TECHNICAL MEMORANDUM

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The Role of Satellite Data in the Forecasting of Hurricane Sandy

Tony McNally, Massimo Bonavita and Jean-Noël Thépaut

Research Department

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European Centre for Medium Range Weather Forecasts
Shinfield Park, Reading, Berkshire RG2 9AX, England

Summary

The excellent forecasts made by ECMWF predicting the devastating landfall of Hurricane Sandy attracted a great deal of publicity and praise in the immediate aftermath of the event. The almost unprecedented and sudden 'left hook' of the storm towards the coast of New Jersey was attributed to interactions with the large-scale atmospheric flow. This led to speculation that satellite observations may play an important role in the successful forecasting of this event.

To investigate the role of satellite data a number of experiments have been performed at ECMWF where different satellite observations are deliberately withheld and forecasts of the hurricane re-run. In each denial experiment the assimilation system cycles for five days without the withheld observations prior to re-launching the key forecast from 00 UTC on 25 October. All tests are performed at full operational resolution (T1279).

Without observations from geostationary satellites the correct landfall of the storm is still reasonably well predicted albeit with a slight timing shift compared to the control forecast. On the other hand without polar-orbiting satellites (which represent 90% of the volume of currently ingested observations) the ECMWF system would have given no useful guidance four to five days ahead that the storm would make landfall on the New Jersey coast. Instead the hurricane is predicted to stay well offshore in the Atlantic and hit the Maine coast 24 hours later. If background errors estimated from the ECMWF Ensemble of Data Assimilations (EDA) are allowed to evolve and adapt to the depleted observing system, then some of the performance loss suffered by withholding polar satellite data can be recovered. The use of the appropriate EDA errors results in a more enhanced use of geostationary satellite observations, which partly compensates for the loss of polar satellite data.

1 Introduction

Hurricane Sandy devastated areas of the Caribbean and the numerous locations along the Eastern Seaboard of the United States and Canada in late October 2012. It has been designated the largest Atlantic storm on record (reaching a diameter of over 1500 Km) and at its most intense had a central core pressure of 940hPa. The storm is thought to have been responsible for the loss of over 250 lives and caused over 60 billion US dollars of damage.

It is generally accepted that this storm was well forecasted by all of the major NWP centres allowing preparations to be made that undoubtedly saved lives. However, the fact that ECMWF gave an early indication that the storm would take a sharp westward turn and make landfall in the Mid-Atlantic States, attracted a lot of attention in the media (particularly in the US). Some warning signals could be seen in ECMWF forecasts seven or eight days in advance and by five days out (on the 25th October at 00UTC) there was a strong convergence between the high resolution forecast (HRES) and the associated ensemble system (ENS).

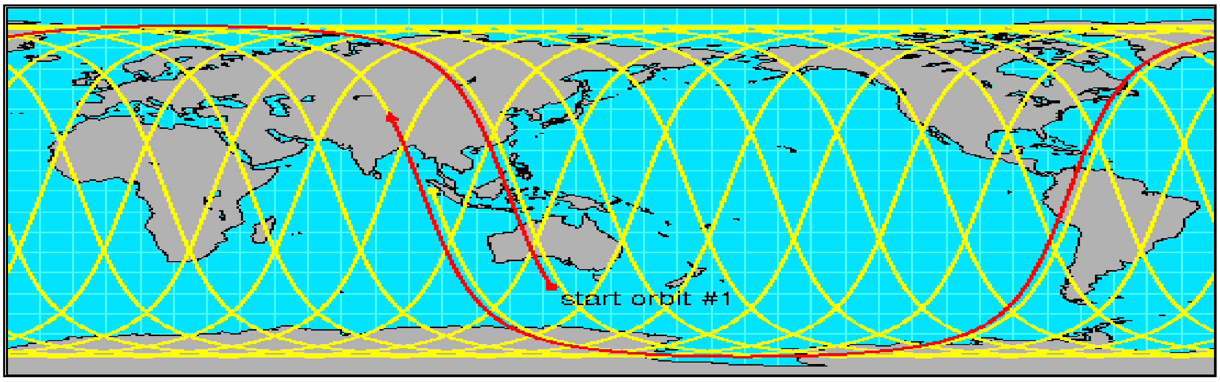
This turn (or left hook as it was dubbed in the US media) has been widely attributed to the interaction of the storm with large-scale weather patterns lying to the north. Thus one might expect that successful medium range predictions of the storm's path from the Caribbean to the mid-latitudes would require an accurate description of the larger scale meteorological environment. Information from the constellation of operational weather satellites gives a unique view of the large scale atmospheric conditions – particularly over oceans where very few conventional measurements are available (e.g. from balloons or aircraft). Geostationary spacecraft located 36000Km above the Earth provide near continuous measurements in the visible and infrared spectrum of low and mid-latitudes. Polar orbiting spacecraft flying at a much lower altitude (below 1000Km) provide global measurements, but at the expense of a reduced time sampling – revisiting the same location typically only twice per day. However, multiple polar satellites can collectively provide information four to six times per day for a given region.

Observing System Experiments (OSEs) are classically used to assess the value of observations in a given Numerical Weather Prediction (NWP) system. They usually consist in denying (adding) a given set of observations from (to) a baseline Observing System scenario, and provide a measure of the impact of these observations on the weather forecast skill. OSEs can be run to assess the value of observations in specific regions of the globe (Kelly et al., 2007), to document the respective contribution of different observation types on the average quality of the forecasts (Bouttier and Kelly, 2001, Bauer and Radnoti, 2009) or to look at the impact of a specific dataset on the forecast of particular weather systems during field campaign experiments (Harnisch and Weissman, 2010, Harnisch et al., 2011).

In this paper, we have adopted a standard OSE framework to test the sensitivity of the ECMWF forecasts of Hurricane Sandy to the denial of geostationary satellite data and the denial of polar orbiting satellite data.

2 Data from Polar orbiting Spacecraft

Polar orbiting spacecraft circle the Earth at altitudes typically below 1000km and carry numerous active and passive sensors to observe the atmosphere and surface (listed in figure 1). With these spacecraft the main emphasis is making measurements at all latitudes with very fine detail (spatial and vertical resolution), but this is achieved at the expense of temporal resolution. A satellite may make measurements from the same location just once or twice per day. However, increasingly the same sensors (e.g. the Advanced Microwave Sounding Unit AMSU) are carried on multiple polar platforms so that similar measurements (albeit not from the same satellite) are obtained from a given location many times per day. At very high latitudes the time sampling from polar satellites is extremely high – with the same satellite returning typically every 100 minutes.



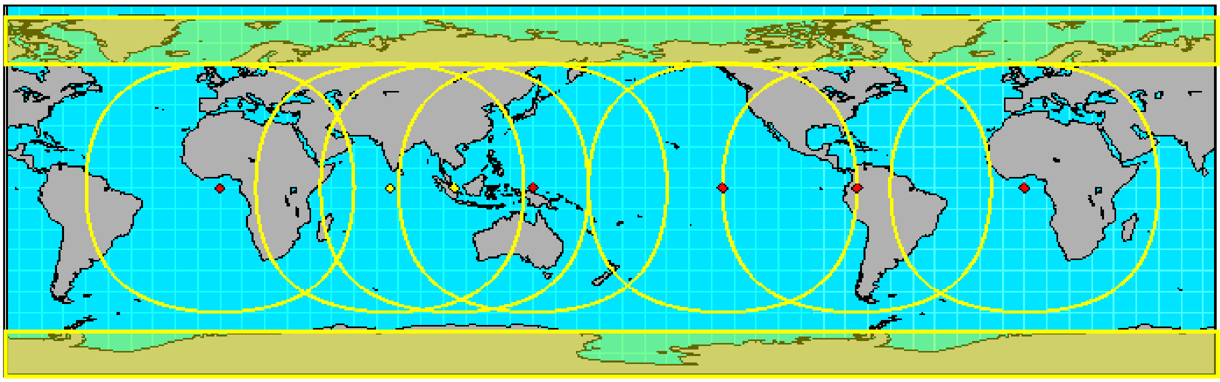
Type	Sensors	Satellites
Infrared Sounding	AIRS, IASI, HIRS (x 2)	AQUA/NOAA/METOP
Microwave Sounding	AMSUA/ATMS (x 7), AMSUB/MHS (x 3)	AQUA/NOAA/METOP
Microwave Imagers	TMI, SSM/IS, AMSRE	TRMM/DMSP/AQUA
SCAT	ASCAT	METOP
GPSRO	GRAS, COSMIC, TERRA-SAR	METOP/VARIOUS GPS NODES

Figure 1 The coverage of polar orbiting satellites and sensors used operationally at ECMWF in October 2012

The heterogeneous array of highly sophisticated sensors carried by polar orbiting spacecraft provides complementary observations. Microwave and infrared sounders and imagers provide information on temperature and humidity with very high spatial resolution by measuring emitted radiation along nadir or near-nadir paths. However, the vertical resolution that can be obtained is rather limited. In contrast GPS radio occultation sensors provide similar information over broader horizontal scales, but with very fine vertical resolution. Active scatterometer instruments provide ocean wind speed information which is useful in its own right, but also assists the interpretation of surface emitted radiation measured by passive sensors. For infrared and microwave sounding (and imager) data radiance measurements are assimilated directly. For the GPS data bending angles are assimilated and for the scatterometer, ambiguous (multi-angle) winds are used.

3 Data from Geostationary Spacecraft

Geostationary spacecraft orbit the Earth at an altitude of 36,000 km and tend to carry just one passive infrared and visible sensor. With these spacecraft the main emphasis is making measurements at low to mid latitudes with very fine spatial scale and very high (near continuous) temporal resolution. However, high latitudes are not measured at all and the geostationary sensors are restricted to visible and infrared sounders with very poor spectral resolution. This limits their ability to make any measurements at all below clouds and even in clear sky the temperature and humidity information has much poorer vertical resolution than that provided by sensors carried on polar platforms. However, the very high temporal sampling allows the motion of atmospheric features such as clouds and water vapour to be tracked very accurately to provide wind information. This tracking is done explicitly by the data provider particularly in cloudy conditions) to produce Atmospheric Motion Vectors (AMVs) or implicitly by the data assimilation scheme (mainly in clear conditions) using time sequences of geostationary radiance measurements. For the purpose of this study AMVs derived from frequent polar orbiting satellite imagery at the poles are grouped together with geostationary AMVs. While these are obviously not geostationary data, NWP systems have tended to make use of the polar and GEO AMVs as a combined data set.



Type	Sensors	Satellites
Atmospheric Motion Vectors	SEVIRI, MVIRI, GOES-I (x2) , MTSAT, AVHRR, MODIS	METEOSAT, GOES, MTSAT, AQUA, TERRA, METOP, NOAA
Geostationary Radiances	SEVIRI, MTSAT, GOES-I (x2)	METEOSAT, GOES, MTSAT

Figure 2: The coverage and measurements / sensors on geostationary spacecraft plus polar AMVs

4 Details of the Satellite Denial Experiments

The experiments have been conducted using the current operational version of the ECMWF forecasting system (CY38R1) with 91 levels in the vertical (up to 0.01hPa) and a horizontal resolution of T1279 (typical grid spacing of 16Km). The initial conditions for the forecast model come from a 12 hour window incremental 4D-Var data assimilation system with T1279 outer loop resolution (used to compare observations with model forecasts) and T159 and T255 inner loop minimizations. It should be noted that this is not identical to the ECMWF daily operational forecast that is based on early-delivery suite, (short cut off 6 hour 4D-Var nested with delayed cut off 12 hour 4D-Var.

A control system has been run that uses all operationally available conventional observations (from the surface, balloons, ships and aircraft) and satellite observations (polar and geostationary). It has been verified that the control forecasts in this study (using initial conditions from a 12 hour window incremental 4D-Var) are almost identical to those produced operationally at the time of Hurricane Sandy (by the early delivery suite configuration of 4D-Var).

In the denial experiments (henceforth NOPOLAR and NOGEO) the respective observations are deliberately withheld from 00UTC on 20th October 2012 onwards. The NOPOLAR experiment removes all polar orbiting satellite observations (except polar AMVs) and the NOGEO experiment removes all geostationary data (as well as polar AMVs). The systems are then cycled without these data for five days until the 25th October at 00UTC after which forecasts are launched each day until the landfall of the Hurricane (on the 30th October). These particular dates are chosen as the five day operational forecasts from the 25th October (both high resolution and ensemble) were the first to accurately and consistently predict the exact timing and location of the landfall on the New Jersey coast.

5 Impact of satellite data denials on the analysis

Figure 3 shows how the NOPOLAR and NOGEO surface pressure analyses have deviated from the control after five days of cycling without observations. As expected, the analysis without polar orbiting data exhibits more extensive differences than when geostationary data are denied. Changes in the immediate vicinity of the storm are rather modest – with just a 1 hPa to 2 hPa weakening of the original tropical cyclone near Cuba. In the North Pacific the absence of polar satellite data causes a weakening of an extra-tropical depression – again by just 1 hPa to 2 hPa, but over a much wider area.

The changes to the analysis that result from the denial of geostationary data are much less. There is a similar weakening of the tropical cyclone near Cuba compared to the control, but very few significant differences elsewhere.

A useful measure of how much the NOGEO and NOPOLAR systems are degraded due to the denial of satellite data is found in the fit of the analyses to other assimilated observations. The fit to radiosonde wind data (both u and v components) computed over the extra-tropical Northern Hemisphere is shown in figure 4 for the two denial experiments. It can be seen that the wind field of the NOPOLAR system is substantially degraded with respect to the control (black lines) whereas the NOGEO system is almost unaffected. This demonstrates the very strong constraining effect the polar orbiting data have upon the analysis of the large scale flow and wind field – despite the fact that most of the information provided is temperature rather than wind observations. In comparison the more direct wind information provided by the geostationary data have a much weaker impact on the analysed wind field. This is in agreement with previous Observing System Experiments (OSEs) and adjoint-based studies of the relative impact of various components of the satellite observing system (Radnoti *et al.*, 2010).

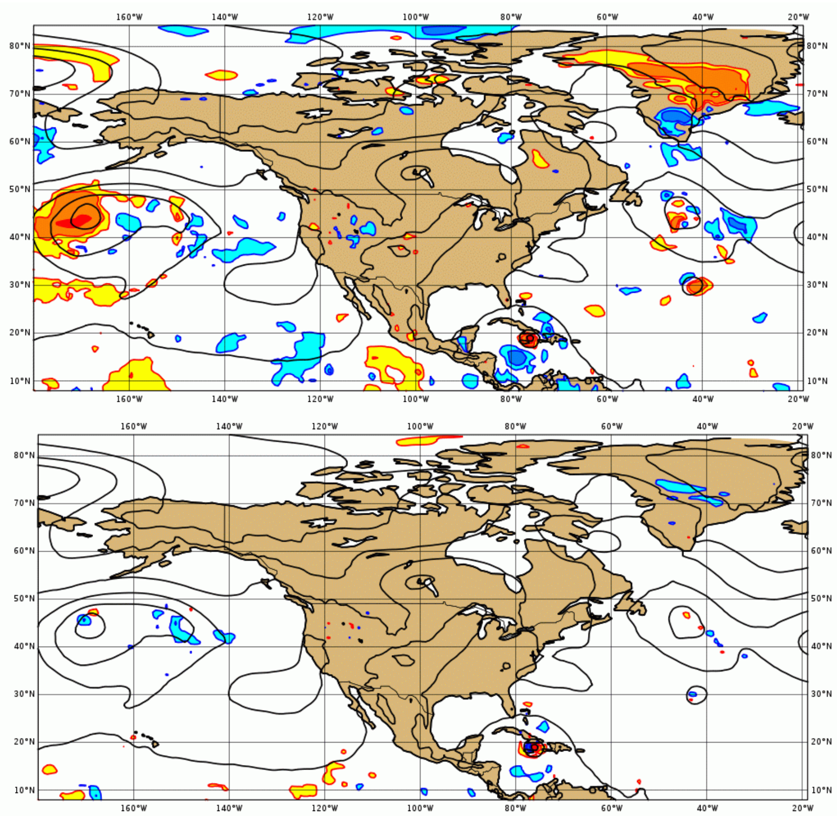


Figure 3: Differences in analysed surface pressure (experiment minus control) for the NOPOLAR (top panel) and NOGEO (bottom panel) systems on the 25th October 2013. Black contours show the control surface pressure. Red/orange (or blue/cyan) shading indicates positive (negative) differences of 1hPa and 2hPa.

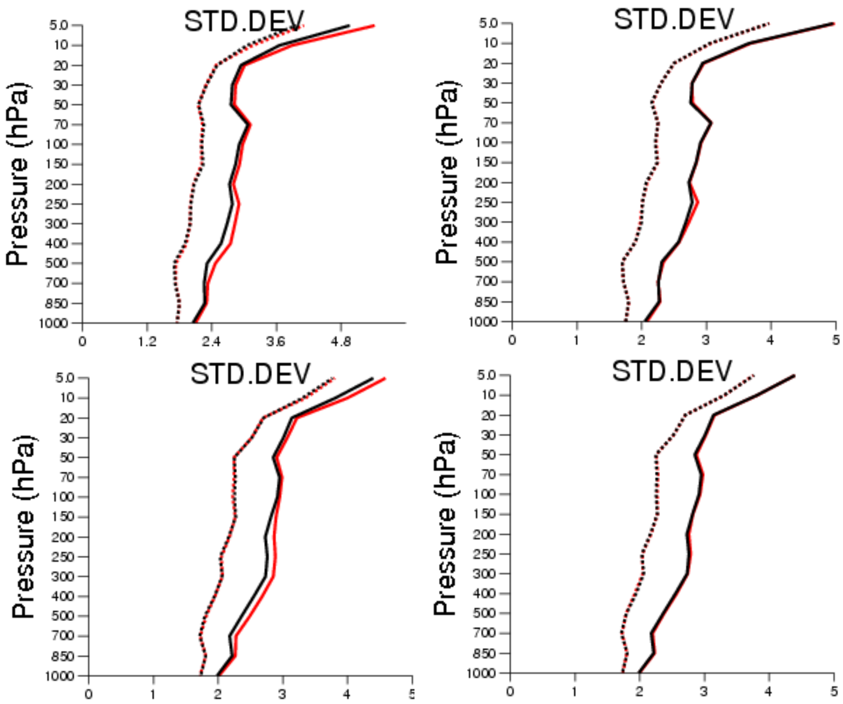


Figure 4: Standard deviation of the fit to radiosonde wind observations (U component upper panels and v component lower panels) for the NOPOLAR system (left) and NOGEO (right). In each case the fit of the denial experiment is in red and the control in black. Solid lines are for the short-range forecast and dotted lines for the analysis. The statistics are evaluated from 20th to the 25th October 2013over the region 20-90 N.

6 Impact of satellite data denials on the forecasts

Forecast have been launched from from the NOPOLAR and NOGEO analyses and compared to those of the control. Starting from the 00UTC on the 25th October, initially all three systems give a rather consistent picture of the storm exiting the Caribbean and entering the Atlantic, such that after 72 hours only very small differences can be seen between the forecasts (shown in figure 5 and 6). Even after 96 hours, while some small departures in the hurricane's forecasted position exist, the NOPOLAR and NOGEO systems are still close to the control and arguably giving useful forecasts. At 120 hours the NOGEO forecast remains very close to the control and it correctly predicts the landfall of the storm (albeit with a very slight timing error) on the New Jersey coast at 00UTC on 30th October. However, at this forecast range the NOPOLAR system deviates dramatically from the control and fails to capture the sudden westward turn of the storm to impact the coast. It keeps the hurricane position well offshore in the Atlantic and 36 hours later (not shown) it goes on to hit the Maine seaboard some 800 km to the north. In figure 5 significant differences can be seen not only in the position of the storm after 120 hours, but also in the large scale flow in the immediate vicinity. In particular the trough - ridge wave structure to the west and north has a significantly stronger amplitude in the NOPOLAR

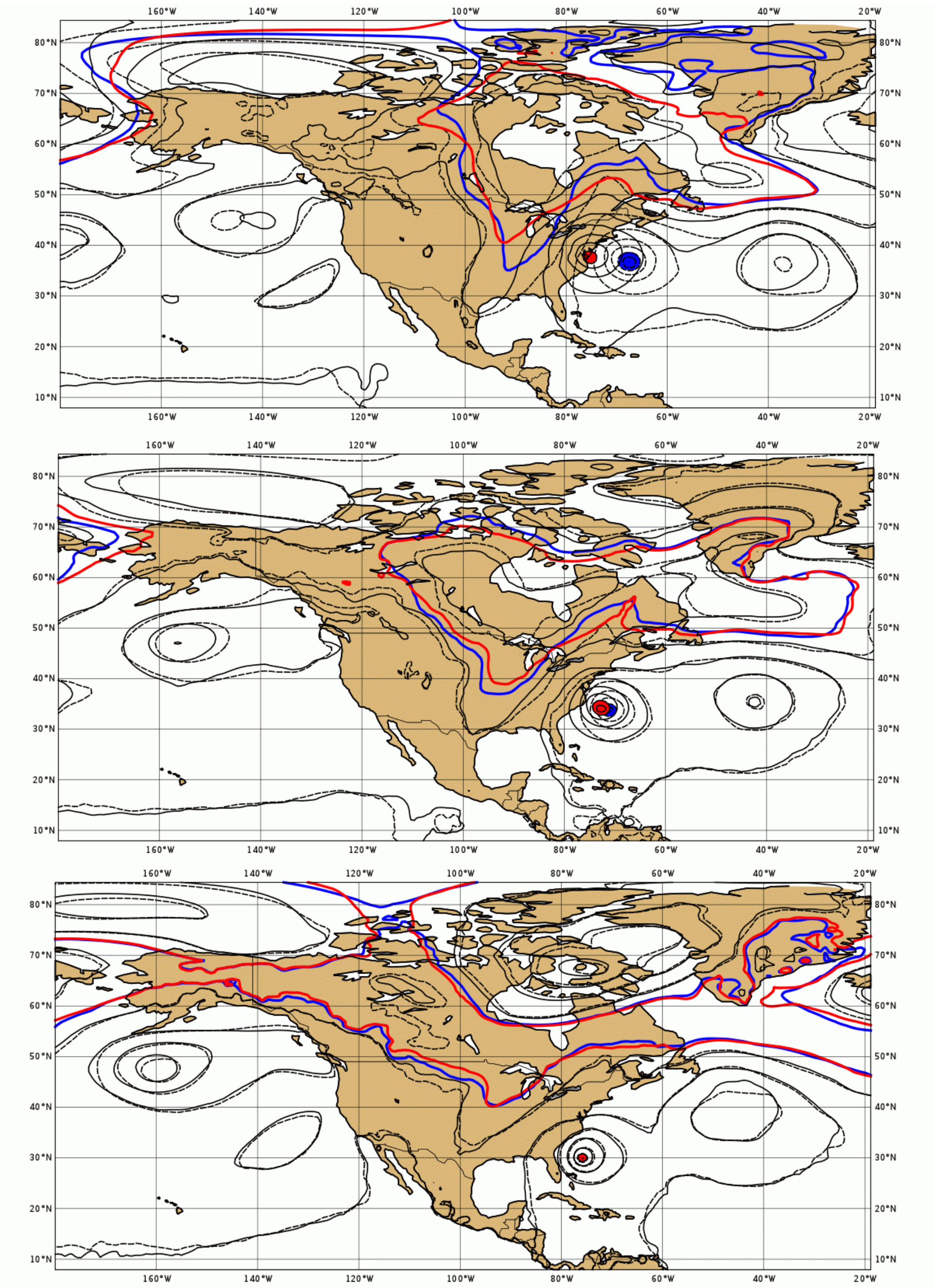


Figure 5: Forecasts of surface pressure launched from 25th October 2013 for the NOPOLAR experiment (dash black contours at 10hPa intervals with blue highlight at 1025hPa and blue shade below 970hPa) and CONTROL system (solid black contours at 10hPa intervals with red highlight at 1025hPa and red shade below 970hPa. Bottom panel shows 72 hour forecast, middle 96 hour forecast and upper panel 120 hour forecast.

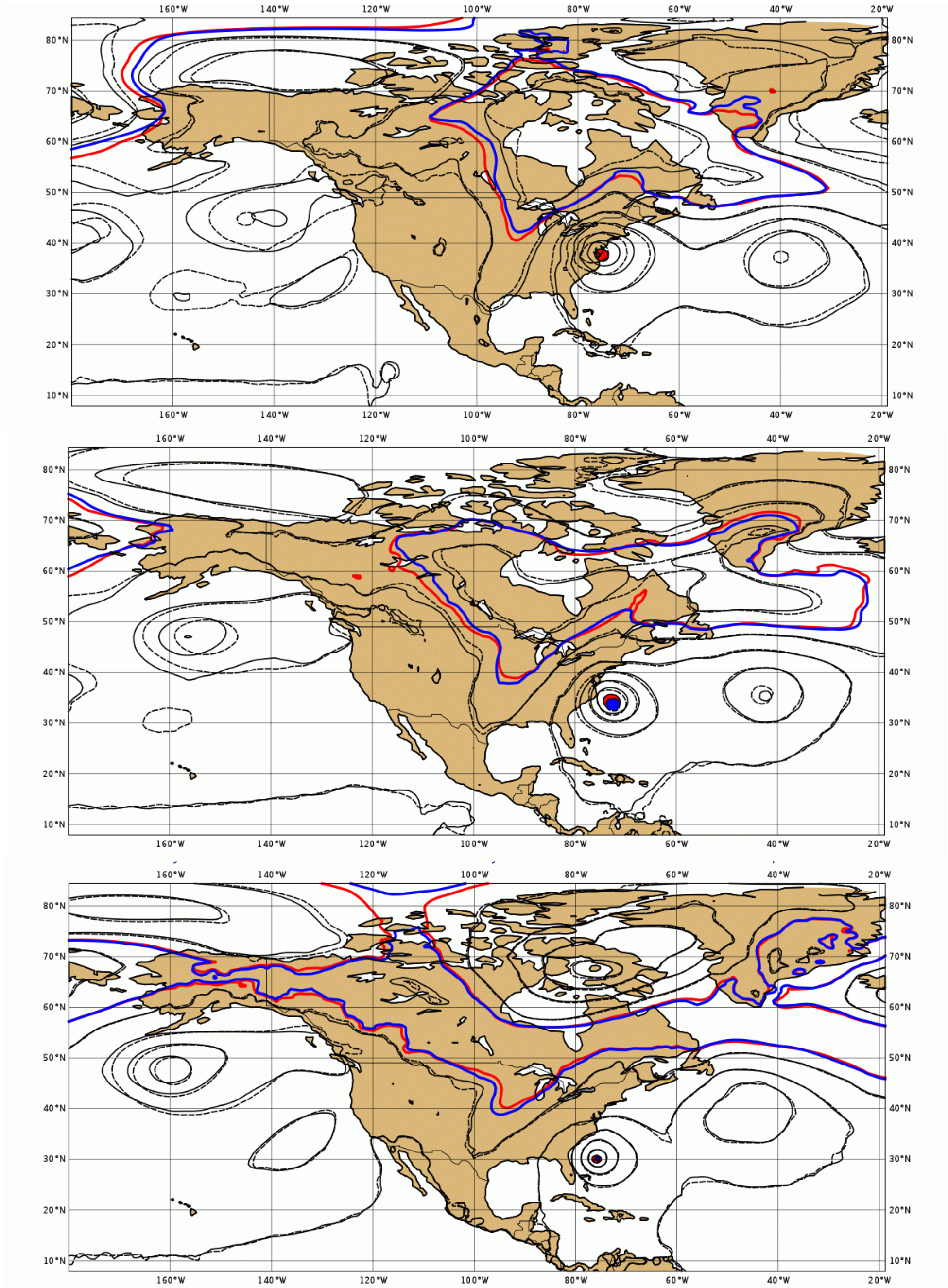


Figure 6: Forecasts of surface pressure launched from 25th October 2013 for the NOGEO experiment (dash black contours at 10hPa intervals with blue highlight at 1025hPa and blue shade below 970hPa) and CONTROL system (solid black contours at 10hPa intervals with red highlight at 1025hPa and red shade below 970hPa. Bottom panel shows 72 hour forecast, middle 96 hour forecast and upper panel 120 hour forecast.

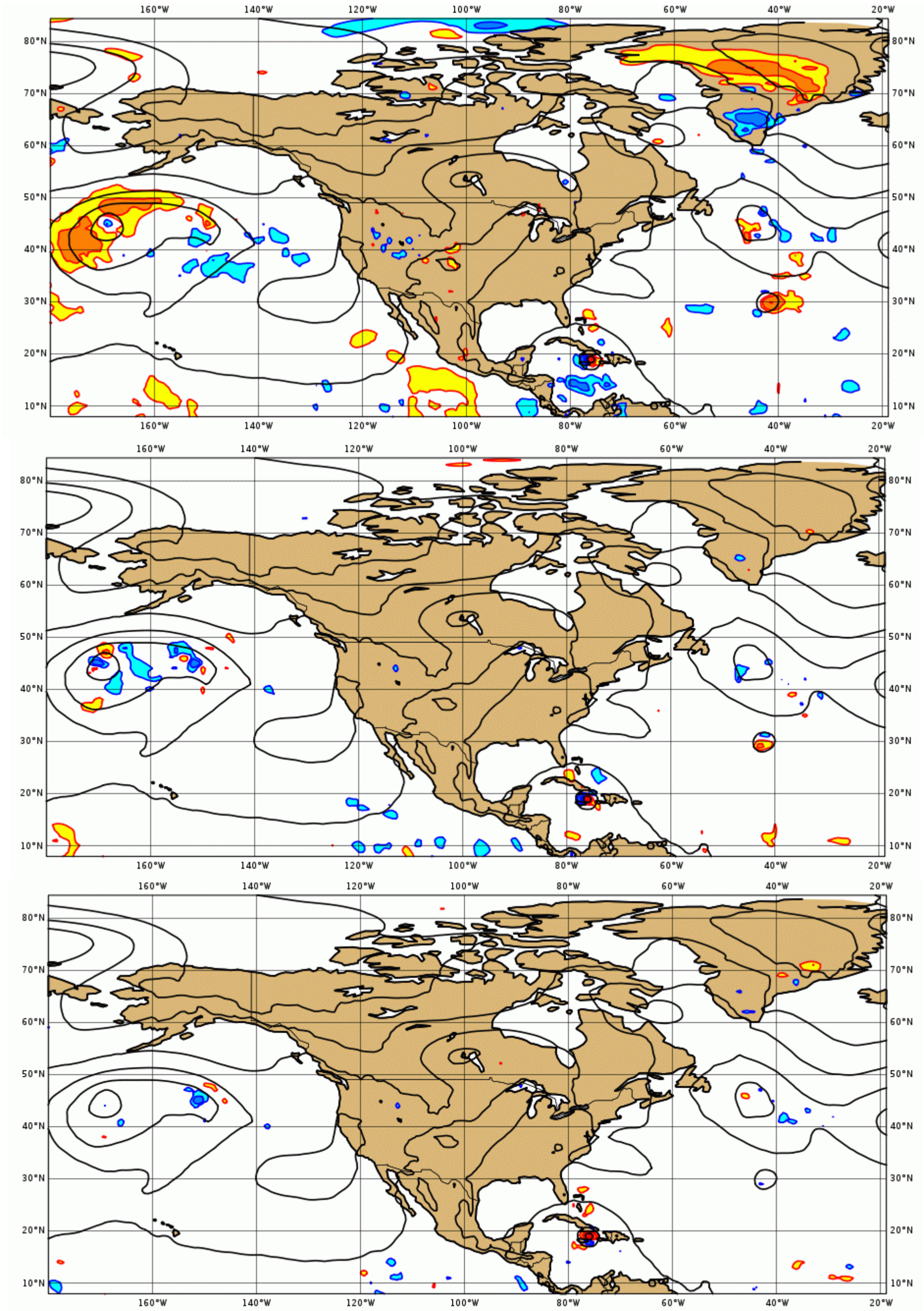


Figure 7: Differences in analysed surface pressure (experiment minus control) for the NORAD (top) NOSCAT (middle) and NOGPS (bottom) systems on the 25th October 2013. Black contours show the control surface pressure. Red/orange (or blue/cyan) shading indicates positive (negative) differences of 1hPa and 2hPa.

system compared to the control as indicated by the highlighted red and blue 1025hPa isobars. Tracing the origin of this wave amplification back in time shows that it is associated with the weakening of the North Pacific depression five days earlier in the initial conditions of the NOPOLAR system (figure 3).

Shorter-range forecasts of the storm have been examined but results are not shown. In brief the failure of the NOPOLAR five day forecast is repeated again in the four day forecast from the next day (00UTC on the 26th October). Only three days out from the event does the NOPOLAR system predict the correct landfall of the storm. The control and the NOGEO forecasts are consistent and accurate at all ranges from five days and shorter until the event happens on the 30th October.

Longer-range forecasts have been examined, but are also not shown here. As discussed in the introduction - the control system from seven days onwards gives a reasonably consistent indication that the storm will make landfall somewhere on the eastern seaboard, with decreasing errors in timing and location between successive forecasts. The NOGEO forecasts are rather similar to the control while the NOPOLAR system only starts to suggest a landfall trajectory 6 days before the event, but with large errors in both timing and location.

7 Individual instrument denial experiments

Additional experiments have been performed in the context of Hurricane Sandy. Given the strong sensitivity to removing all polar orbiting satellite observations, individual data types have been withheld to investigate if any single element was key to the successful prediction (or more precisely identify if losing any single element would reproduce the failure of the NOPOLAR system). The impact of individually removing microwave and infrared radiance observations (NORAD), GPS radio occultation data (NOGPS) and finally scatterometer winds (NOSCAT) upon the analysis quality and forecasts was tested. After five days of cycling (as before from the 20th to the 25th October) the NORAD system demonstrates the most significantly degraded analysis. Indeed it can be seen in figure 7 that the NORAD denial accounts for a large proportion of the changes seen in the degraded initial conditions of the NOPOLAR system (figure 3). The NOSCAT and NOGPS denials result in smaller changes to the analysis, but importantly these are located in the vicinity of the depression in the North Pacific (particularly in the case of the NOSCAT experiment). However, the five day forecast of all three experiments launched from 25th October correctly predicts the timing and location of the storm landfall (i.e. no single data denial reproduces the forecast failure of the NOPOLAR system).

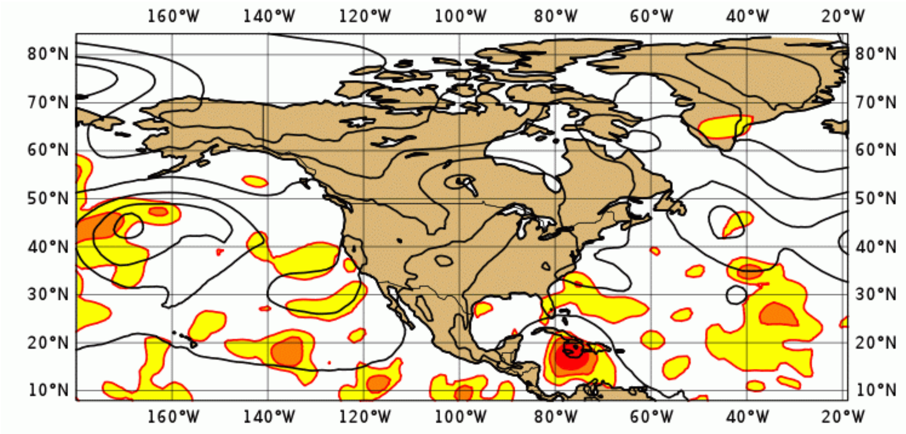
8 Denial experiments with modified background errors

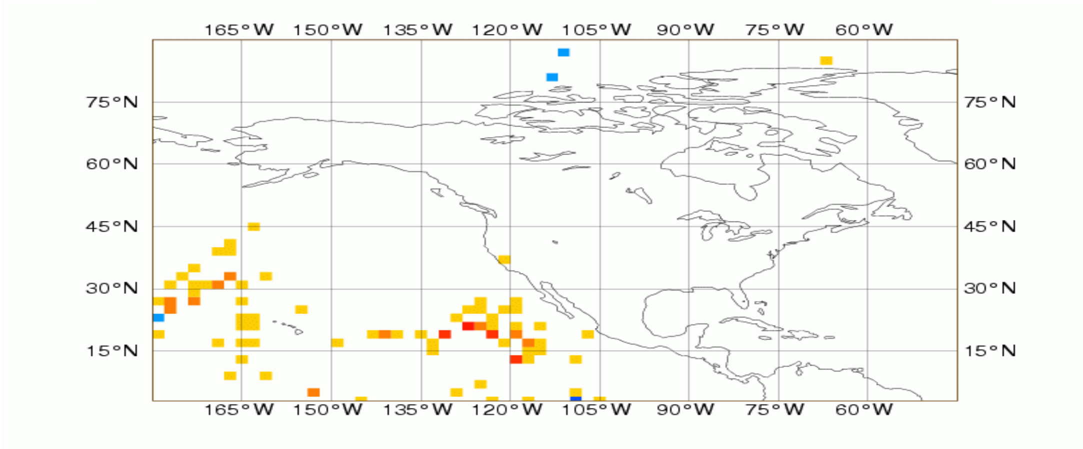
ECMWF runs an Ensemble of Data Assimilations (EDA; Isaksen et al., 2010; Bonavita et al., 2012) in parallel to the main high resolution assimilation and forecasting system. The main purpose of the EDA is to estimate uncertainty in the analysis and in the short-range forecast that is used as a background estimate of the atmospheric state in the ECMWF 4DVAR. Uncertainty is parameterized by randomly perturbing the model physics as well as applying random perturbations to the input observations. This produces background error with spatial variations that not only reflect changes in different meteorological conditions, but also changes related to the distribution and density of available observations. For practical and computational reasons observing system experiments (OSEs) are usually performed using background errors from the operational system (and this was the case for all the experiments described so far in this study). This is obviously sub-optimal, but arguably a reasonable approximation when the changes to the observing system are small. However this is clearly not the case for the NOPOLAR experiment where roughly 90% of the total volume of assimilated observations over ocean are removed. In this case the operational background errors are unlikely to describe those of the significantly depleted system. Thus the NOPOLAR experiment has been re-run using background errors from a consistent EDA which is cycled without polar satellite data (henceforth NOPOLAR-EDA).

Like the experiments described in the previous section, the 4DVAR data assimilation experiments were run without the polar satellite data from the 20th October, but after each 12 hour assimilation window the background errors are recomputed from the spread of the 10 member EDA (where each individual member has the polar data removed). After five days without the polar satellites, background errors have evolved to larger values than the operational background errors (on average 50% larger), with the main differences found in oceanic areas, as shown in the upper panel of figure 8. The largest increase is in the immediate vicinity of the storm, but there are also changes in the North Pacific – a region previously highlighted as important in this case.

In the context of these denial experiments, larger background errors have two main consequences: Firstly more weight is given to those observations that are retained in the assimilation system (in this case geostationary satellite data and conventional data); and secondly, quality control checks based upon observation departures from the background are also effectively relaxed. The threshold for rejection is formulated as a multiple of the combined observation and background error variances – such that an increase of the latter (in response to the degraded observing system) renders observations less likely to be rejected. This effect is illustrated in the centre panel of figure 8 where the difference between geostationary AMV data coverage in the NOPOLAR and NOPOLAR-EDA is shown. More AMV data are used in the North Pacific by the NOPOLAR-EDA system, although in the vicinity of the storm there is no extra data usage. The combination of more weight being given to observations and extra data being used results in analysis differences between the NOPOLAR and NOPOLAR-EDA systems shown in the lower panel of figure 8. Changes are generally rather small and certainly less than those seen between the NOPOLAR and control system (note that the contour interval of figure 8 is half that of figure 3). However, the changes are located in the dynamically active area in the North Pacific which was previously identified as important for the correct forecast of the cyclone track.

When the modified NOPOLAR-EDA analyses are used as initial conditions there is a significant impact upon the forecasts of the storm. Figure 9 shows track predictions from the NOPOLAR and NOPOLAR-EDA systems initialised on the 25th and 26th October (five and four days before landfall). It can be seen that, for the five day forecast, almost all of the accuracy lost due to the denial of polar satellite is recovered by the NOPOLAR-EDA system – the forecast being almost as good as the control. Figure 10 illustrates the downstream propagation of small differences in the NOPOLAR-EDA analysis of the North Pacific depression on 25th October 00UTC, dramatically affecting the forecast of





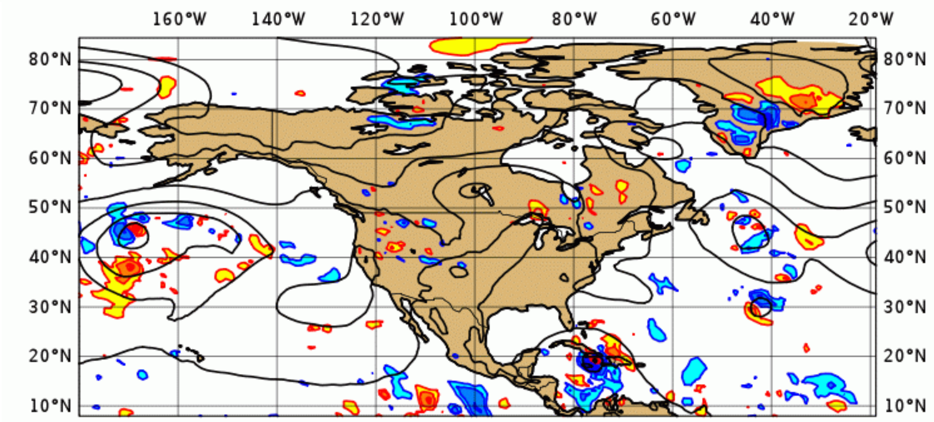


Figure 8: Changes between the NOPOLAR and NOPOLAR-EDA systems on 25th October at 00UTC. Upper panel background error for 700hPa wind (contours at 0.5 and 1m/s). Centre panel AMV data numbers (marker colours, yellow= 1,orange= 2 and red= 5 observation increase per 1 degree grid square, blue= 1observation decrease per grid square). Lower panel analysis difference mean sea level pressure (contours at 0.5 and 1hPa).

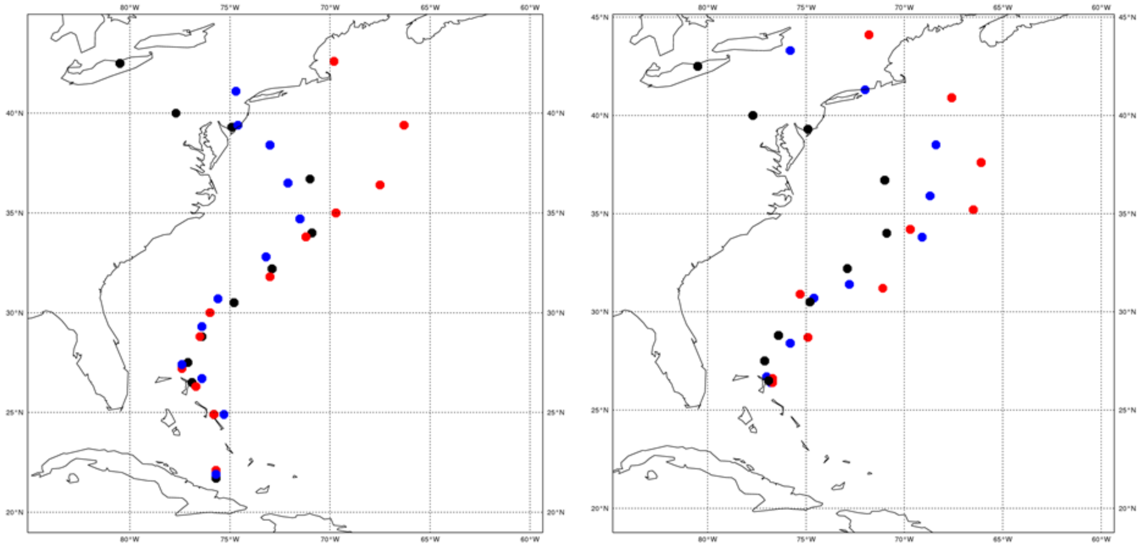


Figure 9: Forecast tracks of Cyclone Sandy from the 25th October 00UTC (left) analysis and from the 26th October 00UTC analysis (right) for NOPOLAR (red) and NOPOLAR-EDA (blue) experiments. Black dots represent Sandy's best track estimate.

Sandy's five days later. Unfortunately such a remarkable improvement is not repeated in the four day forecast (from the 26th October), but the NOPLAR-EDA does provide a marginal improvement over the poor NOPLAR forecast. At longer forecast ranges (six days and beyond) the use of modified background errors in the NOPOLAR-EDA system does not produce better predictions of the storm.

9 Summary and Conclusions from the study

The fact that the withdrawal of polar-orbiting satellite data introduces large time and location errors in the ECMWF forecasts of Hurricane Sandy's track illustrates the importance of these observations for accurate medium-range weather forecasting. Polar satellites provide unique information on the large-scale atmospheric conditions over areas that would otherwise be sparsely observed – information which in this case proved crucial and undoubtedly helped to mitigate the consequences of the Hurricane. These results also corroborate previous OSE impact studies on the important role of polar orbiting satellites play in current global NWP (*McNally 2012*).

In the case of the five day forecast of the storm landfall, it is found that a considerable fraction of the accuracy lost due to the denial of polar satellite data was recovered using inflated background errors from the ECMWF EDA (which better describe errors in the degraded NOPOLAR observing system). The inflated errors increased the use of and the weight given to other observations – particularly geostationary winds over the North Pacific. Although the impact of EDA background errors was less for other forecasts (e.g. day six and day four) the Sandy case clearly demonstrates the value of a

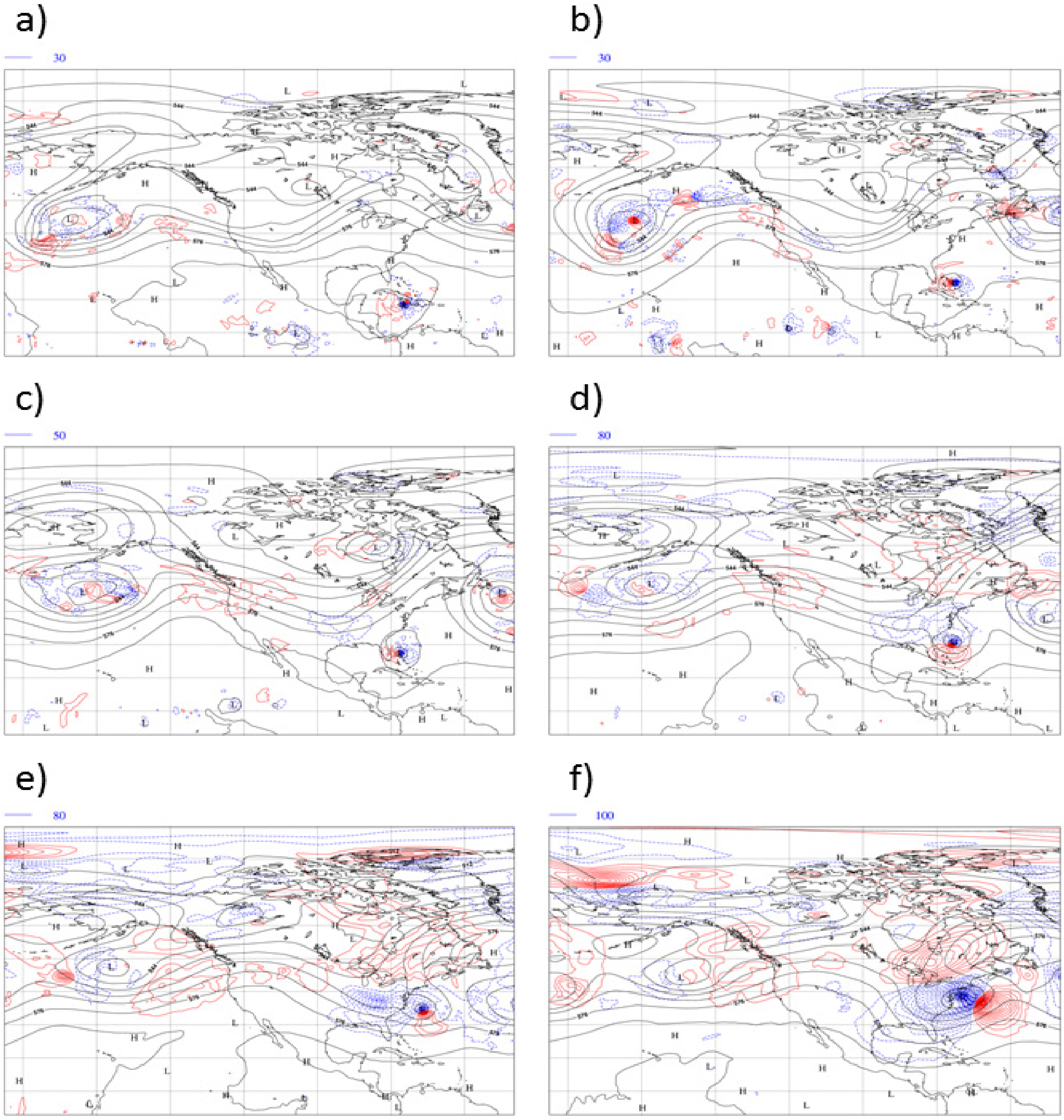


Figure 10: Differences between the NOPOLAR-EDA and NOPOLAR 500 hPa geopotential forecast on 25^{th} October at 00UTC at (a) t+0h,(b) t+24h ,(c) t+48h, (d) t+72h, (e) t+96h) and (f) t+120h. Red contours represent positive values, blue negative. Unit is 30 m^2/s^2(a,b); 50 m^2/s^2 (c); 80 m^2/s^2 (d,e); 100 m^2/s^2 (f);. Black contours are NOPOLAR_EDA 500 hPa geopotential forecasts on 25th October at 00UTC verifying at the same time.

sophisticated data assimilation algorithm with flow-dependent and data dependent uncertainty estimation. It is encouraging that such systems are now being developed and implemented in operational NWP centres.

It is interesting that, for Hurricane Sandy, none of the other data denials (including the NOGEO system) resulted in a failure in the prediction of the storm. However, when GEO data were more extensively used and given more weight in the NOPOLAR_EDA experiment, they clearly provided crucial information which improved the forecasts and compensated (at least partially) for the loss of the polar satellite data. It is also important to note that the geostationary satellites provided vital real time monitoring of the storm's actual progress during the event.

Finally, it should be emphasised that the conclusions drawn from this study are made only within the context of the ECMWF assimilation and forecasting system and only for this one meteorological case.

Acknowledgements

The authors would like to thank Fernando Prates for providing the cyclone track data displayed on Fig.9

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