Ship observations for numerical weather prediction – useful or redundant?

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Numerical weather prediction (NWP) models tend to become more advanced. In addition the number of observations from weather satellites has increased exponentially over the last decades. This raises the question on the usefulness of the relatively small number of ship and buoy observations for NWP.

The meteorological observing network showed large data void areas in the pre-satellite era, in particular over the oceans. A single ship or buoy observation contained a relatively large amount of information. With the advent of weather satellites this has changed dramatically. Cyclo-genesis and their evolution over the oceans are nowadays well monitored by geostationary satellites. These are located on a fixed position 36.000 km altitude above the earth surface and produce images of clouds and humidity every 15 minutes. In addition the number of polar satellites is growing continuously over the last decades. Polar satellites orbit the earth at a much lower altitude, typically between 500 and 900 km above the earth surface, giving a global coverage of mainly temperature and humidity throughout the troposphere and lower stratosphere and wind observations at the ocean surface, see figure 1. Comparison with the surface network in figure 2 may suggest that the added value of conventional observations such as from ships and buoys will be negligible for nowadays NWP. Is this a valid statement?

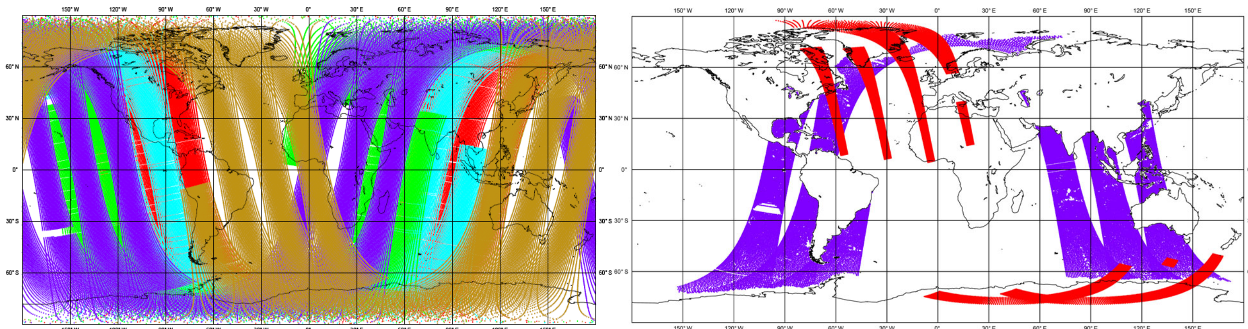

Figure 1. Observation coverage from polar satellites for a 6-hour period on 17 April 2007. Left, 355324 temperature and humidity observations from the American NOAA and the European METOP satellites. Right, 79426 sea surface wind observations from the American Quikscat (purple) and European ERS-2 (red) scatterometers.

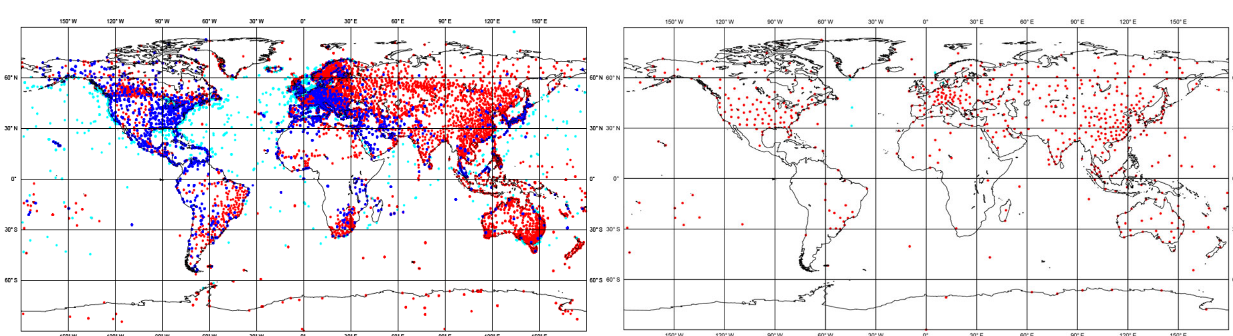

Figure 2. Observation coverage of conventional observing systems for a 6-hour period on 17 April 2007. Left, surface observations from 15862 land stations (red), 1852 ships (light-blue) and 9678 airports (dark-blue). Right, profile observations from 614 radiosondes over land (red) and 5 from ships (light-blue).

Well, not completely. First, the interpretation of satellite observations is not always that simple. Satellites generally do not explicitly measure meteorological parameters such as temperature, humidity and wind, rather implicitly through atmospheric radiance or backscatter of the emitted signal at the ocean surface. Next, complex mathematical equations need to be solved to transform these measurements to meteorological parameters. Nowadays models are still improving to deal with this complexity, but verification with conventional observations, from which the characteristics are quite well known, is indispensable for a correct use of satellite observations into models.

Second, nowadays models are not well capable to extract and include valuable information from geostationary satellites. Assimilation of cloud and humidity images into models is still in its infancy and requires a lot of research. However, the high temporal resolution of 15 minutes of these images is a valuable source of information for operational meteorologists to monitor weather systems and to estimate their development on the short term.

Finally, the available satellites lack a global coverage of wind observations. Scatterometers, see figure 1, only measure the wind at the ocean surface. At higher altitudes wind information may be extracted by tracking cloud features in a sequence of cloud images from geostationary satellites, but the data coverage is limited to cloudy areas and moreover, the retrieved winds are not very accurate mainly because of inaccuracies in the determination of the cloud altitudes. Also wind observations from airplanes have a limited coverage. These are concentrated along flight tracks and limited to the cruising altitude. The World Meteorological Organization (WMO) has stated that the lack of a global coverage of wind observations in the troposphere is the largest deficiency of the current meteorological global observing system. Wind observations are particularly important to resolve the large-scale tropical dynamics and for the synoptic scales in the extra-tropics. The ESA satellite ADM-Aeolus[‡] is the first attempt to fill this gap in the observation network. Its scheduled launch is in the autumn of 2009. Until then radiosonde launches from ships (e.g. ASAP) and platforms are the only contributors to profile the atmosphere above the oceans. Their information is crucial for short and mid-term weather forecasting. However, it is expected that their role is not finished after the launch of ADM-Aeolus.

Observing system impact for NWP

The more qualitative discussion above suggests that the use of ship and buoy observations may not be underestimated for NWP. It would be nice to test this statement quantitatively, e.g. through experiments that assess the impact of observing systems. Operational meteorological offices conduct so-called OSE (Observing System Experiments), also denoted denial experiments, on a regular base to test the newest model versions on their capability to handle existing and new observations, to quantify their impact and to check on possible redundancies of different observing systems. The remainder of this article will discuss results and conclusions of a number of OSEs conducted at the European Centre for Medium-range Weather Forecasts (ECMWF) in 2004. I will use results that Jean-Noël Thépault and Graeme Kelly of ECMWF presented on the “Third WMO Workshop on the Impact of Various Observing Systems on NWP” in Alpbach, Austria, 9-12 March, 2004[§].

The motivation for this particular OSE was a request by EUMETSAT, the European organization responsible for the exploitation of operational weather satellites. One of the objectives of EUMETSAT is to define an optimal network of weather satellites by assessing expected future deficiencies in the observing network and to consider options to fill these gaps with new satellites. Future means here 15 to 20 years, i.e. the typical time span to develop and

[‡] http://www.esa.int/esaLP/LPadmaeolus.html
[§] http://www.wmo.int/files/www/GOS/Alpbach2004/1B_2ThepautJeanNoel.pdf

operationalize new satellites. An OSE provides a good indication of the added value of *existing* observing system for the current models. If it is possible to project these results to the NWP situation in the future, say 20 years ahead, then the OSE results provide an indication of the most needed observations for future models. This will guide the definition of observation requirements and the subsequent design of future (satellite) observing systems to obtain these observations. This projection of results to the situation 20 years ahead is not a trivial exercise, because the progress of models and data assimilation systems is hard to predict.

In the sequel I will explain the OSE experimental setup and present results of the impact of ocean surface observations within a network that is increasingly dominated by observations from satellite systems, see figure 3.

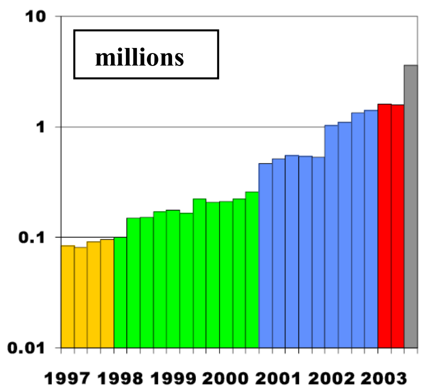

Figure 3. The number of used observations by the ECMWF data assimilation system. New satellites cause an exponential growth of the total number of observations assimilated in NWP models.

Observing System Experiment (OSE)

An OSE is composed of two experiments, both covering the same period of typically a couple of months. For this period, atmospheric analyses and forecasts are generated with a recent version of the operational NWP model. The first experiment, also denoted control experiment, uses all available observations such as in the operational practice. The second experiment is almost identical, yet one observing system is denied in the experiment, for instance all ship observations. Comparing analyses and forecasts of both experiments provides an indication of the added value of the observing system under investigation. It is important to note that the observing system is in competition with other observing systems. To reduce costs, one could decide to no longer use the observing system if the added value turns out to be negligible or even negative. However, negative impacts could also mean that the current model version does not correctly use the observational information or that the model is not well capable to absorb the information. This used to be case for instance for the first generation of satellite radiance measurements. For these situations the experimental results show the need to improve either the model or the use of observations in the model.

Experiment results

ECMWF has conducted two OSE experiments in 2004 with the 2003 operational model. The first experiment covered a 7-week winter and summer period and was conducted at T319L60 (60 km horizontal, 60 model levels in the vertical) model resolution. The second experiment covered a 2-month winter and summer period and was conducted at T511L60 (40 km horizontal) resolution.

The main conclusions are

- Surface observations (SYNOP, SHIP, BUOY, scatterometer) constitute an important part of the current observation network. Denying all surface observations both over sea and land causes relatively large systematic errors (biases). The addition of surface wind observations solves this problem only partly. The use of surface wind observations only (no observations of surface pressure and temperature) has a large negative impact in the Southern Hemisphere.
- Denying observations of sea surface pressure, in the remainder denoted by the NOSPSEA experiment, yields substantially worse forecasts. Thus, the use of just wind observations over sea in addition to surface pressure observations over land is insufficient, see figure 4. The forecast errors are larger on average for the NOSPSEA experiment than for the control experiment.

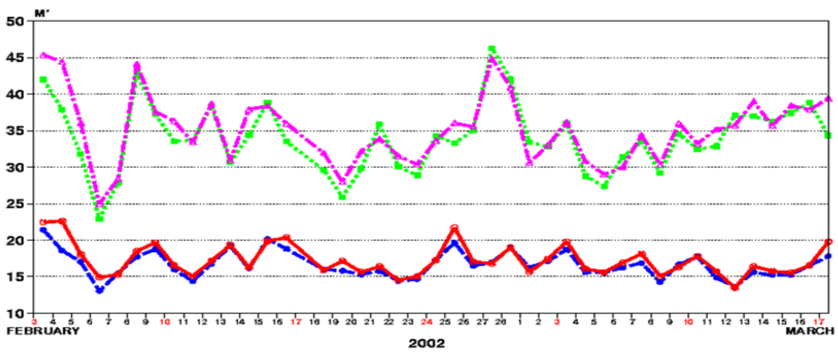

Figure 4. Time series of the 1000 hPa geopotential field forecast error (in meters) for the northern hemisphere above 20 degrees latitude, 48/96-hour forecast error for the control (using all observations) experiment (blue/green) and NOSPSEA (all observations but excluding the sea surface pressure observations) experiment (red/rose).

- Ship and buoy surface pressure observations have a marginally larger impact than wind observations from ship, buoys and Quikscat scatterometer over sea.
- Buoy surface pressure observations have a marginally added value in the Northern Hemisphere, see figure 5 where the green and red curves almost coincide.
- Denying all sea surface pressure observations reduces the scores substantially (blue curve in figure 5), with a reduction of the 5-day forecast quality over Europe ranging from a quarter to half a day. The addition of sea surface pressure observations from ships (green curve) and, to a lesser extent, wind observations above the sea surface improve the forecast substantially, close to the control forecast (red curve).

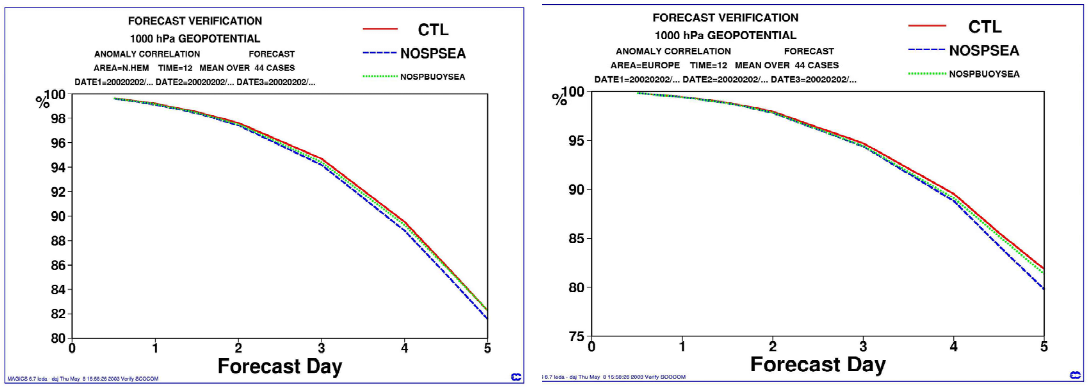

Figure 5. Impact of ship and buoy sea surface pressure observations on the 1-5 day forecast of the 1000 hPa geopotential field. Anomaly correlation coefficient averaged over 44 days for the Northern Hemisphere (left) and Europe (right) for the control experiment (red), NOSPSEA (blue, denying observations of surface pressure over sea) and NOSPBUOYSEA (green, denying observations of surface pressure over sea from buoys only).

- The impact of buoys and ships is about similar. Their impact is larger in winter than in summer.
- Observations of surface pressure are absolutely essential to anchor the surface pressure field. To guarantee a positive impact from surface wind observations, observations of surface pressure are needed. However, the mean impact of sea surface wind observations (buoys, ships, scatterometer) equals that of surface pressure observations (buoys and ships) in the Southern Hemisphere. The relative added value of the sea surface pressure observations is larger in the Northern Hemisphere.
- In the presence of sea surface wind observations, a limited number of accurate sea surface pressure observations already yield a substantial positive impact in the forecast.
- The added value of surface pressure observations has reduced compared to earlier studies, presumably explained by model improvements and/or the data assimilation system and/or new (satellite) observing systems.

Case study

The above summary of the experimental results provides an average and therefore fairly complete indication of the added value of ships and buoys in nowadays NWP. The mean impact may not be large, with a maximum forecast extension of 6 to 12 hour for medium-range forecasts. However, mean statistics may hide interesting cases where the added value is quite substantial. Figure 6 shows a time series of the 1,2, and 3-day forecast error including such an interesting case on 9 August 2002 (circled). De 3-day forecast error verifying at 12 August is almost doubled when ship and buoy observations are denied. Figure 7 indeed shows that the 3-day control forecast (brown curve in Figure 6) initiated at 9 August better verifies with the analysis 3 days later than the forecast initiated with the analysis denying ship and buoy observations (light-blue curve in Figure 6). This is traced back to a single or small number of ship observations close to the American east coast, see Figure 8. These observations were used in the control run and apparently correct the surface pressure model field in the right direction such that the 3-day forecast over Europe improves substantially. This example also clearly shows that small analysis corrections may have a large impact on the forecast quality, in particular when they are located in so-called meteorological sensitive areas where small analysis errors tend to grow rapidly in time giving last forecast errors if not well observed.

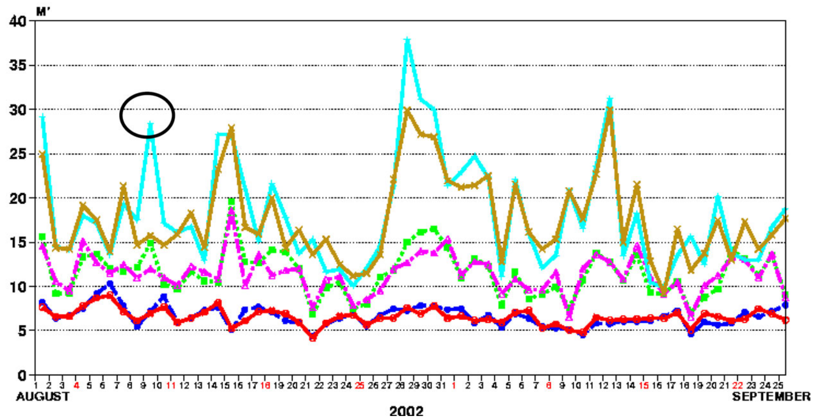

Figure 6. Same as figure 4, but now for 24/48/72-day forecasts for the control experiment and the experiment denying ship and buoy observations.

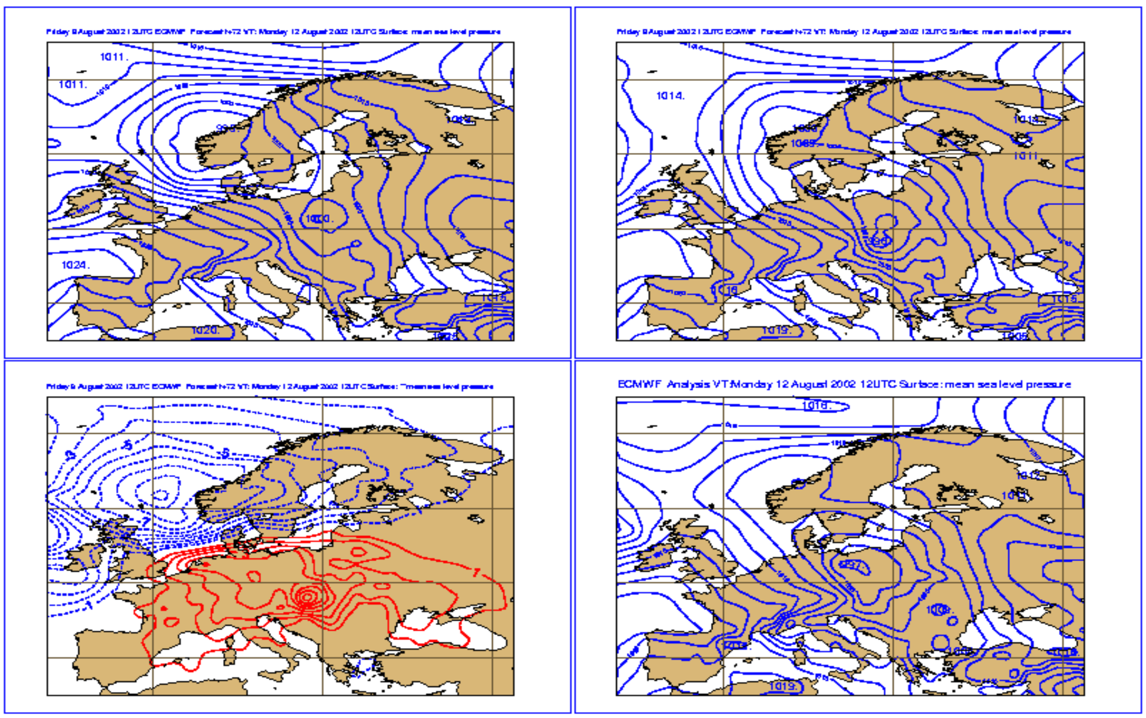

Figure 7. Mean sea level pressure for 12 August 2002. Upper left, 3-day forecast denying ship and buoy observations. Upper right, same but all observations have been used (control experiment). Lower left, difference between the above forecasts. Lower right, the 12 August verifying analysis.

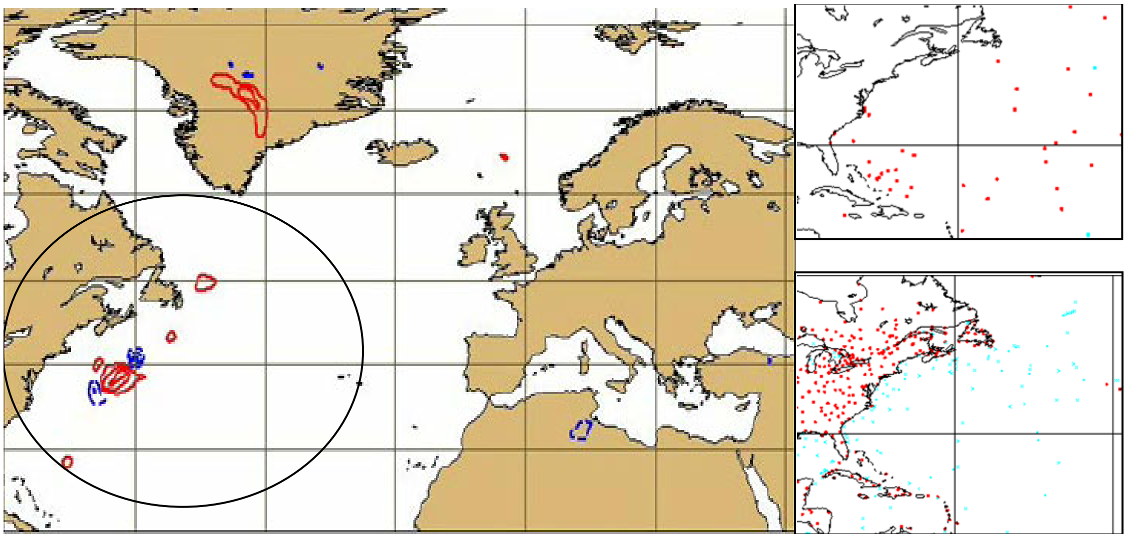

Figure 8. Left, mean sea level pressure analysis difference at 9 August 2002 between the experiments with (control) and without ship and buoy observations. Right, locations of buoy (top panel) and ship (lower panel) observations close to the American east coast.

In conclusion, the OSE conducted at ECMWF in 2004 show that sea surface pressure observations from ships and buoys still contribute substantially to NWP. A clear distinction between the relative importance of ships and buoys can not be made based on these experiments. Both seem to be equally important. They still constitute an important component of the total observing network, despite their relative low number and the growing impact of satellite observations. More concrete, a single observation inside a meteorological sensitive where large analysis errors tend to grow rapidly in time can be of crucial importance for the quality of the short and medium-range forecast. The added value of ship and buoy observations is clearly demonstrated for such events although it is hard to predict a priori where to make the observation to have a maximum impact.