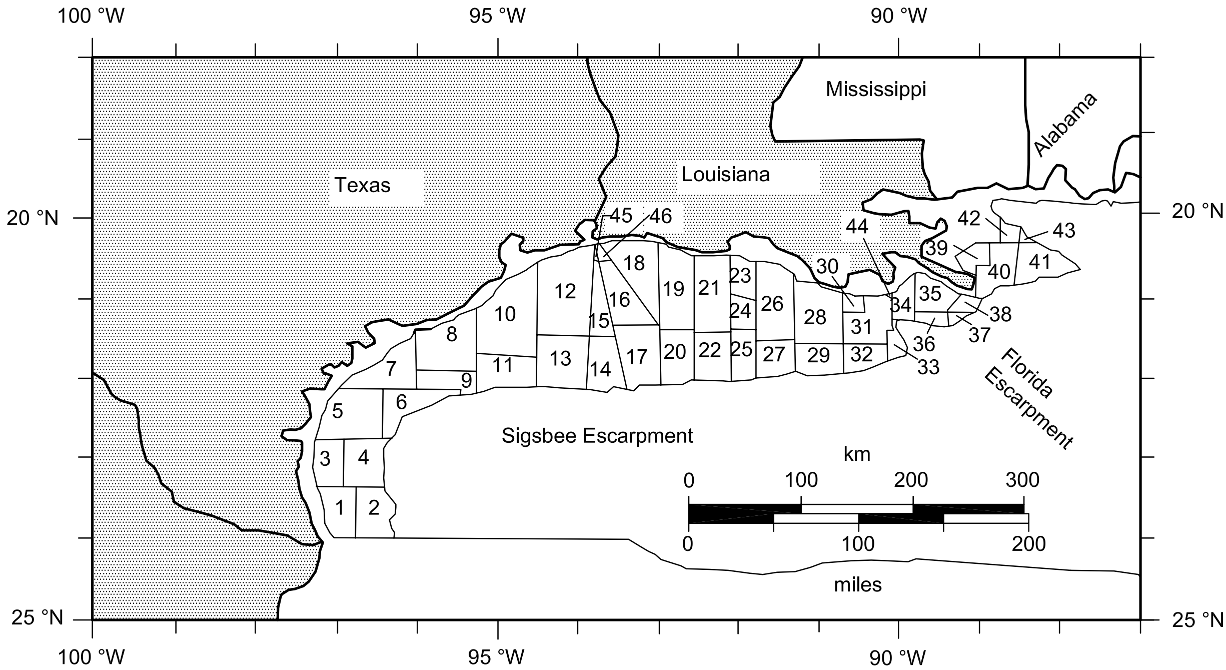
[a] Data taken from NOAA buoy 42001[65].



Key

1	Mobile	14	Green Canyon	27	Sigsbee Escarpment
2	Pensacola	15	Atwater Valley	28	Amery Terrace
3	Viosca Knoll	16	Lloyd Ridge	29	Lund South
4	Destin Dome	17	The Elbow	30	Florida Plain
5	Apalachicola	18	Saint Petersburg	31	Howell Hook
6	Gainesville	19	Port Isabel	32	Pulley Ridge
7	Mississippi Canyon	20	Alaminos Canyon	33	Miami
8	De Soto Canyon	21	Keathley Canyon	34	Campeche Escarpment
9	Florida Middle Ground	22	Walker Ridge	35	Rankin
10	Tarpon Springs	23	Lund	36	Dry Tortugas
11	Corpus Christi	24	Henderson	37	Key West
12	East Breaks	25	Vernon Basin	38	Tortugas Valley
13	Garden Banks	26	Charlotte Harbor	39	Ewing Bank

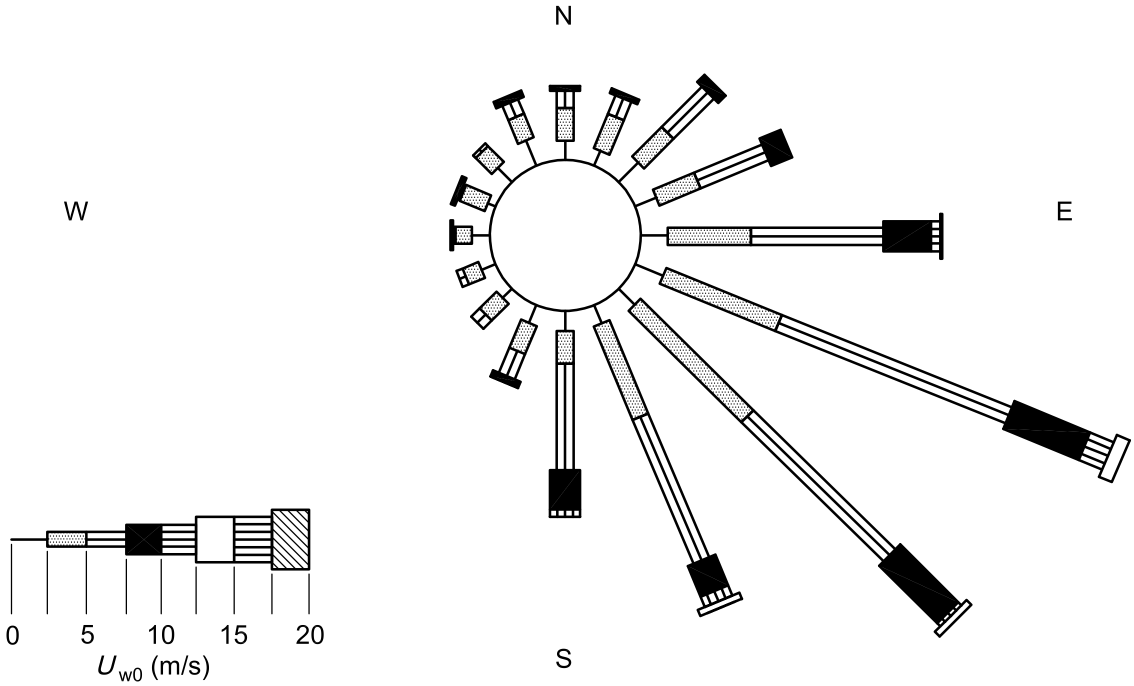
Figure C.6 — Map of northern Gulf of Mexico — Outer continental-shelf and deep water US lease areas[82]



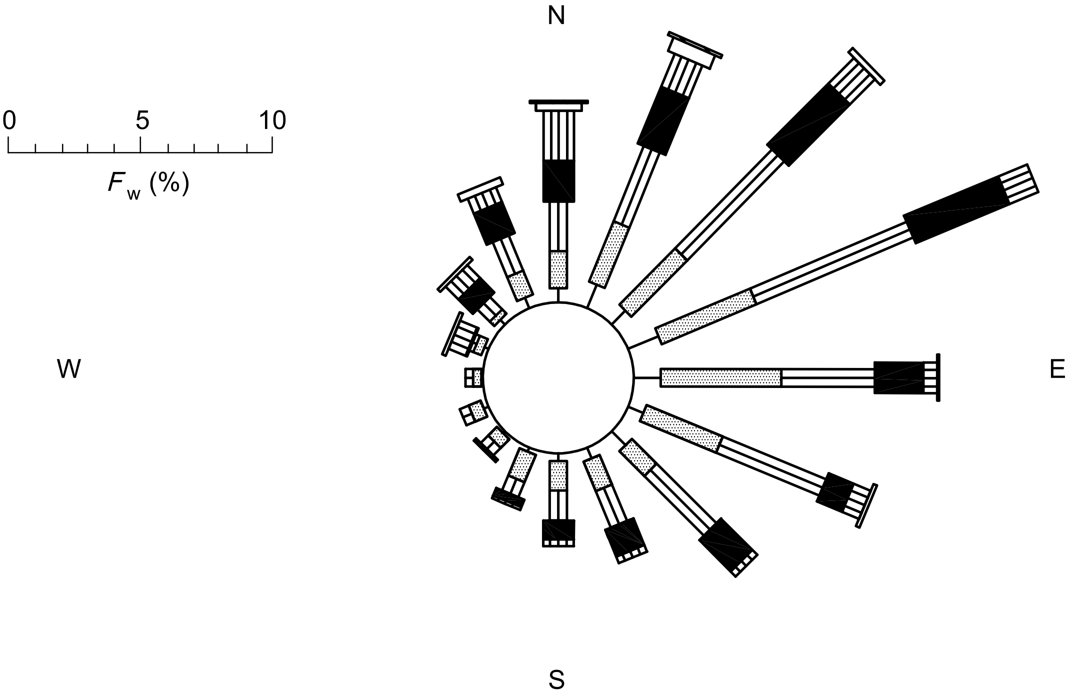
Key

1	South Padre Island	17	West Cameron South	33	Grand Isle
2	South Padre Island East	18	West Cameron	34	Grand Isle
3	North Padre Island	19	East Cameron	35	West Delta
4	North Padre Island East	20	East Cameron South	36	West Delta South
5	Mustang Island	21	Vermilion	37	South Pass South & East
6	Mustang Island East	22	Vermilion South	38	South Pass
7	Matagorda Island	23	South Marsh Island North	39	Breton Sound
8	Brazos	24	South Marsh Island	40	Main Pass
9	Brazos South	25	South Marsh Island South	41	MainPass South & East
10	Galveston	26	Eugene Island	42	Chandeleur
11	Galveston South	27	Eugene Island South	43	Chandeleur East
12	High Island	28	Ship Shoal	44	Bay Marchand
13	High Island South	29	Ship Shoal South	45	Sabine Pass (TX)
14	High Island East South	30	South Pelto	46	Sabine Pass (LA)
15	High Island East	31	South Timbalier		
16	West Cameron West	32	South Timbalier South		

Figure C.7 — Map of northern Gulf of Mexico — Inner continental-shelf US lease areas[82]



a) Typical June wind rose

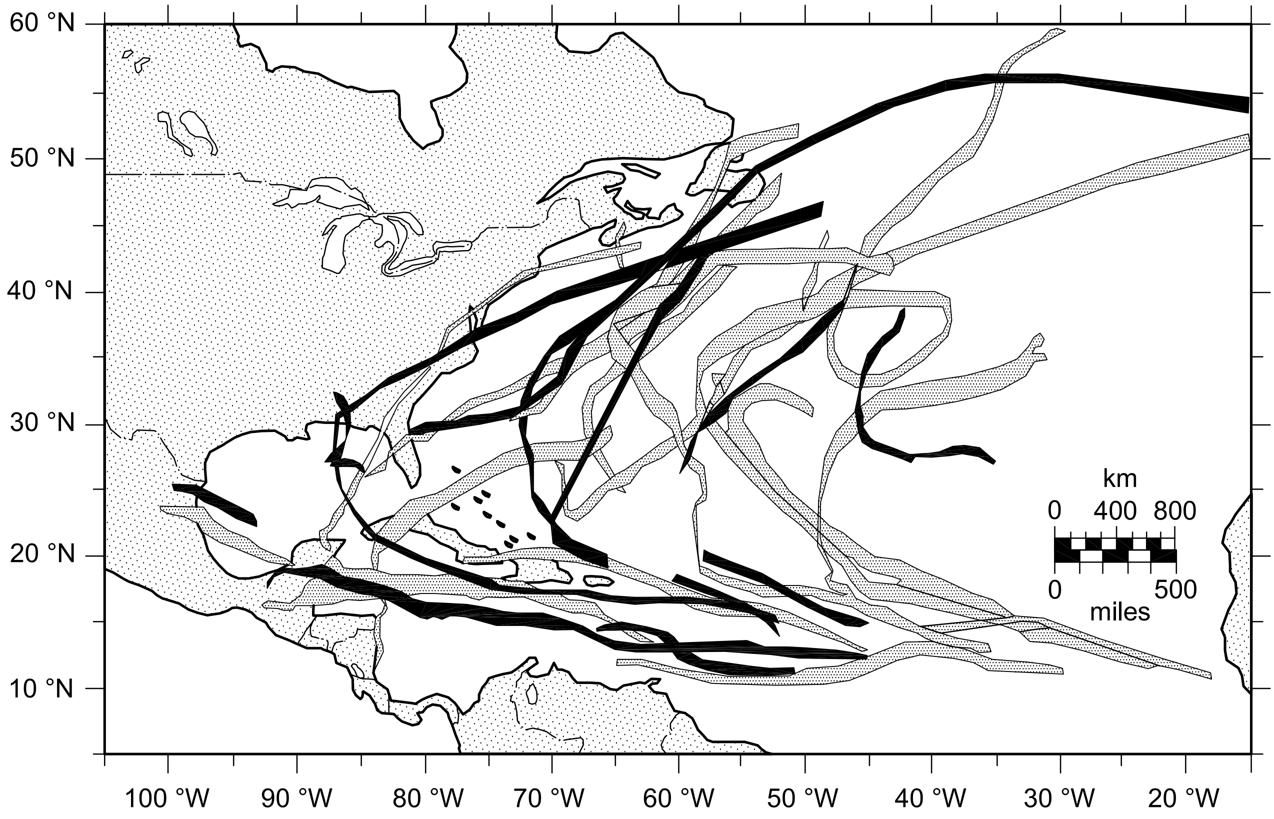


b) Typical December wind rose

Shading indicates wind speed, U_{w0}

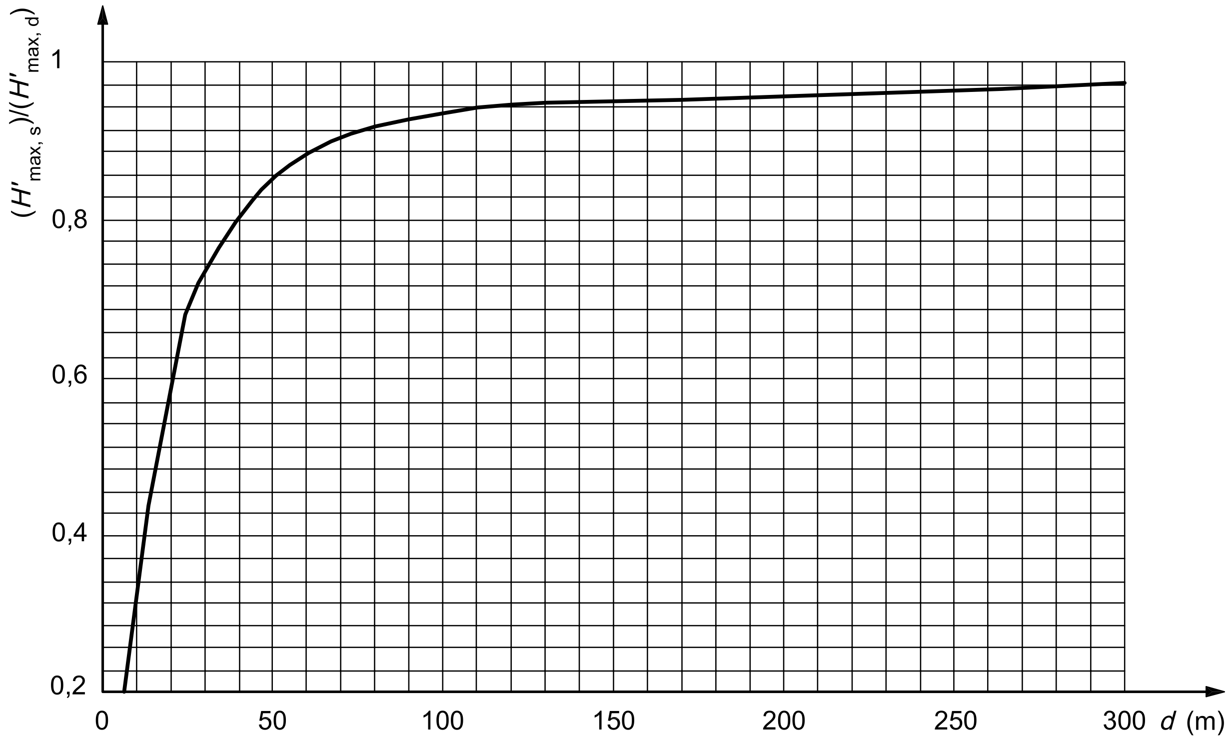
Length indicates percentage of month (F_w) at that direction and wind speed

Figure C.8 — June/December wind roses — Northwest Gulf of Mexico[75]



Relative wind speed, U_{w0}, is indicated by the width of the track line.

Figure C.9 — Tropical storm (light) and hurricane (dark) tracks, 2000 and 2001[75]



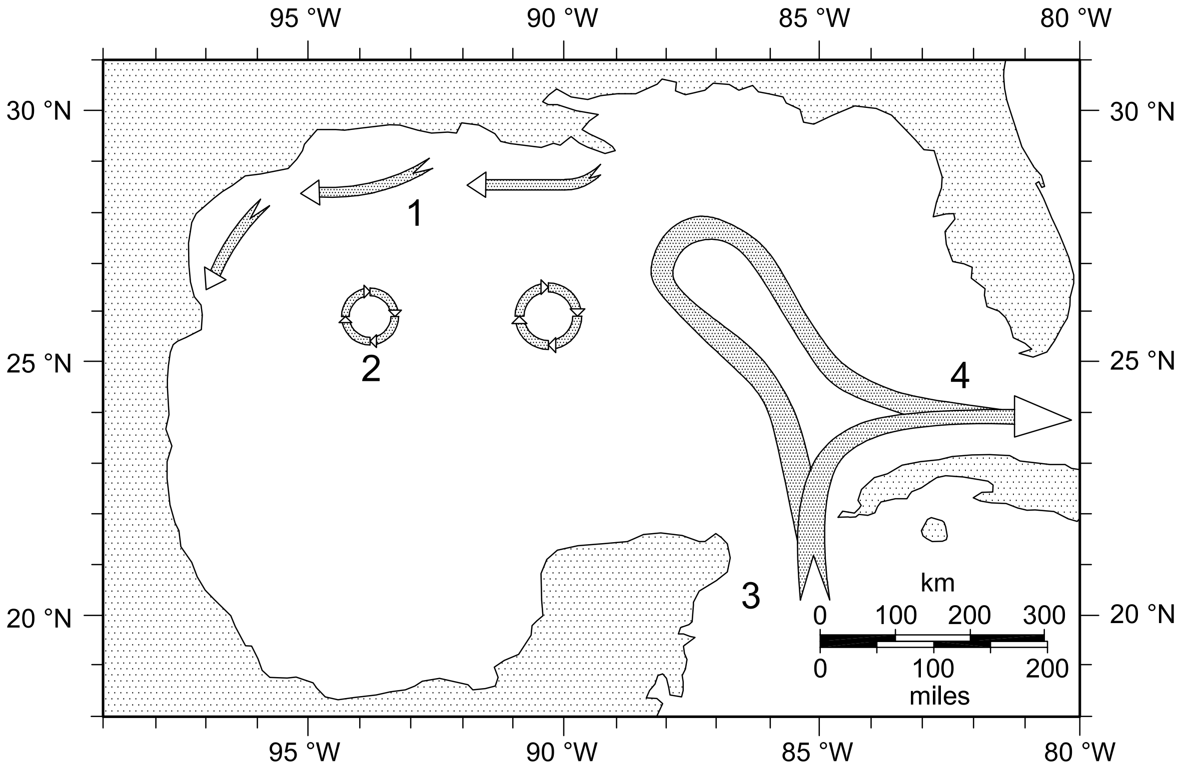
Key

$H'_{max,s}$ max. wave height in shallow water

$H'_{max,d}$ max. wave height in deep water

d water depth

Figure C.10 — Hurricane wave height as function of water depth — Northern Gulf of Mexico



Key

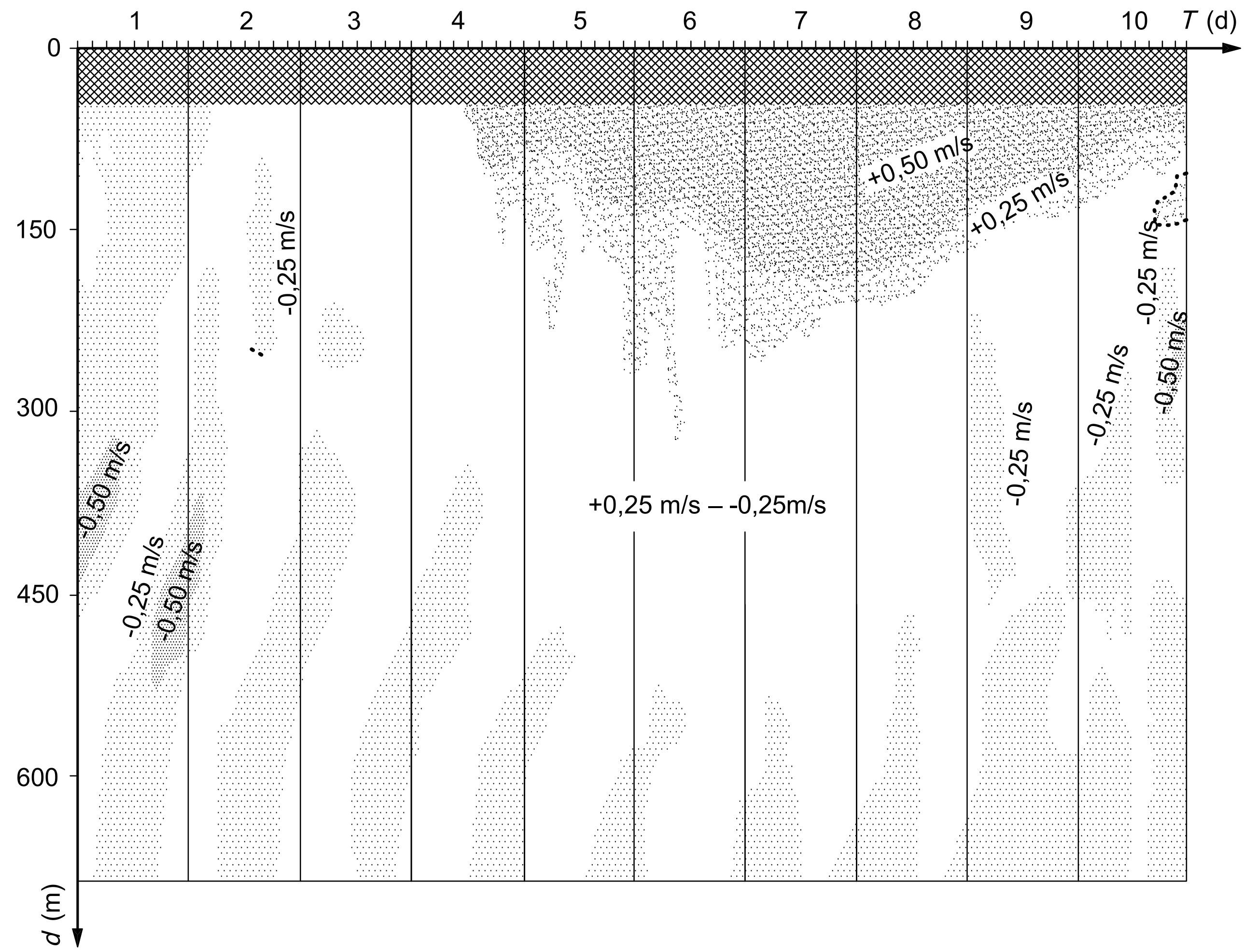
1 Shelf Current

2 Loop Current eddy

3 Yucatan Current

4 Florida Current

Figure C.11 — Circulation in Gulf of Mexico[75]

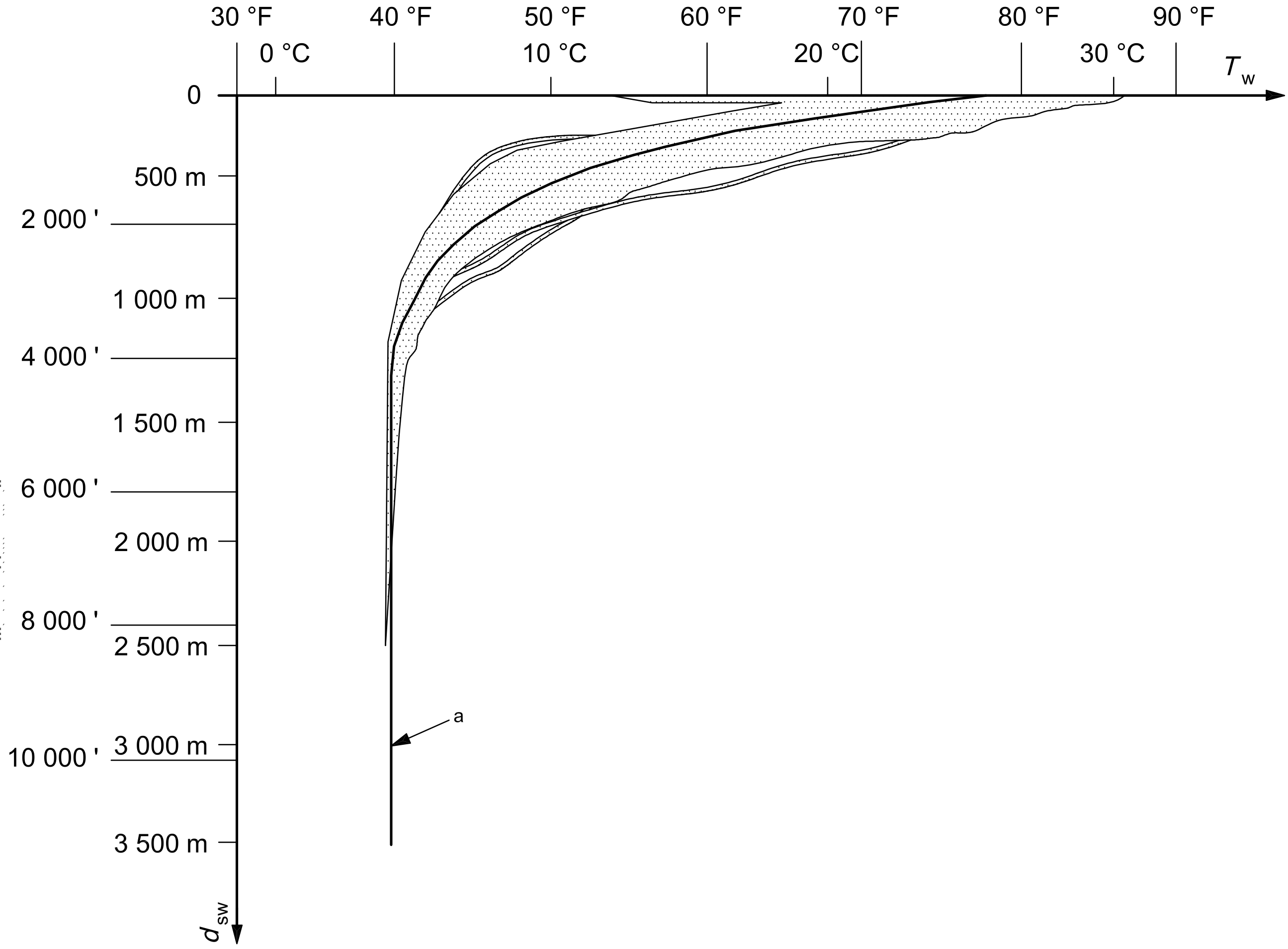


Key

d depth

T elapsed time in days

Figure C.12 — Observations of inertial currents — Western Gulf of Mexico, 2001[75]



Key

d_{sw} depth

T_w water temperature

a Mean temperature.

Figure C.13 — All-year sea temperatures — Western Gulf of Mexico[81]

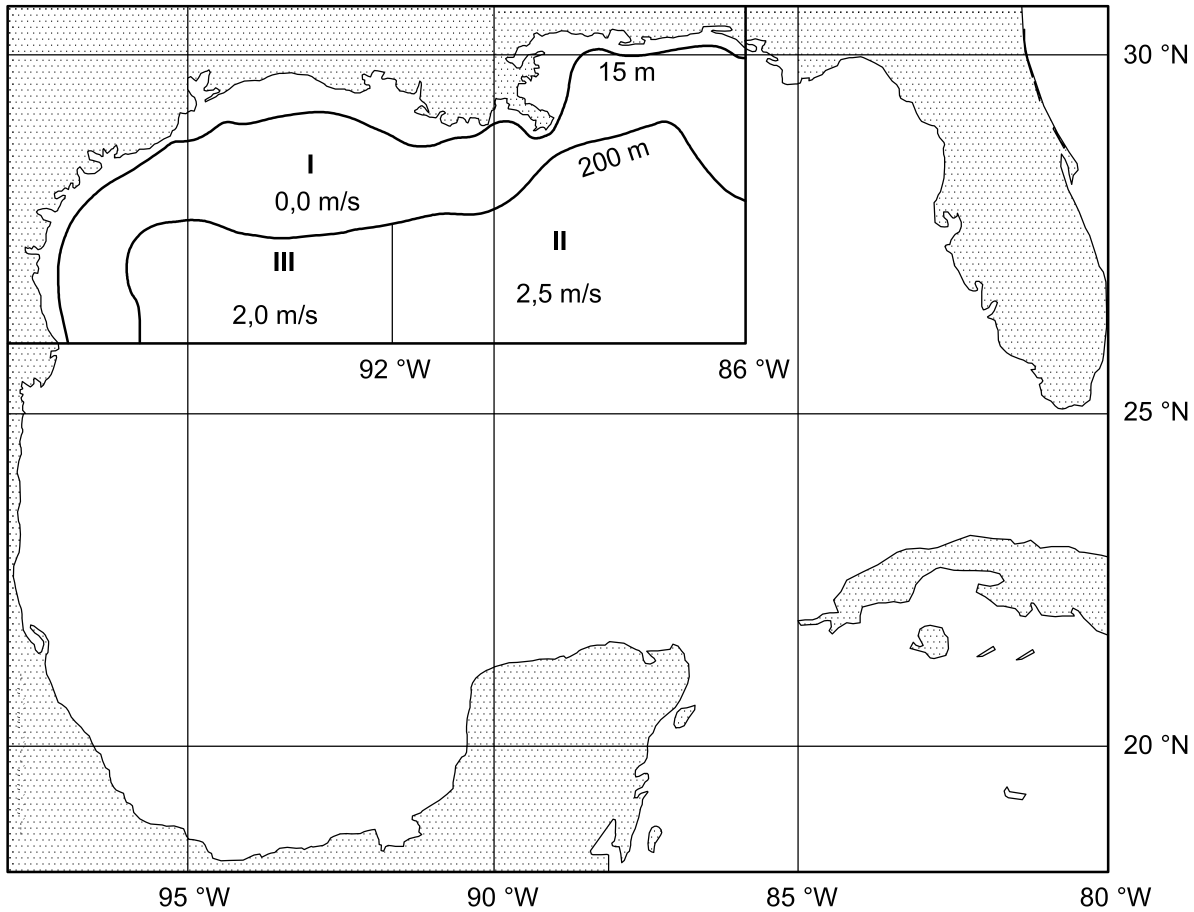


Figure C.14 — Loop Current and eddy current strengths — Northern Gulf of Mexico

C.5 US Coast of California

C.5.1 Description of region

The geographical extent of the region are the waters off the coast of California in the United States, the hydrocarbon producing area being shown in Figure C.15.

The region is primarily the Southern California Bight, which stretches from Point Arguello to San Diego and contains all but one of the offshore oil-producing blocks on the west coast of the lower 48 states of the US. The northern portion of the bight contains an important sub-region, the Santa Barbara Channel, where the majority of offshore production lies. The bight is bounded to the north and east by the California coast and offshore to the west by the Santa Rosa-Cortes ridge (see Figure C.15). There are numerous submarine valleys and mountains within the bight. The peaks of some of the mountains pierce the surface and form the Channel Islands.

C.5.2 Data sources

A comprehensive summary of the available oceanographic (excluding waves) and meteorological data is provided in Reference [83]. In addition, the US minerals management service (MMS) has published the proceedings of a workshop on oceanography of the Southern California Bight[84]. Most of this clause focuses on the bight and the Santa Barbara Channel.

An extensive study[85], [86] of the Santa Barbara Channel included nine current moorings and a similar number of wind stations deployed for three years. Data were collected between 1992 and 1995[85] and analysis was completed in 1997[86].

Extensive wind and wave data sets now exist at several sites along the California coast. There are many years of wind and wave data available at the national data buoy centre (NDBC) from five data buoys lying between 5 and 50 km off the coast in the bight. Some of these buoys have been equipped with acoustic doppler current profilers (ADCP) in recent years. In addition, Scripps Institution of Oceanography has maintained roughly 17 wave stations along the coast in the bight[85]. Some of the stations have operated almost continuously since 1978 and include directional wave information.

A cooperative study between MMS and the state of California, the “Santa Barbara Channel–Santa Maria Basin Circulation Study”, was completed in the late 1990s, with the objectives of determining the frequency, the timing of occurrence and the short-term variability of the major circulation processes of importance in the Santa Barbara Channel–Santa Maria Basin Circulation. Pertinent publications arising from this study include References [87] to [92].

C.5.3 Overview of regional climatology

The climate of the bight is mediterranean, characterized by partly cloudy, cool summers, with little precipitation. Thunderstorms are infrequent. Winters are mostly clear and mild. Precipitation in winter is associated with winter seasonal storms. Fog and low clouds are common along the coast during the night and early morning hours in late spring and early summer. Afternoons are usually clear with sea breezes. The persistent Pacific High over the ocean to the west, combined with thermal contrasts between the land and the adjacent ocean and with effects of the coastal mountain range, result in mild temperatures throughout the year[93].

During the winter season, three weather regimes are common[93]:

— periods of low clouds and fog;

— periods of clear skies, cool nights, and warm days;

— periods of variable cloudiness, shifting and gusty winds, and precipitation.

An atmospheric low, sometimes referred to as the Catalina Eddy, is often present in the Southern California Bight. When this eddy expands northward, short-duration south-easterly sea breezes develop in the Santa Barbara Channel in the afternoon. When the eddy is well developed, the sea breezes can persist all day[93].

C.5.4 Water depth, tides and storm surges

Tides are mixed, with the semi-diurnal constituent dominating the diurnal constituent. Tidal ranges are small, with mean ranges of about 1 m. Maximum water depths within the Santa Barbara Channel are approximately 1 000 m. Water depths increase rapidly west of the Channel Islands. Storm surge is not a major design consideration offshore California.

C.5.5 Winds

Winds tend to be steady all along the California coast and are primarily driven by the subtropical anticyclone over the eastern Pacific. The anticyclone is strongest during the summer months, when it occupies its most northerly position near 30 °N to 40 °N and 140 °W to 150 °W. During the winter, the airflow over the open ocean is generally westerly off northern California and north-westerly off southern California. In the spring, the speed increases and becomes uniformly north-westerly over the entire region. This continues throughout the summer with mean speeds reaching 9 m/s to 10 m/s near points such as Point Conception/Point Arguello. In the autumn, winds weaken somewhat, and slowly return to the two-region winter flow pattern.

The strongest wind forcing during the winter comes from strong fronts moving through the bight toward the east. Winds reach 20 m/s to 25 m/s, and become much more intense around points such as Point Conception. Between fronts, the surface pressure gradient sometimes reverses and this can cause strong low-level offshore flows known as *Santa Anas,* characterized by easterly flow of dry desert air with speeds of 10 m/s to 15 m/s.

Tropical storms can occasionally reach the southern portions of the bight in late summer to early fall; however, as they reach the bight, the storms are rapidly eroded by the bight's cold surface waters.

C.5.6 Waves

The wave environment of the Southern California Bight area is the result of local wind-driven waves and swell from distant storms. The Channel Islands and the ridges shelter the Santa Barbara Channel from much of the offshore wave energy. This effect is dramatically illustrated by the fact that wave spectral energy is an order of magnitude lower at Sunset Beach (south of Los Angeles) than it is at San Nicholas Island. The restricted fetches in the bight result in relatively small amplitude, short period wind seas. The short durations of the sea breezes also tend to keep wave amplitudes low. High waves form in the region only when gale-force winds blow from the west. Individual wave heights as high as 7,6 m have been reported in the San Pedro Channel as a result of these winds. Locally-generated waves are characterized by their choppiness and are always accompanied by high winds. Sheltering effects of the shoreline are reduced because these waves and swell are locally generated.

Long period swell can come from north, west or south, but most is generated by winter storms in the North Pacific Ocean. To the north of Los Angeles and south of the Santa Barbara Channel, the extreme waves are driven by the large extratropical winter storms of the eastern Pacific, between Hawaii and the California coast. The dominant swell period is 16 s.

Extreme wave conditions in the southern part of the bight are dominated by swell from the occasional eastern Pacific hurricane.

C.5.7 Currents

Currents in the bight are complex and poorly understood. Tidal currents are weak and less than 0,1 m/s except near narrow passages like the southern Santa Barbara Channel where velocities can reach 0,1 m/s to 0,2 m/s due to an internal tide. To the north of the bight, the mean flow is dominated by the California Current flowing south with mean speeds of 0,1 to 0,2 m/s. To the south of the Santa Barbara Channel, there is evidence of weak northerly flow that sometimes displays a large cyclonic motion. The Santa Barbara Channel is a mixing zone of the California Current and the northerly flowing warm bight waters. As a result, large water temperature gradients are often evident with unusually complex flows that are independent of local wind.

Extreme currents are generally mild, reaching perhaps 0,5 m/s to 1,0 m/s. They are weakly correlated with the local wind except in shallow water less than 50 m deep. Extreme currents in deeper water (greater than 50 m) are probably driven by non-local, large-scale processes originating from the California Current. Vertical temperature stratification is mild, with a weak thermocline evident between 60 m to 100 m below the surface. Extreme flows tend to be uniform with depth, much as in the North Sea.

C.5.8 Other environmental factors

C.5.8.1 Marine growth

Offshore southern and central California, marine growth thicknesses of 200 mm are common. Site-specific studies should be conducted to establish the thickness variation with depth.

C.5.8.2 Snow and ice accretion

Snowfall and ice accumulations on structures are not design or operational considerations offshore California.

C.5.8.3 Tsunamis

The highest water level increases (1,5 m to 4,5 m) along the California coast are caused by tsunamis. Fortunately, tsunamis occur only infrequently and should not cause serious damage to properly designed offshore structures in deep water.

C.5.9 Estimates of metocean parameters

Indicative extreme values of metocean parameters for two areas offshore California are provided in Tables C.26 and C.27.

Table C.26 — Indicative independent extreme values for winds, waves and hurricane-driven currents for southern California (Santa Barbara and San Pedro Channels)

Metocean parameter	Return period years				
	1	5	10	50	100
Wind speed (m/s)					
10 min mean wind speed	18	22	24	27	28
3 s gust wind speed	22	27	30	34	35
Wave height (m)					
Maximum	6,3	9,4	10,6	13,5	14,6
Significant	3,5	5,2	5,9	7,5	8,1
Wave direction (from)	W-NW	W-NW	W-NW	W-NW	W-NW
Spectral peak period (s)	14 to17	14 to17	14 to17	14 to17	14 to17
Current speed (m/s)					
Surface current speed	1,2	1,2	1,3	1,4	1,5
90 m depth current speed [a]	0,5	0,5	0,6	0,6	0,7
1 m above sea floor current speed	0,5	0,5	0,6	0,6	0,7

[a] For water depths less than 90 m, the seabed current should be calculated from a linear distribution between the surface current and that at 90 m depth in this table.

Table C.27 — Indicative independent extreme values for central California

Metocean parameter	Return period years				
	1	5	10	50	100
Wind speed (m/s)					
10 min mean wind speed	14	18	19	21	22
3 s gust wind speed	17	22	23	26	27
Wave height (m)					
Maximum	9,4	13,5	14,2	15,8	16,4
Significant	5,2	7,5	7,9	8,8	9,1
Wave direction (from)	NW-N	NW-N	NW-N	NW-N	NW-N
Spectral peak period (s)	10-17	12-17	12-17	12-17	12-17
Current speed (m/s)					
Surface	0,6	0,7	0,7	0,8	0,8
90 m depth [a]	0,5	0,6	0,6	0,7	0,7
1 m above sea floor	0,5	0,6	0,6	0,7	0,7

[a] For water depths less than 90 m, the seabed current should be calculated from a linear distribution between the surface current and that at 90 m depth in this table.

Indicative values of operational metocean parameters offshore California are provided in Table C.28.

Table C.28 — Indicative extreme values for other metocean parameters

Mean spring tidal range (m)		1,0 m
Sea water temperature (°C)		
	Min. near surface	12,5
	Max. near surface	20,0
Swell		
	Maximum height (m)	2,5 (spring)
	Period (s)	16 to 18 (winter) 5 to 10 (summer)
	Direction (from)	S to W
Air temperature (°C)		
	Minimum	10,0
	Maximum	21,8

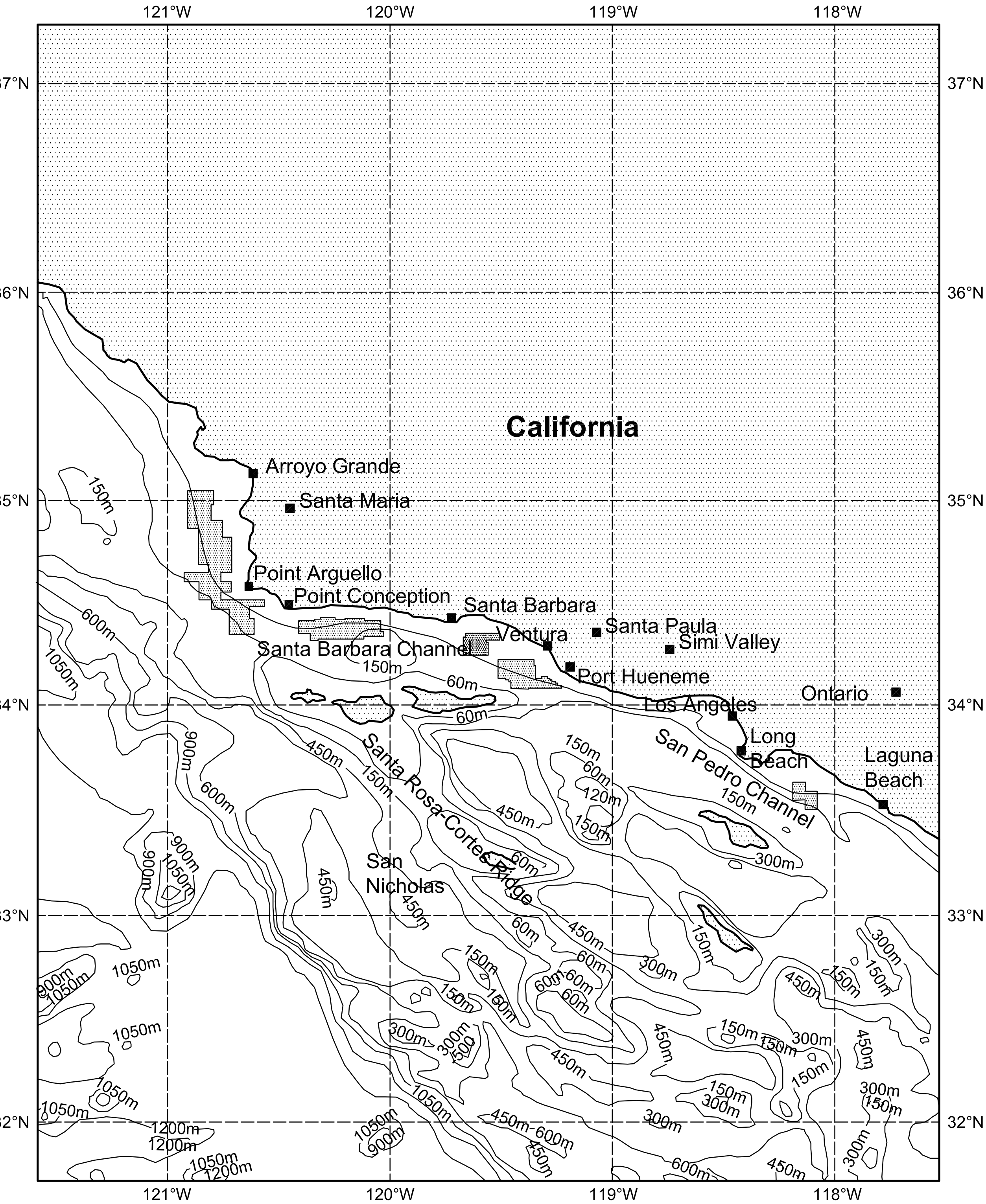


Figure C.15 — Map of California offshore region

C.6 East coast of Canada

C.6.1 Description of region

The geographical extent of the region is the waters off the east coast of Canada.

The current hydrocarbon production operations are located offshore Nova Scotia on the Scotian Shelf near Sable Island and offshore Newfoundland and Labrador on the Grand Banks, as shown in Figures C.16 and C.17.

The Grand Banks have some of the world's largest and richest resources, with both valuable fish stocks and petroleum reserves. Situated off the south-east coast of the Island of Newfoundland, the Grand Banks are a series of raised submarine plateaus with a water depth ranging between approximately 40 m and 200 m. Grand Bank is the largest of several banks comprising the Grand Banks of Newfoundland, and lies to the east and south-east of the Avalon Peninsula. Grand Bank has a relatively flat surface that is generally less than 120 m deep. It is separated from the Island of Newfoundland by the Avalon Channel, which has water depth ranging up to 200 m deep.

The Scotian Shelf comprises an area of approximately 120 000 km^2, is over 700 km long and ranges in width from 100 to 250 km. The Scotian shelf physiography consists of three physiographic zones: the Inner Shelf, the Central Zone and the Outer Shelf.

The Inner Shelf borders mainland Nova Scotia, extending roughly 25 km offshore, with water depths less than 100 m. It is characterized by rough topography.

The Central Zone is about 80 to 100 km in width and lies between the Inner Shelf and Outer Shelf. It is characterized by an inner trough running parallel to the coast, and isolated banks with intervening basins and valleys. Water depth varies from less than 100 m over the banks to about 180 m in the inner trough, with some basins up to 300 m in depth.

The Outer Shelf is bounded by the eastern shelf break and is about 50 to 70 km wide. This shelf is characterized by broad, flat banks with little relief. Sable Island Bank is the largest and most extensive bank on the Scotian Shelf, with water depths less than 100 m. Sable Island is an arc-shaped sandbar more than 40 km long and about 1,3 km wide.

C.6.2 Data sources

Data on metocean conditions in the region are available from a variety of sources. These include regulatory bodies, such as the Canada-Newfoundland offshore petroleum board (CNOPB) and the Canada-Nova Scotia offshore petroleum board (CNSOPB), operators, federal government agencies, and published papers.

Another source of metocean-related information is the AES40 North Atlantic Wind and Wave hindcast model[94]. This model was developed for the Meteorological service of Canada and is a 40 year (1958 to 1997) wind and wave hindcast model of the North Atlantic. It allows the estimation of extreme wind and wave parameters for the Scotian shelf and the Grand Banks of Newfoundland, as well as other locations in the North Atlantic.

For the offshore Newfoundland and Labrador area, environmental impact statements and project-specific design environmental criteria from operators, together with other related information, were used to prepare the information given in this clause. Similarly, for the offshore Nova Scotia area, environmental impact statements and development plan applications were used[95], [96], [97].

Additional environmental- and meteorological-related information sources are presented in Table C.32.

C.6.3 Overview of regional climatology

Offshore Atlantic Canada has very complex and unpredictable weather. The variable climate of the Canadian east coast is influenced by the warm Gulf Stream and the cold water of the Labrador Current. It is also influenced by seasonal changes in air masses, exchanges in energy between the atmosphere and the ocean, seasonal variations in sun radiation, the rugged coastal topography as well as the variability of the Icelandic Low and the Bermuda High, which locally control the Jet Stream and thus storm tracks.

The Icelandic Low is a large low-pressure system normally located near Iceland and southern Greenland. In mid-summer, when it is at its weakest, it can lie as far west as the Hudson Strait. It exerts a major influence on the tracks of lows passing through Atlantic Canada and fosters the strong, cold, north-westerly Arctic air flow across the region in winter and early spring.

The Bermuda High is a semi-permanent high-pressure zone with its mean centre lying east of Bermuda and southwest of the Azores. It can play a major role in the climate of eastern Canada in spring and summer, when it is most persistent. It causes air of tropical origin to penetrate the southern United States and move northward to become entrained in westerly winds. In general, this air can result in periods of warm humid air and heavy precipitation to Atlantic Canada.

High winds and storms are more common in eastern Canada during the winter months. Spring and summer months have fewer, less intense, storms, moderate winds, and precipitation that is usually in the form of fog, drizzle or rain showers. Hurricanes and tropical storms from the south can reach the region in the autumn. Air quality in the region is generally good, both onshore and offshore.

Eastern Canada can experience very cold winters which result in the seasonal occurrence of ice. Under predominantly north-westerly winds and southward branches of the Labrador Current, ice and icebergs move southwards along the Labrador coast. Ice is seasonally encountered offshore Newfoundland and Labrador in a variety of forms and concentrations (pack ice and icebergs). Icebergs of sufficient draft can make contact with the seafloor of the Grand Banks and create scours on the seabed. The maximum water depth at which scours are expected to occur is approximately 200 m. Icebergs are rare offshore Nova Scotia, but pack ice can be encountered and should be considered in the design of offshore facilities.

The Grand Banks area offshore Newfoundland is a harsh environment due to the possibility of intense storms and the potential for sea ice and icebergs. Superstructure icing can also occur between December and March because of the temperature, wind and wave conditions. Restricted visibility due to fog is common, especially in the spring and summer months, when warm air masses overlie the cold ocean surface. The worst visibility conditions are experienced in July. During the winter months, restricted visibility can also be caused by snow in addition to fog and mist.

Major seasonal mean current patterns that influence the regional climatology are shown in Figure C.18.

C.6.4 Water depths

Water depths in the region are generally less than 200 m, as shown in Figure C.17.

The water depths in the offshore Nova Scotia area range from 20 m to 80 m, whereas the waters of the Grand Banks installations are of the order of 80 m to 130 m deep.

There are also deep water locations offshore eastern Canada, such as the Flemish Pass and Orphan Basin offshore Newfoundland, and deep water locations off the Scotian shelf. Metocean parameters for these areas are not included in this edition of ISO 19901-1.

C.6.5 Winds

Extreme surface winds are mainly related to the passage of extratropical cyclones and their associated frontal structures. Large gradients in sea surface temperature in the region, together with the closeness of cold and warm continental air mass source zones, result in unstable boundary layer winds. Hence the strength of surface winds, relative to the pressure-gradient-driven, free-atmosphere flow, tends to be strongly modulated. The strongest surface winds tend to occur in unstable sectors of storms (air colder than sea). Maximum wind speeds, of the order of 25 m/s (1 h average at 10 m elevation), tend to be associated with smaller (than cyclone) scale features such as surface wind jet streaks which propagate rapidly within the broader air flows about each cyclone, within narrow frontal zones and near the cores of nascent explosively-developing cyclones. At even smaller scales, convectively produced squalls can occur during seasons and in areas where cold air overlies relatively warm waters.

C.6.6 Waves

The wind fields associated with extratropical and tropical cyclones excite a wide range of sea states depending on storm size, radius of curvature of the wind field, peak wind speeds, storm propagation speeds, intensity and speed of propagation of surface wind jet streaks, and proximity of land, which will limit fetch for appropriate wind directions. Water depth is an important parameter in the shallower development areas of the Scotian Shelf for all return periods relevant to offshore structures, while on the Grand Banks marginally shallow water can affect seas states in the most intense systems. Even relatively small-scale features, such as the small area of high winds in the right quadrant of a propagating tropical cyclone or cyclone undergoing transformation to extratropical stage, or a jet-stream propagating through a larger air stream, can generate enormous sea states if the propagation speed of the wind feature and its peak wind speed allow optimum resonance coupling (resonance) between the wind field and the surface waves. Extreme wave heights, with maximum individual waves up to 30 m, have been recorded in the region during previous severe storms (e.g. Hurricane Luis in 1995).

C.6.7 Currents

The Labrador Current is particularly important, playing a major role in the transport of colder water to the region. The regional current pattern is a function not only of this large current, but also of tides, encounters with ocean currents (like the warmer eddies and meanders of the Gulf Stream) and storm winds.

The Labrador Current is also responsible for the transport of icebergs from northern areas to offshore Newfoundland. Figure C.18 shows how the Labrador Current divides into an inshore branch and an offshore branch. The offshore branch of the Labrador Current is mainly responsible for the transport of icebergs to the Grand Banks.

C.6.8 Sea ice

Reference [98] provides an accepted description for sea ice and iceberg characterization and its definitions are used throughout this clause.

The regional sea ice regime starts in September with the growth of new ice in northwest Baffin Bay. Beginning in October, a combination of growth and predominantly southward drift, driven by the prevailing northerly winds and the strong, cold, Baffin Current, advances the ice southward. By December, the leading edge of the advancing ice pack lies off northern Labrador. In typical years, the ice edge reaches the northern tip of Newfoundland in early January and the northern Grand Banks in mid-February. The pack ice off Newfoundland generally reaches annual peak coverage in March but can remain at high levels through May. Loose (60 %) coverage of first year ice is the dominant ice form in areas off Newfoundland.

Most sea ice on the Nova Scotia shelf originates in the Gulf of St. Lawrence. It moves under the action of winds and southerly currents generally in a south to southeast direction. It is joined by locally grown sea ice that begins to form along Nova Scotia's coast typically in January, reaching maximum concentrations in February and March. The locally formed ice is mainly confined to inlets and bays, seldom reaching a thickness greater than 300 mm. The ice usually melts if carried out to sea by winds and currents. Depending on sea ice growth and wind conditions, it is possible that sea ice will extend further offshore Nova Scotia and impact the region of hydrocarbon production operations.

The 30-year frequency of sea ice offshore the Canadian East coast for the month of March is presented in Figure C.19[99].

The design or assessment of offshore structures located offshore Nova Scotia, Newfoundland and Labrador should consider the possibility of sea ice occurrence. Site-specific or project-specific studies to develop appropriate sea ice-related criteria shall be prepared. The criteria will change according to location and structural form. As a minimum, the criteria desired shall include information on sea ice occurrence, concentration, floe size and thickness, ice strength and temperature, floe speed and direction and ice type.

C.6.9 Icebergs

The principal origin of the icebergs that travel past the East Coast of Canada are the 100 tidewater glaciers of West Greenland. Between 10 000 and 15 000 icebergs are calved each year, primarily from 20 major glaciers between the Jacobshaven and Humboldt Glaciers. These glaciers account for 85 % of the icebergs that reach the Grand Banks. 10 % of the icebergs reaching the Grand Banks are from glaciers located on the East Coast of Greenland, while the remaining 5 % come from the ice shelves of Ellesmere Island. After calving, the icebergs move north with the West Greenland Current, then south with the Baffin and Labrador Currents, finally melting in the warmer waters of the southern Grand Banks and the Gulf Stream.

Icebergs seldom travel far enough south to reach the coast of Nova Scotia. Data on iceberg sightings for the Scotian Shelf is provided in Reference [100]. Due to the infrequency of sightings, it is not possible to calculate reliable statistics on occurrence, size and impact probabilities.

Between 1965 and 2004 the number of icebergs reaching the Grand Banks each year varied from a low of 0 in 1966 to a high of 2 202 in 1984, with the average of around 800 icebergs per year. Of these, only a small proportion require active iceberg management to reduce the probability of encounter with an offshore structure. The average iceberg distribution offshore Newfoundland is shown in Figure C.20.

Local winds and currents largely determine the movements of free-floating icebergs (i.e., ungrounded icebergs in open water or in low concentrations of sea ice). Iceberg speeds and drift directions on the Grand Banks are less than 35 km/day and 47 % are directed toward the southwest.

Icebergs are characterized according to their height, length and estimated mass. Iceberg physical and mechanical strength criteria are required for the design of offshore structures on the Grand Banks. As a minimum, site- and structure-specific criteria shall provide information on iceberg occurrence/frequency, speed and direction of travel and physical dimensions such as mass, draft, width, length and shape.

Additional information on the ice environment on the Grand Banks is provided in Reference [101].

C.6.10 Ice management

To ensure that wells and offshore structures are protected from potentially hazardous sea ice, appropriate precautionary ice management should include, as a minimum, early detection and reporting of ice, ice tracking, and ice deflection.

Detection of ice is typically accomplished through visual detection using aircraft surveillance, offshore support vessels and marine radar. Iceberg deflection techniques that have been used successfully on the Grand Banks include iceberg towing (using tow ropes or tow nets) and the use of water cannons or “propeller washing” to alter the course of a threatening iceberg.

A critical component of an ice management plan is an effective communications and information-sharing network to facilitate the exchange of information on vessels (location, status), icebergs (location, speed, trajectory), weather forecasts and other information, thereby allowing prompt decisions to be made.

C.6.11 Other environmental factors

C.6.11.1 Iceberg scour

Icebergs can drift into areas where their draft exceeds the water depth, resulting in contact with the seabed and sediment displacement. Sediment displacement is in the form of scours and/or pit features. Iceberg scours have occurred in various locations on the Grand Banks and have been mapped with side scan sonar. Reference [102] is a compilation of data from seabed surveys.

For a typical location on the Grand Banks, the following typical average scour parameters have been estimated:

— average scouring frequency: ~ 1×10^{-4} to 1×10^{-3} scours per square kilometre per year, depending on region;

— average scour length: ~ 650 m;

— average scour width: ~ 25 m.

The average depth of scour depends on the soil conditions. Stiff or compacted sediments can limit the scour depth. For a typical location on the Grand Banks, the average scour depth is about 0,3 m.

C.6.11.2 Snow accumulation and superstructure icing

Installations located offshore eastern Canada can be subject to snow accumulation and superstructure icing.

The extent to which snow can accumulate and its possible effect on the structure shall be considered in the design process. In the absence of specific information, new snow may be assumed to have a density of 100 kg/m^3.

Ice accretion can lead to increased weight and safety hazards (e.g. slippery ladders, inoperable winches, ice on radar antennas). Superstructure icing is the result of both freezing sea spray and atmospheric precipitation. Ice accretion generated by wave-structure interaction sea spray is the dominant source of ice accretion due to the intensity and frequency of the spraying events. The phenomenon is seasonal and its severity depends on the wind speed, air temperature and height above sea level. The design of offshore structures shall consider the possibility of superstructure icing and its overall effect on weight, structural integrity and stability. In the absence of other specific information, the ice that can form on the structure can be assumed to have a density of 900 kg/m^3.

C.6.11.3 Reduced visibility

Low visibility affecting helicopter operations is common off the Canadian east coast. Flying is affected when visibility is reduced by fog, snow and/or rain to less than 1 km. Low visibility occurs on the Grand Banks

— 40 % of the time from April to August, and

— 11 % of the time from September to March.

The, somewhat less, occurrence of low visibility in the Nova Scotia offshore area[97] is

— 23 % of the time from April to August, and

— 6 % of the time from September to March.

C.6.11.4 Marine growth

No specific data is available on the occurrence, type and height/length of marine growth off the Canadian east coast.

C.6.12 Estimates of extreme metocean parameters

Metocean parameters for offshore Newfoundland and Nova Scotia for a nominal water depth of approximately 100 m are provided in Tables C.29 to C.31. These values are indicative and are shown for illustration purposes only. Site-specific metocean parameters shall be obtained for the design or assessment of an offshore structure.

Offshore in the Nova Scotia area, site-specific conditions are highly variable, being dependent on location and the effect of blockage from Sable Island, especially on waves and currents. Site-specific studies are particularly important in shallow areas for an understanding of local wave refraction and current intensification.

Table C.29 — Extreme air and water temperatures

Offshore area	Newfoundland offshore (Grand Banks)	Nova Scotia offshore (Sable Island Bank)
Sea water temperature (°C)		
Min. extreme near surface	−1,7	−1,6
Max. near surface	15 to 19	15 to 20
Min. near bottom	−1,7	−1,3
Max. near bottom	3 to 6	18
Air temperature (°C)		
Minimum	−17 to −19	−14 to −19
Maximum	22 to 25	30 to 35

Table C.30 — Extreme metocean parameters for typical locations off Newfoundland

Metocean parameter	Return period years				
	1	**5** [b]	**10**	**50**	**100**
Wind speed (m/s) [a]					
10 min mean	25 to 31	29 to 33	33 to 34	36 to 39	37 to 41
3 s gust	34 to 39	38 to 42	42 to 45	48 to 52	50 to 55
Wave height (m)					
Maximum	19 to 21	22 to 23	24 to 26	26 to 29	28 to 31
Significant	10 to 11	11 to 12	12 to 13	14 to 15	14,5 to 16
Associated peak period (s)	12 to 17	13 to 18	14 to 18	15 to 20	15 to 20
Current speed (m/s)					
Surface	0,9 to 1,0	1,0 to 1,2	1,1 to 1,3	1,2 to 1,6	1,3 to 1,7
Mid-depth	0,5 to 0,9	0,6 to 1,0	0,7 to 1,0	0,8 to 1,1	0,9 to 1,1
Near-bottom	0,5 to 0,7	0,6 to 0,8	0,7 to 0,8	0,8 to 1,0	0,9 to 1,0
Storm surge above MSL (m)	0,50	0,46	0,61	—	0,70

[a] Based on a reference height of 10 m above sea level.

[b] Based on average of 1 year and 10 year data.

Table C.31 — Extreme metocean parameters for typical locations off Nova Scotia (Sable Island Bank)

Metocean parameter	Return period years				
	1	5 [b]	10	50	100
Wind speed (m/s) [a]					
10 min mean	25 to 30	30 to 34	35 to 38	40 to 43	41 to 45
3 s gust	34 to 37	39 to 43	45 to 48	50 to 55	50 to 58
Wave height (m)					
Max.	15 to 26	15 to 26	16 to 26	18 to 27	19 to 27
Significant	7 to 9	8 to 10	9 to 11	11 to 14	11 to 15
Associated peak period (s)	13 to 14	13 to 15	14 to 15	15 to 17	15 to 18
Current speed (m/s)					
Surface	1,0 to 1,4	1,2 to 1,8	1,3 to 2,1	1,4 to 2,3	1,5 to 2,3
Mid-depth	0,9 to 1,0	0,9 to 1,1	1,0 to 1,1	1,0 to 1,2	1,1 to 1,3
Near-bottom	0,9 to 1,0	0,8 to 1,0	0,7 to 1,0	0,7 to 1,1	0,8 to 1,1
Storm surge above MSL (m)	—	—	0,49	0,5 to 0,6	0,6 to 0,7

[a] Based on a reference height of 10 m above sea level.

[b] Based on average of 1 year and 10 year data.

C.6.13 Sources of additional information

Additional information can be obtained from the agencies listed in Table C.32.

Table C.32 — Source of additional information on conditions in Canadian waters

Required information	Data source	Contact details
Meteorological parameters such as the prediction of severe weather, sea state and icing conditions	Information Services Division, National Archives and Data Management Branch, Meteorological Service of Canada, Environment Canada 4905 Dufferin Street, Toronto Ontario M3H 5T4	Telephone: (416) 739-4328 Fax: (416) 739-4446 Email: Climate.Services@ec.gc.ca
Oceanographic information	Department of Fisheries and Oceans Canada, Marine Environmental Data Service 12W082-200 Kent Street, Ottawa Ontario K1A 0E6	Telephone: (613) 990-6065 Fax: (613) 993-4658 Email: services@meds-sdmm.dfo-mpo.gc.ca http://www.meds-sdmm.dfo-mpo.gc.ca/
	Department of Fisheries and Oceans Canada, Bedford Institute of Oceanography, Ocean Sciences Division P.O. Box 1006, Dartmouth Nova Scotia B2Y 4A2	Telephone: (902) 426-8478 Fax: (902) 426-5153 http://www.mar.dfo-mpo.gc.ca/science/ocean/home.html
	Department of Fisheries and Oceans, Institute of Ocean Sciences, Ocean Sciences and Productivity Division P.O. Box 6000, 9860 West Saanich Road, Sidney British Columbia V8L 4B2	Telephone: (250) 363-6378 Fax: (250) 363-6690
Water depths and tides	Department of Fisheries and Oceans, Canadian Hydrographic Service 615 Booth Street, Ottawa Ontario K1A 0E6	Telephone: (613) 995-5249 Fax: (613) 996-9053 http://www.charts.gc.ca/chs
Ice-related information	Environment Canada, Meteorological Service of Canada, Canadian Ice Service, Operations Division, Client Service Section 373 Sussex Drive, Block E-3 Ottawa Ontario K1A 0H3	Telephone: (613) 996-1550 Fax: (613) 947-9160
	National Research Council Canada, Canadian Hydraulics Centre, Building M-32, Montreal Road, Ottawa Ontario K1A 0R6	Telephone: (613) 993-9381 Fax: (613) 952-7679
East coast seabed conditions	Natural Resources Canada, Geological Survey of Canada (Atlantic), P.O. Box 1006, Dartmouth Nova Scotia B2Y 4A2	Telephone: (902) 426-2396 Fax: (902) 426-6186

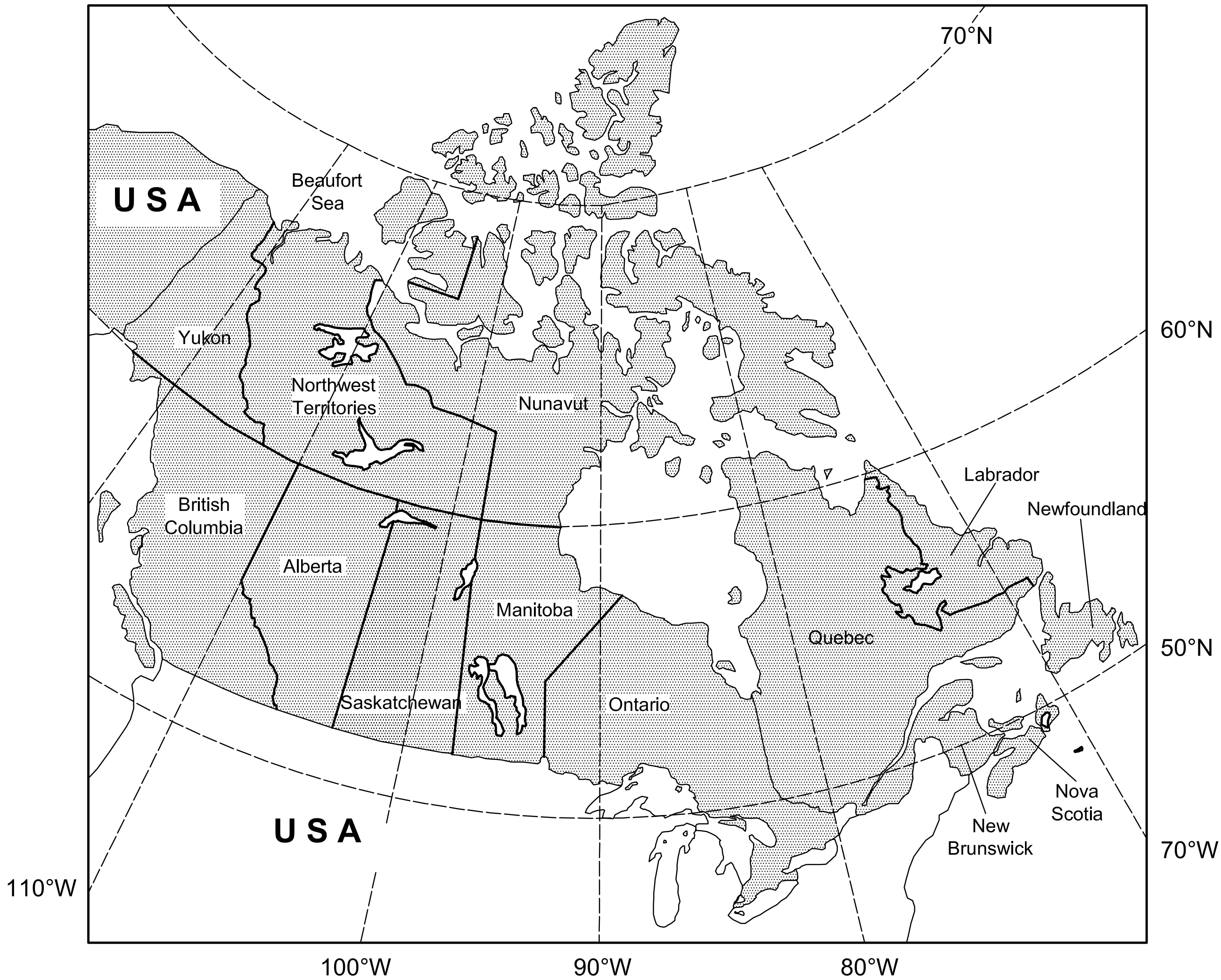


Figure C.16 — Map of Canada

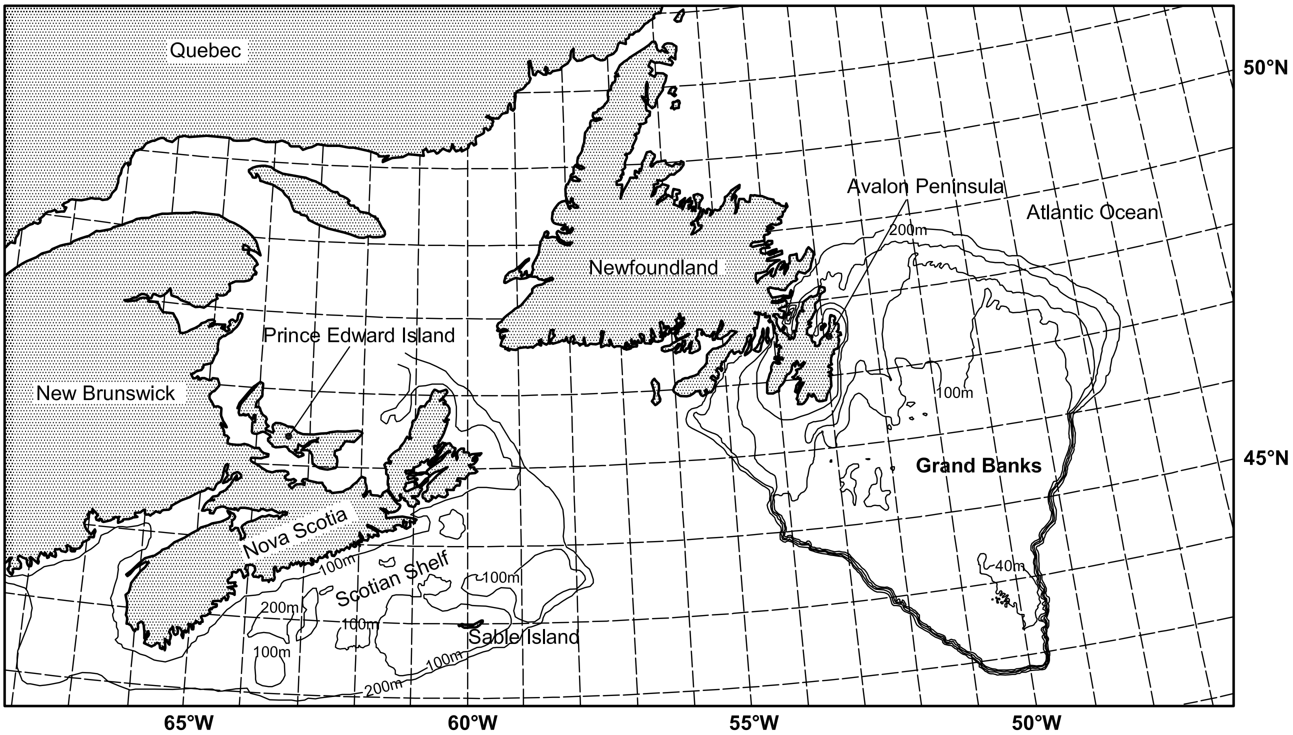


Figure C.17 — Current regions of oil and gas production operations — Canadian east coast — Near Sable Island offshore Nova Scotia and on Grand Banks offshore Newfoundland and Labrador

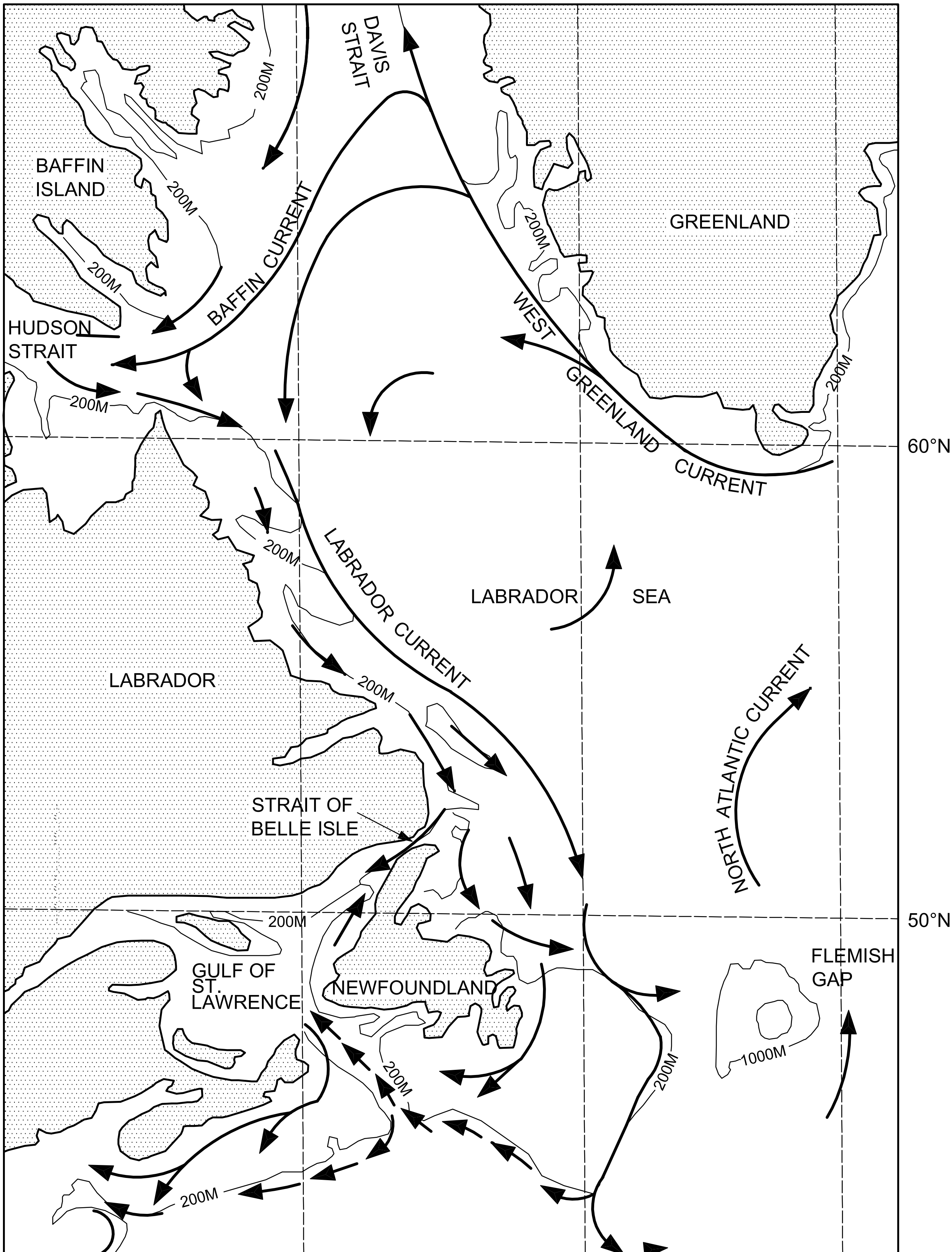


Figure C.18 — Canadian east coast ocean current regime

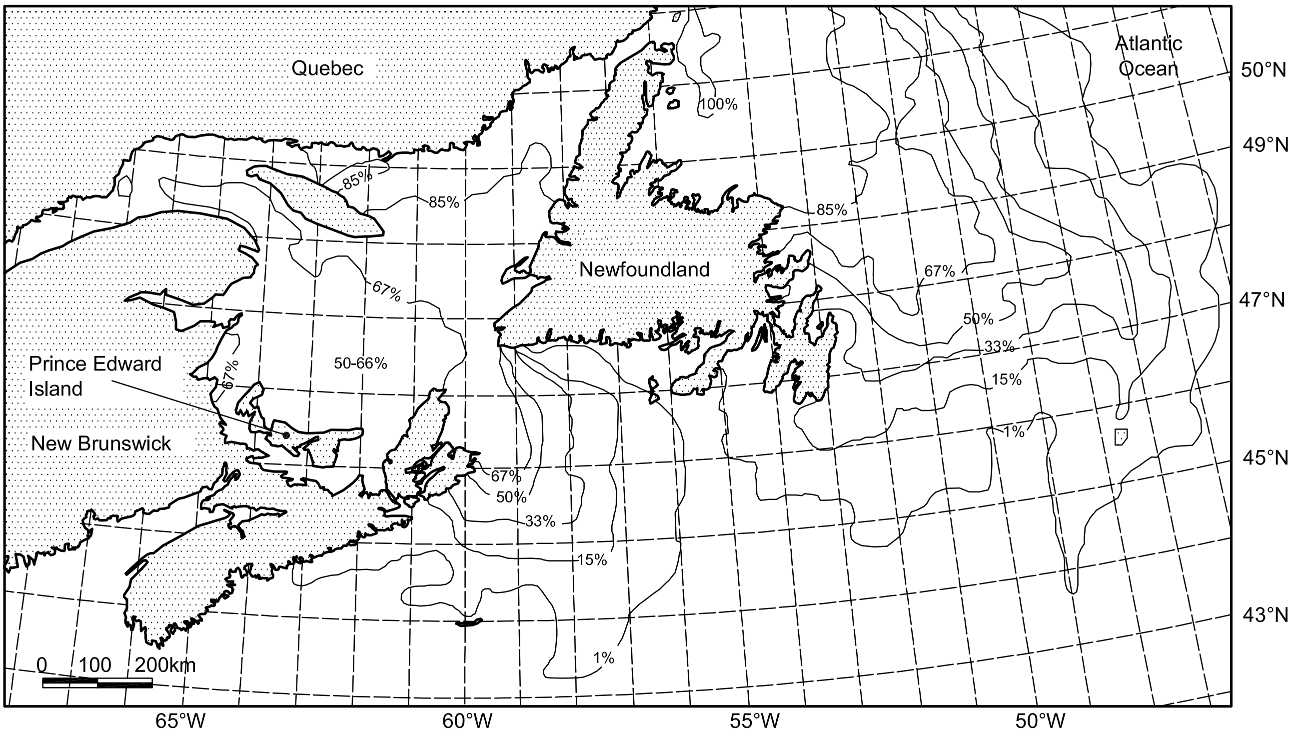
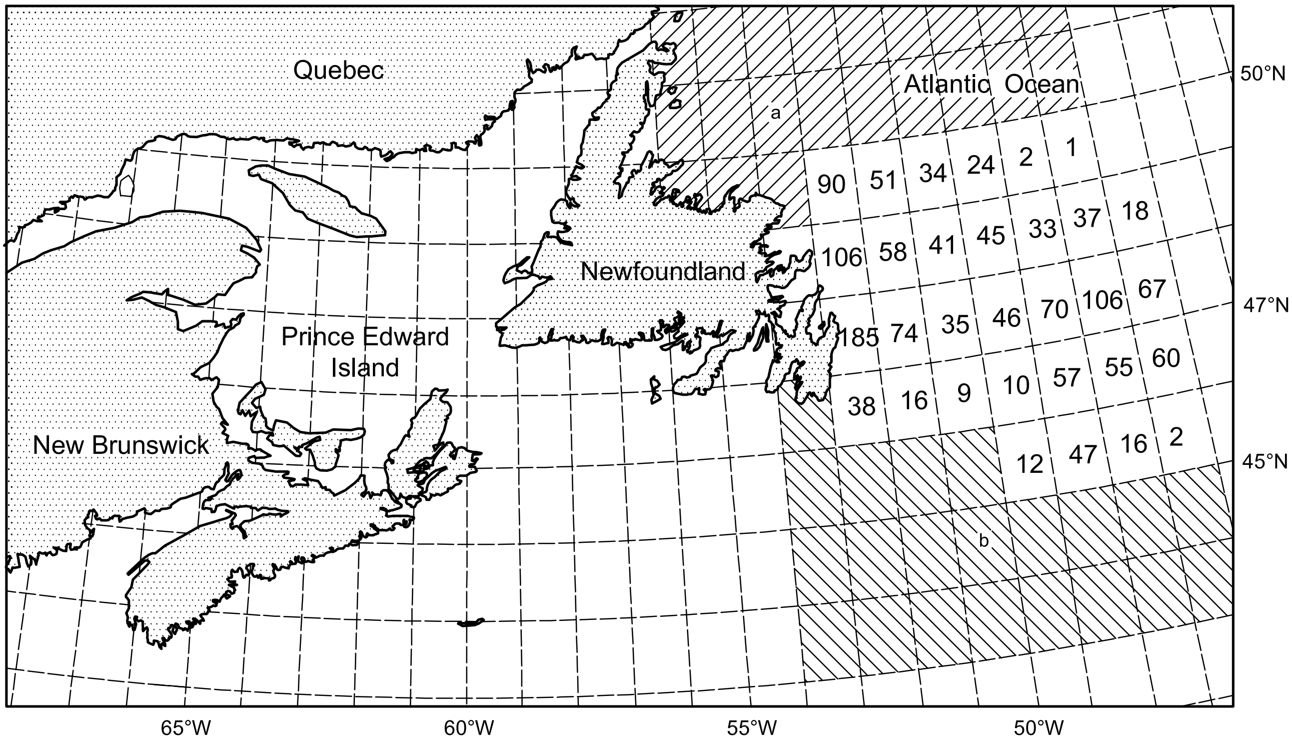


Figure C.19 — 30 year frequency of sea ice — Offshore Canadian east coast — Month of March (based on sea ice climatic atlas, East Coast of Canada, 1971 to 2000, Canadian Ice Service)



a Many icebergs present. Specific data not provided.

b Rare occurrences of icebergs in these waters.

Figure C.20 — Historical yearly mean iceberg distribution — Offshore Newfoundland (based on data from 1981 to 2003, Ice Season Report 2003)

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