Data Assimilation in the Polar Regions

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1. Introduction

The Polar Regions provide challenging environments for data assimilation in several ways. Based on experience from developing a 3D-Var system for Antarctica, Barker et al. (2006, in preparation) highlight:

1) the dearth of in-situ observations;
2) extreme topography;
3) cloud cover issues: coastal Antarctica is one of the cloudiest places on Earth;
4) the impact of highly varying emissivity on satellite-measured radiances (McNally 2006, this volume) and;
5) the forecast model's physical parameterisations may not have been tuned for extreme regimes, as discussed by Beljaars (2006, this volume)

In this paper we briefly review the status of the Artic and Antarctic observing networks and go on to assess analysis accuracy within the ECMWF operational forecast system. In particular, we compare 2001 with 2006, focusing on the progress made in that five-year period due to increased availability of satellite observations, as well as improvements to the model and data assimilation systems (Simmons and Hollingsworth 2002).

Based on April 2001 data, Powers et al. (2003) intercompared the forecast performance for Antarctica of four different forecasting systems: The Antarctic Mesoscale Prediction System (AMPS, also called Polar MM5) at 30 km resolution, ECMWF at T511 (40 km) resolution, The Aviation Model (AVN) of NCEP, and the Global MM5 of NCAR. The comparison was made in terms of surface pressure, 10m-wind, 2m-temperature and 500 hPa geopotential, temperature and wind. They found that:

- "ECMWF performed with the highest overall skill, as defined by generally having the lowest bias and root-mean-square (rms) errors, and the highest correlation for the examined fields."
- "The ECMWF's skill in part reflected its advanced data assimilation system, including 4D-Var and use of satellite radiances from polar orbiting satellites."

In the time since 2001 several upgrades to the ECMWF forecasting system have been implemented, including more extensive use of microwave radiance data from polar orbiting satellites over sea ice and snow covered land. The new polar orbiting TERRA and AQUA satellites, launched by NASA in Dec 1999 and May 2002 respectively, provide the first high spectral-resolution infrared radiances (AIRS), an additional microwave temperature sounder (AMSU) and for the first time a good polar coverage of wind observations. The latter are atmospheric motion vectors (AMVs) derived through tracking of water vapour features in successive images obtained from the MODIS instrument (Key et al. 2003). The cumulative impact of these important new data and changes to the forecasting system between 2001 and 2006 affecting the performance of the data assimilation system are assessed in the following.

In Section 2 we describe the 4D-Var system and its recent evolution. The polar observing systems are briefly discussed in Section 3, and their information contents are assessed in Section 4. In Section 5 we illustrate the general improvement of the assimilation system through study of analysis increments, and differences between ECMWF and MetOffice analyses. In Section 6, we use results from an ensemble of independently cycling assimilations to assess analysis uncertainty in the Polar Regions. In Section 7 we compare the ECMWF analysis with a rare set of North Pole radiosondes obtained from the Oden Arctic expedition in 2001. Conclusions and summary are presented in Section 8.

2. The 4D-Var system and its recent evolution

The ECMWF forecast system uses a 4D-Var data assimilation scheme (Rabier et al 2000; Bouttier 2001; Haseler 2004) to produce global analyses of temperature, wind, humidity, ozone and surface pressure. These analyses are primarily used to initialize twice-daily medium-range forecasts. The incremental formulation of 4D-Var is used as described in Courtier *et al.* (1994). The statistical model for background-error covariances is that of Fisher (2003a) and Hólm et al. (2002). Concerted efforts to exploit more satellite observations (Thépaut and Andersson, 2003) have between 2001 and 2006 led to a five-fold increase in the number of used observations, from about 1.4 to 7 million data items per day. Several of the assimilated data types are obtained from instruments onboard polar-orbiting satellites which naturally provide very good data coverage over the Polar Regions (McNally, 2006, this volume).

The data assimilation system uses the latest version of the model and is run at the same resolution as the operational forecast model. A complete list of ECMWF model changes can be accessed via the link provided in the footnote[1]. In January 2001, the T319/L60 model was upgraded from T319/L60 to T511L60 (~40 km resolution and 60 model levels), with analysis increments computed at T159 resolution. In February 2006 the model was upgraded to T799/L91 (~25 km and 91 model levels) with analysis increments at T255. The resolution increases clearly improve the representation of steep topography, as seen for example in Figure 1 for the area surrounding Ross Island and the McMurdo station. Improved topography allows a more accurate

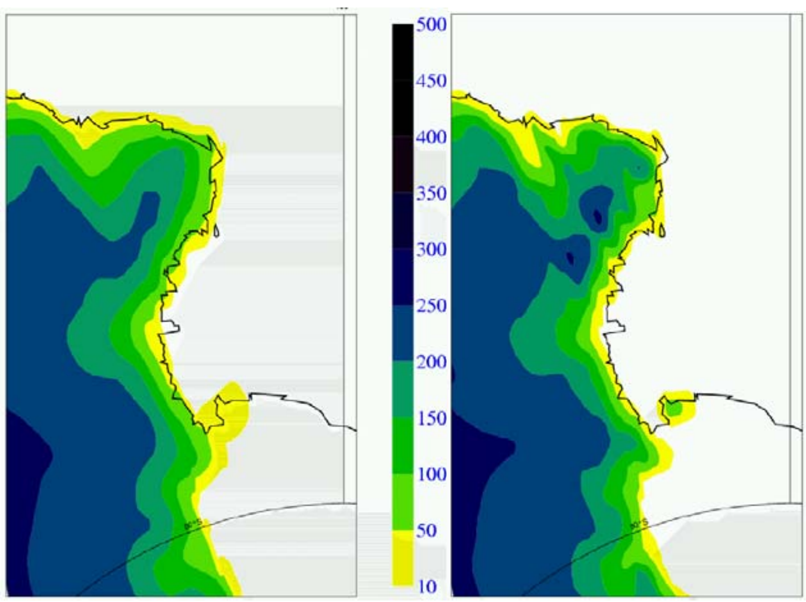

Figure 1 Model orography as represented by the T319 resolution model (~63 km, left) operational until January 2001 and the T799 model (~25 km, right) introduced in February 2006. Ross Island, where the McMurdo station is situated, is now separated from the mainland.

[1] See www.ecmwf.int/products/data/operational_system for a complete list of model changes.

comparison between model and observations, and enables increased use of surface pressure observations and winds in the assimilation system.

High resolution is also key to successful simulation of katabatic winds and the associated formation of small-scale cyclones which can be strong and frequent in areas of steep orography around Antarctica and Greenland. In the vicinity of Ross Island this type of event is a dominant feature of the weather and can occur as often as once or twice per week (Powers et al 2005). This requires a dense network of surface stations and mesoscale assimilation systems with a resolution of a few km. In the 25-km resolution (T799) global system of ECMWF, this type of event can only be captured if occurring at large-enough scale, such as seen in Figure 2. However, there are difficult issues about how to impose the appropriate mass/wind balance of analysis increments in complex terrain, and precisely how to extrapolate information from coastal stations to the relatively data void inland and ocean areas. Not surprisingly, many smaller-scale events are poorly represented or missing altogether in ECMWF analyses: In the Ross Sea area, visual inspection of ECMWF surface wind and pressure analyses in the 2006 season showed about one event per month, i.e. an under-representation by a factor 4 to 8. The assessment of analysis accuracy that follows in the next sections is entirely based on ECMWF's global system, and is thus limited to synoptic-scale features; the error contributions due to misrepresentation of smaller-scale features are neglected.

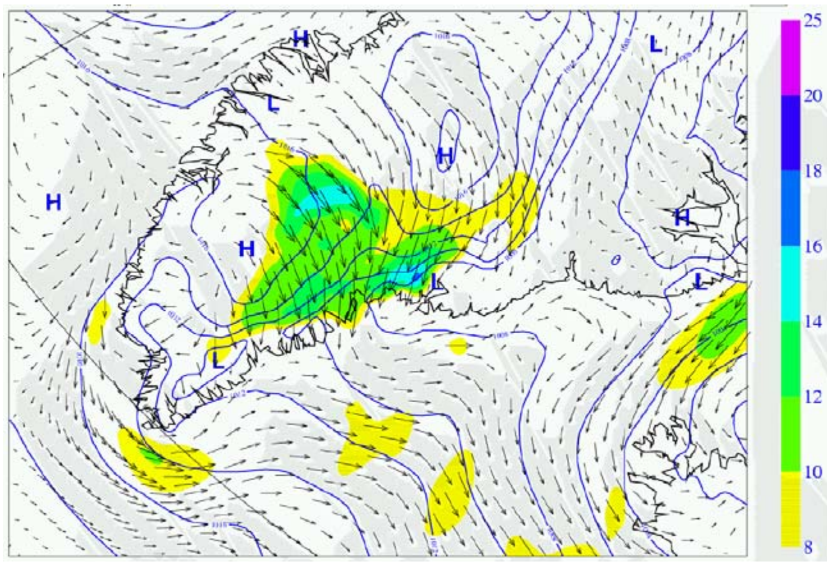

Figure 2 ECMWF analysis of a relatively large-scale katabatic wind event and associated formation of lee cyclones along the east coast of Southern Greenland, 20060701-12 UTC. The wind arrows show wind speed and direction, the shading shows wind speed (m/s, see legend) and blue contours show mean sea-level pressure (2 hPa interval).

3. Availability of observations in the polar regions

Radiosondes provide the backbone of the polar observing system for NWP.

- The Arctic (Figure 3, left) has good **radiosonde** coverage up to 70-75 North, and even to 80 North in the Canadian Islands and Northwest Greenland. The Antarctic coast at 65-70 S (Figure 3, right panel) is well covered apart from a major data gap in western Antarctica, where ice conditions prevent research stations from being maintained on a permanent basis. There are two radiosonde stations, Vostok and the South Pole, in the Antarctic interior.

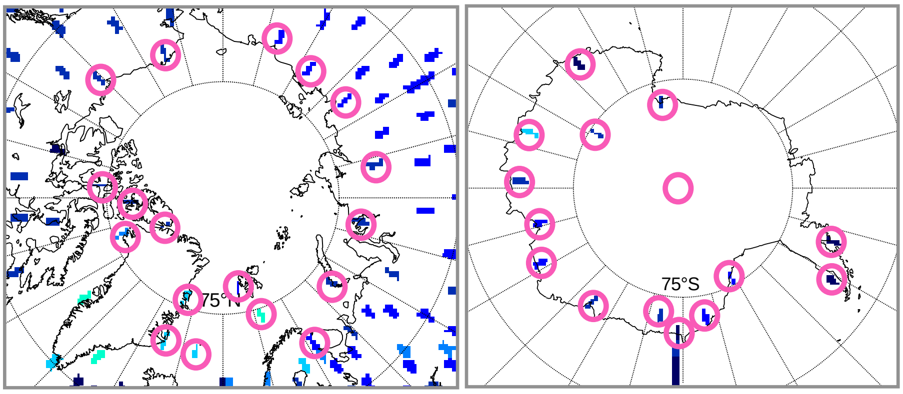

Figure 3 Radiosonde data coverage, with stations at very high latitudes highlighted by circles (pink). The colour marker at each station location indicates the number of reports received in July 2006, increasing from dark to light blue colours.

- The provision of **surface pressure observations** from SYNOP stations, SHIPs and BUOYs is reasonably good in most parts of the Arctic (not shown), except in the interior of Greenland, and in the Arctic Ocean. In the Antarctic, there are a good number of frequently reporting stations (Järvinen et al. 1999) along the coast and many drifting buoys in the open ocean, but there are large data voids in the areas of frozen sea, and in the interior.
- **Commercial aircraft** provide increasing numbers of temperature and wind observations (AMDAR) in the Arctic, primarily en route between Europe, North America and Japan (Cardinali et al. 2003). These data provide important information around flight level (typically ~10 km), over Greenland, Canada, Alaska and Siberia (not shown). Only a very small number of flights cross the Artic Ocean, which therefore remains almost entirely void of AMDAR data. The Antarctic has no AMDAR data. Occasionally in the South Indian ocean, flights between Australia and South Africa reach just south of 60 S.
- **MODIS winds** have been assimilated at ECMWF since January 2003 (TERRA) and April 2004 (AQUA). This data set[2] provides unprecedented coverage of wind observations throughout the Polar Regions pole ward of 65 degrees north and south. Observing system experiments comparing assimilations with and without MODIS data (Bormann and Thépaut 2004) have shown very substantial impact of these data on analysis and forecast quality
- The coverage and impact of satellite radiance data from infrared (AIRS and HIRS) and microwave (AMSU-A and AMSU-B) polar orbiting satellites are comprehensively discussed by McNally (2006, this volume).

4. Information content in the main polar observing systems

The information content contributed to the analysis by each of the main observing systems can be measured objectively by the 'degrees of freedom for signal', DFS. Practical methods for computing DFS for the global 4D-Var system have recently been developed (Cardinali et al. 2004; Fisher 2003b). Global results for each of the main observing systems were presented by Cardinali et al. (2004), showing that currently the DFS of the ECMWF analyses is dominated by the information obtained from satellite sounding data. The profiling

[2] First derived by the Cooperative Institute for Meteorological Satellite Studies (CIMSS, University of Wisconsin), and more recently by the National Environmental Satellite, Data and Information Service (NESDIS, Washington).

observing systems TEMP (radiosondes), PILOT (wind profiles) and AIREP also make important contributions in terms of DFS.

Using the method of Fisher (2003b), we have calculated DFS information content for each of the main polar observing systems pole ward of 65 N and S. This was done by comparing the DFS of a baseline analysis excluding Arctic/Antarctic data to the DFS obtained from analyses with polar observing systems added to the baseline one at a time (either satellite radiances, Sondes, MODIS winds or surface data), and to the DFS of analyses using all data. The results are shown in Figure 4. We see that in total, the Arctic is about 1.7 times better observed than the Antarctic. It is also evident from these results that satellite radiances dominate DFS in both Polar Regions. In the Arctic, radiosondes provide more information to the analysis than the MODIS winds, whereas in the Antarctic it is the other way round. The low DFS for surface stations is a reflection of them being single-level data, and the scarcity of data in the Antarctic. It is important to note that DFS as presented here should not be interpreted as a measure of value, as no value-weighting is involved in its calculation. For example, the stratosphere accounts for a large part of the satellite radiance data DFS, without necessarily resulting in a proportionately large weather forecast impact.

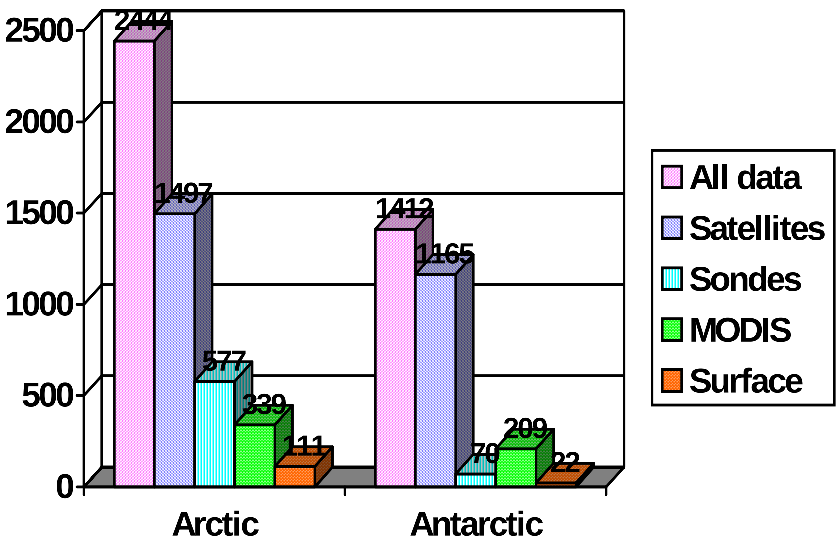

Figure 4 Information content (DFS) for each of the main observing systems contributing to the analysis in the Arctic (north of 65 N) and the Antarctic (south of 65 S).

5. Analysis performance improvements 2001 to 2006, and comparison between ECMWF and MetOffice polar atmospheric analyses

Twice a day, based on the available observations in the last 12 hours, the data assimilation system calculates corrections to the model atmosphere. These corrections are the analysis increments. A well-performing data assimilation system built around an accurate forecast model needs to make only small corrections to keep the model in step with the real atmosphere. The amplitude of the analysis increments can thus be used as an indicator of analysis performance. For example, long time series of analysis increment standard deviations from the ECMWF 40-year reanalysis (ERA-40, Uppala et al. 2005) clearly show the impact of major changes in the global observing system. Similarly, comparisons between analysis increments of ERA-40 (3D-Var) and the earlier ERA-15 (Optimal-Interpolation) system show reduced analysis increments reflecting model and data assimilation improvements. In the same vein we compare here the standard deviations of analysis increments in ECMWF's operational analyses in July 2001 against July 2006. The results are shown for the Arctic (Figure 5) and the Antarctic (Figure 6).

The plots show a dramatic reduction in analysis increments between 2001 (left) and 2006 (right panels). The radiosondes in the Canadian Arctic, northern Greenland and Spitzbergen created analysis increments that were about twice as large in 2001 than in 2006. We interpret this as an indication that analysis and short-range forecast errors developing in the Arctic Ocean have been very significantly reduced in the recent 5-year period. Similarly, Figure 6 shows that in 2001 (left panel) the radiosondes along the Antarctic coast and the south tip of South America had to do a lot of 'work' in the assimilation to correct errors developing in the data sparse upstream areas. In 2006 these increments have drastically reduced, indicating reduced upstream errors, presumably due to more extensive use of satellite data.

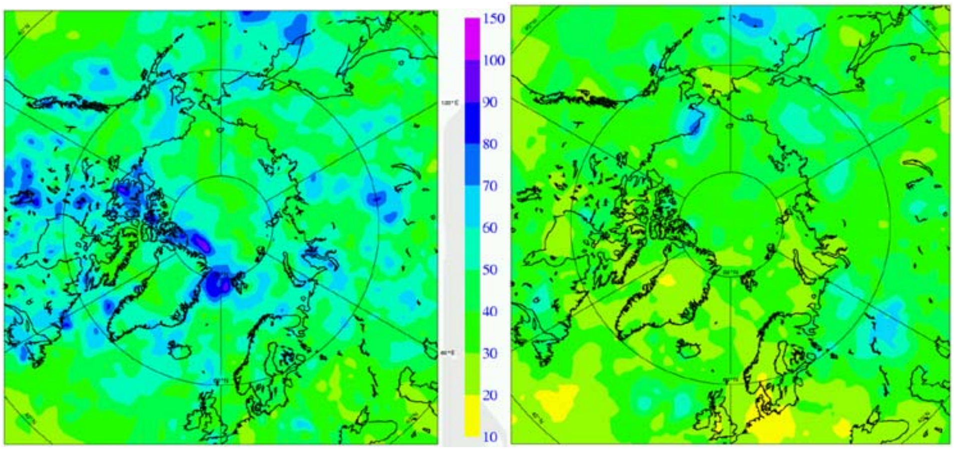

Figure 5 Standard deviation of 500 hPa geopotential analysis increments (shaded in m^2s^{-2}, see legend) in the Arctic comparing July 2001 (left) and July 2006 (right).

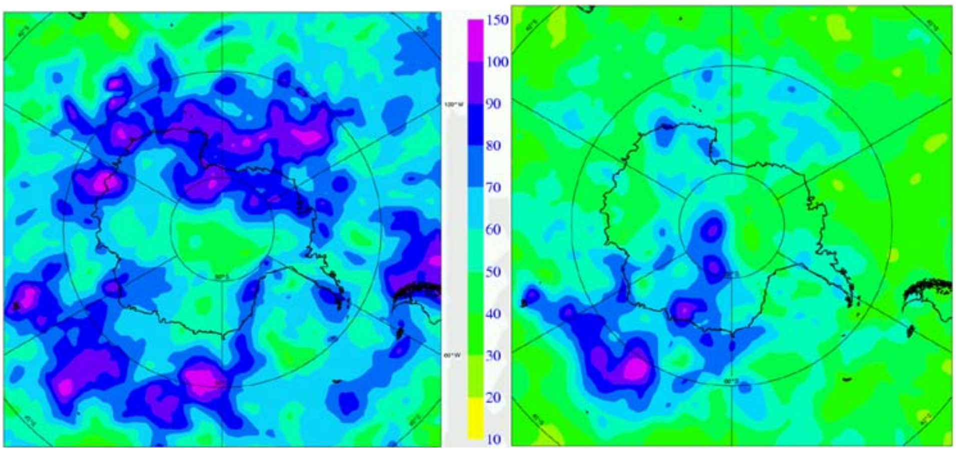

Figure 6 As Figure 5 for the Antarctic.

The United Kingdom MetOffice runs a similar global data assimilation system to ECMWF's. Their analyses can serve as an independent external reference that we can compare the ECMWF analyses against. Both NWP centres have benefited from improved availability of satellite data in the Polar Regions. The comparisons are shown for the Arctic (Figure 7) and the Antarctic (Figure 8) in terms of standard deviations of differences in 500 hPa geopotential analyses. We can see that from July 2001 (left) to July 2006 (right panels) the differences in the Arctic Ocean region have decreased significantly. This convergence between ECMWF and the MetOffice reflects the analysis improvement at both centres. The convergence of analyses has been even more dramatic in the Antarctic region (Figure 8). These charts confirm the conclusion that NWP analyses have become much more accurate over the recent five-year period, and the improvement has been most rapid in parts of the Polar Regions. In 2006, there is nevertheless a very noticeable contrast between land and sea areas in the northern hemisphere, indicating that there are still significant differences in satellite data usage at the two centres.

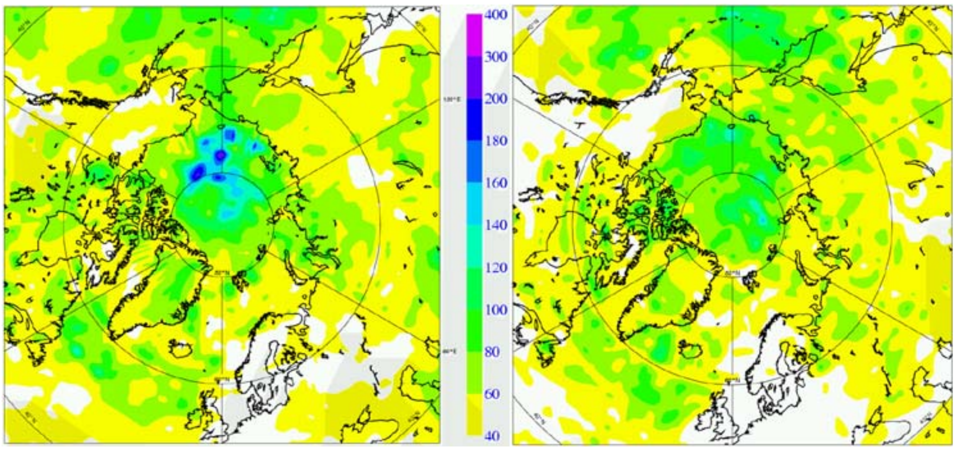

Figure 7 Standard deviation of 500 hPa geopotential analysis differences between ECMWF and the MetOffice (m^2s^{-2}, see legend) in the Arctic comparing July 2001 (left) and July 2006 (right)

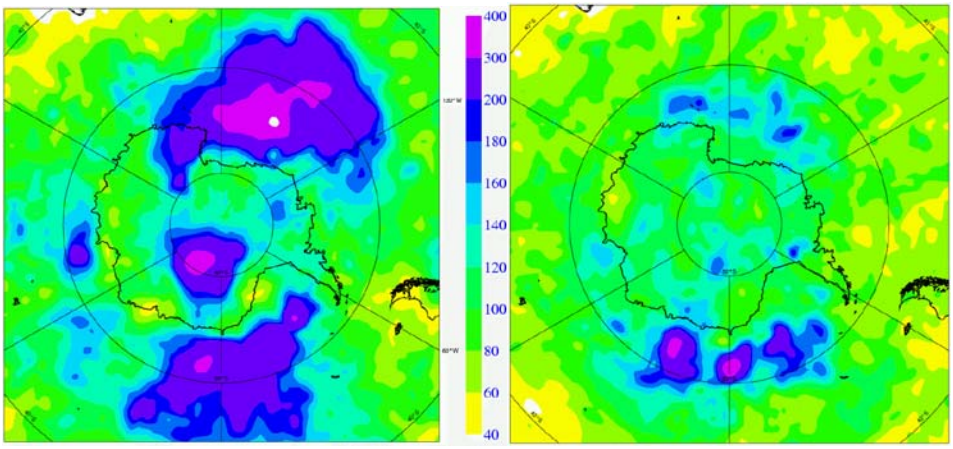

Figure 8 As Figure 7 for the Antarctic

6. Assessment of analysis uncertainty in 2003

Ensemble data assimilation methods naturally provide estimates of analysis uncertainty based on the spread between members of the ensemble of analyses (e.g. the ensemble Kalman filter, Houtekamer and Mitchell 2001; Houtekamer et al. 2005). However, most operational NWP centres currently produce their analyses using variational data assimilation techniques (3D-Var or 4D-Var schemes), for which analysis uncertainty is not so readily available. Here we will use a combined 4D-Var and ensemble approach to generate estimates of 4D-Var analysis and forecast uncertainty, with varying observing systems. The combined approach was proposed and used by Fisher (2003a) for calibration of background error covariances (see Žagar et al. 2005 for explanation and justification). In these ensembles, the assimilations use the static backgound error specifications of standard 4D-Var. No use is made of the ensemble's ability to cycle covariance information as would be the case with an ensemble Kalman filter. Its purpose is purely diagnostic, associating ensemble spread with analysis uncertainty of the 4D-Var.

The results presented in this section are derived from an ensemble of 10 cycling 4D-Var assimilations 20030906 to 20031007. Figure 9 shows 500 hPa height analysis uncertainty as estimated from the 2003 ensemble for the Arctic (left) and Antarctica (right panel). In the Arctic we see that the analysis uncertainty is largest north of the Siberian coast. In the Antarctica the plot clearly shows the beneficial impact of the radiosondes along the eastern coast of the continent, whereas the lack of stations along the western coast results in significantly larger analysis uncertainty there. It appears that these errors continue to grow as they propagate eastwards over the Weddle Sea area.

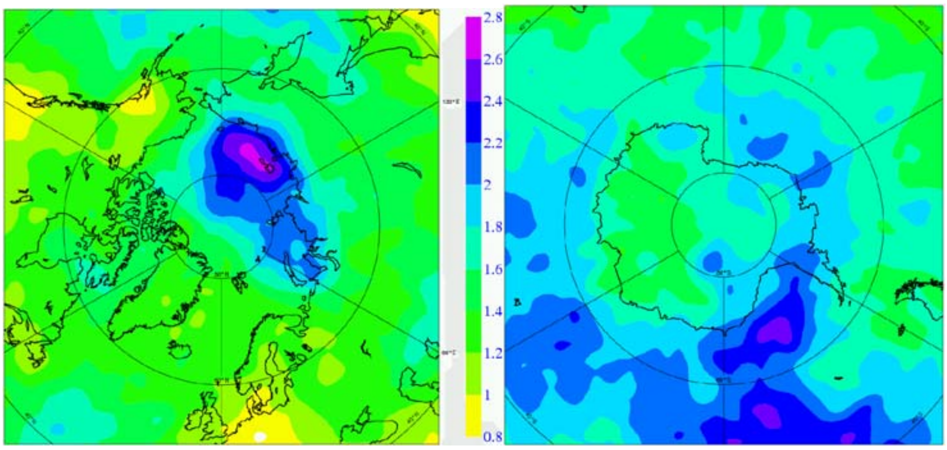

Figure 9 Average daily standard deviations of differences between members of an ensemble (i.e. spread) of independently cycling assimilations, 20030906-20031007. The plots show 500 hPa geopotential height (m, shading see legend).

Maps of Eady index (Figure 10) can indicate where analysis errors are most likely to grow quickly in the early stages of forecasts, and where errors in cycling data assimilation are likely to grow fast unless corrected by information from new observations. The plots show the locations of the main baroclinic zones in this 2003 period and the mid-latitude storm-tracks. At very high latitudes we find baroclinicity maxima across southern Greenland, along the Siberian coast, and along the west Antarctic coast. The latter two locations correspond to areas with larger analysis uncertainty. We can expect that short-range forecast errors develop in these locations. This is indeed confirmed in Figure 11 which shows 24-hour forecast uncertainty derived from the ensemble. Comparing Figure 11 with Figure 9 we see that errors grow in forecasts most rapidly in the storm track regions of the mid-latitudes: in the southern Ocean, the North Pacific and in the area between Greenland and Iceland. At very high latitudes we see that error growth has occurred primarily in the sector between Siberia and Alaska, in the Canadian Arctic, and in the western Antarctica.

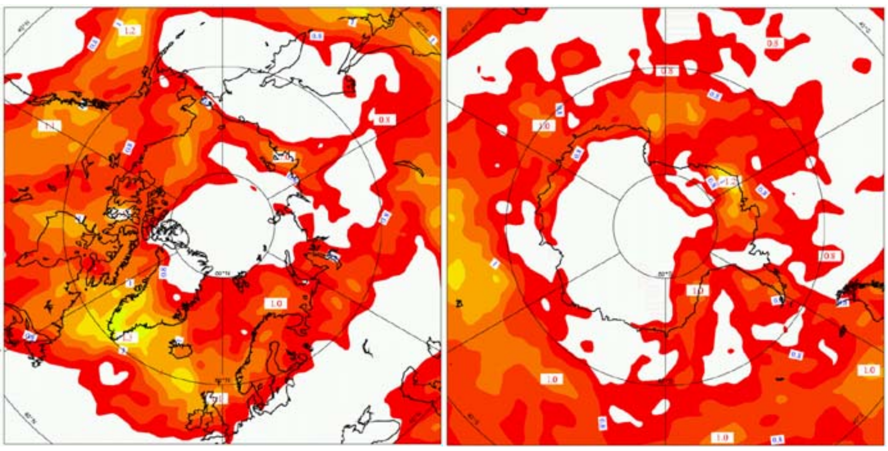

Figure 10 Eady index averaged over the period corresponding to Figure 9.

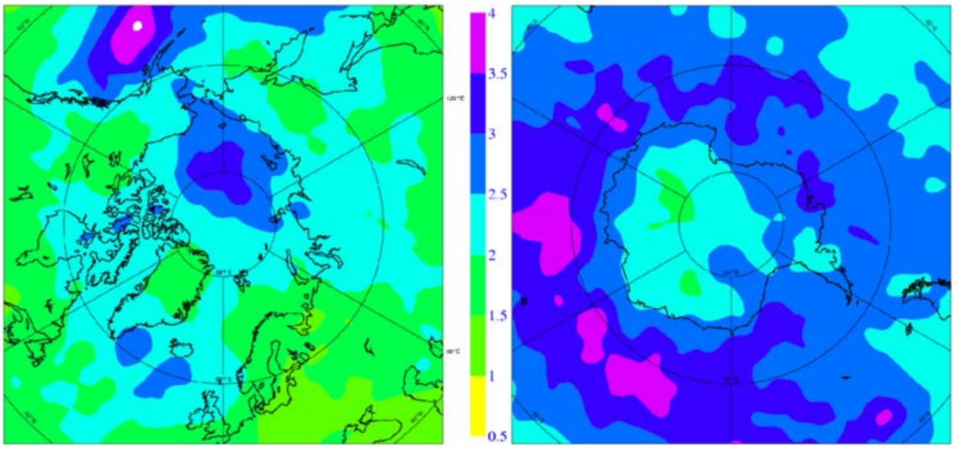

Figure 11 Like Figure 9, but for 24-hour forecast uncertainty

The next two figures (Figure 12 and Figure 13) show analysis uncertainty in terms of 850 hPa temperature and 300 hPa wind, respectively. These show that temperature in the lower troposphere remains uncertain in these analyses, which is due to the difficulty to distinguish between surface and atmospheric contributions in the measured radiances, especially over ice covered surfaces, and in cloudy conditions (McNally 2006, this volume). However, thanks to the availability of MODIS wind observations, the analysis uncertainty for wind is relatively small in the Polar Regions (Figure 13).

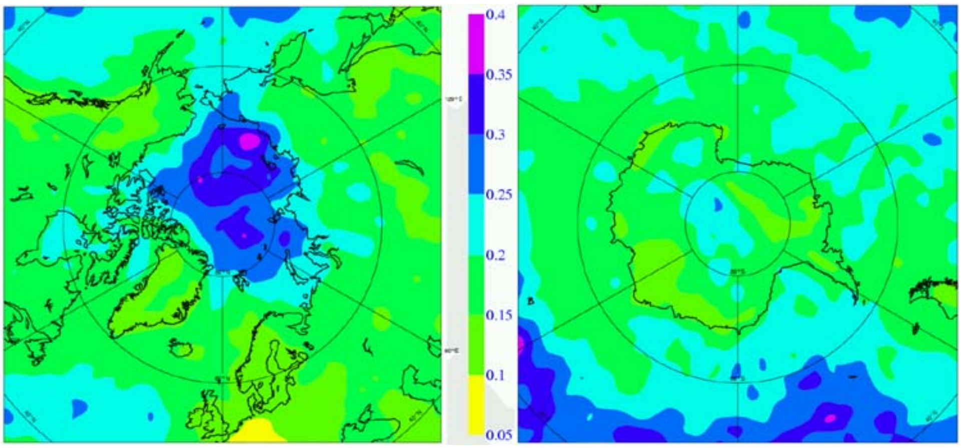

Figure 12 Like Figure 9, but for 850 hPa temperature (K, shaded)

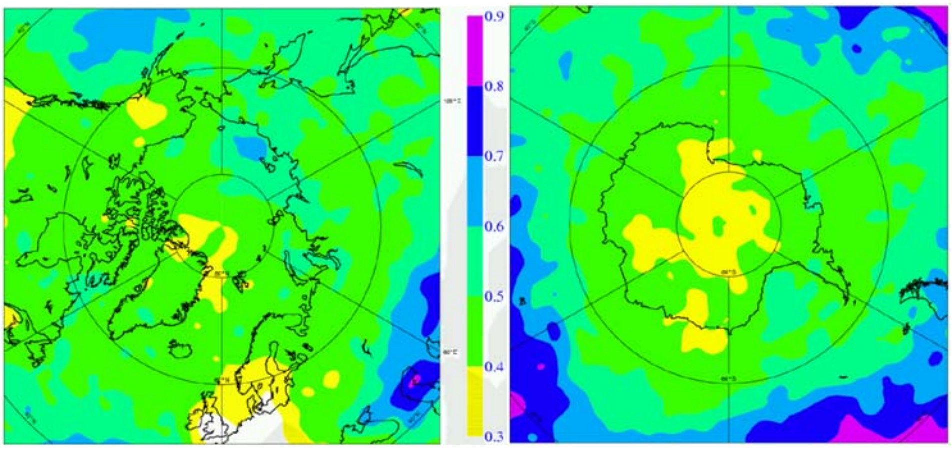

Figure 13 Like Figure 9, but for 300 hPa wind (ms^{-1}, shaded)

7. Comparison with radiosonde profiles from the Odin Artic Expedition in 2001

During the summer of 2001, the Swedish Polar Research Secretariat carried out a two-month expedition to the high Arctic (Tjernström 2002). The ice breaker Oden (Figure 14, right panel) was anchored to drifting sea ice very close to the North Pole for a period of 3 weeks. In this time, a total of 80 TEMPSHIP radiosonde launches were carried out, and these were made available to NWP users via the GTS. The data were received at ECMWF, and used in the operational assimilation system. The data set provides a very rare opportunity to validate the analyses and short-range forecasts against in situ data in the Arctic. For the purpose of this comparison we can assume that the short-range forecast at the Oden position is nearly independent of previous Oden data assimilated in earlier analysis cycles. The results of the comparison are shown in Figure 14, in terms of standard deviations of temperature differences. We see that the analyses (dotted) and short-range forecasts (full lines) agree very well with the radiosonde data in the mid troposphere and the stratosphere. Much larger differences are seen close to the surface and around tropopause level. It appears that the satellite sounding data, which dominate the temperature analyses in the Arctic, constrain the large-scale structures in the free atmosphere. However, the sharp temperature inversion at the tropopause and the surface layer are poorly resolved by the satellites. The latter is consistent with the results shown in Figure 12. Wind errors (differences between Oden radiosondes and ECMWF short-range forecasts, not shown) were around 3 m/s (500-250 hPa), and around 2 m/s in the boundary layer and 200-100 hPa.

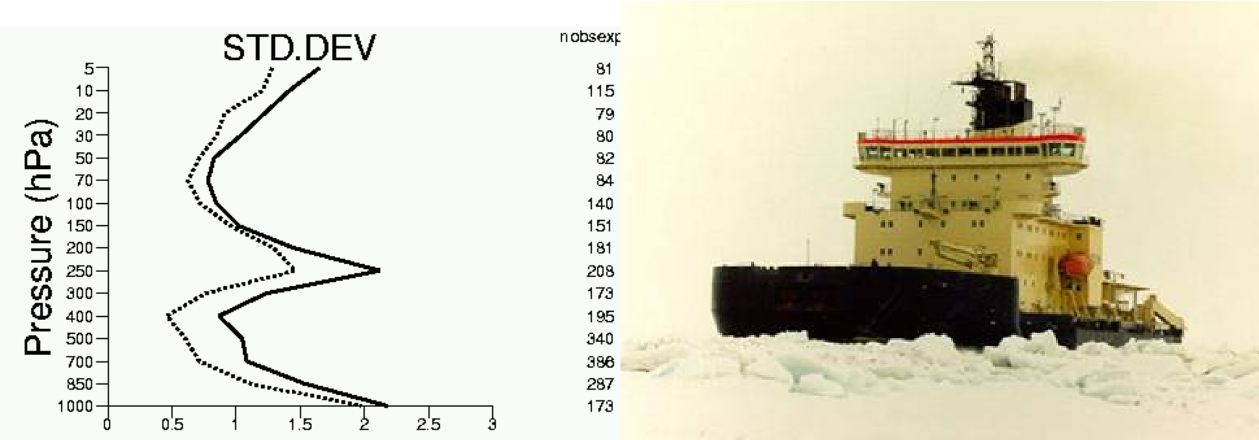

Figure 14 Comparison between ECMWF operational assimilation and temperature sounding data from the Swedish icebreaker Oden (right), during a three-week period (20010801-20010822) when the ship was anchored to the drifting sea ice very close to the North Pole. The two curves show standard deviation of temperature differences (K) between observations and analysis (dashed) and background (full line).

8. Summary and conclusions

Comparing ECMWF's operational analyses for 2001 and 2006 we have found that there has been a very significant improvement in analysis quality over the past five years in both Polar Regions, and particularly so in the Antarctic. The magnitude of analysis increments has been reduced, and the difference between ECMWF and Met Office analyses has also reduced significantly. This is likely due to more extensive use of polar orbiting satellite data at both NWP centres. In the five-year period to 2006, additional temperature sounding infrared and microwave data are being assimilated, and MODIS winds have been introduced.

Based on data assimilation ensemble results we found that the remaining analysis errors (in 2003) are largest along the north coast of Siberia, and in the western Antarctica. These errors occur in baroclinic regions, and grow and evolve into the Artic Ocean, and over the Weddle Sea, respectively, during the early stages of forecasts.

Judging by the number of ‘degrees of freedom for signal’ (DFS) contributed to the analysis by the various observation types, it is clear that satellite radiance measurements are the dominant data source in both Polar Regions. The total DFS attributable to observations pole ward of 65 N (65 S) is 2444 (1412) of which radiances contribute 1497=58% (1167=83%). We deduce that the Arctic is about 1.7 times better observed than the Antarctic. In the Arctic, radiances are followed by radiosonde profile data (577) and MODIS winds (339), whereas in the Antarctic MODIS winds (209) dominate over the radiosondes (70). Single-level surface pressure observations contribute 111 and 22 DFS in the two regions, respectively.

Comparison with a unique set of North-Pole radiosonde measurements provided by the 2001 Oden expedition showed good temperature accuracy in the free atmosphere of the ECMWF operational analyses. The short-range forecast error (~6 hours) was 1K or less between 700-400 hPa, and also between 150-50 hPa. This is a very good result considering that there are no regular, in situ, upper-air data in the Arctic Ocean. Within the boundary layer and around the tropopause, however, the errors reach 2 K, which can be explained by the relatively poor vertical resolution of satellite sounding data, and difficulties distinguishing between surface and atmospheric influences on radiance measurements that partly sense the ground. Based on these 2001 results and the documented improvement since then, we have reason to expect that 2006 results would be even better in the free atmosphere. The analysis of the high-latitude tropopause may have benefited from the use of AIRS radiances (assimilated since October 2003) with better vertical resolution than HIRS and AMSU-A, and also by improved representation of the background errors at high latitudes provided by the “wavelet Jb” formulation (implemented April 2005, Fisher 2003). In the near future, it is expected that the use of radio-occultation data (Healy et al. 2006) will provide vertically resolved temperature data with good accuracy and in a few years’ time that the ADM-Aeolus satellite (Stoffelen et al. 2005) will provide wind-profile measurements with similar accuracy to radiosondes.

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