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A Global Ocean Observing System for Measuring Sea Level Atmospheric Pressure: Effects and Impacts on Numerical Weather Prediction

By

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Abstract

Since 1994 the US Global Drifter Program (GDP) and its international partners cooperating within the Data Buoy Cooperation Panel (DBCP) of WMO-UNESCO have been deploying drifters equipped with barometers primarily in the extra-tropical regions of the world's oceans in support of operational weather forecasting. To date, the impact of the drifter data isolated from other sources has never been studied. This essay quantifies and discusses the effect and the impact of in situ sea-level atmospheric pressure (SLP) data from the global drifter array on numerical weather prediction using observing system experiments and forecast sensitivity observation impact studies. The in situ drifter SLP observations are extremely valuable to anchor the global surface pressure field and significantly contribute to accurate marine weather forecasts, especially in regions where no other in situ observations are available, like, for example, in the Southern Ocean. Furthermore, the forecast sensitivity observation impact analysis indicates that The SLP drifter data is the most valuable per-observation contributor from the Global Observing System (GOS). All these results give evidence that surface pressure observations of drifting buoys are essential ingredients of the GOS and their quantity, quality and distribution should be preserved as much as possible in order to avoid any analysis and forecast degradations. The barometer upgrade program offered by the GDP, under which GDP funded drifters can be equipped with partner-funded accurate air pressure sensors, is a practical example of how the DBCP collaboration is executed. Interested parties are encouraged to contact the GDP to discuss upgrade opportunities.

Capsule Summary

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 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 UNESCO, has been deploying Surface Velocity Program (SVP[1]) Lagrangian drifters drogued at 15m depth and equipped with barometers (SVPB hereafter) in the world's oceans with focus in the extra-tropical 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 as gathering accurate in-situ sea surface temperature (SST) data whilst 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.*,

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

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.

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, that ranges between 0.05°C and 0.1°C, is 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 September 18, 2015.

The SVPB drifter (Figure **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 15m. The much larger drag of the drogue than that of tether and surface buoy combined ensures that the drifter behaves as a Lagrangian instrument, i.e. that it moves with the same velocity of the surrounding water at the target depth of 15m. 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 $1{\cdot}10^{-2}$ ms^{-1} for winds up to 10 ms^{-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 onboard 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 (HPB) by Honeywell, stable over the two years long nominal lifespan of the drifters and with an accuracy of ±0.4hPa, or with 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 or 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. The GDP is targeting an optimum mix of data telemetry communications to minimize the data latency. Additional delays typically of less than 15 minutes, 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 European National Meteorological Services (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 leave substantially under-sampled 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 Systems 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 hereafter), discussed in this essay was performed at 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 models, the ECMWF Integrated Forecast System (IFS) four-dimensional variational (4D-Var) system [*Janisková and Lopez*, 2013; *Rabier et al.*, 2000] in this case, 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 40km 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 (Figure **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. (2016) 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, only the results from one of the two seasons are shown since 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 the denial experiments (Figure **3**). The NWP analysis is represented in the model grid (around 40km horizontal resolution) and the differences between the sea level pressure fields of the control and denial experiments are computed and then averaged over the 2 months. Therefore, the averaged differences shown in Figure **3** are smooth and relatively small due to the 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 Figure **2** and Figure **3** for winter 2010 shows that even the denial of few 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°N, 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) SLP root mean-squared (RMS) forecast error differences between the control and denial experiment (Figure **4**) clearly indicates a substantial forecast degradation up to 72 hours ahead when the drifter data are denied. The beneficial effect of the drifter data is 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 region 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 (**Figure 5**, left panel) show that the strong beneficial effect of the drifter data is 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. 2016). The beneficial effect of the SVPB data (up to 5 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 (Figure **5**, right panels). Full details of the OSE study can be found in Horányi et al. (2016).

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-squared error for instance) at all forecast ranges. In contrast, the adjoint-based Forecast Sensitivity Observation Impact (FSOI) 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 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 (Figure **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. (2016). 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]

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, 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 of 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 high impact on society.

The latest International Panel for Climate Change (IPCC) Report [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 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 effect (a variation of 1 mbar 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 US Global Drifter Program and its international partners that operate under the DBCP umbrella, in improving short- to medium-range NWP. The study periods have sufficiently large number of drifter-borne 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. 2016). 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 partly be 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. Figure **4** and Figure **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 FSOI or similar diagnostics.

The FSOI analysis indicates that The SLP drifter data is the most valuable per-observation contributor from the Global Observing System (see Horányi et al. 2016 for a 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 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 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 US GDP, under which GDP-funded drifters can be equipped with partner-funded accurate air pressure sensors, is a practical example of how such collaboration is executed. Entities interested in this upgrade program can contact the GDP offices located at the Scripps Institution of Oceanography or at 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 (http://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 the key for the success of this program.

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Figure Captions

Figures

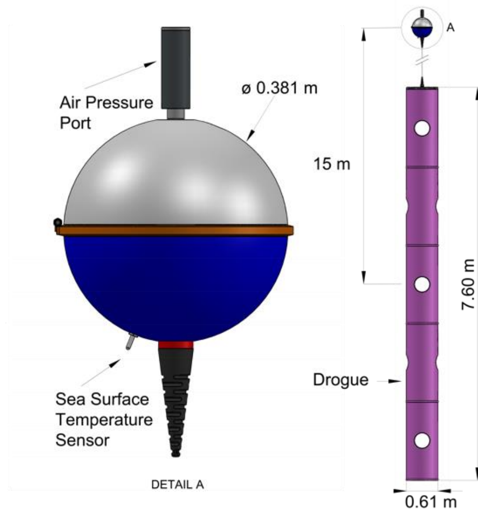

Figure 1: Schematic of the SVPB drifter manufactured at the Scripps Institution of Oceanography

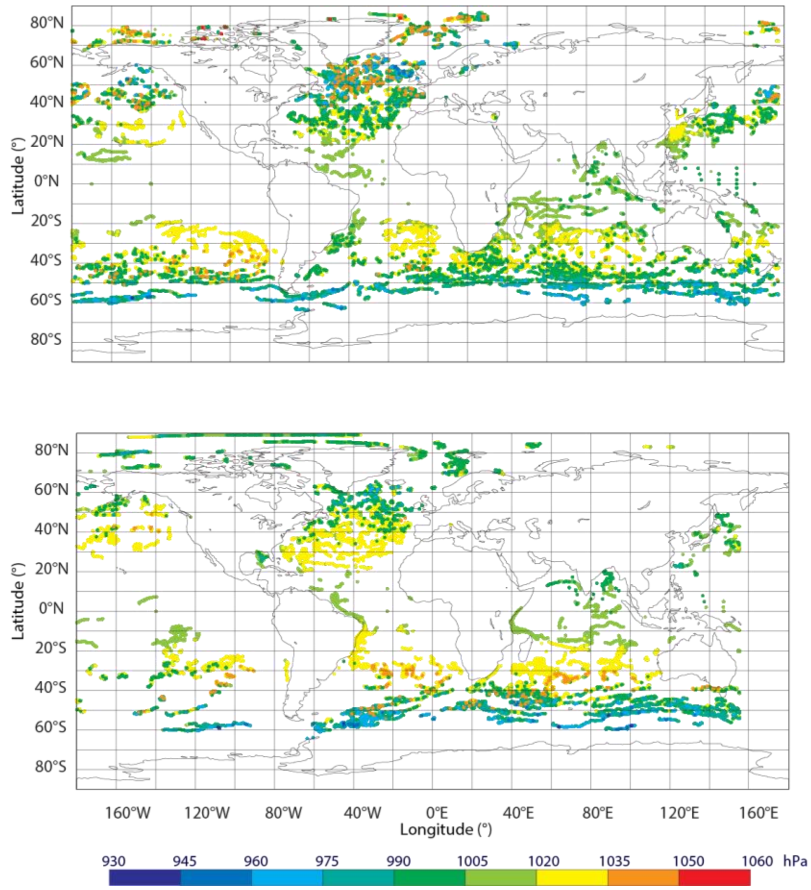

Figure 2: Total distribution of buoy data in the control experiments. Top: November-December 2010; bottom: July-August 2012. The colors indicate the sea level pressure values, in hPa, measured by the drifting buoys. In the top panel, 879,107 SLP data locations are shown, and 720,257 are shown in the bottom panel. Since the drifters collect and report the data hourly, many point nearly overlap on the global scale maps.

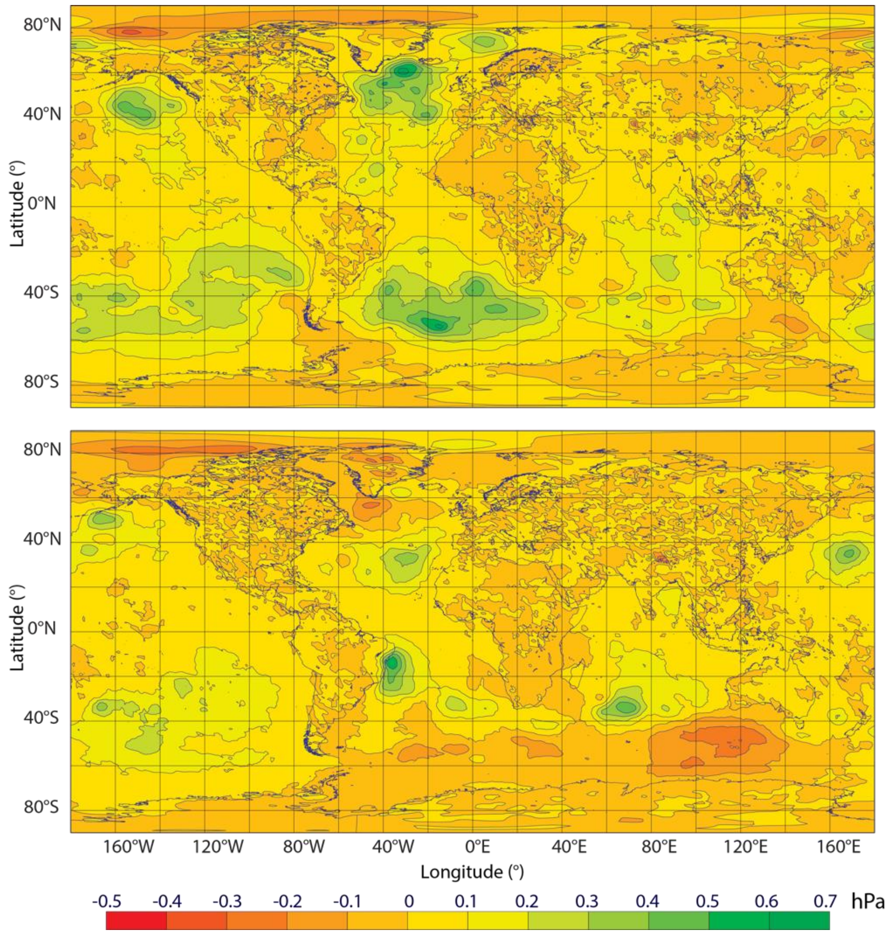

Figure 3: Average sea level pressure analyses differences, in hPa, between the control and denial experiments. Top: November-December 2010. Bottom: July-August 2012.

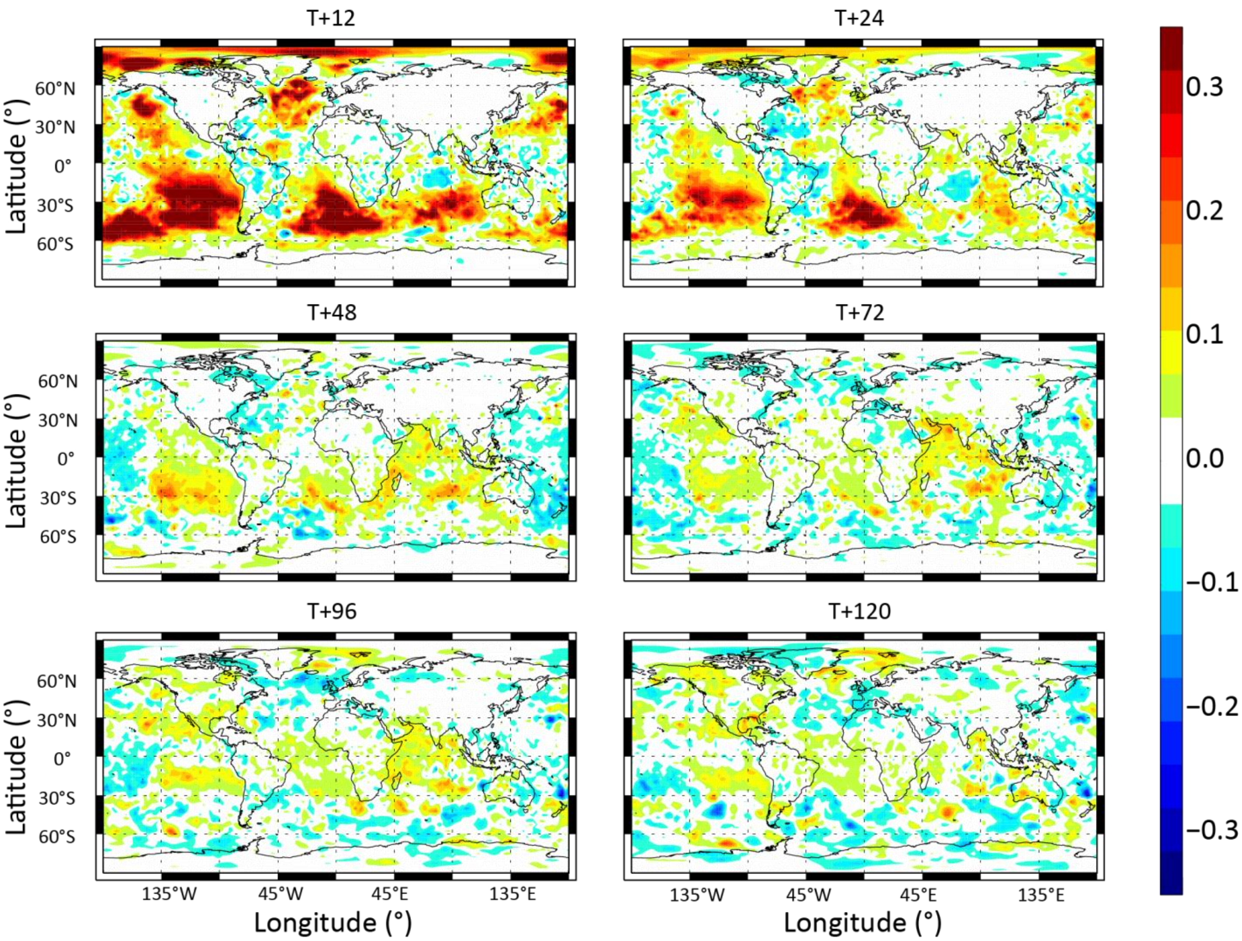

Figure 4: Differences of mean sea level pressure RMS errors, normalized by the RMS error of the control, between the control and denial experiment for November-December 2010. Red (blue) colors indicate degradations (improvements) in the denial experiment. Forecast ranges: 12h, 24h, 48h, 72h, 96h and 120h.

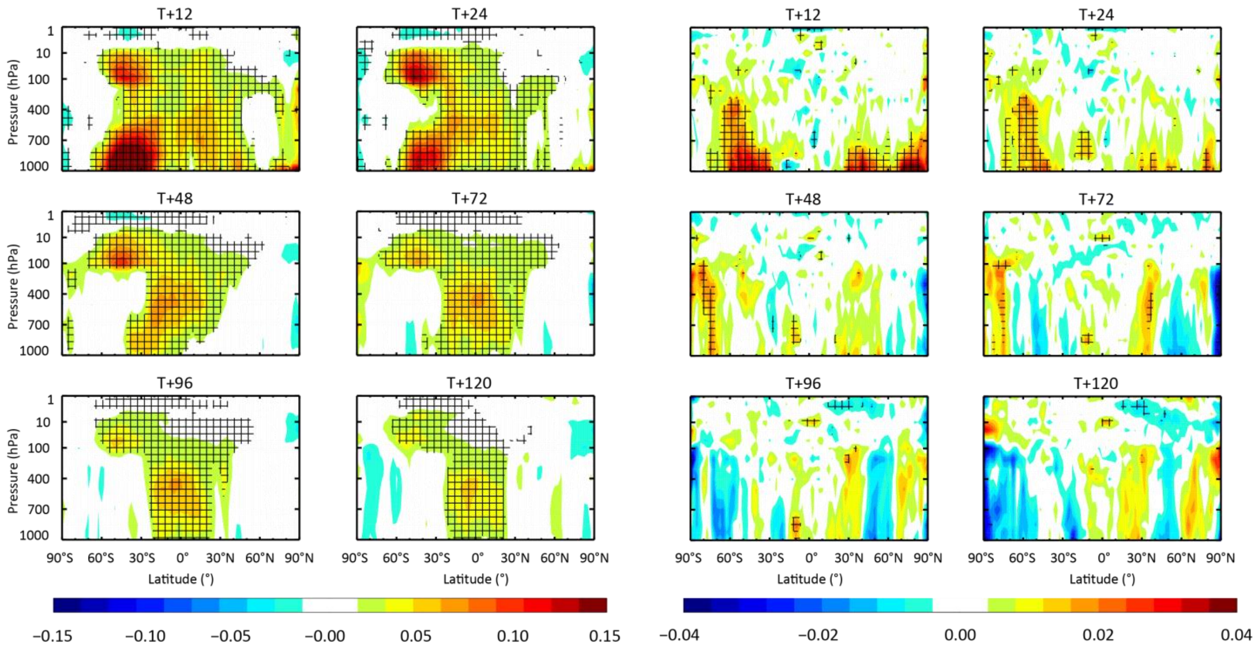

Figure 5: Normalized root mean-squared error difference latitude-pressure cross sections between the control and denial experiments. November-December 2010. Left: geopotential height, right: vector wind normalized root mean-squared error difference latitude-pressure cross sections between the control and denial experiments. Significant differences are denoted by hashes. Red (blue) colors indicate forecast degradations (improvements) for the denial experiment.

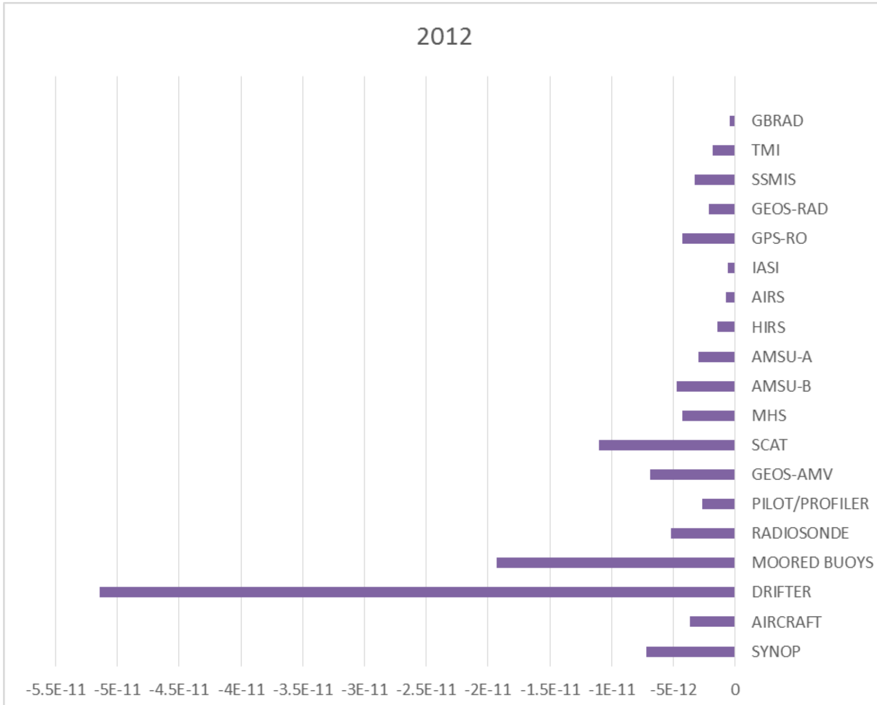

Figure 6: ECMWF operational mean FSOI for the different observing systems for July-August, 2012. The FSOI values are also normalized by the total forecast error for easier comparison. The observing systems displayed are SYNOP surface observations (surface pressure, moisture and wind), aircraft measurements (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 (wind), scatterometer (surface wind), microwave sounder radiances (MHS, AMSU-B and AMSU-A), infrared sounder radiances (HIRS, AIRS and IASI), satellite radio occultation (GPS-RO), geostationary satellite radiances (GEOS-RAD), microwave imager (SSMIS, TMI, AMSR-E), multi-spectral radiometer (MERIS) and radar precipitation (GBRAD).