Met Office

Meteorology Research and Development

Global data denial experiments using 4D-Var

Technical Report No. 532

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Document History for NWP Technical Report No. 532

Date	Version	Action/comments	Approval
24/3/09	0.1	Initial draft	Andrew Lorenc

ABSTRACT

A global data denial experiment is carried out using a version of the Met Office operational NWP system. The experiment is run over a one month period using observations from 24th May 2007 to 24th June 2007. Data from all the main observing systems (satellite, radiosonde, aircraft, surface) are denied. Two additional scenarios that deny all conventional (non-satellite) data and European profiler data are also run. Thirty forecasts run from 12UTC observations from the period are verified against observations and the analyses from the 'all data' run. The results are compared with a similar experiment carried out 5 years previously.

Results indicate that the Met Office NWP system has gained between 12-18 hours of forecast skill over the 5-year period. Satellite data are increasingly the most important data source being at least as important as radiosondes in the Northern Hemisphere and clearly the most important source in the Southern Hemisphere. The increase in the importance of satellite data is thought to be due to increased volume and quality of the data combined with improved data assimilation techniques. Conventional data continue to play an important role, in the Northern Hemisphere particularly, with radiosonde data being the most important data source. Aircraft data have a significant positive impact, particularly in the Northern Hemisphere at flight levels. Significant impact cannot be detected from the European wind profiler network. Surface data continue to be essential for the forecasting of PMSL, although rather surprisingly the impact of all conventional data is less on PMSL than surface data only.

The removal of all major observing systems causes a statistically significant reduction in mean forecast skill which indicates that the Met Office 4D-Var scheme is working well.

1. Introduction

The aim of global data denial experiments is to provide an overall check on the performance of an NWP system, particularly the skill of the data assimilation scheme. By denying whole observing systems from assimilation by NWP, it would be expected that mean forecast skill would be reduced. If the effect of removing an observing system is to improve forecasts, then it would suggest a problem with the observations themselves or the way they are assimilated. Clearly, both matters would require further investigation. Additionally, global data denial studies can give an insight into the relative benefit of observing systems. Such information is useful in deciding how to develop and fund the Global Observing System (GOS).

The first set of global data denial studies were carried using the Met Office NWP system as it was in 2001 when, in particular, a three-dimensional variational data assimilation scheme was in use. The study used observations from two one month periods in July 2001 and January 2002 (Dumelow, 2005). For convenience this study will be subsequently referred to as DU2005.

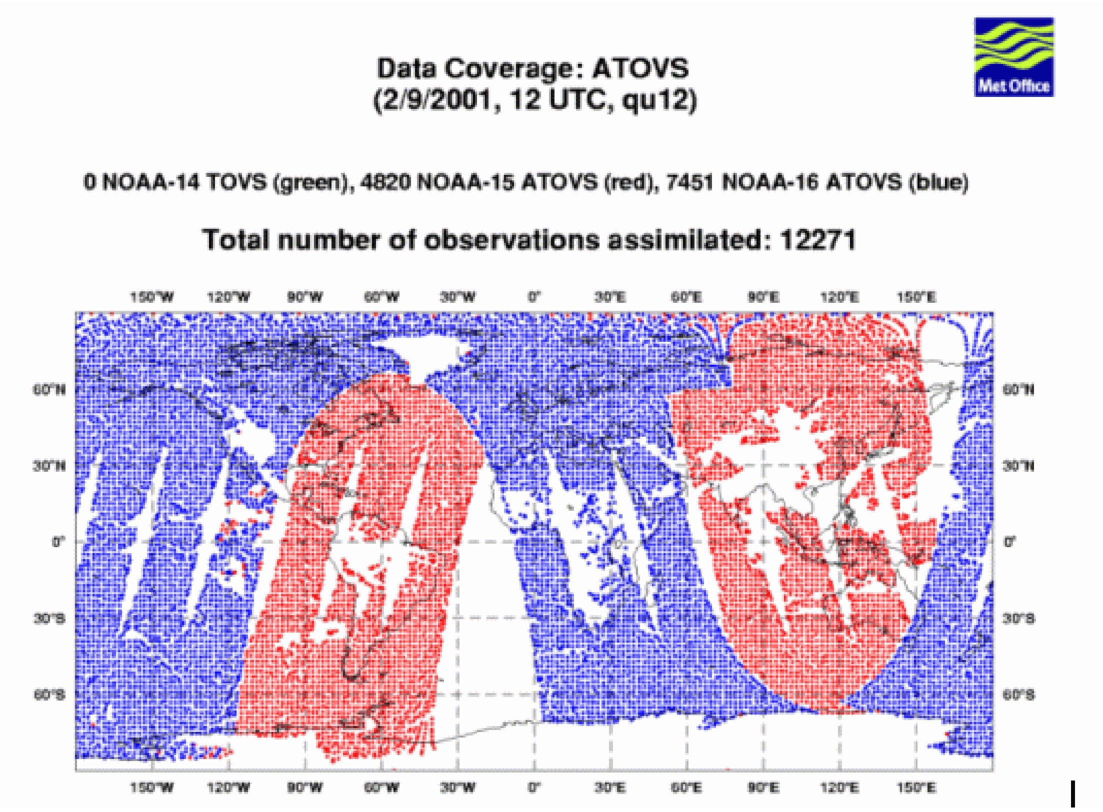
Since 2001 the Met Office NWP system has been subject to continuous modification and improvement, most notably due to the introduction of a four dimensional data assimilation scheme and by an increase in horizontal resolution. Between 2001 and 2007, the Met Office global model horizontal resolution was increased from 60km to 40km and the vertical resolution from 30 to 50 levels although in DU2005 a reduced horizontal resolution of 90km was used to reduce the computational expense of running the experiment.

Furthermore, the GOS has undergone major changes including the introduction of large volumes of satellite data of higher resolution and accuracy (Figure 1) plus more automated data from aircraft. Table 1 compares the volume of data assimilated in 2001 with 2007.

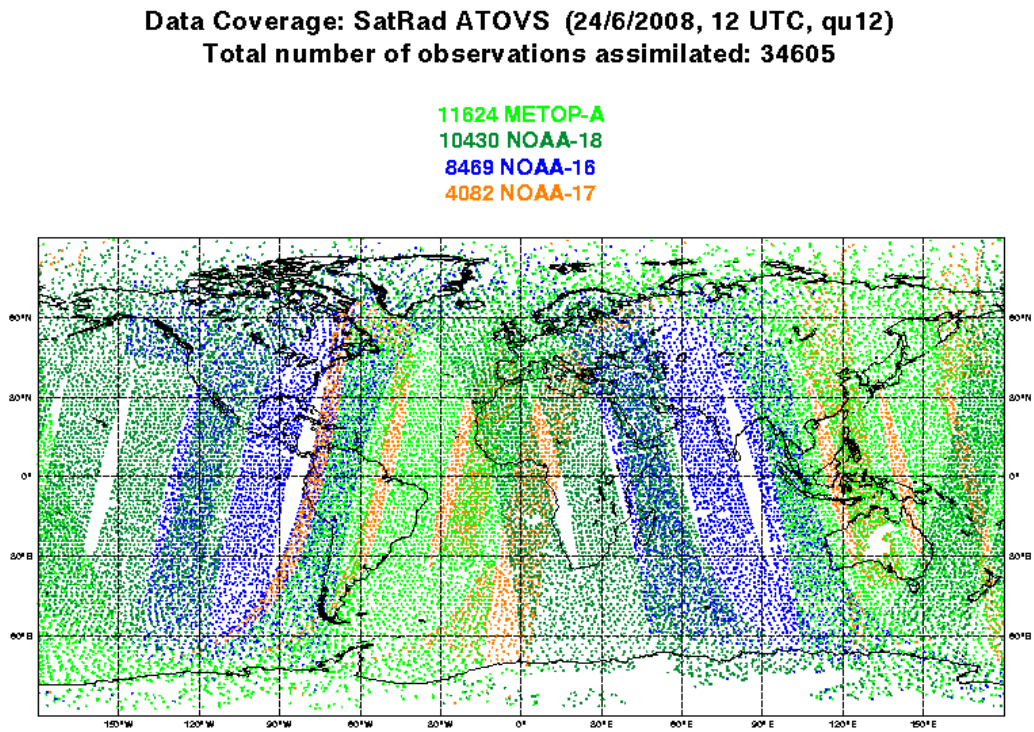
This study updates the work carried out in the first study taking account of the changes in the Met Office NWP system and its use of observational data.

Observing system	Number of reports assimilated per day	
	July 2001	June 2007
Aircraft	40000	58000
Radiosonde	2100	2100
Wind profilers and WRWPs	1200	7500
Surface (SYNOP, buoy, ship)	30500	38000
ATOVS	48000	136000
Satellite winds	27700	28600
Scatterometer winds	0	32000
SSMI	8000	4000
SSMIS	0	3500
AIRS	0	3000
GPSRO	0	1200

Table 1. Average data volumes assimilated in 2001 and 2007.



(a)



(b)

Figure 1. Typical data coverage around 12UTC in (a) 2001 (b) 2008 (similar to 2007).

2. The NWP system

The first step in the NWP process is to specify the initial conditions that start a numerical model integration. The initial conditions (analyses) are obtained from the information provided by weather observations. As these observations are irregularly distributed in space and time, it is assumed that a good analysis can be obtained by blending the information obtained from current observations with the information from past observations projected forward in time by the forecast model as a short-range (e.g. 6-hour) forecast that provides a dynamically consistent first guess analysis or 'background' field. For a forecast model with N grid points updated by M observations, then linear estimation is used to obtain an analysis:

$$\mathbf{x}^{\mathbf{a}} = \mathbf{x}^{\mathbf{b}} + \mathbf{K}(\mathbf{y}^{\mathbf{o}} - \boldsymbol{H}(\mathbf{x}^{\mathbf{b}})) \qquad (2.1)$$

where $\mathbf{x}^{\mathbf{a}}$, $\mathbf{x}^{\mathbf{b}}$ are (Nx1) column vectors of model analysis and background values respectively, $\mathbf{y}^{\mathbf{o}}$ is an (Mx1) column vector of observed values and ***H*** is a non-linear operator that maps model values into observation space and **K** is linear operator [(NxM) matrix] used to weight model and observation values. **K** is obtained by minimising the mean square analysis error. A forecast at time **t** can then be obtained by using the non-linear forecast operator ***M***:

$$\mathbf{x}^{\mathbf{t}} = \boldsymbol{M}(\mathbf{x}^{\mathbf{a}}) \qquad (2.2)$$

where $\mathbf{x}^{\mathbf{t}}$ is an (Nx1) column vector of forecast values at time t.

In principle equations (2.1) and (2.2) could be used to produce forecasts but the linear operator **K** and non-linear operators ***H*** and ***M*** cannot be defined exactly and have to be approximated. The process of refining these approximations currently forms the core of NWP research.

In this experiment, four-dimensional variational optimisation is used to obtain an approximation for **K** (Rawlins et al, 2007) and the approximations to ***H*** vary from simple three-dimensional linear interpolation to the use of a radiative transfer model when satellite radiance data are being assimilated. The approximation to ***M***, or forecast model, is described by Davies et al (2005). The Met Office NWP versions used for this work were as in the PS18 package using UM 6.4.

It should be noted that as NWP research proceeds, the impact of observing systems on forecast skill will change as a result of improving approximations to equations (2.1) and (2.2).

3. Experimental set-up

As in the previous study, an Observing System Experiment was run in which the reports from whole observing systems were excluded from assimilation. For the period over which the experiment was run, the Met Office operational NWP system assimilated the following data:

(a) radiance from three NOAA polar orbiting satellites: from the AMSU-A and AMSU-B instruments on NOAA-16; AMSU-B instrument on NOAA-17; AMSU-A, and MHS instruments on NOAA-18
(b) radiance from the AIRS, AMSU-A & HSB instruments on the Aqua polar orbiting satellite
(c) radiance from the AMSU-A1, AMSU-A2, HIRS/4 instruments on MetOp-A polar orbiting satellite
(d) radiance from the SSMIS instrument on the DMSP-F16 polar orbiting satellite
(e) atmospheric motion vectors (AMVs) from instruments on geostationary satellites Meteosat 7,9; GOES 11,12; and MTSAT-1R
(f) polar winds from polar orbiting satellites: the MODIS instrument on the Aqua and Terra satellites; the AVHRR instrument on the NOAA 15, 16, 17, 18 satellites
(g) surface wind speed over the sea from the SSM/I instrument on the DMSP-F13 and DMSP-F15 polar orbiting satellites
(h) surface vector wind over the sea from the scatterometer instruments on the QuikSCAT and ERS-2 polar orbiting satellites
(i) refractivity from the GPS on the COSMIC 2, 3, 5 & 6 low earth orbiting satellites
(j) temperature, humidity and wind profiles from radiosondes
(k) temperature and wind from manually or automatically taken measurements from all phases of aircraft flights
(l) surface pressure measurements from land stations and drifting buoys; surface pressure and wind measurements from ships and moored buoys
(m) profiles of winds from VHF/UHF wind-profiler radars and VAD/VVP derived winds from weather radars.

The experiment included the following runs:

1. All data
2. All data – all satellite (No satellite)
3. All data – all radiosonde (No radiosonde)
4. All data – all aircraft (No aircraft)
5. All data – all surface (No surface)
6. All data – all conventional (No conventional)
7. All data – European wind profilers (No EURO wind profilers)

Scenarios 1-5 were used previously. Scenario 6 assess the impact of using satellite data only and Scenario 7 looks at the impact of the European wind profiler and weather radar winds.

The Met Office operational NWP system, which uses 4D-Var, was run at full operational resolution using observations from the one month period from 24th May to 24th June. Forecasts up to 6 days were run from 12UTC and standard fields were verified against observations and the ‘All data’ run analysis. The observing stations used for verification were taken from a WMO approved list and their reports were required to pass the objective quality control checks before use.

4. Results

Some results showing the impact of observations on mean forecast performance, averaged over 30 forecasts, are presented.

4.1 Comparison with the previous study

For ease of comparison with the results in DU2005, absolute values of verification statistics with no statistical significance testing are presented in this section; it should be noted that not all differences between runs are statistically significant. The results presented here can be compared directly with DU2005 noting that this previous study used two one-month periods and so the scores showed in the figures were averaged over 60 cases whereas the current study used 30.

4.1.1 Impact on upper air fields

Figure 2 and Figure 3 below can be compared with Figure 4 and Figure 5 in DU2005.

Comparing the values in the figures, it can be seen that all forecasts from all runs now have lower errors. For example, comparing the RMS vector wind errors for corresponding ‘All data’ runs, it can be seen that there has been a gain in forecast skill of between 12 and 18 hours depending on forecast range. Another point to note is that the least skilful forecasts from the current experiment (e.g. the ‘No satellite’ run) are more skilful that the most skilful run (‘All data’) from the previous experiment. For height (anomaly correlation coefficient) the results are similar although the gain in forecast skill is up to 60 hours in the tropics.

As before, satellite data continue to be the most important source of observational data in the Southern Hemisphere with the skill of forecasting height improving by up to 48 hours (Figure 2(c)) as in DU2005. In the tropics, satellite data continue to be the most important data source for forecasting height (Figure 2(b)) and now are also the most important data source in the tropics for forecasting wind exceeding the value of radiosonde data (Figure 3(c)). The impact of satellite data on height forecasts can be clearly seen at T+24 in the Southern Hemisphere in the mean difference plots from the ‘All data’ run (Figure 4(a)) and to a lesser extent in the tropical and Southern Hemisphere wind forecasts (Figure 5(a)).

In the Northern Hemisphere, satellite data are now the most important data source for forecasting height (Figures 2(a), 2(d)) whereas radiosonde data were the most important in DU2005. For the forecasting of wind, radiosonde data were the most important data source when verified against radiosondes in the Northern Hemisphere and tropics in DU2005 whereas satellite data are now the most important data source for forecasting wind in the tropics and North America.

There continues to be small benefit from aircraft on height forecasts (Figure 2) although an increased impact can be seen in the wind forecasts particularly over Europe (Figure 3(a)), North America (Figure 3(b)) and the tropics (Figure 3(c)).

As noted in DU2005, the mean impact statistics hide the daily variations in the differences in forecast skill between runs. For example, the difference in forecast skill between the All data and No satellite runs is usually positive but can be negative particularly at longer forecast ranges such as T+120 (Figure 3(e)).

It can be clearly seen from difference maps the impact of radiosonde and aircraft data for T+24 forecasts of height is largest in the Northern Hemisphere (Figures 4(b), 4(c)) although the impact on the wind field is less clear in these maps (Figures 5(b), 5(c)).

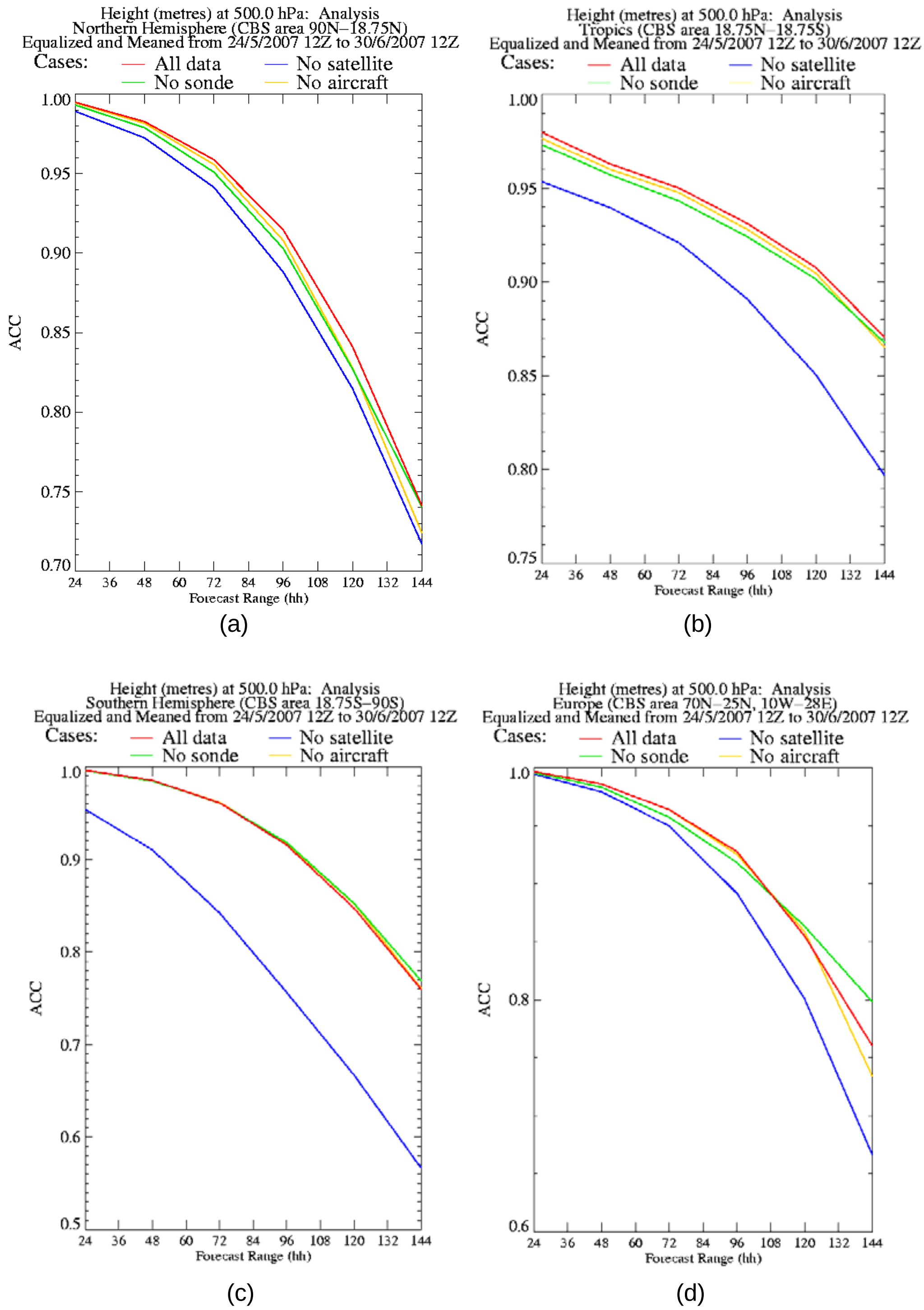


Figure 2. Comparison of satellite and surface-based data. 500 hPa height anomaly correlation coefficient for (a) Northern hemisphere (b) Tropics (c) Southern hemisphere (d) Europe.

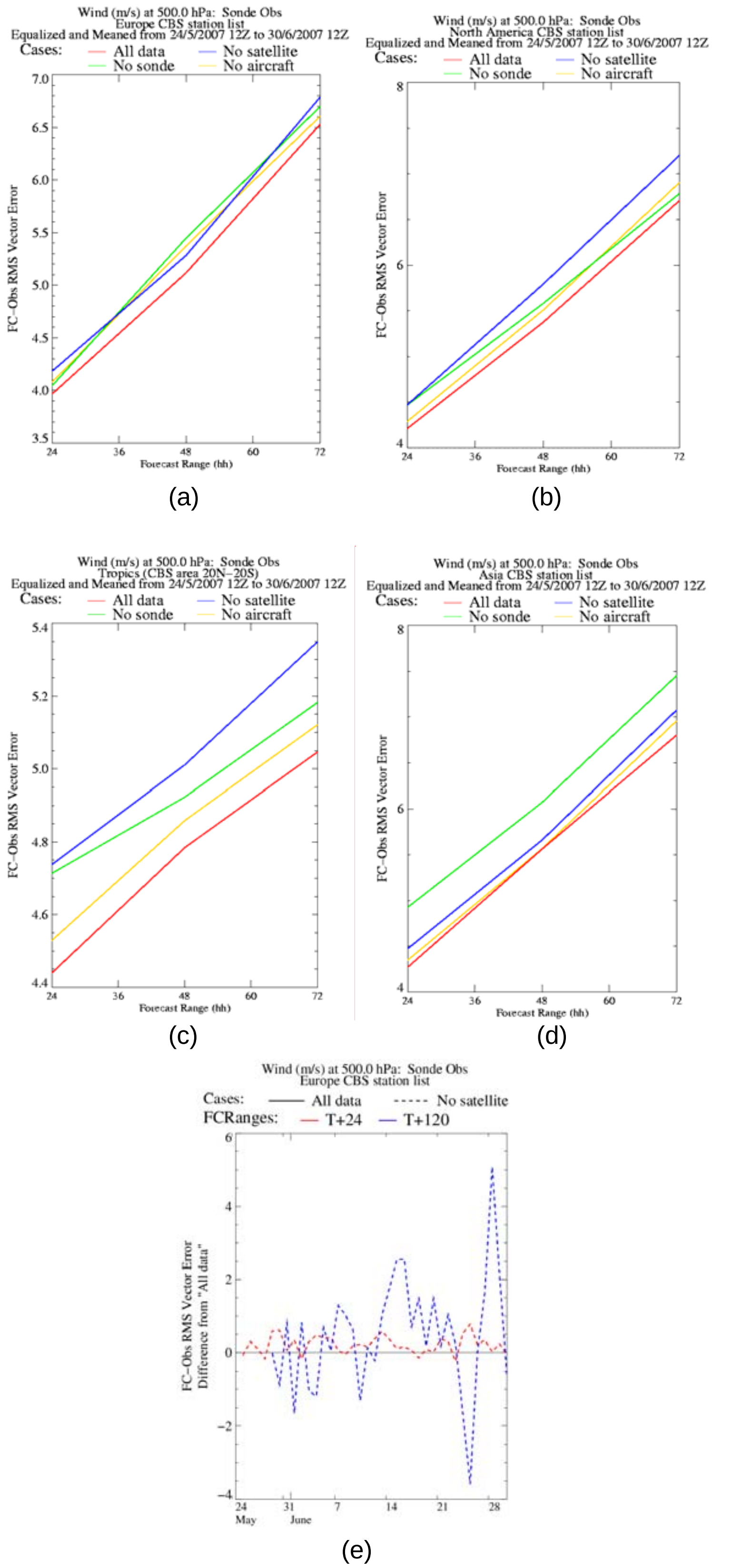
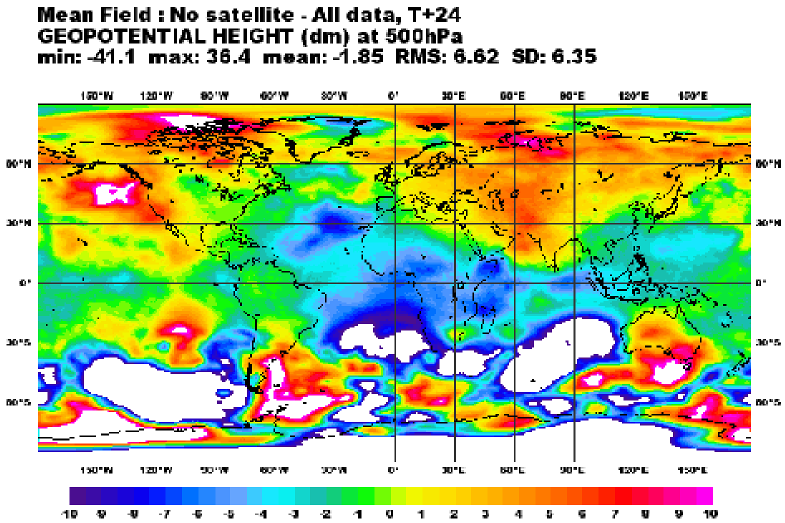
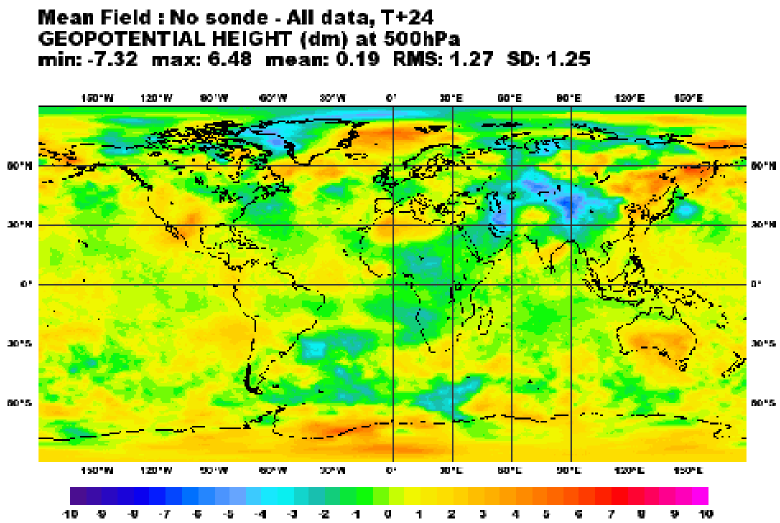


Figure 3. Comparison of satellite and surface-based data. (a) –(d) RMS vector wind error for 500 hPa wind versus radiosondes for (a) Europe, (b) North America, (c) Tropics, (d) Asia. (e) Time series of differences (No satellite – All data) in 500 hPa vector wind errors versus European radiosondes for 24-hr and 120-hr forecasts.



(a)



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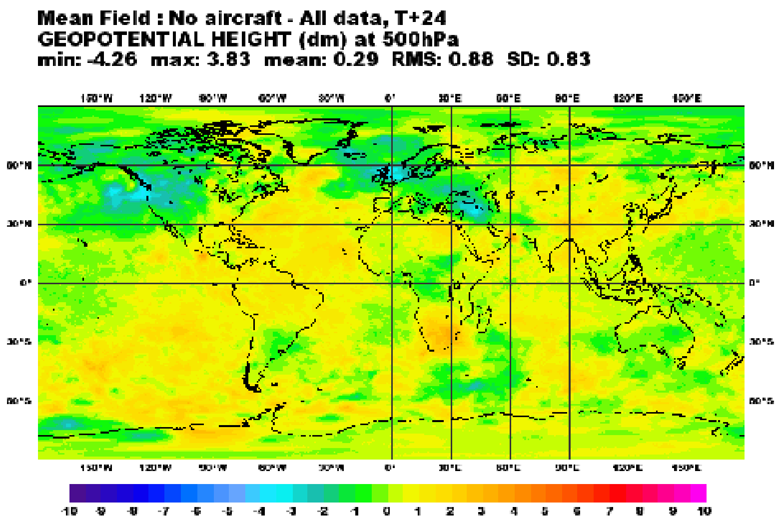


(c)

Figure 4. Mean difference in the 24-hr forecast fields of 500 hPa height from the 'All data' run and the No satellite (a), No radiosonde (b) and No aircraft (c) runs.

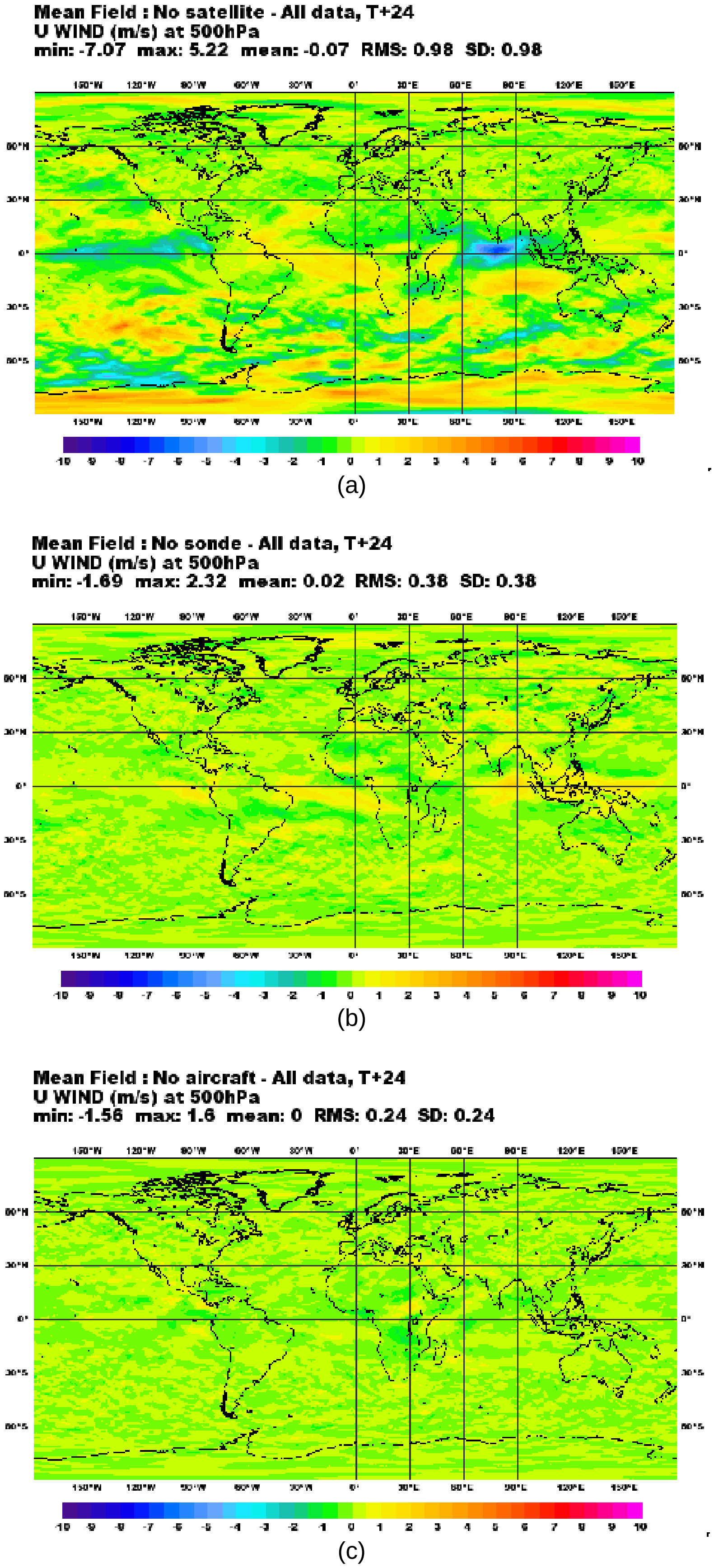
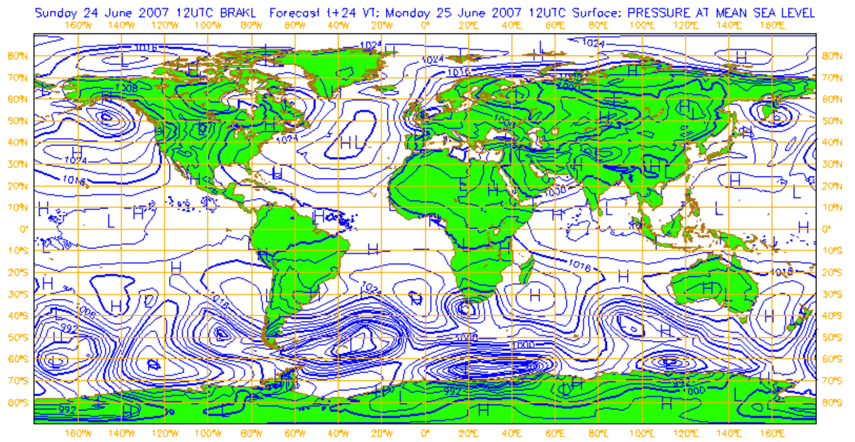


Figure 5. Mean difference in the 24-hr forecast fields of 500 hPa u-component from the ‘All data’ run and the No satellite (a), No radiosonde (b) and No aircraft (c) runs.

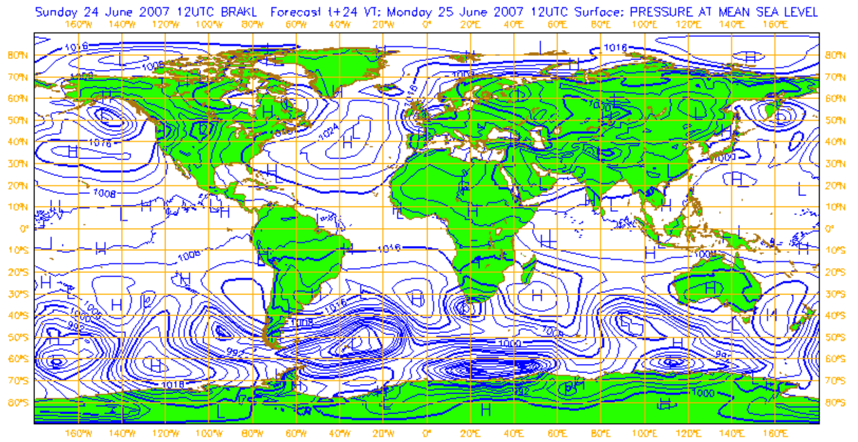
4.1.2 Impact on surface fields

As shown in DU2005, removing surface data has a large negative impact on RMS errors for MSLP with errors more than tripling for 24-hour forecasts (Figures 7(a) & 8(a)) with most of the error explained by an increase in negative bias (Figure 7(b)) which can be clearly seen in the mean difference maps from the 'All data' run (Figure 7(a)). The removal of surface data does not impact on the upper level temperature field (Figures 7(c) & 8(b)) but can be measured in the upper level geopotential height field as a result of the error in the forecast of MSLP (Figures 7(d) & 8(c)).

Although large differences between the All data and No surface runs can be seen in the average RMS errors, it has been found that meteorological features in individual MSLP forecasts remain similar in both runs. However, there is a systematic lowering of pressure in the No Surface run which produces deeper lows and weaker highs. An example of this effect can be seen in Figure 6 which shows the T+24 forecast of PMSL verifying at 12UTC 25/06/07, near the end of the experimental period. Note in particular how the Atlantic high pressure system is about 4hPa higher in the All data run compared with the No surface run. Other features show similar differences.



(a)



(b)

Figure 6. T+24 forecast of MSLP from the All data (a) and No surface (b) runs verifying at 12UTC 25/06/07.

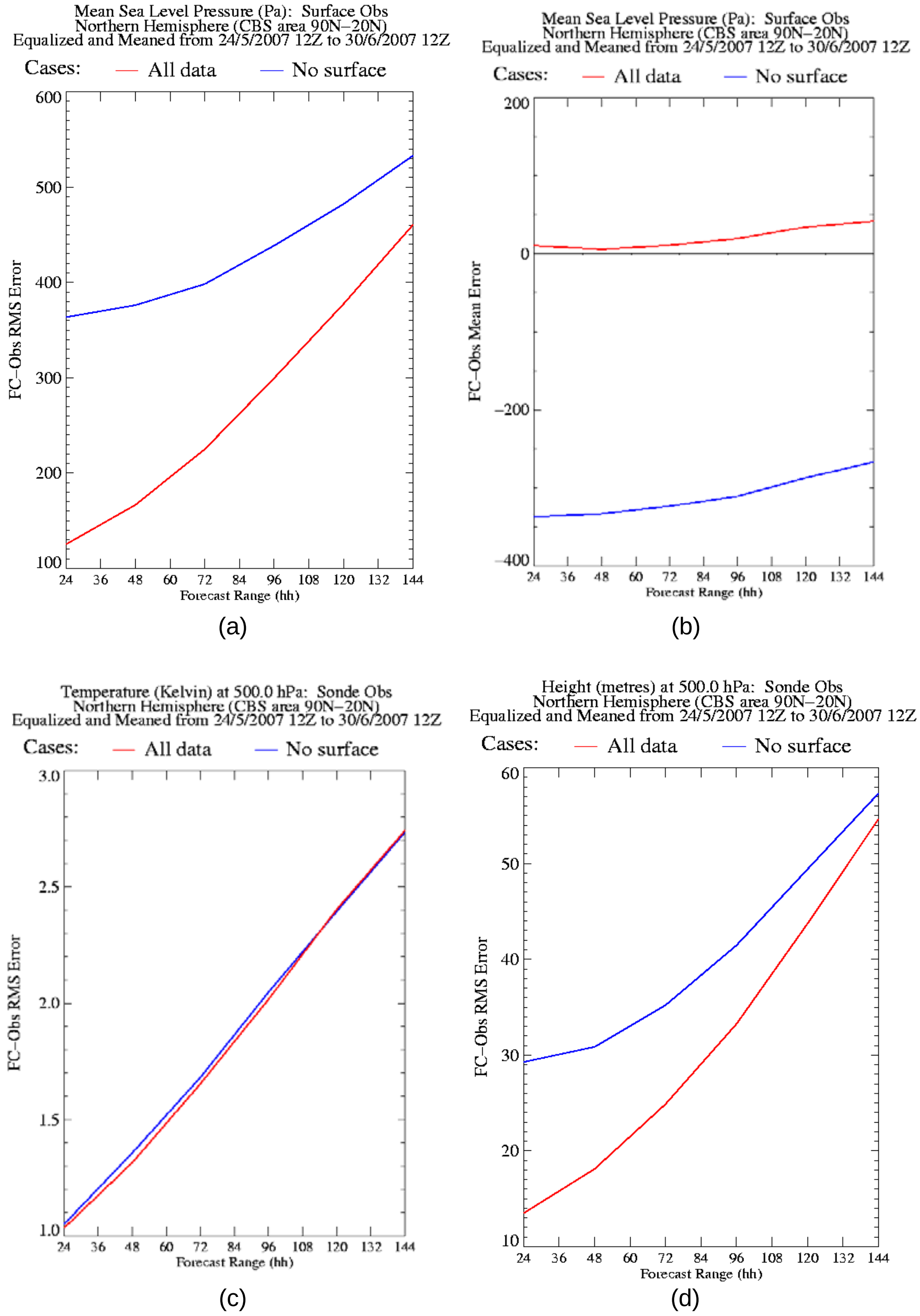
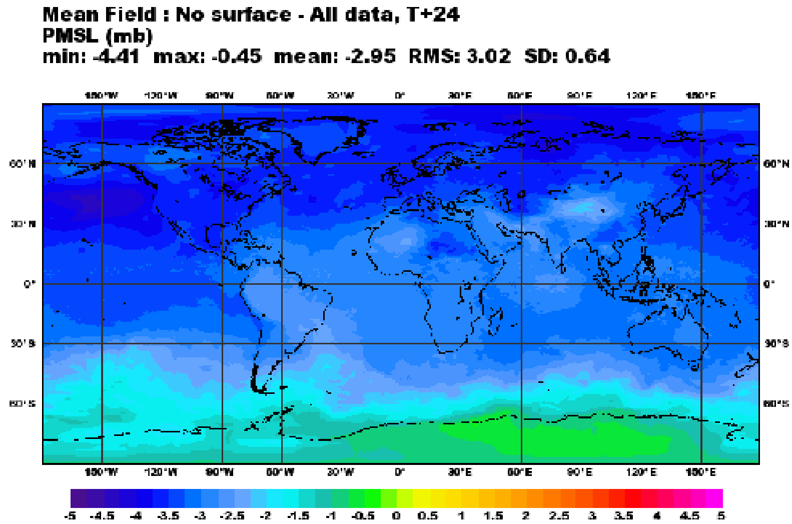
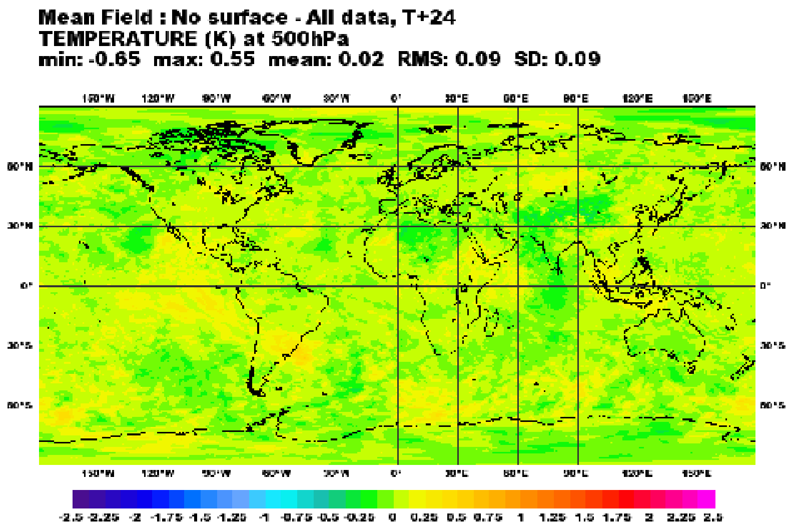


Figure 7. Mean impact of surface and conventional data in the Northern Hemisphere vs observations on (a) RMS MSLP error (b) MSLP mean error (bias) (c) 500 hPa temperature (d) 500 hPa geopotential height.



(a)



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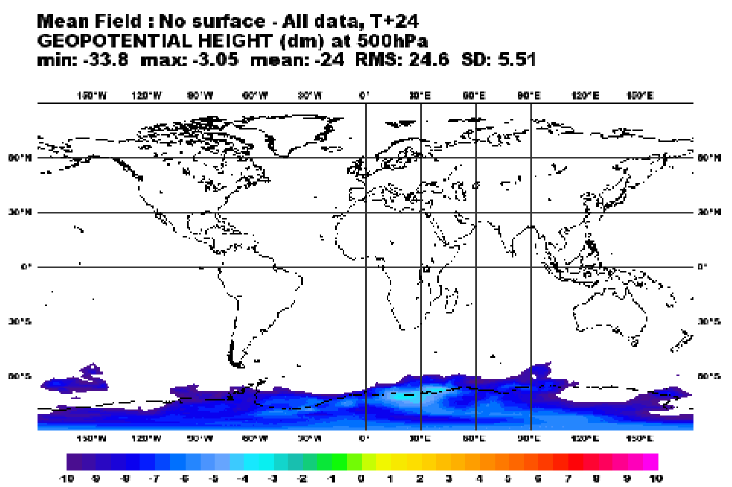


(c)

Figure 8. Mean difference in the 24-hr forecast fields between the ‘No surface’ and the ‘All data’ run for (a) PMSL (b) 500 hPa temperature (c) 500 hPa geopotential height.

4.2 Further results

4.2.1 Impact of the main observing systems

The following figures show the impact of the individual observing systems on the temperature and wind field at upper levels. The results are plotted as a difference from the 'All data' run with error bars denoting statistical significance at the 90% level.

As expected from previous studies, in the Southern Hemisphere satellite data have a large statistically significant positive impact on forecasts, in the range 20-60% at almost all levels and forecast ranges for both temperature and wind forecasts (Figure 9(a), 9(b)). In the Northern Hemisphere there is a much smaller but still statistically significant impact in the temperature and wind forecasts at all levels and forecast ranges except T+144 with the largest impact at shorter forecast ranges (Figure 9(c), 9(d)). In the tropics, statistically significant impact can be seen in the wind field at all forecast ranges and levels up to 200 hPa but the same benefit cannot be seen in the temperature forecasts (not shown).

Statistically significant impact from radiosonde data can been seen in the wind forecasts in the tropics and Southern Hemisphere but are less clear in the temperature forecasts. As the impacts from radiosonde data are largest in the Northern Hemisphere only these results are shown. It can be seen that the data are having a positive impact at all levels up to T+96 and the impact overall is similar to slightly more than for satellite data (Figure 10).

An analysis of similar plots to those shown in Figures 9 and 10 but for aircraft data indicate a positive impact on the wind forecasts mainly around flight levels. The impact on the forecasts of 250hPa wind in all three regions is shown in Figure 11. A statistically significant impact can be seen up to T+72 in the Northern Hemisphere (Figure 11(a)), T+120 in the tropics (Figure 11(b)) and T+48 in the Southern Hemisphere (Figure 11(c)).

The main input from surface data has found to be on the forecasts of PMSL as shown in Section 4.1. However, positive impact has been found on upper level fields particularly for short-range forecasts most noticeably in the Northern Hemisphere. An example is given in Figure 12 which shows the impact of surface data at 500hPa. At this level, there is a statistically significant impact in the temperature forecasts up to T+96 [Figure 12(a)] and for wind forecasts up to T+72 [Figure 12(b)].

The impact of European wind profilers is not statistically significant at most forecast ranges and levels. For example, for forecasts at 500hPa in the Northern Hemisphere of temperature and wind, there is not significant benefit at nearly all forecast ranges (Figure 13).

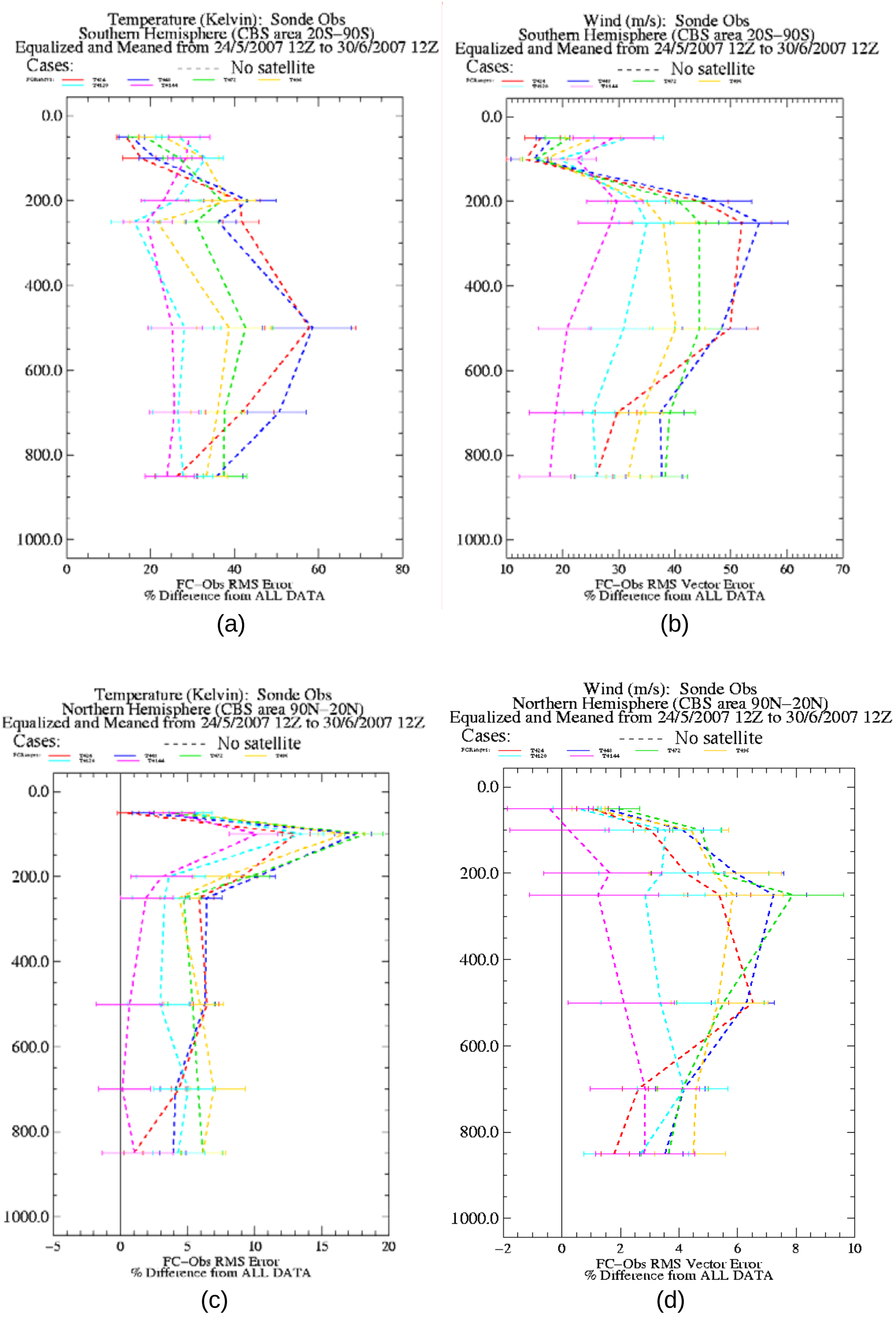
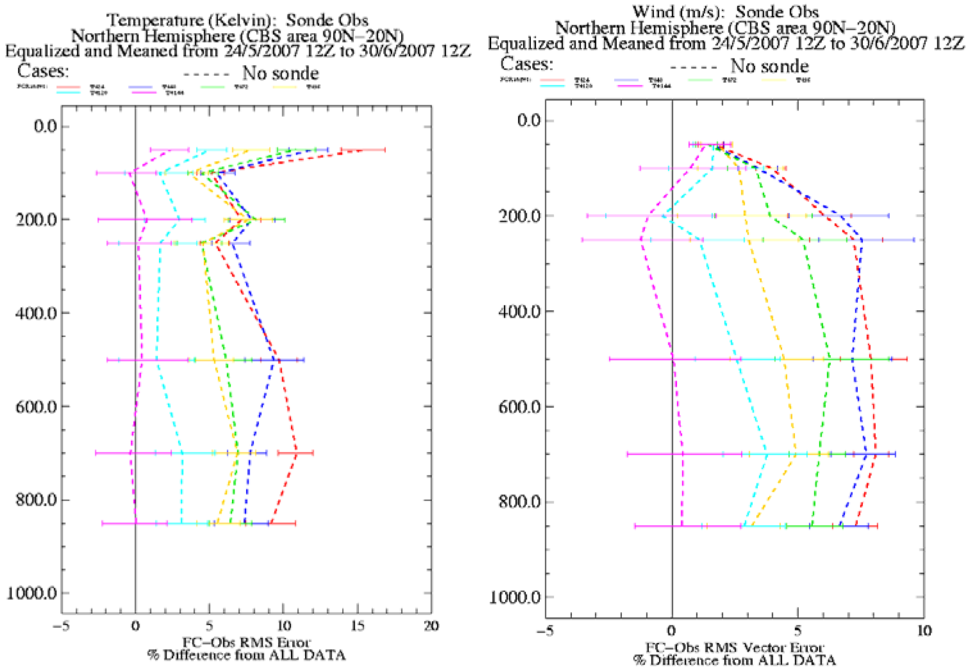


Figure 9. Impact of satellite data in versus pressure level on (a) Southern Hemisphere temperature (b) Southern Hemisphere wind (c) Northern Hemisphere temperature (d) Northern Hemisphere wind . Error bars show 90% statistical significance.



(a) (b)

Figure 10. Impact of radiosonde data in the Northern Hemisphere versus pressure level on (a) temperature (b) wind. Error bars show 90% statistical significance.

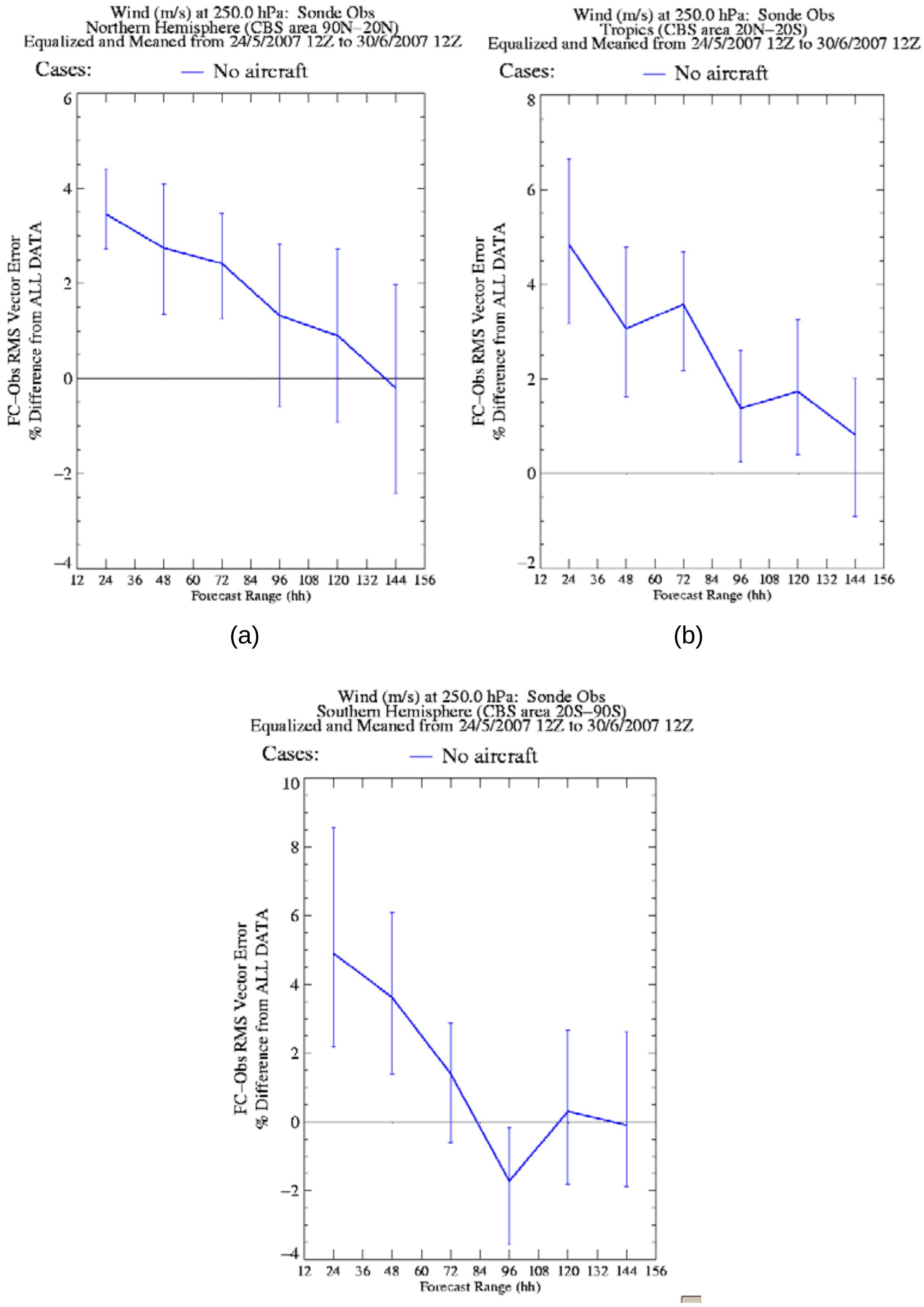
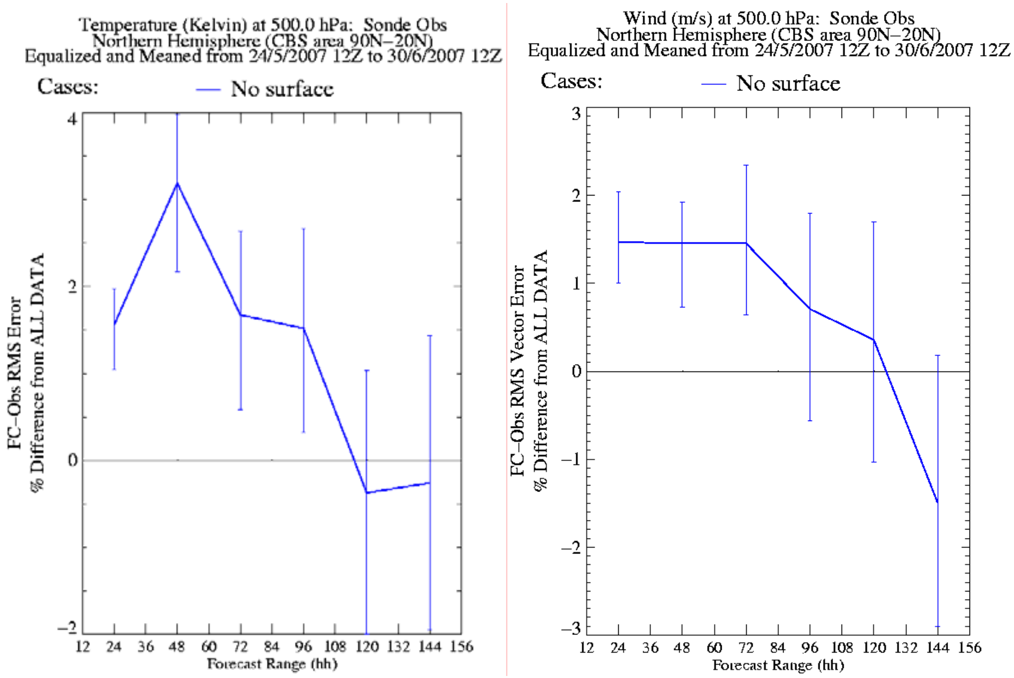
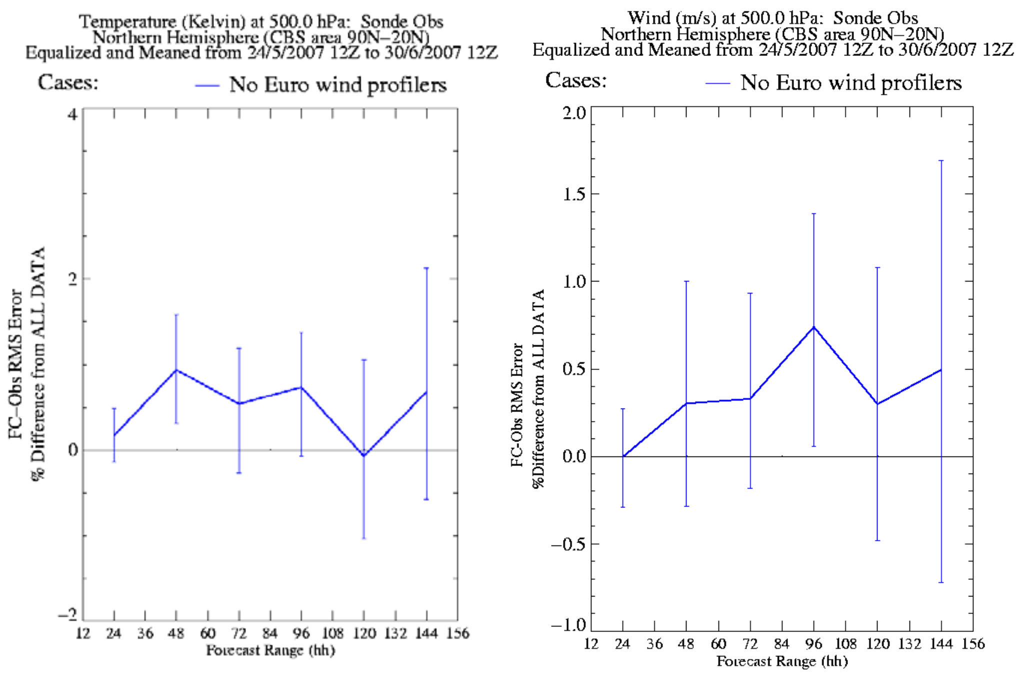


Figure 11. Impact of aircraft data on the wind forecasts at 250 hPa in the (a) Northern Hemisphere (b) tropics (c) Southern Hemisphere. Error bars show 90% statistical significance.



(a) (b)

Figure 12. Impact of surface data in the Northern Hemisphere versus at 500 hPa on (a) temperature (b) wind. Error bars show 90% statistical significance.



(a) (b)

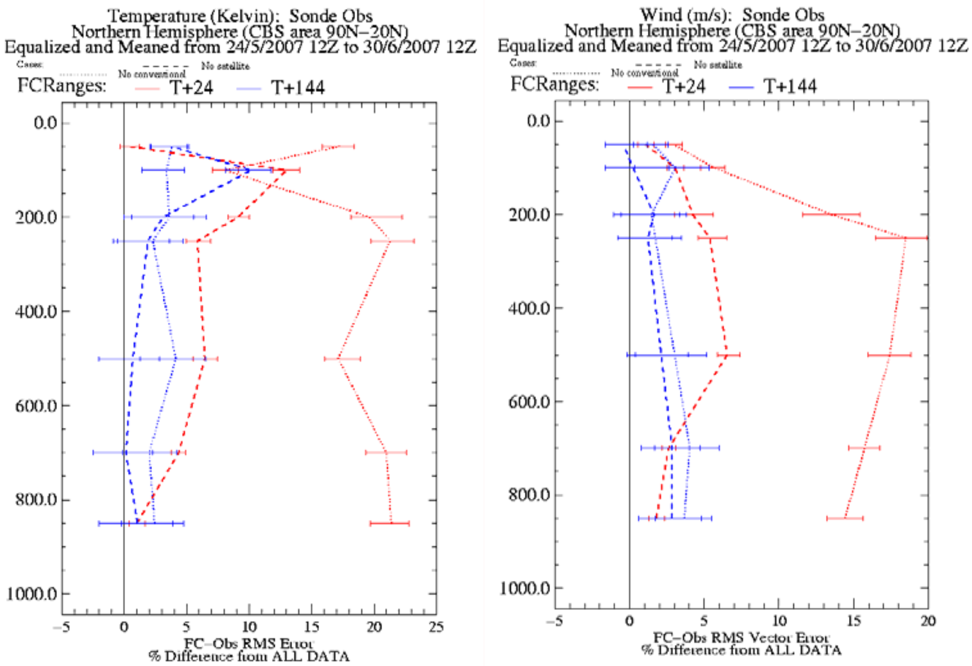
Figure 13. Impact of European profile data in the Northern Hemisphere at 500hPa on forecasts of (a) temperature (b) wind. Error bars show 90% statistical significance.

4.2.1 Impact of conventional data

An attempt has been made to assess the overall impact of conventional data and compare it with the impact of satellite data. Such a comparison compliments the findings of the space-terrestrial study for EUCOS, which investigated the correct mix of satellite and conventional data by using a ‘base line up’ approach (Dumelow, 2008).

Figure 14 shows the relative impact of the two data sources in the Northern Hemisphere where most of the conventional data occur. For clarity, only the impact on the T+24 and T+144 forecasts is plotted. At T+24, conventional data give about 10% extra benefit at most levels compared with satellite data. At T+144 the overall impact of observations is much less but conventional data appear to give more benefit although the difference compared to the impact of satellite data is not statistically significant.

It is interesting to see which of the conventional observing systems contribute most to the overall impact at upper levels. In Figure 15 the impact of conventional systems on the forecast of 500hPa wind in the Northern Hemisphere is shown. As expected from the results presented in Section 4.1, radiosonde data have the largest impact which is statistically significant up to T+120. Aircraft and surface data have a similar and smaller impact which is significant up to T+72. Note that the total impact of conventional data is greater than the sum of the impact of individual systems at all forecast ranges.



(a) (b)

Figure 14. Impact of satellite and conventional data in the Northern Hemisphere on (a) temperature (b) wind.

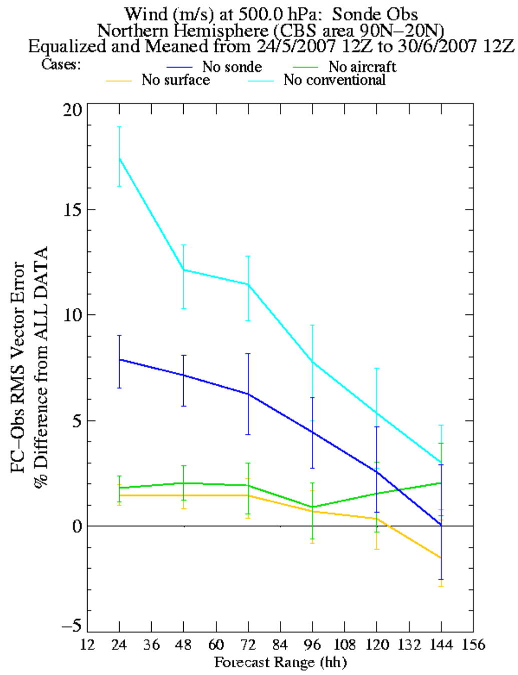
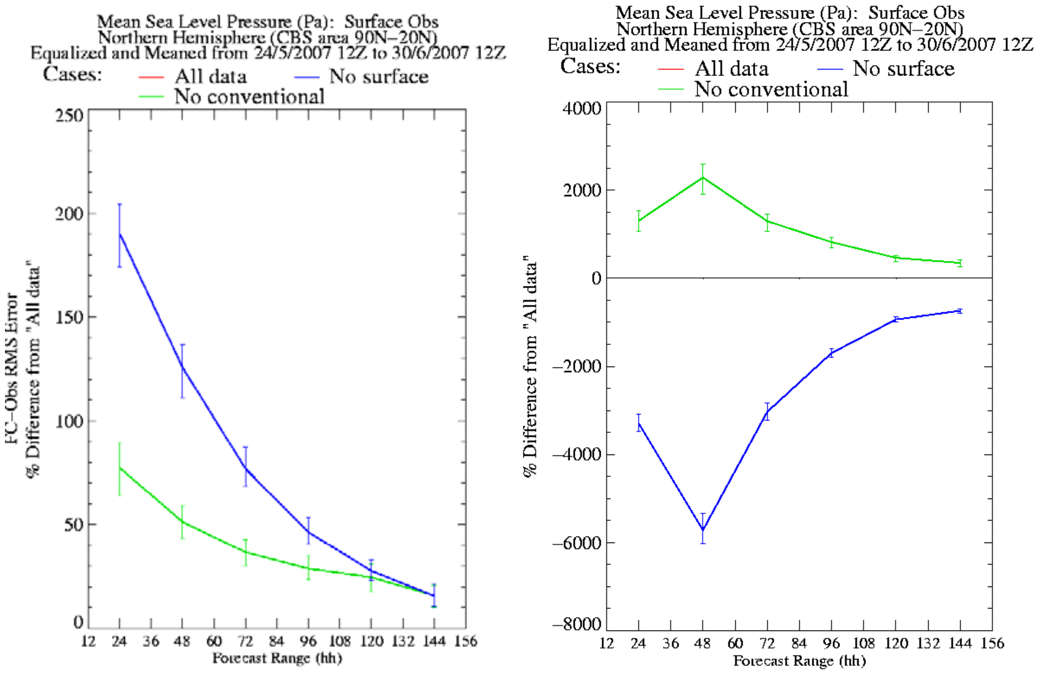


Figure 15. Impact of conventional observing systems on the 500 hPa wind in the northern hemisphere.

As shown in Section 4.1, surface data are essential for the forecasting of surface pressure. However, removing all conventional data including surface data has less detrimental effect on the MSLP than removing only surface data (Figure 16(a)). The increase in RMS error can largely be explained by a bias which is positive when all conventional data are removed rather than negative when surface data only are removed (Figure 16(b)). The increase in MSLP bias that occurs when conventional data are removed can be seen throughout the globe, especially in the 24-hour forecast (Figure 17).

4.2.2 Impact on the NWP index

Table 2 shows the impact of all the observing systems on the global NWP index arranged in descending order of magnitude. Due to its large impact on the short-range forecasts of PMSL in the Northern Hemisphere, surface data have the largest impact on the NWP index. Satellite data, having a large impact in the Southern Hemisphere and a significant impact in the Northern Hemisphere comes second followed closely by all conventional data due to its impact in the Northern Hemisphere. Radiosonde data are clearly more important than aircraft data and European profiler data has a small positive impact on the index that is probably not statistically significant.



(a) (b)

Figure 16. Impact of surface data only compared with all conventional on MSLP in the Northern Hemisphere. (a) RMS error (b) Mean error (bias).

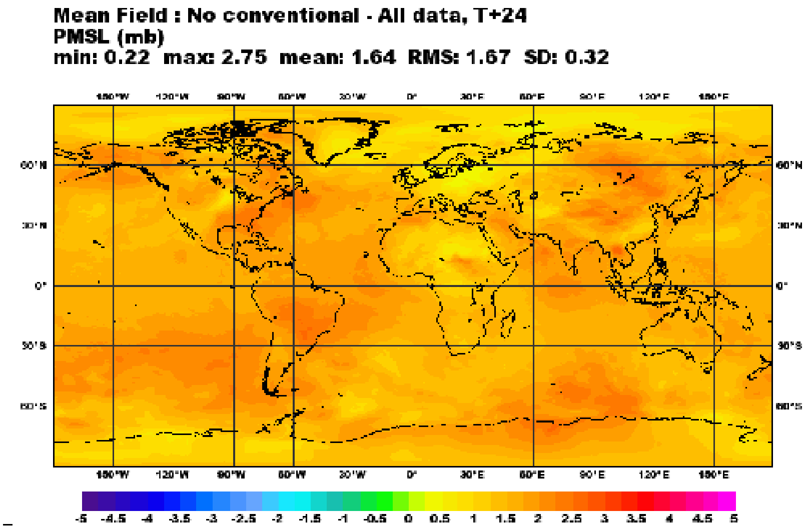


Figure 17. Mean difference in the 24-hr forecast fields between the ‘No surface’ and the ‘All data’ run for PMSL.

Observation type removed	Reduction in global NWP index (percentage)
Surface	42.33 (32.48)
Satellite	27.92 (21.28)
All conventional	27.21 (20.89)
Radiosonde	8.31 (6.36)
Aircraft	4.79 (3.64)
European wind profilers	0.67 (0.51)

Table 2. Impact of observing systems on the global NWP index.

4.2.2 Discussion

It should be noted that any conclusions based upon this study are based upon just 30 forecasts from a one-month period. Thus, given the relatively small number of forecasts under consideration, the scores averaged over larger areas such as the Northern Hemisphere are likely to be more representative than those averaged over smaller areas such as Europe. Longer runs, using observations from more than one season, would be required to give more reliable results.

Since the last study (DU2005) the forecast errors have reduced as would be expected as a result of improvements in NWP. The size of the improvement over the 5-year period, of about 12-18 hours in skill, is in line with estimates from other NWP systems (Simmons & Hollingsworth, 2002).

Conventional data in total appear to be more important than satellite data in the Northern Hemisphere. However, the greater importance of conventional data than satellite data in the Northern Hemisphere found in this study appears to be inconsistent with the findings of Zapotocny et al (2007) who, using a 2003 period and the NCEP Global Data Assimilation/Forecast System, found that satellite and conventional data have similar importance. A longer study, using observations from more than one season, would be required to determine whether the discrepancy between the findings of the two studies is due to differences in the observations used or the weather during the period of the experiment. Some differences in the results might be expected due to the differences in the NWP systems used. Zapotocny et al used a 32-km/60-layer limited area model with 3D-Var whereas this study used 40 km/50 level model and 4D-Var. A significant difference in the impact of observations when using 3D-Var compared with 4D-Var was found in the ECMWF NWP system (Kelly et al, 2007).

The large impact of satellite data in the Southern Hemisphere is a well known result seen in many studies (e.g. Bouttier and Kelly, 2001). It is mainly explained by the fact that satellite data are by far the predominant data source in this region. The Southern Hemisphere contains large oceanic areas that are well observed by satellites and contain few conventional observations. A newer result is that satellite data have become a more important data source compared with radiosonde data in the Northern Hemisphere. This may be explained by a number of factors. Table 1 shows that the ATOVS data volumes assimilated have increased by nearly a factor of three and completely new satellite data sources, such as AIRS and GPSRO, have become available. Furthermore, the quality of satellite data has improved in terms of accuracy and resolution. The AIRS instruments, for example, provide much more detailed information on atmospheric structure than it was possible to obtain from ATOVS. Improvements in the assimilation of such data, in particular through the introduction of 4D-Var, have been implemented. All these factors are likely to have increased the impact of satellite data.

In contrast, the volume of radiosonde data has remained about the same as five years ago. As most radiosonde observations are taken at the main synoptic hours of 00UTC and 12UTC then the introduction of 4D-Var, which is well-suited to the assimilation of non-synoptic data, is unlikely to have caused a significant improvement in its assimilation. Hence the decline in the importance of radiosonde data relative to satellite data is not unexpected.

As shown in Table 2, aircraft volumes have increased significantly over the 5-year period between this study and DU2005 including more high quality profiles of temperature and wind available from the ascent and descent phases of flights. Most of the extra data are available at flight levels in the Northern Hemisphere and much of this is over the oceans where little other 'in-situ' data are available. Hence a significant impact on the temperature and wind fields around 250hPa in the Northern Hemisphere would be expected. The positive impact seen at other levels may in part due to the vertical spreading of the information through the assimilation process, and partly due to the observations taken during the ascent and descent phase of flights. These profile data can provide measurements at times when no radiosonde data is available and in regions with no radiosonde coverage. The complimentary benefit of aircraft and radiosonde data was also found by an ECMWF study (Thépaut & Kelly, 2007).

The large impact of surface data on forecasts of PMSL was reported in DU2005 and has been seen by studies using the ECMWF NWP system (Thepaut, 2003). A positive impact is seen in upper level temperature and wind fields (not shown) and may be partly due to the effect of the data assimilation scheme spreading information upwards, and partly due to the observational impact being propagated through assimilation cycles via the background field.

The fact that the impact of all conventional data is greater than the sum of the impact of the individual systems suggests that the conventional systems are acting in a complimentary manner. Although there may be some duplication between radiosonde and aircraft profile data, surface and aircraft flight level data provide information in regions where there is little radiosonde coverage such as the oceans and Africa. Putting all this information together may well provide a much better analysis of atmospheric structure than any reduced set of conventional data can provide.

It is difficult to explain why removing all surface data should result in a large negative bias in the short-range forecasts of MSLP whereas removing all conventional data (including surface) results in a small positive bias. It may be that there is a negative interaction between the assimilation of satellite data and conventional so that the removal of the latter allows the model to adjust its fields to a single, consistent satellite data source.

The lack of statistically significant impact from European wind profiler data is to be expected given that the data are relatively few in number and that the scores presented are averaged in space and time. A much more detailed study would be required to detect significant impact from European profilers.

5. Summary and conclusions

The main conclusions from this study are:

- The Met Office system has improved by about 12-18 hours in forecast skill over a 5-year period.
- Given that all observing systems give a statistically significant impact on average forecast skill, it appears that the overall performance of 4D-Var is good.
- Satellite data are now as important as radiosonde data in the Northern Hemisphere and remain the most important data source in the Southern Hemisphere. Their increased importance compared with 5-6 years ago is probably due their better coverage and quality, and due to improved assimilation techniques.
- Conventional data, in total, are more important than satellite data in the Northern Hemisphere. Radiosonde data are the most important conventional source. Aircraft data are significant for the forecasting of wind and temperature in the Northern Hemisphere, particularly at flight levels.
- The total value of conventional data is much greater than the sum of the individual observing systems.
- Surface data are essential for the forecasting of surface pressure.
- A positive impact from European wind profilers cannot be detected in the mean scores from this experiment.

References

Bouttier F, Kelly G 2001. Observing-system experiments in the ECMWF 4D-Var data assimilation system. *Q. J. R. Meteorol. Soc.* **127**: 1469-1488.

Davies T, Cullen MJP, Malcolm AJ, Mawson MH, Staniforth A, White AA Wood N 2005. A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Q. J. R. Meteorol. Soc.* **131**: 1759-1782.

Dumelow R 2005. Observing System Experiments using the Met Office three-dimensional variational assimilation scheme. *Met Office, Forecasting Research Technical Report* No. **461**.

Dumelow R 2008. The impact of conventional observations on global and regional NWP forecasts. Met Office, *Meteorology Research and Development Technical Note* No. **516**.

Kelly G, Thepaut J-N, Buizza R, Cardinali C 2007. The value of targeted observations. Part I. Data denial experiments for the Atlantic and the Pacific. *Q. J. R. Meteorol. Soc.* **133**: 1803-1815.

Rawlins F, Ballard SP, Bovis KJ, Clayton AM, Li D, Inverarity GW, Lorenc AC, Payne, TJ 2007. The Met Office global four-dimensional variational data assimilation scheme. *Q. J. R. Meteorol. Soc.* **133**: 347-362.

Simmons AJ, Hollingsworth A 2002. Some aspects of the improvement in skill of numerical weather prediction. *Q. J. R. Meteorol. Soc.* **128**: 647-677.

Thépaut J-N 2003. Impact studies at ECMWF. *E-SAT meeting,* 14-15 May, ECMWF, Reading, UK.

Thépaut J-N, Kelly G 2007. EUCOS terrestrially based Observing System Studies. *E-SAT meeting,* 14-15 April, ECMWF, Reading, UK.

Zapotocny TH, Jung JA, Le Marshall JF, Treadon RE 2007. A two-season impact study of satellite and in situ data in the NCEP Global Data Assimilation System. *Weather and Forecasting* **22 (4)**: 887-909.

Acronyms

AIRS	Atmospheric Infrared Sounder
AVHRR	Advanced Very High Resolution Radiometer
AMSU	Advanced Microwave Sounding Unit
ATOVS	Advanced TIROS Operational Vertical Sounder
COSMIC	Constellation Observing System for Meteorology, Ionosphere & Climate
DMSP	Defence Meteorological Satellites Program
ERS	European Remote Sensing
GPS	Global Positioning System
HIRS	High Resolution Infra Red Radiation Sounder
HSB	Humidity Sounder for Brazil
MetOp	Meteorological Operational satellite programme
MHS	Microwave Humidity Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MTSAT	Multi-functional Transport Satellite (Japan)
NCEP	National Centre for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
PMSL	Pressure at Mean Sea Level
SSMI	Special Sensor Microwave Imager
TIROS	Television Infrared Observation Satellites
UHF	Ultra High Frequency
VAD	Vertical Azimuth Display
VHF	Very High Frequency
VVP	Volume Velocity Processing
WRWP	Weather Radar Wind Profile