This study was conducted to assess the impact on NWP and to provide guidance on drifting buoy observation density, with particular attention to the North Atlantic. The impact of halving the buoy density was studied using observing system experiments; as expected half the density has more than half the impact, but there is still scope for improvement with a higher density of observations. For drifting buoy pressure data, both large observation-minus-background differences and large forecast sensitivity tend to be in synoptically active, cyclogenesis regions. It is noted that almost half of drifting buoys do not have a pressure sensor—this is regrettable given the importance of pressure data in remote oceanic areas.

1 | BACKGROUND

In Numerical Weather Prediction (NWP) the primary variable assimilated from buoys and ships is pressure at mean sea level (Pmsl). Sea surface temperature (SST) is also important but is not considered here as the European Centre for Medium-Range Weather Forecasts (ECMWF) currently uses an externally provided SST analysis. Drifters (drifting buoys) were originally developed for oceanographic purposes, to measure surface currents (Niiler et al., 1987) and SST. Improvements to drifter SST quality are in progress, partly for the calibration and validation of satellite SST. Currently 40% of global drifters (mainly in the tropics and sub-tropics) are deployed without pressure sensors. The two main programs deploying Surface Velocity Program Barometer (SVPB) drifters are the U.S. Global Drifter Program (GDP) and the EUMETNET surface marine observation programme (E-SURFMAR).

Centurioni et al. (2017) and Horányi et al. (2017) show results from assimilation experiments without global drifter pressure reports for Nov–Dec 2010 and Jul–Aug 2012. Perhaps surprisingly even in the Northern Hemisphere the drifters had more impact in Jul-Aug 2012 (often observations show less impact in summer, when the weather is less active). There were some differences in buoy coverage, but atmospheric activity probably played a role (Horányi et al., 2017) and Nov–Dec 2010 was part of an anomalously calm period for Europe. Between mid-2009 and mid-2011 there was higher predictability than usual for the Northern Hemisphere extra-tropics coinciding with the Arctic Oscillation being in a prolonged negative phase (Thorpe et al., 2013).

One useful diagnostic available from modern NWP systems is the forecast sensitivity to observation impact (FSOI), see for example Cardinali (2009) and Lorenc and Marriott (2014). Typically the analysis one day later is taken as the “truth” and estimates of the error reduction due to different components of the observing system are calculated. Overall, satellite observations now provide approximately 70% of the error reduction. However if FSOI is normalized by the number of observed values then drifter pressure comes out as the most useful (Centurioni et al., 2017, their figure 6). This is because:

1. Pmsl is an important variable providing information on the leading (barotropic) mode of extratropical synoptic variability.
2. Some drifters are measuring Pmsl in very data sparse ocean areas and.
3. Satellite data still provide little information about Pmsl.

Eyre and Reid (2014) combined FSOI results with estimates of the cost (to weather services) of observations and concluded that SVPB drifter pressure measurements were the second most cost-effective component (after aircraft reports) and an order of magnitude more cost-effective than many other components. Whilst FSOI has its limitations...
(discussed below) and costs can be difficult to estimate/attribute there is no doubt that drifter pressure measurements are very valuable and cost-effective.

2 | DIAGNOSTICS

Figure 1a shows the average standard deviation of buoy pressure observation-minus-background (O–B) differences globally for 2014–2016. The background is a short-range ECMWF forecast—nominally 12 hr, but this varies from 3 to 15 hr, as the forecast is compared to the observation at the appropriate time. Drifter reports are relatively evenly spread in the open ocean (they occur less or not at all in enclosed seas, such as the Mediterranean). The standard deviation shows maxima in the cyclogenesis regions of the western North Atlantic and western North Pacific, the Southern Ocean stormtrack and the Arctic. Near some of the Arctic coasts there is a maximum in the drifter differences: perhaps partly an adverse effect of ice on the sensors or perhaps the model background is poor in some situations, for example, because of not fully capturing orographically driven mesoscale circulations (especially in winter). There are minor pressure biases in the O–B Pmsl field (not shown). Ship pressure O–B differences (not shown) were larger overall and more variable—consistent with Ingleby (2010). Winds from ships and moored buoys are also assimilated but the available evidence suggests that their effect is secondary to the pressure assimilation. Very few drifters report wind (see Ingleby, 2010, and references).

Figure 1b shows the average FSOI for buoy pressure reports for 2014–2016. Negative values indicate a reduction of forecast error—there are large impacts in the storm track of the Southern Ocean, over the Gulf Stream and also near the Kuroshio current. Note that in the tropics the FSOI is predominantly negative although somewhat noisy (unfortunately there is a lack of drifter pressure observations in the tropical Pacific). Caveats about verification against analysis also apply to these FSOI results and are discussed further below. There is a clear correlation between FSOI values and the Eady-index of baroclinic instability, shown in Figure 1c. The Eady-index was defined by Lindzen and Farrell (1980) as a measure of baroclinic instability. We use the Hoskins and Valdes (1990) formulation:

$$\text{Eady-index} = 0.31 f \left( \frac{\partial v}{\partial z} \right) N^{-1},$$

where $f$ is the Coriolis force, $\frac{\partial v}{\partial z}$ the wind shear and $N$ is the Brunt-Väisälä frequency, computed for the layer 300 to 850 hPa.

The large values of the Eady index go up to the coasts of North America and Japan whereas the FSOI values reduce somewhat there—because there will be some influence of land reports in the coastal areas and there are some moored buoys in coastal waters. These development regions are where a synoptician would probably regard observations as most vital, but as far as we know they have not been shown using FSOI before.

The FSOI at ECMWF uses a dry energy norm to assess the observation impact at 24 hr forecast range. FSOI accuracy relies on tangent-linear model perturbations to be similar to non-linear perturbations, which typically only applies up to 24 hr forecast range. It does not measure the cumulative effect of removing, say, drifter pressures day after day. For this, more costly Observing System Experiments are needed in which the assimilation/forecast system is run removing certain data subsets—see next section.

3 | DATA DENIAL TRIALS

The period used was November 2015 to February 2016, using the ECMWF IFS cy43r1 (operational during the first half of 2017) using a horizontal grid spacing of about 25 km
and 137 vertical levels. ECMWF assimilates up to one report per buoy in each 30 min timeslot. All the buoy data used was from the alphanumeric FM-18 BUOY format. (At the time some buoys were also reporting in the binary BUFR format—BUFR BUOY data became operational at ECMWF in July 2016. More details of the transition of marine data to BUFR can be found at https://software.ecmwf.int/wiki/display/TCBUF/E-SURFMAR). It was decided to withhold Northern Hemisphere (NH) data only. The experiments were:

- Control – all data included
- NoNHsh – withhold ship data from NH
- HalfNHdr – withhold half of drifter data from NH
- NoNHdr – withhold all drifter data from NH
- NoNHdrsh – withhold all drifter and ship data from NH

The “half of drifters” experiment was set-up to characterise the NWP impact as a function of observation density. The last digit of each buoy identifier was examined, those with an odd number were withheld, and those with an even number were assimilated. This results in approximately 50% of the pressure values being omitted with a reasonably even geographical spread of “odd” and “even” buoys. Some moored buoys also report in FM-18 BUOY code—these were assimilated in all experiments.

4 | RESULTS

Figures 2 and 3 show changes in the geopotential height anomaly correlation relative to the Control for NoNHdr and HalfNHdr—verifying against own analysis. For NoNHdr there is a marked deterioration in NH scores throughout the troposphere at short-range. For HalfNHdr the signal is still clear but the magnitude is less than half that in Figure 2. At short range (T + 12) the NoNHdr impact is mainly over the western North Atlantic and western North Pacific (not shown) but it then becomes much less localised. Verification against own analysis can be problematic at short-range (and into the medium range in the tropics) because the analyses have a dependence on the earlier forecasts—this dependence decreases as more observations are assimilated. Verification results against own analysis at short range often tell us more

FIGURE 2  Vertical cross-section of the change in geopotential height anomaly correlation (averaged using the fisher Z-transform) for NoNHdr versus control, verified against own analysis for the period February 11, 2015—February 28, 2016. Scores shown for the forecast ranges 12, 24, 48, 72, 96 and 120 hr. Cross-hatching indicates 95% confidence, blue colours indicate that the experiment is worse than the control.
about the magnitude of analysis increments, rather than whether these increments are beneficial. The results here are consistent with verification against operational analyses (not shown). To provide reassurance comparisons of background fields (nominally a 12 hr forecast, as discussed above) with drifter pressures are also provided (Table 1). Because these observations have not yet been assimilated in the forecast run at the time they are considered, they may be regarded as independent. A number of satellite O–B statistics (not shown) also suggest that removing NH drifters is detrimental (this is expected, but cannot be taken for granted).

The rms of O–B departures for marine data in Table 1 show larger values at higher latitudes (50°–90°N) than lower latitudes (20°–50°N). The ratio values show the marine data has more impact in the Northern Region. In the Control experiment both North Atlantic (EUCOS area) and North Pacific have similar rms, but ratio values show that removing the marine data has more impact in North Pacific. The impact of removing ship data is small (especially at higher latitudes). As would be expected, it is larger without drifter data (going from NoNHdr to NoNHdrsh). For the EUCOS area removing half of the drifters has 30% of effect of removing all drifters plus ships (see last column). Qualitatively this is expected: introducing one observation in a data void will have a large effect, a second observation even at a relatively large distance does not provide completely independent information, so it will have a smaller impact. With an optimal assimilation system adding extra unbiased observations will always improve the analysis, but there are

---

**FIGURE 3**  Vertical cross-section of the change in geopotential height anomaly correlation (averaged using the fisher Z-transform) for HalfNHdr versus control, verified against own analysis for the period February 11, 2015–February 28, 2016. Scores shown for the forecast ranges 12, 24, 48, 72, 96 and 120 hr. Cross-hatching indicates 95% confidence, blue colours indicate that the experiment is worse than the control.

**TABLE 1**  Results for drifter pressure rms(O–B) in hPa for different areas and trials (~T + 12 verification against observations). Areas: N. Pacific: 10°–90°N, 120°E–100°W; EUCOS: 10°–90°N, 70°W–40°E. Number is the number of drifter Pmsl reports in each area. Ratio is the control rms divided by NoNHdrsh rms. The EUCOS% column shows the percentage of rms change for the EUCOS area normalized so that control is 100% and NoNHdrsh 0%.

| Area       | Number | Control | NoNHsh | HalfNHdr | NoNHdr | NoNHdrsh | Ratio |
|------------|--------|---------|--------|----------|--------|----------|-------|
| 20°–50°N  | 640,724| 0.719   | 0.721  | 0.737    | 0.773  | 0.777    | 0.925 |
| 50°–90°N  | 450,719| 0.978   | 0.978  | 0.845    | 0.870  | 0.949    | 0.906 |
| N. Pacific | 495,993| 0.844   | 0.854  | 0.868    | 0.901  | 0.904    | 0.887 |
| EUCOS     | 469,553| 0.853   | 0.854  | 0.868    | 0.901  | 0.904    | 0.944 |
| EUCOS%    |        | 100.0%  | 99.4%  | 69.9%    | 4.5%   | 0.0%     |       |
diminishing returns as the observation density increases, also found for radio occultation observations by Poli et al. (2008). Based on the numbers in Table 1 we can conclude that the ECMWF data assimilation system would benefit from more Pmsl drifter data. An example of buoy distribution is shown in Figure 4. Over 40% of drifters do not measure pressure, and many of the tropical moored buoys do not either. The impact of buoy pressures at low latitudes is less clear cut but it appears to be weakly positive. Given the cost-effectiveness mentioned earlier, the inclusion of barometers on all drifters should be pursued, for example via participation in the GDP barometer upgrade scheme, under which partners can fund the incremental cost of a barometer on GDP-funded SVP drifters for around US $1,200 per drifter (Luca Centurioni, Personal Communication).

5 | SUMMARY

- Areas of large pressure FSOI are linked to baroclinic development, these areas should be a priority for pressure measurements. In the North Atlantic the area associated with the Gulf Stream, from the East coast of North America extending towards Scotland, is highlighted. Data sparse areas (such as the Arctic) also have relatively large FSOI and extra buoy data here should benefit forecasts. The surface pressure data to be collected during the upcoming Year Of Polar Prediction buoy campaign will be welcome to better understand the impact of Arctic Pmsl data.
- Buoy pressure is better quality than ship pressure, ship quality varies with the type and size of the vessel (see Ingleby, 2010). However, drifting buoys cannot fully replace ships as they don't provide enough information to estimate surface fluxes, which help diagnose problems with NWP models in the longer term.
- Observing system experiments were performed for Nov 2015–Feb 2016. The main results were:
  - Northern Hemisphere drifter pressure measurements have significant impact.
  - Removing half the drifters has about 30% of the short range impact of removing all drifters plus ships.
  - The analyses change most in the west of the ocean basins.
  - For financial and historical reasons over 40% of drifters do not measure pressure. Given the impact and relative cheapness of drifter pressure measurement, more WMO member countries should consider participating in the GDP barometer upgrade program.

ACKNOWLEDGEMENTS

EUMETNET provided financial support to this project. The design of experiments was discussed and agreed with Paul Poli, E-SURFMAR manager. Paul Poli (Météo-France), Luca Centurioni (Scripps Institution of Oceanography) and Steve English (ECMWF) provided useful comments on the manuscript. Mohamed Dahoui and Anabel Bowen (both ECMWF) helped in the production of Figure 1.

ORCID

Bruce Ingleby http://orcid.org/0000-0002-3410-3951
REFERENCES
Cardinali, C. (2009) Monitoring the observation impact of the short-range forecast. *Quarterly Journal of the Royal Meteorological Society*, 135, 239–250.
Centurioni, L., Horányi, A., Cardinali, C., Charpentier, E. and Lumpkin, R. (2017) A global ocean observing system for measuring sea level atmospheric pressure: effects and impacts on numerical weather prediction. *Bulletin of the American Meteorological Society (BAMS)*, 98, 231–238. https://doi.org/10.1175/BAMS-D-15-00080.1.
Eyre, J. and Reid, R. (2014) Cost–benefit studies for observing systems. Met Office Forecasting Research Technical Report No. 593.
Horányi, A., Cardinali, C. and Centurioni, L. (2017) The global numerical weather prediction impact of mean-sea-level pressure observations from drifting buoys. *Quarterly Journal of the Royal Meteorological Society*, 143, 974–985.
Hoskins, B. and Valdes, P. (1990) On the existence of storm tracks. *Journal of the Atmospheric Sciences*, 47, 1854–1864.
Ingleby, B. (2010) Factors affecting ship and buoy data quality: a data assimilation perspective. *Journal of Atmospheric and Oceanic Technology*, 27, 1476–1489. https://doi.org/10.1175/2010JTECHA1421.1.
Lindzen, R.S. and Farrell, B. (1980) A simple approximate result for the maximum growth rate of Baroclinic instabilities. *Journal of the Atmospheric Sciences*, 37, 1648–1654.

Lorenc, A.C. and Marriott, R.T. (2014) Forecast sensitivity to observations in the Met Office global numerical weather prediction system. *Quarterly Journal of the Royal Meteorological Society*, 140, 209–224. https://doi.org/10.1002/qj.2122.
Niiler, P.P., Davis, R.E. and White, H.J. (1987) Water-following characteristics of a mixed-layer drifter. *Deep Sea Research*, 34, 1867–1881. https://doi.org/10.1016/0198-0149(87)90060-4.
Poli, P., Healy, S.B., Rabier, F. and Pailleux, J. (2008) Preliminary assessment of the scalability of GPS radio occultations impact in numerical weather prediction. *Geophysical Research Letters*, 35, L23811. https://doi.org/10.1029/2008GL035873.
Thorpe, A., Bauer, P., Magnusson, L. and Richardson, D. (2013) *An evaluation of recent performance of ECMWF’s forecasts*, pp. 15–18 in ECMWF newsletter 137. Available at: https://www.ecmwf.int/sites/default/files/elibrary/2013/14579-newsletter-no137-autumn-2013.pdf

How to cite this article: Ingleby B, Isaksen L. Drifting buoy pressures: Impact on NWP. *Atmos Sci Lett*. 2018;19:e822. https://doi.org/10.1002/asl.822