Field Laboratory for Ocean Sea State Investigation and Experimentation:
FLOSSIE
Intra-Measurement Evaluation of 6N Wave Buoy Systems

R.E. Jensen[1], V.R. Swail[2], R. H. Bouchard[3], R.E. Riley[3], T.J. Hesser[1], M. Blaseckie[4] and C. MacIsaac[4]

[1]US Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory (ERDC-CHL)

[2]Environment Canada

[3]National Oceanic and Atmospheric Administration
National Data Buoy Center (NOAA-NDBC)

[4]AXYS Technologies

ABSTRACT

Point-source wave measurements have and continue to be an important element in assessing the wave conditions, aiding the Weather Prediction Center's evaluations of their forecast, used in data assimilation, wave modeling investigations, used in algorithms estimating waves from satellite-based altimeters, climate studies, wave energy resource assessments and other applications. The work presented here assesses the similarities/differences between various sensor/payload packages housed in a 6N NOMAD buoy that is deployed in Monterey Canyon as part of the Buoy Farm, and a comprehensive intra-measurement evaluation.

INTRODUCTION

The National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC) and Environment Canada (EC) have been operating networks of meteorological and wave measurement sites in the Atlantic, Pacific, Gulf of Mexico and Great Lakes for the past four decades (Timpe and Van de Voorde, 1995; Skey et al. 1995). The platforms used by these two agencies vary from discus buoys of varying sizes to a standard 6-m (6N) Navy Oceanographic and Meteorological Automatic Device, or NOMAD buoy. These data sets have been instrumental in the evaluation of wave model results in a hindcast or forecasting mode, used by the satellite-based remote sensing community building algorithms estimating the significant wave height from altimeters, and SAR images, and in research efforts studying the role of surface-gravity wind waves in air-sea interactions and surface flux estimations.

Over the period of record there have been modifications to the platform, sensor and payload (on-board analysis package) that can affect the long-term records (Gemmerich et al., 2011) that have been used to assess the trends in the wave climate (e.g. Allan and Komar, 2008; Ruggerio et al., 2010; and Menéndez et al., 2008). Using altimeter data as a common reference, Durrant et al. (2009) compared EC and NOAA-NDBC wave height data and found a systematic difference of 10-percent in significant wave height reported by EC and NDBC. Large portions of the point-source measurements were derived from 6N buoy systems. With these results, and NDBC planning to decommission all of their NOMAD buoys, it became a necessity to construct a meaningful experiment in hopes of answering some of the questions regarding these long-standing data records.

In 2012, a plan for an experiment Field Laboratory for Ocean Sea State Investigation and Experimentation (FLOSSIE[1]) was developed, where a 6N hull would be configured with all historical sensor, and payload packages used by NDBC during the past four decades. Gemmrich et al. (2011) identified the various configuration changes in seven wave platforms located in the Pacific. They identified over time where the hull, payload, and processor changes occurred at these sites. The changes reflected discontinuities in the data records from -0.66-m to +0.59-m. If these different configurations were placed in one hull and evaluated it would provide a means to account for temporal changes in payloads and sensor systems by NDBC while evaluating the accuracy of the archive data sets. In addition to the NDBC sensor (and payload systems), AXYY® has provided their new sensor system (TRIAXYS) and two payloads that will be used to directly assess differences between EC and NDBC 6N buoy records.

FLOSSIE is part of the continued effort of the U.S. Army Corps of Engineer (USACE) Engineer Research and Development Center's Coastal and Hydraulics Laboratory (CHL) to test and evaluate wave measurements. This has been identified in the US IOOS Waves Plan (IOOS, 2009). Insights of the Test and Evaluation have been documented in Swail et al. (2009) and Jensen et al. (2011). In a subsequent paper (Luther et al. 2013) provided detailed procedures to be followed, also identified in the Alliance for Coastal Technologies (ACT/UMCES, 2012). The recurring theme across these documents was the need to test and evaluate historical and existing wave measurement platforms and seek a standard evaluation for new technological advancements.

A secondary motivation of FLOSSIE was based on an investigation by Durrant et al. (2009). Their study was based on significant wave height measurements from sixty-three point source measurements located in the Atlantic, Gulf of Mexico, and Pacific. Of the total, fifty-one were NDBC buoys, ten Environment Canada (EC) buoys and two buoys from an Integrated Ocean Observing System (IOOS) regional domain. Data were also obtained from a variety of wave measurement platforms, as shown in Table 1.

Table 1. Number of Buoy Systems and Co-Located Altimeter Observations (from Durrant et al. (2009)

Owner	**Atlantic**			**Pacific**			**Gulf of Mexico**			**Total 6N/Tot**	***Jason* Obs.**	***Envisat* Obs.**
	12-10D	**3D**	**6N**	**12-10D**	**3D**	**6N**	**12-10D**	**3D**	**6N**			
NDBC	0	8	6	1	7	13	3	13	0	19/51	3452	2157
EC	0	5	0	0	2	3	0	0	0	8/10	1128	478
IOOS	0	2	0	0	0	0	0	0	0	0/2	N/A	N/A
TOTAL	0	15	6	1	9	16	3	13	0	22/63		

The analysis used altimeter data (*Jason-I* and *Envisat*) as a common reference. The results of the analysis concluded the EC buoys under estimated the significant wave heights relative to the NDBC buoys by about 10-percent. These results suggests a disparity between two North American wave measurement providers using very similar buoy systems defined by the hull, mooring, superstructure. The differences also grew with increasing significant wave heights. Despite shortcomings in the analysis procedures it does point out the two primary North American wave data providers differ in the estimates of the significant wave heights.

Three primary efforts in this investigation are:

1. To study the similarities and differences in NDBC's 6N historical configurations defined by the payload, sensor, and processor.
2. To study the similarities and differences between NDBC and EC 6N sensor/payload configurations.

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[1] The project is named in honor of the pioneering World War II Naval meteorologist, Commander Florence (Flossie) Van Straten (1913 – 1992), USNR, who coined the acronym for NOMAD.

3. To investiagte the accuracy in estimating directional properties derived from non-symmetric hull configurations?

<u>FLOSSIE AND THE BUOY FARM</u>

FLOSSIE is configured with multiple sensor and payload systems housed in one hull, combined with a standard suite of NDBC meteorological sensors (anemometers, barometric pressure, air and water temperature sensors). This is illustrated in Figure 1. There are four primary compartments in a 6N buoy, (Figure 1). Compartments 1 and 4 (Figure 2) are empty except for cable pass-through. Compartment 2 contains the HIPPY, and TRIAXYS (MacIsaac and Naeth, (2013) sensor and payloads (WATCHMAN and Wave Module), batteries and internal temperature sensor. Compartment 3 houses NDBC's motion systems:

- Data acquisition and Control Telemetry Wave Analyzer (DACT WA) using an inclinometer to measure vertical acceleration (NDBC, 1996),
- Acquisition and Reporting Environmental System Directional Wave Processing Module (ARES DWPM[2]) using a Datawell HIPPY 4- to measure vertical acceleration, pitch and roll, magnetotometers provided Earth magnetic flux measurements to determine the buoy's orientation with respect to magnetic north, and
- NDBC Smart Module Digital Directional Wave Module (DDWM, Riley et al., 2011) using the Microstrain 3DM-GX1® that has output from three orthogonal accelerometers, three orthogonal angular rate sensors and three orthogonal magnetometers.

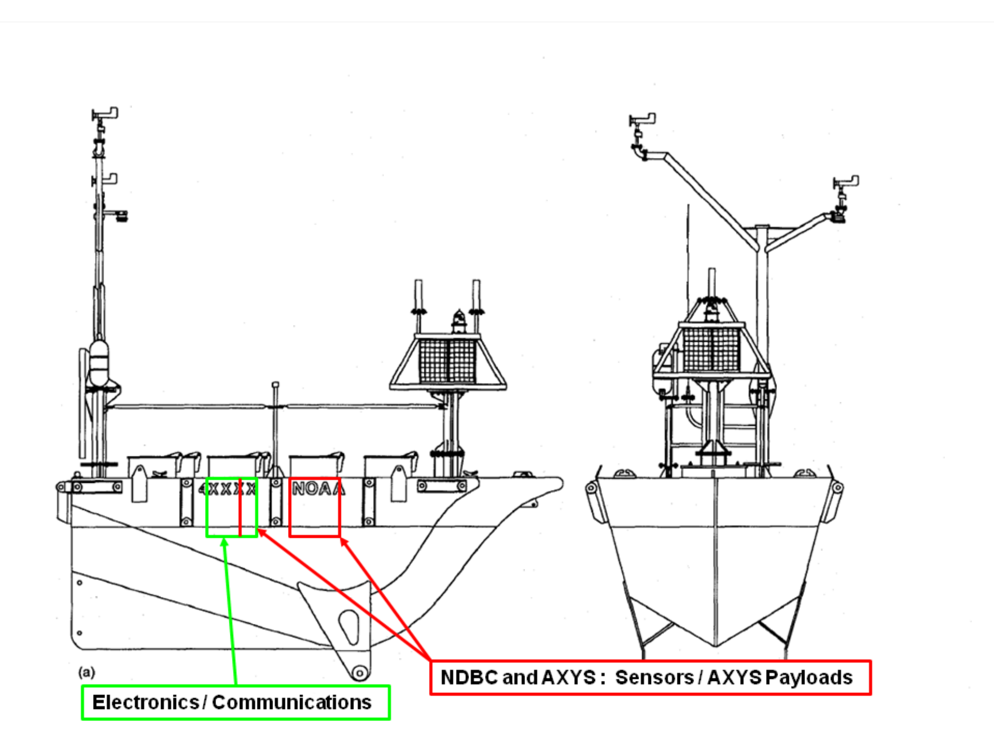

Figure 1. Schematic of a 6N buoy configuration, from Timpe and Van de Voorde, 1995. Anemometers are positioned differently (see Figure 2) from this diagram.

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[2] DWPM is not covered in NDBC (1996) but is essentially WPM (Wave Processing Module).

All real-time NDBC and AXYS® data are transmitted separately via IRIDIUM communications. The 3DMG and AXYS® original time series are also stored to disks onboard. These disks will be recovered during scheduled maintenance runs to the buoy on a yearly basis. There are a total of five different data sets recovered from FLOSSIE:

1. NDBC: Inclinometer / DACT WA(non-directional).
2. NDBC: HIPPY/Magnetometer DWPM (original sensor/payload package to estimate directional waves)
3. NDBC: Motion Sensor MicroStrain 3DM-GX1® DDWM
4. AXYS®: TRIAXYS Next Wave II Directional Wave Sensor / Wave Module (new payload package used for directional wave measurements, e.g. TRIAXYS buoys).
5. AXYS®: EC-Watchman (strapped down accelerometer used by Environment Canada)

FLOSSIE is the focal point of this paper, however there is much more to the intra-measurement evaluation that is part of the Buoy Farm located in Monterey Bay Canyon (Figure 3). Besides FLOSSIE containing multiple sensor/payloads, three other wave measurement systems have been deployed. This is one of two primary wave measurement evaluation locations defined by ACT/UMCES (2012), and Luther et al. (2013). The Buoy Farm now consists of FLOSSIE, an NDBC 3-m aluminum discus hull NDBC discus buoy containing two sensor/payload packages (HIPPY/ MicroStrain 3DM-GX1® , Riley et al., 2011), and a Datawell® Directional Waverider buoy operated by the Coastal Data Information Program (CDIP, http://cdip.ucsd.edu/).

6. NDBC: HIPPY / DWPM payload (directional estimates)
7. NDBC: MicroStrain3DM-GX1® / DDWM payload (directional estimates)
8. CDIP/USACE: Datawell® Directional Wavrider (directional estimates)

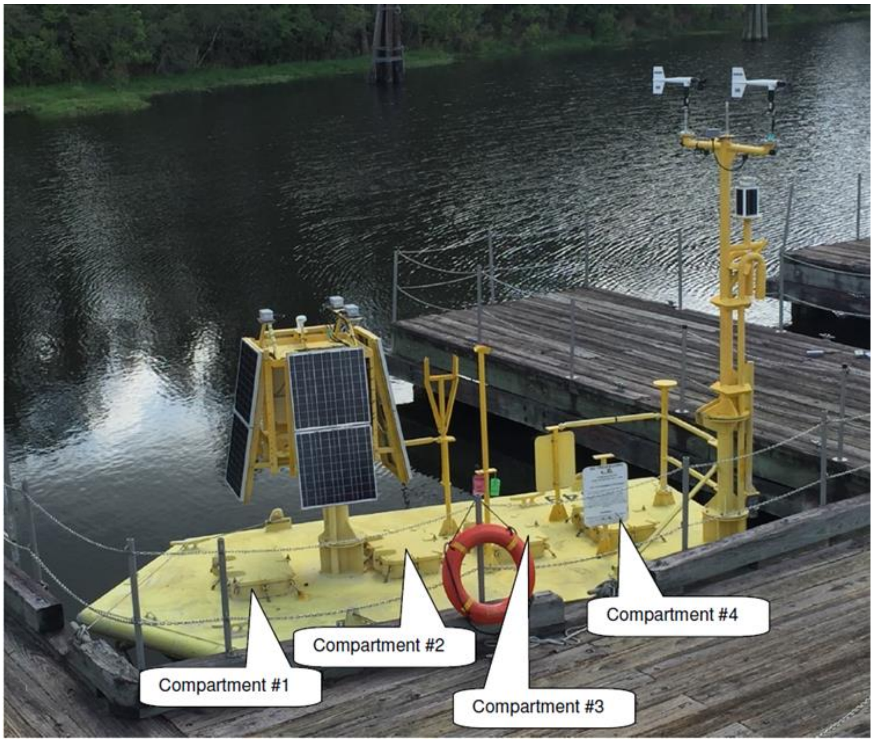

Figure 2. Picture of FLOSSIE dockside at NDBC, (provided by R. Riley, NDBC).

The Datawell® Directional Waverider buoy was selected as the *relative reference* to be used in all wave intra-measurements evaluations (IOOS, 2009; ACT/UMCES, 2012 and Luther et al. 2013). This is not to suggest a Datawell buoy is the standard for wave measurements; it was selected because these systems have been used operationally for over forty-years by a wide variety of users, including CDIP and the international offshore oil and gas industry. Data are transmitted from these systems on a sixty or thirty minute interval via IRIDIUM communication protocols. All raw data (e.g. time series) is saved to flash drives and internally stored onboard. These data sets will be retrieved during scheduled maintenance of the various buoys in Monterey Canyon. The Datawell transmits the raw time series directly to the CDIP operational center on a sixty minute interval via Iridium.

AXYS® has also offered an additional TRIAXYS sensor/payload package to be mounted on an NDBC 3D buoy and a complete TRIAXYS buoy system. Plans are underway to add these systems to the existing array of wave measurement systems presently deployed in the Buoy Farm.

MEASURED DATA FROM THE BUOY FARM

In general there are two primary data files for each of the eight wave measurement systems. The first data set contains the integral wave parameters: significant wave height (H_{mo}), wave period (the peak spectral wave period T_p, and/or a mean wave period T_{mean}), and an estimate of the wave direction (mean wave direction at the peak frequency $\theta_{mean}(f_m)$. AXYS® systems provide additional integral wave parameters derived from the raw time series: H_{ave} (average wave height), H_{max} (maximum wave height), T_{max} (maximum wave period), $H_{1/10}$, $T_{1/10}$ (highest one-tenth wave height, and wave period), T_{ave} (average wave period), H_{sig}, T_{sig} (significant wave height and period defined from the average of the highest one third wave height in the record), T_{p5} (peak period READ method) , and the wave steepness. Meteorological instrumentation onboard NDBC 46042 and 46FLO provides measurements of:

- Wind Speed, U_5 / Wind Gust, U_G
- Wind Direction, θ_{wind},
- Barometric Pressure, B_p
- Air and Water[3] temperature, T_{air}, T_{water}.

The second data set consists of spectral and directional estimates derived from the time series of the buoy motion. These parameters are defined by:

$$S(f,\theta) = S(f)[a_1 \cdot \cos\theta + b_1 \cdot \cos\theta + a_2 \cdot \cos 2\theta + b_2 \cdot \sin 2\theta + a_2 \cdot \cos 2\theta + b_2 \cdot \sin 2\theta \\ + b_3 \cdot \sin 3\theta + b_4 \cdot \sin 4\theta + \cdots] \tag{1}$$

S(f,θ) is the two dimensional wave spectra defined by the range in frequencies (f), and direction (θ). S(f) is the frequency spectra and sometimes defined by a_0 where $a_0 = S(f)/\pi$. The terms defined by a_1, b_1, a_2, b_2, … are the Fourier coefficients. Directional buoy measurements return the First-5 components in the infinite Fourier series (a_0, a_1, b_1, a_2, b_2) defined in Equation 1. The Datawell and AXYS systems spectral estimates are defined by the First-5 Fourier coefficients defined at each frequency band.

The NDBC computes Fourier coefficients onboard the buoy but recasts them as:

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[3] The Datawell Directional Waverider is equipped with a water temperature sensor.

$$S(f,\theta) = C_{11} \cdot \left\{ \frac{\left[{}^{1}\!/_{2} + r_1 \cdot \cos(\theta - \theta_1) + r_2 \cos(2(\theta - \theta_2)) \right]}{\pi} \right\} \tag{2}$$

C11 is equivalent to S(f) in Equation 1. The directional Fourier coefficients r1 and r2 are related to the a_1, b_1, a_2, b_2 values as:

$$r_1 = \sqrt{a_1^2 + b_1^2} \Big/ a_0 \tag{3}$$

$$r_2 = \sqrt{a_2^2 + b_2^2} \Big/ a_0 \tag{4}$$

$$\theta_1 = \tan^{-1}\left({}^{b_1}\!/_{a_1} \right) \tag{5}$$

$$\theta_2 = \left({}^{1}\!/_{2} \right) \tan^{-1}\left({}^{b_2}\!/_{a_2} \right) \tag{6}$$

NDBC represents the mean directional components (θ_1 and θ_2) by α_1 and α_2 where:

$$\alpha_n = \left({}^{3\pi}\!/_{2} \right) - \theta_n \tag{7}$$

where α_n represents the direction FROM which the waves originate following the conventions of the World Meteorological Office (WMO, 1995) and Frigaard et al. (1997). There is an ambiguity in θ_2. This value is either θ_2 or ($\theta_2+\pi$) whichever minimizes the difference between θ_1 and θ_2.

Altimeter estimates (track positions of various altimeters, from GLOBwave, http://globwave.ifremer.fr/) of the significant wave height will be accessed and compared to the data provided from FLOSSIE's multiple sensor/payload packages. An example for a one month period is displayed in Figure 3. The blue dots represent the significant wave height estimates from four altimeters (JASON-1, JASON-2, CRYOSAT, and SARL). There may be sufficient co-located altimeter and buoy data to perform a similar analysis performed by Durrant et al. (2009), to support or dispute the 10-percent differences they noted.

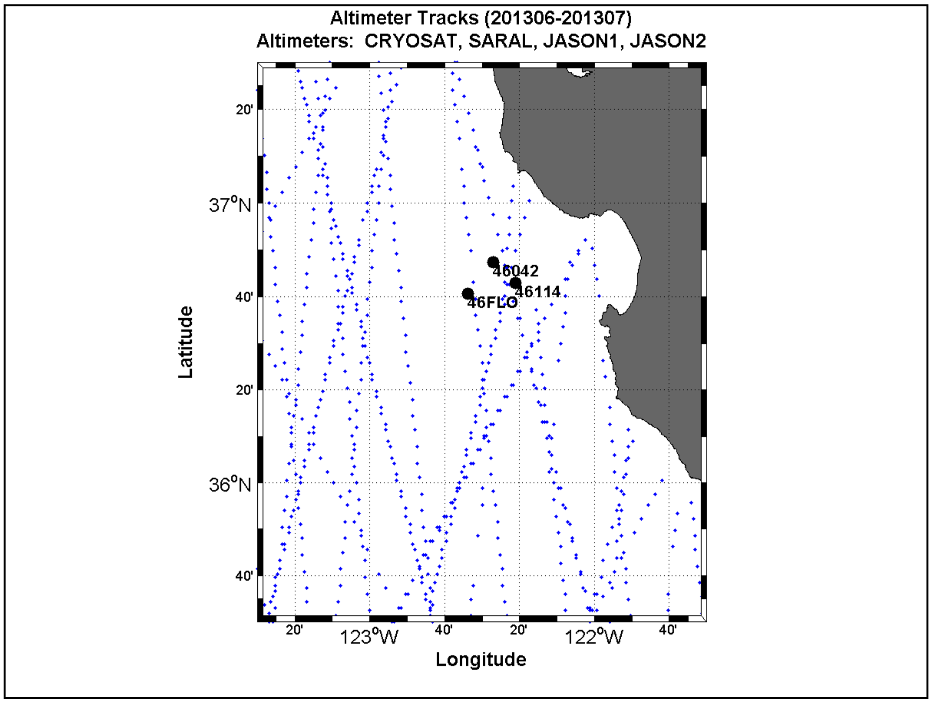

Figure 3. Buoy Farm located in Monterey Canyon. FLOSSIE (46FLO), NDBC 3D dual sensor (HIPPY/3DMG) buoy (46042), and a Datawell® Directional Waverider (46114). Altimeter tracks from various platforms are noted.

ESTIMATES IN THE EXPECTED BUOY FARM WAVE CLIMATE

FLOSSIE was deployed and became operational on 28 July 2015. General information regarding the various buoy platforms is provided in Table 2. All sites are stationed in deep water, roughly 20 to 30 nautical miles from the nearest coastline, and are located in a Marine Sanctuary. There are additional logistics and requirements to deploy in this area. Because the region is defined as a Marine Sanctuary there will be limited access from commercial activity. As noted in Table 2, 46042 and 46114 have been on-site for the past 28- and 4-years respectively measuring meteorological (46042) and wave conditions. Both NDBC and CDIP provide products to investigate the wind and wave climate by accessing their large data base and generating products.

Table 2. General Characteristic of Buoy Platforms

BUOY NO	Hull Type	Location		Depth (m)	Record Length	
		Latitude	Longitude		Start Date	Gaps
46FLO	6N	36° 40'14" N	122° 33' 43" W	2377	20150728	-
46042[1]	3D	36° 47'29" N	122° 27' 06" W	2098	19980619[2]	Intermittent
46114	0.9 Spherical	36° 43'00" N	122° 30' 59" W	1463	20111101	201212-201305

[1] Dual sensor system (HIPPY/3DMG) start date 200910

[2] Start of directional wave measurements. Non-directional wave measurements started 19870709.

NDBC routinely generates graphical products depicting the variation in wind and wave conditions on a monthly basis. Figures 4 through 6 display the significant wave height, dominant wave period (identical to the peak spectral wave period), and wind speed. These plots clearly illustrate the inter-monthly and seasonal variation found in the wave and wind conditions occurring at one location in the Buoy Farm. The results found in Figure 4 identify the general low wave energy environment during the summer months. Moving into the fall and winter seasons, the mean significant wave height increases by 1-m, and for this population, the maximum observed significant wave height approaches 10-m, nearly a factor of 2.5 greater than what occurred in July, where the lowest energy exist. There is a reasonable expectation to observe storm peak events above 6-m during the FLOSSIE deployment. Similarly, there are periods where significant wave heights can be less than 0.5-m. The other observation from Figure 4 is the range in the standard deviation is relatively consistent month to month with exception to the summer season. This suggests the probability distribution defining the range in significant wave heights occupies a very limited defined interval.

The west coast of the US (California, Oregon and Washington) wave climate is dominated by long-period swell energy derived from meteorological events developing in the western Pacific Ocean and migrating in an easterly direction. These conditions resonate in Figure 5, where the mean dominant wave period range from 10- to about 12-s, and have a have a similar trend as in the significant wave height monthly variation. The standard deviation from month to month is ± 2.5-s suggesting there is a very small range in wave periods found in the probability distribution. For the larger and more distant events, the dominant wave periods exceed 20-s each and every month. In many cases (as will be shown in the latter section) there are multiple wave systems occurring at one time, where local wind-seas are created by the winds in the region and generally running along a much different wave direction compared to the swells.

Local winds will play a role in the FLOSSIE study. The variation in the mean wind speed (Figure 6) on an inter-monthly interval is on the order of 3kt (~1.5m/s). The variation about the mean wind speed consistently runs at about ± 3kt (~1.5m/s) suggesting again the probability distribution is narrow occupying a very small range in wind speeds. There are times during the winter season where the local winds can exceed 30kts (~15m/s) for a peak storm event. The mean and maximum wind speed trend is similar to the wave parameters; however the minimum monthly condition occurs in September rather than in August. The maximum mean wind speeds also occur from March through June rather than in the winter months found in Figures 4 and 5. This could suggest that the number of meteorological storm events increases in the spring, however the amount of energy created from the local winds will have a limited impact on the wave climate.

It does appear from data obtained at 46042, that the wave climate is at times well behaved. The inter-monthly mean variation is rather constant at about 1.5-m in wave height, 2-s in wave period and for the wind speed about 3kt (1.5m/s). There is a distinct seasonal variation for the waves that could be complicated by the shift in conditions found in the winds especially in the spring. This simple analysis that is mainly observational and qualitative will provide a certain degree of understanding when the data from FLOSSIE begins to flow and the analysis is performed.

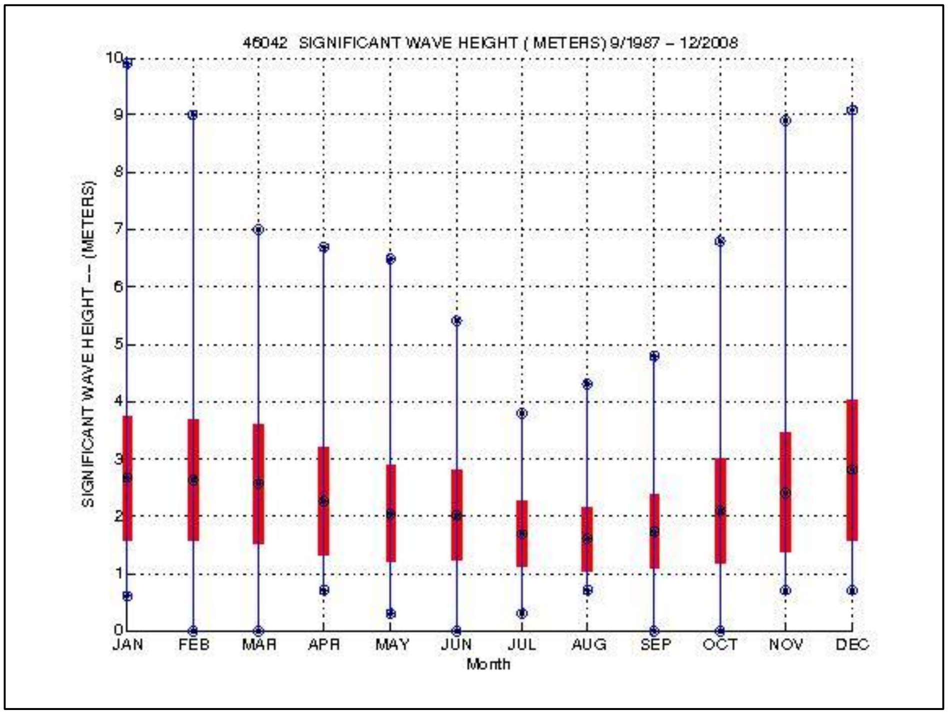

Figure 4. Mean and maximum significant wave height variation over months, from NDBC (http://www.ndbc.noaa.gov/station_history.php?station=46042). Period of record is 22-yrs.

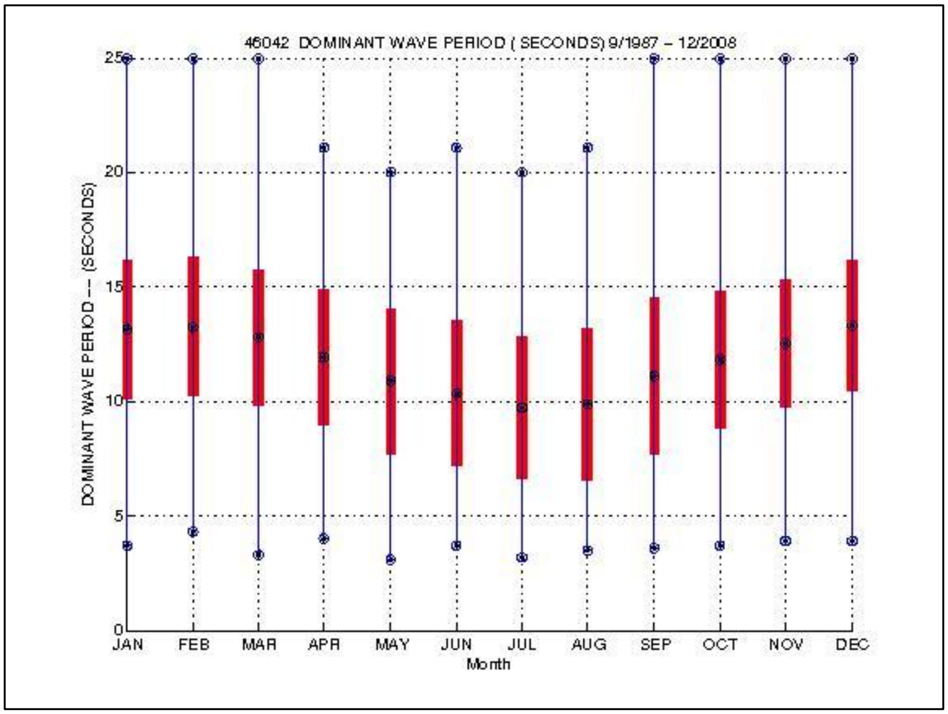

Figure 5. Mean and maximum dominant wave period (peak spectral wave period) variation over months, from NDBC (http://www.ndbc.noaa.gov/station_history.php?station=46042). Period of record is 22-yrs.

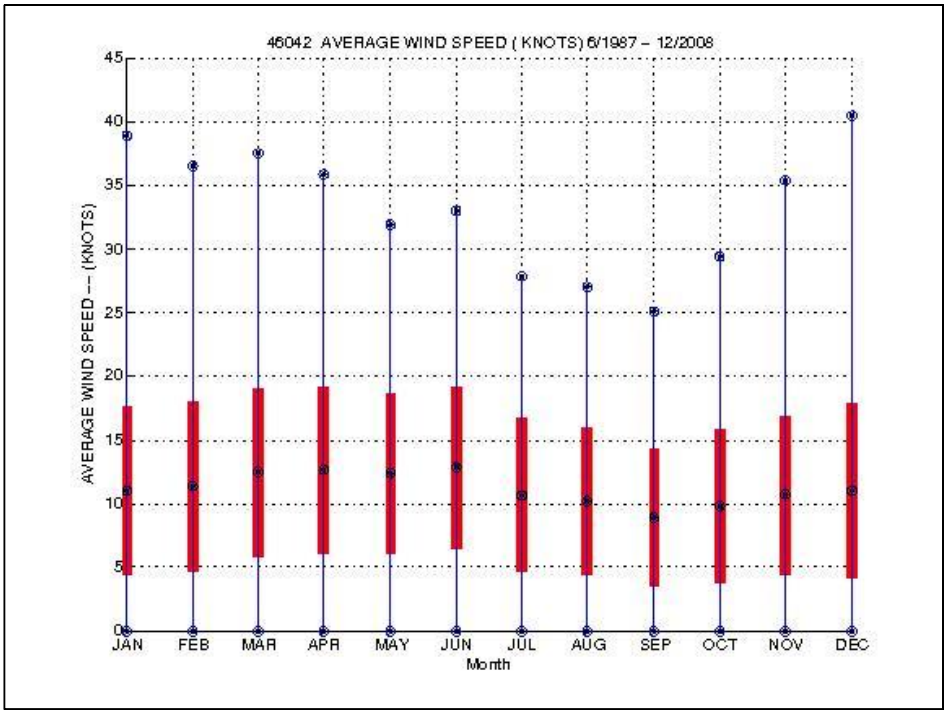

Figure 5. Mean and maximum wind speed variation over months, from NDBC (http://www.ndbc.noaa.gov/station_history.php?station=46042). Period of record is 22-yrs.

FLOSSIE PRELIMINARY DATA ANALYSIS

At the time of this paper, FLOSSIE has been deployed for nearly two months. Return on the data (one month to date) from various sensor/payloads was exceptional where the number of *dropouts* or *flagged* (not passing Quality Control, NDBC, 2009) data were less than five for each of the wave systems. The population size for these data sets is quite small, about 730 observations for 60-minute wave records and 1460 records for 30-minute sampling interval. No quantitative conclusions will be drawn from these data and the discussion will be restricted to a qualitative observational summary. The discussion is also limited to the data obtained from FLOSSIE and the Datawell® Directional Waverider. Intra-measurement evaluations of data recovered from 46042 (NDBC dual sensor: HIPPY/MicroStrain's 3DM-GX1®) is summarized in Bouchard et al. (2015).

Of the eight potential wave measurement sources, five will be summarized for the August 2015 period of record. Table 3 identifies the sensor/payload systems used in this preliminary analysis and defines the naming convention used in subsequent graphics. As noted in Table 3, of the five sensor/payload packages, two provided non-directional wave estimates, NDBC-SM133 (Inclinometer) and EC-SDA (strapped down accelerometer). The latter data set was not available at the time of this reporting period. Two data sets provided wave estimates on a 30-minute interval. For this analysis the time stamp for any data not reporting at 00 or 30 minutes was shifted six or ten minutes to be consistent with the other records.

Table 3. Sensor/Payload								
System	Name[1]	Wave System	Sensor	Payload	Direction	Sampling Information (min)		
						Interval	Time Stamp	Time Used
NDBC-SM133	DACT	WA	Inclinometer	DACT	No	60	00	00
NDBC-SM142	HIPPY	DWPM	HIPPY	ARES	Yes	60	00	00
NDBC-SM143	3DMG	DDWM	3DMG	SM	Yes	30	00 30	00 30
AXYS-NW-II	AXYS	--	TRIAXYS	Wave Mod	Yes	60	20	30
EC-SDA[2]	MEDS	--	Accelerometer	Watchman	No	TBD	TBD	TBD
CDIP Waverider	CDIP	--	HIPPY	Datawell	Yes	30	24 54	30 00

[1] Naming convention used in the following graphics and discussion
[2] Environment Canada Strapped Down Accelerometer (to be supplied by EC / MEDS). Not yet available for this analysis.

The wave parameters defined in the analysis are assumed to be the zeroth moment wave height (H_{mo}), the peak spectral wave period (T_p), and the vector mean wave direction at the peak frequency ($\theta_{MEAN}(f_m)$). AXYS mean wave direction is defined by the 'weighted average over the entire frequency spectrum.' This differs from CDIP and NDBC directional estimates and will be dependent on the wave state. If multiple wave systems occur (i.e. low frequency swell energy and locally generated wind seas) the reported AXYS mean wave direction will differ. The difference in the wave direction will be dependent on the energy contained in the frequency range defining the two peaks. These conditions are best illustrated in Figure 6, a *feather plot* of the mean wave directional estimate defined for each frequency from the CDIP Datawell® Directional Waverider buoy in August 2015, the first full month of the FLOSSIE deployment. The vector lengths define the relative energy contained in the discrete frequency band. The longer the vector length of a frequency band the larger the energy level contained in that frequency. For the month of August, there is a noticeable trend of the swell energy (< 0.07-Hz) defining the wave energy from a northerly direction. The higher frequencies (> 0.1-Hz) are generally directed from the southeasterly direction. Results displayed in Figure 6 show two local wind-sea events moving through the Buoy Farm around 6-10 August and a larger event from 15-23 August. During this time the swell energy exists but the magnitude is much lower compared to the wind-sea. Toward the end of the month, the data indicate a large influx of swell energy that is much greater than the wind-seas. Given these observations it is reasonable to expect a divergence in the AXYS wave direction estimates during mixed wind-sea and swell occurrences.

Use of the T_p and $\theta_{MEAN}(f_m)$ will have a dependency on the frequency range an intervals used by the various data providers. The frequency range and Δf is provided below:

- CDIP: 0.025 to 0.580 Δf=0.005 (0.0250-0.0950) Δf=0.01 (0.11-0.58) (note no f=0.100 defined as 0.1013)
- DACT: 0.010 to 0.400 Δf=0.01
- HIPPY: 0.025 to 0.485 Δf=0.005 (0.0325-0.0925) Δf=0.01 (0.10-0.35) Δf=0.02 (0.365-0.4855)
- 3DMG: 0.025 to 0.485 Δf=0.005 (0.0325-0.0925) Δf=0.01 (0.10-0.35) Δf=0.02 (0.365-0.4855)
- AXYS: 0.025 to 0.580 Δf=0.005 (0.025-0.101) Δf=0.01 (0.11-0.58) (note no f=0.01 defined as 0.101).

Sample times for the sensors also vary that may contribute to differences in the wave parameter and spectral estimates. The start and end times are defined as min:sec and are:

- CDIP: (24 and 54) 24:45 to 51:25 and 54:45 to 21:25
- DACT: (00) 29:00 to 49:00
- HIPPY: (00) 20:00 to 40:00
- 3DMG: (00 and 30) 30:00 to 50:00 and 00:00 to 20:00
- AXYS: (20): 20:00 to 40:00

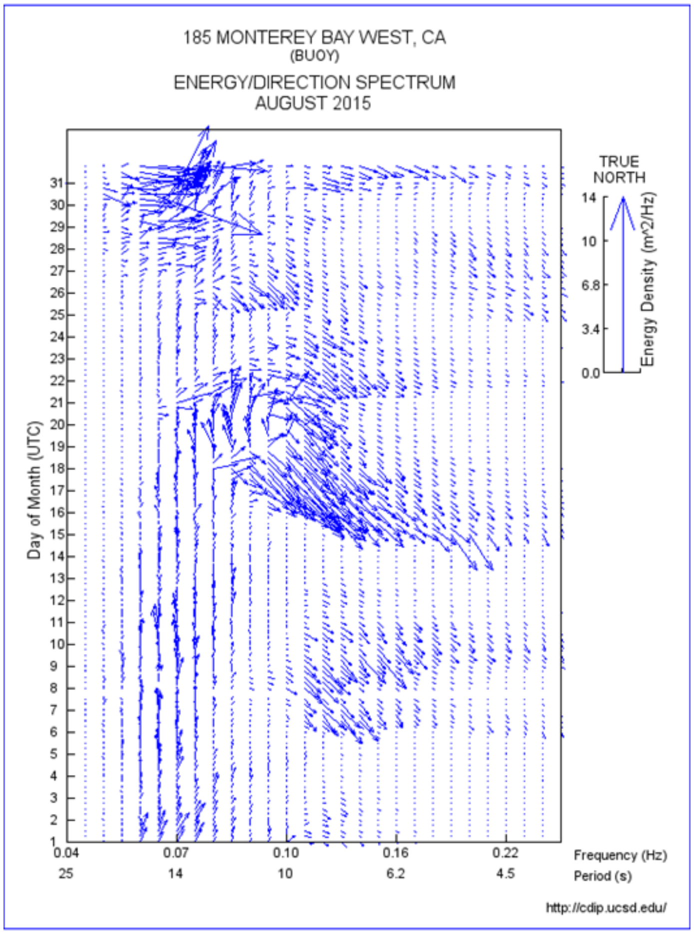

Figure 6. *Feather plot* defining the vector mean wave direction at each frequency band from the CDIP buoy (46114) during August 2015.

Preliminary analyses of the August 2015 data sets were performed. As previously noted, the analysis assumed all data obtained were Quality Controlled by the various data providers passing their standard operational testing procedures. A time plot of the H_{mo}, T_p and $\theta_{MEAN}(f_m)$ are displayed in Figure 7, where the top panel is the H_{mo} results, the middle panel T_p and the bottom panel $\theta_{MEAN}(f_m)$. There were two primary storm events occurring during the month, the first initiated around 5 August peaking at 6 and then 9 August at about 2-m. The second event initiated its growth sequence mid-day on 14 August, peaking around 16 August nearing 2.5-m. There is a strong indication of an energetic system entering the Buoy Farm toward the end of the month where the peak H_{mo} is increasing above 2.5-m. The T_p results show a mixed or dominant wind-sea/swell wave climate. The peak spectral wave periods range from 5-s to a maximum of 16-s. There are times when the T_p oscillates between the 5-s to 16-s indicating multiple wave populations (wind-sea and swell) at similar peak energy values. The T_p plot also illustrates the classic wind-wave growth of the second event (mid-day on 14 August) a sharp drop in the T_p and then over a two to three day period an increase in the T_p increase with an accompanying H_{mo} storm peak. The θ_{MEAN} (bottom panel, Figure 7) follows the oscillation pattern found in the T_p results, again an indication of a mixture of multiple wave systems during the initial month deployment. The directional estimates also clearly show two distinct directional patterns tending around 340° or around 200°. Note the AXYS® system reports a different θ_{MEAN} (weighted average over the frequency spectra) and diverges from all other directional estimates especially during these mixed wave conditions.

The similarities and/or differences in the wave estimates are difficult to determine from the results plotted in Figure 7. In general, the results of the five sensor/payload systems produced similar wave parameter estimates. There are noticeable differences in the H_{mo} estimates especially around 18 August 2015. Significant wave height data recovered from the Datawell (CDIP, black line in the top panel Figure 7) is from about 0.25- to 0.5-m higher than the four sensor/payload packages onboard FLOSSIE. The elevated conditions observed at CDIP compared to the NDBC 3D buoy (46042) contained similar results. These elevated conditions observed at CDIP could be a transient wave system only appearing at this site (eastern most location), affected by surface currents or some other physical process. Additional investigations are warranted and will be carried out in the future. This is required because the CDIP buoy and data (i.e. Datawell directional waverider) are defined as the *relative reference* and all subsequent evaluations are conducted using these data as the independent variable.

To better illustrate the similarities and/or differences between the suite of wave measurements, a difference plot is constructed and provided in Figure 8. The differences are computed using CDIP as the base and subtracted from the four alternate data sets or: DIFF = TEST – CDIP where TEST is defined by either the DACT, HIPPY, 3DMG or AXYS wave parameters (H_{mo}, T_p and θ_{MEAN}[4]).

There are noticeable differences between the CDIP compared to the other four sensor/payload packages, especially during the period where the CDIP site observed higher wave energy. A portion of those differences may be attributed to phase differences of the time series analysis and/or by the temporal translation (see Table 3) required for time-pair analyses. The general range in the difference (omitting the elevated CDIP event) is about ±0.25-m with a maximum of +0.5-m. The overall trends (oscillations over time) are generally followed between sensor/payload packages. Data derived from the 3DMG is noisier compared to the other three measurements, possibly an artifact from the 30-minute sampling interval of the 3DMG compared to 60-minutes for the DACT, HIPPY and AXYS® systems. Differences in all wave height data increase with increasing H_{mo} estimates that will require further data to evaluate. The T_p results (Figure 8 middle panel) appear to be more consistent showing no persistent positive or negative bias. Variations will occur in the T_p results because of the frequency intervals used for each system. The deviations will become more pronounced for dominant long-period swell conditions where changes in one discrete frequency band will result in a 1- to 2-s change in the T_p. Large differences may occur during mixed wind-sea and swell conditions. The wind-sea and swell peak energy are similar in magnitude. Hence selection of the f_m or T_p would be assigned to wind-sea or swell, and varies from observation to the next. Oscillations will exist and persist until one system dominates. The directional differences are also plotted in Figure 8 (lower panel). These results, especially from the 3DMG and HIPPY sensors onboard FLOSSIE, are of secondary importance in the study. The data will, however, add corroboration to the AXYS TRIAXYS sensor package and the ability to estimate directional characteristics in a 6N buoy (Jensen et al., 2011; Collins et al., 2014). The $\theta_{MEAN}(f_m)$ data from the 3DMG and HIPPY sensors provide reasonable estimates compared to the CDIP data. Omitting the records where there is mixed wind-sea and swell present (6-10 August and 19-22 August 2015) the 3DMG and HIPPY have a positive bias of about 10° to as 40° compared to the CDIP $\theta_{MEAN}(f_m)$. It would be difficult to assess the AXYS θ_{MEAN} results because of the differences in definitions. Similarities exist only during the period when unimodal frequency spectra exist. These occurrences (see Figure 5) are very rare during August 2015 but appear to exist toward the end of the month.

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[4] Note the θ_{MEAN} is defined by $\theta_{MEAN}(fm)$ with exception of the AXYS data where it refers to a weighted average over the frequency range and energy contained in the discrete frequency band.

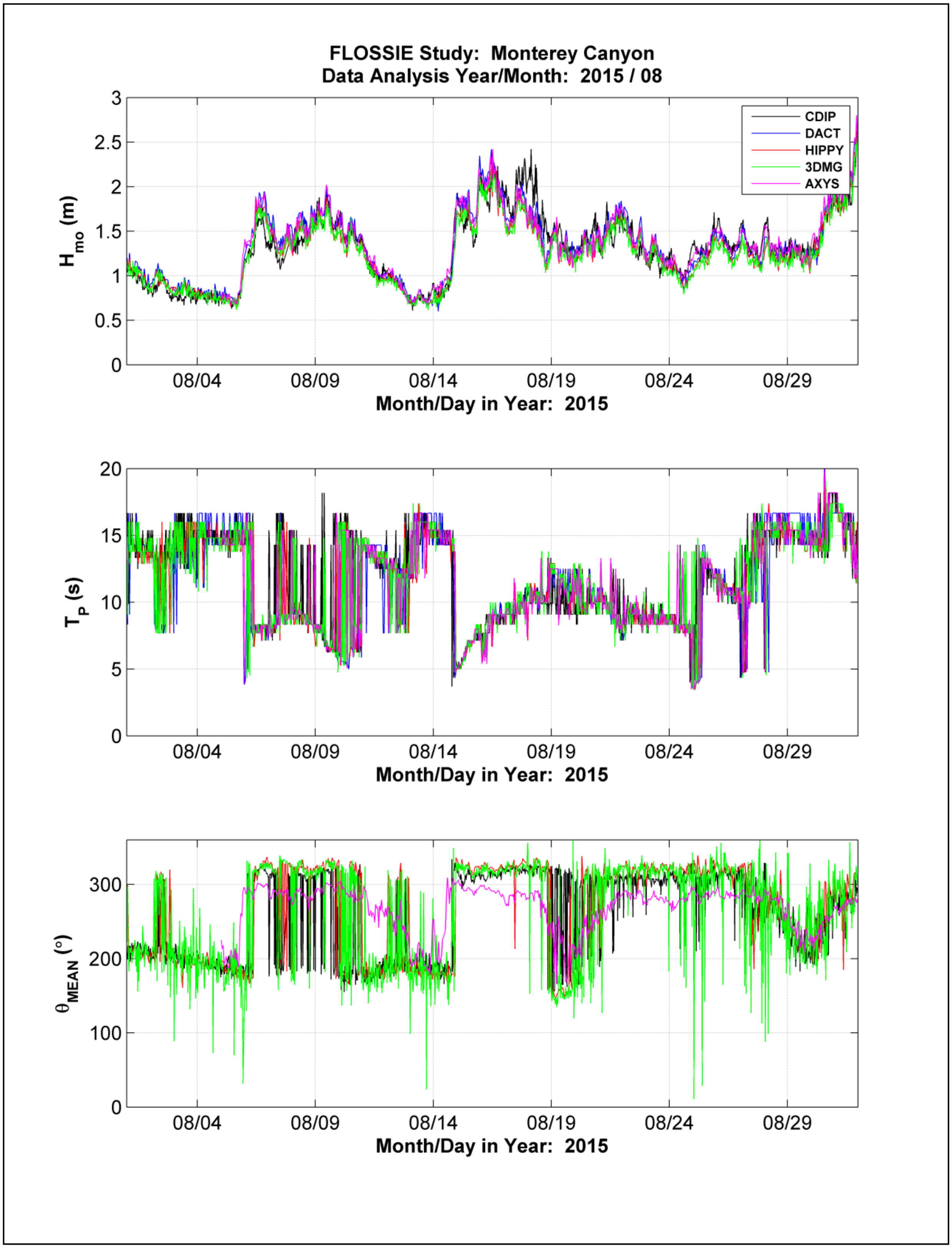

Figure 7. Time plot of H_{mo} (top panel), T_p (middle panel) and $\theta_{MEAN}(f_m)$ (bottom panel) for five wave sensor/payload systems during August 2015. The AXIS θ_{MEAN} is a weighted average across the frequency range of a spectrum.

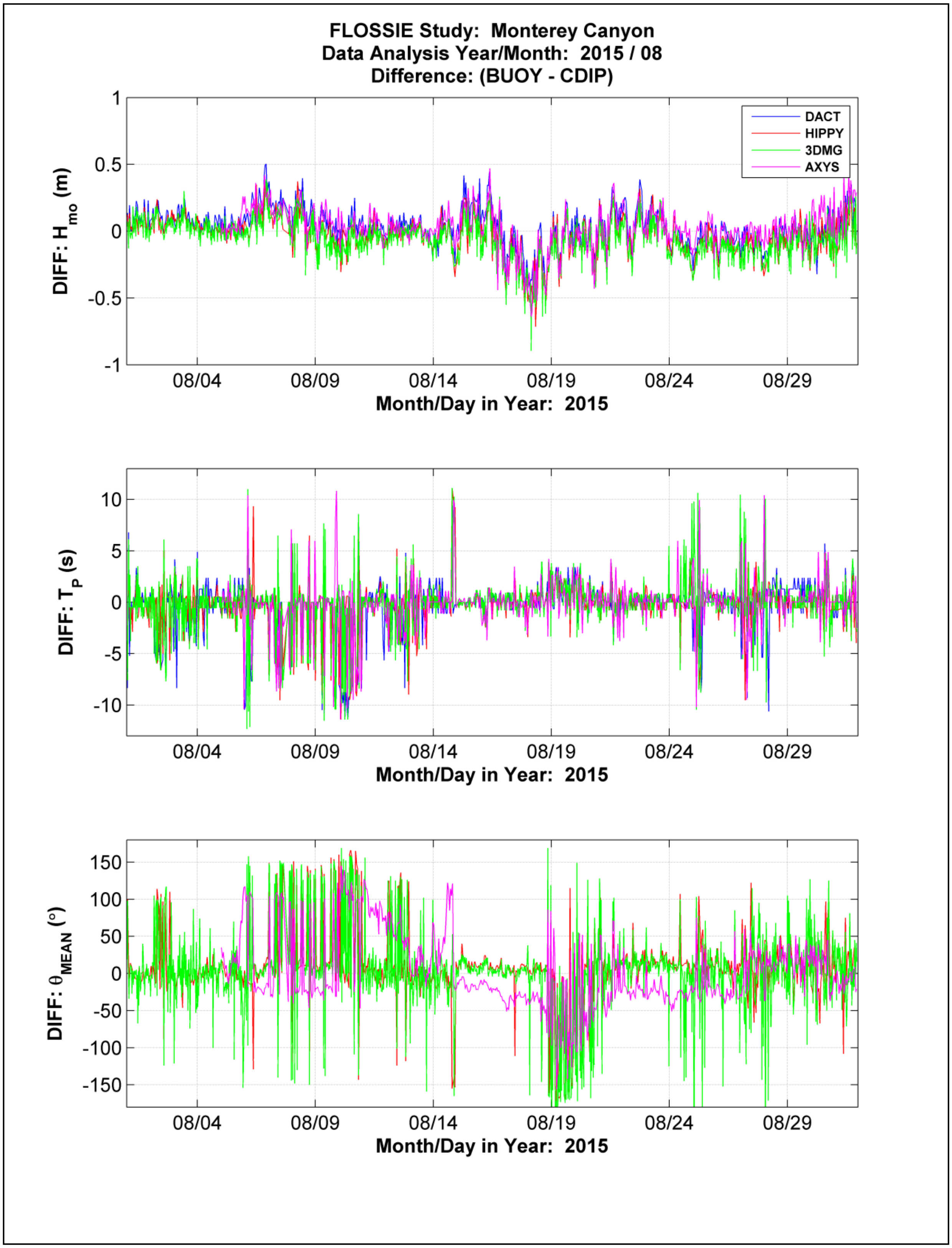

Figure 8. Difference plot of H_{mo} (top panel), T_p (middle panel) and $\theta_{MEAN}(f_m)$ (bottom panel) for five wave sensor/payload systems during August 2015. The AXIS θ_{MEAN} is a weighted average across the frequency range of a spectrum.

Improved integral wave parameter evaluations are planned in the future where the First-5 Fourier coefficients are used to construct $S(f,\theta)$ estimates using the Maximum Entropy Method (Lygre and Krogstad, 1986) and computing directional estimates of $\theta_{MEAN}(f_m)$ for the AXYS data as well as weighted averages θ_{MEAN} for the other three directional measurement platforms. This evaluation will be expanded to the higher order moments in the directional wave properties beyond the first moment: θ_{MEAN}, to the second moment defined by the directional spread, the third and fourth moment defined by the skewness and kurtosis, respectively, (O'Reilly et al., 1996).

It was shown the T_p property will be highly variable in a mixed wind-sea, swell environment. Other definitions can be used for T_p, such as the first moment wave period, the inverse first moment, the Rice[5] average wave period $\bar{T}_2 = 2\pi\sqrt{\frac{m_0}{m_2}}$ where m_0 and m_2 are the zeroth and second moments of the frequency spectra given by:

$$m_0 = \int_0^\infty S(f)df \tag{8}$$

and

$$m_2 = \int_0^\infty f^2 \cdot S(f)df \tag{9}$$

Testing for differences of integral wave parameters from various platforms are important, however results from these evaluations can mask larger errors in the frequency range of a spectrum. The H_{mo} is an integral wave parameter calculated from integrating the energy density spectrum ($S(f)$, or C_{11}) over the entire operational range of frequencies. If the integration of a spectrum is performed over discrete frequency ranges and compared there could regions where the there are positive biases and alternate regions containing negative biases. WaveEval Tools (Jensen et al. 2011) dissects the magnitude of the energy, and the directional moments: mean wave direction, spread, skewness and kurtosis for each discrete frequency band at a time interval. The two sets of data are then evaluated in the form of graphical products. WaveEval Tools requires at a minimum of three months of data to adequately perform the analysis. Hence, this evaluation will have to wait until more data are recovered. The power and usefulness of this tool will provide insights into where two data sets are similar and where they differ relative to magnitude in energy and discrete frequency.

SUMMARY AND CONCLUSIONS

Three years have transpired from the initial thoughts of the Field Laboratory for Ocean Sea State Investigation and Experimentation (FLOSSIE). The ability to house a suite of historical sensor and payloads from NDBC and EC in a single hull, deploy it in an area containing other wave measurements platforms and start to recover data from these systems became a reality in July 2015.

The motivation of FLOSSIE was threefold. First it will provide an opportunity to investigate the similarities and/or differences in historical changes to sensor/payload packages used for nearly 40-years in 6N buoys. Second is to compare the two North American wave measurement systems and evaluate the data sets to altimeter wave estimates. Third and more important to EC is to determine the accuracy in directional wave estimates from NOMAD 6N hull systems. NDBC will be decommissioning all 6N buoy systems in the near future despite nearly 20- to 40-years of near continuous wave measurements taken from many of the now operational buoys.

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[5] Historically the Rice average period was used by NDBC and named in his behalf.

Initial data from August 2015 have been analyzed in terms of integral wave parameters: H_{mo}, T_p, and $\theta_{MEAN}(f_m)$. Five data sets were used in this analysis; four derived from sensor/payload packages onboard FLOSSIE, and one from a Datawell® Directional Waverider buoy, and is used as the *relative reference* in the evaluations. Data obtained from a nearby NDBC 3D buoy (46042) containing two sensor/payload packages has been analyzed and is summarized in Bouchard et al. (2015).

The data revealed subtle differences where the H_{mo}, and T_p results varied by ±0.25-m and ±1.5-s respectively. This was based on reported significant wave heights of roughly 1.75-m in the mean, and two storm events of 2- to 2.5-m. The DACT and HIPPY significant wave height differences were very similar, and showed slightly more positive bias with increasing wave height. The 3DMG differences were generally biased negatively. The AXYS results seemed to have less overall bias but generally ran positive. The wave climate generally had multiple wave systems occurring, local wind-seas from passing meteorological events and long-period swells derived from distant storms in the Pacific Ocean. There was one 30-hr period where the Datawell reported significant wave heights nearly 0.5-m greater than the other four data sets. This deviation was also verified using data from the nearby NDBC 3D buoy. With a separation between the three buoys of 10-km or less determining the cause for this rise will require further investigations. A parallel study is being conducted where two Datawell Directional Waveriders have been deployed at Harvest Platform (west of Point Conception, California). These data will provide further insights into the role of the Datawell used as a relative reference assessing the differences in identical system data sets.

It was surprising to see that the directional estimates from the HIPPY and 3DMG compared fairly well to the Datawell (~30° offset), however the 3DMG 30-min records showed a large oscillation until the wave climate exceeded about 1.5-m during one of the events in August. The AXYS sensor wave direction differed from the Datawell, HIPPY and 3DMG where it was computed from a weighted average across the frequency range and not evaluated at the peak frequency. The AXYS results had an offset in the directional estimates but would be attributed to the mixed wind-sea swell regime. When the wave climate became unimodal toward the end of the month during the growth stages of a storm event, the reported AXYS directions were in-line with the other sensor data.

The results of one month of data (about 700 or 1400 observations for a 60-min or 30-min interval) restrict the evaluation to integral wave parameters and general qualitative assessments. It is also anticipated the EC/MEDS (strapped down accelerometer) data will soon be available for analysis. As the population size increases the data will be further analyzed using the WaveEval Tools, assessing where, when and why there are similarities and differences between sensor/payload packages.

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REFERENCES

Alliance for Coastal Technologies (2012). Waves measurement systems test and evaluation protocols, *[UMCESCBL] 12-028*, (http://www.act-us.info/Download/Workshops/2012/USFUM_Wave_Measurement/).

Allan, J. C. and P.D. Komar, (2000). Are ocean wave heights increasing in the eastern North Pacific? *EOS, Trans. American Geophysical Union*, 47, 561-567.

Bouchard, R. H., R.E. Riley and W. McCall, (2015-in preparation). Long-term intercomparison between a Datawell wave buoy and an NDBC directional wave buoy: part 1: bulk sea state parameters, 14th *International Workshop on Wave Hindcasting and Forecasting*, 9-13 November 2015, Key West Florida.

Collins III, C.O., B. Jund, R.J. Ramos, W.M. Drennan and H.C. Graber, (2014). Wave measurement intercomparison and platform evauation during the ITOP (2010) experiment, *Journal of Atmospheric and Ocean Technology*, Vol. 31, 2310-2329.

Durrant, T.H, D.J.M. Greenslade, and I. Simmonds, (2009). Validation of *Jason-1* and *Envisat* remotely sensed wave heights, *Journal of Atmospheric and Ocean Technology*, Vol. 26, 124-134.

Frigaard, P, Helm-Petersen, J, Klopman, G, Standsberg, CT, Benoit, M, Briggs, MJ, Miles, M, Santas, J, Schäffer, HA & Hawkes, PJ (1997), 'IAHR List of Sea Parameters: an update for multidirectional waves'. in Mansard, Etienne (ed.), *Proceedings of the 27th IAHR Congress, San Francisco, 10-15 August 1997: IAHR Seminar : Multidirectional Waves and their Interaction with Structures*. Canadian Government Publishing, pp.15-24.

Gemmrich, J., B. Thomas, and R. Bouchard (2011). Observational changes and trends in the Pacific wave records, *Geophy. Res. Letters*. Vol 38, L22601.

Integrated Ocean Observing System (2009). A National Operational Wave Observation Plan, (http://www.ioos.gov/library/wave_plan_final_03122009.pdf.

Jensen, R.E., V.R. Swail, B. Lee and W.A. O'Reilly, (2011). Wave measurement evaluation and testing,12th *International Workshop on Wave Hindcasting and Forecasting*, 30 October-4 November 2011,Kohala Coast, Hawaii, (http://www.waveworkshop.org/12thWaves/index.htm).

Luther, M.E., G. Meadows, E. Buckley, S.A. Gilbert, H. Purcell and M.N. Tamburri, (2013). Verification of wave measurement systems, *Marine Technology Society Journal*, Vol 47, No. 5, 104-116.

Lygre. A. and H.E. Krogstad, (1986). Maximum entropy estimation of he directional distribution in ocean wave spectra, *J. Phys. Ocean.*, **16**, 2052-2060.

MacIsaac, C. and S. Naeth, (2013). TRIAXYS next wave II directional wave sensor: the evolution of wave measurements , http://axystechnologies.com/wp-content/uploads/2013/11/TRIAXYS-Next-Wave-II-The-Evolution-of-Wave-Sensor.pdf .

Menendez, M., Mendez, F.J., Losada, I., Graham, N.E.,(2008). Variability of extreme wave heights in the northeast Pacific Ocean based on buoy measurements. Geophysical Research Letters 35, L22607. doi:10.1029/2008GL035394.

NDBC (1996). *NDBC Technical Document 96-01, Nondirectional and Directional Wave Data Analysis Procedures*, National Data Buoy Center, Stennis Space Center, MS, 43 pp. (http://www.ndbc.noaa.gov/wavemeas.pdf)

NDBC (2009). *NDBC Technical Document 09-02, Handbook of Automated Data Quality Control Checks and Procedures*, National Data Buoy Center, Stennis Space Center, MS, 78 pp. (http://www.ndbc.noaa.gov/NDBCHandbookofAutomatedDataQualityControl2009.pdf)

O'Reilly, W.C., T.H.C. Herbers, R.J. Seymour, and R.T. Guza, (1996). A comparison of directional buoy and fixed platform measurements of Pacific swell, . *J. Atmos. Oceanic Technol.*, **13**, 231-238.

Riley, R., C.-C. Teng, R. Bouchard, R. Dinoso and T. Mettlach, (2011). Enhancements to NDBC's digital directional wave module, *Proceedings of MTS/IEEE Oceans 2011 Conference*, Kona, Hawaii, September 2011.

Ruggerio, P., J.C. Allan, and P.D. Komar, (2010). Increasing wave heights, and extreme-value projections: the wave climate of the U.S. Pacific Northwest, *Coastal Engineering*, 57(5), 539-552.

Skey, S.G.P., K. Berger-North and V.R. Swail, (1995). Detained measurements of winds and waves in high seastates from a moored NOMAD weather buoy, *4th International Workshop on Wave Hindcasting and Forecasting*, 16-20 October 1995, Banff, Alberta Canada, 213-223.

Swail, V., R.E. Jensen, B. Lee, J. Turton, J. Thomas, S. Gulev, M. Yelland, P. Etala, D. Meldrum, W. Birkemeier, W. Burnett, and G. Warren (2009). Wave measurements, needs and developments for the next decade, *Proceedings of OceanObs'09*, Vol. 2 II-1-87, 999-1008.

Timpe, G.L., and N. Van de Voorde, (1995). NOMAD buoys: an overview of forty years of use, *OCEANS'95 MTS/IEEE, Challenges of Our Changing Global Environment*, 9-12 October 1995, San Diego, CA, Vol. 1, 309-315.

Van Straten, F.W (1966). *Weather or Not*, Dodd, Mead & Company, New York, NY, 252 pp.

WMO, (1995), "FM65 –XI WAVEOB", World *Meteorological Organziation (WMO) Manual on Codes, International Codes Vol.I.1, Part A – Alphanumeric Codes, WMO-No.306,* pp. 129-132.