Model performance and data impact over polar regions

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In this paper, general scores and analysis differences are presented for global models over polar areas. Data monitoring results and the impact of observations is discussed over the Southern pole, while results are presented for the assimilation of IASI data over the Antarctic plateau and of microwave satellite data over sea ice.

1. Introduction

The positive impact of Numerical Weather Prediction (NWP) on safety and economic competitiveness is widely recognized. Until recently, forecasting applications have been mainly assessed in the densely populated mid-latitude and tropical regions. However, a critical issue for society is whether climate change can result in a severe depletion of the Arctic sea ice and in a significant change of the mass budget of the Antarctic ice sheet which could impact global sea-level.

Models and reanalyses datasets are vital tools to assess the evolution in time of the precipitation distribution and other fields important to the mass budget. Accurate real-time analyses and forecasts are also of importance for local weather prediction (used for the safety of local population and in field operations), as well as for a better understanding of more global interactions between polar areas and other regions. There are many challenges in this field. The polar areas are operationally and climatologically data sparse, due to highly limited surface observing facilities. Satellite measurements have the potential to fill these data gaps, but they present their own unique challenges and difficulties. The meteorological conditions are also extreme, with small scale phenomena and a high importance of the coupling between the atmosphere, sea-ice and snow.

The World Weather Research Programme (WWRP) Polar Prediction Project's mission Statement is to "Promote cooperative international research enabling development of improved prediction services for the polar regions, on time scales from hourly to seasonal". Their general Recommendations for Verification of NWP systems include a formal inter-comparison of polar predictions (pole-wards of 60° N and 60° S) and the strengthening of verification activity utilizing operational and research data bases. The Working Group for Numerical Experimentation (WGNE) also noted these needs and recommended a first study to be performed along these lines, and some data monitoring to be performed in particular during the Concordiasi field experiment (Rabier et al, 2010).

This article is a contribution as a first step to achieve these goals. In the first part, preliminary results from polar forecast scores compiled from a few NWP centres by the European Centre for Medium-range Weather Forecasts (ECMWF) and analysis differences compiled by NRL are presented. In the second part, data from the Concordiasi field campaign over Antarctica are used to provide in depth model monitoring statistics over the Southern polar area in Austral spring 2010. In the third part, results from satellite data retrievals and assimilation are presented over polar areas.

2. Polar scores and data impact over the Southern Pole

2.1. Polar scores

As stated above, the WCRP-CAS sponsored Working Group for Numerical Experimentation (WGNE) has recently promoted actions contributing to the investigation and inter-comparison of performances of NWP systems over polar areas. ECMWF is coordinating this activity and has been inviting NWP centres to provide their respective forecast scores for areas under scrutiny, poleward of 60degrees. At the time of writing, it was possible to compare scores from 5 NWP centres: ECMWF, Météo-France, the UK MetOffice, the US National Centers for Environmental Prediction (NCEP), and the Canadian Meteorological Centre (CMC).

Forecast scores naturally vary depending on weather regimes and seasons. In order to assess long term progress in model performances over polar areas, the ECMWF ERA-interim reanalysis (Dee et al., 2010), which uses a fixed model and assimilation system throughout the period 1979 to present, has been used as an independent performance evaluation tool, in order to diminish the effect of inter-annual and seasonal variability on the scores' evolution.

Fig. 1 shows the evolution over the last 12 years of 3-day range 500 hPa geopotential height forecast error RMS scores (12 month running average) from different NWP centres over the Arctic and Antarctic domains (see legend for details). The first remark is that since 2000, all NWP centres have dramatically and continually improved their forecast skill over both regions. It can also be noted that ERA-interim shows a long term slow but positive forecast skill trend, indicating an improvement in the observing system. It is in particular very likely that the increase in the number of AMSU instruments over the last decade explains this positive trend.

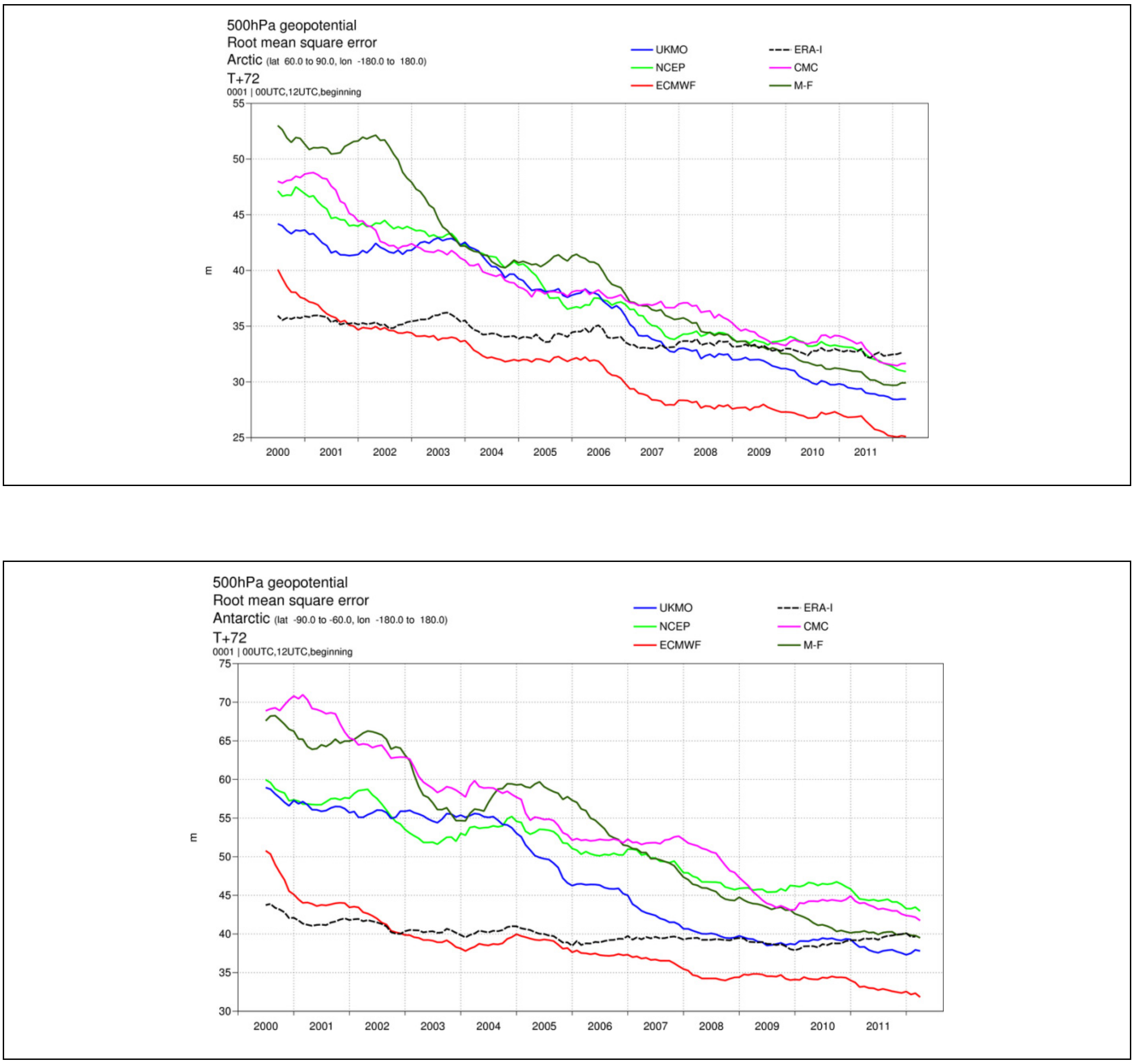

Figure 1: Root mean square error of 500 hPa geopotential height for 3-day forecasts for the Arctic area (North of 60N, top panel) and for the Antarctic area (South of 60S, bottom panel), plotted in the form of annual running means of scores for the period 2000 to 2012. Scores are displayed for ECMWF (red), UK Met Office (blue), Météo-France (dark green), NCEP (light green), CMC (pink), and ERA-interim (Dotted black). Each Centre is verified against its own analysis.

Another interesting feature is that by 2011, over the Arctic domain, all centres are performing better than the fixed, 2006-based, low resolution (80km grid) ERA-interim system. Remarkably, ERA-interim remained the second best until the end of 2007. The slope of the trends is rather similar across the centres, with the noticeable exception of Météo-France between 2002 and 2006 which corresponds to the gradual introduction of more radiances in the system, and UK MetOffice since 2004-2005 which corresponds to the implementation of 4D-Var. Overall and especially for the short-range, the discrepancy between the different models performance has reduced over the last decade.

Over the Antarctic area, forecast errors are larger in general, and the spread of models performance is also somewhat larger. A noticeable feature is that ERA-interim remains in the middle of the distribution, and is only outperformed by the ECMWF and the UK MetOffice NWP systems, Météo-France also getting very close since 2011.

It is also useful to examine systematic differences in atmospheric analyses produced by different data assimilation systems (as in Langland et al, 2008). In the following, the analyses of Météo-France, the Global Modeling and Assimilation Office (GMAO, US), the Naval Research Laboratory (NRL, US) and ECMWF are compared. These analysis differences represent an approximation to the error in estimates of the true atmospheric state, and are closely correlated with the distribution of in-situ and satellite observations, and with atmospheric error growth rates. The average "static-time variance" of analysed 500 hPa geopotential height for 27 Sept. to 16 Nov. 2010 is shown in Figure 2. For this quantity, large variance is found where there are frequent and relatively large differences between the four analyses. If all 500 hPa height analyses were identical at every time, the average static-time variance would be zero. Note that Fig 2 is not a variance of 500hPa height over time. Here, "static-time variance" indicates that the variance is with respect to the mean of four analyses valid at the same time. Static-time variance in 500 hPa height analyses is due to various factors, including differences between analysis/forecast systems in observation selection, quality control, bias correction, data assimilation methodology, and in the forecast models that provide background forecasts for the data assimilation procedure. In addition, analysis differences may typically be larger in regions with strong atmospheric dynamics and rapid error growth, as found along the polar front jet, since this can create larger spread between background forecasts of the various forecast systems.

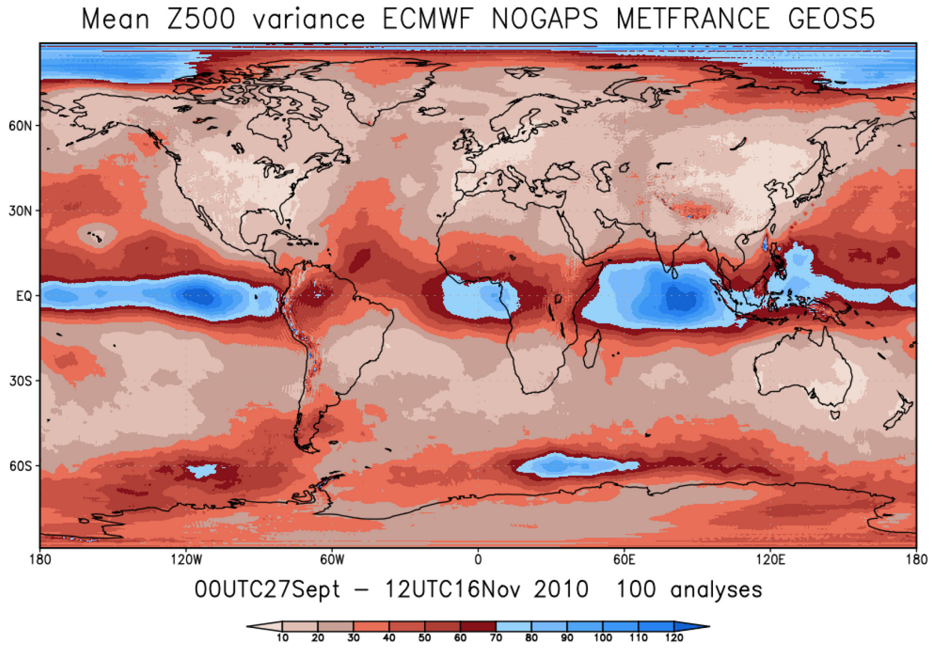

Figure 2: Average static-time variance of analyzed 500 hPa geopotential height for the four models, for analyses at 00UTC and 12UTC from 27Sept to 16 Nov 2010. The average variance is calculated by producing an average of the four separate analyses at each analysis time (00UTC and 12UTC daily) and taking the variance of each model's analysis from the average analysis. These variances are then summed and divided by the number of analyses, to produce the average static-time variance plot. [There are 100 separate analyses included from 27Sept to 16 Nov 2010.] Units are m^2.

It is seen in Fig. 2 that largest average static-time variance in analysed 500hPa height for this time period is found in three different zones, the Tropics and two polar areas extending from about 50 to 70 degrees south and from 75 to 90 degrees north. The Southern ocean "ring of uncertainty" is an area with a relative gap in satellite-wind observation coverage, and subject to strong atmospheric dynamics. The averaged intensity of singular vectors computed over the polar region for the ECMWF system during this period is indeed located in this area. It corresponds to the areas where small perturbations of the flow will grow the fastest in the short-range (Buizza and Palmer, 1995).

2.2. Data impact over the Southern Pole

We will now focus on the Southern Pole, and document the impact of polar observations, which correspond to observations at latitudes poleward of 60 degrees south in the period from 27 September to 16 November 2010, which corresponds to the Concordiasi field experiment. Concordiasi was a multi-disciplinary effort jointly operated by France and the United States to study the lower stratosphere and troposphere above Antarctica as well as the land surface of the Antarctic continent (Rabier et al, 2010, Rabier, et al, 2012). In 2010 an innovative constellation of balloons provided a unique set of measurements covering both volume and time (Cohn et al, 2013). The balloons drifted for several months on isopycnic surfaces in the lowermost stratosphere around 18km, circling over Antarctica in the winter vortex. The balloon flotilla formed a regional observatory of the atmosphere, which provided in situ measurements inside the winter stratospheric polar vortex and allowed the performance, on command, of hundreds of soundings of the troposphere. Overall, 644 high-quality dropsonde profiles were recorded, with a uniform distribution over the Southern polar area. Data were distributed fast enough to be placed on the Global Telecommunication System (GTS) in real time. Most NWP centres were then able to include these data in their systems, either in passive or active mode.

The calculation of the impact of observations using the adjoint of a data assimilation system (e.g., Langland and Baker 2004, Cardinali, 2009, Gelaro, et al, 2007), was performed. Data impacts are investigated in the numerical weather prediction systems run by four centres involved in the Concordiasi project: Météo-France (France), the Global Modeling and Assimilation Office (GMAO, U.S.), the Naval Research Laboratory (NRL, U.S.) and the European Centre for Medium-Range Weather Forecasts (ECMWF, Europe). Results are shown in Figure 3.

The impact of the different observation groups are not equally distributed. For GMAO, Météo-France and ECMWF, in particular, 75 to 79 % of the total forecast error reduction comes from 3 instruments which are not the same ones depending on the system. For the NRL system, the impact comes from more observation sources and is better distributed among 6 of them.

As in the global context (not shown), AMV wind observations in the NRL system have the largest impact on forecast error reduction in the south polar region due to assimilation of MODIS and AVHRR wind data. This case notwithstanding, AMSU-A and IASI have a good impact in all systems, representing around 60 % of the total contribution (except for NRL, for which it is 33%).

Each system has its particularities reflecting different assimilation strategies. Météo-France shows detrimental impact of AMVs in this region, which should be investigated further. AMSU-B radiances account for more than 13 % of total forecast error reduction in the Météo-France system, reflecting efforts made in recent years to assimilate more AMSU-A and AMSU-B radiances, particularly over land and sea ice. For ECMWF and Météo-France, conventional observations coming from synop stations, ship and buoys play an important part in improving forecasts, representing 4.8 and 12.2 % of the error reduction respectively. This is also true in the NRL system where this group of observations explains nearly 8 % of the forecast error reduction.

Measurements made by radiosondes contribute between 6 and 10 % to the total in all systems except in the ECMWF system where they surprisingly contribute only 1.3 %. In contrast, AIRS data play an important part in ECMWF system as they contribute more than 22 % of the total. This is the only system where they have such a large impact.

GPS radio-occultation measurements play a very important role in the GMAO system. In second position when looking at the ranking, they contribute nearly 18 % of the total impact. Although this value is less important in NRL (4.7 %) and ECMWF (6.4%), these observations have a good impact. Only the Météo-France system is less responsive to these observations with only 2.3 % of the total impact. The explanation may lie in the number of data assimilated, as they were vertically thinned to keep only one datum per model vertical layer at that time. This vertical thinning is not applied in the other systems, and is not applied anymore at Météo-France. SSMI/S data have a relatively good impact in the NRL system (8.4%), the only system that assimilates them in this experiment.

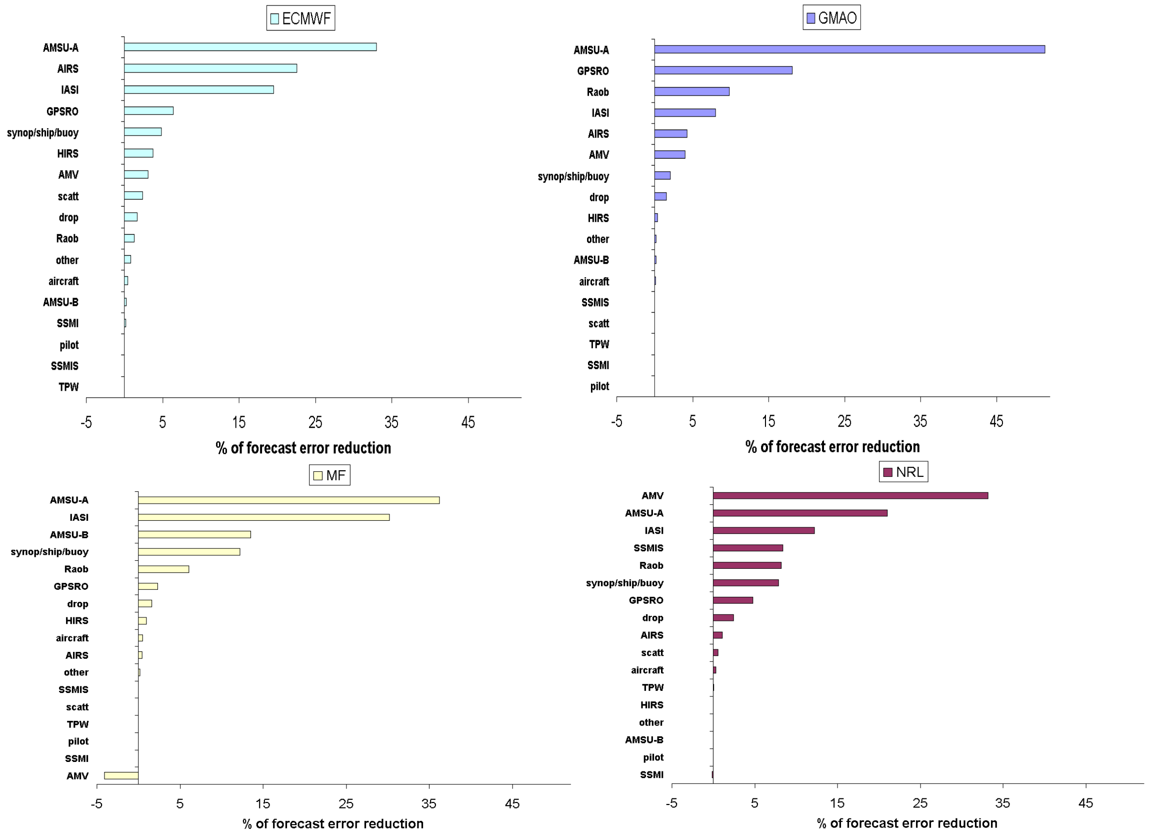

Figure 3 : Normalised impact of different observation groups for ECMWF, GMAO, Météo-France and NRL systems. It corresponds to the percentage of reduction of 24-hour forecast error, for data in the Southern polar area.

Additional results looking at the impact of radiosondes and dropsondes show that, at lower levels of the atmosphere, the temperature observations have the largest impact, while at the upper levels the winds have the largest contribution.

3. Model performance over Antarctica during the Concordiasi field experiment

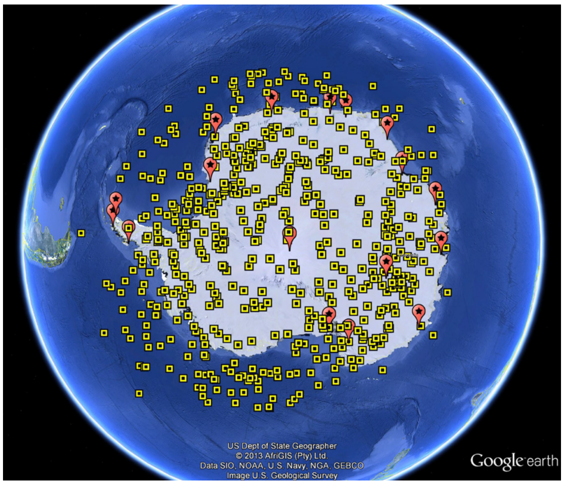

Figure 4: Map of Antarctica, with the location of Concordiasi dropsondes (in yellow) and of a few radiosonde stations (in red). Two stations are located inland (South Pole and Concordia), two at the peninsula (Rothera and Marambio), and the rest along the coast of Antarctica.

During the Concordiasi field experiment, a comparison between short-range forecasts and the radiosonde and dropsonde data was investigated for 9 centres in the United States, France, Canada, Japan, Germany, and the United Kingdom. Locations of radiosondes and dropsondes are illustrated in Figure 4.

3.1. Radiosonde monitoring statistics

Figure 5 shows the standard-deviations of background departures (Observation minus short-range forecasts) for all the NWP centres, for temperature at standard pressure levels, for the radiosondes assimilated in the area. A standard quality control has been applied to all sets (deviation smaller than 5K). The number of data points is indicated on the right. The time period is September-November 2010, during the Concordiasi field campaign. During this time, there were more frequent radiosonde ascents from Dumont d'Urville and Rothera. The statistics are presented for different sets of stations: the peninsula, the coast, the South Pole (Amundsen-Scott) and Concordia.

In general, ECMWF is performing particularly well in the lower troposphere, DWD not so well in the higher troposphere and stratosphere (probably due to an under-utilization of satellite radiances compared with other centres). In most cases, errors increase close to the surface. Over the peninsula, one can note quite a large variability in the upper atmosphere, with errors significantly larger than 1K above 400hPa, whereas for the other areas errors stay within 1K up to 100hPa. This peninsula area is very active meteorologically, with a strong gravity wave activity, which could be responsible for these features. It should be noted that not all centres were receiving Concordia observations in real-time (this has been corrected since then).

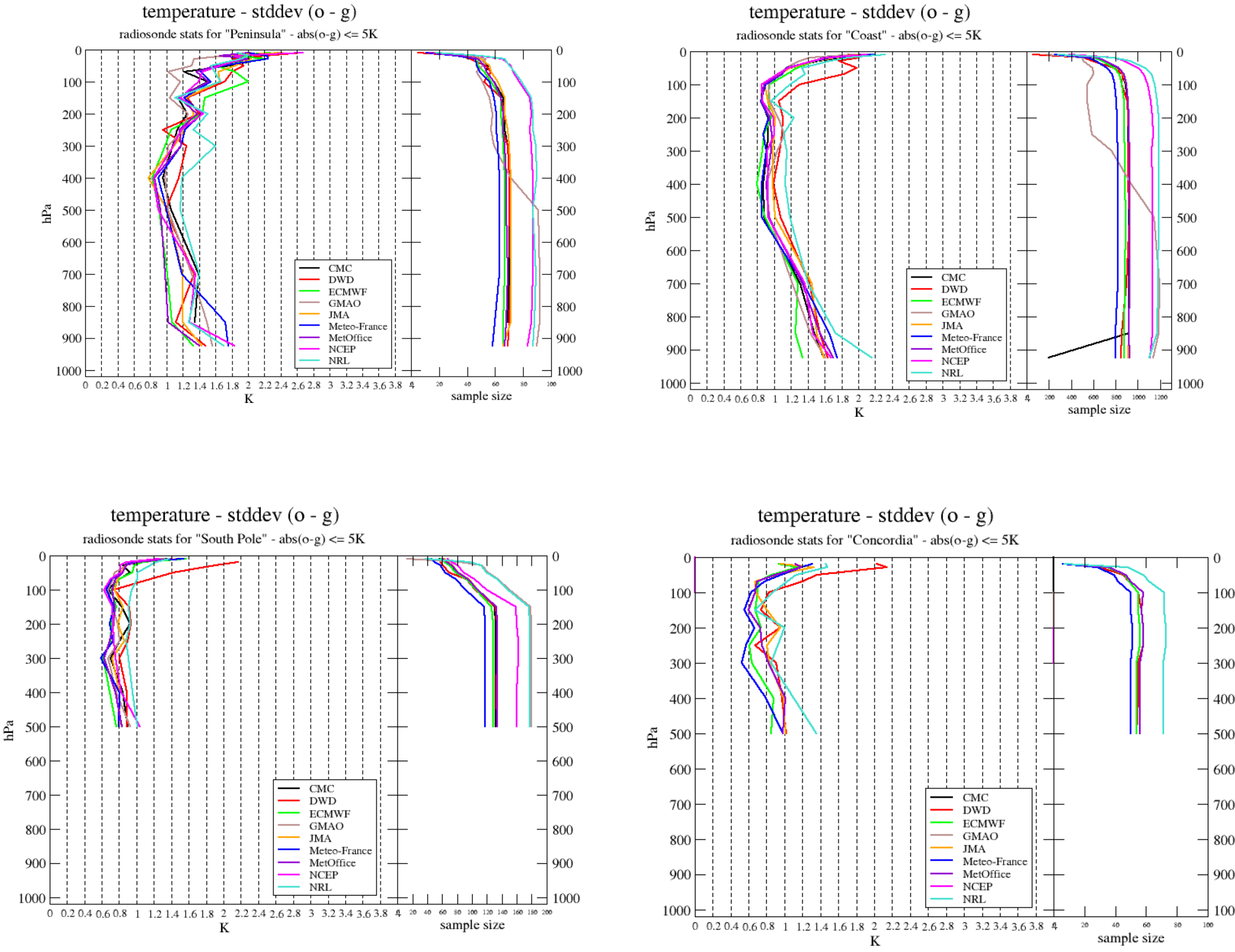

Figure 5: Standard-deviations of background departures (Observation minus background) for 9 NWP centres, for temperature at standard pressure levels. A standard quality control has been applied to all sets (deviation smaller than 5K). The number of data points is indicated on the right. The time period is September-November 2010. The areas are the Peninsula (top left) , the Antarctic Coast (top right), South Pole (botton left) and Concordia (bottom right).

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3.2 **Dropsonde monitoring statistics**

Compared to radiosonde stations, the dropsondes provided a more comprehensive picture of the Antarctic atmosphere during the field experiment. Furthermore, drops were chosen to be coincident with satellite overpasses. Some comparisons were then performed between dropsonde profiles and satellite retrievals (as well as model profiles). The following figure shows a comparison of two dropsonde profiles with neighbouring IASI retrievals performed at EUMETSAT (August et al, 2012) and ECMWF model fields. It is evident that the atmospheric profiles exhibit a strong inversion near the surface, difficult to capture by the models and even more so by retrievals. For more results, see Wang et al, 2013. Another difficulty is that the cloud detection schemes used in retrievals and data assimilation algorithms are not optimal in the case of strong thermal inversions (and strong discrepancies between models and observations at the surface). This implies that a significant number of soundings are classified as cloudy whereas they actually are clear of clouds, leading to a sub-optimal use of the low-peaking channels (the most sensitive to clouds).

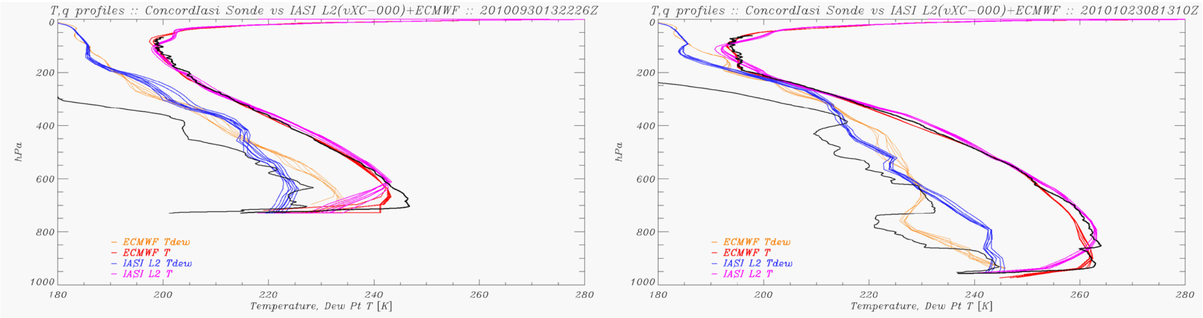

Figure 6: Temperature and dewpoint temperature profiles for dropsonde profiles at different dates (30/09/2010 and 23/10/2010). Comparison of dropsonde profiles (in black), of ECMWF model profiles (in red and orange) and of IASI retrievals (in magenta and blue).

Additional results show that models suffer from deficiencies in representing near-surface temperature over the Antarctic high terrain. Departures between dropsonde observations and model fields at the lowest observed level are seen to be quite negative (model too warm) over inland Antarctica for all models. Examples are given for two models in Figure 7.

The very strong thermal inversion observed in the data is a challenge in numerical modelling, because models need both a very good representation of turbulent exchanges in the atmosphere and of snow processes to be able to simulate this extreme atmospheric behaviour.

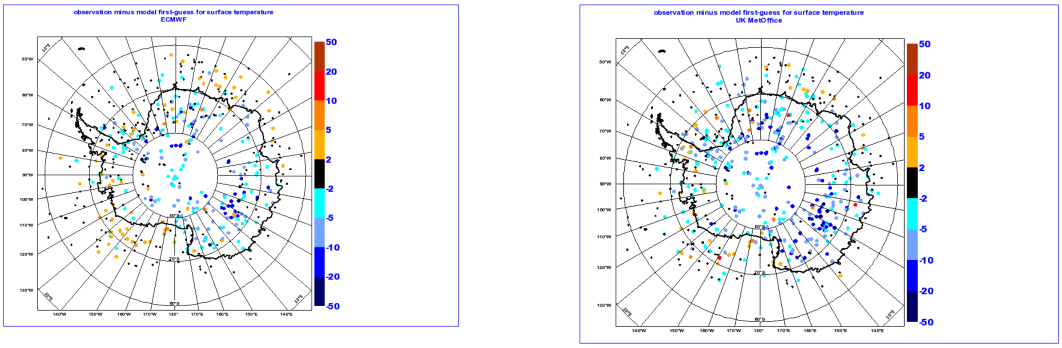

Figure 7: Maps of temperature departures, for the lowest observed pressure level, for the ECMWF model (left panel) and the Met Office model (right panel). No quality control has been applied. Negative values indicate that the observation is colder (model too warm)

4. Satellite data impact experiments

A set of data assimilation experiments over the Southern pole area indicated a large impact of microwave observations over sea-ice and of hyperspectral data (Bouchard et al, 2010). We will illustrate below some of the potential of these two data sources to improve NWP.

4.1. IASI retrievals over the Antarctic Plateau

The IASI sounder has a large potential for the observation of meteorological conditions over Antarctica. It supplies data at this location lacking in in situ measurements. In Vincensini et al (2012), the analysis of IASI radiances at Concordia has permitted to better estimate the temperature and the specific humidity in comparison with the additional radio soundings launched during the autumn 2009 component of the concordiasi field experiment (Austral spring). An optimization of the background error covariances was undertaken and the improvement due to the background error modification was measured quantitatively by improvement in the analyses fit to collocated radiosonde data. This configuration provided the best possible retrievals. Analysis–radiosounding rms errors significantly decreased compared with background–radiosounding rms errors. IASI was also found to be very informative for surface conditions. Retrieved skin temperatures reproduced measured surface data (BSRN and manual measurements) with good fidelity with an rms error around 1.2 K (see Figure 8). However, only 11 cases with clear-sky conditions were assimilated. Clouds have an important radiative impact on infrared radiances, and a difficulty in the detection of clouds comes from the use of a wrong surface model and a wrong skin temperature. The Advanced Very High Resolution Radiometer is a radiation-detection imager that can be used to determine both cloud cover and surface temperature. Therefore, it can inform about the cloudiness in IASI pixels which could help detect clouds with more accuracy. An improvement of snow models, which would improve the surface temperature, is another challenge to have a better system.

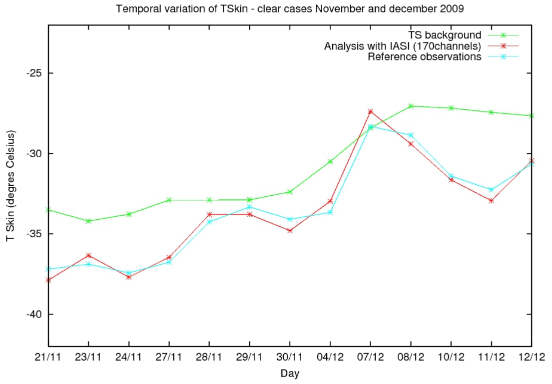

Figure 8: Surface temperature for clear cases in November and December 2009 for (green line) background and (red line) analyses and compared with in situ measurements: BSRN data combined with manual measurements (cyan line)

4.2. Microwave data assimilation over sea-ice

A sea ice emissivity model suitable for AMSU-A and AMSU-B data has been developed in Karbou et al (2013) and its impact was studied through two assimilation experiments run during the period of the arctic winter. The first experiment is representative of the operational version of the Météo-France NWP model whereas the other one uses the sea ice emissivity parametrization and assimilates a selection of AMSU channels above polar regions. It is shown that the assimilation of AMSU observations over sea ice has a significant effect on atmospheric analyses (in particular those of temperature and humidity). The effect on temperature results in a warming of the lower troposphere, more pronounced around 850hPa, weaker close to the surface. This leads to an increase in the Arctic inversion strength over the Arctic ice cap by almost 2 K (Figure 9). An improvement of medium range forecasts is also noticed when the NWP model assimilates AMSU observations over sea ice.

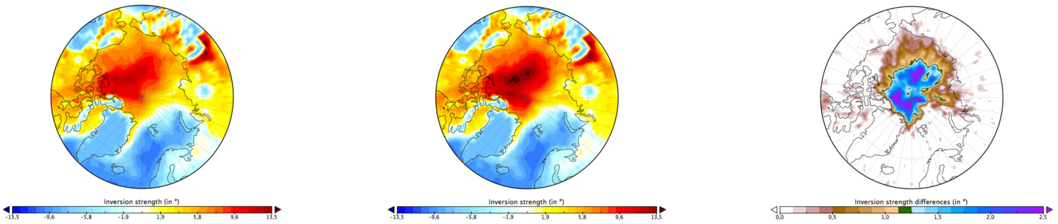

Figure 9: Average inversion strength for : the Control experiment CTL (January 5th to January 25th 2009), the EXP experiment using more AMSU observations over sea-ice (same period) and mean differences (EXP minus CTL).

5. Conclusions

In this paper, it was shown that large improvements in model performance over polar regions occurred over the last decade. In terms of data impact, the most important players are AMSU, IASI, AIRS, GPS-RO, RAOB, surface and AMV data. For sounding data over Antarctica, one can note a large impact of temperature at low levels, and a large impact of winds at high levels. Results show that models suffer from deficiencies in representing near-surface temperature over the Antarctic high terrain. There is a large potential for satellite data to correct surface temperature, but because of the very strong thermal inversion, IR data are often wrongly classified as cloudy and thus poorly used. The use of co-located imager data and of a better snow model are potentially helpful. For microwave observations, the correct specification of surface emissivity is needed for their use over sea-ice. The use of AMSU is then shown to strengthen the thermal inversion over the Northern Polar area and improve scores. Over the Antarctic continent, one might need to go one step beyond the simple parametrisation of emissivity and change the underlying physical assumptions (specular vs Lambertian reflection, Guedj et al, 2010).

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