STATEMENT OF GUIDANCE FOR OCEAN APPLICATIONS

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This Statement of Guidance (SoG) was developed, through a process of consultation, to document observational data requirements for ocean applications and the present/planned observing capabilities. This version is based on the JCOMM User Requirement Document, which was prepared by the Chairpersons of the Expert Teams within the JCOMM Services Programme Area. It is expected that the Statement will be reviewed at appropriate intervals by the JCOMM Services Programme Area Coordination Group to ensure that it remains consistent with the current state of the relevant science and technology. This document therefore presents an analysis of the gap between user requirements and the available/planned observation capabilities to address these requirements.

1. INTRODUCTION

Marine Meteorology and Oceanography occupy a global role, serving a wide range of users, from international shipping, fishing and other met-ocean activities on the high seas, to the various activities which take place in coastal and offshore areas and on the coast itself. In preparation of analyses, synopses, forecasts and warnings, knowledge is required of the present state of the atmosphere and ocean. The three major met-ocean application areas that critically depend on highly accurate observations of met-ocean parameters are: (a) Numerical Weather Prediction (NWP); (b) Seasonal to Inter-annual Forecasts (SIA), and (c) Met-Ocean Forecasts and Services (MOFS), including marine services and ocean mesoscale forecasting.

The key met-ocean variables to be observed and forecast in support of NWP and SIA are addressed in the Numerical Weather Prediction and the Seasonal to Inter-annual Forecast Statements of Guidance. This Statement of Guidance provides a brief discussion on how well the present and planned met-ocean observing systems meet the user requirements for MOFS, concentrating on those parameters not covered by previous sections of this document, such as waves, storm surges, sea-ice, ocean currents, etc. Variables such as precipitation, air temperature, humidity and cloud cover, also required for marine services, are addressed in the global and regional NWP SoG.

The requirements for MOFS stipulated here are based on a consensus of the met-ocean modelling and forecasting communities. This statement builds on the requirements for global and regional wave modelling and forecasting, marine meteorological services, including sea-ice, and ocean mesoscale forecasting, and represents in addition those variables that are known to be important for initialising, testing and validating models and assimilation, as well as for providing services.

2. GAP ANALYSIS: DATA REQUIREMENTS AND OBSERVING CAPABILITIES

The following terminology has been adhered to as much as possible:

- *poor* (minimum user requirements are not being met),
- *marginal* (minimum user requirements are being met),
- *acceptable* (greater than minimum but less than optimum requirements are being met), and

- *good* (near optimum requirements are being met).

2.1 Wind-Wave parameters (significant wave height, dominant wave period, Wave 1D energy frequency spectrum, and Wave direction energy frequency spectrum)

Global and regional wave models are used to produce short- and medium-range wave forecasts (typically up to 7 days) of the sea state, with a horizontal resolution of typically 30-100km for global models, and down to 3-4km for regional models (with a natural progression to higher resolution expected). Marine forecasters use wave model outputs as guidance to issue forecasts and warnings of important wave variables (such as, significant wave height and dominant wave period) for their area of responsibility and interest, in support of several marine operations. Specific users usually require additional parameters that are obtained from the directional spectrum of wave energy density.

The observational requirements for global and regional wave modelling depend on the applications for which the data are required and are based on the need to provide an accurate analysis of the sea state at regular intervals (typically every 6 hours). These requirements include: (a) assimilation into wave forecast models; (b) validation of wave forecast models; (c) calibration / validation of satellite wave sensors; (d) ocean wave climate and its variability on seasonal to decadal time scales, and (e) role of waves in coupling. Additionally, wave observations are required for nowcasting (0 to 2 hours) and issuing / cancelling warnings, very-short-range forecasting (up to 12 hours) of extreme waves associated with extra-tropical and tropical storms, and freak waves (in this case, in combination with other variables such as ocean currents). Whilst nowcasting is largely based on observational data, very-short range forecasts are being generated using high-resolution regional wave models.

The key model variables for which observations are needed are: (i) significant wave height; (ii) dominant wave period; (iii) Wave 1-D energy frequency spectrum; (iv) Wave directional energy frequency spectrum, and (v) 2-D frequency-direction spectral wave energy density. Also important are collocated surface wind observations, which are advantageous for validation activities. Further additional parameters are of value for use in delayed mode validation (e.g. full time series of sea surface elevation).

The geographical coverage of *in situ* wave data is still very limited and most measurements are taken in the Northern Hemisphere (mainly off the North American and Western European coasts). The majority of these data are provided by *in situ* non-spectral and spectral buoys and ships with *acceptable* frequency and *marginal* accuracy. A limited number of *in situ* spectral buoys is available around the globe. Current *in situ* reports are not standardized resulting in impaired utility. Differences in measured waves from different platforms, sensors, processing and moorings have been identified. In particular, a systematic 10% bias has been noted between US and Canadian buoys, the two largest moored buoy networks. Standardized measurements and metadata are essential to ensure consistency between different platforms.

In situ measurements are currently too sparse in the open ocean (*poor* coverage) to be of particular value, but could potentially provide higher accuracy observations to complement and correct for biases in satellite products. For dominant wave period and significant wave height, the requirement for horizontal spacing for real-time validation and assimilation, as well as maritime safety services, ranges from

20km for regional to 60km for global models, with a minimum accuracy of 1 second and 0.25m respectively. The equivalent requirement for wave 1D energy frequency spectrum and wave direction energy frequency spectrum ranges from 100km for regional to 300km for global models with a minimum accuracy of $0.2m^2Hz^{-1}$ and $0.2m^2Hz^{-1}rad^{-1}$ respectively. The required observation cycle is 24 hours.

Satellite altimeters provide information on significant wave height with global coverage and *good* accuracy. However, horizontal/temporal coverage is *marginal*. A minimum of 20km and 60km resolution is required for use in regional and global wave models respectively. Along track spacing is likely to be adequate to meet this requirement; cross-track spacing is not. Multiple altimeters are therefore required to provide adequate cross-track sampling. Fast delivery (within 6 hours at most) is required with accuracy of 10% / 25cm for wave height, and 1 second for wave period. Long-term, stable time series of repeat observations are required for climate applications.

Information on the 2-D frequency-direction spectral wave energy density is provided by SAR instruments with *good* accuracy but *marginal* horizontal/temporal resolution. Horizontal resolution of 100km is required for use in regional models, with fast delivery required (within 6 hours). Real aperture radar capability is expected to be available within 5 years.

Coastal wave models require different observing methods to those used for the open ocean, due not only to their high resolution, but also due to limitations of the satellite data close to land. Hence for these models systems such as coastal HF radar are of particular importance. These radars provide information on significant wave height with limited coverage, *good* accuracy and *acceptable* horizontal/temporal resolution. High-resolution observations (up to 100m resolution) are required over coastal model areas.

Potential contribution from other technologies and platforms (e.g. navigation radar, other radars and shipborne sensors such as WAVEX) should be developed where they can contribute to meeting the specified requirements.

2.2 Sea Level

Traditionally, permanent sea level stations around the world have been primarily devoted to tide and mean sea level applications, neither requiring real or near-real time delivery. This has been the main objective of the Global Sea Level Observing System (GLOSS). Because of this focus, not only are wind-waves filtered out from the records by mechanical or mathematical procedures, but any oscillation between wind-waves and tides (e.g. seiches, tsunamis, storm surges, etc.) has not been considered a priority. In fact, these phenomena are not properly monitored (standard sampling time of more than 5 to 6 minutes). The main component of GLOSS is the 'Global Core Network' (GCN) of 289 sea level stations around the world for long term climate change and oceanographic sea level monitoring. Due to the increased demand for tsunami, storm surge and coastal flooding forecasting and warning systems, for assimilation of in situ sea level data into ocean circulation models, and for calibration/validation of the satellite altimeter and models, this part of the spectrum needs to be covered from now on, and should be considered when choosing a new instrument and in the design of in situ sea level stations. Additionally, there has been an emphasis on making as many GLOSS gauges as possible deliver data in real and/or near-real time, i.e., typically within an hour. An ongoing issue with these data is that sea level measurements have not been well integrated into National Meteorological and Hydrographic Services (NMHSs).

The aim of any tide gauge recording should be to operate a gauge which is accurate to better than 1cm at all times; i.e., in all conditions of tide, waves, currents, weather, etc. This requires dedicated attention to gauge maintenance and data quality control. In brief, the major requirements for *in situ* sea level stations are:

- For storm surge and tsunami forecasting a spacing of 10km is required, while for climate modelling 50km spacing will meet the threshold. This will therefore require a denser network than is available today.

- A sampling of sea level, averaged over a period long enough to avoid aliasing from waves, at intervals of typically 6 seconds or less if the instrument is to be used also for tsunami, storm surges and coastal flooding forecasting and warning.

- Gauge timing be compatible with level accuracy, which means a timing accuracy better than one minute (and in practice, to seconds or better with electronic gauges) – *marginal* accuracy.

- Measurements must be made relative to a fixed and permanent local tide gauge bench mark (TGBM). This should be connected to a number of auxiliary marks to guard against its movement or destruction. Connections between the TGBM and the gauge zero should be made to an accuracy of a few millimetres at regular intervals (e.g. annually) – *acceptable* accuracy.

- GLOSS gauges to be used for studies of long term trends, ocean circulation and satellite altimeter calibration/validation need to be equipped with GPS receivers (and monitored possible by other geodetic techniques) located as close to the gauge as possible;

- The readings of individual sea levels should be made with a target accuracy of 10mm – *acceptable* accuracy;

- Gauge sites should, if possible, be equipped for recording tsunami and storm surge signals, implying that the site be equipped with a pressure sensor capable of 15-seconds or 1-minute sampling frequency, and possibly for recording wave conditions, implying 1-second sampling frequency – *poor* accuracy; and,

- Gauge sites should also be equipped for automatic data transmission to data centres by means of satellite, Internet, etc., in addition to recording data locally on site.

Coastal sea level tide gauges are invaluable for refining tsunami warnings, but due to nearshore bathymetry, sheltering, and other localized conditions, they do not necessarily always provide a good estimate of the characteristics of a tsunami. Additionally, the first tide gauges to receive the brunt of a tsunami wave do so without advance verification that a tsunami is under way. In order to improve the capability for the early detection and real-time reporting of tsunamis in the open ocean, some countries have begun deployment of tsunameter buoys in the Pacific, Indian, and Atlantic Oceans and other tsunami-prone basins. Due to cost constraints, the number of DART buoys deployed and maintained is still limited – *marginal* geographic coverage and *good* accuracy.

The geographic coverage of the *in situ* sea level data is therefore *poor* for both studies of long-term trends and for forecasting storm surges and tsunamis. Basins prone to tsunamis and storm surges (e.g. Bay of Bengal, Gulf of Mexico and Pacific Islands) require a higher density of sea level observations. Sea level measurements should be accompanied by observations of atmospheric pressure, and if possible, winds and other environmental parameters, which are of direct relevance to the sea level data analysis.

Satellite altimeters provide information on sea surface height with global coverage and *good* accuracy, i.e. within 1cm over basin scales. However, horizontal/temporal coverage is *marginal*. The main limitation of the satellite altimeter in reproducing the non-long-term sea level changes is the spatial sampling: the repeat orbit cycle leads to an across-track spacing of about 300km at mid-latitudes. This sampling cannot resolve all spatial scales of mesoscale and coastal signals which have typical wavelengths of less than 100km at mid-latitude. The scales are even shorter at high latitudes (around 50km), but fortunately the ground track separation decreases with latitude. Thus, to cover the whole mesoscale and coastal domain it is necessary to increase the spatial sampling by merging (in an optimal way with cross-calibration) different altimetry data sets. The temporal changes in sea level are usually determined along the repeat tracks of altimetry satellites. In areas close to the coasts (less than 20km offshore) the difficulty is even larger because of the proximity of land, for which the track spacing is too coarse to resolve the short scales of the sea level changes. Thus, adaptive trackers and/or specific re-tracking of altimeter waveforms and near-shore geophysical corrections (such as coastal tide models and marine boundary layer tropospheric corrections) are needed.

2.3 Sea Surface Height Anomalies (SSHA or Sea Level Anomalies)

SSHA is a derived observation product used by all operational ocean forecasting systems. The observation products are processed by the space agencies and distributed to the forecasting centres. SSHA therefore not only involves the direct observation of the ocean topography, but also the accurate estimation of the reference mean dynamic topography, the ocean tides, sea state bias and several other atmospheric and solid earth corrections.

SSHA provides an estimate of the integrated distribution of mass within the ocean (the analogue of sea level pressure for the atmosphere) and therefore provides information of the specific volume anomalies of the water column. Combined with a data assimilation scheme to define the covariability of the temperature and salinity with SSHA, observations of SSHA have the greatest impact on ocean forecasting from the current observing system. Gradients in SSHA (or pressure) drive ocean circulation on spatial scales ranging from sub-mesoscale to gyre scale and temporal scales of hours through decades. The impact of SSHA includes nowcasting and forecasting the currents and salinity and forecasting the temperature for the upper ocean. In this case the depth scale of the upper ocean is defined by the covariability of temperature and salinity with SSHA, and varies in space and time. We also note that the nowcasting of temperature of the mixed layer is well served by remotely sensed sea surface temperature that observes the foundation temperature.

Improvements to altimetry, the cal/val process, the determination of correction terms and the verification of data assimilation statistical models will have a direct impact for ocean forecasting in the near term. The greatest improvements however will come from improvements in temporal and spatial resolution, each of which has to be traded-off against the other for any given satellite. Better temporal resolution (which comes at the cost of poorer spatial resolution) allows rapidly changing features (e.g. near fronts or major ocean currents) to be observed adequately: better spatial resolution (which comes at the cost of poorer temporal resolution) allows mesoscale features (e.g. eddies) to be resolved.

The present altimeter constellation consists of three main satellites. Two satellites, Jason-1 and Jason-2, fly in formation, allowing the same spot on the ocean to be observed relatively frequently (every 5 days) but with relatively widely-spaced ground tracks (315km at the equator). Envisat has a longer repeat cycle (currently 30 days), but tighter ground track spacing (90km at the equator).

SSHA has been observed through a series of narrow swath instruments since 1992 (TOPEX-Poseidon, Jason-1, Jason-2, ERS, ERSII, Envisat, Geosat and GFO-1). Throughout this period, as many as four altimeters have been operational, with demonstrable improvements in higher spatial and temporal coverage. It is now commonly accepted that a minimum of two interleaved operational satellites is required to support ocean forecasting applications.

The timescale for scheduling satellite missions and the competition for budgets has threatened the continuity of altimetry over the past decade and into the future. Securing continuity of satellite altimetry is critical to national service providers delivering the reliable, quality ocean services that are required to generate the full spectrum of applications. Full integration of forecasts of SST and surface currents for NWP and wave forecasting cannot be realised until ocean prediction systems achieve homogeneous skilful performance. The future progression toward fully coupled ocean-wave-NWP systems for short-range prediction will similarly require high reliability and quality from the ocean observing system. SSHA is currently considered the most critical component of this observing system for ocean prediction systems.

SSHA is used in ocean models to provide adjustments to the sub-surface density structure of the ocean. It is also critical that a global *in situ* profiling system (e.g. Argo) be maintained to calibrate/validate these projections and further constrain the deep ocean through assimilation of density profiles. SSHA observations can also be exploited in the coastal regions. However the spatial and temporal requirements in the coastal zone place greater demands on the observing system. Wider-swath observations would add significant value in this zone as well as in the open ocean. Enhancing existing coastal tide gauges networks will also add significant value to ocean prediction systems in the shelf zone.

2.4 Sea-Ice parameters (thickness, coverage/concentration, type/form, movement)

Sea-ice charts containing information of sea-ice thickness, coverage/concentration, type/form and movement are produced in support of marine operations, validation of models and for climatological studies.

Although broad knowledge of the extent of sea-ice cover has been totally revolutionized by satellite imagery, observations from shore stations, ships and aircraft are still of great importance in establishing the “ground truth” of satellite observations. At present, observations of floating ice depend on instrumental and, to a lesser extent, on visual observations. The instrumental observations are made by conventional aircraft and coastal radar, visible and infra-red airborne and satellite imagery, and by more recent techniques, such as passive microwave sensors, laser airborne profilometers, scatterometers, side-looking (airborne) radar (SLAR / SLR) or synthetic aperture radar (SAR, satellite or airborne).

Visual observations from coastal settlements, lighthouses and ships can provide an ice report several times a day as the ice changes in response to wind and ocean currents, but the total area of ice being reported is very small (e.g., from a ship, observations can cover a radius of only 7-8km; from a coastal lighthouse, observations can cover a radius of up to 20km). In some marine areas, such as the Baltic Sea, visual observations may be present in sufficient numbers that a reasonable proportion of the ice cover can be reported each day by a surface network. In others such as the Gulf of St Lawrence, where the waterways are broad and the shores often unsettled, no shore reporting system can provide data on more than a very small percentage of the total ice cover. Although surface based reports can provide excellent detail about the ice, especially its thickness, it is generally recognized that for most areas, the surface reports are not really adequate to describe ice conditions fully.

Surface reports from shore stations, ships and drifting buoys provide accurate information on ice amount, thickness, movement and its deformation over rather small areas. When many vessels and fixed observing points are available accurate information can be provided in restricted waterways. Many areas of the Kattegat and Baltic Sea coastline fall into this category.

Reports about ice coverage taken from the air, i.e., helicopters and fixed-wing aircraft, have the advantage of a much better coverage, the platform’s flying speed allowing a great deal more of the sea-ice to be reported and problems of remoteness from airports or other suitable landing sites being overcome by using long-range aircraft. In the various stages of development of sea-ice, estimates of its amount; notes on its deformation and snow cover or stage of decay data are provided by visual estimation. Comprehensive aerial reporting has its own particular requirements beginning with an accurate navigational system when out of sight of land. Inclement weather – fog, precipitation and low cloud – will restrict or interrupt the observations and the usual problems of flying restrictions at the aircraft base may also be a factor even if the weather over the ice is adequate for observing.

Recent advances in technology are now permitting more accurate data to be obtained by aerial observations. SLAR and SAR can provide information which documents precisely the distribution and nature of the ice in one or two belts along the flight path of the aircraft for distances of up to 100km on each side. Unlike most other sensors, the radar has the capability of monitoring the ice under nearly all weather conditions.

When no fog or low clouds are present a laser airborne profilometer can be used to measure the height and frequency of ridges on the ice, and under similar conditions an infra-red airborne scanning system can provide excellent information with regard to floe thickness in the range below 30cm.

The advent of polar-orbiting meteorological satellites has added a third, and now the most important and predominant mode of observing sea ice, but again there are some restrictions. The spectral range of the sensors may be visible, infra-red, passive or active microwave or a combination of these. Satellite coverage may be broad at low resolution or cover a narrow swath at high-resolution. In the latter case, data from a particular location may be obtained only at intervals of several days.

In general, most meteorological satellites make 10–12 passes daily in the polar regions, i.e., complete broad-swath coverage once or twice a day. These satellites provide visible and infra-red imagery with resolutions of 250m–1km; and passive microwave and scatterometer data at coarser resolutions of 6–70km, i.e. *good* spatial/temporal coverage.

Visible and infra-red sensors do not have cloud-penetrating capability, while microwave data are practically cloud independent. Active microwave SAR data are characterized by improved ground resolution (approximately 10–100m) but a reduced coverage due to narrow swaths and greater revisit time between exact repeat orbits. Snow cover on the ice and puddles on the floes are other complicating factors. Interpretation of SAR images may be even more difficult due to the ambiguities associated with SAR backscatter from sea-ice features that vary by season and geographic region.

Space-borne sensors, especially radars, can provide precise data on the location and type of ice boundary, concentration and the presence or absence of leads, including their characteristics. Less accurate information can be extracted on the stages of development of the sea ice (including the First-Year/Multi-Year ratio) and its surface morphology. Flow motion over approximately 12–24-hour intervals can often be determined through the use of imagery from sequential orbits.

2.5 Sea-Surface Temperature (SST)

High-resolution sea-surface temperature (SST) observations are required for: (i) NWP (addressed in the global and regional NWP SoGs); (ii) Seasonal to Inter-annual Forecast (addressed in the SIA SoG); (iii) ocean forecasting systems (assimilation in and validation of ocean models); climate modelling; and, (iv) marine services.

Coastal and inland seas users are defined as those using SST data products for regional ocean modelling and marine services. SST in the coastal and inland regions has a large variability due to the diurnal cycle of solar radiation, which creates significant changes to the surface characteristics of the land and sea and forces land-air-sea interactions, i.e., land-sea breezes. Typically, this user group has a requirement for ultra-high resolution SST data sets (1km spatial resolution and <6 hours temporal resolution), with good accuracy (< 0.1K) and temporal coverage (hourly).

Ships and moored and drifting buoys provide observations of SST of good temporal frequency and acceptable accuracy as long as required metadata are provided. For example, the depth of the measurement is essential for deriving the diurnal cycle and the foundation temperature. Coverage is marginal or poor over some areas of the global ocean. The goal for high quality SST in the open ocean is ideally 5km spatial scale with accuracy 0.5K, and fast delivery (availability within 1 hour). In coastal regions, the goal is 1km with a delivery delay of 1 hour (accuracy 1K on 10km spatial scale).

Drifting buoy and other in situ SST measurements are used for calibration/validation of satellite data, in the error estimation for observations products and in combined analysis products. They are critically important in providing bias correction of these data. Satellite biases can occur from orbit changes, satellite instrument changes and changes in physical assumptions regarding the physics of the atmosphere (e.g. through the addition of volcanic aerosols). Thus, drifting buoy and other in situ data are needed to correct for any of these changes.

Satellite measurements provide high-resolution SST data. Both infra-red and microwave satellite data are important. Microwave data have a significant coverage advantage over infra-red data because microwave data can be retrieved in cloud-covered regions while infra-red cannot. However, microwave SST is at a much lower spatial resolution and higher uncertainty than infra-red. In addition microwave SST cannot be obtained within roughly 50km of land. A combination of both infra-red and microwave data is needed because each has different coverage and error properties.

Instruments on polar-orbiting satellites provide global coverage in principle, good horizontal and temporal resolution and acceptable accuracies (once they are bias-corrected using in situ data), except in areas that are persistently cloud-covered, which includes significant areas of the tropics. High-resolution SST (1km) can be retrieved by polar-orbiting infra-red radiometers and rather degraded resolution SST (5km) from radiometers on board geostationary satellites. In addition, microwave radiometers cannot be used for coastal applications because of (a) rather coarse spatial resolution and (b) contamination by land signals.

2.6 Sea-Surface Salinity (SSS)

We note that the standard units for salinity have recently been changed following TEOS10 (http://www.teos-10.org/), which was adopted by the Intergovernmental Oceanographic Commission at its 25th assembly in June 2009. Practical Salinity Units (PSU) have been replaced by the SI unit Absolute Salinity SA, (g/kg).

High resolution and high quality Sea-Surface Salinity (SSS) observations are required for ocean forecasting systems (assimilation in and validation of ocean models).

The remote sensing instrumentation remains experimental and the full impact of these observations is yet to be determined. Nonetheless, there is a requirement to constrain this state variable at the surface where the variability is greatest and the mass fluxes are known to have large errors.

Coastal and inland sea users are defined (as per SST above) as those using SSS data products for regional ocean modelling and marine services. SSS in the coastal and inland regions have a larger variability due to coastal systems (e.g. upwelling/downwelling processes) and river discharge as well as enhanced evaporation in regions shallower than the optical depth or with weak circulation. Typically, this user group has a requirement for higher resolution SSS data sets (1km-5km spatial resolution and <6 hours temporal resolution), with good accuracy (< 0.1-0.7SA) and temporal coverage (hourly). The spatial scales of variability in the open ocean are dominated by the mesoscale with a resolution of 10-25km and temporal resolution of 12-24 hours. The accuracy range represents thresholds of accuracy that will impact an analysis and depend on the region of the ocean being observed.

As long as the required metadata are provided (e.g. the depth of the measurement is important for deriving the freshwater lens effects), ship and moored and other in situ observations of sea-surface SSS are of good temporal frequency and acceptable accuracy. Coverage is marginal or poor over some areas of the ocean globe. There is a requirement for high quality SSS in the open ocean, ideally with accuracy < 0.1SA on a 10km spatial scale, and fast delivery (availability within 1hour). In coastal regions, higher density is required (accuracy < 0.1 SA on a 1km spatial scale).

2.7 Sub-surface Temperature, Salinity and Density

Sub-surface temperature, salinity and density observations are required for: (i) Seasonal to Inter-annual Forecasts (SIA) (addressed in the SIA SoG); (ii) testing and validation of ocean forecasting models, and (iii) marine services/modelling.

The Tropical Atmosphere Ocean (TAO) / TRITON moored buoy network provides data with *good* frequency and accuracy, and *acceptable* spatial resolution for the tropical Pacific. The TAO Tropical Moored Buoy Arrays provide data of *marginal* vertical resolution for marine services applications (~50m down to 500m), which require high vertical resolution data in the mixed layer. The tropical moored network in the Atlantic (PIRATA) is *acceptable*. The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) is being developed but is providing only *marginal* sampling at the moment. Sustained funding for the Tropical Moored Buoy Arrays remains a matter of concern.

Ships (XBT profiles) provide temperature profile data of *acceptable* spatial resolution over many of the targeted frequently repeated and high [horizontal resolution] density lines. However, sampling of about half of the targeted lines remains *poor*. Temporal resolution is generally *marginal*, but *acceptable* in some ship-specific lines. XBTs provide data with *good* vertical resolution (typically 1m) down to 1000m depth in delayed mode, but real-time data are constrained by limitations in the traditional GTS character codes being used at the moment.

Argo profiling floats provide near-global coverage of temperature and salinity profiles to ~2000m, mostly with *acceptable* to *good* vertical (every ~5m) and spatial resolutions, but only *marginal temporal* resolution, particularly for marine services. The accuracy is *acceptable* for assimilation by ocean models and for marine services.

The existing sampling is *adequate* for ocean prediction in regions of large spatial and temporal scales. However, there are many important regions where the spatial and temporal scales are shorter and the present sampling pattern is *poor*. Targeted deployments into these regions together with adaptive cycling patterns might be considered.

2.8 Ocean chlorophyll, nitrate, silicate and phosphate concentration

Ocean chlorophyll concentration observations are required for marine services applications and for validation of ocean models. Ocean chlorophyll concentration with high-spatial resolution (250m to 1km) can be deduced from remote sensing images of biological and non-biological parameters. Ocean chlorophyll concentration data can indicate several types of marine environmental problems, e.g. environmental pollution, marine eutrophication, harmful algal blooms and the level of primary productivity. Parameter retrieval algorithms in turbid waters are not yet established, but developments of an observation system based on remotely sensed ocean chlorophyll concentration have presented promising results for a future operational observing system. *In-situ* measurements are needed to complement satellite ocean chlorophyll concentration observations. These measurements should be accompanied by real-time daily observations of ocean temperature, surface wind and nutrients (i.e. phosphate, nitrate, nitrite, ammonium, silicate).

Nitrate concentration observations are required for parameterization and validation of marine ecological models. From surface to bottom waters, ocean nitrate concentration can be measured by *in-situ* observation or common chemical test in laboratory. Moored buoys and automatic online water quality analyzers are available for *in-situ* observation. For oligotrophic ocean, nitrate concentration can only be obtained by chemical test in laboratory. Nitrate concentration data are helpful to evaluate environmental pollution, marine eutrophication, N cycle, plant growth and the state of dissolved oxygen.

Silicate concentration observations are required for parameterization and validation of marine ecological models. Ocean silicate concentration can be measured by *in-situ* observation or common chemical test in laboratory. Moored buoys and automatic online water quality analyzers are available for *in-situ* observation. Silicate is necessary for the growth of diatoms to absorb Opal (Opal, $SiO_2 \cdot 2H_2O$) to constitute cells' shells. After debris of diatoms settling down to the bottom, silicate becomes a major component of deep-sea sediments. Nitrate concentration data can indicate the growth of diatoms and the silicon state in the sediment.

Phosphate concentration observations are required for parameterization and validation of marine ecological models. Phosphorus is an essential nutrient utilized by phytoplankton for energy transport and growth and phosphate availability can be an important factor influencing phytoplankton species composition and abundance. Phosphate may be the sole source of phosphorus directly absorbed by phytoplankton. From surface to bottom waters, ocean phosphate concentration can be measured by *in-situ* observation or common chemical test in laboratory. Moored buoys and automatic online water quality analyzers are available for *in-situ* observation. For oligotrophic ocean, phosphate concentration can only be obtained by chemical test in laboratory. Phosphate concentration data are helpful to evaluate environmental pollution, marine eutrophication, P cycle and the primary productivity.

Ocean chlorophyll, nitrate, silicate and phosphate concentration are required for validation of ocean ecological forecasting models.

Satellite measurements provide high-resolution chlorophyll data. There is a requirement to constrain this state variable at the surface where the variability is greatest. The accuracy in the open sea is *acceptable* for assimilation by ocean ecosystem models and for marine services. However, the chlorophyll data along the coastal region is poor and need be constrained by the *in-situ* data.

Ships provide chlorophyll, nitrate, silicate and phosphate concentration data of *poor* spatial-temporal resolution over many regions. These products are *poor* in terms of timeliness required for marine services applications.

2.9 3-D Ocean Currents

Observations of 3-D ocean currents are required for marine services applications, and for testing and validation of ocean models.

Inferred surface currents from drifting buoys are *acceptable* in terms of spatial coverage and accuracy and are *marginal* in terms of temporal resolution. Targeting deployments of drifting buoys into regions of high variability such as boundary currents and downstream geostrophic turbulence would help enhance their impact on ocean prediction systems. Moored buoys are *good* in temporal resolution and accuracy, but *marginal* or *poor* otherwise. The Acoustic Doppler Current Profiler (ADCP) provides observations of ocean currents over a range of depths, with *acceptable* accuracy. Coverage is *marginal* or *poor* over most areas of the ocean globe, with *marginal* vertical resolution for marine services applications, which require high vertical resolution data in the mixed layer.

Satellite altimetry is being used to infer the distribution of ocean currents (geostrophic velocity). Satellite altimetry provides more homogeneous space and time coverage than *in situ* observations, permits to derive the ageostrophic motion (e.g. centrifugal, Ekman, ageostrophic submesoscale) and the time-mean motion. Satellite altimetry also permits to detect geostrophic eddies. Global mean dynamic topography can be obtained by combining information on the geoid, altimeters, drifters, wind field, and hydrography. These products are *poor* in terms of timeliness required for marine services applications. HF Radars provide for *good* temporal and spatial resolution in coastal regions, with *marginal* accuracy.

2.10 Bathymetry, Coastal Topography and Shorelines

Observations of bathymetry, coastal topography and shorelines are required for ocean and coastal modelling. Very high resolution data are required due to the gradual changes of the coastline through erosion and accretion processes relating to coastal meteorological and oceanographic phenomena (e.g. waves, storm surges and sea ice). Visible and infrared imagers (i.e. Landsat, SPOT), synthetic aperture radar (SAR) and aerial photography provide good information on the coastline and coastal topography.

Many sonar techniques have been developed for bathymetry. Satellite altimeters also map deep-sea topography by detecting the subtle variations in sea level caused by the gravitational pull of undersea mountains, ridges, and other masses. These provide global coverage and *acceptable* to *good* accuracy.

2.11 Surface Wind Vector over the Ocean and Coastal Areas

High-resolution surface wind vectors over the ocean and coastal areas are required as an input field to ocean models (including wave models) for marine services, marine modelling and atmospheric modelling. The surface wind-field is a key variable for driving ocean models and to nowcast and forecast marine meteorological and oceanographic conditions. It is strongly influenced by the coastal topography and land-sea surface conditions. Traditional global and regional NWP products do not have adequate spatial resolution for marine services applications, as well as for coastal modelling.

Voluntary Observing Ships (VOS) and meteorological and oceanographic moored buoys provide observations of *acceptable* frequency and accuracy. Coverage is *marginal* or *poor* over large areas of the ocean globe. The tropical moored buoy network has been a key contributor to surface wind measurements over the last decade, particularly for monitoring and verification, providing both *good* coverage and accuracy in the equatorial Pacific. Fixed and drifting buoys and VOS outside the tropical Pacific provide observations of *marginal* coverage and frequency; accuracy is *acceptable*. Wind observations from drifting buoys are *poor*.

Polar-orbiting satellites provide information on surface wind, with global coverage, *good* horizontal resolution, and *acceptable* temporal resolution and accuracy. Satellites provide for *good* temporal and spatial resolution in coastal regions.The accuracy is *acceptable* for ocean models and for marine services. Microwave scatterometers have *marginal* spatial resolution (25km), whereas the wide swath SAR measurement has *marginal* temporal resolution (one measurement every few days) and provides no wind direction.

2.12 Surface pressure

Ships and buoys take standard surface observations of several atmospheric variables, including surface pressure. In relatively shallow waters, oil platforms do the same, but the frequency and spatial coverage are *marginal* for marine services applications. Mean sea level pressure is vital to detect and monitor atmospheric phenomena over the oceans (e.g. tropical cyclones) that significantly constrain shipping.

2.13 Surface heat flux over the ocean

High-resolution surface heat flux observations over the ocean are required as input fields to ocean models and for marine services. Surface heat flux is of critical importance to improve the skill of forecasts of sea surface temperature and entrainment of heat into the surface mixed layer. Improved performance will reduce background errors in ocean data assimilation. Total heat flux is composed of downward shortwave, net longwave, latent heat and sensible heat fluxes. Accuracy strongly depends on both cloud and radiation physics parameterisations, and adequate atmospheric observing systems. NWP products are reliable and provide *adequate* products for current applications.

High quality marine meteorological stations are required to more accurately observe fluxes over the ocean. Deployment of meteorological stations in mid- and high-latitudes will further enhance this development over the range of conditions that occur at the air-sea interface.

2.14 Visibility

Poor visibility is a major hazard to all vessels because of the increased danger of collision. Surface visibility observations are made primarily by ships, and at coastal stations (mainly at harbours, where VTS (Vessel Traffic Services) is usually available). This parameter can vary substantially over short distances. Accuracy is *acceptable* in coastal areas and *marginal* in the open ocean. Horizontal / temporal resolution is *poor* over the most of the global ocean. Typically, visibility is deduced from the output of regional atmospheric models (see regional NWP SoG).

2.15 Summary of the Statement of Guidance for Ocean Applications

The following key points summarize the SoG for Ocean Applications:

- A large part of marine and ocean observing systems is currently maintained by research funding with limited duration. This has the potential of leaving observational gaps unless ongoing funding for sustained observing networks is guaranteed. The ocean observing community should therefore ensure sustained funding for the key observing systems (e.g. tropical moorings, Argo, surface drifters with barometers, as well as altimeter, scatterometer, microwave SST and sea ice measurements from satellite missions);

- The uneven geographical coverage of the *in situ* ocean observing network is also an ongoing issue for ocean applications. Considering the regional variability in requirements as well as to ensure optimized planning for observing networks with limited resources, geographical variability in spatial/temporal resolution for ocean observations should be emphasised;

- Ocean observing communities should also improve geographical coverage of ocean observing systems, particularly for measuring SST, SSHA, SSS and visibility, along with higher resolution geometry and extend open-ocean and coastal wind-wave observing networks (e.g. 400 time-series reporting in open ocean), possibly developing other existing observing sites (e.g. global sea level and tsunami monitoring network) into multi-purpose stations;

The critical met-ocean variables that are not adequately measured (more accurate and frequent observations and better spatial/temporal resolution are required) by current or planned systems are:

- Sea surface height anomaly - noting the high impact of this observation on ocean forecasting systems to derive both the ocean state and circulation of the upper ocean, supporting a large number of applications, it is recommended that the observing system capabilities be given high priority and that a minimum service level target be agreed and sustained;

- Wave parameters (significant wave height, dominant wave period, Wave 1-D and wave directional energy frequency spectrum) - noting that extreme wave and wind gusts events significantly constrain shipping and other marine operations, it is recommended to collocate of wind and wave sensors;

- Sea level – noting the wide range of requirements for sea level data (from early detection of tsunamis to long-term trends of sea level rise), the requirements for this variable should be carefully addressed;

- Surface pressure – noting that sea-surface pressure data from drifting and moored buoys are still limited, particularly in tropical regions where these data are vital to detect and monitor atmospheric phenomena over the oceans (e.g. tropical cyclones) that significantly constrain shipping, it is recommended to install of barometers on all deployed drifters (1250);

- Visibility – noting that visibility data are critical for operations and as these are still very limited, the NMHSs are encouraged to measure visibility.

It is therefore recommended that ocean observing communities should (i) ensure that state-of-art technologies are employed to improve accuracy for all measurements; (ii) extend collaboration among themselves at national/regional levels to enhance wave measurement networks (e.g. moored buoy networks) for validation and evaluation; and (iii) develop visibility measurement capability over the ocean (consultation needed with JCOMM experts on how to practically achieve this).

Satellite data are the only means for providing high-resolution data in key ocean areas where *in situ* observations are sparse or absent. In general, *in situ* met-ocean data and observations are *poor* for marine services (in particular, for monitoring and warning marine-related hazards) and *marginal* for assimilation into ocean models, including wave models.

There is a need for satellite operators to ensure (i) a combination of both infra-red and microwave measurements for better coverage of SST observations; (ii) improved observations in coastal regions (altimetry, SST); (iii) a minimum of two interleaved operational satellites providing SSHA observations to support ocean forecasting applications, and (iv) the development satellite measurements of SSS on an operational basis.