IOOS Wave Observations, a National Perspective

William A. Birkemeier, Robert E. Jensen
US Army Corps of Engineers, ERDC-CHL
Vicksburg, MS, USA

Landry J. Bernard, Richard Bouchard
National Data Buoy Center, NOAA
Stennis Space Center, MS, USA

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***Abstract*— The 2009 National Operational Wave Observation Plan is being updated in 2012 to reflect the present state of the wave observation network and revised to better define priority placements and upgrades, and to identify the stations with the longest data records. The revised plan, which is based on the existing 200 locations, defines a perimeter *Backbone* network of observing sites and proposes adding 47 new locations and upgrading the directional wave measurement of 87 stations. 10 Rover Buoys are recommended to be used with one year deployments to evaluate regional wave models so that they can be used as virtual wave gauges. The plan also identifies 60 of the existing US backbone locations with record lengths of 20 years or longer (the longest record is 38 years). These *Sentinel Stations* are critical to understanding climatic changes to the Nation's wave conditions. In this paper, we review the status of the nation's wave observation network, present a number of proposed changes and describe a process using wave models and short-term wave sensor deployments to optimize the wave observations in a particular region.**

***Index Terms*— waves, observations, models, climate, IOOS**

I. Introduction

Surface waves are an oceanographic parameter of primary interest to the maritime community for many uses including safety at sea. Long-term wave records are important for studies of climate change, wave-derived energy resources and to identify extreme wave conditions – crucial information for the design of coastal and offshore structures and facilities. Real-time observations support marine operations and decision making. Wave models, verified with observations, provide accurate wave forecasts and can be used to fill in gaps between observations.

In 2009 the Interagency Ocean Observation Committee (IOOC) issued the *National Operational Wave Observation Plan* [1] (herein referred to as the *2009 Waves Plan*), which was developed as an interagency effort coordinated by the Integrated Ocean Observing System (IOOS®) Program led by NOAA and developed by the US Army Corps of Engineers (USACE) and NOAA's National Weather Service (NWS) National Data Buoy Center (NDBC). At that time, there were 180 wave observation sites nationwide and just over half reported wave direction at varying directional accuracy. From a national perspective, many were located in an ad hoc fashion and had been located primarily to support weather, not wave observations. The 2009 Waves Plan proposed a comprehensive system design that defined the *First-5* requirement as a standard level of accuracy [2], assessed the existing measurement locations, proposed adding observations in critical "gap" locations, proposed upgrades to existing platforms to meet the First-5 requirement and recommended a program of continuous testing and evaluation of wave sensors.

The proposed network consisted of four strategically-positioned arrays, or subnets of wave observing stations designed to monitor the generation and evolution of waves from the open ocean, through coastal boundary currents and islands, across the continental shelf, and finally to beaches and harbor entrances. The four subnets (Fig. 1) include: *offshore, outer-shelf, inner-shelf* and *coastal* and complement the operational and validation requirements of modern wave models and forecasts.

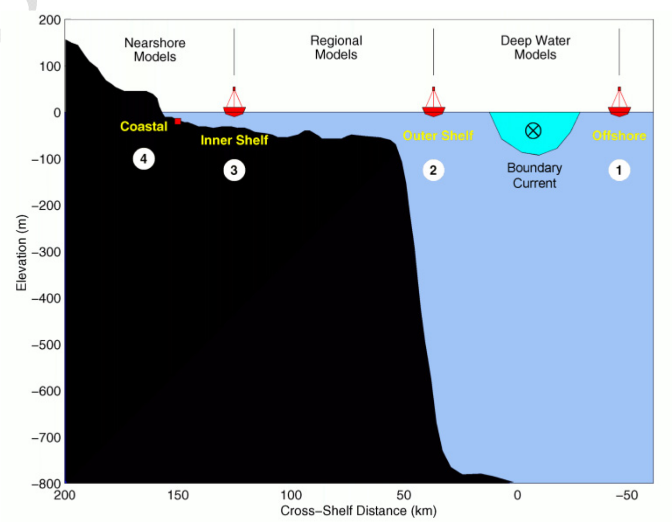

Figure 1.The four wave observation subnets (Offshore, Outer-Shelf, Inner-Shelf and Coastal) related to ocean bathymetry on a wide continental shelf (black area) and numerical modeling requirements. The boundary current is shown in light blue and denotes a current coming out of the page

Though not fully implemented, the 2009 Waves Plan has already served as a planning tool for site relocations, capability upgrades and service priorities, and has provided the impetus for NDBC and the National Ocean Data Center (NODC) to expand the archive records to include more system metadata, quality flags, and all redundant measurements. It also prompted an international inter-comparison of wave sensors under the Joint Technical Commission for Oceanography and

Marine Meteorology (JCOMM). This effort is leading to a much improved understanding of the accuracy of existing (and future) wave data, and indirectly to better numerical wave models.

The National Operational Wave Observation Plan is being updated in 2012 to reflect the network changes that have taken place and to better recognize the fiscal realities of today. The plan includes:

- Strategic recommendations for directional upgrades;
- A reassessment of the number, location of, and priority for new locations
- Tighter integration between wave observations and wave modeling
- Identifying the longest running wave gauges as *Sentinel Stations*, crucial to wave climate studies.

Whereas in the 2009 Waves Plan, every existing wave sensor was automatically included in the design, in the 2012 update the design is based on the sensors required to create a national perimeter-*Backbone* for deep ocean, shelf, mid-shelf and coastal wave observations. Backbone sensors are of the highest priority for long-term sustainment. Traditionally the responsibility of the federal agencies, backbone locations may be supported by non-federal IOOS partners. Sensor locations that fall outside the backbone are identified as *Supporting Observations*. Supporting observations may be important, even critical locally, but are not as important from a national perspective. Supporting Observations are the responsibility of local IOOS regions and partners.

To help with prioritization, spatial gaps and equipment upgrades are identified only for Backbone locations. In addition, a point system was established to rank each location based on five criteria:

- Length of service (>20 yrs, 1 point; >35 yrs, 2 points)
- Proximity to Major US port (<80 km, 1 point)
- Directional Capability (directional, 1 pt, *First-5* directional, 2 points)
- Proximity to nearest backbone station (>100 km, 1 pt.)
- Network Location (Backbone, 2 pts; Supporting, 1 pt.)

The maximum score under this system is 8 points (6 points for a new location) and although the criteria will be further refined, it was found to have useful skill in identifying the highest priority network changes and upgrades.

A 2015 update of the National Operational Wave Observation Plan is a milestone in the Administration's National Ocean Policy Implementation Plan and it is anticipated that comments on the 2012 update will be incorporated into the 2015 document. Although it is a National plan, it is not an implementation document and there are no requirements to adhere to this plan. However, it should serve as a guide for future decisions about wave observation investments, siting, and instrument selection.

II. IOOS WAVE OBSERVATIONS IN 2012

In comparison to the 180 locations in 2009, in 2012 there are 200 active wave US sites being operated by a number of data partner organizations and reported through the National Data Buoy Center (http://www.ndbc.noaa.gov). Of these, 163 make up the *Backbone* and 37 are *Supporting* observations. An additional 17 locations operated by Environment Canada are also considered as *Supporting* since they extend the backbone coverage.

Table 1 summarizes the *Backbone* locations by basin, platform, and whether the location measures wave direction (108) or not (55). That 66% of the sensors are directional is an increase over the 57% in 2009. Of the directional sensors, 56 (52%) satisfy the *First-5* directional criteria (34% of the total), a significant increase over the 30 that existed in 2009. There's also been a shift in the observing platforms. In 2009 there were 13 10-m and 12-m discus buoys in use, now down to 4. The number of 6-m ship-like NOMAD buoys is also down from 38 to 23. The 3-m discus buoy (aluminum or foam) is the most popular platform with 73, up from 57.

Table 1. Summary of Existing Backbone Wave Observing Platforms (diameters in m)

	Discus		Nomad	Discus	Other Buoy Configurations							
Region	12	10	6	3	2.5	2.4	2	1.75	1.12	0.9	Bottom Mount	Total
Atlantic Coast			7	24		1	1	1		11	2	47
Non-Directional			7	9		1	1					18
Directional				15				1		11	2	29
Gulf of Mexico		2		9						1		12
Non-Directional				1								1
Directional		2		8						1		11
Pacific Coast				25						22		47
Non-Directional				11								11
Directional				14						22		36
Alaskan Coast	2		14							2		18
Non-Directional	2		14									16
Directional										2		2
Pacific Islands				7		1				8	1	17
Non-Directional				2								2
Directional				5		1				8	1	15
Great Lakes				5		4			4			13
Non-Directional				1		2						3
Directional				4		2			4			10
Caribbean			2	3	3					1		9
Non-directional			2		2							4
Directional				3	1					1		5
Total	2	2	23	73	3	6	1	1	4	45	3	163
Non-directional	2		23	24	2	3	1					55
Directional		2		49	1	3		1	4	45	3	108

Although there are 20 more active US stations in 2012 (200 vs.180), a significant number (24, 12%) were reported to be offline at the time of the inventory. Thirty-four stations were decommissioned since 2009 including three with data records in excess of 28 years (44004, 42007 and 46023). This reflects the dynamic nature of the network and the challenge of maintaining a national array that depends on partnerships and is not funded by a single entity. Some of these lost sites were critical to the continuity of the original network design. Fifty-four new stations were deployed, of these, 11 filled proposed

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locations in the 2009 Plan, an indication of the value of the 2009 Waves Plan and the independent nature of IOOS deployments, when many different factors and requirements necessarily go into siting decisions.

A growing number of studies have attempted to determine trends in the wave climate using the historic observations [3,4,5,6]. This is challenging since none of the sensors were originally deployed with climate observations in mind and each location has seen changes in position, platform, sensor, sampling scheme and analysis software [7]. The longest wave records in the US are just 38 years (46001, Gulf of Alaska and 46002, Coos Bay OR). Compared to the longest tide record (158 years in San Francisco Bay), our wave records are short. Longer records, combined with a careful reanalysis of the historic data to identify and remove biases, are required. Of the existing wave measurement stations, 60 Backbone sites (72 if Supporting and Environment Canada stations are included) have been identified as *Sentinel Stations* with observation records longer than 20 years; 11 stations have more than 35 years of observations. Figure 2 illustrates the record length of the existing stations in 5-yr bins. Sentinel Stations are well distributed around the country (Fig. 3), although there are some gaps.

To insure climate quality data from these stations requires that:

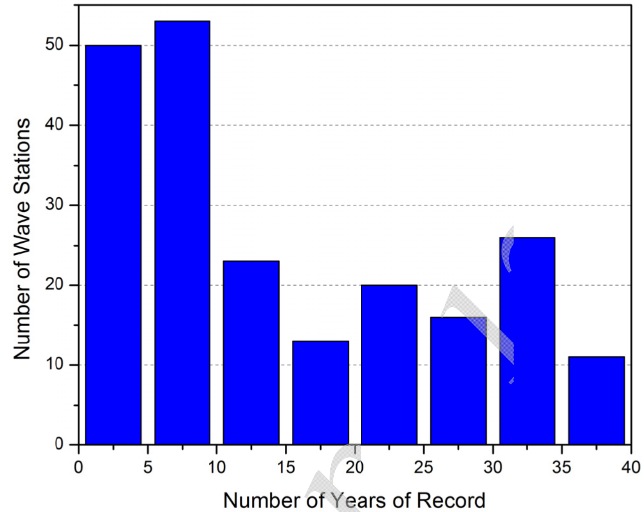

Figure 2. Observation statistics for active wave stations. Sentinel Stations are those with record lengths of 20 yrs or more.

- they receive the highest priority in terms of funding and field support to keep downtime to the absolute minimum;
- they are able survive the most extreme conditions, guaranteeing that even the most infrequent severe storm conditions are observed;

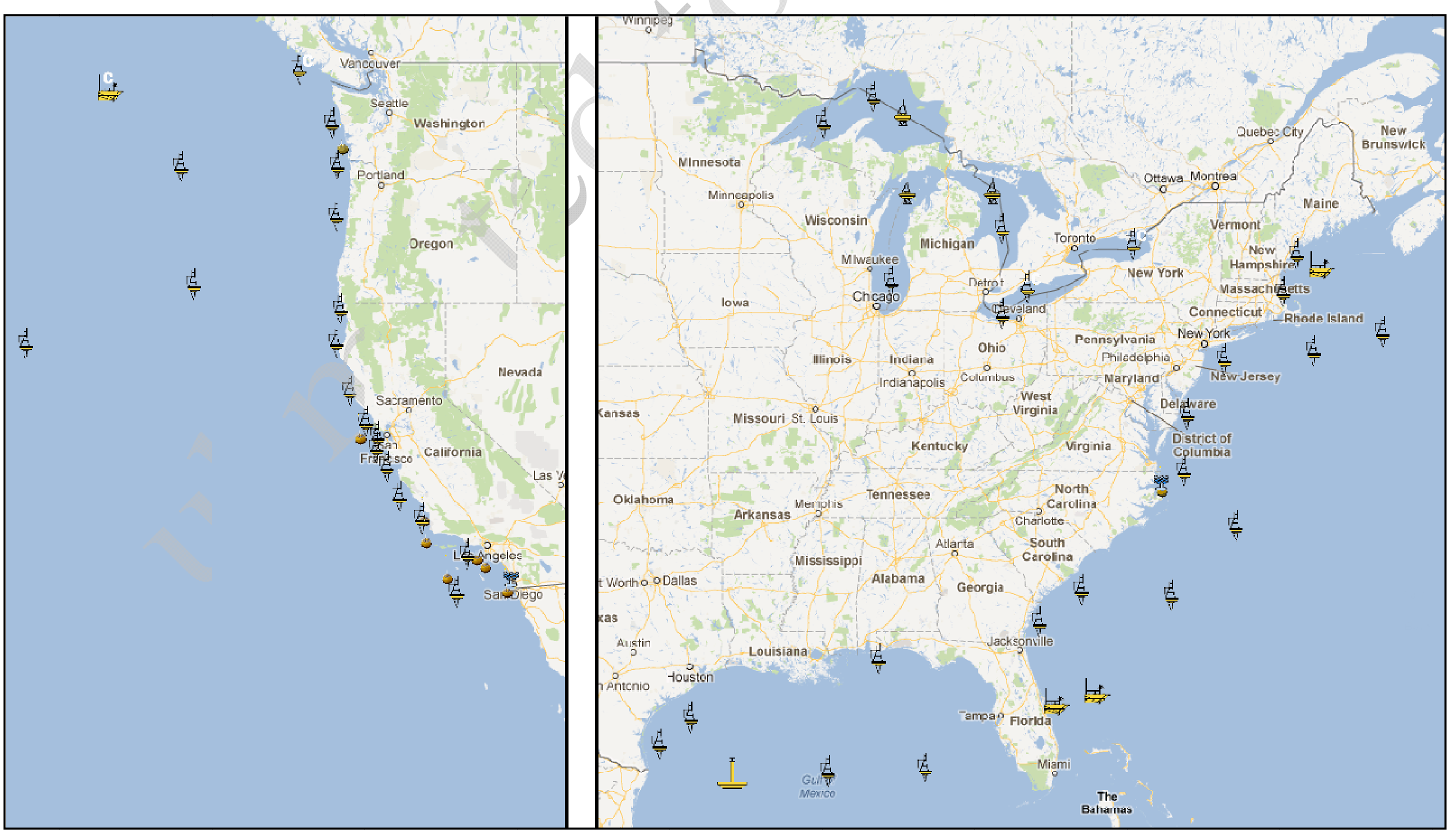

Figure 3. Sentinel wave observing stations with 20+ years of collected data (white "C" next to an icon indicates an Environment Canada location.)

Table 2. Summary of Proposed and Existing Wave Observation Locations																										
	Subnet																				**Total**					
	Offshore				**Outer-Shelf**					**Inner-Shelf**					**Coastal**											
Region	*Backbone Design*	*Backbone Exists*	*Proposed*	*Backbone Sentinel*	*Backbone Design*	*Backbone Exists*	*Proposed*	*Supporting*	*Backbone Sentinel*	*Backbone Design*	*Backbone Exists*	*Proposed*	*Supporting*	*Backbone Sentinel*	*Backbone Design*	*Backbone Exists*	*Proposed*	*Supporting*	*Backbone Sentinel*	*Rover Buoy*	*Backbone Design*	*Backbone Exists*	*Proposed*	*Directional Upgrade*	*Supporting*	*Backbone Sentinel*
Atlantic Coast	13	11	2	3	10	7	3	2	4	11	10	1	2	4	31	19	12	15	4	4	65	47	18	26	20	15
Gulf of Mexico	4	4		3	6	2	4		1	5	4	1		1	10	2	8	3	1	1	25	12	13	10	4	6
Pacific Coast	11	10	1	6	25	25		3	17				1		12	12		4	2	4	48	47	1	20	11	25
Alaskan Coast	7	7		1	9	9			1	5		5			2	2		3		5	23	18	5	11	10	2
Pacific Islands	10	9	1	4	1	1									12	7	5			2	23	17	6	6		4
Great Lakes										13	9	4	6	8	4	4		3		13	17	13	4	9	9	8
Caribbean	5	5													4	4					9	9		5		
Total	50	46	4	17	51	44	7	5	23	34	23	11	9	13	75	50	25	28	7	29	210	163	47	87	54	60

- any impact or bias resulting from future instrument/software improvements should be quantified so as to not adversely impact the historic record;
- any biases or problems with the historic data be documented and resolved (as much as possible) in order to remove, or at least minimize the impact of instrument changes on the long-term record.

To further the use of wave observations for climatic studies, NDBC and the National Ocean Data Center (NODC) have made changes to the NDBC wave records archived since January 2011 (http://www.nodc.noaa.gov/buoy/). These records now include all data, not just the released data along with any quality control indicators, more extensive metadata, and a new file format which uses the network Common Data Form (netCDF).

It should be noted that while wave model results can be used to fill short gaps in the observation record, since wave models are based on wind input, they are unable to reproduce subtle changes in the wave climate, observations are needed.

Some Sentinel Stations are unique like the 26-yr record at FRFLA in Duck, NC by the US Army Corps of Engineers. Because of its multi-pressure sensor design, FRFLA provides the highest directional resolution of any observation station and can be used to determine if there has been a directional shift in the mid-Atlantic coastal wave climate. Most of the Sentinel Stations are on the Pacific Coast (28). Four surround the Hawaiian Islands. There are no Sentinel Stations in the Caribbean. Along the Pacific Coast, adjacent Sentinel locations are as close as 50km, a level of coverage likely not necessary for analyzing climate trends.

As a step toward improving the quality of existing and historic wave observations, JCOMM has been working with NDBC, USACE, the Coastal Data Information Program (CDIP), the Environment Canada and others in an ongoing evaluation of existing platforms and sensors using side-by-side comparisons. This important work is identifying new information about biases in commonly used devices, a result that will have far reaching implications to models and to remote sensing systems that have used in situ measurements made with these systems for calibration and evaluation.

III. RECOMMENDED NETWORK CHANGES

The 2009 Waves Plan and the 2012 revision are five year plans. We can assume that waves will continue to be an important IOOS observation parameter and that the network will continue to be dynamic and a challenge to sustain both from operational and funding perspectives. Consequently a dynamic yet robust plan which objectively prioritizes locations and strategically identifies and fills gaps is required.

The 2012 Waves Plan is based on the existing observations locations (independent of owner) and an updated analysis of the proposed locations from the 2009 Waves Plan. Emphasis was given to (1) Outer-Shelf locations because they serve a wide region but are still relevant to the coast and (2) Coastal locations. Coastal locations are in 10-20 m water depth, deep enough to be outside the breaking wave zone during extreme events.

As listed in Table 2 and shown in Figs 4, 5, 6 and 7, the updated plan proposes 47 new permanent locations (compared to 115 in the 2009 Plan) and 87 directional upgrades (compared to 128). The upgrades would bring the total number of sites meeting the directional accuracy standard up to 190. Most of the proposed locations address high priority gaps in the

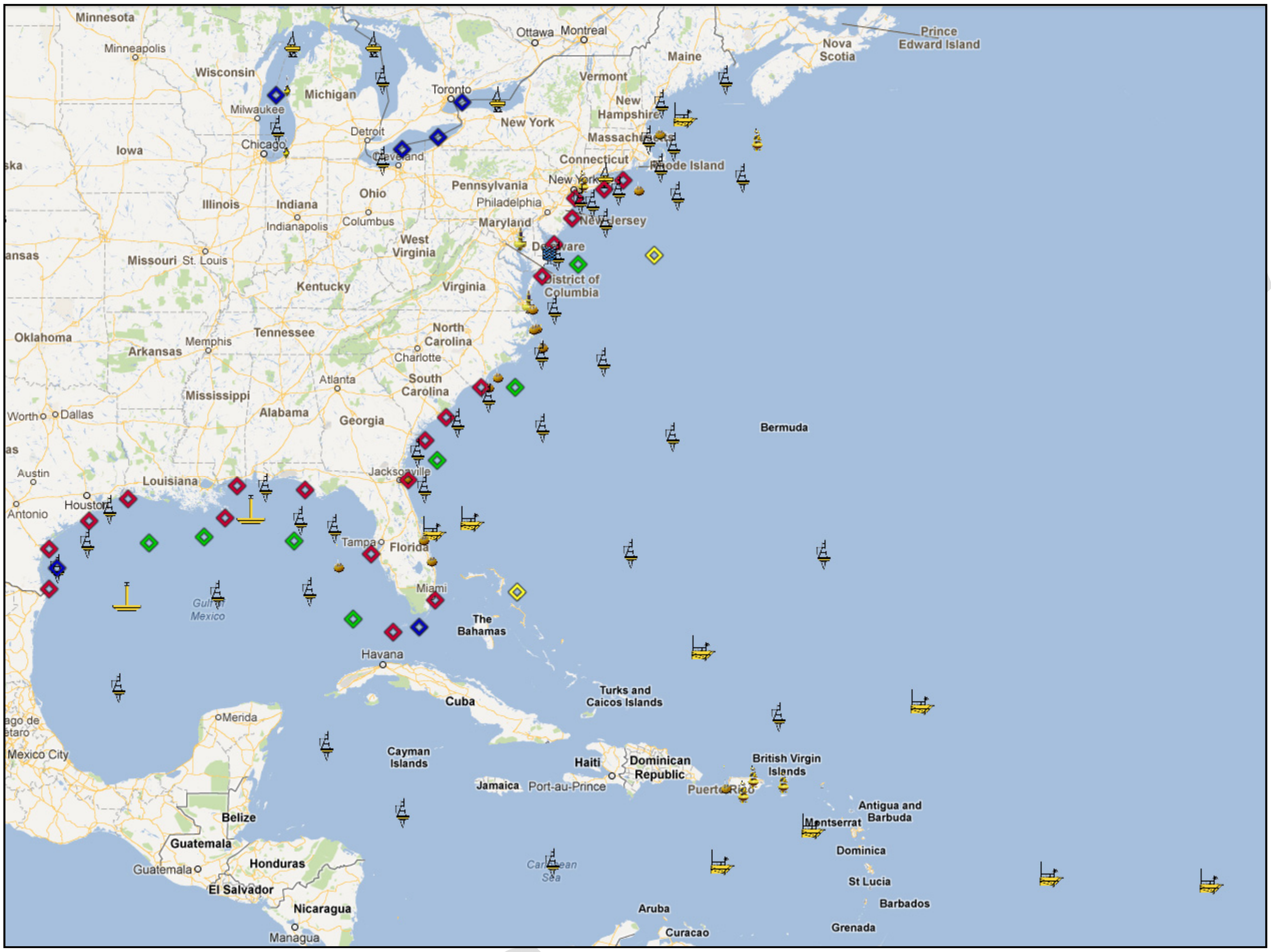

Figure 4. Locations of backbone and proposed (colored symbols) wave observing locations in the Atlantic, Gulf of Mexico and the Great Lakes. Symbol color indicates subnet: red, coastal; blue, inner-shelf; green, outer-shelf; yellow, offshore.

backbone, particularly near major ports. Using the 8-pt ranking system described above, 12 of the proposed new locations scored a 4, 31 scored a 5, and 4 scored a 6, the maximum amount for new stations. In fact, all the proposed stations ranked higher than 42 existing stations that scored a 3 or lower.

The score is lower for a non-directional site or for a station with low directional resolution. Whereas in the 2009 plan, every sensor was to be brought up to the First-5 standard, in the update, directional upgrades are strategically planned based on location and ease of upgrade. Most of these locations can simply accept an improved directional sensor during a maintenance call. There's also some recent evidence that 6-m NOMADS, traditionally considered non-directional, may be upgradable, a feature that JCOMM is looking into.

When fully deployed, there would be ~210 permanent backbone wave sensors reporting, a national network that would improve the nation's overall wave observations in terms of spatial coverage and data quality. This plan does not address any regional or local requirements and only includes limited estuary support based on port traffic.

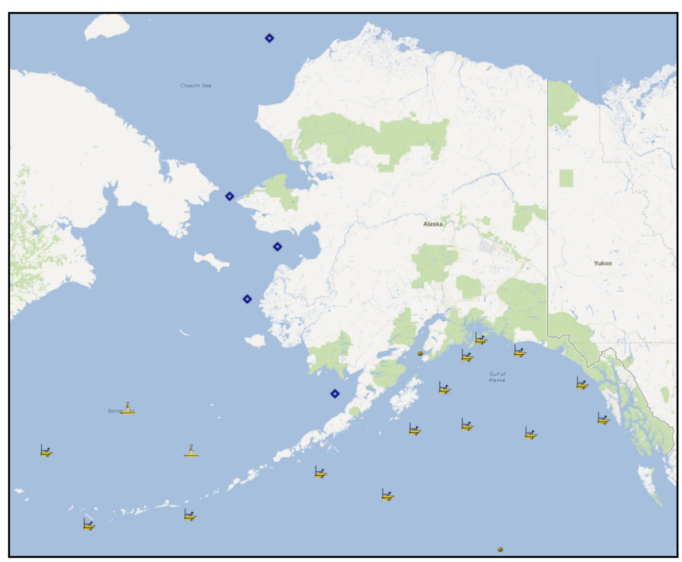

Figure 5. Locations of backbone and proposed (colored symbols) wave observing locations for Alaska. Blue symbol indicates inner-shelf subnet

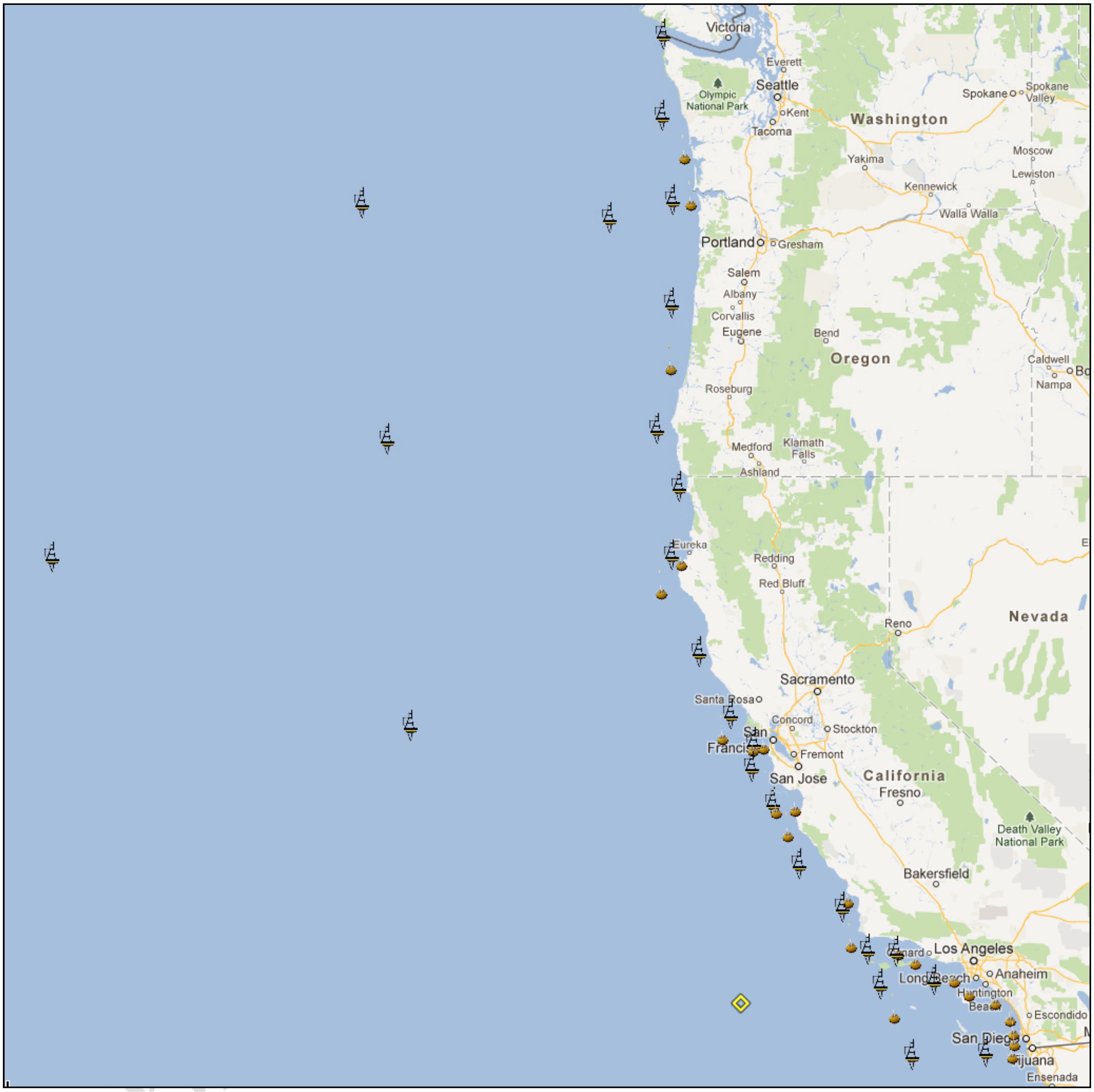

Figure 6. Locations of backbone and proposed (colored symbol) wave observing locations for the Pacific West Coast. Yellow symbol indicates offshore subnet.

The 2012 Waves plan proposes the use of "*Roving Buoys,*" strategically deployed for one or two years for the specific purpose of improving local numerical wave model hindcasts, nowcasts and forecasts. The process of using existing observations and *Roving Buoys* will be similar to conducting an Observing System Experiment or OSE where the impact of selectively removing an observation is quantified on predictive results. Since wave models use wind information as input and don't assimilate wave observations, a classic OSE can't be performed. Instead strategically placed observations can be used to verify model results and to fine tune model parameters like grid resolution, bottom friction and bathymetric detail. Once a model is evaluated/verified, the *Roving Buoys* can be moved to a new location. These experiments can also be used to identify, refine, and prioritize the permanent wave observing locations in an area.

A suite of ~10 *Roving Buoys* is recommended and an initial 29 locations are identified where they would be useful. Eventually as wind and wave models and their forecasts improve, the number of permanent wave observation locations could be reduced.

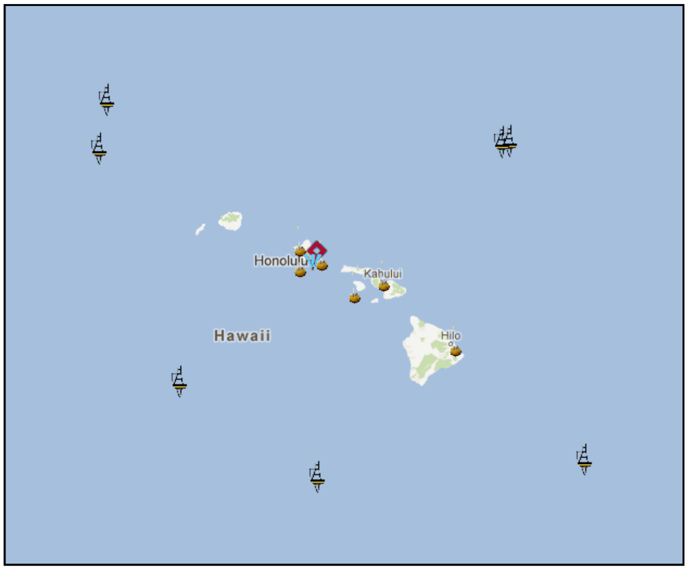

Figure 7. Locations of backbone and proposed (colored symbols) wave observing locations for Hawaii. Not shown are seven Pacific Island locations which are outside of Hawaii.

IV. IMPLEMENTATION

Though not an implementation plan, revising the IOOS Waves Plan raised a number of significant issues that will have to be addressed by the ocean observing community and data providers, including:

- How to sustain the existing system in the present economic climate. Long-term 24/7 operational observations at sea are expensive.
- How to prioritize the observations based on an overall network design. The observations serve a wide community but are often funded by individual partners. When funding is cut, an important sensor which many depend on may simply disappear.
- What are the appropriate metrics for prioritization? Distance to ports? Length of data record? Importance to ocean wave forecasting? A process is required to reconcile the priorities of individual sponsors into national priorities.
- How best to capture the use of the existing wave locations so that information can be incorporated into the prioritization and decision making process.
- How to identify and take advantage of new and evolving observation and software technology to increase reliability and accuracy while minimizing costs (capital investment, O&M, and data handling);
- How to reconcile local and national wave observing requirements.

Many of these questions are not specific to wave observations but apply equally to other IOOS observations.

V. OBTAINING MORE INFORMATION

Details about the National Operational Wave Observation Plan including the 2009 Waves Plan, a draft of the 2012 Waves Plan, a KMZ file of the locations for overlay on Google Earth™ and a spreadsheet with detailed station information can be found online at: http://www.ioos.gov/waves. The KMZ file is particularly useful as it allows the network to be graphically explored by location, subnet, ranking, years of service, and ownership. This website also allows comments to be submitted. Comments are encouraged regarding network design, spatial coverage, site prioritization, regional plans, user requirements, network benefits, and partnerships.

VI. CONCLUSIONS

The 2009 National Operational Wave Observation Plan is being updated to reflect the current state of the wave observation network and revised to better define priority placements and upgrades. Several significant changes to the 2009 Waves Plan are the identification of *Backbone* and *Supporting* sites; the use *Rover Buoys* to refine to improve regional wave models and to refine the network design, and the identification of *Sentinel Stations* as those with the longest data records. The wave observation network has evolved since 2009 with more assets in the water and more locations meeting the plan's high quality directional wave accuracy standard. When fully deployed, the 2012 Waves Plan recommends a backbone network consisting of 210 locations with 190 stations meeting the directional accuracy standard and including 60 *Sentinel Stations.*

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