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Observing System Experiments to Assess the Impact of Possible Future Degradation of the Global Satellite Observing Network

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Summary

The aim of this study is to estimate how future changes to the global network of polar orbiting meteorological satellites might influence the accuracy of Numerical Weather Prediction (NWP) forecasts. A recent operational version of the ECMWF analysis and forecasting system has been re-run over a test period covering the winter of 2009/2010 with a number of satellites deliberately withheld to simulate a variety of potential network reduction scenarios. Performance is referenced to that of a two satellite baseline system that consists of one polar satellite from the United States (here termed USPS) combined with one European polar satellite (here termed EPS).

The results confirm that the availability of observations from polar satellites has a clear positive impact on forecast accuracy - as measured by the headline skill scores averaged over this three-month study period. The simultaneous loss of both the EPS and the USPS would be expected to result in a significant and damaging loss of medium range forecast accuracy, 10% for Europe and North America (roughly equivalent to 12 hours of lost useful predictability) and around 30% for the Southern Hemisphere (roughly equivalent to 24 hours of lost useful predictability). These figures should be appreciated as significant - historically, the combination of enhanced observing systems, model development and increased computer power has led to average gains of just 1 day of useful predictive skill per decade.

Losing just one polar satellite results in marginally reduced forecast skill compared to the two satellite baseline. It is clear that with modern data assimilation techniques, one satellite is able to compensate to a large extent for the loss of the other. However, these results are very geographically dependent and also strongly linked to the way the assimilation windows are constructed.

It is also evident from these results that there are significant benefits to flying more than 2 polar orbiting satellites, as seen in the enhanced skill of a data rich control system compared to the baseline. This study has considered only contributions from the US and Europe for the post-EPS timeframe, but these results suggest it would be wise to work closely with other potential satellite providers (e.g. China) to ensure as dense as possible network of polar orbiting observations.

The sensitivity of Tropical forecasts to the assimilation of polar orbiting satellite data is much less than seen for the mid-latitudes, although satellites are clearly important at the shorter ranges. The dominant role of moist physical processes means that forecast errors have a very different character in the Tropics, saturating rather quickly with forecast range. However it should be noted that the exploitation of all sky microwave imager data in the Tropics is still relatively recent and may be improved significantly in the future.

The synoptic case studies clearly demonstrate that the medium range forecasting of high impact weather events can be very sensitive to the available satellite observing systems. In one case (the Washington snowstorm) the loss of polar satellites results in a failure to give guidance of the event 3 days in advance – whereas a good prediction is made when the satellites are assimilated. However, from the other cases studies there is probably not sufficient evidence to conclude that the presence of polar orbiting satellites produced unambiguously better forecasts.

Introduction and scope of the study

Numerical Weather Prediction systems currently benefit from a high availability of observations made by numerous polar orbiting spacecraft (data from as many as 10 satellites are assimilated – excluding individual GPS nodes). However, it is unlikely that the current wealth of data provision is sustainable as future financial limitations restrict the frequency of new satellite launches.

The purpose of this study is to estimate how future reductions in the global network of polar orbiting meteorological satellites might influence the accuracy of Numerical Weather Prediction forecasts. A recent operational version of the ECMWF analysis and forecasting system has been re-run over a test period covering the winter of 2009/2010 with a number of satellites deliberately withheld to simulate a variety of potential reduction scenarios. This period was selected as it covers three particularly high-impact meteorological events that affected the European and North American regions.

It is expected that a baseline operational observing system in the future may consist of one polar satellite from the United States (here termed USPS) combined with one European polar satellite (here termed EPS). Details of the instruments to be carried on these future platforms are of course unknown at this stage, but some reasonable assumptions can be made. It is likely that both will carry at least a high spectral-resolution InfraRed Sounder (IRS) together with a Microwave Sounding capability (MWS). Additional instruments might include a dedicated Microwave Imager (MWI) surface sensing Scatterometer (SCAT) and a Radio Occultation GPS receiver (GPSRO). With these assumptions in mind the hypothetical future polar satellites have been constructed using existing elements of the current observing network.

The ECMWF system has been run for 3 months assimilating combinations of these hypothetical polar satellites and the quality of the resulting atmospheric analyses and forecasts has been quantified. For the analysis the primary measure of skill is the fit to radiosonde observations of temperature, wind and humidity. The forecasts have been verified in two ways. Firstly by comparison to the ECMWF operational analysis, and secondly by comparison to radiosonde observations. In both cases the primary metric is the root mean square error (RMSE) in 500hPa geopotential height – although for the Tropics humidity and wind are assessed. The performance of the forecasts during the December 2009 snowfalls and February 2010 wind storm is evaluated from a synoptic viewpoint.

Details of the ECMWF analysis and forecasting system

The experiments have been conducted using version CY37R2 of the ECMWF forecasting system with 91 levels in the vertical (up to 0.01hPa) and a horizontal resolution of T511 (typical grid spacing of 40Km). While this horizontal resolution is somewhat coarser than the current operational system (T1279, typical grid spacing 16Km), experience at ECMWF has shown that it is adequate for the running of Observing System Experiments (OSEs). With limited computer resources, running at this reduced resolution allows many more scenarios to be tested for longer periods than would otherwise be possible. The 4D-Var data assimilation system provides initial conditions for the forecast model. In all experiments a minimum set of core observations are used, consisting of conventional data (in situ measurements from the surface, balloons, ships and aircraft) and products from METEOSAT and GOES geostationary spacecraft (clear-sky radiances and atmospheric motion vectors). The polar satellite observations supplied as input to the 4DVAR are varied depending on the scenario being tested. Radiance observation bias corrections are taken from the ECMWF operational system and fixed for the duration of the experiment. While this is a departure from the normal practice of adaptively estimating biases during the assimilation – it avoids potential problems of corrections (for a particular sensor) varying with different satellite configurations.

Hypothetical future polar orbiting satellites

A *baseline* and a set of reduced observing systems have been tested with hypothetical future polar satellites constructed from existing elements of the current observing network.

EPS	**IASI, AMSU-A, MHS, ASCAT** and **GRAS** onboard the Metop-A **morning satellite**
USPS	**AIRS, AMSRE** from AQUA and **AMSU-A, AMSU-B** from NOAA-18 **afternoon satellites**

Note that to achieve a combination of an IRS and fully functioning MWS, sensors from two platforms (AQUA and NOAA-18) have been used to construct the USPS. The AMSUA instrument performance on AQUA is significantly degraded and the Humidity Sounder of Brazil (that would have provided a MHS type capability) failed soon after launch. However, as the AQUA and NOAA-18 platforms are in very similar orbits and no explicit co-location of the data takes place (outside of 4DVAR) this choice should have a negligible impact upon the results.

Observing System Experiments

Using the hypothetical polar satellites combined with the core observations, experiments have been run that assess the performance of a baseline system using just two satellites (EPS and USPS) compared to degraded scenarios when either one or both polar satellites are withheld from the assimilation system. For completeness a control system is also run that uses all available satellite data from multiple NOAA platforms, METOP, TRMM and COSMIC. This data rich system is shown purely for comparison and such an extensive constellation of polar orbiting satellites is not considered a realistic possibility for the future. The test period is 1st December 2009 until 28th February 2010. The observation content of the various scenarios tested are detailed in table 1 and a brief description of how data from the various satellite sensors are used is provided below (sensors not in bold are only present in the control system):

AIRS *and* **IASI:** Infrared radiance measurements in up to 120 channels for AIRS and 175 channels for IASI are assimilated. These can be in completely clear sky, partly cloudy conditions above the cloud level or completely overcast conditions above homogenous cloud. Data from all major spectral bands except ozone are used in these experiments. No tropospheric information is used over land surfaces. (for details see McNally et al 2006, Collard and McNally 2009 and McNally 2009).

AMSU-A, AMSU-B / MHS: Microwave radiance measurements are used in clear sky or when the contamination signal due to cloud liquid water is sufficiently low. Tropospheric information is used over land and sea surfaces. (for details see McNally 1999, Bormann 2009).

AMSR-E (*TMI / SSMI*)

Microwave imager radiance measurements are used in all sky conditions over sea. Rain affected data are simulated explicitly using a scattering radiative transfer model applied to rain rates from the NWP model. No data are used over land. (for details see Bauer et al. 2010, Geer et al. 2010).

ASCAT (*ERS*)

Surface backscatter data are converted to ambiguous (multi-directional) sea surface wind estimates which are then assimilated in the 4DVAR. (for details see Hersbach 2010).

GRAS (*COSMIC*)

Bending angle profiles are assimilated globally with a one-dimensional operator that includes non-ideal gas compressibility and tangent-point-drift. Data are used between altitudes 8Km to 50Km. (for details see: Healy and Thépaut 2006 and Healy 2011).

HIRS: Infrared radiance measurements in up to 9 channels are assimilated. These can be in completely clear sky, partly cloudy conditions above the cloud level or completely overcast conditions above homogenous cloud. No tropospheric information is used over land surfaces.

Observing system	**Baseline (EPS+USPS)**	**EPS only**	**USPS only**	**No Polar sounders**
Conventional	Yes	yes	yes	yes
GEO (RAD+AMV)	yes	yes	yes	yes
IRS	Yes (AIRS+IASI)	Yes (IASI)	Yes (AIRS)	no
MWS	Yes (2 AMSUA/B/MHS)	Yes (AMSUA/MHS)	Yes (AMSUA/B)	no
MWI	Yes (AMSRE)	no	Yes (AMSRE)	no
SCAT	Yes (ASCAT)	Yes (ASCAT)	no	no
GPSRO	Yes (GRAS)	Yes (GRAS)	no	no

*Table 1a: **Baseline** and reduced observing systems*

Observing system	Data Dense Control (ECMWF operations)
Conventional	Yes
GEO (RAD+AMV)	Yes
IRS	(AIRS+IASI)
MWS	(AMSUA x 4, AMSUB/MHS x 3 HIRS x 3)
MWI	(TMI + AMSRE + SSMI)
SCAT	(ASCAT + ERS)
GPSRO	(GRAS + COSMIC)

Table 1b: ***Control*** *observing systems*

Forecast Impact

Forecasts are run from 00z and 12z each day during the experiment period and these are verified using the ECMWF operational analysis. This is the primary verification and arguably the best globally available estimate of the true atmospheric state. Additional radiosonde observation based verification has been performed, but the results are not shown here as they are generally consistent with those from the analysis based verification. The only exception to this is in the results for the short range forecast (day 1) where the impact of losing polar satellite data appears significantly less measured against radiosonde observations than against the operational analysis. The reason for this is that the geographical sampling of the radiosonde verification is (by definition) very restricted and biased to conventional data dense areas where we expect the impact of satellite data to be a minimum.

The skill of the forecasts is quantified in terms of root mean square error (RMSE) of 500hPa geopotential height for the extra tropical regions, with vector wind and relative humidity presented for the Tropics. In all cases an assessment of statistical significance of the results is provided (based on the spread of population). In each case the percentage loss of skill in the degraded systems with respect to that of the *baseline* is shown (green only USPS assimilated, blue only EPS assimilated and red when both polar systems are lost). The grey bar indicates the difference between the *baseline* system and the data rich *control* that uses all available satellite data (similar to ECMWF operations).

Extra-Tropical Regions

The results for the extra Tropics are shown in figure 1, separated in to four geographical areas. In all areas it can be seen that the presence of the polar satellites has a clear and unambiguous positive impact on forecast accuracy. Over Europe and North America the simultaneous loss of both EPS and USPS would be expected to degrade the forecast skill by around 10% at all ranges. In the short range (day 1) this figure equates to a loss of around 4 to 6 hours of useful predictive skill and in the medium ranges (day 3 -5) up to 12 hours of lost skill. For the wider Northern Hemisphere (that includes the Atlantic and Pacific oceans) the absence of both satellites results in a much larger loss of short-range skill, exceeding 40% or 12 hours (losses in the medium range being broadly the same as for those for Europe and North America). As expected, the most dramatic loss of skill without the polar satellites is in the Southern Hemisphere. Error increases of 50% in the short range and 25% to 35% in the medium range typically equate to 24 hours of lost predictive skill.

When just one of the polar satellites is removed (either EPS or USPS) we see more modest losses of forecast skill. Indeed the results suggest that to a large extent the presence of one satellite is able to compensate for the loss of the other. This is particularly evident in the Southern Hemispheric *statistics* where retaining just EPS or just USPS retains a significant proportion of the two satellite *baseline* skill. The most striking example of compensation is seen the North American region statistics. Here it appears that the USPS polar satellite can be removed with almost no loss of skill as long as the EPS satellite is retained. However, unlike in the Southern Hemisphere (where the skill could be retained with either polar satellite) if EPS is removed the USPS is unable to sustain the accuracy of the forecasting system. While the EPS arguably has a more comprehensive suite of sensors onboard than the USPS, the near equivalent performance of the two platforms in the Southern Hemisphere suggests

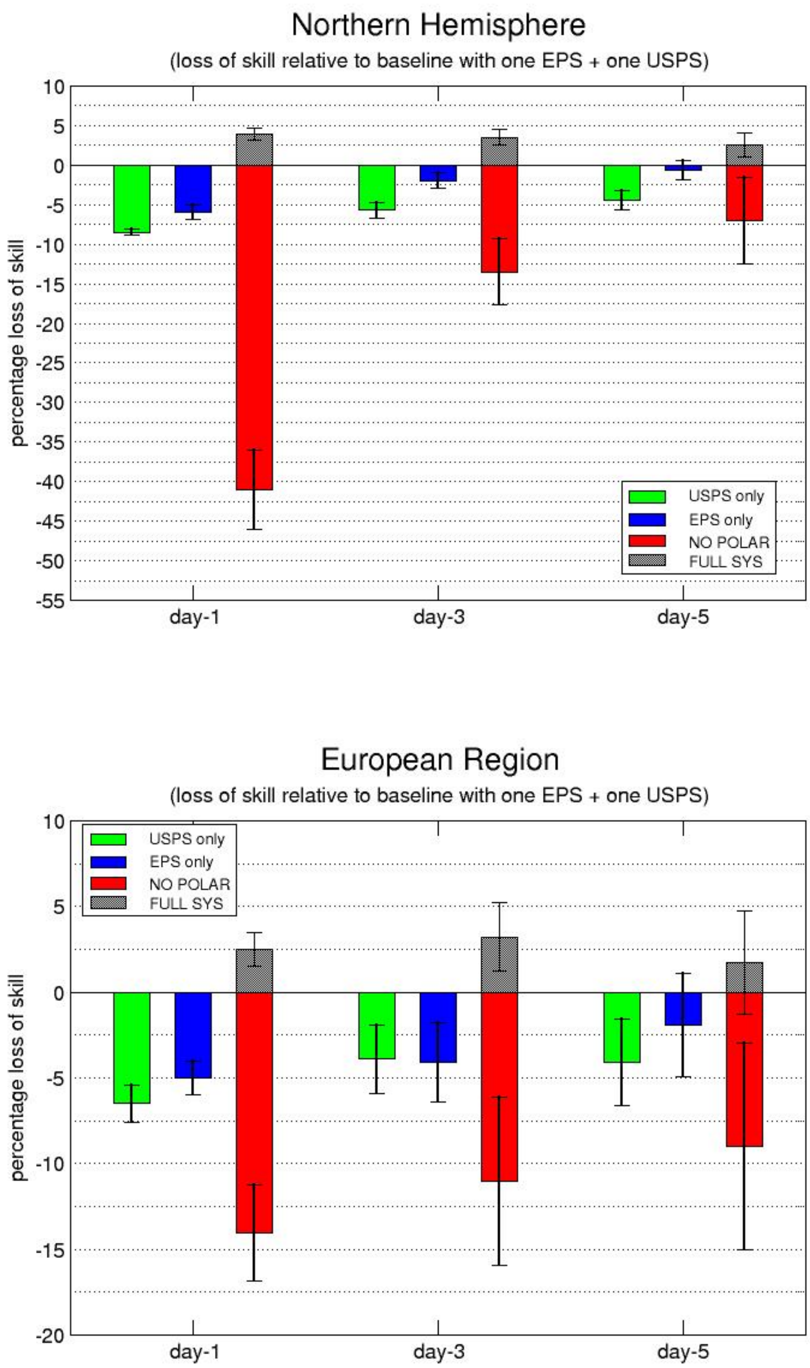


Figure 1a: Percentage loss of forecast skill with degraded observing systems (relative to the baseline) for 500hPa geopotential height, evaluated in Europe (upper panel) and the N. Hemisphere (lower panel). The error bars indicate 5% significance intervals.

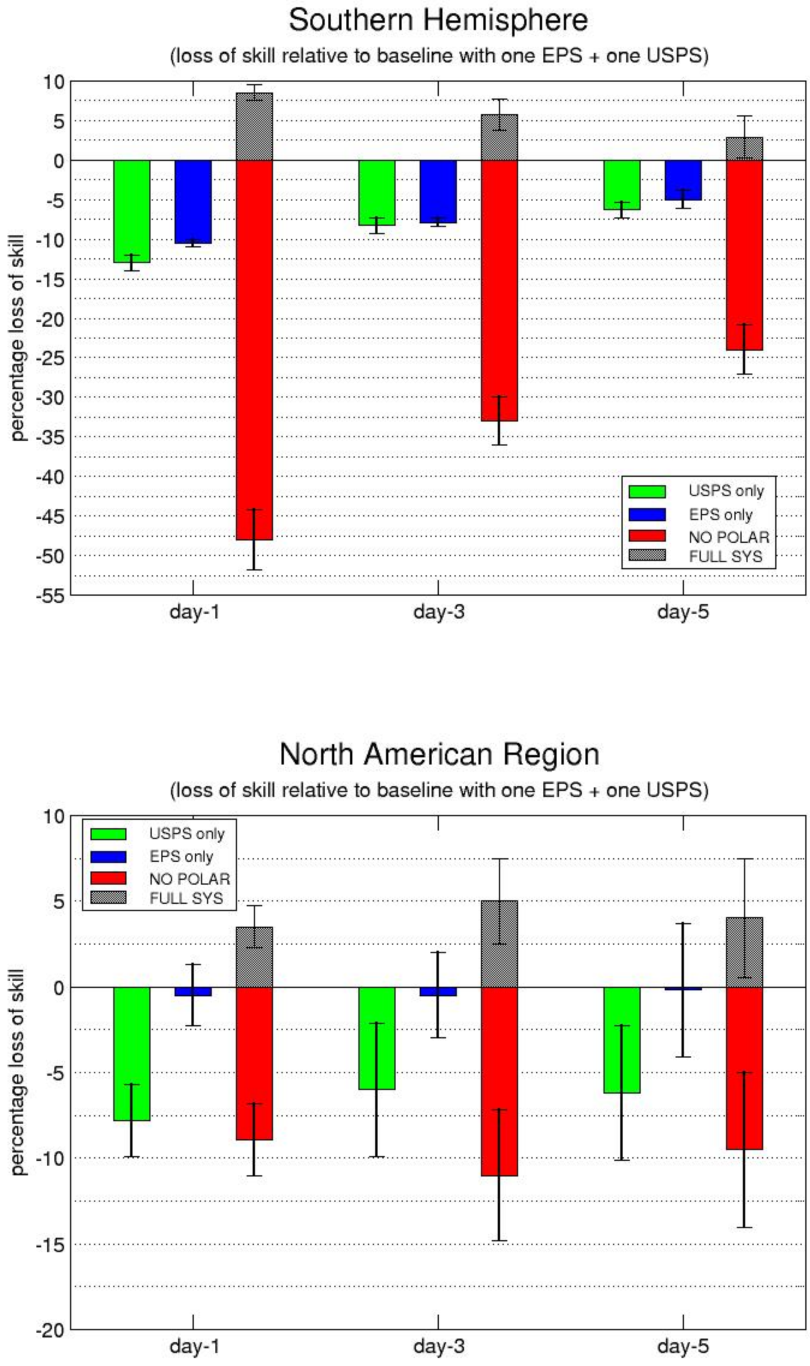


Figure 1b: Percentage loss of forecast skill with degraded observing systems (relative to the baseline) for 500hPa geopotential height, evaluated in North America(lower panel) and the S. Hemisphere (upper panel). The error bars indicate 5% significance intervals.

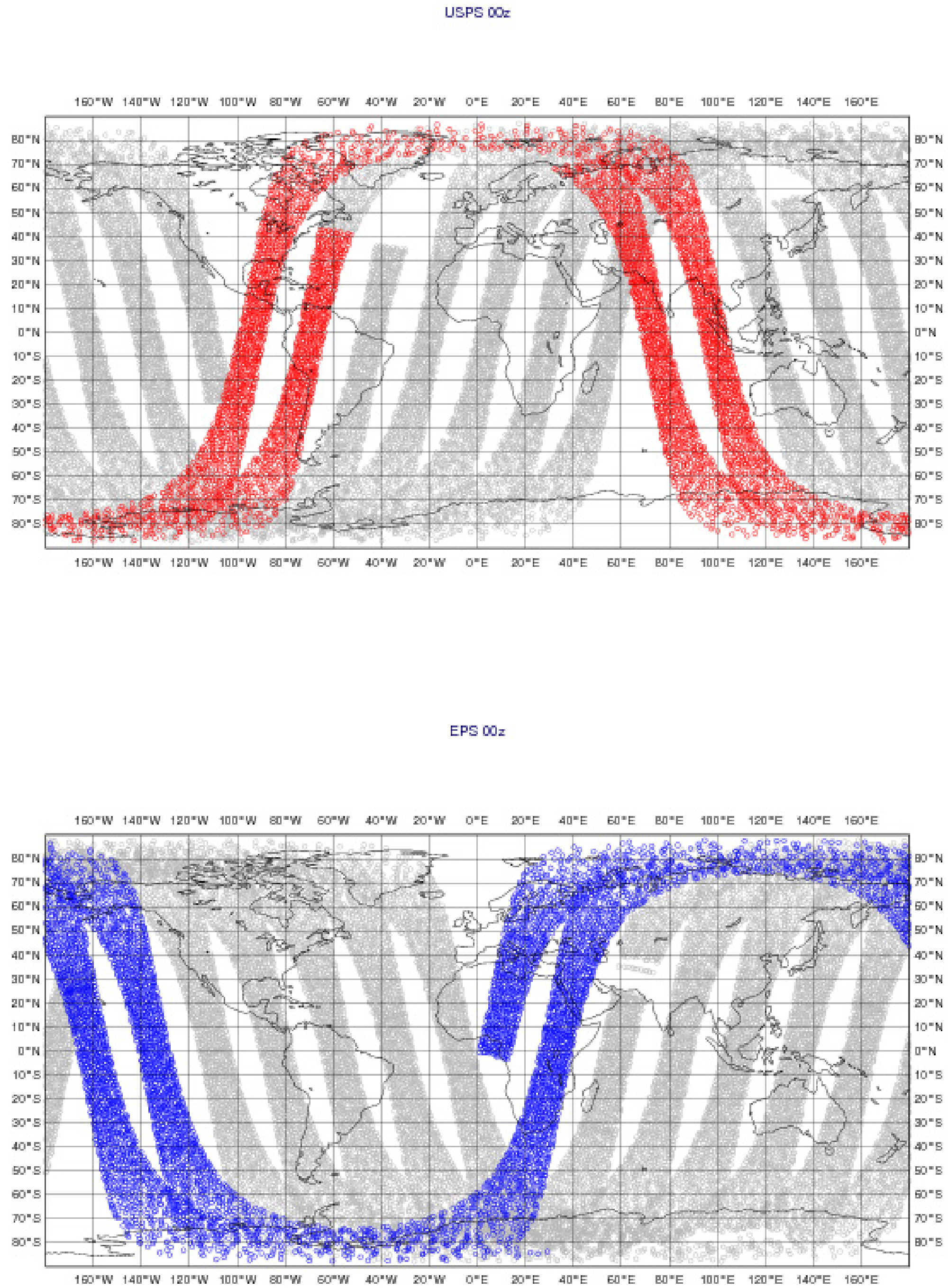


Figure 2: Orbits of the EPS and USPS in the 00z 4DVAR 12 hour assimilation window. Those coloured red (for USPS) and blue (for EPS) are observed in the lattermost 3 hours of the assimilation window.

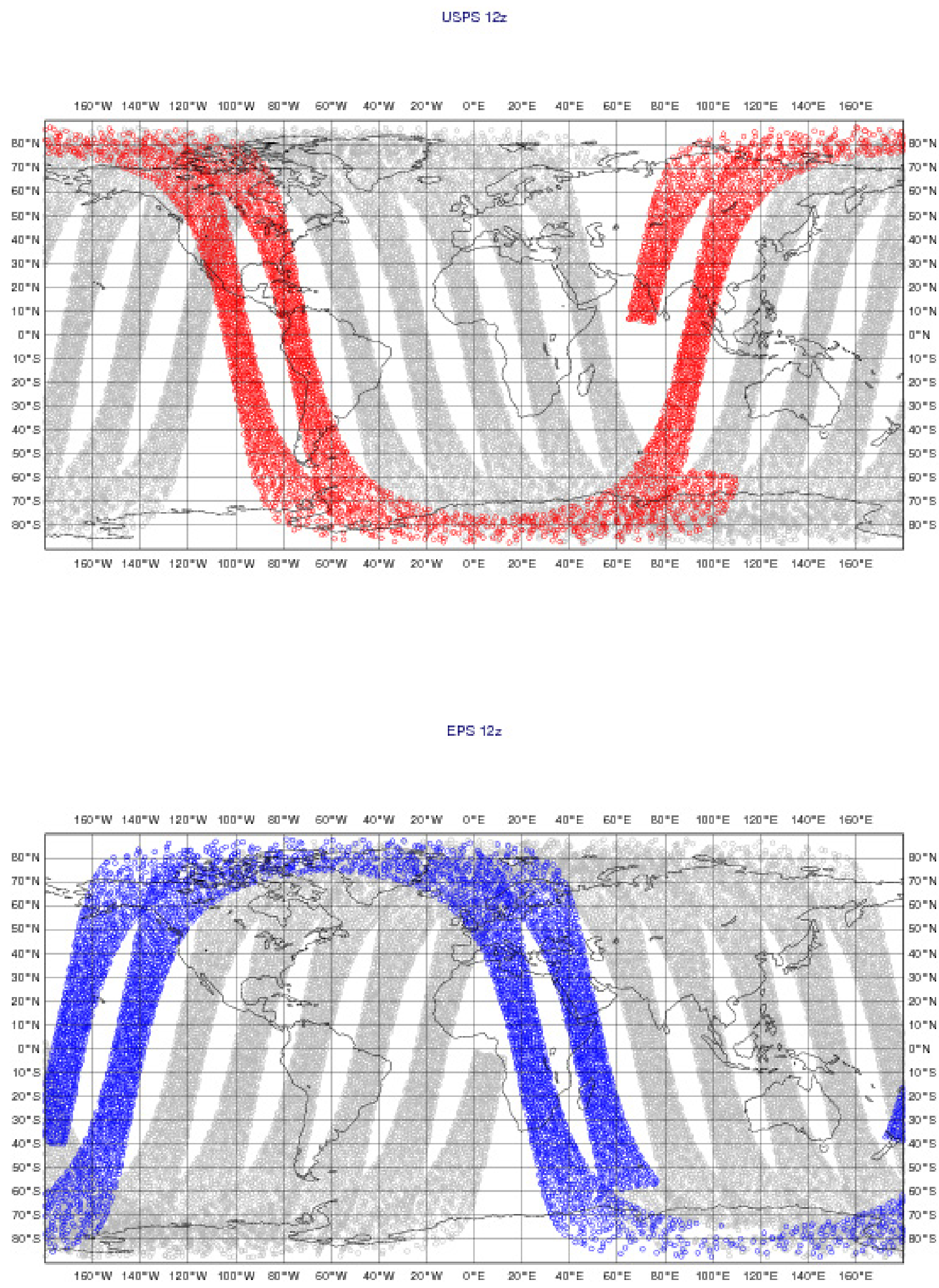


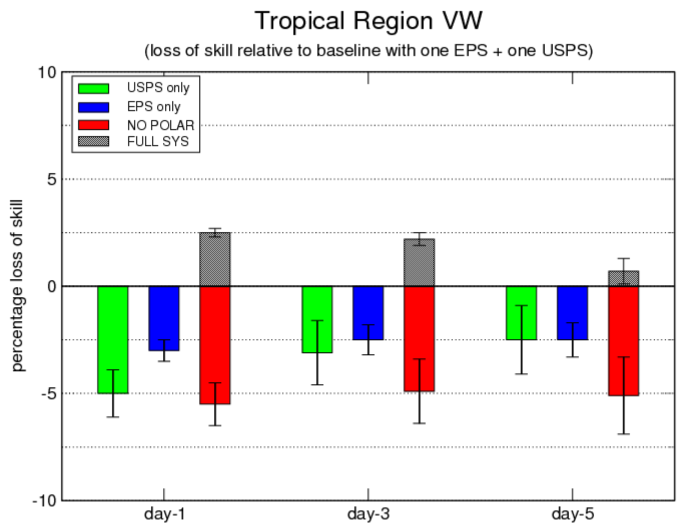
Figure 2b. Orbits of the EPS and USPS in the 12z 4DVAR 12 hour assimilation window. Those coloured red (for USPS) and blue (for EPS) are observed in the lattermost 3 hours of the assimilation window.

another factor is involved. In any 12-hour data assimilation window each of the polar platforms give almost complete geographical coverage as shown in figure 2. However, studies have shown (Peubey and McNally 2010) that the most influential observations are those located near the end of the 4DVAR window as these can provide a strong constraint upon the dynamical evolution of the analysis trajectory. In figure 2 the later most orbits are shown coloured red (for USPS) and blue (for EPS). For EPS (at both 00z and 12z) these data are perfectly positioned over the North Pacific Ocean to constrain initial conditions upstream of the North American continent. Employing the same argument we might expect that the positioning of the influential orbits of USPS over North America and the Atlantic Ocean (upstream of the European continent) to result in USPS having a more dominant impact upon the forecast skill for Europe. While there is a slight advantage for USPS over EPS in the day 3 European statistics (slightly more so in the radiosonde verifications not shown) it is not a significant advantage and by day 5, EPS is again the dominant platform. This may result from many of the USPS influential orbits being located over the North American land surface where the use of satellite data is significantly restricted.

Finally we see that in all areas and at all ranges the very data rich *control* system (grey bars) produces better forecasts than the two satellite *baseline*. The increase in skill is typically of a similar magnitude to that lost when a single satellite is removed from the *baseline* and suggests that there are measurable benefits from flying more than two polar orbiting satellites.

Tropical Regions

The results for the Tropics (defined as 20N to 20S) are shown in figure 3 and indicate that forecasts are significantly less sensitive to the presence of polar orbiting satellite data than was found in the extra-Tropics. For vector wind at 850hPa we generally see much smaller losses of skill (less than 5%) even when both polar orbiting satellites are removed. There is also a much weaker compensation evident – the loss of a single satellite typically resulting in about half of the loss skill of removing both satellites. For relative humidity the only strong sensitivity to losing the polar orbiting satellites is seen in the short range (day 1) at 850hPa. Indeed the loss of skill from removing one satellite is roughly the same magnitude as that from removing two, which in turn is similar to the skill difference between the *baseline* and the data rich *control*. The latter suggests that data present in the *control*, but not in the *baseline* (most likely the microwave imagers TMI and SSMI) have a strong impact upon the forecasting of low level humidity.



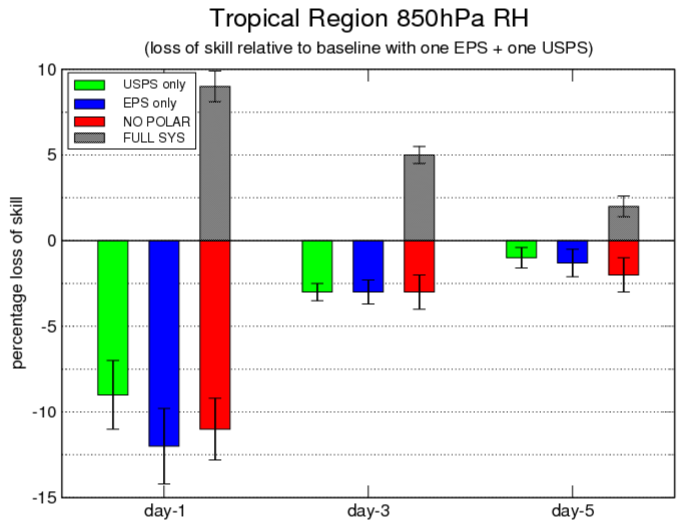


Figure 3: Percentage loss of forecast skill with degraded observing systems (relative to the baseline) for 850hPa vector wind and relative humidity evaluated in the Tropics (20N to 20S) The error bars indicate 5% significance intervals.

Synoptic evaluation of severe weather case studies

The test period covers three particularly interesting meteorological events that affected the North American and European regions.

The first synoptic case studied was a heavy snowfall that caused widespread disruption over Northern Europe beginning around the 17th December 2009 (figure 4). Qualitatively it can be said that all of the systems tested gave reasonably good and similar guidance as to the arrival of this event. Thus it cannot be said that the presence or otherwise of polar orbiting data played any significant role in the forecasting of this event.

The second event was another severe snow fall, this time over the East Coast of the USA (figure 5). The snow storm moved up the Eastern seaboard of the USA and caused major disruption in the Washington DC area. The sensitivity to the assimilation of polar orbiting satellites can be seen to be very different in this case. While the exact timing and intensity of the snowfall differs slightly from the verification, the system that used EPS + USPS gave an extremely good warning of the snowstorm 3 days in advance. In contrast the system with no polar orbiting data gave no warning of the event at this range (although closer to the event the signal became present). Note that the system with just EPS actually performs rather well, but the system with only USPS does not.

The final event was the landfall of cyclone Xynthia that caused a number of fatalities on the 28th February 2010 (figure 6) With both polar satellites the forecasted wind gusts 3 days ahead of landfall are much stronger compared to the assimilation systems that only use one satellite (EPS or USPS), but in this case the system with no polar satellites actually gave some good indication of the approaching storm. However, between the various systems tested there was a high degree of inconsistency between the forecasts of different ranges and it is difficult to make any clear conclusions about the role of polar orbiting satellites in the prediction of this wind storm.

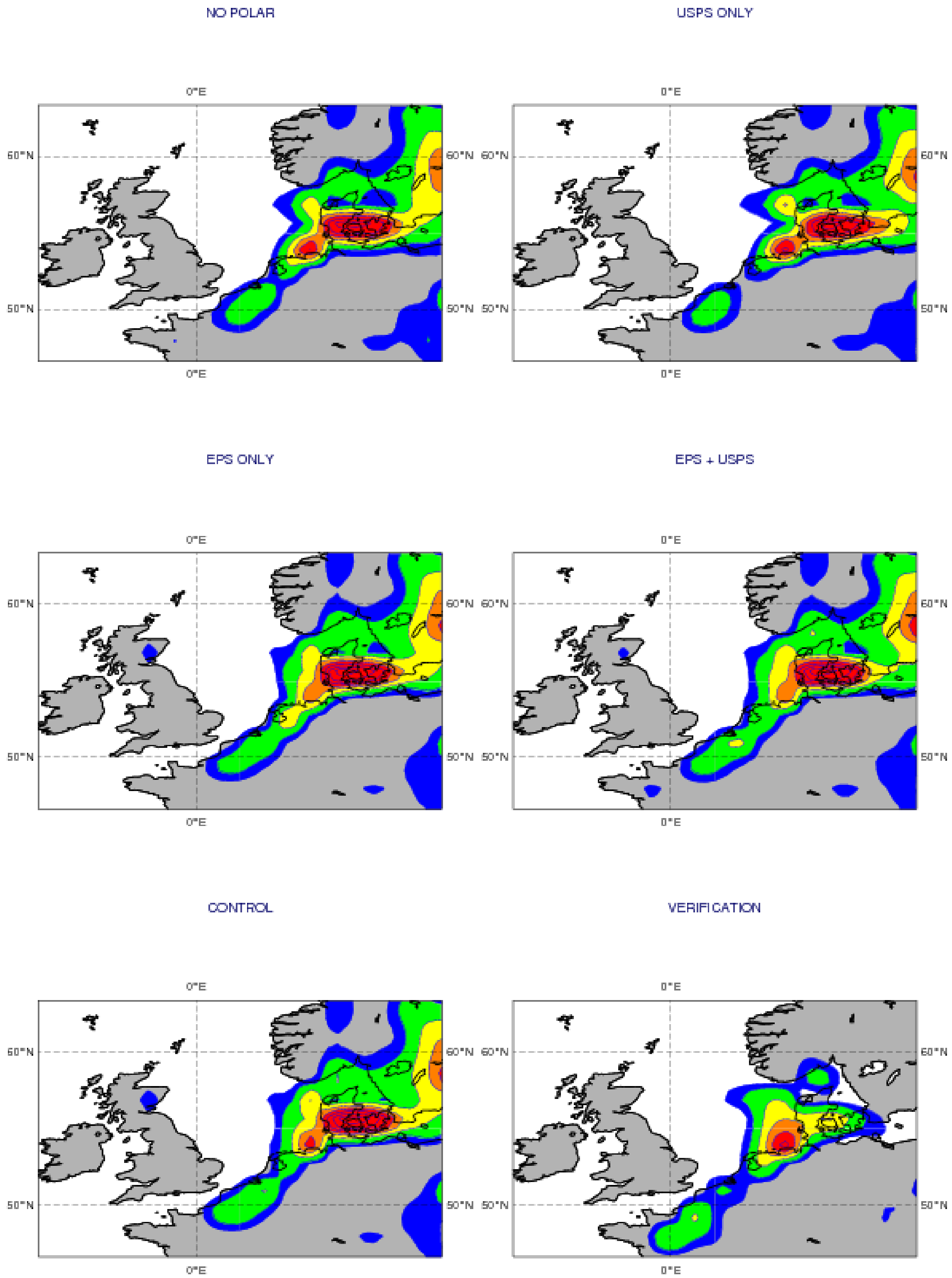


Figure 4: Snowfall forecasts over Northern Europe 3 days in advance of the 17th December 2009 at 12z, from the assimilation system with no polar satellites (upper left), just USPS (upper right), just EPS (centre left), EPS + USPS (centre right), the data rich control (lower left) and verification from the ECMWF analysis (lower right). Contours start at 5cm and are at 5cm intervals. Red indicates more than 20cm.

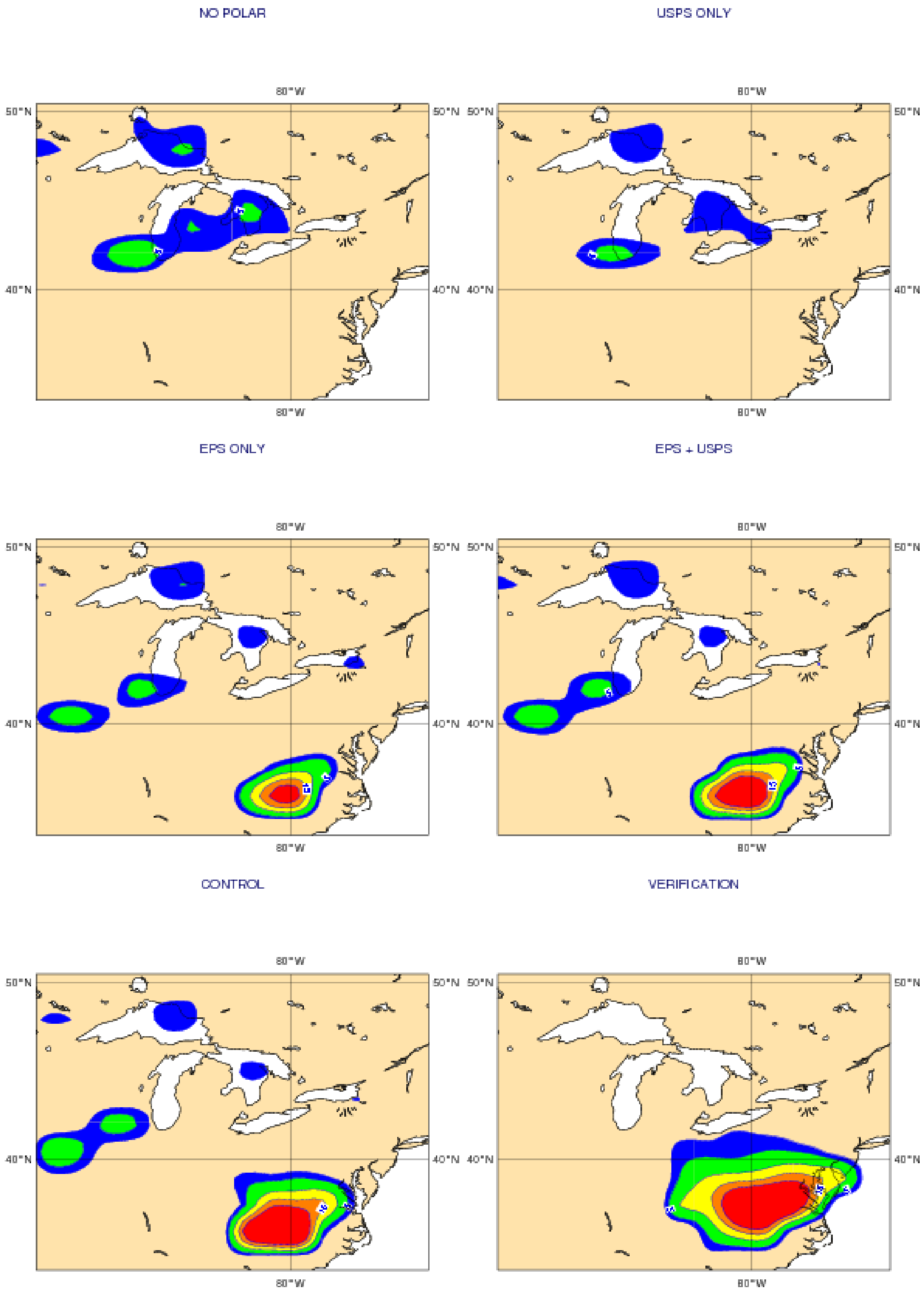


Figure 5: Snowfall forecasts over North Eastern USA, 3 days in advance of the 19th December 2009 at 12z, from the assimilation system with no polar satellites (upper left), just USPS (upper right), just EPS (centre left), EPS + USPS (centre right), the data rich control (lower left) and verification from the ECMWF analysis (lower right). Contours start at 5cm and are at 5cm intervals. Red indicates more than 20cm.

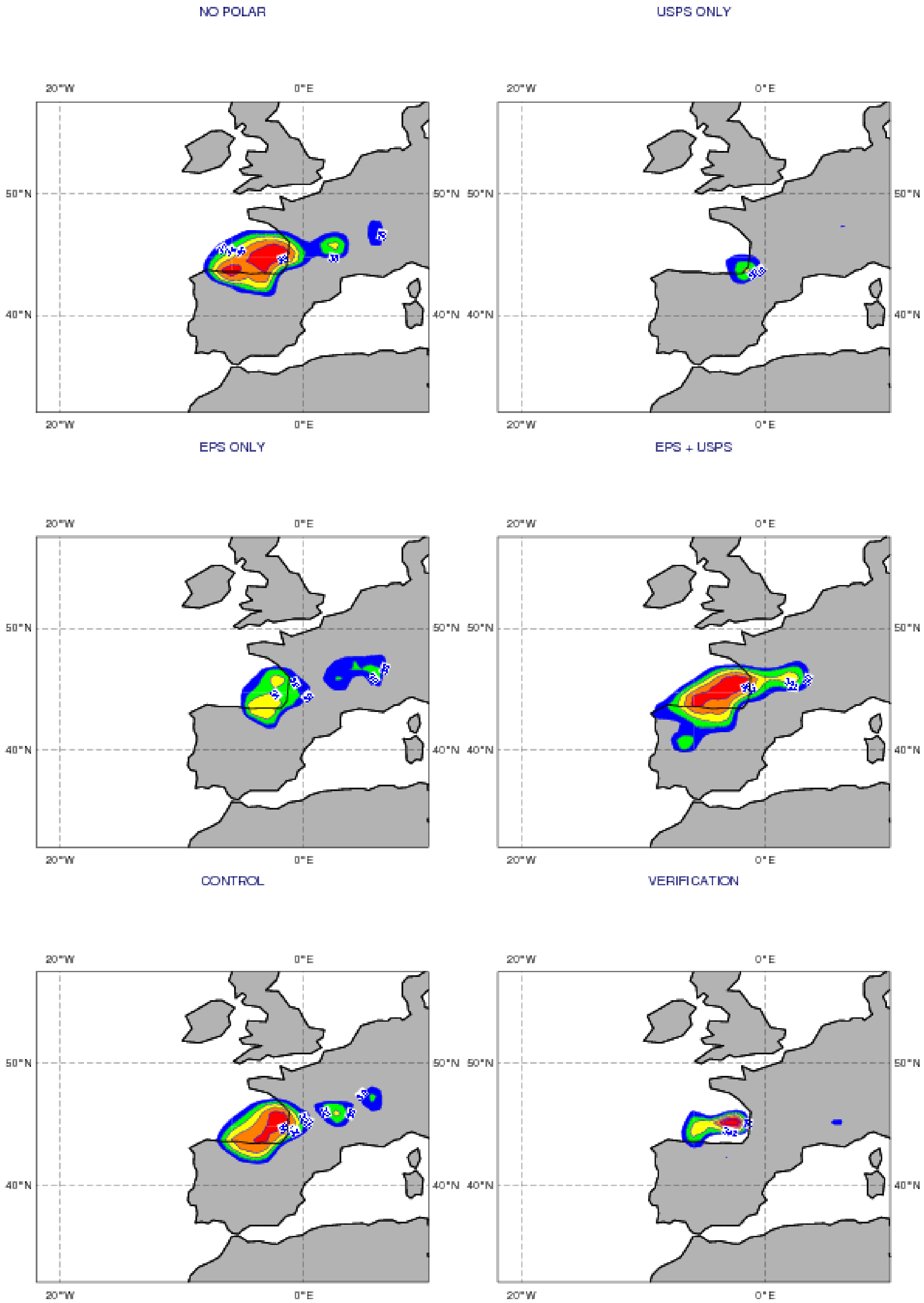


Figure 6: Forecasts of maximum surface (at 10m) wind gusts (m/s) made 3 days in advance of the 00z on the 28th February 2010, from the assimilation system with no polar satellites (upper left), just USPS (upper right), just EPS (centre left), EPS + USPS (centre right), the data rich control (lower left) and verification from the ECMWF analysis (lower right). Contours start at 20m/s and are at 5m/s intervals. Red indicates more than 40m/s wind gusts.

Diagnostics from the data assimilation system

Apart from providing initial conditions for forecasts atmospheric analyses are becoming increasingly important in their own right. Atmospheric process research, environmental monitoring and climate studies require high quality estimates of the complete atmospheric state. When important components of the observing network are withheld from the data assimilation system we expect the quality of the resulting atmospheric analyses to degrade. A well established diagnostic indicating the quality of the analysis is the fit to radiosonde wind and temperature observations. While these are not *independent* – as they are actively assimilated – these data are arguably the best available in situ detailed measurements of the atmospheric state. In the scenarios tested only the loss of both polar satellites produces a significantly degraded fit to radiosonde observations. This is shown in figure 7 for temperature and wind in the Southern Hemisphere (where the degraded fit is most evident). It is clear that the polar satellite data are not only constraining random errors in the assimilation system, but that large biases also develop when the satellite data are not available (while not shown, these biases are also seen in degraded Northern Hemisphere and Tropical radiosonde fits and are most likely due to systematic errors in the NWP model). For humidity, the loss of both polar satellites slightly degrades the random fit of the analysis to radiosonde humidity measurements, but in contrast it significantly improves the mean fit to these data in the Tropics (figure 7). Results from the single satellite removal experiments suggest that the majority of this drying of the mean analysis occurs with the USPS satellite – the only platform providing microwave imager radiances. This result is consistent with previous studies that show the all-sky assimilation of these data systematically drying the analysis (Geer 2010).

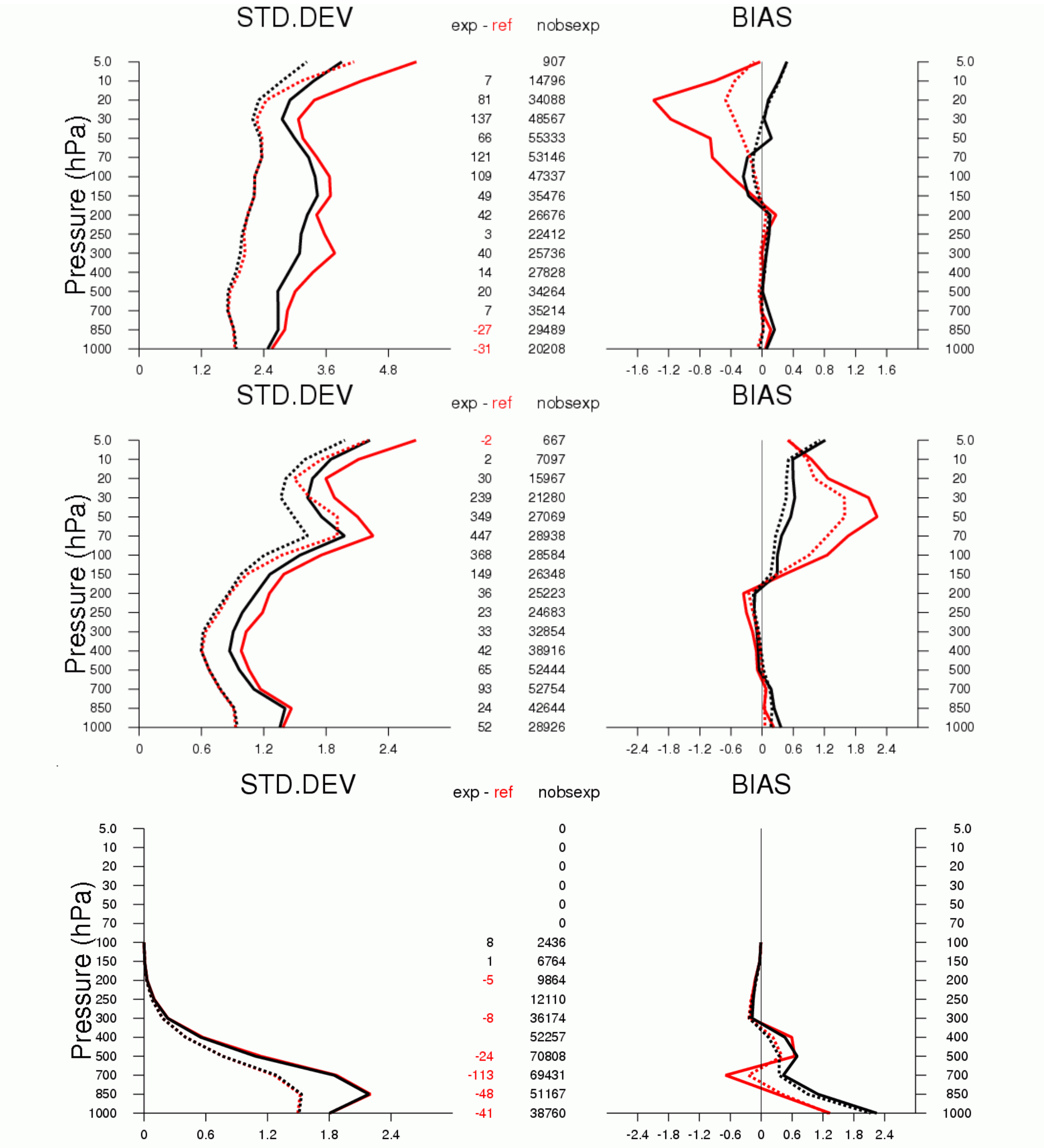


Figure 7: Short-range forecast (solid lines) and analysis (dotted lines) fits to radiosonde observations for the assimilation system with no polar satellites (red) and the assimilation system with EPS + USPS (black). The Upper panel shows Southern Hemisphere wind data (m/s), the centre panel shows Southern Hemisphere temperature data (K) and the lower panel shows Tropical humidity data (g/Kg)

Summary and Conclusions from the study

The presence of the polar satellites in this study has a clear and unambiguous positive impact on forecast accuracy as measured by the headline skill scores averaged over this three-month period. The simultaneous loss of both EPS and USPS would be expected to result in a significant and damaging loss of medium range forecast accuracy, 10% for Europe and North America (roughly equivalent to 12 hours of lost useful predictability) and around 30% for the Southern Hemisphere (roughly equivalent to 24 hours of lost useful predictability). These figures should be appreciated as significant - historically, the combination of enhanced observing systems, model development and increased computer power has led to average gains of just 1 day of useful predictive skill per decade.

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The synoptic case studies clearly demonstrate that the medium range forecasting of high impact weather events can be very sensitive to the available satellite observing systems. In one case (the Washington snowstorm) the loss of polar satellites results in a failure to give guidance of the event 3 days in advance – whereas a good prediction is made when the satellites are assimilated. However, from the other cases studies there is probably not sufficient evidence to conclude that the presence of polar orbiting satellites produced unambiguously better forecasts.

This impact study has been performed over a three-month period, leading to a statistical population of 178 forecast cases (00Z and 12Z). A more comprehensive period of investigation would be needed to perform a full assessment of these hypothetical scenarios (e.g. seasonal dependence). This would have required time and resources that were not available at the time of this study. However, the large and significant (as indicated by the error bars accompanying the score charts) signals emerging from this study give us confidence in the robustness of the results presented in this report.

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