A GLOBAL OCEAN OBSERVING SYSTEM FOR MEASURING SEA LEVEL ATMOSPHERIC PRESSURE

Effects and Impacts on Numerical Weather Prediction

Luca Centurioni, András Horányi, Carla Cardinali, Etienne Charpentier, and Rick Lumpkin

In situ sea level air pressure data from the global array of surface drifters significantly contribute to accurate marine weather forecasting

A GLOBAL ARRAY OF DRIFTING BAROMETERS. Since 1994, the National Oceanic and Atmospheric Administration (NOAA)-funded Global Drifter Program (GDP; Maximenko et al. 2013; Niiler 2001), in collaboration with the international partners of the Data Buoy Cooperation Panel (DBCP), a joint body of the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), has been deploying Surface Velocity Program (SVP) Lagrangian drifters drogued at 15-m depth and equipped with barometers (SVPB[1]) in the world's oceans with a focus on the extratropical regions. The SVPB drifters are designed to make accurate measurements of sea level atmospheric pressure (SLP) and to report the data in real time through the Global Telecommunication System (GTS) of the WMO Information System (WIS) in order to contribute to the World Weather Watch (WWW).

The synergy between the oceanographers and the meteorologists, particularly under the WMO and IOC umbrella, has fostered a very successful and ongoing collaboration in which the oceanographers that manage the GDP offer the opportunity to upgrade standard drifters with barometers for a very low cost and the meteorologists provide hardware and valuable deployment infrastructures for the drifters.

In general, oceanographers are mostly concerned with studying the circulation and the dynamics of the ocean currents at global and regional scales, as well

AFFILIATIONS: Centurioni—Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California; Horányi and Cardinali—European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom; Charpentier—World Meteorological Organization, Geneva, Switzerland; Lumpkin—NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
CORRESPONDING AUTHOR E-MAIL: Luca Centurioni, lcenturioni@ucsd.edu

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-15-00080.1

In final form 27 April 2016

[1] The name SVP (and SVPB, etc.) for designating Lagrangian drifters was kept as a legacy of the former Surface Velocity Project (SVP) of the World Ocean Circulation Experiment (WOCE; 1990–2002)

as gathering accurate in situ sea surface temperature (SST) data, while meteorologists are mainly interested in global in situ SLP data with particular attention in regions where observations are sparse.

The SLP data from drifters are generally regarded as important for operational weather forecasting and for other oceanographic and severe weather forecast applications (Healy 2013; Maximenko et al. 2013; WIGOS 2012). However, until now, a formal assessment of the effect and impact of SLP data from SVPB drifters on numerical weather prediction (NWP) was never conducted. This essay reports on the main findings of a study sponsored by the DBCP under the framework of the pilot project called "Evaluation of the Impact of Sea Level Atmospheric Pressure Data over the Ocean from Drifting Buoys on Numerical Weather Prediction Models" (PP-SLP), and it is meant to raise awareness among the oceanographic and atmospheric communities of the role of the global drifter array in supporting NWP and climate services. This essay is also intended to promote the drifter barometer upgrade program sponsored by the GDP and discussed every year at the DBCP plenary sessions.

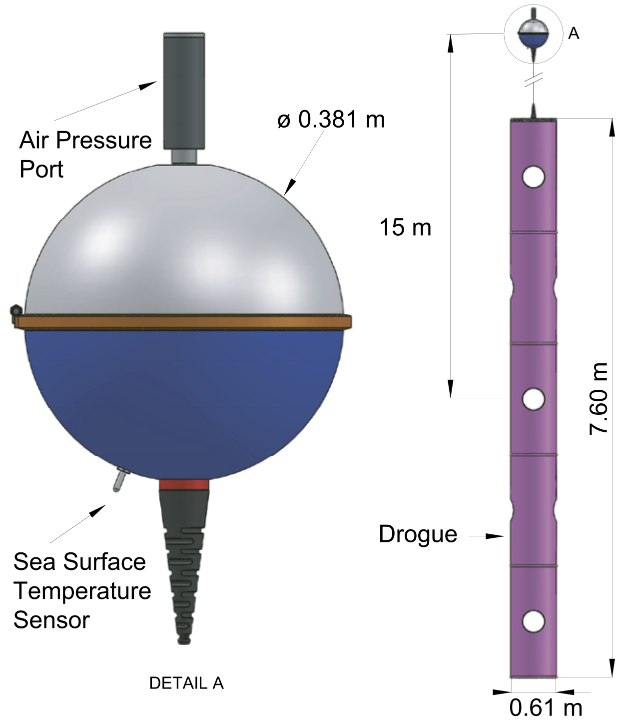

Fig. 1. Schematic of the SVPB drifter manufactured at the Scripps Institution of Oceanography.

THE GLOBAL DRIFTER PROGRAM, THE SVPB DRIFTER TECHNOLOGY, AND THE DATA DENIAL STUDY. The SVP drifter design emerged from "holey sock" drogue drifters deployed as early as 1979 in the tropical Pacific and standardized in 1987 as part of the former Tropical Ocean and Global Atmosphere (TOGA) program (Lumpkin and Pazos 2007; Niiler 2001). This regional drifter program quickly grew into a global array and to date more than 22,000 drifters have been deployed to fulfill the GDP objective of maintaining a global array of 1,250 drifters. This size of the array is sufficient to keep the potential satellite SST bias error (PSBE) below 0.5°C because the number and distribution of drifters, as well as the accuracy of their SST data, which ranges between 0.05° and 0.1°C, are directly proportional to the PSBE (Zhang et al. 2009). The GDP was the first component of the Global Ocean Observing System (GOOS) to be fully implemented when the array reached 1250 drifters for the first time on 18 September 2015.

The SVPB drifter (Fig. 1) has the same drogue (sea anchor) and surface buoy of the SVP drifter (Niiler 2001). The drogue is a cylindrical tube of Cordura nylon connected to the surface buoy with a tether. The center of the drogue is located at a depth of 15 m. The much larger drag of the drogue than that of the tether and surface buoy combined ensures that the drifter behaves as a Lagrangian instrument; that is, it moves with the same velocity of the surrounding water at the target depth of 15 m. The error of the Lagrangian velocity is essentially due to the slip of the drogue through the water due to the action of wind and waves on the surface buoy, and it is less than 1×10^{-2} m s^{-1} for winds up to 10 m s^{-1} (Niiler et al. 1995). A more complete description of the SVP drifter technology can be found in Niiler (2001).

Since the drag of the drogue is much larger than that of the surface buoy, the latter is often pulled underwater by surface gravity waves. Therefore, the tube that connects the barometer sensor with the atmosphere is protected from water intrusions by a self-draining air pressure port waterproofed by two Gore-Tex screens. The invalid air pressure readings taken when the drifter is submerged are removed on board before being transmitted. The SLP filtering algorithm is very robust and has been successfully tested in a variety of environments, including hurricane conditions. Drifters are fitted with either a high-precision barometer by Honeywell [Honeywell Precision Barometer (HPB)], stable over the 2-yr-long nominal life span of the drifters and with an accuracy of ±0.4 hPa, or an integrated pressure transducer, also by Honeywell, that has similar specifications and accuracy.

The SLP is measured every hour and two satellite data telecommunication systems—Argos and Iridium—are used to telemeter the data. The data latency depends mostly on the satellite system of choice. The Argos satellite network adds an average of about one to two hours to the data latency, but the average delay drops to a few minutes if the Iridium satellite system is used. For this reason, the GDP is rapidly moving toward an array of instruments that use only Iridium satellite communication. Additional delays typically of less than 15 min and inherent to the way the data are processed, quality controlled, encoded, and distributed over the GTS are also introduced.

Since 2007 about 50% of drifters in the global array are of the SVPB type and the growth of the barometer array has been primarily limited by funding. Most of the SVPB hardware is supported by the GDP but significant contributions also come from DBCP members by way of SVPB hardware purchase or upgrades of GDP's SVP drifters with barometers. The operational service for Surface Marine Observations (E-SURFMAR) of the Economic Interest Group (EIG) of the European Meteorological Network (EUMETNET) also provides an important contribution to the SVPB drifter array, mainly in the North Atlantic Ocean.

Besides the SVPB drifters, other sources of in situ SLP data over the ocean exist, and these include but are not limited to automatic weather stations (AWS) installed on voluntary observing ship (VOS) and moored buoys. The AWS coverage is limited to standardized shipping lanes and leaves substantially undersampled areas in the Southern Hemisphere and in the Southern Ocean. The SLP data from moorings are mainly coming from coastal areas with few exceptions, such as the deep-water tropical moored arrays. Ice buoys are also used to make observations, including SLP over sea ice in the polar regions.

With regard to satellite observations, while SLP pressure field gradients can be estimated relatively well from the satellite-derived surface vector wind observations over the oceans (mainly from scatterometer data), it is not possible to anchor adequately the surface pressure field with these satellite data alone. Global Navigation Satellite System radio occultation (GNSSRO) provides useful information on the SLP field. However, such data are also sensitive to atmospheric temperature and humidity profiles, and small biases in prior knowledge of these variables lead to biases in retrieved surface pressure estimates. Because of this problem, GNSSRO measurements cannot fully compensate for the lack of in situ observations of surface pressure (Healy 2013).

The data denial study, or observing system experiment (OSE), discussed in this essay was performed at the European Centre for Medium-Range Weather Forecasts (ECMWF) and was designed to quantify the effect of the SVPB drifter data only. The principle of the OSE is that a data assimilation and forecast model—in this case, the ECMWF Integrated Forecast System (IFS) four-dimensional variational data assimilation system (4D-Var; (Janisková and Lopez 2013; Rabier et al. 2000)—is used to produce a control run in which all of the available data are assimilated, and also a data denial run in which the SLP observations from the SVPB drifters are withheld. The experiments were run at forecast model resolution around 40 km horizontally and 91 model levels vertically. The error of the two runs is computed for selected variables by comparing them with the higher-resolution operational ECMWF analyses. Two OSEs were performed, one for November–December 2010 and one for July–August 2012. In the former, 879,107 SLP-SVPB data were denied, corresponding to 96.3% of the available SLP data from all buoys; and in the latter, 720,257 SLP-SVPB data were denied, corresponding to 94.8% of the available SLP data from all buoys (Fig. 2). The two periods were chosen because the amount of SLP data was largest and to contrast two different seasons. The full details of the OSE experiment are discussed in Horányi et al. (2017) and in this essay the main results are highlighted.

THE EFFECT OF THE SLP DATA FROM DRIFTERS ON WEATHER FORECAST IS SIGNIFICANT. In the following discussion, and for the sake of brevity, the results from only one of the two seasons are shown because they are very similar. A first proof of the significant influence of the SVPB data is given by the mean difference, up to 0.7 hPa, of the SLP analyses between the control and denial experiments (Fig. 3). The NWP analysis is represented in the model grid (around 40-km horizontal resolution), and the differences between the sea level pressure fields of the control and denial experiments are computed and then averaged over the two months. Therefore, the averaged differences shown in Fig. 3 are smooth and relatively small due to time averaging. It should be noted that the differences between the control and denial experiments computed for each assimilation/denial run are significantly larger than the accuracy of the barometers.

The largest SLP differences, which show also a seasonal dependence, are found where the majority of the SVPB data were collected, particularly in the Arctic, in the Southern Ocean, and in the North Atlantic.

Interestingly, a comparison between Figs. 2 and 3 for winter 2010 shows that even the denial of few

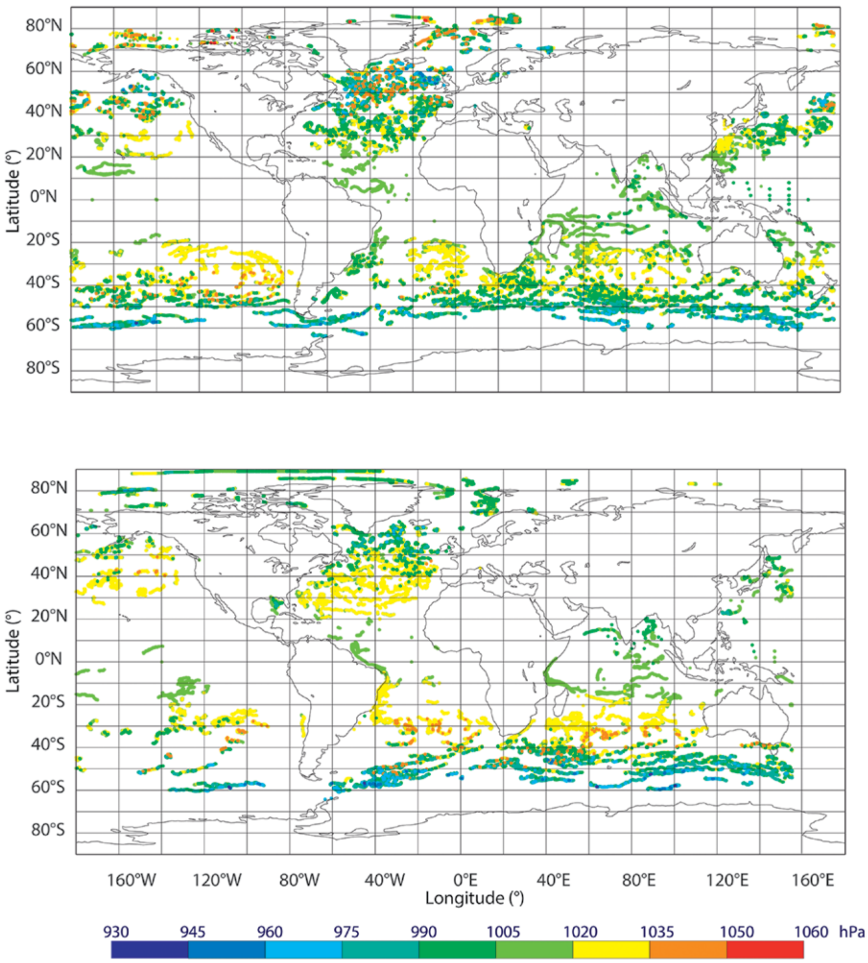

Fig. 2. Total distribution of buoy data in the control experiment. (top) Nov–Dec 2010. (bottom) Jul–Aug 2012. The colors indicate the SLP values (hPa) measured by the drifting buoys. In the top panel 879,107 SLP data locations are shown, and in the bottom panel 720,257 SLP data locations are shown. Since the drifters collect and report the data hourly, many points nearly overlap on the global-scale maps.

SVPB drifters in the tropical eastern Pacific (at about 20°N, 140°W), in the western tropical Atlantic (at about 15°N, 45°W), and in the equatorial Indian Ocean (at about 0°, 95°E) can have a large effect on the initial conditions, suggesting the importance of in situ SLP data at low latitudes, where SVPB drifters are not normally deployed apart from targeted small arrays in the paths of some tropical cyclones.

The normalized (by the control run) SLP root-mean-square (rms) forecast error differences between the control and denial experiments (Fig. 4) clearly indicate a substantial forecast degradation up to 72 hours ahead when the drifter data are denied. The beneficial effect of the drifter data are most pronounced in the Southern Hemisphere and in the Arctic Ocean. However, substantial drifter positive impact can be seen in all ocean basins, as well as in the tropical and equatorial regions of the eastern Pacific Ocean.

Substantial degradations of the denial run are also found for the near-surface (1,000 hPa) wind forecast (not shown). One remarkable result of this study is that the beneficial effect of the drifter observations is not just limited to the surface but extends high into the troposphere. For example, the normalized geopotential height rms error differences (Fig. 5, left panel) show that the strong beneficial effects of the drifter data are located in the subtropical region of the Southern Hemisphere, as well as in the equatorial and tropical regions up to 250 hPa (Horányi et al. 2017). The beneficial effect of the SVPB data (up to five days ahead), for the geopotential height, lasts longer in the equatorial and tropical regions. Similarly, the drifter data improve the wind forecast in the subtropical and high-latitude regions and up to 400–200 hPa (Fig. 5, right panels). Full details of the OSE study can be found in Horányi et al. (2017).

OTHER TECHNIQUES INDICATE POSITIVE IMPACT OF THE SLP DATA FROM DRIFTERS ON NUMERICAL WEATHER PREDICTION. OSEs are expensive to run but have the benefit of quantifying the effect of a single perturbation—in this case, the denial of the SVPB drifter data—on all forecast metrics (root-mean-square error, for instance) at all forecast ranges. In contrast, the adjoint-based forecast sensitivity observation impact (FSOI) technique quantifies the value 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). While much less expensive than OSEs, the reliance of the FSOI technique on the adjoint model, and the inherent assumption of linearity, restricts its use to forecast ranges of less than two days for most global applications.

Here we use the FSOI technique to quantify the contribution of each assimilated observation in the ECMWF IFS to the reduction of a measure of 24-h global forecast error combining wind, temperature, and surface pressure in terms of a dry energy norm. A comparative diagram of these contributions (Fig. 6) shows that the SVPB drifters have the largest impact on a per-observation basis of all the data types assimilated in the ECMWF system during this period. It should be noted, however, that the combined impact of all SVBP observations is still relatively small (not shown), since they are far fewer in number than many other data types, especially compared to satellite observations. More details of the FSOI evaluation can be found in Horányi et al. (2017). Additional information comparing the impact of various observing systems on NWP, including the high impact on a per-observation basis of SLP from drifters can be found in WIGOS (2012).

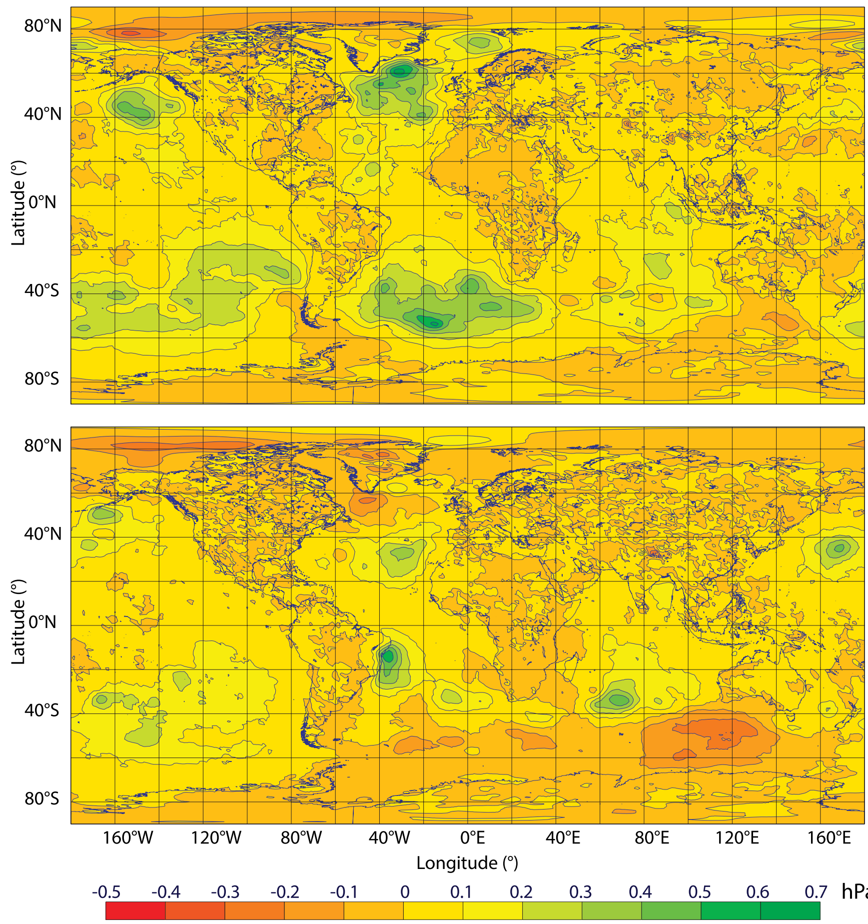

Fig. 3. Average SLP analyses differences (hPa) between the control and denial experiments. (top) Nov–Dec 2010. (bottom) Jul–Aug 2012.

CLIMATE APPLICATIONS OF IN SITU SLP DATA OVER THE OCEAN AND FINAL REMARKS. Global and accurate SLP observations are important because they allow the description, with a good approximation, of the geostrophic and barotropic global atmospheric circulation (Blunden and Arndt 2013), which accounts for the largest part of the total atmospheric circulation.

Climate changes are often felt through changes in ocean temperature, ocean circulation, sea level rise, and perhaps even more dramatically, through changes in air temperature and atmospheric circulations (e.g., increase/shift of storminess and extreme events). Changes in the atmospheric circulations will also impact ocean surface waves and wind regimes, such as the monsoons, the hydrological cycle via modifications of the precipitation and evaporation patterns, and can potentially induce localized climate changes that will likely have a high impact on society.

The latest Intergovernmental Panel on Climate Change report (IPCC 2013) states that humanity has likely altered global SLP patterns. Notable examples include the likely link between stratospheric ozone depletion and the positive trend of the southern annular mode (SAM) in the austral summer, and a poleward shift of the southern Hadley cell during austral summer (IPCC 2013). The former is directly correlated to sea level pressure changes over the high latitudes/subtropics (IPCC 2013).

SLP data, including those collected by the SVPB drifters, are used in multiple ways by climate scientists, including trend computations, climate model diagnostics, and constructing climate indexes. Long-term mean SLP changes also affect the mean sea level due to the inverse barometer effect (a

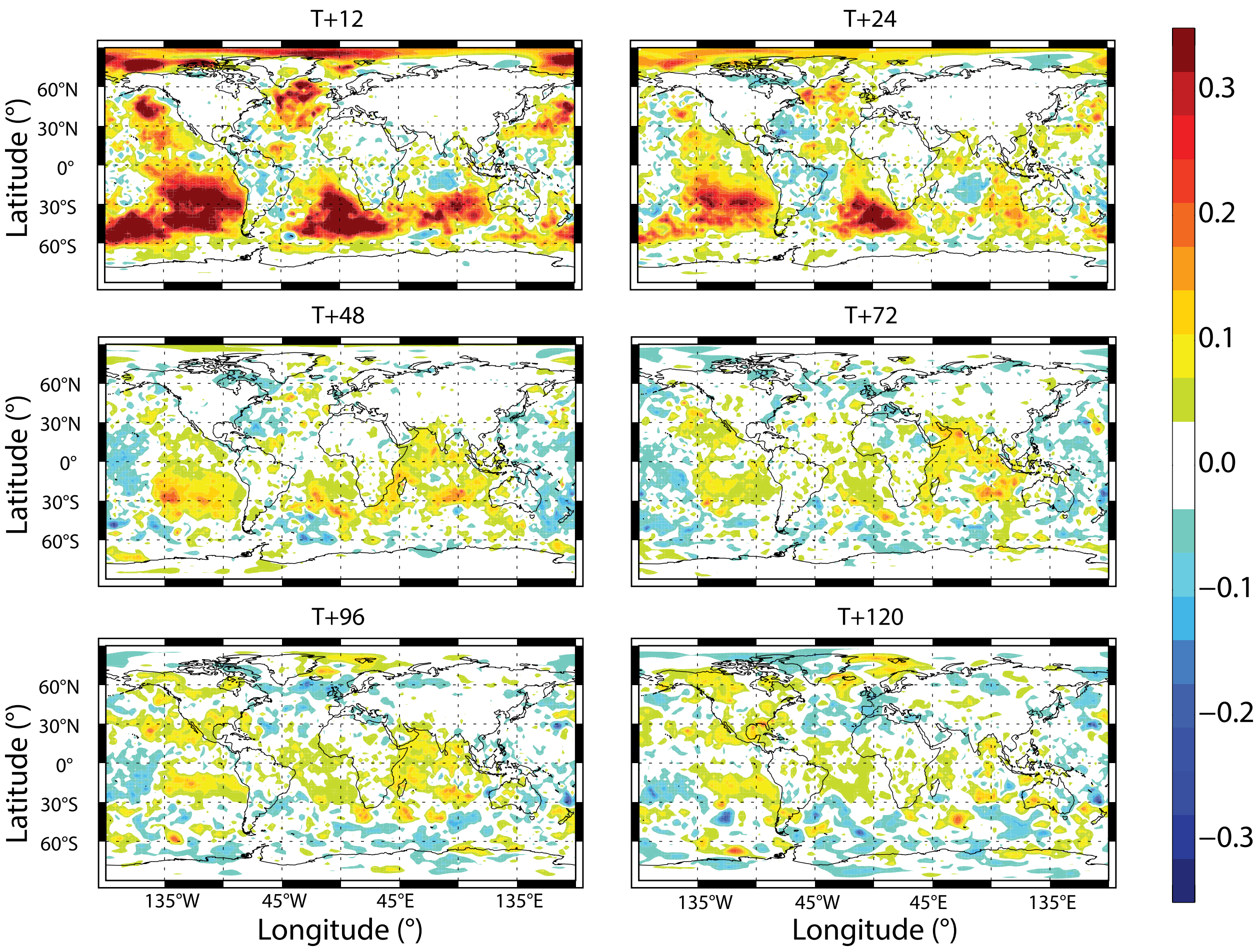

Fig. 4. Differences of mean SLP rms errors, normalized by the rms error of the control, between the control and denial experiments for Nov–Dec 2010. Red (blue) colors indicate degradations (improvements) in the denial experiment. Forecast ranges: 12, 24, 48, 72, 96, and 120 hours.

variation of 1 mb corresponds, approximately, to a change of 1 cm in sea level), thus providing another strong rationale for the deployment of a global array of SVPB drifters.

The OSE and FSOI studies described in this essay further highlight in a quantitative fashion the crucial role of the SVPB drifter data, collected by the U.S. Global Drifter Program and its international partners that operate under the DBCP umbrella, in improving short- to medium-range NWP. The study periods have a sufficiently large number of drifterborne observations and are of sufficient length to detect statistically significant beneficial effects and positive impacts of the data.

The beneficial effect of the SVPB drifter data in the forecast is detectable not only near the surface but also higher in the troposphere, up to 250 hPa (Horányi et al. 2017). The largest beneficial effect is observed in the mean sea level pressure field forecast, but also the predicted wind field is significantly affected.

The reduced improvements of the SLP forecast in the OSE simulation in the tropical and equatorial regions can be partly attributed to the relatively small variability of the signal at low latitudes, but it should also be noted that very few drifter SLP observations were available there for the denial. Furthermore, when even a few in situ data points are available in the tropics or at the equator, the local beneficial effect is large (see, e.g., Figs. 4 and 5). This suggests that an attempt to extend the SVPB drifter array to the tropical region should be made and the impact of the data should be monitored and quantified with the FSOI analysis or similar diagnostics.

The FSOI analysis indicates that the SLP drifter data are the most valuable per-observation contributor from the Global Observing System [see Horányi et al. (2017) for more complete discussion details]. The in situ drifter SLP observations are extremely valuable to anchor the global surface pressure field and significantly contribute to accurate marine

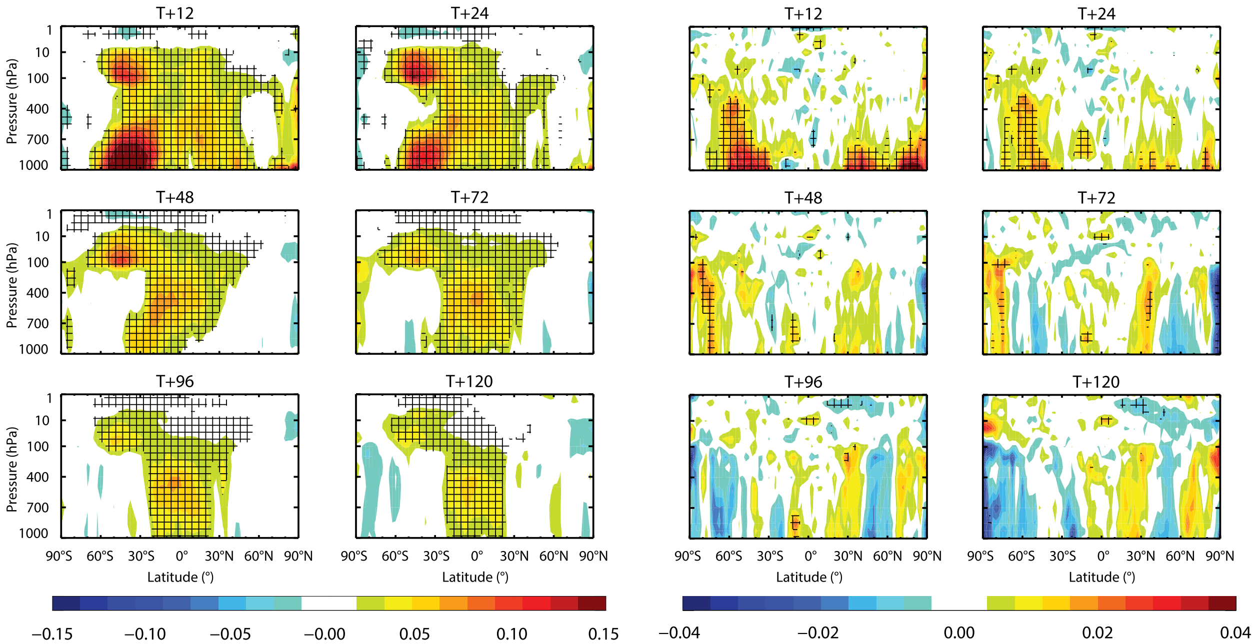

Fig. 5. Normalized rms error difference latitude–pressure cross sections between the control and denial experiments for Nov–Dec 2010. (left) Geopotential height and (right) vector wind normalized rms error difference latitude–pressure cross sections between the control and denial experiments. Significant differences are denoted by hashes. Red (blue) colors indicate forecast degradations (improvements) for the denial experiment.

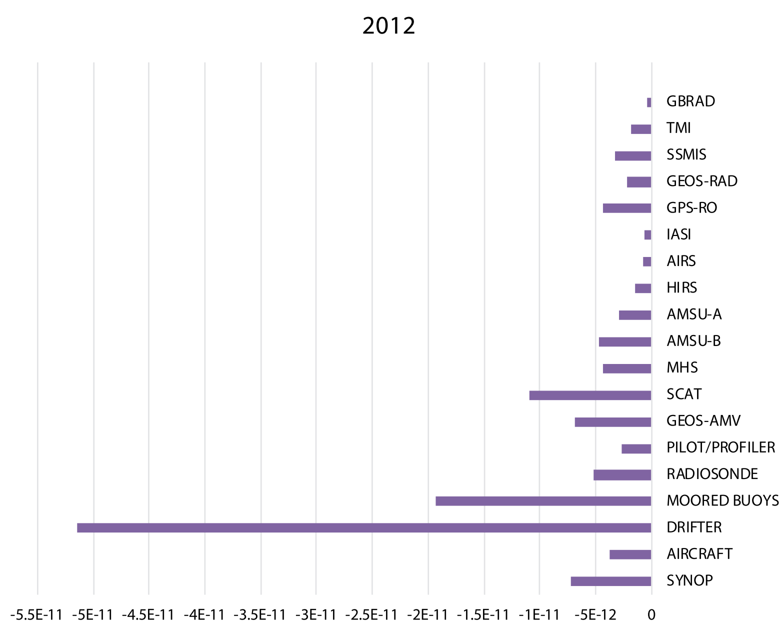

Fig. 6. ECMWF operational mean FSOI values for the different observing systems for Jul–Aug 2012. The FSOI values are also normalized by the total forecast error for easier comparison. The observing systems displayed are synoptic surface observations (SYNOP; surface pressure, moisture, and wind), aircraft measurements (wind and temperature), drifters and moored buoys (surface pressure and wind from drifters and moored buoys), radiosondes (wind, temperature, and moisture), pilot/profiler (wind), geostationary atmospheric motion vectors (GEOS-AMV; wind), scatterometer (surface wind), microwave sounder radiances [Microwave Humidity Sounder (MHS) and Advanced Microwave Sounding Unit (AMSU-B and AMSU-A)], infrared sounder radiances [High Resolution Infrared Radiation Sounder (HIRS), Atmospheric Infrared Sounder (AIRS), and Infrared Atmospheric Sounding Interferometer (IASI)], satellite radio occultation (GPS-RO), geostationary satellite radiances (GEOS-RAD), microwave imager [Special Sensor Microwave Imager/Sounder (SSMIS), Tropical Rainfall Measuring Mission Microwave Imager (TMI), Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E)], multispectral radiometer [Medium-Resolution Imaging Spectrometer (MERIS)], and radar precipitation ground-based radar (GBRAD).

weather forecasts, especially in regions where no other in situ observations are available. All these results give evidence that surface pressure observations of drifting buoys are essential ingredients of the Global Observing System and that their quantity, quality, and distribution should be preserved as much as possible in order to avoid any analysis and forecast degradations.

The global drifter barometer array is mainly implemented through international collaboration under the WMO–UNESCO umbrella. The barometer upgrade program offered by the U.S. GDP, under which GDP-funded drifters can be equipped with partner-funded accurate air pressure sensors, is a practical example of how such a collaboration is executed. Entities interested in this upgrade program can contact the GDP offices located at the Scripps Institution of Oceanography or the Atlantic Oceanographic and Meteorological Laboratory. The participation in the activities of the DBCP, where the implementation of the SVPB array is discussed every year, is open to all United Nations member states (www.jcommops.org/dbcp/). The tasks involved in maintaining the Global Observing System are demanding, and wide and proactive participation of national and international entities is key to the success of this program.

ACKNOWLEDGMENTS. This work was supported by the Data Buoy Cooperation Panel of the World Meteorological Organization, NOAA Grant NA10OAR4320156, and NOAA's Climate Program Office.

REFERENCES

Blunden, J., and D. S. Arndt, 2013: State of the Climate in 2012. *Bull. Amer. Meteor. Soc.*, **94** (8), S1–S258, doi:10.1175/2013BAMSStateoftheClimate.1.

Cardinali, C., 2009: Monitoring the observation impact on the short-range forecast. *Quart. J. Roy. Meteor. Soc.*, **135**, 239–250, doi:10.1002/qj.366.

Gelaro, R., Y. Zhu, and R. M. Errico, 2007: Examination of various-order adjoint-based approximations of observation impact. *Meteor. Z.*, **16**, 685–692, doi:10.1127/0941-2948/2007/0248.

Healy, S. B., 2013: Surface pressure information retrieved from GPS radio occultation measurements. *Quart. J. Roy. Meteor. Soc.*, **139**, 2108–2118, doi:10.1002/qj.2090.

Horányi, A., C. Cardinali, and L. Centurioni, 2017: The global numerical weather prediction impact of mean sea level pressure observations from drifting buoys. Quart. J. Roy. Meteor. Soc., doi:10.1002/qj.2981, in press.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, 1535 pp., doi:10.1017/CBO9781107415324.

Janisková, M., and P. Lopez, 2013: Linearized physics for data assimilation at ECMWF. *Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications*, S. K. Park and L. Xu, Eds., Vol. II, Springer, 251–286, doi:10.1007/978-3-642-35088-7_11.

Langland, R. H., and N. L. Baker, 2004: Estimation of observation impact using the NRL atmospheric variational data assimilation adjoint system. *Tellus*, **56A**, 189–201, doi:10.1111/j.1600-0870.2004.00056.x.

Lumpkin, R., and M. Pazos, 2007: Measuring surface currents with Surface Velocity Program drifters: The instrument, its data, and some recent results. *Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics*, A. Griffa et al., Eds., Cambridge University Press, 39–67.

Maximenko, N., R. Lumpkin, and L. Centurioni, 2013: Ocean surface circulation. *Ocean Circulation and Climate: A 21st Century Perspective*, G. Siedler et al., Eds., International Geophysics Series, Vol. 103, Academic Press, 283–304, doi:10.1016/B978-0-12-391851-2.00012-X.

Niiler, P. P., 2001: The world ocean surface circulation. *Ocean Circulation and Climate: Observing and Modelling the Global Ocean*, G. Siedler, J. Church, and J. Gould, Eds., International Geophysics Series, Vol. 77, Academic Press, 193–204.

——, A. Sybrandy, K. Bi, P. M. Poulain, and D. Bitterman, 1995: Measurements of the water-following capability of holey-sock and TRISTAR drifters. *Deep-Sea Res. I*, **42**, 1951–1964, doi:10.1016/0967-0637(95)00076-3.

Rabier, F., H. Järvinen, E. Klinker, J.-F. Mahfouf, and A. Simmons, 2000: The ECMWF operational implementation of four-dimensional variational assimilation. I: Experimental results with simplified physics. *Quart. J. Roy. Meteor. Soc.*, **126**, 1143–1170, doi:10.1002/qj.49712656415.

WIGOS, 2012: Final report of the Fifth WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction. WMO Integrated Global Observing System Tech. Rep. 2012-1, 25 pp.

Zhang, H.-M., R. W. Reynolds, R. Lumpkin, R. Molinari, K. Arzayus, M. Johnson, and T. M. Smith, 2009: An integrated global observing system for sea surface temperature using satellites and in situ data: Research to operations. *Bull. Amer. Meteor. Soc.*, **90**, 31–38, doi:10.1175/2008BAMS2577.1.

Zhu, Y., and R. Gelaro, 2008: Observation sensitivity calculations using the adjoint of the Gridpoint Statistical Interpolation (GSI) analysis system. *Mon. Wea. Rev.*, **136**, 335–351, doi:10.1175/MWR3525.1.