THE GLOBAL DRIFTER PROGRAM: EVOLUTION, CURRENT STATUS, IMPACTS, AND FUTURE DIRECTIONS

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ABSTRACT

The main scientific and technical achievements of the NOAA funded Global Drifter Program (GDP) are described, together with a succinct historical perspective. The GDP, a global array of Lagrangian surface drifting buoys delivers measurements of Essential Climate Variables such as sea surface temperature (SST), sea level atmospheric pressure (SLP), and sea surface velocity (SSV). The GDP data are publicly available in real-time through the Global Telecommunication System of the World Weather Watch and as a quality controlled delayed mode dataset from NOAA/AOML. The positive impact of the drifter data is particularly significant for the calibration and validation of remotely sensed SST and for numerical weather prediction (SLP). The GDP dataset has been used to support a very large number of peer-reviewed publications and a subset its scientific achievements is briefly discussed here, including the computation of the ocean's global dynamic topography, the evaluation of global currents from drifter data, and the mapping of tidal currents throughout the World's ocean. Constant research and development efforts by the GDP supports a very cost-effective array that currently exceeds its target goals of 1,250 drifters. New sensors are constantly evaluated and transitioned to operations, including wind sensors, conductivity sensors, and directional wave spectra sensors. The future perspectives of the GDP are also briefly discussed.

1. INTRODUCTION

The goal of this whitepaper is to discuss the evolution, the current status and the future perspectives of the Global Drifter Program (GDP) from a scientific and technological standpoint. We begin with a short historical overview of the program and of the underpinning technology. We then present the current status of the drifter array, its main scientific and operational impacts, and we conclude with a discussion of the future directions of the GDP.

The Global Atmospheric Research Programme (GARP), was established in 1978 under the World Meteorological Organization (WMO) and the Intergovernmental Council of Scientific Unions (ICSU) to investigate the physical processes necessary to improve weather and climate forecasting on planetary scales. The First GARP Global Experiment (FGGE) also had an oceanographic component [United Nations Educational, Scientific and Cultural Organization (UNESCO) report SC-78/WS/91, available online at http://unesdoc.unesco.org/images/0003/000348/034822eb.pdf]. The drifters deployed during FGGE measured sea surface temperature (SST), air temperature and seal level air pressure (SLP). One of the most remarkable aspects of FGGE is that it established a storng collaboration between oceanographer and meteorologist, which is still a major driver for the GDP. The FGGE drifters were too expensive for sustained global implementation and did not have good Lagrangian (i.e. water following characteristics), although some attempted to recover ocean currents from them [viz *Pazan and Niiler*, 2001].

The Surface Velocity Program (SVP) was established during the Tropical Ocean Global Atmosphere (TOGA) experiment in 1988 [*Hansen and Poulain*, 1996] and led to the creation of the GDP [*Niiler*, 2001]. A description of drifting buoy technology available before the GDP can be found in *Lumpkin and Pazos* [2007]. The drifters made in the early 1980's consisted of a surface buoy containing batteries, a digital/analog controller, a satellite transmitter, a suite of surface sensors and a drogue. Several studies investigated the optimal drogue design to maximize water following capabilities [*Niiler et al.*, 1995] to find that the drifter is a good Lagrangian instrument as long as the ratio of the drag area of the drogue to the sum of the drag area of all the other submerged elements is larger than 40 [*Niiler et al.*, 1995]. Such criterion is still used in modern drifters to ensure that the drifters can follow the water with an accuracy of about 0.9 cm s^{-1} for winds up to 10 m s^{-1} [*Niiler et al.*, 1995]. The GDP adopted the holey-sock drogue because it can collapse into a package which is easy to store, ship and deploy, thus opening the way to global implementation.

The pre-2002 drifter design consisted of a surface sphere with a diameter of 0.28 m, a subsurface float with a diameter of 0.2 m located at 2 m depth and a holey-sock drogue approximately 6 m long and with a diameter of 0.84 m [*Niiler et al.*, 1995]. The center-depth of the drogue was set to 15 m to reduce the effect of the surface waves (i.e. stokes drift) and to measure ocean currents in the mixed layer over most of the oceans. In 2002 a smaller version of the SVP drifter without the subsurface float was introduced.

The GDP was the first component of the Global Ocean Observing System (GOOS) to reach completion with the ceremonial launch of drifter 1,250 by Dr. Peter Niiler of the Scripps Institution of Oceanography and by Dr. Mike Johnson of NOAA from the Tall Ship Silva near Halifax, Nova Scotia, on September 18, 2005.

An example of a modern drifter is the one designed and fabricated by the Lagrangian Drifter Laboratory at the Scripps Institution of oceanography (*Figure 1*).

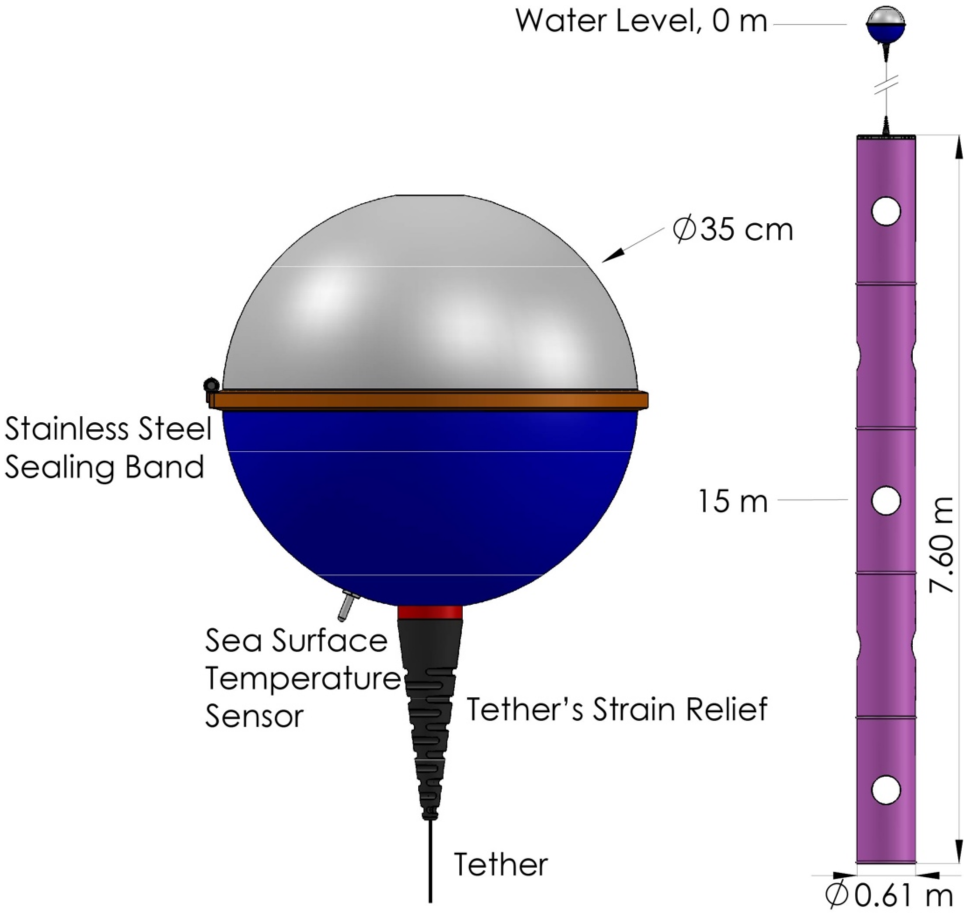

Figure 1: Schematics of the SVP drifter designed and produced by the Lagrangian Drifter Laboratory at the Scripps Institution of Oceanography

The drifter's hull has a diameter of 38cm and is equipped with a drogue-on sensor. The holey-sock drogue is made of 600 den (or better) Cordura® nylon. The laboratory accuracy of the SST probe is ±0.05 °C. Given the high importance of the GDP array to calibrate and validate SST from space, efforts are underway to evaluate the overall accuracy of SST data from the entire drifter system. Drifters that carry barometers are termed SVPB drifters.

Since 2016 the GDP drifters use exclusively the Iridium satellite system because of the shorter data latency compared to the Argos satellite system (1 minutes vs 90—120). Since the geolocation computed from the Doppler shift of the transmitter carrier frequency for Iridium is less accurate than the one obtained from Argos satellites [~200 m to ~2 km *Lopez et al.* [2014]] all of the Iridium drifters are equipped with a Global Positioning System (GPS) engine (accuracies of ~2m—50 m rms). Adding a GPS requires care to prevent the fast depletion of the batteries. The digital/analog controller was designed by the LDL and it handles data collection and satellite transmission. A comprehensive set of diagnostic data, including the battery voltage, the hull's internal pressure, temperature and humidity, are also transmitted. The ruggedized 12 V, 56 Ah alkaline battery pack of the drifter is designed to support a lifespan in excess of two years.

2. CURRENT STATUS OF THE DRIFTER ARRAY

The nominal size of the drifter array (*Figure 2*) of 1,250 drifters (roughly corresponding to one drifter in every 5°X5° cells) is in compliance with the GOOS goals for SST and is described in GCOS-81 (2002), GCOS-82 (2003) and GCOS-92 (2004), which takes into account also the existence of the tropical moored buoys. Although the equatorial mooring network also provides in-situ SST data, the equatorial drifters return highly valuable information on near-equatorial currents and SST observations where there are no equatorial moorings with operational current and SST measurements (Lumpkin et al., 2016).

The GDP is managed in close cooperation between NOAA/AOML in Miami, Florida and the LDL. Private drifter manufacturers and the LDL supply the equipment according to specifications closely monitored by the LDL. AOML is responsible for most drifter deployments, and for the delayed mode quality control of the data, maintains the metadata archive, and hosts the GDP website (www.aoml.noaa.gov/phod/dac) from which quality controlled data can be obtained. The LDL supervises the industry, acquires most of the drifters from the various manufacturers, upgrades the technology, develops new sensors, handles the posting of the real-time data to the Global Telecommunication System (GTS) for the Iridium drifters and several key aspects of the Iridium data stream.

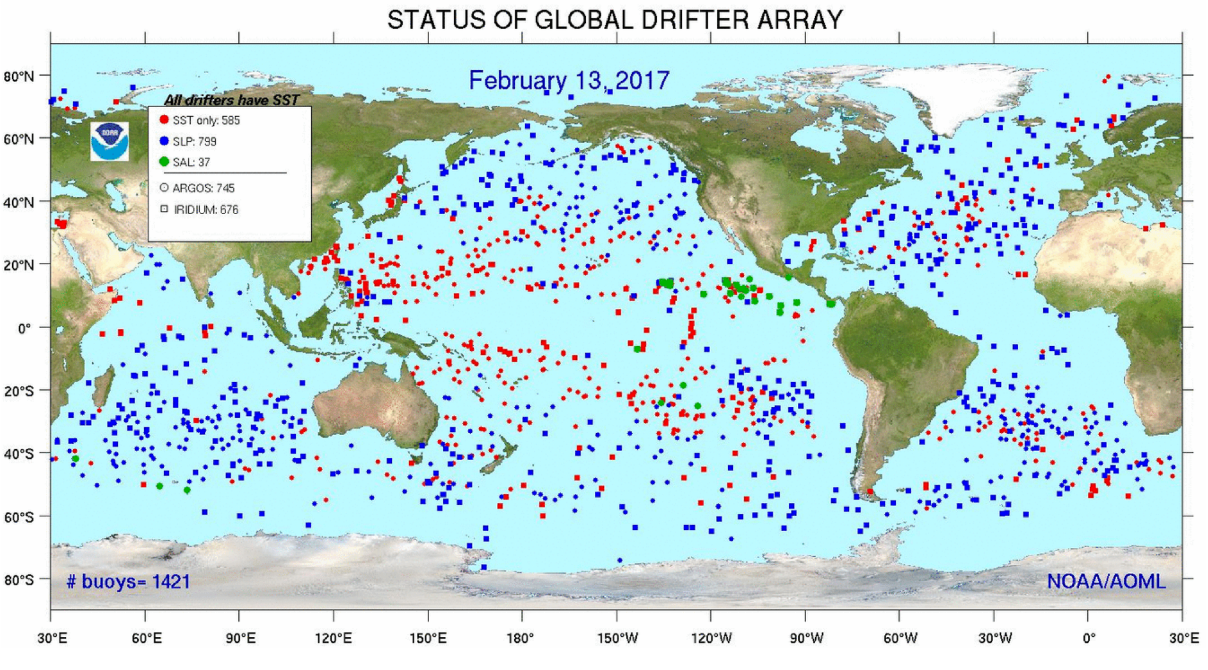

Figure 2: Status of the Global Drifter Array as of February 13, 2017. SST (red marker) indicates drifters measuring only sea surface temperature. SLP (blue marker) indicates drifters measuring sea surface temperature and sea-level atmospheric pressure, and SSS (green marker) indicates drifters measuring sea surface salinity and sea surface temperature. The legacy Argos drifters are indicated with a circle and the Iridium drifters with a square. These maps are updated weekly and are available online at http://www.aoml.noaa.gov/phod/dac/gdp_maps.php

The GDP relies on numerous national and international partners such as the Office of Naval Research to provide additional drifters to meet GDP instrument requirements, and also to provide deployment opportunities worldwide. The international collaboration is fostered through the activities of the Data Buoy Cooperation Panel

(DBCP), a joint body of the WMO and of the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

3. OPERATIONAL IMPACT OF THE DRIFTER DATA

The Global Ocean Observing System is composed of several components designed to observe various essential climate variables (ECVs), including SST, SLP and near sea surface velocity (SSV).

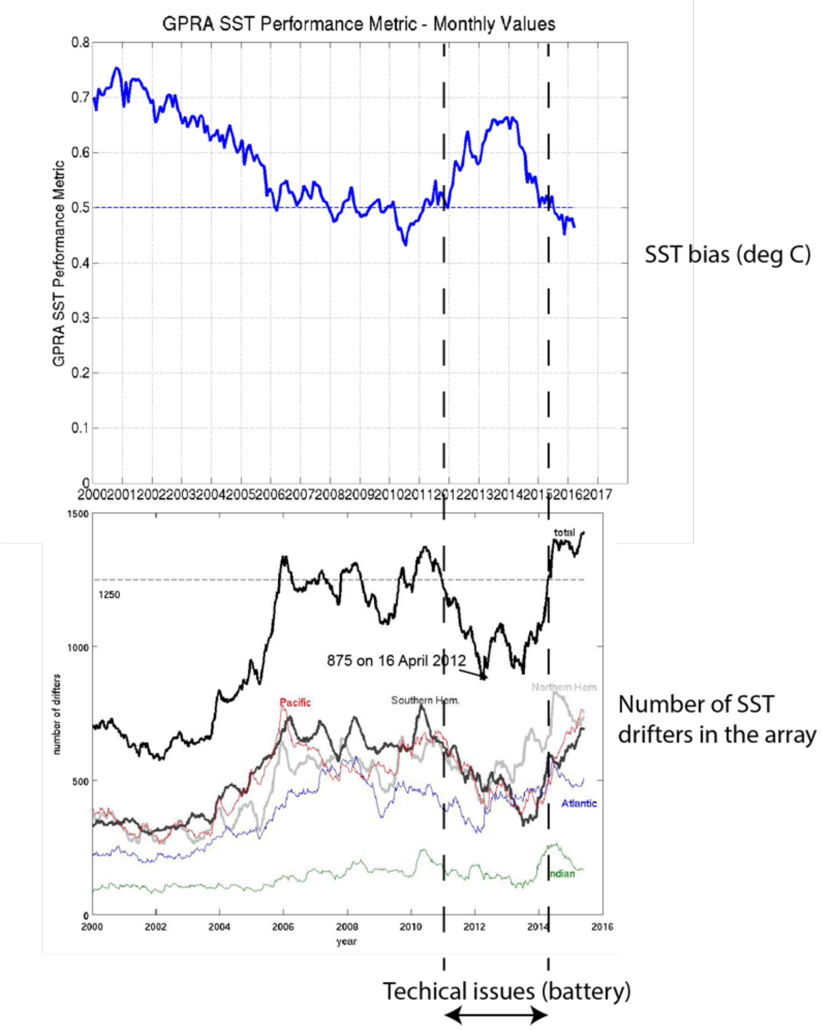

Figure 3: Satellite SST bias (updated from Zhang et al., 2009, courtesy H. M. Zhang), top panel, and number of SST drifters in the GDP array, bottom panel. Note the increase of the SST bias between 2011 and 2014 when the drifter array was below its target size due to a combination of technical issues that shortened the endurance of the drifters.

The modern requirement for *in-situ* SST observations has been refined to focus on reducing the potential bias in satellite-derived measurements (Zhang et al., 2009) below the Needler et al. (1999) upper threshold of 0.5ºC (*Figure 3*). To date, the GDP is the largest provider of in-situ SST observations, and it constitutes the benchmark against which most satellite SST products are calibrated and/or validated.

An analogous requirement has yet to be established for SSV and it is unknown how the current sampling impacts errors in satellite-derived surface currents or how accurately it resolves seasonal and lower-frequency circulation. But it is rather intuitive that understanding the dynamics of the ocean in order to improve weather and climate coupled models require a much higher sampling than the global drifter array currently provides. Furthermore, satellite altimetry data and CTD casts from Argo floats can only determine the geostrophic currents, i.e. how the ocean is in balance. Understanding how the wind imparts momentum to the ocean requires knowledge of the ageostrophic velocity as well, which is measured in-situ and globally by the drifter array.

Since most Numerical Weather Prediction (NWP) systems pull drifter SLP observations from the GTS in real time, there was a pressing need to quantify the impact of these observations. Recent studies [*Centurioni et al.*, 2016; *Horányi et al.*, 2016] have addressed this problem to conclude that the SVPB drifter data positively impact the forecast up to 5 days ahead and not only near the surface, but also higher in the troposphere, up to 250 hPa. The largest beneficial effects are observed in the mean sea level pressure field forecasts, but also in the predicted wind field and suggest that the expansion of the SVPB drifter array to the tropics should be considered. Data denial studies are lengthy and expensive, but other approaches using adjoint-based Forecast Sensitivity Observation Impact (FSOI) can quantify the impact of any or all components of the observing system on a specific measure of forecast impact when the entire observational dataset is present in the assimilation system [*Cardinali*, 2009; *Gelaro et al.*, 2007; *Langland and Baker*, 2004; *Zhu and Gelaro*, 2008], although the inherent linearization assumption restricts the range of the forecast assessment to about two days. With the FSOI approach, when the impact per observation or the fraction of beneficial observations are computed the SLP observations from drifters provide some of the largest values amongst the several components of the Global Observing System (*Figure 4*) [*Centurioni et al.*, 2016].

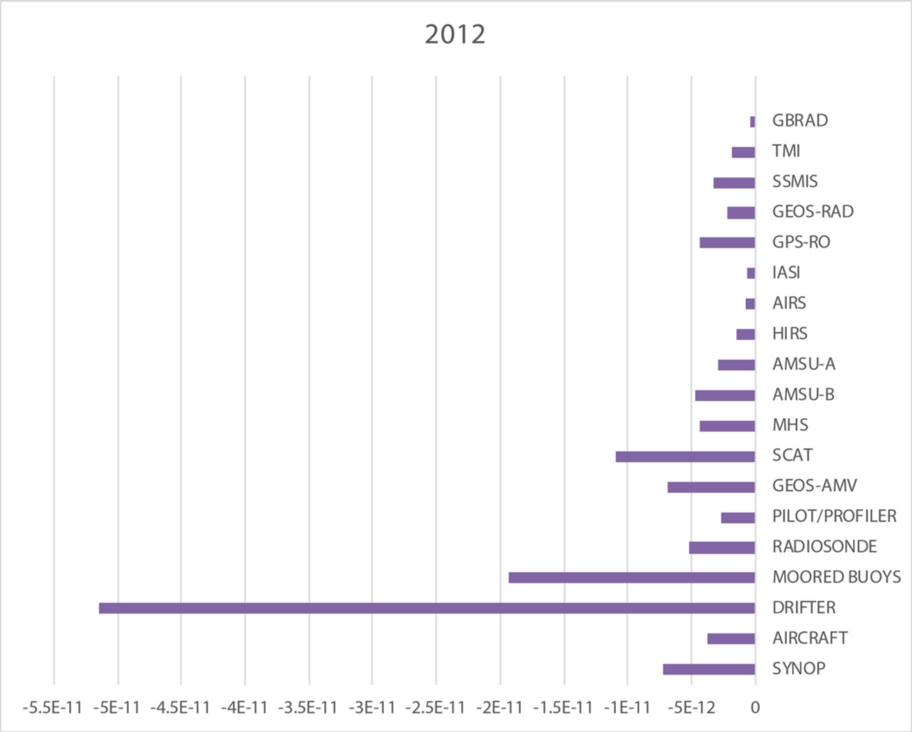

Figure 4: ECMWF operational mean FSOI for the different observing systems for July-August, 2012. The FSOI values are computed on a per-observation basis and are also normalized by the total forecast error for easier comparison. From Centurioni et al. [2016].

Drifter SLP data are also used by climate scientists for trend computations, for climate model diagnostics and for constructing climate indexes. Long-term mean-SLP changes also affect the mean sea-level due to the inverse barometer effects (a variation of 1 mbar corresponds, approximately to a change of 1 cm in sea level). Therefore, SLP drifter observations not only address climate monitoring requirements but also those for climate services, numerical weather prediction and marine services.

The demonstrated far-reaching role of SVPB drifters in climate research and NWP could justify the installation of barometers on all of the GDP drifters (currently only 60% of the global drifter array carries barometers).

Practical considerations of equal importance exist. One difficult tasks for the GDP is maintain a globally uniform array. Key to achieve this goal is the synergy with national meteorological services from, for example, the U.S. National Weather Services, France, the United Kingdom, Canada, Australia, South Africa, New Zealand, India and many other partners, coordinated by the DBCP.

4. SCIENTIFIC IMPACT OF THE DRIFTER DATA

A large number of studies have used drifter observations to map currents and their variability in various regions. Recent examples (2000–present) have focused on the North Atlantic [*Flatau et al.*, 2003], Labrador Sea [*Cuny et al.*, 2002], Caribbean Sea [*Centurioni and Niiler*, 2003; *Richardson*, 2005], subtropical eastern Atlantic [*Zhou* *et al.*, 2000], tropical Atlantic [*Grodsky and Carton*, 2002; *Hormann et al.*, 2012; *Lumpkin and Garzoli*, 2005; *Perez et al.*, 2014], South Atlantic [*Largier and Boyd*, 2001; *Lumpkin and Garzoli*, 2011], tropical Pacific [*Grodsky and Carton*, 2001; *Johnson*, 2001; *Yaremchuk and Qu*, 2004], central subtropical Pacific [*Flament et al.*, 2001; *Lumpkin and Flament*, 2001; *Lumpkin and Flament*, 2013], western Pacific[*Niiler et al.*, 2003], North Pacific [*Rabinovich and Thomson*, 2001], eastern Pacific/California Current System [*Centurioni et al.*, 2008], tropical Indian [*Peng et al.*, 2015] and Southern [*van Sebille et al.*, 2015; *Zhou et al.*, 2002] oceans. Several studies also focused on marginal seas including the Japan/East Sea [*Lee and Niiler*, 2005], South China Sea [*Centurioni et al.*, 2004; *Centurioni et al.*, 2009] and Black Sea [*Poulain et al.*, 2005; *Zhurbas et al.*, 2004]. A global evaluation of drifter-derived currents was performed by *Lumpkin and Johnson* [2013], and a global census of submesoscale to mesoscale eddies identified by looping drifter trajectories was published by *Lumpkin* [2016].

An exciting development is the synthesis of drifter observations and satellite altimetry. *Niiler et al.* [2003] synthesize Ekman-removed drifter velocity with gridded altimetric velocity anomalies in regions where they are significantly correlated. By applying a similar approach, *Maximenko et al.* [2009] produced a map of the dynamic topography of the global ocean. In a similar study, *Rio and Hernandez* [2004] synthesized a geoid model, operational winds, and observations from drifters, altimetry, and hydrography to produce an alternative global mean dynamic topography. Similar methods are used in *Centurioni et al.* [2009] to evaluate the partition between geostrophic and Ekman currents. Drifter, wind, and altimetry data were synthesized in *Lumpkin and Garzoli* [2011] to examine climate-scale fluctuations in the circulation of the South Atlantic. Drifter SVP data are also used to improve and evaluate the satellite-based Ocean Surface Current Analysis Real-time [OSCAR *Dohan et al.*, 2010; *Lagerloef et al.*, 1999] product.

Another exciting new application is the use of the drifter data, to map, for the first time, the tidal currents throughout the World Ocean. The global drifter data was used to describe the global spatial structure of the surface tidal currents with a resolution of 2°[*Poulain and Centurioni*, 2015].

Lagrangian drifters and other in-situ observations from gliders and moorings are a very important to study the dynamics of fast-varying western boundary currents and their interactions with marginal seas, when satellite sea-level data sometimes inadequate [*Andres et al.*, 2015; *Centurioni et al.*, 2004; *Gordon et al.*, 2014; *Lien et al.*, 2015; *Rudnick et al.*, 2011; *Vélez-Belchí et al.*, 2013].

Salinity drifters, termed SVPS, can reliably measure sea surface salinity SSS for over one year [*Hormann et al.*, 2014a] and can help quantify salt-water fluxes at the ocean surface [e.g. *Centurioni et al.*, 2015] and at the same time provide valuable data for the calibration and validation of SSS from space.

Drifters of various types (measuring wind and subsurface temperature to 150 m depth) have been air deployed to study ocean-tropical cyclones interaction [*D'Asaro et al.*, 2013]. Wind data from drifters were used to investigate the drag coefficient parameterization of wind stress using model sensitivity studies to find that significant improvements of the difference between modeled and observed SST changes can be obtained [*Zedler et al.*, 2009]. Other important applications include investigations of currents and the persistence of the cold wake generated by tropical storms, [*Chang et al.*, 2014; *Chang et al.*, 2016; *Chang et al.*, 2012; *Chang et al.*, 2013; *Hormann et al.*, 2014b].

Drifting thermistor chains, a variant of the hurricane drifters, and SVP drifters, were also used to study the upper structure and the phase velocity of large amplitude non-linear internal waves in the South China Sea [*Alford et al.*, 2015; *Centurioni*, 2010].

5. NEW DEVELOPMENTS

Since the GPS engine can also be used to obtain directional wave properties, an exciting opportunity that is actively pursued by the GDP is the addition of directional wave spectra estimates from drifters. The advantages of GPS-derived wave properties are both practical [*Herbers et al.*, 2012] and financial. Undrogued drifters can be turned into directional wave riders and can become the first *in situ* global network of wave sensors. It is anticipated that wave forecasting model will greatly benefit from this application. There is also growing interest by the scientific community in increasing the use of thermistor chains and/or dual salinity sensors to study thermohaline stratification near the ocean surface.

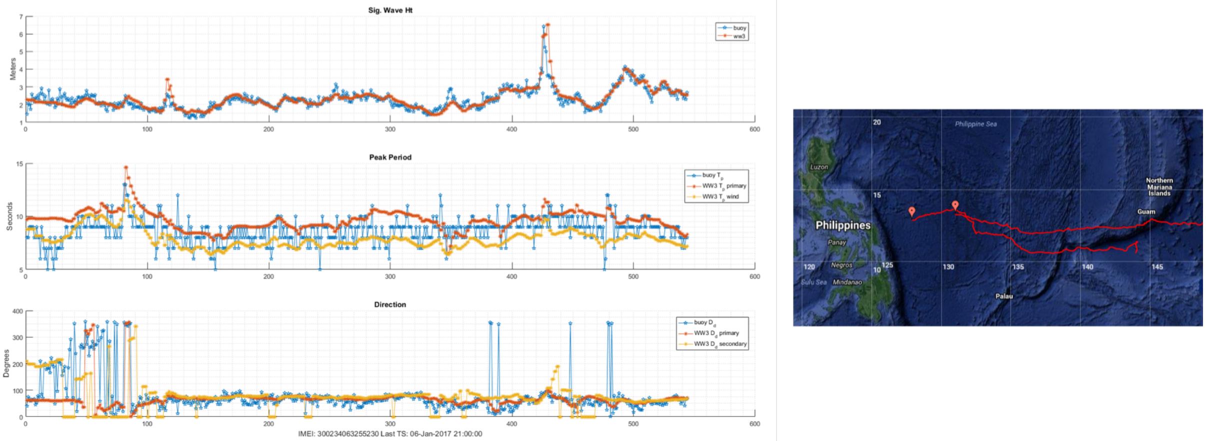

Figure 5: Left. Directional wave characteristics from an experimental GPS wave drifter deployed near Palau (track shown in the right panel) compared with Wave Watch III. Note the significant wave height observed on nearly 7 m observed by the drifter and also forecasted by the model

6. FUTURE PERSPECTIVES AND CONCLUSIONS

The Global Drifter Array is a unique infrastructure strategically located at the interface between the ocean and the atmosphere that provides observations of ECV's needed to monitor the changing ocean/atmosphere system and to support basic research to understand the physical principles underlying these changes. It also addresses the need to understand how accurately weather prediction and coupled ocean-atmosphere models can represent the environment and produce forecasts, from weekly to decadal and inter-decadal scales.

More than 1,000 peer reviewed scientific articles published using GDP data have demonstrated the large scientific impact of the GDP. Large uncertainties are still associated with our understanding of the physics of air-sea interaction. A proper physical representation/parameterization of how the momentum imparted by the wind to the ocean sets the latter in motion is still missing, as demonstrated by the fact that drifer velocity observations from drifters are very difficult to assimilate in ocean circulation models. The GDP is well placed to make a very significant impact in this field with the advancement of the technology and the implementation new sensors. For example, global measurements of the velocity shear in the upper ocean will provide a wealth of data for assimilation/evaluation of numerical models and will help understanding the physics of the mixed layer, where the wind stress, turbulent momentum fluxes, surface waves and internal waves, heat and salt fluxes interact in a non-linear fashion to couple the ocean and the atmosphere.

Ultimately, understanding the relative role of geostrophic and ageostrophic currents, the sum of which is at present exclusively measured globally with SVP drifters will improve the physical descriptions of heat and freshwater exchanges with the atmosphere and of their lateral transport within the mixed layer.

The departure of upper ocean currents from geostrophy is known to be significant. *Centurioni et al.* [2008] and *Maximenko et al.* [2009] have shown that the geostrophic circulation computed from dynamically balanced ocean topography is very different from the one obtained with direct measurements. Futhermore, the vertical structure of the upper-ocean ageostrophic circulation is virtually unknown. Understanding how heat and freshwater are forced, advected [*Centurioni et al.*, 2015; *Schmitt et al.*, 2015] and mixed requires a deeper knowledge of the three-dimensional upper ocean circulation. Resolving the Ekman currents and the convergence patterns of the ageostrophic currents that drive the upper-ocean vertical circulation will be crucial to constrain ocean circulation and climate models towards a more realistic physical representation and will ultimately lead to improved ocean state and climate forecasts.

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