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Data assimilation in the polar regions

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Data assimilation in the polar regions

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The polar regions provide challenging environments for data assimilation. In situ meteorological stations are difficult and costly to establish and maintain, and remote sensing is often hampered by extensive cloudiness. Therefore, there used to be a general lack of data for initialization of higher-resolution models. Lower-resolution models are inadequate in the areas of extreme topography encountered in parts of Antarctica and Greenland. The shifting surface conditions (ice, snow and open water) gives rise to highly varying surface emissivity, which impacts the satellite measurements and makes their interpretation in terms of atmospheric parameters more difficult. In the last five years, however, tremendous progress has been made due to the availability of new satellite instruments and improved data assimilation techniques. This article contrasts 2001 with 2006 in terms of analysis accuracy in the Arctic and Antarctic.

Observations and the assimilation system

Concerted efforts to exploit more satellite observations (*Thépaut & Andersson,* 2003, *ECMWF Newsletter No. 97*) have led to a five-fold increase in the number of observations used in global data assimilation, from about 1.4 million data items per day in 2001 to 7 million in 2006. 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. The availability of meteorological observations in the polar regions is reviewed in Box A.

At ECMWF, the data assimilation system is run at the same resolution as the operational forecast model. In February 2006 the model was upgraded to T799L91 (approx. 25 km and 91 model levels, *Untch et al.,* 2006, *ECMWF Newsletter No. 108*) with 4D-Var analysis increments at T255 (~80 km). The resolution increases clearly improve the representation of steep topography, as seen in Figure 1 for the area surrounding Ross Island and the McMurdo station in Antarctica. Improved topography allows a more accurate 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. This requires a dense network of surface stations and mesoscale assimilation systems with a resolution of a few kilometres. 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 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 such event per month (i.e. an under-representation by a factor 4 to 8).

The assessment of analysis accuracy which will now discussed 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.

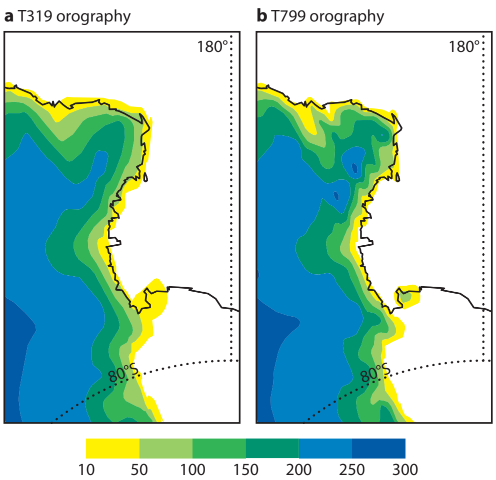

Figure 1 Model orography as represented by (a) T319 resolution model (~63 km) operational until January 2001 and (b) T799 model (~25 km) introduced in February 2006.

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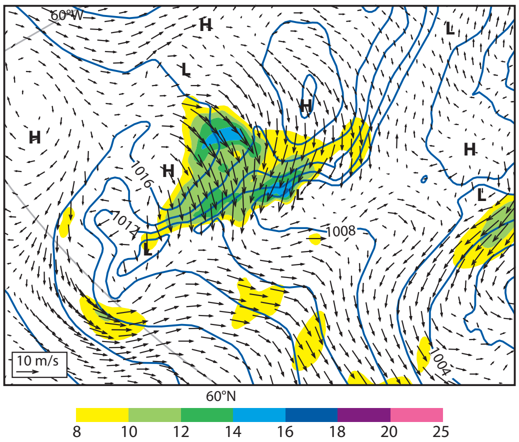


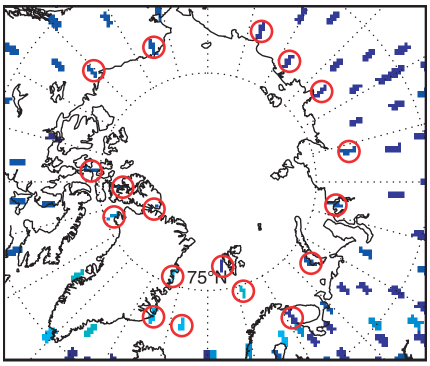
Figure 2 ECMWF analysis of a relatively large-scale katabatic wind event and associated formation of lee cyclones along the east coast of Southern Greenland, 12 UTC on 1 July 2006. The wind arrows show wind speed and direction, the shading shows wind speed ($m\,s^{-1}$, see legend) and blue contours show mean sea-level pressure (2 hPa interval).

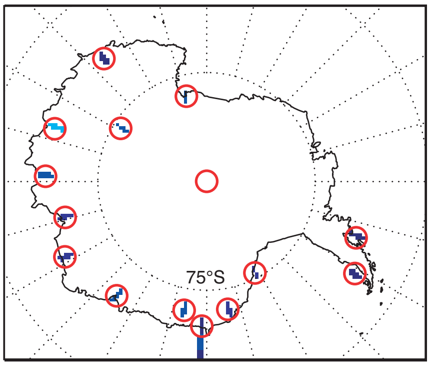
Meteorological observations in polar regions

A

The Arctic has good **radiosonde** coverage up to 70–75°N, and even to 80°N in the Canadian Islands and Northwest Greenland (left panel). The Antarctic coast at 65–70°S (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.

The provision of **surface pressure observations** from SYNOP stations, SHIPs and BUOYs is reasonably good in most parts of the Arctic, except in the interior of Greenland, and in the Arctic Ocean. In the Antarctic area, there are a good number of stations along the coast and many drifting buoys in the open ocean reporting hourly surface pressure data, but there are large data voids in the areas of frozen sea and in the interior.





Radiosonde observations in the Arctic and Antarctic. The marker at each station indicates the number of reports received in July 2006: dark blue indicates one TEMP per day and light blue indicates two TEMPs per day.

There is an increasing number of temperature and wind observations in the Arctic provided by **commercial aircraft**, primarily en route between Europe, North America and Japan. This data provides important information around flight level (typically ~10 km) over Greenland, Canada, Alaska and Siberia. Only a very small number of flights cross the Artic Ocean, which therefore remains almost entirely void of such data. The Antarctic has no aircraft 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 provides unprecedented coverage of wind observations throughout the regions poleward of 65°N and 65°S. Observing system experiments comparing assimilations with and without MODIS data have shown very substantial impact of these data on analysis and forecast quality

There is a very comprehensive coverage of **satellite radiance** data from infrared (AIRS and HIRS) and microwave (AMSU-A and AMSU-B) instruments on polar-orbiting satellites. The current constellation of spacecraft provides frequent data from partly overlapping orbits at high latitudes.

Performance improvements and comparison between ECMWF and Met Office polar 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.

Here we compare the standard deviations of analysis increments in ECMWF's operational analyses in July 2001 against July 2006. Figure 3 shows the results for the Arctic and the Antarctic. The plots show a dramatic reduction in analysis increments between 2001 (left panels) 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 five-year period. Similarly, in 2001 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.

The United Kingdom Met Office runs a similar global data assimilation system to ECMWF's. The Met Office analyses can serve as an independent external reference against which we can compare the ECMWF analyses. Both NWP centres have benefited from improved availability of satellite data in the polar regions. The comparisons are shown in Figure 4 for the Arctic and the Antarctic in terms of standard deviations of differences in 500 hPa geopotential analyses. We can see that from July 2001 (left panels) to July 2006 (right panels) the differences in the Arctic Ocean region have decreased significantly. This convergence between ECMWF and the Met Office reflects the analysis improvement at both centres. The convergence of analyses has been even more dramatic in the Antarctic region. These charts support the conclusion that NWP analyses and models 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 ECMWF and the Met Office.

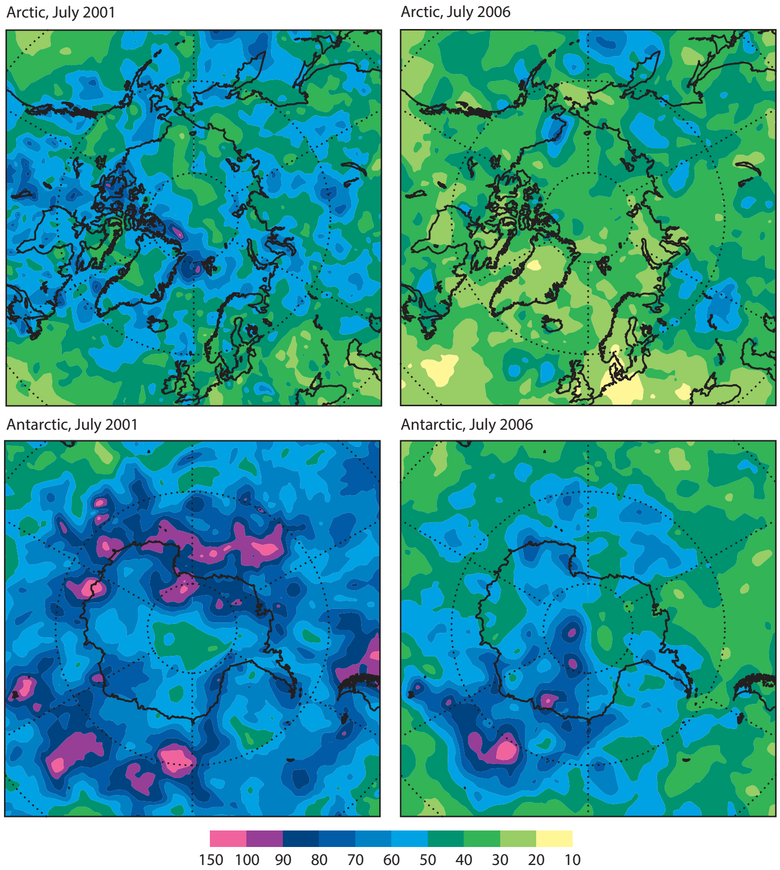


Figure 3 Standard deviation of 500 hPa geopotential analysis increments (shaded in m^2s^{-2}, see legend) comparing July 2001 (left) and July 2006 (right), for the Arctic (top) and Antarctic (bottom).

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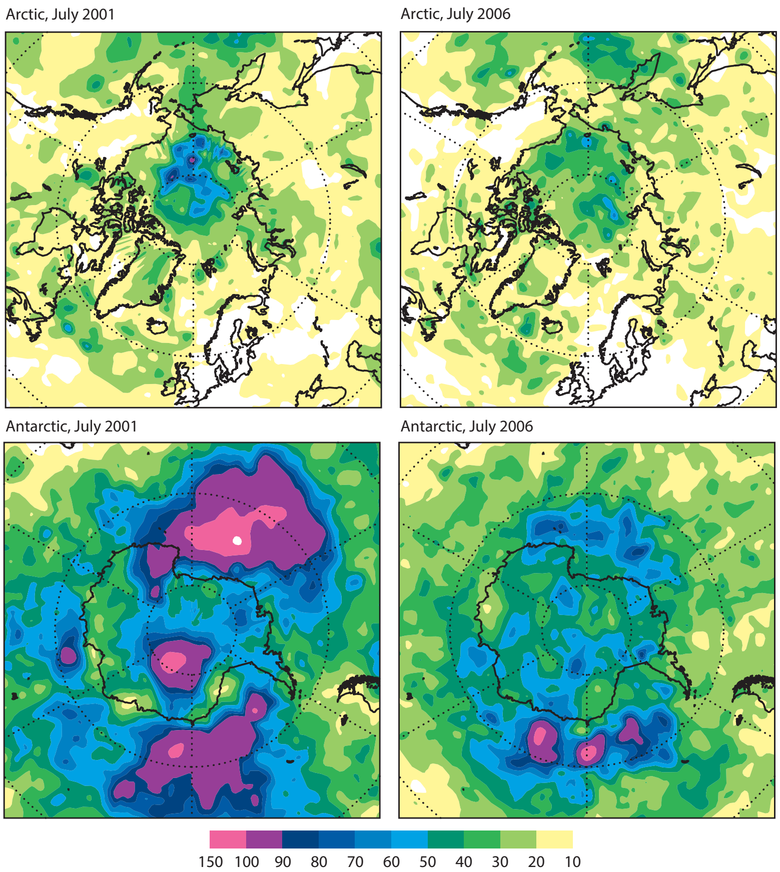

Figure 4 Standard deviation of 500 hPa geopotential analysis differences between ECMWF and the Met Office (m^2 s^{-2}, see legend) comparing July 2001 (left) and July 2006 (right), for the Arctic (top) and Antarctic (bottom).

Assessment of analysis uncertainty in 2003

Now consider an assessment of uncertainty based on an ensemble of ten cycling 4D-Var assimilations from 6 September to 7 October 2003. The spread between members of the ensemble provides a measure of analysis uncertainty. Figure 5 shows analysis uncertainty as estimated from the 2003 ensemble for the Arctic (left panels) and Antarctica (right panels).

From Figure 5(a) we see that in terms of 500 hPa height the analysis uncertainty in the Arctic is largest north of the Siberian coast. The corresponding results for Antarctica clearly show 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.

Figures 5(b) and 5(c) show analysis uncertainty in terms of 850 hPa temperature and 300 hPa wind. Note that the temperature in the lower troposphere remains uncertain in these analyses; this is due to the difficulty in distinguishing between surface and atmospheric contributions in the measured radiances, especially over ice covered surfaces, and in cloudy conditions. However, thanks to the availability of MODIS wind observations, the analysis uncertainty for wind is relatively small.

Comparison with radiosonde profiles from the Odin Arctic 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 6(a)) was anchored to drifting sea ice very close to the north pole for a period of three weeks. During 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 was 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 Oden's position is nearly independent of previous Oden data assimilated in earlier analysis cycles.

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The results of the comparison are shown in Figure 6(b) in terms of standard deviations of temperature differences. We see that the analyses and short-range forecasts agree very well with the radiosonde data in the mid troposphere and 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 5(b). Wind errors (differences between Oden radiosondes and ECMWF short-range forecasts) were around 3 $m s^{-1}$ (500–250 hPa), and around 2 $m s^{-1}$ in the boundary layer and 200–100 hPa.

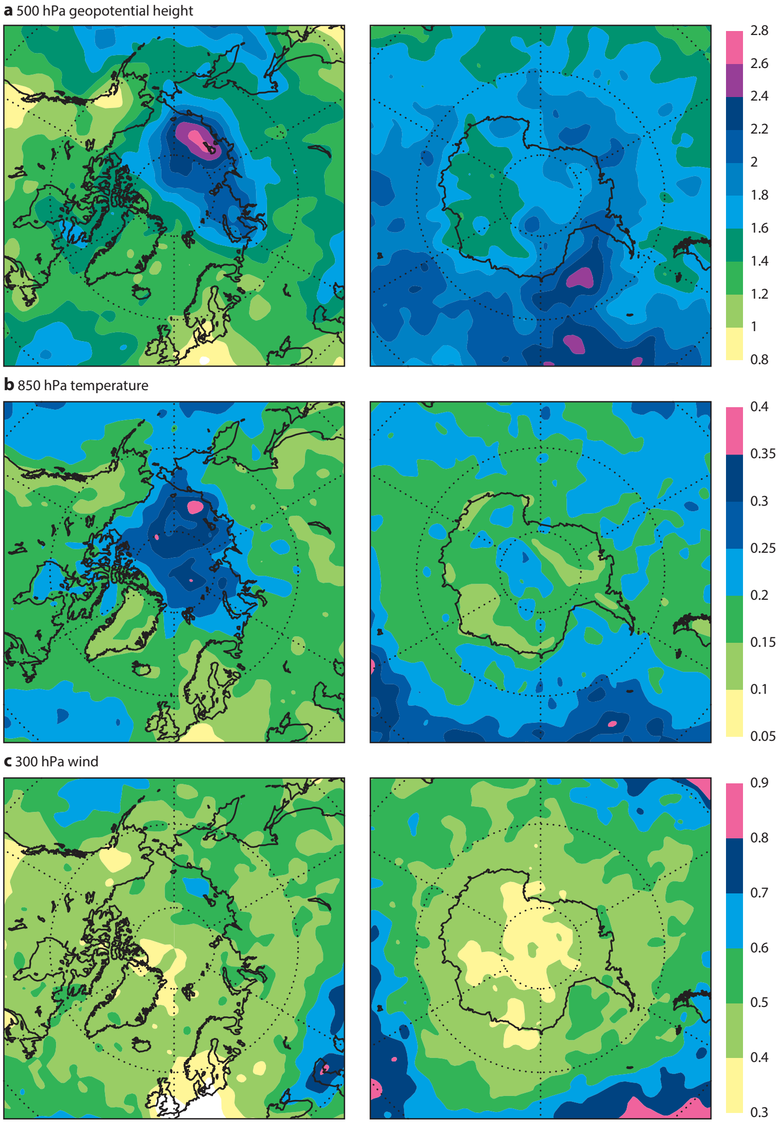

Figure 5 Average daily standard deviations of differences between members of an ensemble (i.e. spread) of independently cycling assimilations, 6 September to 7 October 2003 for the Arctic (left) and Antarctic (right): (a) 500 hPa geopotential height (m, shading see legend), (b) 850 hPa temperature (K, shaded) and (c) 300 hPa wind (ms^{-1}, shaded).

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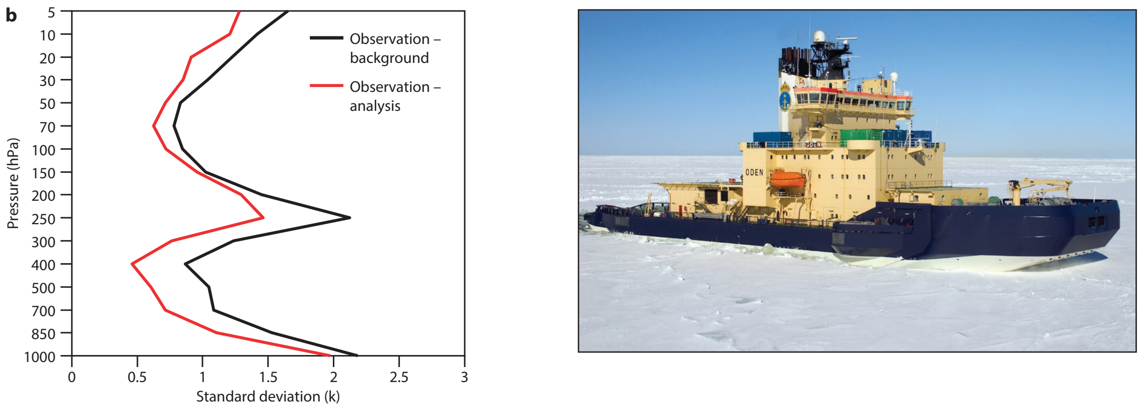

Figure 6 (a) The Swedish icebreaker Oden from which temperature soundings were made in polar regions. (b) Comparison between ECMWF operational assimilation and temperature sounding data during a three-week period (1 to 22 August 2001) when Oden was anchored to the drifting sea ice very close to the north pole. The two curves show the standard deviation of temperature differences (K) between observations and analysis (red line) and observations and background (black line).

Summary and outlook

The current work was presented at the 2006 ECMWF Seminar devoted to the impending International Polar Year (IPY, www.ipy.org). Comparing ECMWF's operational analyses for 2001 and 2006 we 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, and improved forecast models in general. In the five-year period to 2006, additional temperature soundings using infrared and microwave data are being assimilated, and MODIS winds have been introduced.

Comparison with a unique set of radiosonde measurements at the north pole 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 1 K 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. This can be explained by the relatively poor vertical resolution of satellite sounding data, and the difficulties in 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 radiances from AIRS (Atmospheric InfraRed Sounder), assimilated at ECMWF since October 2003; this data has a better vertical resolution than data from HIRS and AMSU-A. Also the improved representation of the background errors at high latitudes provided by the "wavelet Jb" formulation (*Fisher,* 2005, *ECMWF Newsletter No. 106*) may have been beneficial. In addition the recent introduction of radio-occultation data into operations (*Healy,* 2007, *ECMWF Newsletter No. 111*) now provides vertically resolved temperature data with good accuracy in the upper troposphere and lower stratosphere.

It is expected that in a few years' time the ADM-Aeolus satellite (*Tan & Andersson,* 2005, *ECMWF Newsletter No. 103*) in polar orbit will provide wind-profile measurements with similar accuracy to radiosondes. This will further improve the analyses in polar regions.

Further reading

Tjernström, M., 2002: Arctic Ocean 2001 expedition. *Vaisala News,* **159,** 6–10.