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Wave measurements, needs and developments for the next decade

Lead author

Val Swail
Environment Canada
4905 Dufferin Street
Toronto, Ontario CANADA M3H 5T4
+1-416-739-4347 (Voice)
+1-416-739-5700 (Fax)
Val.Swail@ec.gc.ca

Contributing authors

Robert Jensen	USACE ERDC	+1 601 634 2101	Robert.E.Jensen@usace.army.mil
Boram Lee	IOC	+33 1 45 68 39 88	b.lee@unesco.org
David Meldrum	SAMS	+44 1631 559 273	dtm@sams.ac.uk
Jon Turton	Met Office	+44 1392 886647	jon.turton@metoffice.gov.uk
Sergey Gulev	Shirshov Institute	+7-495-1247985	gul@sail.msk.ru
Margaret Yelland	NOCS	+44 23 8059 6406	M.Yelland@noc.soton.ac.uk
Julie Thomas	Scripps	1-858-534-3034	jot@cdip.ucsd.edu
Paula Etala	Servicio Meteorológico	+54-11 4317 2000x3152	etala@ara.mil.ar
Graham Warren	Bureau of Meteorology	+61 3 96694041	g.warren@BoM.gov.au
William A. Birkemeier	USACE ERDC	1-601-631-2953	William.Birkemeier@usace.army.mil
Bill Burnett	NDBC	1-228-688-4766	Bill.Burnett@noaa.gov

Executive Summary

Global and regional wave observational requirements are dependent on the application and include: (a) assimilation into wave forecast models; (b) validation of wave forecast models; (c) ocean wave climate and its variability on seasonal to centennial time scales; (d) role of waves in ocean-atmosphere coupling; and (e) coastal wave applications such as sediment transport. Additionally, wave observations are also required for short-range forecasting and nowcasting as well as for warning 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). *In situ* wave observations are also needed to calibrate/validate satellite wave sensors. The key observations 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. In the study of ocean waves, high quality wind observations, both in situ and remote are often as important as the wave observations.

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A recent community workshop on *in situ* wave measurement technology noted that: (1) geographical coverage of *in-situ* data is still very limited especially as far as any measure of wave directionality is concerned, and most measurements are taken near coasts in the Northern Hemisphere; (2) present *in situ* reports are not standardized resulting in impaired utility; (3) significant differences exist in measured waves from different platforms, sensors, processing and moorings. Three main topics were discussed: (1) how to add wave observing capabilities to drifting buoys; (2) how to assess and improve the quality of observations from the present networks of moored buoys; 3) the addition of wave observation capabilities to future moored buoy networks, in particular the OceanSITES moorings.

This paper will describe the development of components of a global integrated ocean observing plan for waves, including various *in situ* observation systems and also complementary remote sensing systems, both land and space-based, capable of providing the type, quantity, quality and distribution of wave observations necessary for the wide range of direct and indirect wave applications.

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Introduction

Surface gravity waves (whose frequencies range from 1.0 to 0.033 Hz) entering and crossing a nation's waters, whether generated by a distant storm, local sea breeze, or a tropical storm, have a profound impact on navigation, offshore operations, recreation, safety, and the economic vitality of a nation's maritime and coastal communities. User requirements for wave information differ: commercial fisherman want the wave conditions at their fishing grounds, as well as a forecast for the length of their trip; ship captains want to know if they will be able to safely clear the waves breaking on a dangerous outer bar before they leave port; surfers look for large swell while recreational fisherman and divers seek calm waters; lifeguards want to know if the high surf warnings of yesterday will be needed today; marine engineers require continuous wave measurements in order to identify extreme waves; and Navy and commercial ship captains require wave information for safe and efficient ship routing to reduce fuel usage. Long-term wave records are also important for studies of climate change and for the design of coastal and offshore structures and facilities.

Although waves are a fundamental oceanographic variable and measurement systems exist, the total number of in situ real-time wave observations is relatively small and very unevenly distributed (Figure 1a,b). Even for the United States, the most well sampled geographical region in the world, the total number of in situ real-time wave observations for the nation's approximate 17,000 mile-long coastline is only about 200 nationwide, and only about one-half report some measure of wave direction (US IOOS Wave Plan: NOAA and USACE, 2009).

This paper describes the requirements for, and benefits of, an enhanced global wave observation network, including various in situ observation systems and complementary remote sensing systems, both land and space-based. In particular, it describes the development of components of a global integrated ocean observing plan for waves, capable of providing the type, quantity, quality and distribution of wave observations necessary for the wide range of user applications, and maps the way forward in the next decade towards better spatial and temporal coverage from wave observing systems and a better understanding of the measurement uncertainties.

Wave Data Requirements

Requirements for wave information were described in detail in the report of the OceanObs99 meeting (Swail et al., 2001) and the overall requirement and underpinning applications remain largely unchanged. Since then modest progress has been made towards those requirements, primarily with respect to additional moored buoy deployments along coastal margins and an increased percentage of directional wave measurements.

As noted earlier, there are a large number of users who require wave information covering a broad range of complexity, from simple measures of average wave height, sometimes with average wave period, to separations of the sea and swell components, to full 2-D spectral wave measurements for vessel response and shoreline erosion studies.

Global and regional wave observational requirements are dependent on the application and include: (a) assimilation into wave forecast models; (b) validation of wave forecast models; (c) ocean wave climate and its variability on seasonal to decadal time scales; and (d) role of waves in ocean-atmosphere coupling. Additionally, wave observations are also required for short-range forecasting and nowcasting as well as for warning 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). In situ wave observations are also needed for calibration/validation of satellite wave sensors. The key observations 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 and desirable are observations of individual wave components (sea and swell). In the study of ocean waves, high quality wind observations, both in situ and remote, are often as important as the wave observations themselves.

Accuracy levels of directional wave measurements required by various user groups vary considerably. However if the most stringent requirement is followed, then the requirements of the diverse user groups and applications will be met. The most stringent requirements come from the wave physics groups followed by operational forecast offices and ultimately numerical wave modelers. Tolerance requirements suggested by these groups are on the order of centimeters in amplitudes, tenths of seconds in periods (inverse frequencies), and directional estimates on the order of two to five degrees. The latter includes the higher directional moments of spread, skewness and kurtosis, which can only be successfully estimated from high-quality, First-5 (consisting of the first five Fourier coefficients of the spectrum) over the entire frequency range of surface gravity waves. If this requirement is set for any directional wave measurement, *ground-truth* would be established, analyses of these data sets would no longer require a-priori assumptions for the type of device, hull design, mooring system, transfer functions used to approximate surface gravity waves.

Quantification of multi-component wave systems with differing directions at the same carrier frequency can affect all littoral processes including sediment transport, navigation, dredging operations, articulate rip currents and even cause flooding on reefed islands. Here lies the paradox: numerical wave model technologies rely on wave measurements. Ultimately, wave experts rely on directional wave measurements to gain knowledge leading toward improving wave modeling technologies. Historically these improvements have relied on large-scale, short term field experiments. These field activities have diminished over the last decade, and so have model improvements, (The WISE Group, 2007). Increasing the number of directional wave measurements with First-5 capabilities will directly lead to improvements of modeling technologies and will translate into better wave forecasts for the user community.

The WMO Rolling Review of Requirements and Statements of Guidance (http://www.wmo.int/pages/prog/sat/RRR-and-SOG.html), lists the wave requirements in detail for the applications described in the following paragraphs. Typically these requirements specify significant wave height accuracy of 5-10%, or 10-25 cm; wave periods of 0.1 to 1 second, wave directions to 10 degrees, and wave spectral densities to 10%. As noted above, for certain applications, especially in coastal regions, required accuracies may be even higher, which presents enormous challenges.

1. Assimilation into offshore wave forecast models

This includes assimilation into both global and regional scale offshore wave models. Assimilation is currently largely based around use of satellite observations. Altimeter wave height observations provide the most straightforward data set to use, and are generally used alongside associated wind speed observations. SAR derived wave spectra can also be used, but present more technical challenges. In situ measurements are currently too sparse in the open ocean to be of value, but could potentially provide higher accuracy observations to complement (and correct for biases in) the satellite observations. In general, the availability of observations with some spatial coverage (e.g. HF radar data, swath data) would offer significant benefits for assimilation though the ability to fully initialize features on a range of scales.

The requirements are dependent upon the resolution of the models employed, with a need to constrain model evolution across the model grid, and a need for sufficient resolution to capture the synoptic scales. Current global model resolutions are typically ~30-100km, with regional model resolutions down to 3-4 km (with a natural progression to higher resolution expected). Coastal models require different observing methods to those for the open ocean, due not only to their higher resolution, but also due to limitations of the satellite data close to land. Hence for these models, systems such as coastal radar systems are of particular importance. The real-time nature of the application, together with the rapid response time of sea state parameters to changes in winds makes timeliness a priority.

2. Validation of wave forecast models

The requirements for validation are driven by two main activities: real-time validation with requirements very similar to those for assimilation; and delayed mode validation with requirements that place greater emphasis on accuracy, but with more relaxed timeliness requirements.

In situ buoy data are currently the key data source for validation due to their accuracy and the availability of spectral data, particularly for delayed mode validation. Due to the dependence of wave forecasts on surface winds, there is significant value from use of collocated surface wind data in validation activities. However, spatial sampling of buoy data does not currently meet the requirement for validation of offshore wave models, and so altimeter data are also widely used. As for assimilation, availability of observations with some spatial coverage would provide significant benefits allowing a more spatially homogeneous validation.

Again, requirements are dependent upon model resolution, though the required sampling is less dense than required for assimilation. The key requirement, however, is to ensure that sampling is sufficient to include a representative sample of different physical regimes globally. There is also a strong requirement for improved coverage of high quality spectral observations, especially to improve representation of swell in wave forecast models.

3. Calibration / validation of satellite wave sensors

Whilst the satellite instruments clearly have the potential to provide observations with synoptic global coverage, the quality and usability of these observations is dependent upon good calibration of the satellite sensors. This can only be achieved through use of a sufficiently dense network of accurate in situ measurements. Such data are required for validation of altimeter wave measurements, whilst spectral data are required for use with SAR derived wave spectra.

Sampling requirements are similar to those for validation of forecast models, with the additional consideration that buoy observations located along satellite ground tracks would be of particular value. Accuracy is of greater importance than timeliness.

4. Ocean wave climate and variability

Sea state is defined as an essential climate variable (ECV) in the GCOS-92 report (WMO, 2004). Determination of ocean wave climate requires a long time-series of stable data, with sufficient sampling to capture the physical regimes of the global ocean. This application therefore requires stability and sustainability of the observing platform. In situ measurements provide the natural source for such a time-series (analyzed wave information, e.g. height period, spectra performed on a routine basis), though the open ocean in situ sampling is currently inadequate for this purpose. Satellite observations can provide complementary information, but cannot be used in isolation without in situ observations. Timeliness is not a consideration for this application.

5. Role of waves in coupling

Investigation of the role of waves in coupling requires collocated observations of a wider range of parameters than is required for other applications, most notably air-sea flux measurements. Spatial sampling is generally restricted to a small number of open ocean locations to allow processes to be studied in detail. Again, timeliness is not a consideration for this application.

This application differs from the others in that observations are generally focused around dedicated campaigns rather than routine monitoring. Hence the requirements are specific to the particular process studies, and in general are not addressed by the same platforms as the routine observation requirements.

Elements of a Global Wave Observing System

As stated in the GCOS-92 report (WMO, 2004), there is no sustained global observing effort at present for sea state. At present best estimates of sea state for much of the world ocean are computed from model reanalysis and analysis systems. Observing networks, satellites and analysis activities contributing to the knowledge of regional and global sea state include:

- Numerical weather prediction (analysis/reanalysis and hindcasting) systems.
- Networks of moored buoys.
- Satellite altimetry.
- Satellite Synthetic Aperture Radar (SAR).
- Voluntary Observing Ships (VOS) visual wave observations.

The minimum observation variables and their present global ocean observing systems/platforms are listed in the table below (ref SOG). As noted above, the observation requirement extends beyond the minimum to include full 2-D spectral data.

Observation variables (minimum)	Observing System/Platform
Significant Wave Height, Peak Period, and 1-D Spectra	Moored Buoys
	Satellite Altimeter
	Synthetic Aperture Radar (SAR)
	HF Coastal Radar
	Other Technologies (e.g., Navigation Radar, other radar, shipborne sensors such as WAVEX, shipboard wave recorders)

In Situ Wave Measurements

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The vast majority of existing wave measurements are made in the coastal margins of North America and Western Europe, with a huge data void in most of the rest of the global ocean, particularly in the southern ocean and the tropics (as shown in Figure 1a), while other existing observational systems have often considerable coverage in these areas (Figure 2). Also, the existing sea state 'reference' moored buoys are not collocated with other ECV reference sites.

Wave measurements in shallow water (depths less than ~10m) are measured with bottom-mounted or less commonly, surface-piercing instruments (capacitance and resistance gauges). Surface-piercing instruments have to be mounted on a structure and are used close to shore or on offshore platforms and towers. Bottom-mounted sensors include pressure sensors and acoustic wave sensors which also measure currents. While the above wave instruments can easily measure non-directional waves, multiple sensors are required to estimate the directional attributes of surface gravity waves on fixed structures or near the sea floor.

In general, for all non-coastal or deep water applications, the preferred wave measurement platform is a buoy. These buoys can be spherical, discus, spar (or multi-spar), or boat-shaped hull. The most popular and widely used method measures buoy motion and then converts the buoy motion into wave motion. Based on its hydrodynamic characteristics, each buoy has its own response function to characterize its motion in waves. Once the buoy motion is measured, wave motion can be derived based on the buoy's response function. For non-directional wave measurement, only the buoy's heave motion, usually measured by an accelerometer, is needed to obtain wave data. If the accelerometer is fixed on the buoy hull, the heave motion could be contaminated by other buoy tilt or horizontal motions. Thus, corrections are required for accurate wave estimates.

Directional buoy wave measurements based on buoy motion can be categorized into two types: translational (also referred to as particle-tracking or particle-following) or pitch-roll (or slope-following) buoys. For both types, a variety of different sensor technologies are used to measure buoy motion. As Teng and Bouchard (2005) noted: "because directional wave information is derived from buoy motions, the power transfer functions and phase responses associated with the buoy, mooring, and measurement systems play crucial roles in deriving wave data from buoys." This dependence is particularly important at low energy levels and at both short and long wave periods where the wave signal being measured is weak and potential for added signal contamination increases.

Ideally, the buoy wave measurement could be more accurate if a buoy is used exclusively for wave measurement because its hydrodynamic responses and filters can be optimally adjusted. However, many buoys are used to measure more than wave data especially in deep water. Thus, accuracy of non-directional and directional wave estimates from these "multi-function" buoys can be significantly compromised.

All of the in-situ wave systems discussed above base their directional estimators on the measurements of three concurrent time series which can be transformed into a description of the sea surface. All of these devices will provide good integral wave parameter estimates (height, peak period, mean direction at the peak period, etc.). However not all sensor systems have the capability of returning high quality "First-5" estimates because of the inherent inability of the sensor to separate wave signal from electronic and system/buoy response noise.

Existing wave measurement systems and moored buoy networks are often "legacy" systems, so standardization of sensors, system configurations, or hull type would be costly and impractical, and not necessarily desirable. This clearly points out the need for comprehensive metadata and comparability in wave measurement systems; both of these issues are dealt with further in following sections.

Other In-situ Wave Observing Systems

In situ wave observations also include waves visually observed from VOS, which provide the longest records of wave data worldwide (including separate estimates of sea and swell), effectively from the mid 19th century. For certain applications (e.g. climate variability studies, extreme case studies) the length of record and/or worldwide coverage of VOS wave data make them more useful than other sources of wave information. One advantage of these data is that generally observational practices have not changed. All visual wave reports are included in ICOADS (Worley et al. 2005) and the number of reports with wave information is close to 60%. After 1958 VOS reports provide separate estimates of heights, periods and directions of wind sea and swell, making the VOS data a unique source of such information. Uncertainties in VOS wind wave heights are thoroughly described by Gulev et al. (2003a), and Grigorieva and Gulev (2009).

In addition to observational uncertainties, VOS-based climatological estimates of wave characteristics suffer from inhomogeneous spatial and temporal sampling, with the largest sampling errors in the poorly observed regions of the Southern Ocean and sub-polar Northern Hemisphere. Furthermore, temporal inhomogeneity of sampling may significantly affect estimates of trends and interannual variability. Nevertheless accurate quality control and processing of visual data allows for the development of global climatologies of wind wave characteristics covering the period from 1958 onwards (Gulev et al. 2003a, www.sail.msk.ru/atlas/index.htm). Although visual wave data have generally poor accuracy, these data represent a substantial block of our knowledge about wind waves and should be further used and better validated.

Given the quality concerns related to visual estimates of waves from ships, there is clearly a need for automated measurements from ships. Some research vessels carry automated wave measurement systems in addition to making visual wave observations. There are two main types of automated systems. The first is a ship-borne wave recorder (SBWR) which uses vessel motion and pressure sensors to derive surface elevation (Tucker, 1956) and hence 1-D wave spectra. This system does not provide information on wave direction and does not compensate for ship speed through the water, but does provide reasonable wave height data (Holliday et al., 2006). The second is commercial wave radar, which use the raw signal from marine X-band scanners (as used for ship navigation) to obtain a series of 2-D images of the wave surface. These data provide excellent information on wave period and direction, but infer wave height using commercially-confidential algorithms. A complete description of sea state requires the use of both systems together, but most research vessels carry only one, or none at all. The exception is the Ocean Weather Ship *Polarfront* which has had a SBWR since 1978 and a wave radar system since 2006. Comparison of data from *Polarfront* showed that wave heights from the wave radar were often significantly overestimated, particularly in low/moderate wind speeds where the sea state was swell-dominated (Yelland et al., 2007). There is a need for development of both systems: however the SBWR is no longer manufactured commercially and the wave heights from the wave radar systems require improvement.

Wave Information from Remote sensing instruments

With respect to space-based wave measurements, satellite radar altimeters provide information on significant wave height with global coverage and high accuracy. However, spatial and temporal coverage, although homogenous, and suitable along the satellite track, is still marginal orthogonal to it. Multiple altimeters are therefore required to provide denser coverage. Long-term, stable time-series of repeat observations with high temporal resolution are required for validation of space-borne data and climate applications.

Altimeter data have been used for more than two decades, from many different satellites and sensors, including Topex/Poseidon, Envisat, Jason, ERS-1&2, for validation of hindcast and forecast model output as well as for direct real-time and wave climate uses. However, the wave estimates from satellites must be calibrated and validated against high quality in situ measurements to ensure accuracy and consistency. Bidlot et al. (2008) showed systematic differences between the altimeter wave height measurements from ERS-1, ERS-2 and Envisat which must be accounted for when used in applications such as reanalysis. However, well calibrated and validated altimeter wave observations remain a key component of a global wave observing program.

New Technologies & Complementary Wave Measurements

This section recognizes the importance of emerging in situ, ground-based and space-borne technologies that will improve and complement existing wave observations. Directional wave measurements can be estimated remotely from satellites and by ground-based radars. These observations have a unique advantage over in situ sensors, as they are able to image the entire wave field directly and over large areas. Satellite synthetic aperture radar (SAR) and Advanced Synthetic Aperture Radar (ASAR) can image the ocean surface day and night, and in all weather conditions. Present SAR sensors such as the Canadian RadarSat-1, European ERS-2 and Japanese ALOS/PALSAR and the European ENVISAT ASAR can provide sea surface information with 25m resolutions over long strips about 100km wide, or 100m resolution over 500km wide area strips (e.g. Pichel, 2008). Nearly the entire US East Coast (about 2100km) could be covered by a low earth orbiting satellite pass in 5 minutes. New SAR sensors such as the Canadian RadarSat-2, Italy Cosmo-SkyMed, and German TerraSAR-X can image the ocean surface at a spatial resolution as small as 1m. Unlike altimeter systems which provide only wave height estimates, SAR systems have the capability to provide “First-5” directional spectral estimates along large swath widths, with repeat cycles from 10 hours to two days. Real Aperture radar capability is expected to be available within 5 years. Moreover, much of the infra-structure (data manipulation, product generation and data management) can be shared, reducing costs and increasing data integration.

Coastal wave applications require different observing methods to those used for the open ocean, due not only to the need for higher density coverage, but also due to limitations of the satellite data close to land, hence for these applications systems such as ground-based high frequency (HF) and nautical radar instruments are of particular importance. These radars provide information on significant wave height with limited coverage, good accuracy and acceptable horizontal/temporal resolution. The two primary commercially available HF radar technologies are direction finding and phased-array systems. These have significantly different wave measurement capabilities. Direction finding HF systems can only provide a single, averaged (over radial rings of about 1km radial spacing) wave observation. In contrast, phased-array HF systems provide two-dimensional spatial mapping of independent wave observations with maximum ranges up to about 100km. Preliminary inter-comparisons between a phased-array radar system with directional wave buoy measurements show promise (Voulgaris et al, 2008, Shay et al, 2008; Haus, 2007). Nautical radars can provide continuous directional wave properties at very high spatial resolution for ranges up to 2 to 4 km. As these systems mature, they will complement and expand directional wave measurements.

Pre-operational and Emerging Technologies

Pre-operational technologies are those devices that have undergone extensive research, have been field tested beyond the “proof of concept” stage and are awaiting further evaluation prior to operational implementation. Examples of devices that fall into this category are acoustic current profilers being used to measure waves, as well as currents. Upward looking acoustic current profilers directly measure the pressure response of the free surface (when equipped with a pressure sensor), or follow the free surface itself (using a surface-tracking acoustic beam), and use sub-surface wave velocities computed using the Doppler shift in returns from an array of the upward looking acoustic beams. Estimates of the directional waves are constructed from these data using linear wave theory relationships to the free surface. Another example is the Air-Sea Interaction Spar (ASIS, Graber et al. 2000) buoy which provides a stable platform to measure surface fluxes and directional wave spectra.

Potential contributions from other technologies and platforms (e.g. navigation radar, other radars, and ship borne sensors) are emerging as potential solutions to specific coastal wave requirements.

Continuous improvement of the wave measurement network requires incremental upgrades of existing instrumentation and the identification, nurturing and adoption of innovative technologies as they are proven. Research and development of new sensors and sensor platforms is necessary to improve the accuracy and reliability of the operational data stream, while reducing the capital and/or maintenance cost per station.

Complementary Data Sources

In situ Wind data

Wherever possible it is very advantageous to make co-located in situ wind measurements from the same platforms as the wave measurements. This is already the case for most moored buoy wave measurements, most shipboard observations and other platforms. Wind observations, as well as waves, are an important component of any surface reference mooring network. They provide a two-way quality control with the wave observation, and provide a necessary input to model applications to infer waves at other locations where wave measurements may not exist.

Satellite Wind Data

With few exceptions (e.g. SWADE IOP-1; Cardone et al., 1995) errors in marine surface wind fields developed from conventional data remain sufficiently large to mask errors arising out of uncertainties in the physics of wave models, thereby inhibiting further progress. Satellite winds offer a potent solution to the need for reference quality forcing fields and improved wave hindcasts and forecasts. While satellite estimates of surface marine wind have long been available from passive (e.g. SSM/I) and active microwave sensors (e.g. ERS1/2 SCAT, NSCAT, satellite altimeters) it was not until the launch of QuikSCAT (QS) in June 1999 with its Ku-band wide-swath scatterometer that a truly global, accurate and now reasonably long term record of marine vector winds has been achieved. QS operates long past its design lifetime and while the Metop ASCAT C-band scatterometer will carry on, the impact of QS is so striking that high priority should be given to the replacement of a Ku-band capability in space.

The accuracy of QS winds has become well established (e.g. Ebuchi et al., 2002; Bourassa et al., 2003; Cardone et al., 2004) such that QS wind speeds estimated in cells that are free of land, ice and rain contamination exhibit bias of less than 1 m/s and scatter of ~2 m/s over the range of 10m neutral cell-scale wind speeds of 2 m/s to ~40 m/s. The range and accuracy of QS winds speeds are greater than ship wind speeds (visual or anemometer), and also greater than winds from moored or drifting buoys and satellite altimeters over the upper half of the dynamic range. The unique ability to "see" into this range in the real time QS data stream has had significant impact on the practices of regional marine warning centers and in the appreciation of the occurrence of a class of extreme extra-tropical cyclones dubbed "winter hurricanes" (e.g Von Ahn et al., 2006). The dynamic range of satellite altimeter wind speeds is about half that of Ku-band scatterometers and there have been issues of sensor to sensor calibration differences and sea state effects leading to bias issues with the wind speed estimates, and, of course, the coverage is sparse; nevertheless, satellite altimeter winds can make a valuable contribution. Extreme winter storms associated with very extreme sea states (HS > 15 such as the Rockall Trough storm, Holliday et al., 2006) can provide an important test-bed for wave model physics (e.g. Cardone et al., 1996) especially in view of the growing evidence that the relationship between wind stress and boundary layer wind speed under extreme wind forcing does not simply extrapolate from moderate wind speed conditions (Donelan et al., 2004).

Metadata

As with any source of observational data, an accompanying comprehensive metadata record is essential to properly understand the wave information originating from the different platforms, payloads and processing systems. This is necessary to understand systematic differences in the measurements from differing observing networks, and for climate applications to ensure temporal homogeneity of the records to eliminate spurious trends. The IOC-WMO Joint Commission for Oceanography and Marine Meteorology (JCOMM) has established an Ocean Data Acquisition System (ODAS) metadata standard which is hosted at the China Meteorological Agency (http://www.odas.org.cn/). All agencies measuring waves from ODAS are encouraged to include their metadata in this database.

Research requirements

Enhancement of the future global wave observing network requires not only an increased deployment of assets as described in the preceding paragraphs, but significant research efforts to address the development of new technologies and assessment of both existing and new measurement systems. Recent discussions have centered around three main topics:

1) The quality of observations from the current networks of moored buoys;
2) The addition of wave observing capabilities to drifting buoys;
3) The addition of wave observation capabilities to future moored buoy networks.

Testing and Evaluation

Continuous testing and evaluation of operational and pre-operational measurement systems is an essential component of a global wave observing system, equal in importance to the deployment of new assets. The overriding objective of this evaluation is to ensure consistent wave measurements to a level of accuracy that will serve the requirements of the broadest range of wave information users. Inter-platform tests have been pursued in the past (O'Reilly et al, 1996; Teng and Bouchard, 2005), however with the global variations in hull, sensors and processing systems, evolution of sensors, changes in buoy designs, and new platform systems, a fresh look is required. The need for this is graphically illustrated in Figure 3, and noted by recent investigations (Queffelou, 2006; Durrant et al., 2009), where large systematic differences are seen between different observing networks, including a systematic 10% difference in significant wave height measurements between the U.S. and Canadian networks.

In October 2008 a wave measurement technology workshop was held in New York (www.jcomm.info/wavebuoys) with broad participation from the scientific community, wave sensor manufacturers and wave data users, following on from a March 2007 Wave Sensor Technologies Workshop (www.act-us.info). The overwhelming community consensus resulting from those workshops was that:

- The success of a wave measurement network is dependent in large part on reliable and effective instrumentation (e.g., sensors and platforms);
- A thorough and comprehensive understanding of the performance of existing technologies under real-world conditions is currently lacking, and
- An independent performance testing of wave instruments is required.

The workshops also confirmed the following basic principles:
:

- the basic foundation for all technology evaluations, is to build community consensus on a performance standard and protocol framework;
- multiple locations are required to appropriately evaluate the performance of wave measurement systems given the wide spectrum of wave regimes that are of interest;
- an agreed-upon wave reference standard (e.g., instrument of known performance characteristics, Datawell Directional Waverider MK Series) should be deployed next to existing wave measurement systems for extended periods (e.g., 6-12 months, including a storm season) to conduct "in-place" evaluations of wave measurement systems.

All integral wave properties - height, period and direction - are derived from the motion of the platform. This depends both on the capability of the sensor being used and the influence of the platform. Because of this complexity, the measurement of waves is dependent on the capabilities of the specific system being used and is therefore unlike the measurement of other slowly changing oceanographic variables, such as ocean temperature, which is independent of the sensor used (excepting for measurement accuracy). In order to serve the full range of users, a wave observation network should accurately resolve the details of the directional spectral wave field as well as providing the standard integrated parameters. It is strongly recommended that all directional wave measuring devices should reliably estimate the so-called "First 5" standard parameters.

Technically, “First-5” refers to 5 defining variables at a particular wave frequency (or period). The first variable is the wave energy, which is related to the wave height, and the other four are the first four coefficients of the Fourier series that defines the directional distribution of that energy. At each frequency band, not only is the wave direction defined but the spread (second moment), skewness (third moment) and kurtosis (the fourth moment). The skewness resolves how the directional distribution is concentrated (to the left or right of the mean) and the kurtosis defines the peakedness of the distribution. Obtaining these three additional parameters (spread, skewness and kurtosis) for each frequency band yields an improved representation of the wave field. For example, high quality First-5 observations can be used to resolve two component wave systems at the same frequency, if they are at least 60 degrees apart, whereas other measurement parameters cannot. Although there are more than five Fourier coefficients, the First-5 variables provide the minimum level of accuracy required for a directional wave observing system, as it covers both the basic information (the significant wave height, Hs, peak wave period, Tp, and the mean wave direction at the peak wave period, θm) along with sufficient detail of the component wave systems to be used for the widest range of activities. Figure 4 (a,b) shows the application of the First-5 approach to compare co-located buoy wave observations.

Wave observations from moored buoys

While most directional wave instruments presently in use are able to resolve basic wave parameters, few are capable of satisfying the First-5 standard. Establishing the First-5 capability in directional wave measurements is critical to inter-compare different observing networks. It will also be important to determine the ‘transfer functions’ needed to correct for the fact that moored buoys are not perfect wave-followers.

As a result of the New York workshop a Pilot Project was proposed and subsequently approved by the DBCP on Wave measurement Evaluation and Test from moored buoys (WET), with the following objectives:

- Develop the basis for an international framework for the continuous testing and evaluation of existing and planned wave buoy measurements.
- Coordinate buoy inter-comparison activities.
- Develop technical documentation of differences due to hull, payload, mooring, sampling frequency and period, processing (e.g. frequency bands & cutoff), precision, transmission.
- Develop training material to educate users about how to deploy and operate wave sensors appropriately.
- Contribute appropriate material to the JCOMM Standards and Best Practice Guide.
- Establish confidence in the user community of the validity of wave measurements from the various moored buoy systems.
- Sponsor the work needed to arrive at the most promising technique.

Among the first tasks of the Pilot Project has been to develop a work plan that:

- Establishes standards and protocols for the intercomparison of moored buoy wave measurements including length of time for testing, length of test, analysis and quality control software and dissemination of results.
- Documents existing procedures for moored buoy wave measurements.

- Establishes standards and contributes to development of guidelines for best practices for wave data and metadata.
- Undertake coordinated evaluations of buoy wave measurements according to the agreed-on standard.

Wave observations from drifting buoys

A second topic addressed during the New York workshop was the potential for development of wave measurement capabilities from drifting buoys. A drifter becomes a good wave following device when it is freely floating at the surface and not tethered to (or having lost) its drogue. As the number of drifters presently exceeds the original global target of 1250, this is a potential resource for global wave measurements. Two potential technologies were identified that might yield high quality 2-D wave spectra from drifters: (1) downward looking ADCP to infer 2-D spectra from wave orbital velocities; (2) GPS to measure the motion of the drifter at periods of <100s. Whereas ADCPs are expensive (~$30K), GPS sensors are relatively low cost (~$500) and easy to install. The GPS technique would require the development of specialized software and some companies have already been active in this field.

As a result of the New York workshop a Pilot Project on Wave Measurement from Drifting buoys (WMD) was proposed and subsequently approved by the DBCP, with the following objectives

- Evaluate the feasibility of wave measurement from drifters.
- Explore in particular use of GPS as a cost-effective means of yielding 2-dimensional wave spectra.
- Prove the technology by measurements and intercomparison with recognized industry standards through a careful test and evaluation programme.
- In the event that good results are obtained, to sponsor the construction and deployment of up to 50 GPS wave drifters so as to develop confidence in the use of this technology.
- Establish confidence in the user community in the validity of wave measurements from drifters.

Extending wave observing capabilities to observing systems that do not have any

The New York workshop also noted the existence of many ocean observing platforms worldwide. The OceanSITES project was attempting to rationalize these activities and establish a global network of ocean reference stations, and had expressed an interest in adding waves to the list of observables. However, the taut moorings that are used at many of these sites are not immediately suitable for measuring waves as the surface buoys are not designed to follow the waves. If such platforms are to be used, and there are very large benefits to using them given the spatial distribution of the proposed sites and especially the geographical locations of many of them in the southern ocean and mid-ocean (Figure 5), there might still be new techniques that could be developed whereby buoy motion is observed (e.g. using GPS) and is used to correct direct observations of waves as could be made by ADCP or radar). However, any new technologies developed must be subject to the test and evaluation procedures noted above.

Regional Wave Observing Systems

The preceding sections have presented largely a global perspective on wave observing programs, or at least a general one. The key elements in such a system include wave measurements from both moored and drifting buoys, satellite altimeter and SAR, along with complementary satellite wind measurements, and from ships of opportunity and research vessels, together with new measurement capabilities on reference moorings.

For regional, or national, observing systems in the coastal domain the network requirements are considerably more demanding. The range of measurement technologies will be similar, but the emphasis will be different and the density requirement will be higher. For example, most satellite sensors suffer from land contamination close to the coast, so radar-based systems become more important. One approach to the network design issue to address the nearshore requirement is given in the U.S. IOOS Wave Plan (NOAA and USACE, 2009), where the design of the national network is based on establishing four along-coast observational subnets (see Figure 6). These include:

- Offshore Subnet: deep ocean outpost stations that observe approaching waves, prior to their passage into coastal boundary currents;
- Outer-Shelf Subnet: an array of stations along the deepwater edge of the continental shelf-break where waves begin to transition from deep to shallow water behavior;
- Inner-Shelf Subnet: on wide continental shelves (notably the Atlantic and Gulf of Mexico coasts), an array of shallow water stations to monitor cross-shelf bottom dissipation and wind generation of waves;
- Coastal Subnet: shallow coastal wave observations, which provide local, site-specific information.

Summary and Recommendations

This paper has described the requirements for, and benefits of, an enhanced global wave observation network based on both in situ observation systems and also complementary remote sensing systems (both land and space-based), identified critical research requirements to develop key components of a future observing system for waves and suggested a possible scenario for regional network design.

The main conclusions are that geographical coverage of wave data is still very limited, especially as far as any measure of wave directionality is concerned. For directional wave measurements it is recommended that all systems should reliably estimate the 'First 5' standard parameters. In general, for all non-coastal applications the preferred wave measurement platform is a buoy, while coastal wave applications require different observing methods to those used for the open ocean. Satellite radar altimeters provide information on significant wave height with global coverage and high accuracy, although spatial and temporal coverage is still marginal. SAR systems have the capability to provide 'First-5' directional spectral estimates along large swath widths, with repeat cycles from 10 hours to two days.

Emerging in situ, ground-based and space-borne technologies will improve and complement the existing moored buoy wave observations. Drifters offer a potentially substantial resource for global wave measurements using inexpensive GPS-based techniques. Also, there are potentially very large mutual benefits to extending the OceanSITES moorings for wave measurements. It is very advantageous to make co-located in situ wind measurements and satellite winds offer a potent solution to the need for reference quality forcing fields.

Continuous testing and evaluation of operational and pre-operational measurement systems is an essential component of a global wave observing system, as a thorough and comprehensive understanding of the performance of existing technologies under real-world conditions is currently lacking. An accompanying comprehensive metadata record is essential in order to inter-relate wave data from different observing platforms and measurement systems.

In order to develop the proposed global wave observing system for the next decade the following recommendations are made:

- Continuity of the established buoy networks and expansion of directional measurements (First-5 compliant) is a priority both for operational and climate assessment requirements.
- Additional moorings capable of measuring waves should be deployed in data sparse areas, in particular the Southern Ocean; the proposed OceanSITES reference mooring network could provide much improved coverage.
- VOS wave data should be further used and better validated.
- A comprehensive metadata record should be developed to understand the wave information originating from different platforms, payloads and processing systems.
- The DBCP Pilot Projects on Wave measurement Evaluation and Test from moored buoys (WET), Wave Measurement from Drifting buoys (WMD), and follow on efforts are essential components of the wave measurement plan and should be supported by national and intergovernmental agencies.
- Research should be conducted into the development of wave observing capabilities for observing systems that presently do not have any, in particular the OceanSITES moorings
- In order to address issues such as detection and documentation of possible rogue waves, as well as other applications, measurements of wave time series with a sampling rate of at least 1 second should be made at a subset of buoy locations and either stored on board until scheduled service visits or in some cases transmitted in real time
- Multiple satellite altimeters are required to provide denser coverage and long-term, stable time series of repeat observations with high temporal resolution.
- SAR wave measurements should be an important component of any future wave observation program
- High priority should be given to replacement of a Ku-band scatterometer capability in space for measurement of winds.
- There is a need for development of both SBWR and marine X-band radar systems.

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Figure 1 (a) In Situ observations from buoy and platforms where wind and wave data were collocated with the ECMWF model. Most data are from the GTS but also from SAWS, BoM, Puertos del Estado, Oceanor and SHOM

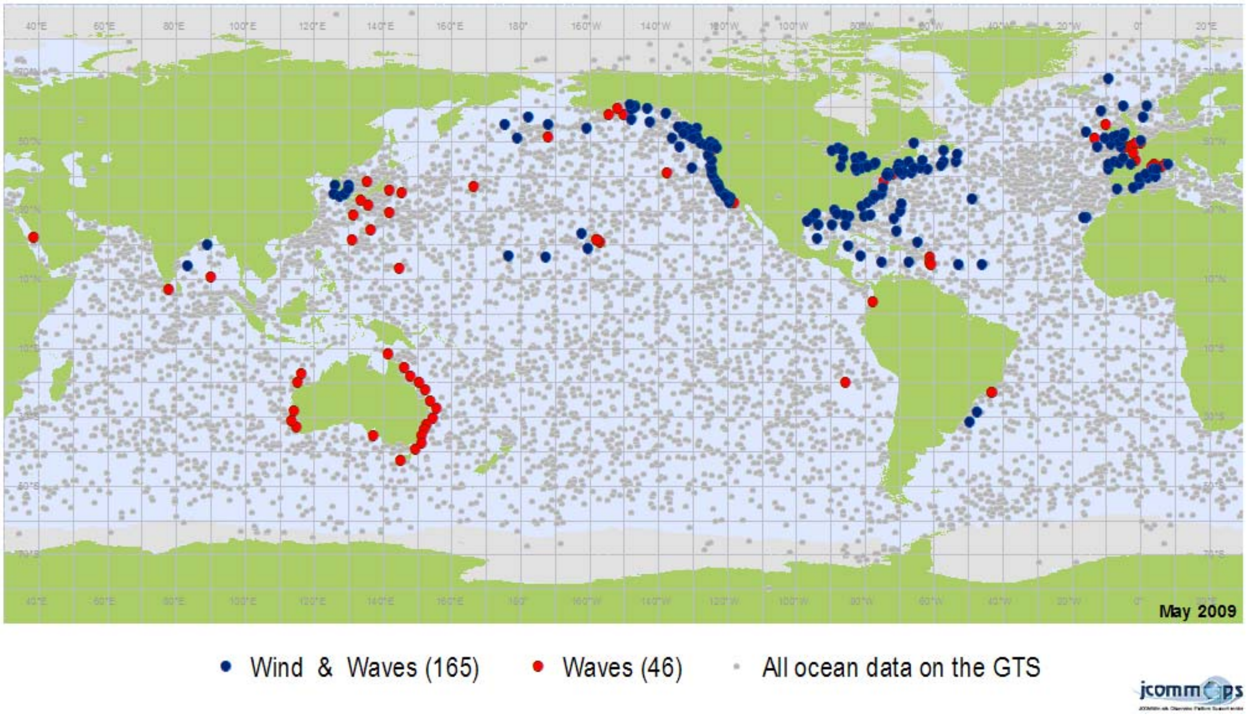

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Figure 1(b) Fixed locations for ocean wave and wind data regularly available on GTS in 1999 (from Swail et al., 2001).

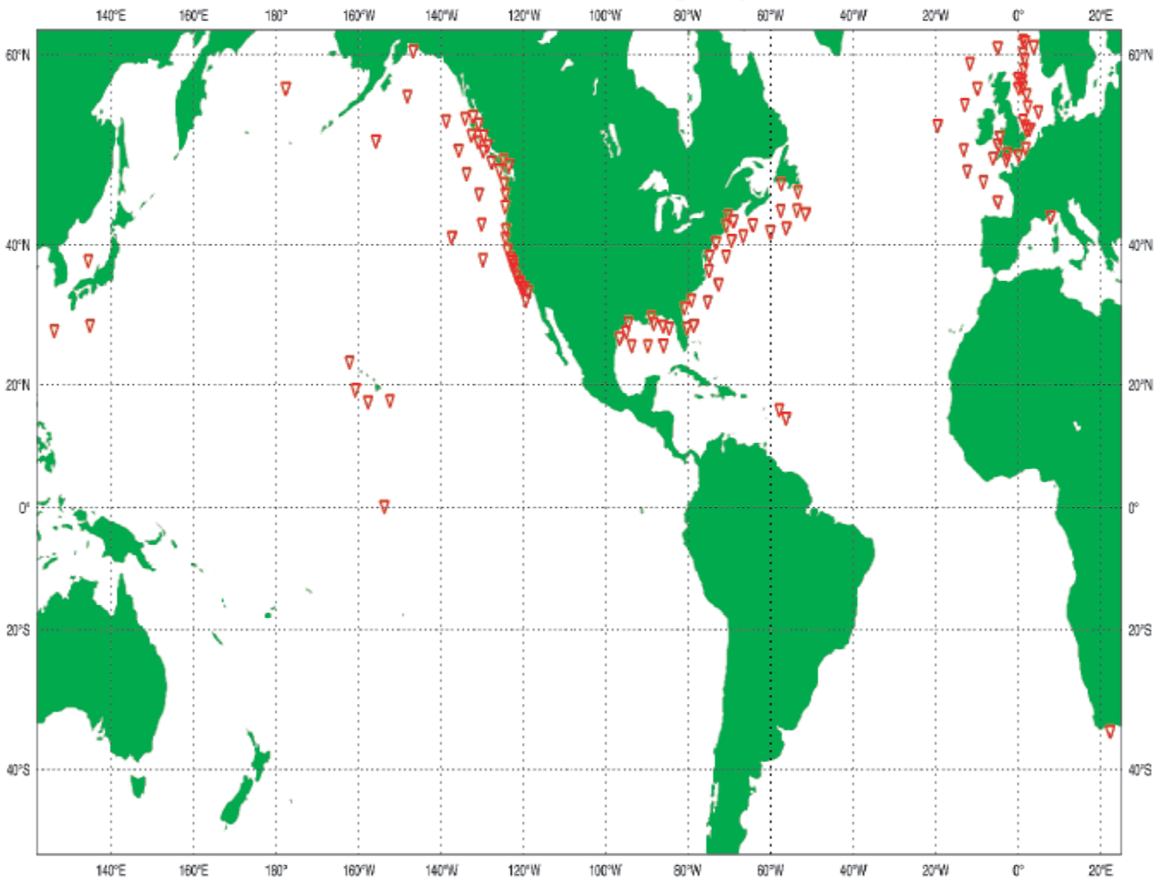

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Figure 2. Status of Observational systems as of January 2009.

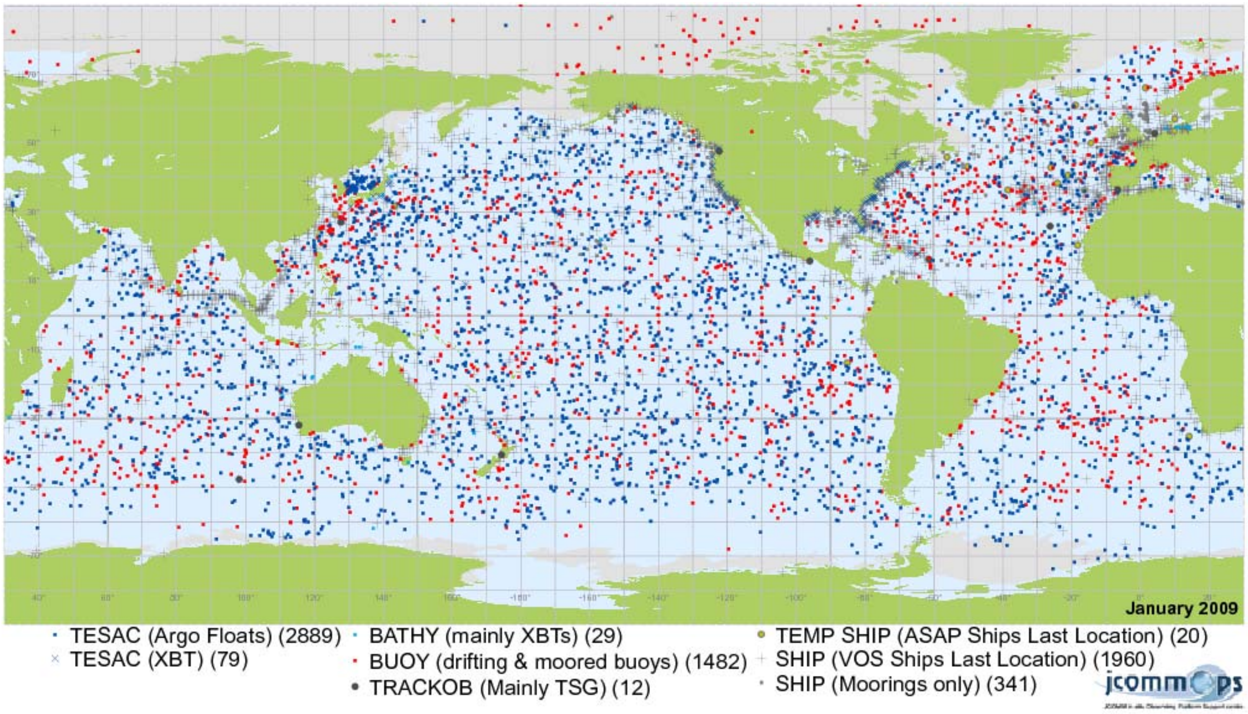

Figure 3. Discrepancies in wave observations. Bias (altimeter – in situ), symmetric slope (ratio of variance altimeter to variance in situ) Courtesy Jean Bidlot.

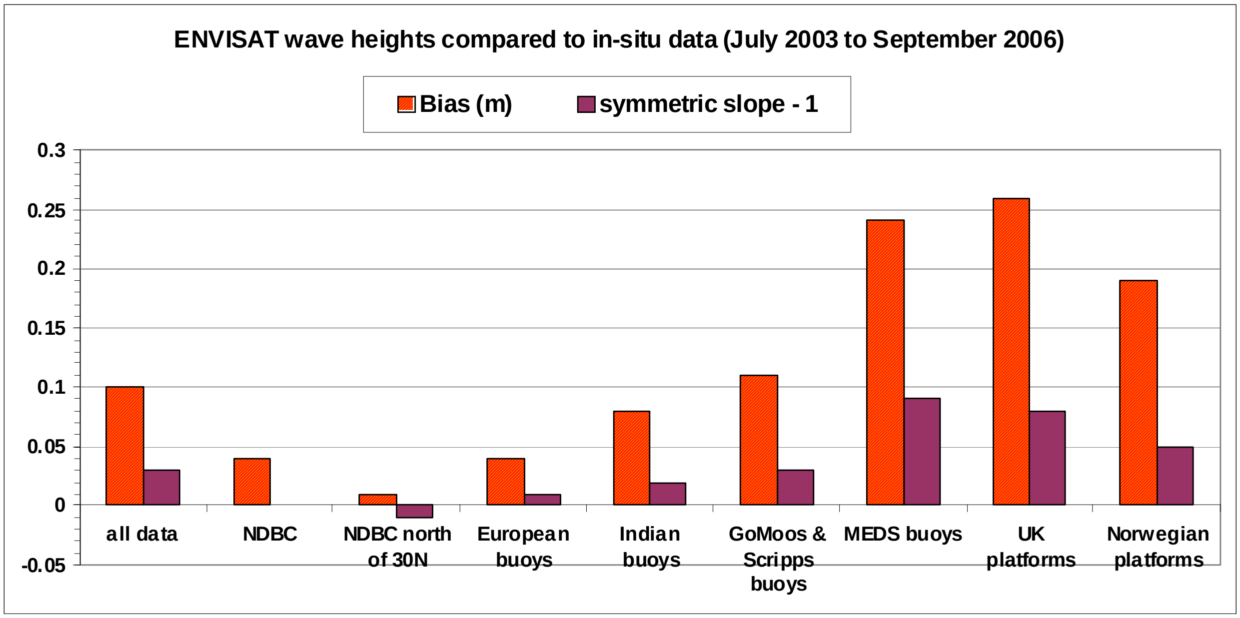

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Figure 4a. Comparison of energy-frequency measurements for a buoy against a reference standard. Blue indicates good agreement, red poor agreement.

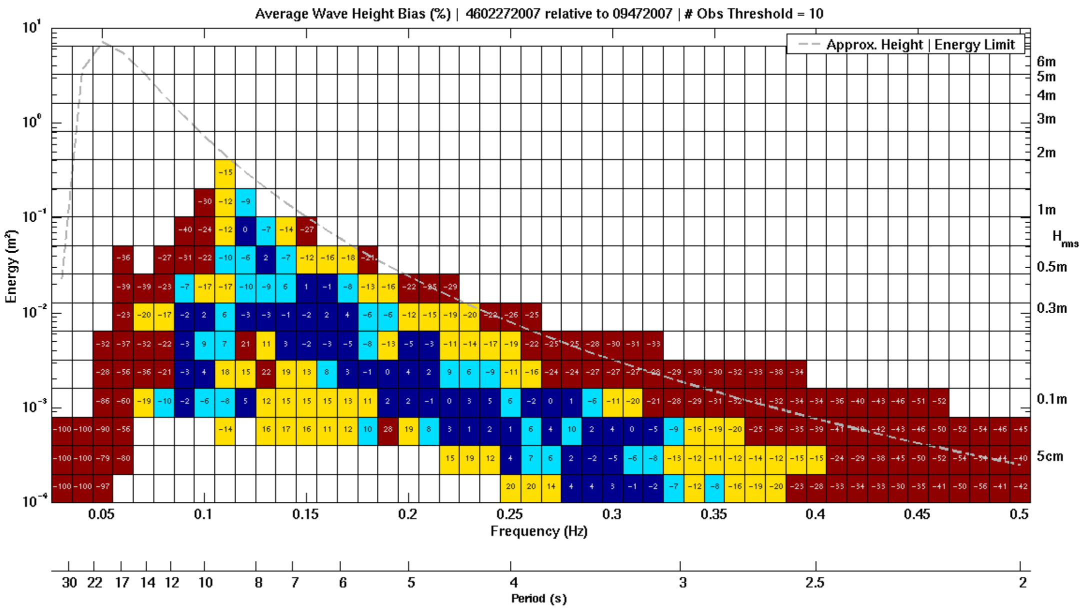
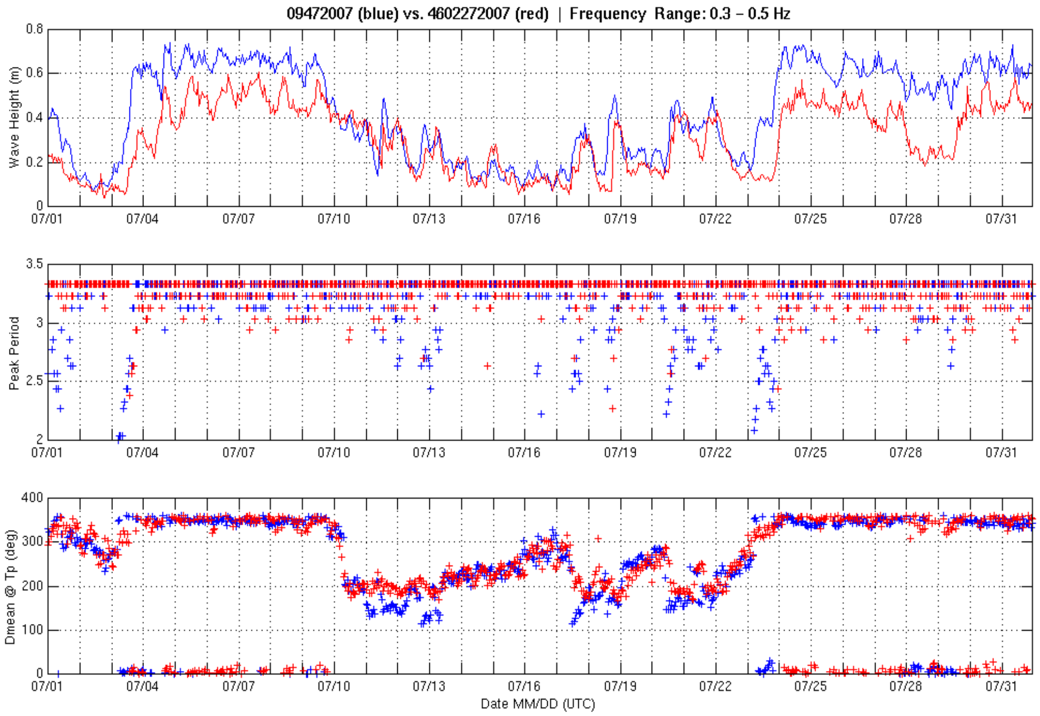


Figure 4b. Time series comparisons against the reference buoy for wave height, period and direction for a specified frequency range.



CDIP Wave Spectra Comparison Tool, Beta Version

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Figure 5. Proposed Vision for OceanSITES reference mooring network.

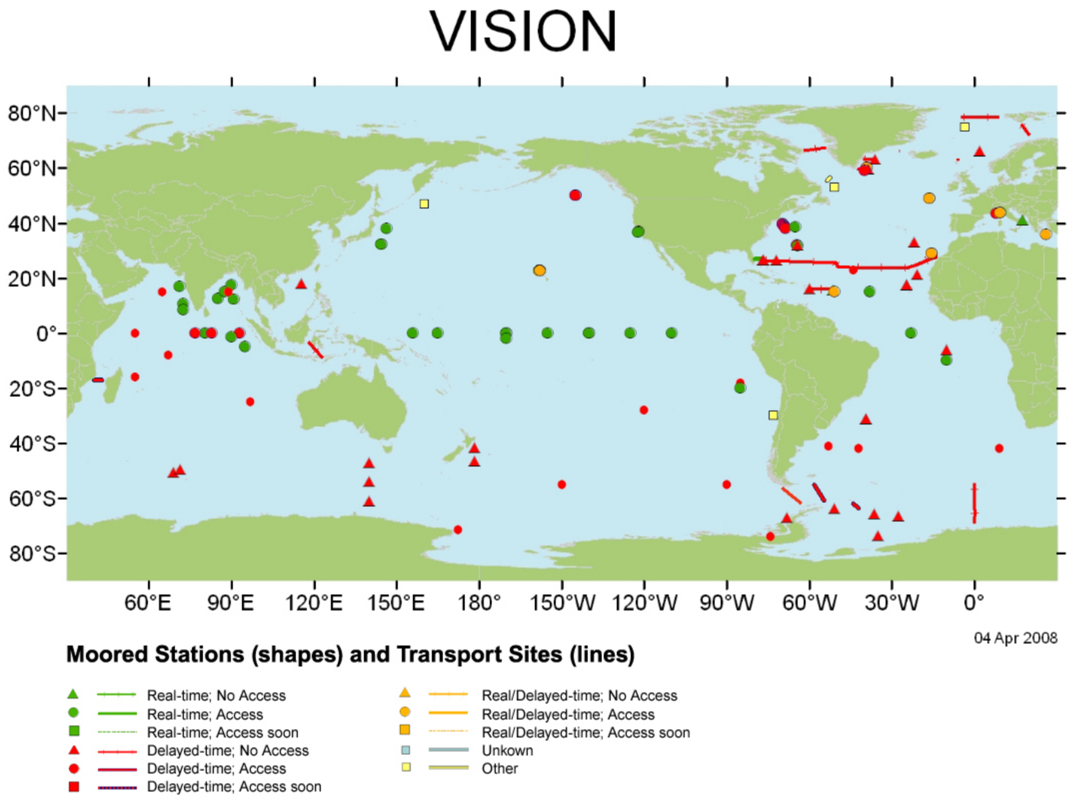

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Figure 6. Schematic subnets for a wide continental shelf.