

Drifter Technology and Impacts for Sea Surface Temperature, Sea-Level Pressure, and Ocean Circulation Studies

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Abstract The purpose of this chapter is twofold. First, we illustrate the technology used by the Lagrangian drifters deployed by Global Drifter Program (GDP), which is the principal component of the Global Drifter Array; second, we review and summarize the most recent studies on the impact of drifter data for calibration and validation of sea surface temperature (SST) satellite products, Numerical Weather Prediction (NWP) and climate studies, tropical cyclones (TCs)-ocean interaction and ocean circulation studies. Several types of drifters are described, starting from the simplest configuration that measures SST and sea-level atmospheric pressure (SLP), continuing with special drifters designed to measure sea surface salinity (SSS) and sea-level wind (SLW), and ending with air-deployable drifting thermistor chains that measure the temperature of the upper 150 m of the ocean, which are used to study the interaction of the ocean's mixed layer with TCs. We also discuss the implications of the satellite telecommunication technology on the accuracy of drifter's geolocation and on the timeliness of the near real-time data stream.

New opportunities for expanding the scope of the GDP are also discussed.

1 Lagrangian Drifter Technology

The use of Lagrangian drifters to measure near-surface ocean currents is more than a century old. As pointed out by Niiler [30] describes the early use of drifting buoys during the HMS Challenger expedition between 1872 and 1876 and presents the first complete and comprehensive historical and modern perspective of the Global Drifter Program (GDP). Here, we use the term Lagrangian, which in mechanics usually refers to the description of the trajectories of a system of particles from their position and time derivatives, interchangeably with water-following capabilities. Therefore, a good Lagrangian drifter is a device capable of following a volume of water at the surface of the ocean for a certain length of time with minimal relative motion, or slippage, with respect to the surrounding water. It should be emphasized

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that surface Lagrangian drifters are not designed to follow the vertical motion of the water.

Starting in 1978, the Global Atmospheric Research Program (GARP), established under the framework of the World Meteorological Organization (WMO) and of the Intergovernmental Council of Scientific Unions (ICSU) with the objective to better understand the large-scale physical processes necessary to improve weather forecasting and the physical basis of climate, launched the First GARP Global Experiment (FGGE). Interestingly, FGGE had a substantial 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>] and it supported the deployment of several hundred drifters designed to collect sea surface temperature (SST), air temperature, and sea-level atmospheric pressure (SLP). The FGGE program was one of the earliest examples of successful collaboration between oceanographers and meteorologists, which today is still a major thrust of the GDP. However, most FGGE drifters were expensive and did not have an efficient drogue (term used to define the sea anchor that ensures the water following capability of the drifter) attached. The inability of the FGGE drifters to accurately follow near-surface ocean currents was perhaps the main reason behind the decision to abandon this design [30], although some attempts were made to recover ocean current measurements from them [36].

A detailed account of the surface Lagrangian drifter designs in use before the GDP was established is given by Lumpkin and Pazos [23] and shall not be repeated here. It suffices to say that the drifter design that emerged in the early 1980s consisted of a surface buoy containing batteries, electronics such as a digital controller, analog signal digitizers, a satellite modem, and a suite of surface sensors. The surface buoy was attached to a drogue with a tether. In the early days of the GDP, considerable efforts were devoted to investigate the drifter and drogue design that would ensure optimal water-following capabilities, as reported by Niiler et al. [32]. Both holey-sock (Fig. 1) and TRISTAR (Fig. 2) drogues were tested extensively with vector-measuring current meters and dye to quantify the slip of the drogue through the surrounding water. The TRISTAR drogue was determined to be slightly more efficient than the holey-sock, although both types performed satisfactorily as long as the ratio of the drag area of the drogue to the sum of the drag area of all the other elements of the drifters (mainly the tether and the surface sphere) was larger than 40 [32]. The holey-sock drogue was chosen because it allows the drifter to be compacted in a smaller volume package than the TRISTAR, thus making storage, shipping, and deployment of the drifters easier and less expensive, thus opening the way to the implementation of a sustainable global array. The drag area ratio criterion is still used in modern drifters and it ensures that when the drogue is present the drifters can measure the ocean currents with an accuracy of about 0.9 cm s^{-1} for winds up to 10 m s^{-1} [32].



Fig. 1 (a) Holey-sock drogue. (b) Dye release and holey-sock drogues fitted with vector-measuring current meters to measure the slip of the drogue through the surrounding water



Fig. 2 (a) SVP drifter with TRISTAR drogue with Dr. Peter Niiler holding the surface buoy. (b) Diver checking the current meters used to measure the slip of the TRISTAR drogue through the surrounding water

1.1 *The Velocity-Temperature (SVP) Drifter*

The Surface Velocity Program (SVP) was the precursor of the GDP and was established in conjunction with the Tropical Ocean Global Atmosphere (TOGA) program in 1988 [15]. The simplest version of an oceanic drifter, commonly called the SVP drifter, was the system of choice used to implement the GDP. The GDP was the first component of the Global Ocean Observing System (GOOS) to reach completion with the ceremonial launch of drifter 1250 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.

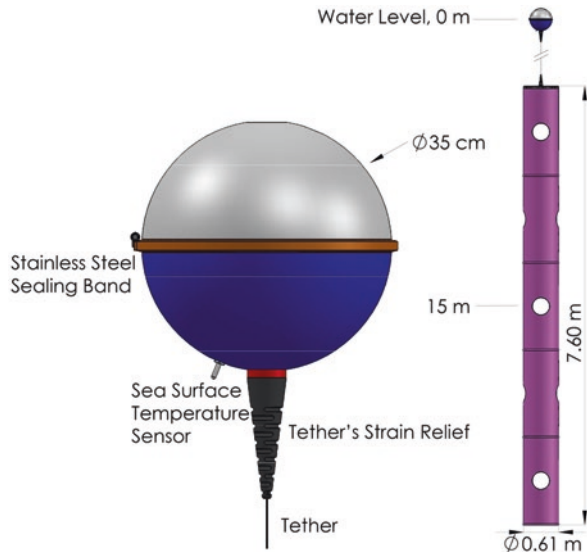
The SVP drifter used until 2002 consisted of a surface sphere with a diameter of 0.28 m, a subsurface float with a diameter of 0.2 m located at a depth of about 2 m, and a holey-sock drogue approximately 6 m long and with a diameter of 0.84 m [32]. The length of the tether was standardized so that the center of the drogue along its longest side was located at a depth of 15 m. Such depth was chosen to reduce the direct effect of the surface waves on the drogue (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 was introduced, which consisted of a slightly larger surface buoy (0.38 m in diameter) and a shorter drogue of smaller circular cross section (about 0.6 m of diameter). The subsurface float was removed. The exact size of the surface buoy and of the drogue depends on several factors, including the diameter of the tether, but they are chosen so that the drag area ratio is larger than 40 [32], which, as of today, is a strict requirement for all the drifters operated by the GDP. The smaller version of the SVP drifter was introduced primarily to reduce the cost of the equipment and ease the logistics without affecting its Lagrangian properties.

The SVP drifter designed and produced today by the Lagrangian Drifter Laboratory (LDL) at the Scripps Institution of Oceanography (SIO) is presented here as an example of the modern technology.

In its simplest configuration (Fig. 3), the SVP drifter measures only SST and ocean currents at a depth of 15 m (i.e., the center depth of the drogue).

The drifter's hull has a diameter of 35 cm and is made of acrylonitrile butadiene styrene (ABS). The drogue consists of cylindrical tube of 600 den, or higher, ripstop fabric Cordura® nylon connected to the surface buoy with an impregnated steel wire-rope tether. A thermistor potted with a thermally conductive resin encapsulated into a stainless-steel enclosure is mounted in the bottom part of the surface buoy, 18 cm below the floatation line. The base of the thermistor enclosure that commu-

Fig. 3 Schematics of the SVP drifter designed and produced by the Lagrangian Drifter Laboratory at the Scripps Institution of Oceanography



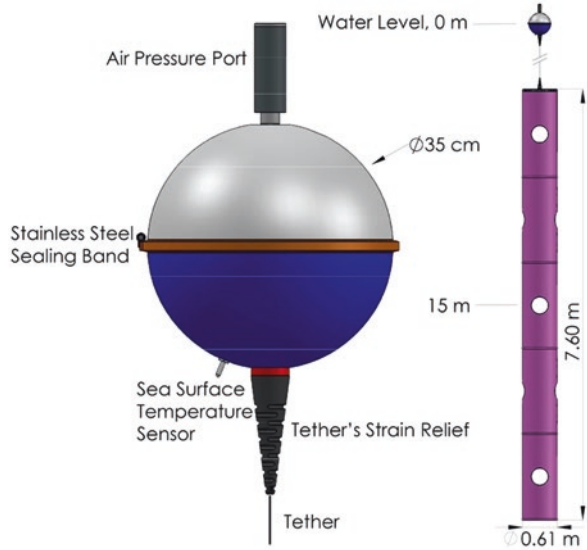
nicates with the inside of the drifter is thermally insulated from the inside of the buoy with a special resin to avoid biased SST readings that may occur when the drifter's hull overheats under the sun. The bench accuracy of the SST measurements is ± 0.05 °C after 5-point calibration across the sensing range of the thermistor (-5°C – 40°C).

The presence of the drogue is detected with a strain gauge mounted inside the hull and near the tether attachment. The strain gauge senses the deformation of the hull due to the pull of the tether, that is enhanced when a drogue is attached and surface waves interact with the drifter's hull.

All drifters carry a satellite modem for data telemetry. The Argos satellite system has been used in the past to transmit the data to shore and to compute the drifter position using the Doppler shift of the transmitter carrier frequency, yielding a geolocation accuracy that ranges from ~ 200 m to ~ 2 km [22]. In 2016, the GDP has begun a transition to the Iridium satellite system. The main advantages of Iridium telemetry are that the data are received by the drifters' operators in a shorter time (typically 1 min compared to 90–120 min with Argos) and the positions are measured with a Global Positioning System (GPS) engine that yields typical geolocation accuracy of 2–50 m (rms). An LDL designed digital controller handles the duty cycle of the data collection (typically once per hour, but it can be changed underway using the two-way Iridium communication) and formats the data (SST and position) for satellite transmission. A comprehensive set of diagnostic data, that are crucial to monitor the health of the drifter array, such as the battery voltage, the hull's internal pressure, temperature, and humidity, are also formatted and appended to the data message.

The GDP drifters are fitted with diode-protected, alkaline D-Cell, 12 V, 56 Ah battery packs. Although alkaline D cells are not designed to withstand shocks and vibrations, they are preferred because they are less hazardous than primary lithium batteries. Since the target lifetime of the drifter is in excess of 400 days, it means that through its life the surface buoy undergoes several millions of impacts resulting from surface waves with mean periods ranging from ~ 3 s for wind waves to ~ 20 s for swell [20]. To prevent a quick degradation of the power source, expanding foam and a special resin are used to secure the cells forming the battery pack within a special bucket solidly connected to the drifter's hull. Other padding materials are added to the top of the potted battery pack to further minimize the adverse effects of impacts and vibrations, resulting in a life span in excess of 2 years. Other points of mechanical and electrical failure of drifters have been identified through years of examination of instruments recovered at sea or after running aground. These include the tether, the connections between the tether and the surface buoy, the drogue attachments, and the fabric used for the drogue.

Fig. 4 Schematics of the SVPB drifter designed and produced by the Lagrangian Drifter Laboratory at the Scripps Institution of Oceanography



1.2 The Barometer Drifter (SVPB)

The SVP Barometer (SVPB) drifter (Fig. 4) has the same capability of the SVP drifter but it also carries a barometer to measure SLP [3, 16, 27, 30]. The air pressure sensor can either be a High Precision Barometer (HPB) by Honeywell, stable over the 2 years long nominal life span of the drifters with an accuracy of ± 0.4 hPa, or an Integrated Pressure Transducer, also by Honeywell that has similar specifications and accuracy. Since ocean waves often pull the surface buoy underwater the air intake that communicates with the barometer is protected with a specially designed self-draining port and waterproofed with two GORE-TEX® membranes.

When the drifter goes underwater, erroneous SLP readings will occur, and these are filtered out by an on-board algorithm before the data message is formatted and queued for satellite transmission. Like the SVP, the life span of the SVPB drifter is in excess of 2 years.

1.3 The Salinity Drifter (SVPS)

The SVP Salinity (SVPS) drifter [7, 17] also stems from the SVP drifter design and it can be configured with a barometer. It carries Sea Bird Electronics SBE37 sensors and it is significantly more expensive than the SVP and SVPB versions. The salinity sensor is located at a depth of 0.5 m and a slightly bigger drogue is used to compensate for the larger drag area of the surface buoy and of the salinity sensor mount combined, as needed to keep the drag area ratio larger than 40 (Fig. 5). The life span

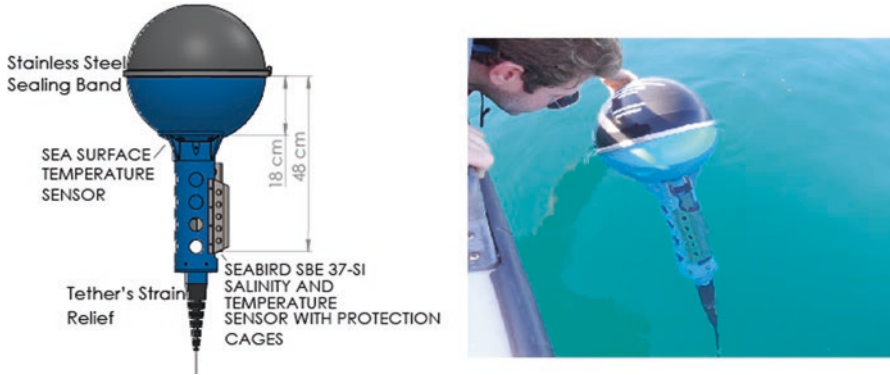


Fig. 5 *Left*, schematic of the SVPS drifter. The standard version has two SST sensors, one directly mounted on the drifter's hull and the second integrated in the SBE37-SI salinity sensor. The schematics of the drogues have been omitted for clarity. *Right*, one LDL SVPS being tested at the Scripps Institution of Oceanography in La Jolla, California

of the SVPS drifter is about one year and is significantly shorter than that for the SVP and SVPB drifters, which is about 1 year.

1.4 *The Minimet Wind Drifter (SVPW) and the Autonomous Drifting Ocean Station (ADOS)*

The SVPW or Minimet drifter (Fig. 6) was designed to be air-deployed in front of tropical cyclones. It carries the same air pressure sensors of the SVPB drifter and a sonic anemometer, for example, the Gill WindSonic that measures wind speeds up to 60 m s^{-1} with a 2% accuracy FS. The wind direction is measured with an internal compass integrated in the LDL controller and has direction accuracy of $\pm 2^\circ$ accuracy after calibration. The surface buoy of the Minimet is larger than the one used for the SVPB drifter and features a wind vane that has the purpose to stabilize the buoy in the presence of strong winds. An algorithm similar to the one installed on the SVPB drifter is used to discard the invalid anemometer data that occur, for example, when the drifter is submerged.

The ADOS (Fig. 6) can also be air-deployed. The surface buoy is identical to the one used for the SVPW drifter and a 150-m long tether replaces the drogue, thus making the ADOS a non-Lagrangian device. The device measures SST and 15 pods that measure water pressure and temperature are attached to the cable with 10 m spacing. The subsurface pods use inductive communication technology to send the data through the single-conductor impregnated steel wire rope combined with a sea water contact that closes the electrical circuit. The life span of the ADOS is approximately 3 months. Several air deployments have been made to date to measure the temperature structure of the upper ocean during the passage of tropical storms and

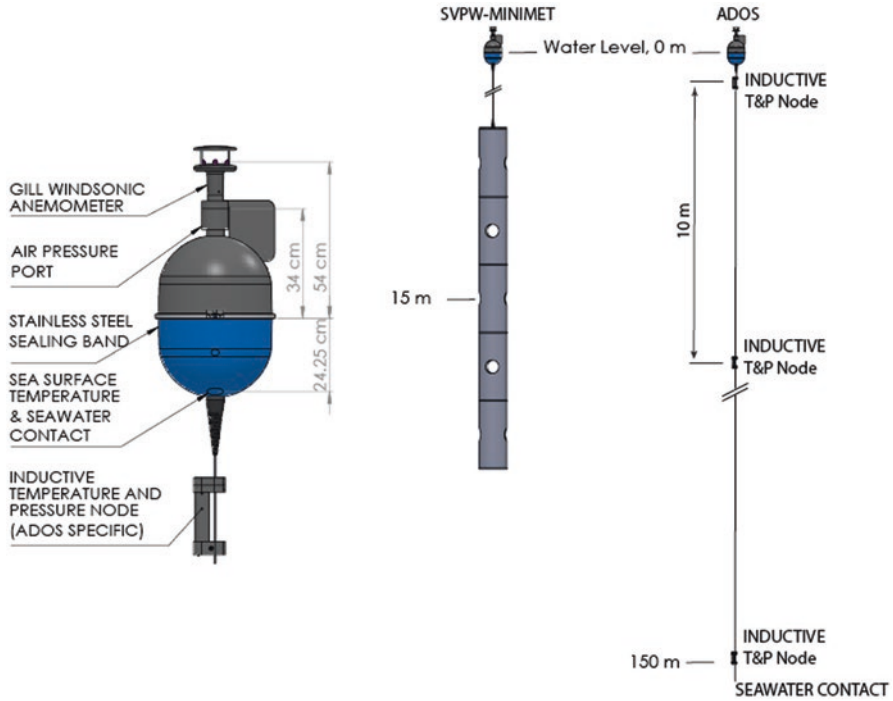


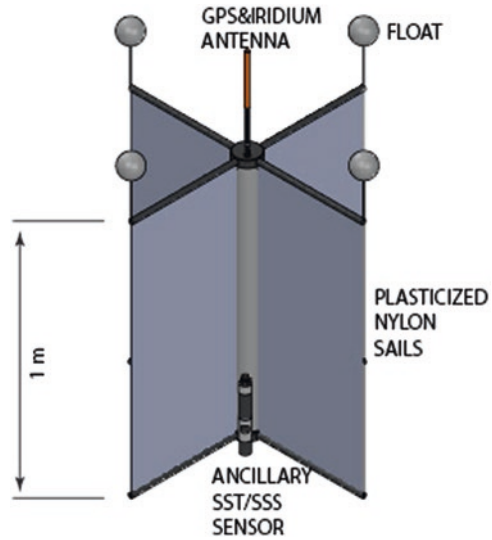
Fig. 6 *Left*, schematics of the surface buoy of the SVPW and ADOS drifters. A modified air pressure port is used to mount the wind sensor. The inductive temperature and pressure pod, specific to the ADOS, is also shown. *Center*: SVPW/Minimet configuration with drogue centered at 15 m depth. The size of the drogue is larger than that for the SVP and SVPB drifters to ensure that the the drag area ratio is larger than 40. *Right*: ADOS configuration with 150 m long tether, and temperature and pressure nodes spaced by 10 m

the evolution of the cold wake [9, 18, 29]. An enhanced version of the ADOS fitted with vertically profiling acoustic current meters was used to measure the properties of large-amplitude nonlinear internal waves in the northern South China Sea [4].

1.5 Coastal Ocean Dynamics Experiment (CODE) Drifter and River Drifter (RD)

The CODE drifter [10] was designed as an inexpensive water follower to track currents in the upper meter of the oceanic mixed layer. However, as of today, the cost of a CODE and SVP drifter is similar. The CODE drifter consists of a cylindrical hull, 10–15 cm in diameter that contains the batteries and electronics. The drag element consists of four sails made of plasticized nylon arranged in a cross-like shape (Fig. 7). The CODE drifter is slightly negative buoyant and four small floats

Fig. 7 Schematics of the CODE drifter configured with an external salinity and temperature sensor



connected to the end of the arms to which the sails are attached provide the extra buoyancy to ensure floatation. The CODE drifter carries the same SST sensors installed on the SVP drifter and can be configured with an external SSS sensor. The CODE drifter is considered an accurate water follower, and laboratory wave tank testing has shown that, if the drifter stays upright, the slip through the surrounding water is of the order of 1 cm/s for moderately sized waves [10]. However, it is likely that in presence of large breaking waves, the drag of the submerged part is affected by substantial tilting of the buoy, thus resulting in possible rectification of the relative motion of the drifter with respect to the wave orbital velocity. Poulain et al. [39] have found that the CODE drifters measure a wind-induced Ekman current that is approximately directed at 28–30° to the right of the wind (in the northern hemisphere). This is much less than the 45° angle predicted by the Ekman theory [13] and closer to the angle found for undrogued SVP drifters, which is generally more downwind, at about 17–20° to the right of the wind. This suggests that the CODE drifter may be subject to more wave-induced downwind leeway than the SVP drifter. The life span of the CODE drifter is about 1 year.

The River Drifter (RD) stems from the CODE drifter design and was conceived and designed by the LDL. This development originated from the need to have a Lagrangian drifter capable of operating in calm and shallow water bodies, such as lagoons and estuaries, or in the surf-zone, while also measuring the water depth and vertical shear of the three-dimensional currents underneath. A fleet of RDs can be used, for example, to study the dispersion of near-surface water and pollutants and their dependence on bed forms and on the vertical shear of the horizontal currents.

The central body of the RD is 0.6 m long, and the cross-sectional area of the sails and hull combined is 0.39 m² (Fig. 8). As for the CODE drifter, the hull contains the battery pack and the LDL controller to manage the sensors, the data acquisition, and

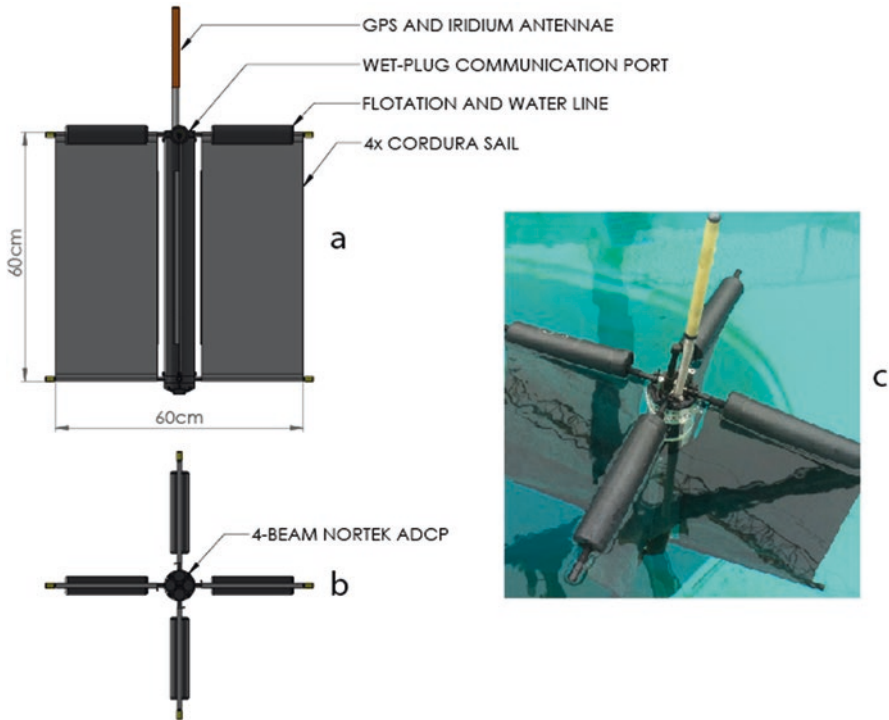


Fig. 8 Schematics of the side (a) and bottom (b) views of the river drifter adapted from [37] and flotation test of the river drifter (c)

telemetry. The sensor suite includes a GPS engine, data logger, as well as a specially designed acoustic Doppler current profiler (ADCP) by Nortek. The ADCP has four transducers, three to measure the three-dimensional water velocity and the fourth to measure the water depth. Two versions of the RD ADCP exist, 1 and 2 MHz, which allow operations at different water depths and with different vertical resolutions of the current. The data telemetry options include a direct RF link and the Iridium (Short-burst Data-SBD-modem) for global applications. A direct data link is also available through a wet-pluggable connector located next to the dual Iridium-GPS antenna which allows direct communications with the instrument for ADCP calibration, sensor configuration, data retrieval, and diagnostic output via RS-232 protocol.

Depending on the duty cycle and on the type of batteries, the endurance of the RD can vary from 1 to 7 days. A full description of the instrument and examples of applications can be found in Postacchini et al. [37].

2 The Global Drifter Program

The NOAA funded GDP [27, 30] is the principal component of the Global Surface Drifting Buoy Array, a branch of NOAA's GOOS and a scientific project of the DBCP. The DBCP is an international program coordinating the use of autonomous data buoys to observe atmospheric and oceanographic conditions over ocean areas where few other measurements are taken. The DBCP was created in 1985 as a joint body of WMO and of the Intergovernmental Oceanographic Commission (IOC) of UNESCO. The DBCP constitutes the data buoy component of the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM).

The long-term objectives of the GDP are to:

- Maintain a global ocean observing network of at least 1250 Lagrangian drifters with a nominal resolution of $5^\circ \times 5^\circ$ that, through the Argos and primarily the Iridium satellite systems, return data of Essential Climate Variables (ECV) including near-surface ocean currents (15 m depth), SST, SSS, SLP, SLW, and subsurface temperature in front of tropical cyclones;
- Innovate the drifter technology and expand the scope of the program by transitioning new sensors into operation; and
- Make the drifter data available in near-real time through the Global Telecommunication System (GTS) of the WMO Information System (WIS) in order to contribute to the World Weather Watch (WWW), and provide a data processing system and a delayed-mode, quality-controlled data archive for the scientific use of the drifter data.

The requirements of GOOS call for the GDP to maintain an array of 1250 drifting buoys, as needed to achieve a density of one drifter in $5^\circ \times 5^\circ$ boxes. More details can be found in Lumpkin et al. [25] that also discusses the optimal implementation strategy to fulfill the goals of the GDP.

At the time of writing, the historical drifter dataset contains data starting from 1979, generated by over 20,000 surface Lagrangian drifters drogued at 15 m depth (Fig. 9), and it supports a detailed description of most oceanic mesoscale features and of the major persistent current system of the world's ocean (Fig. 10). Standardized quality control techniques and interpolating procedures onto regularly spaced 6-hourly time series are described in Niiler [30] and Maximenko et al. [27].

The GDP is managed by two groups that operate in close collaboration. The first, the drifter Operations and Data Assembly Center is located at the Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida, and oversees most of the global drifter deployments, performs the delayed-mode quality control of the drifter data, creates several gridded products, and archives the data. The second, the Lagrangian Drifter Laboratory at the Scripps Institution of Oceanography, La Jolla, California, provides most of the drifters for the global array either through fabrication and purchasing, oversees the drifter technology,

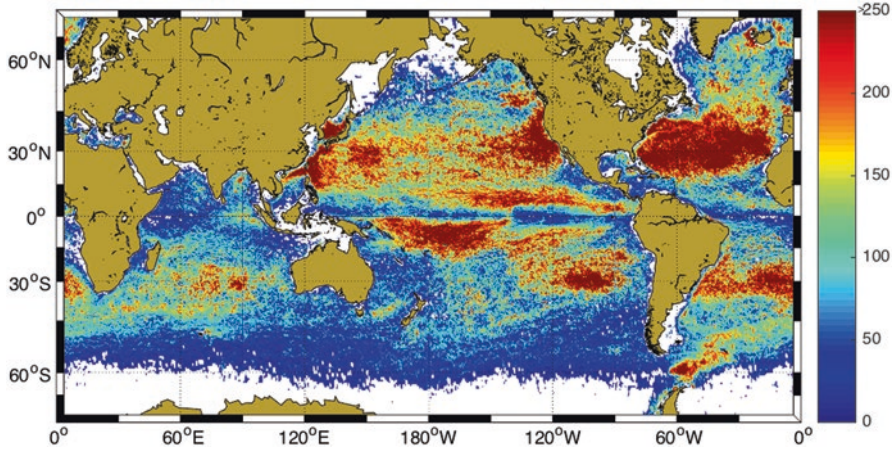


Fig. 9 Number of 6-hourly observations in $1/3^\circ \times 1/3^\circ$ bins between February 15, 1979 and December 31, 2015. The total number of drifter observations in this time interval is 31,802,475

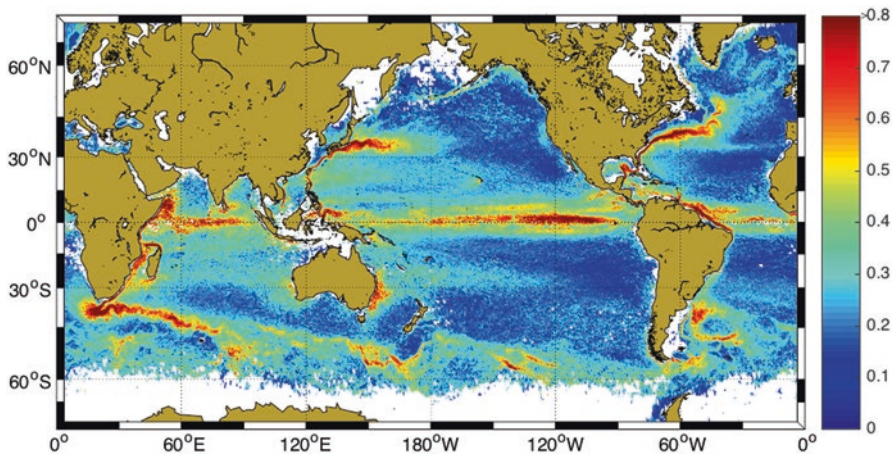


Fig. 10 Speed of the ocean currents obtained from bin-averaging the 6-hourly drifter observations in $1/3^\circ \times 1/3^\circ$ bins

designs and fabricates new types of drifters, manages the real-time incoming data stream from the Iridium satellite system (Fig. 11), posts the data to the GTS, archives and distributes the data to its partners, maintains real-time statistics on the performance of the drifters, and provides project-specific web-based visualization interfaces. Multiple computer servers are operated by the LDL with considerable redundancies to ensure the continuity of the operations. Two server racks are operated in parallel, one located in the SIO colocation data center and one at the San Diego Supercomputer Center at UC San Diego. These two racks receive, process,

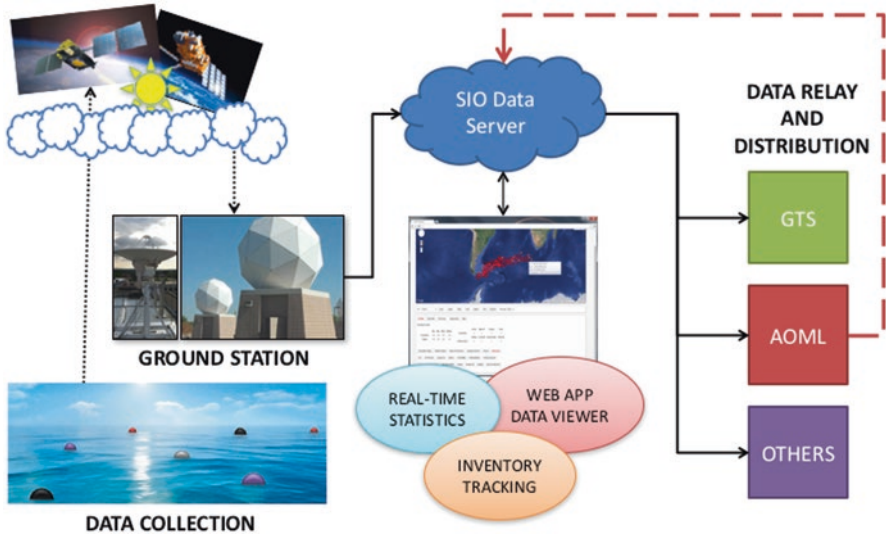


Fig. 11 Schematics of the GDP data route from the data collection in the field to the distribution of the converted data to the several partners and to the international community through the GTS

and relay real-time drifter data for collaborating partners. Further, a third remote system is operated using a commercial web service in the US Government Cloud data center for a real-time offsite archiving of all the incoming data.

3 Impacts of the Global Drifter Program Data

3.1 Sea Surface Temperature

Drifters measure and report SST at a depth of approximately 0.2 m every hour and are currently the largest source of global in-situ data [45] which are essential to validate and calibrate satellite SST products. Accurate global SST data are important for climate research and numerical weather prediction, among others. SST products can have small globally and annually averaged biases, but regional and seasonal biases can be much larger, often in excess of 0.5 °C [47]. For example, SST products derived from the advanced Along Track Scanning Radiometer are known to have differences between day and nighttime versions and have annually or globally averaged biases ranging from -0.04 °C to 0.2 °C [34]. Zhang et al. [47] introduced the Potential Satellite Bias Error (PSBE) metric, defined as the “residual satellite bias that cannot be further reduced at a given buoy density (sic),” to show that a global array of 1250 nearly uniformly distributed SVP drifters is needed, together with underway ship observations, to keep the regional and seasonal PSBE below 0.5 °C. The relationship between the PSBE and the number of drifters operating in

the global array at any one time is almost linear and inversely proportional; it is assessed quarterly by NOAA's Climatic Data Center and it is used to evaluate the compliance of NOAA's contribution to GOOS, as required by the US Government Performance Results Act of 1993.

The nominal accuracy of the SST sensor of drifters deployed before 2014 is ± 0.1 °C, but the use of more accurate temperature sensors, with smaller drift and an accuracy of ± 0.05 °C is becoming increasingly common. Some studies have discussed the possibility that the accuracy of drifter's SST is actually worse than 0.1 °C, setting it at 0.23 °C after three-way error analysis [35]. However, the possibility that geophysical variability may negatively affect the analysis and bias, the accuracy estimate when pointwise in-situ observations are compared with satellite observations that sense SST is ~ 1 km wide pixels, has not been ruled out. Other subtle issues may play a role in the observed discrepancy between nominal and inferred drifter SST accuracy, and these include differences in the satellite retrieval algorithms and the stability of the SST analog electronic circuit and the drifter's sampling methodology that has evolved through the years. Nevertheless, it can be anticipated that more accurate SST drifter observations, together with measurements of the depth at which SST is sampled, of the sea state and improved geolocation resulting from the exclusive use of a GPS engine, will improve the quality of SST satellite products in the near future.

3.2 Sea-Level Atmospheric Pressure: Climate Studies

SLP observations constitute one of the longest data records of interest to climate science. Historically, atmospheric pressure sensors were well distributed over land and became progressively widespread over the ocean with the expansion of commercial shipping routes, the implementation of a Voluntary Observing Ship (VOS) program, and of the Global Drifter Array. In most areas, the drifter array represents the most accurate, and often unique, source of in-situ SLP data. The spatial distribution of SLP data over the ocean, if surface drifting buoys were removed, would be severely and negatively affected by the large gaps that exist in commercial shipping lanes. Notable examples of regions where there is very little ship traffic are the Southern Ocean and the Arctic region [45]. Even on trafficked shipping lanes, drifters are often the only source of most valuable SLP data when a storm develops and VOSs perform avoidance maneuvers.

The modern SLP drifter dataset contributes significantly to many re-analysis products used for climate assessment. Climate-related changes of the mean atmospheric load, or SLP, can induce long-term sea-level changes quantifiable in ~ 1 cm for a 1 mbar change, the so-called inverse barometer effect [46]. Although a formal assessment of the impact of SLP drifter data on the correction of satellite altimetry has never been performed (P.Y. Le Traon, Pers. Comm.), it is safe to assume that drifters are underpinning the sea-level correction in areas where they are the main source of oceanic SLP data, for example, in the Southern Ocean.

In-situ drifter SLP data are used in a variety of ways by climate scientists, including for trends computation to diagnose climate models and to construct climate indexes. The tropical Pacific SLP field is used to define the Multivariate El Niño–Southern Oscillation (ENSO) Index (MEI) [44]. The Southern Annular Mode (SAM) index is defined as the SLP difference between 40°S and 65°S [14]. As mentioned before, the drifters are probably the most reliable source of SLP data in this latitude band. Drifter data are widely used to compile global climate products such as the Hadley Centre’s monthly historical mean sea-level atmospheric pressure dataset (HadSLP2) and the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) v. 2.5 (ranging 1662–2007) and subsequent updates based exclusively on NOAA/NCEP GTS [45]. Substantial differences between several data products are observed in regions where data are sparse, particularly over the higher latitudes of the Southern Ocean and in the southeastern Pacific [1]. Improving the coverage of SLP observations from drifters is expected to improve the quality of several climate indexes. Other climate products that use the drifter (velocity, SST and SLP) data are the Climate Forecast System Reanalysis (CFRS) of the United States National Centers for Environmental Prediction [41] and the twentieth-century reanalysis project [8].

Reports of the weakening of the Pacific Walker circulation indicated by trends in the zonal SLP gradients across the equatorial Pacific exist [43]. Similar conclusions were reached by way of analysis of other climate variables, thus enhancing the confidence on such pattern of climate variability.

Other climatically relevant results based on SLP observations include changes in the occurrence and intensity of extratropical storms, monsoons variability, and trends in extreme winds events. The IPCC report, however, concludes that the confidence in some of these evaluations is low, primarily, because of inconsistencies between (and internal to) re-analysis products that must merge data from different years (some going back to early 1800s) and of different quality and “by the lack of long term data, particularly in the Southern Hemisphere (2013 Climate IPCC report pg. 2–62).” Therefore, it is important to ensure the continuity of the widely used in-situ SLP dataset coming from a variety of sources, including the Global Drifter Array.

3.3 Sea-Level Atmospheric Pressure: Numerical Weather Prediction

The impact of SLP drifter observations in Numerical Weather Prediction (NWP) is beneficial and very significant. Recent studies have addressed the issue of quantifying the implication of removing the drifter data from the GTS real-time data feed [3]. The vast majority of NWP systems run by many national meteorological agencies pull a large number of observations from the GTS in real time. The observations with in-situ platforms must be available with the shortest possible delay since

the assimilation window of NWP models is typically 3–6 h long. The Iridium satellite telecommunication system is able to deliver the observations to the LDL's servers within 1 min from the moment the data are sent by the drifters. The LDL servers push the data to the GTS with a total delay shorter than 15 min from the time of data collection. Other GTS processing systems have very similar delays.

The Observing System Experiment (OSE), or data denial experiment, discussed by Centurioni et al. [3] and Horányi et al. [16], was performed at the European Center for Medium range Weather Forecasting (ECMWF) and with the objective to quantify the impact of the SVPB drifter data only. The principle of the OSE is that a data assimilation and forecast models, the ECMWF Integrated Forecast System (IFS) four-dimensional variational (4D-Var) system [19, 40], is used to produce a control run, in which all of the available data, including the SVPB data, are assimilated, and also a data denial run in which the SLP observations from the SVPB drifters are withheld. The main conclusions of the study are that the in-situ SVPB drifter data of SLP 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 atmospheric pressure field forecasts, but also in the predicted wind field and the study also suggests 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 metric of forecast impact when the entire observational dataset is present in the assimilation system [2, 12, 21, 48], although the inherent linearization assumption restricts the range of the forecast assessment to about 2 days. Such assessments are often run operationally by ECMWF and by other agencies, such as the Global Modeling and Assimilation Office of the US National Aeronautics and Space Administration (NASA), and when the impact per observation or the fraction of beneficial observations is computed the in-situ SLP drifter data provide some of the largest values among the several components of the Global Observing System [3].

The demonstrated far-reaching role of the drifter barometer program in climate research and NWP would probably justify the installation of barometers on all of the GDP drifters, but, at the time of writing, only about 60% of the drifters carry a barometer.

Practical considerations that justify the barometer drifter program exist. One of the most difficult tasks for the GDP is to keep a nearly uniform distribution of drifters globally. A key to achieve this effort is the synergy with national meteorological services from, for example, the US National Weather Services, France, the United Kingdom, Canada, Australia, South Africa, New Zealand, India and many other partners, coordinated by the Data Buoy Cooperation Panel and implemented through the drifter barometer program upgrade and the direct purchase of barometers by the GDP. The collaboration with the meteorologists, who rely on a global network of marine barometers located at the interface between the ocean and the atmosphere, creates every year a large number of deployment opportunities (25%–30% of all deployments) of crucial importance for sustaining the Global Drifter Array.

3.4 Subsurface Temperature, Air Pressure and Wind: The Seasonal Hurricane Array

The track of a tropical cyclone (TC) is largely dictated by the large-scale atmospheric flow; therefore, the track forecasting depends crucially on the accuracy of the global atmospheric circulation models. Improvements in track forecasting have been achieved in the past few years but much less improvement has been obtained with respect to predicting the intensity [11]. The intensity of a TC is controlled by external processes that are regulated by the large-scale flow and by internal processes. These include TC-ocean interactions that affect the enthalpy and the momentum fluxes at the ocean-air interface. The numerical initialization of a TC is very challenging and the data to constrain the numerical models are seldom available. Furthermore, the ocean component of coupled models is often poorly represented and only recently the numerical ocean modules are being upgraded to provide more realistic representations of the ocean conditions.

The TC's enthalpy flux also depends on the thermal stratification of the upper ocean, and the amount of heat available can lead to TC intensification. The passage of a storm also creates some cooling, primarily caused by mixing and upwelling that can last long after the storm has passed [9, 18, 29].

The seasonal hurricane array of the GDP has been designed to provide the ocean and atmospheric models with the data needed for assimilation, especially on the scale of a TC inner core. In the case of a tropical cyclones threatening the US mainland, the 53rd Weather Reconnaissance Squadron (AFRC), also known as "Hurricane Hunters" usually deploys a transect of 10 ADOS and SPVW (Minimet) drifters. The transect can be about 300–500 km long and is designed to intersect the storm track about 24 h ahead of the forecasted intersection point. More ADOS drifters than Minimets are deployed on the right-hand side of the storm to capture the intensity of the developing cold wake [9, 29]. All the data (wind, SLP, SST, and subsurface temperature) are posted to the GTS in near-real time. The drifter data are also important for hurricane postseason assessments.

3.5 Ocean Currents

The quality-controlled ocean currents dataset that is released quarterly by AOML has supported more than 1000 peer-reviewed scientific publications (see http://www.aoml.noaa.gov/phod/dac/gdp_biblio.php for a partial list).

Several peer-reviewed publications have scrutinized the quality of the data collected by the drifters [26, 27, 30] and correction for biases have been discussed and attempted also for drifters that have lost their drogue [36].

At the time of writing, the ocean current data are only available in delayed time mode because the strain gauge data that indicate the drogue presence require a considerable amount of manual evaluation before a determination about the drogue

presence can be made [26]. Undeniably, enabling a stream of real time, 15-m depth ocean currents from the global drifter array would be very useful for the evaluation and the future assimilation in ocean forecasting. The widespread use of the GPS technology to obtain the location of the drifters may offer a solution for the near real-time drogue presence detection problem. The GPS parameter time-to-first-fix is generally longer when the drogue is present because the drifters are frequently pulled underwater when waves are present and it takes longer for the GPS engine to acquire signal and navigation data.

A good synopsis of recent ocean circulations studies based on drifter observations can be found in Maximenko et al. [27] and a modern climatology is discussed by Lumpkin and Johnson [24]. A particularly powerful approach to remove the biases inherent to the irregular spatial and temporal sampling of the drifter array consists in combining satellite altimetry, wind reanalysis products, and sometimes the large-scale geoid to compute the near-surface geostrophic velocity field and the ageostrophic component of the surface velocity in the form of Ekman currents [13]. Such techniques provide a very detailed description of the near-surface flow and, in regions where the drifter velocity data are highly correlated with the altimetry-derived currents, can provide the temporal resolution that lacks in the drifter dataset [5, 6, 28, 31, 33]. A new exciting approach is the use of the high-frequency (super-inertial and super-tidal) drifter velocity data to measure, for example, the amplitude and phase of the baroclinic and barotropic tidal currents [38]. The introduction of Iridium-GPS drifters will provide the scientific community with a highly accurate, hourly velocity dataset that will improve the studies of global near-inertial and tidal currents.

4 Conclusions

The Global Drifter Array, supported by the US Global Drifter Program and by its international partners operating under the Data Buoy Cooperation Panel framework, is a unique infrastructure strategically located at the interface between the ocean and the atmosphere that addresses the pressing need for in-situ global observations needed to monitor the changing ocean-atmosphere system and to conduct and 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. Global observations of essential climate variables, such as SST and sea-level atmospheric pressure are critical for data assimilation and for the evaluation of forecasts of the state of the ocean and of the atmosphere on a variety of temporal scales.

More than 1000 peer-reviewed scientific articles published using GDP data have demonstrated the tremendous impact of the Global Drifter Array and of its data in basic research, weather forecasting, climate change studies, and many other fields and in operational efforts. Existing measurements of SST, SLP, and ocean currents

at regional scales are already capable of supporting studies of regional climate change, indicated also by changes of the coupled atmospheric and oceanic circulations. However, considerably large uncertainty is still associated with our understanding of the physics of air-sea interaction and of the oceanic mixed layer. A proper physical representation and effective parameterizations of how the momentum imparted by the wind to the ocean surface sets the ocean in motion is still missing, as demonstrated by the fact that in-situ velocity observations from drifters are very difficult to assimilate in ocean circulation models. Improving such physical description is critically important and the Global Drifter Array is well placed to make a very significant impact in the next decade because technical developments and new sensors will allow the collection of key global observations. For example, global measurements of the velocity shear in the upper ocean will not only provide a wealth of data for assimilation in numerical models, model skill evaluations, and impact studies, but will help us gain a much deeper understanding of the physics of the mixed layer, where the wind stress, turbulent momentum fluxes, surface waves and internal waves, heat and salt fluxes all interact in a nonlinear 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 in the upper ocean, that is, where the transfer of momentum and vorticity from the wind occur, 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. Recent publications [5, 28] have shown that the geostrophic circulation maps that are computed from dynamic height or from dynamically balanced ocean topography are very different from maps obtained with direct measurements of near-surface ocean velocity. While surface drifters measure globally the total near-surface velocity, the vertical structure of the ageostrophic circulation in the upper ocean is virtually unknown. Understanding how heat and freshwater are forced, advected [7, 42], and mixed in the upper ocean requires a much better knowledge of the three-dimensional upper ocean circulation than we currently have. A better knowledge of the Ekman currents and of the convergence patterns of the ageostrophic currents that drive the vertical circulation of the upper ocean will be crucial to constrain ocean circulation and climate models toward a more realistic representation of upper ocean physics and will ultimately lead to improved ocean state and climate forecasts.

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