CGMS

CGMS-36 WMO-WP-22
v1, 13 October 2008
Prepared by WMO
Agenda Item: E2
Discussed in Plenary

JCOMM SATELLITE OBSERVATIONAL REQUIREMENTS FOR OCEAN APPLICATIONS

This document highlights the priority satellite observation requirements in support of ocean applications as detailed in the JCOMM Observations Programme Area strategic work plan for building a sustained Global Ocean Observing System in support of the Global Earth Observation System of Systems. These include (i) sea surface temperature, (ii) sea surface height, (iii) surface vector winds, (iv) ocean colour, and (v) sea ice. The gap analysis produced by JCOMM as part of the Statement of Guidance for Ocean Applications is addressing the requirements for Met-ocean forecasts and services (global and regional wave modelling and forecasting, marine meteorological services, including sea-ice, and ocean mesoscale forecasting). Wave observations and sea level are key variables for which satellite observations are needed.

CGMS Members are invited to note that the JCOMM Observations Programme Area is working on producing a more comprehensive document on the integrated (space and *in situ*) observing strategy for a number of geophysical variables including sea surface temperature, sea surface height, ocean vector winds, chlorophyll-a, sea-ice, sea state, and sea surface salinity. The document should be delivered for JCOMM-III (Morocco, November 2009) will address the integrated (space and *in situ*) observing strategy for these geophysical variables with emphasis on operational utility and on the integrated nature of the space and *in situ* observing components.

JCOMM SATELLITE OBSERVATIONAL REQUIREMENTS FOR OCEAN APPLICATIONS

1 INTRODUCTION

1.1 The JCOMM strategic work plan for building a sustained Global Ocean Observing System in support of the Global Earth Observation System of Systems is largely addressing the implementation targets for the GCOS *Implementation Plan for the Global Observing System for Climate in support of the UNFCCC* (GCOS-92).

2 SATELLITE OBSERVATIONAL REQUIREMENTS

2.1 In the plan, JCOMM has identified the following priority requirements for satellite observations as part of the initial ocean observing system for climate: 1) sea surface temperature, 2) sea surface height, 3) surface vector winds, 4) ocean colour, and 5) sea ice. These satellite contributions are detailed in other international plans, but continued close coordination with the *in situ* systems is essential for comprehensive ocean observation.

2.2 The sixth JCOMM Management Committee (Paris, France, 3-6 December 2007) requested the Chairperson of the JCOMM Cross-cutting Task Team on Satellite Data Requirements, Dr Eric Lindstrom, to draft a document on the integrated (space and *in situ*) observing strategy for a number of geophysical variables including sea surface temperature, sea surface height, ocean vector winds, chlorophyll-a, sea-ice, sea state, and sea surface salinity. The document which should be delivered for JCOMM-III (Morocco, November 2009) will address the integrated (space and *in situ*) observing strategy for these geophysical variables. The document is envisioned to be similar in scope and granularity to the IGOS Ocean Theme Report of January 2001, but different in perspective – having a much greater emphasis on operational utility and emphasis on the integrated nature of the space and *in situ* observing components.

2.3 Meanwhile, the following satellite observation requirements appear in the JCOMM Observations Programme Area Strategic work plan:

"2.3.1Sea surface temperature: Satellite measurements provide high-resolution sea surface temperature data. Both infrared and microwave satellite data are important. Microwave sea surface temperature data have a significant coverage advantage over infrared sea surface temperature data, because microwave data can be retrieved in cloud-covered regions while infrared cannot. However, microwave sea surface temperatures are at a much lower spatial resolution than infrared. In addition microwave sea surface temperatures cannot be obtained within roughly 50 km of land. A combination of both infrared and microwave data are needed because they have different coverage and error properties. Drifting buoy and other in situ data are critically important in providing calibration and validation in satellite data as well as providing bias correction of these data. Satellite biases can occur from orbit changes, satellite instrument changes and changes in physical assumptions on 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.

2.3.2 Sea surface height: The value of spaced-based altimeter measurements of sea surface height has now been clearly demonstrated by the TOPEX/Poseidon and Jason missions. Changes in sea level during major El Nino events can now be discerned at high resolution and provide realistic model initializations for seasonal climate forecasting. The same data, when calibrated with island tide gauge observations, are also able to monitor the rate of global sea level change with an accuracy of 1 mm per year. The planned NPOESS altimeter will be adequate for shorter term forecasting, but the NPOESS altimeter will not fly *in the same orbit as TOPEX/Poseidon and Jason; and for monitoring long-term sea level change, continuation of precision altimeter missions in the TOPEX/Poseidon/Jason orbit is necessary. Jason follow-on altimeter missions (Ocean Surface Topography Mission, OSTM) are necessary to continue the long-term sea level record.*

2.3.3 Surface vector winds, ocean colour, and sea ice: The best methods of sustaining satellite measurement of surface vector winds, ocean colour, and sea ice are still research and development questions. Over the next five years satellite agencies will weigh the alternatives and determine the long term strategy for maintenance of these elements."

2.4 Satellite observations requirements for met-ocean services

2.4.1 The JCOMM Statement of Guidance for Ocean Applications is specifically addressing the requirements for Met-ocean forecasts and services (global and regional wave modelling and forecasting, marine meteorological services, including sea-ice, and ocean mesoscale forecasting) and provides for a gap analysis based on a consensus of the met-ocean modelling and forecasting communities. The Statement of Guidance is available on line at : http://www.wmo.int/pages/prog/sat/Refdocuments.html#SOG . It is also provided in the Annex.

2.4.2 Satellite data are the only means for providing high-resolution data in key ocean areas where *in situ* observations are sparse or absent. JCOMM has identified the following critical met-ocean variables that are not adequately measured (more accurate and frequent measures and better spatial/temporal resolution are required) by current or planned systems are:

Waves parameters;
Sea level; and
Visibility.

ANNEX

STATEMENT OF GUIDANCE FOR OCEAN APPLICATIONS

(*Updated June 2008*)

This Statement of Guidance (SOG) was developed through a process of consultation to document the observational data requirements to support ocean applications. This version was based originally on the JCOMM Users Requirement Document, which was prepared by the Chairpersons of the Expert Teams under 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.

1. Introduction

Marine Meteorology and Oceanography have a global role and embraces 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. There are three major met-ocean application areas that critically depend on highly accurate observations of met-ocean parameters: (a) Numerical Weather Prediction (NWP); (b) Seasonal to Inter-annual Forecast (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 forecasted in support of NWP and SIA are addressed in the Numerical Weather Prediction and the Seasonal to Inter-annual Forecast Statements of Guidance (SoG). Met-ocean Services which refer to special elements, such waves, storm surges, sea-ice, ocean currents, etc., critically depend on relevant observational data. This Statement of Guidance provides a brief discussion of the key met-ocean observational requirements for Met-Ocean Services, concentrating on those parameters not covered by previous sections of this document. In particular, variables, such precipitation, air temperature, humidity and cloud cover, required for marine services, and surface heat fluxes required for NWP, are addressed in the global and regional NWP SoG.

The requirements for met-ocean forecasts and services stipulated here are based on a consensus of the met-ocean modelling and forecasting communities. It 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. Data Requirements

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 direction, wave period, 1D frequency spectral wave energy density, and 2-D frequency-direction spectral wave energy density)

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

30-100 km for global models, and down to 3-4 km 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 direction) 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 are depended on the applications for which the data are required and based on the need to provide an accurate analysis of the sea state at regular intervals (typically every 6 hours). These includes: (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 also required for nowcasting (0 to 2 hours) and issuing / cancelling warnings, and 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 forecasting is being generated based on high-resolution regional wave models.

The key model variables for which observations are needed are: (i) significant wave height; (ii) dominant wave direction; (iii) wave period; (iv) 1-D frequency spectral wave energy density; 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 the *in situ* wave data is still very limited and most measurements are taken in the Northern Hemisphere (mainly in the North America and Western Europe coasts). The majority of these data are provided by *in situ* non-spectral and spectral buoys and ships with acceptable frequency and marginal accuracy. 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 are identified. In particular, a systematic 10% bias identified 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 the satellite observations. Validation requirement is for average 1000km spacing requiring a network of around 400 buoys with minimum 10% / 25cm accuracy for wave height and 1 second for wave period. Higher density (horizontal resolution of 500km) would be advantageous for data assimilation. In regions where known non-linear interactions between waves and local dynamic features exist (e.g., Agulhas Current, Gulf Stream, and Kuroshio Current) higher density (horizontal resolution of 100km) would be also advantageous.

Satellite altimeters provide information on significant wave height with global coverage and good accuracy. However, horizontal / temporal coverage is marginal. Minimum 20km resolution is required for use in regional wave models. 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 high 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, both non-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). Due to the increased demand for tsunamis, storm surges 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 range of the spectrum should be covered from now on, and it would be necessary to consider this when choosing a new instrument and designing the *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 sea level measurements have not been well integrated into NHMSs.

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:

A sampling of sea level, averaged over a period long enough to avoid aliasing from waves, at intervals of typically 6 or 15 minutes, or even 1 minute or less if the instrument is to be used also for tsunami, storm surges and coastal flooding forecasting and warning; but in all circumstances the minimum sampling interval should be one hour, which these days is an insufficient sampling for most applications – marginal accuracy;

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 10 mm – 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 be also 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 constrains, 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 acceptable for studies of long-term trends, but marginal for other applications. Tsunami and storm surge-prone basins (e.g., Bay of Bengal, Gulf of Mexico and Pacific Islands) require 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 at a basin scale. 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 because 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) the difficulty is even larger because of the proximity of land which the track spacing is too coarse to resolve the short scales of the sea level changes. Thus, adaptive tracker 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-Ice parameters (thickness, coverage / concentration, type / form, and 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 lesser extent, on visual observations. The instrumental observations are by conventional aircraft and coastal radar, visible and infra-red airborne and satellite imagery, and more recent techniques, such as passive microwave sensors, laser airborne profilometer, scatterometer, side-looking (airborne) radar (SLAR / SLR) or synthetic aperture radar (SAR, satellite or airborne).

Visual observations from coastal settlements, lighthouses and ships 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 7–8 km; from a coastal lighthouse, observations can cover a radius of 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 the ice coverage taken from the air, i.e., helicopters and fixed-wing aircraft, have the advantage of a much better viewing angle; the platform's flying speed allows a great deal more of the sea-ice to be reported; and problems of remoteness from airports or other suitable landing sites can be overcome by using long-range aircraft. In the various stages of development of sea-ice, estimates its amount; notes its deformation and the 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 limits 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 ranges below 30cm.

The advent of earth-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 swathe at high-resolution. In the latter case, data from a particular location may be obtained only at temporal intervals of several days.

In general, most meteorological satellites provide 10–12 passes daily in the Polar Regions, i.e., complete coverage of Polar Regions 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 – good horizontal / temporal coverage.

Visible and infra-red data 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 swathes 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 can provide precise data on the location and type of ice boundary, concentration or concentration amounts (in tenths or percentages) and the presence or absence of leads, including their characteristics, if radar sensors are used. Less accurate information is provided on the stages of development of the sea ice including the FY / MY ratio, forms, with an indication of whether ice is land-fast or drifting, stages of ice melting and ice surface roughness. Flow motion over approximately 12–24-hour intervals can often be determined through the use of imagery from sequential orbits.

2.4 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); 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 have a large variability due to the diurnal cycle of solar radiation, which enhances 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 (< 0.1 °C) and temporal coverage (hourly).

The table below specifies the consolidated user requirements for ocean forecasting systems and marine services.

	Spatial resolution (km)	Delivery timeliness (hours)		Accuracy (°C)
		Target	Threshold	
Coastal Ocean	< 1	1	3	< 0.1
Open Ocean	5-10	1	6	< 0.1

Ships and moored and drifting buoys provide observations of sea-surface temperature of good temporal frequency and acceptable accuracy as long as required metadata (e.g., the depth of the measurement is essential for deriving the diurnal cycle and the foundation temperature) are provided. Coverage is marginal or worse over some areas of the ocean globe. There is a requirement for high quality SST in open ocean, ideally with accuracy < 0.1 °C on 5km spatial scale, and fast delivery (availability within 1h). In coastal regions, higher density is required (accuracy < 0.1 °C on 1km 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 the combined analysis products. They are critically important providing bias correction of these data. Satellite biases can occur from orbit changes, satellite instrument changes and changes in physical assumptions on 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 sea surface temperature data. Both infra-red and microwave satellite data are important. Microwave sea-surface temperature data have a significant coverage advantage over infra-red sea-surface temperature data, because microwave data can be retrieved in cloud-covered regions while infra-red cannot. However, microwave sea-surface temperatures are at a much lower spatial resolution than infra-red. In addition microwave sea-surface temperatures cannot be obtained within roughly 50km of land. A combination of both infra-red and microwave data are needed because they have different coverage and error properties.

Instruments on polar satellites provide information with 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 SSTs (1 km) can be retrieved by the LEO infra-red radiometer and rather degraded resolution SSTs (5 km) from the GEO IR radiometer. However, quantitative detection of the SST diurnal cycle is still challenging subject but drifters can provide high temporal resolution SST data. In contrast, microwave radiometers cannot be used for the coastal applications because of: (a) rather coarse spatial resolution; and, (b) contamination of land signals in the measurement in the coastal sea.

2.5 Sub-surface Temperature, Salinity and Density

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

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, about half the targeted lines are still poorly sampled. Temporal resolution is marginal, and 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 to limitation in the GTS traditional character codes being used at the moment.

The *Argo* profiling floats provide global coverage of temperature and salinity profiles to ~2000 m, 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 in ocean models and for marine services.

2.6 Ocean Colour

Ocean colour observations are required for marine services applications and for validation of ocean models. The ocean colour remote sensing provides images of biological / non-biological parameters with high-spatial resolution (250m to 1km). The ocean colour can detect several types of marine pollutions, harmful algae and red tide plankton blooms. Parameter retrieval algorithm in turbid waters is not established yet, but developments of an observation system based on the Ocean Colour remote-sensing have presented promising results for a future operational observing system. *In situ* measurements are needed to complement satellite ocean colour observations. These measurements should be accompanied by real-time daily observations of ocean temperature, surface wind and derived dynamic height.

2.7 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 marginal temporal resolution. Moored buoys are good in temporal resolution and accuracy, but marginal or worse otherwise. The Acoustic Doppler Current Profiler (ADCP) provides observations of ocean currents over a range of depths, with acceptable accuracy. Coverage is marginal or worse over some areas of the ocean globe, and 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, but they cannot determine mean currents. Velocities derived from Lagrangian drifters are acceptable in terms of accuracy (2 cm / s) and spatial coverage (5° lat. / lon.), but marginal temporal resolution (typically 1 month). Satellite altimetry permits to derive the ageostrophic motion (e.g., centrifugal, Ekman, ageostrophic submesoscale) and the time-mean motion. Satellite altimetry 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, and marginal accuracy.

2.8 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 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.

2.9 Surface Wind over the Ocean and Coastal Areas (10m)

High-resolution surface wind over the ocean and coastal areas is required as an input field for ocean models (including wave models), and for marine services. The surface wind 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 enough 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. Accuracy is acceptable. Coverage is marginal or worse over large areas of the ocean globe. The tropical moored buoy network has been a key contributor for surface winds 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 satellites provide information on surface wind, with global coverage, good horizontal resolution, and acceptable temporal resolution and accuracy. The microwave scatterometer has limited spatial resolution (25km), and the wide swath SAR measurement has limited temporal resolution (one measurement every few days) and provides no wind direction.

2.10 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. As stated in the SoG for Synoptic Meteorology, even very isolated stations may play an important role in synoptic forecasting, especially when they point out differences with NWP model outputs.

2.11 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 the coastal stations (mainly at harbours, where the VTS (Vessel Track System is usually available)). This parameter can vary substantially over short distances. Accuracy is acceptable in coastal areas and marginal in open ocean. Horizontal / temporal resolution is poor over the most of the global ocean. Visibility is deduced from the output of regional atmospheric models (see regional NWP SoG).

2.12 Summary of the Statement of Guidance for Ocean Applications

The following key points summarize the SoG for Ocean Applications:

- 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 insufficient for marine services (in particular, for monitor and warning marine-related hazards) and marginal for assimilation in ocean models, including wave models;

- Many met-ocean measurements have not been well integrated into NHMSs; and, In general, there is a requirement for fast delivery of met-ocean data.

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

Waves parameters;

Sea level; and

Visibility.