Observation impact over the Antarctic during the Concordiasi field campaign

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Abstract

The impact of observations on analysis uncertainty and forecast performance was investigated for Austral Spring 2010 over the Southern polar area for four different systems (NRL, GMAO, ECMWF and Météo-France), at the time of the Concordiasi field experiment. The largest multi model variance in 500 hPa height analyses is found in the southern sub-Antarctic oceanic region, where there are strong atmospheric dynamics, rapid forecast error growth, and fewer upper air wind observation data to constrain the analyses. In terms of data impact the most important observation components are shown to be AMSU, IASI, AIRS, GPS-RO, radiosonde, surface and atmospheric motion vector observations. For sounding data, radiosondes and dropsondes, one can note a large impact of temperature at low levels and a large impact of wind at high levels. Observing system experiments using the Concordiasi dropsondes show a large impact of the observations over the Antarctic plateau extending to lower latitudes with the forecast range, with a large impact around 50 to 70° South. These experiments indicate there is a potential benefit of better using radiance data over land and sea-ice and innovative atmospheric motion vectors obtained from a combination of various satellites to fill the current data gaps and improve NWP in this region.

1 Introduction

Because of the remoteness and harsh environment of the polar regions, and of Antarctica especially, in situ atmospheric observations in these regions are relatively sparse. As a result, compared with other regions of the globe, our knowledge of the atmospheric state is particularly limited. The Concordiasi project was an international collaboration which gathered innovative observations over Antarctica (Rabier et al. 2010). It was a contribution to the THORPEX-IPY projects (The Observing System Research and Predictability Experiment International Polar Year projects), with the main meteorological objective to improve numerical weather prediction systems (Rabier et al., 2013a). The additional in-situ observations provided by Concordiasi constitute a reference dataset which was used to compare in situ data with satellite retrievals (Wang et al, 2013) and numerical forecasts (Cohn et al, 2013) in order to document shortcomings in models and data assimilation. This knowledge can then be used to improve forecasting and assimilation and lead to more accurate real-time analyses as well as improved re-analyses.

The additional observations were mainly intended to complement routine observations, and to match with satellite overpasses. In-situ atmospheric observations (surface observations and upper-air profiles) are made routinely in Antarctica, but mainly along the coast (15 sites over 17), except for the Amundsen-Scott station at the South Pole (managed by the USA) and Concordia on the plateau at Dome C (managed by Italy and France), as shown by the red dots in Figure 1. Amundsen-Scott performs two radiosoundings per day, and Concordia provides a radiosounding at 1200 UTC on most days. Concordia has the advantage of being under the swath of sun-synchronous satellites several times a day. In 2008 and 2009, the campaign was based on radiosounding measurements made primarily at Concordia to study the meteorology of the plateau in Antarctica and to provide a baseline for comparison with satellite data. In 2010, the Concordiasi project used a constellation of stratospheric long-duration instrumented balloons.

The French Centre National d'Etudes Spatiales (CNES) launched 19 stratospheric balloons from the station of McMurdo in September and October 2010. Among the 19 balloons launched, 13 of them were of the “driftsonde” type and released more than 600 dropsondes, on demand, to provide high-resolution vertical profiles of temperature, humidity, winds and pressure (Figure 1). The driftsondes (balloons and release systems of dropsondes) were developed through a partnership between CNES (responsible for the balloons) and the U. S. National Center for Atmospheric Research (NCAR, responsible for the dropsondes and the gondolas, see Cohn et al, 2013). The drifting balloons followed the air currents in a quasi-Lagrangian way over the Antarctic for several months, at an altitude of 18 km. The release of dropsondes was mainly targeted to coincide with satellite over-passes, while some dropsondes were devoted to predictability studies and others were used to validate GPS radio-occultations measured from receivers on board the balloons (Haase et al. 2012). Eventually, the dropsonde coverage was quite uniform over the Southern polar area, as seen in Figure 1.

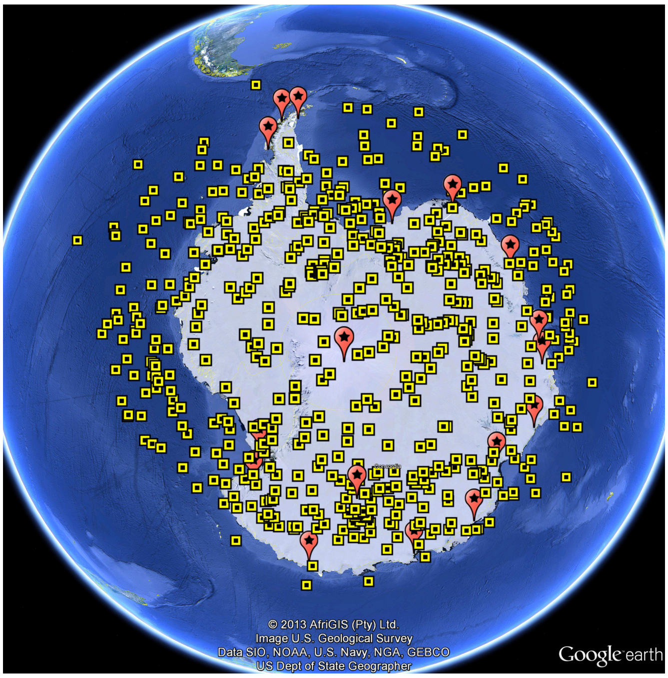

Figure 1: Map of dropsonde released over Antartica during the concordiasi experiment (yellow squares). Routine radiosonde observations are shown with red dots.

The goal of our study is to investigate the impact of polar observations (observations at latitudes poleward of 60 degrees south) on the forecast quality over the Southern polar area, with a focus on the assimilation of the additional dropsondes launched during the 2010 Concordiasi campaign. We focus on a period of interest during the 2010 campaign from 27 September to 16 November when most dropsondes were launched. Both the calculation of the impact of observations using the adjoint of a data assimilation system (e.g., Langland and Baker 2004), but also more classical Observing System Experiments (OSE) in the context of 4D-Var (e.g., Rawlins et al. 2007) are 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.A.), the Naval Research Laboratory (NRL, U.S.A.) and the European Centre for Medium-Range Weather Forecasts (ECMWF). Section 2 illustrates data coverage and analysis differences in the Antarctic area. The data impact is shown with adjoint sensitivity tools in section 3 and with observing system experiments in section 4. Section 5 concludes this paper.

2 Observation coverage and analysis uncertainty in the southern polar area

In order to understand the characteristics of data assimilation systems in the Southern polar area, it is relevant to investigate what is the data availability and usage. In Figure 2, the observation density is displayed for most observation types in the NRL system. One can notice the sparseness of in-situ observations, in particular inside the Antarctic continent. One can also notice a gap in satellite-wind observation coverage in a zone extending from about 50 to 70 degrees south, with geostationary winds equatorward of 50°S, and MODIS and AVHRR winds over the Antarctic continent. This is also an area where the satellite radiance usage is generally poor due to the difficulty in using radiances over sea-ice. However, some developments have recently taken place in Météo-France to better characterize the microwave sea-ice emissivity in order to be able to assimilate AMSU-B/MHS data on this surface (Karbou et al, 2013), and the coverage is then improved for this particular centre (see Figure 3).

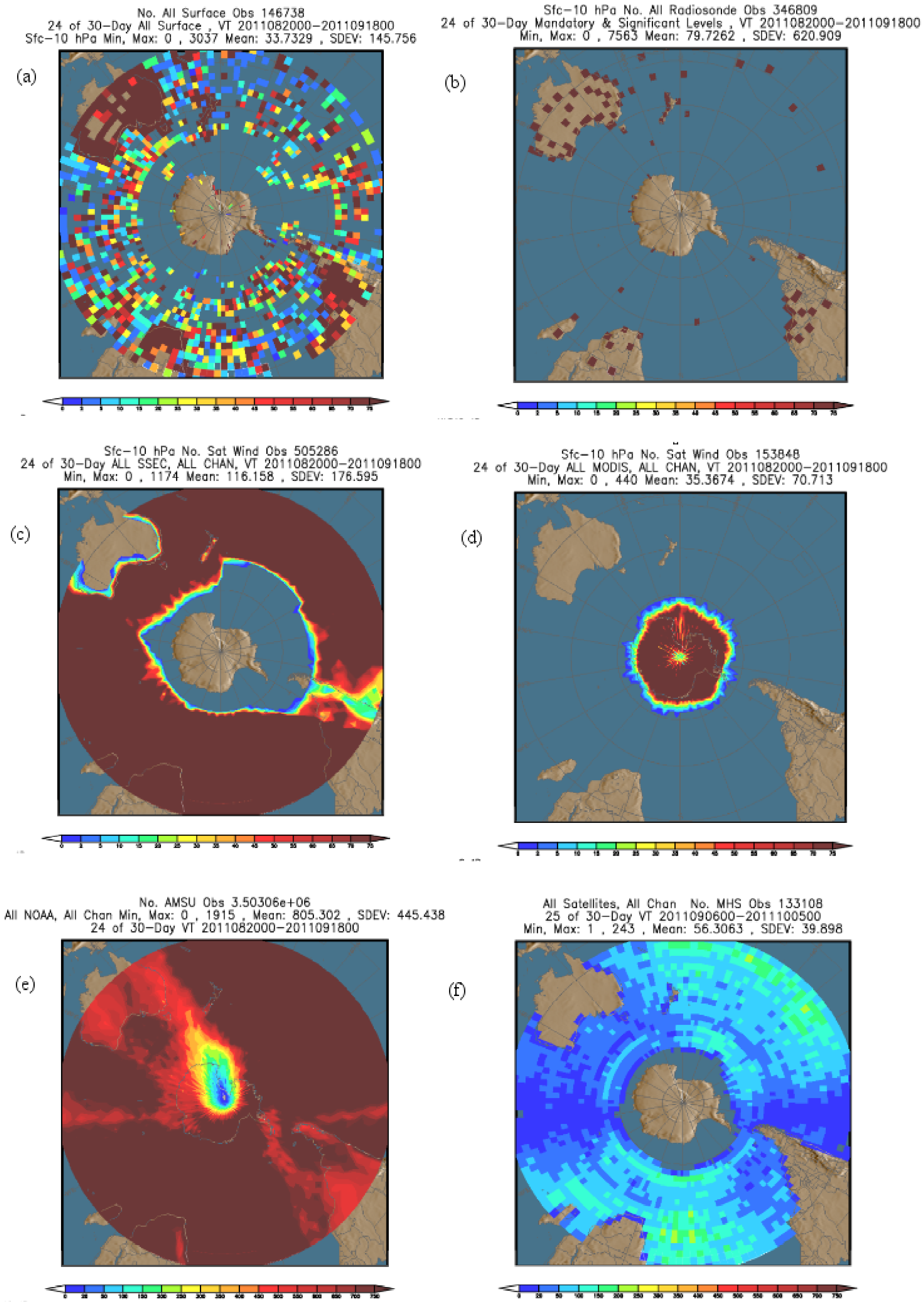

Figure 2: Maps of observations density for (a) all surface observations, (b) radiosonde, (c) satwind observations, (d) polar wind from MODIS, (e) AMSU-A and (f) MHS observations used at NRL over 30 days [20 Aug. to 18 Sept. 2011].

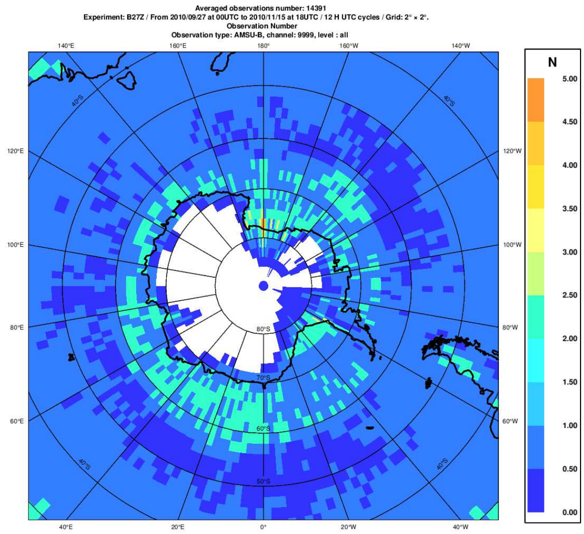

Figure 3: AMSU-B/MHS observation density in the Météo-France assimilation system.

The assimilation of all these observations produces analysis increments, which represent the work performed by the analysis to correct the a priori state of the model and fit the observations. Figure 4 presents the root mean square error of increments for the geopotential height at 500 hPa, computed for two centres, ECMWF and Météo-France. It is clear that the analysis is not much influenced by observations over the Antarctic plateau due to the lack of observations. The larger increments are found in the surrounding oceans. They are larger for ECMWF than Météo-France and the maximum value is not seen at the same longitude. This highlights the region where uncertainties in the forecast have to be reduced the most by the available observations. For ECMWF, a cross section of analysis increments is presented in figure 5 along 110°E across the area with maximum activity. The vertical structure shows an interesting feature, namely a 10 degree latitudinal offset of the maximum between lower-mid troposphere and upper troposphere - lower stratosphere. The northward displacement of the area with large increments at lower levels is mostly caused by the Antarctic continent reaching lower latitudes in this region pushing out low-level disturbances.

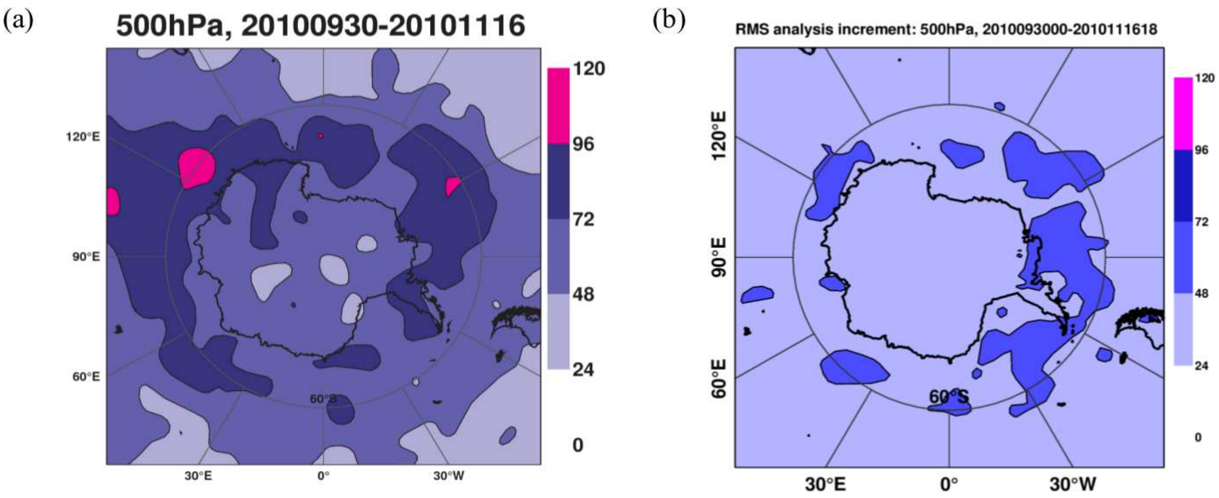

Figure 4: (a) ECMWF and (b) Météo-France root mean square of analysis increments for geopotential height at 500 hPa averaged over the period ranging from end-September to mid-November 2010. Unit is m.

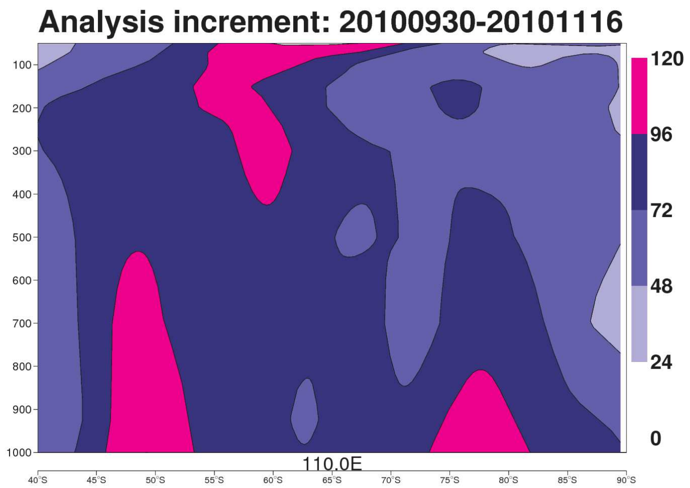

Figure 5: ECMWF cross section along 110°E between 40 and 90°S of analysis increments root mean square for geopotential height averaged over the period ranging from end-September to mid-November 2010. The vertical axis represents height in hPa and unit of the color scale is m. Note that levels below ~700 hPa south of 75°S should be discarded.

It is also relevant to examine systematic differences in the atmospheric analyses produced by different data assimilation systems. 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 (Langland et al. 2008). The average "static-time variance" of analysed 500 hPa geopotential height for 27 Sept. to 16 Nov. 2010 is shown in Figure 5. 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. 5 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.

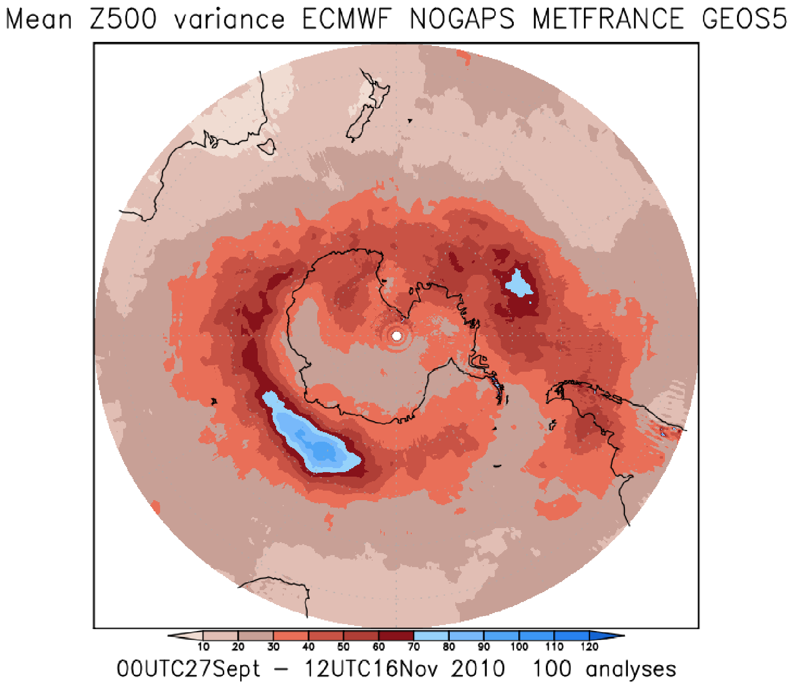

Figure 6: Average static-time variance of analyzed 500 hPa geopotential height for the four models, for analyses at 00UTC and 12UTC from 27Sept to 16 Nov 2010. The average variance is calculated by producing an average of the four separate analyses at each analysis time (00UTC and 12UTC daily) and taking 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 27 Sept. to 16 Nov. 2010]. Units are m^2.

It is seen in Figure 6 that largest average static-time variance in analysed 500hPa height for this time period is found in a zone extending from about 50 to 70 degrees south, similarly to the area with large increments in Figure 4. This is a region with a relative gap in satellite-wind observation coverage, as discussed previously, and subject to strong atmospheric dynamics. Figure 7 illustrates potential for error growth associated with the atmospheric instability. It represents the averaged intensity of singular vectors computed over the polar region for the ECMWF system during this period. It corresponds to the areas where small perturbations of the flow will grow the fastest in the short-range (Buizza and Palmer, 1995).

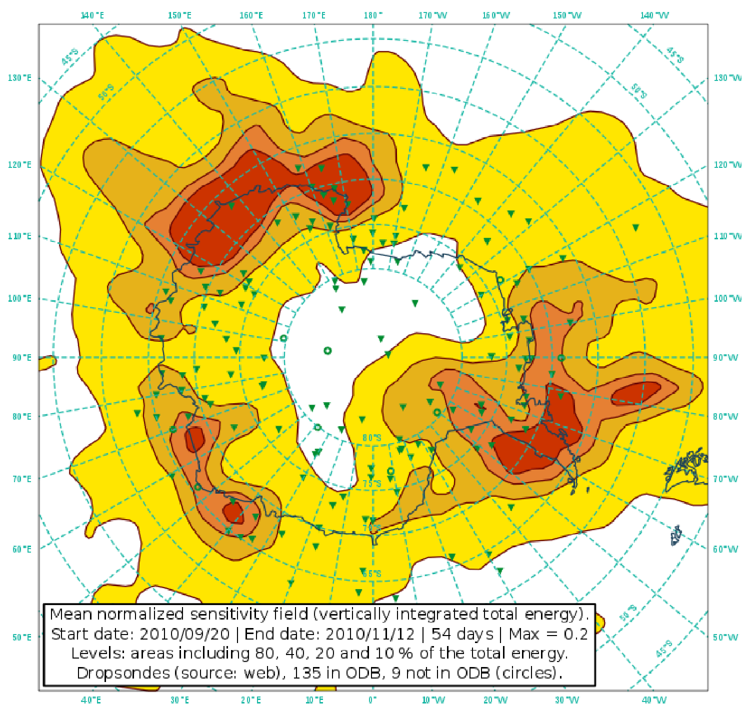

Figure 7: Averaged Singular Vectors for the ECMWF system [20 Sept.-12 Nov.].

Static-time variance in analysed 500hPa height is generally lower over the Antarctic continent, except for the region of Victoria Land, including the area around Dome C and the Concordia radiosonde station. Apparently, during this time period, the additional observation data provided by Concordia radiosonde profiles were not sufficient in number to offset large variance in analysed 500hPa height caused by factors not simply related to observation density. Such factors include relatively large uncertainty in background forecasts for data assimilation over this region, due to the particular difficulty in forecasting the extreme weather over the Antarctic plateau, with strong thermal inversions and strong coupling with the snow-covered surface.

Differences in static-time variance of analysed 500hPa height from one model system to another can be quite large, as shown in Fig. 8. This is an indicator of analysis reliability, since low static-time variance indicates that a particular height analysis product is consistently closer to the average of the four separate analyses. In this context, it is seen that the 500hPa height analyses of ECMWF (Fig 8b) and Météo-France systems (Fig8d) have the lowest average static-time variance, while the variance of NRL (Fig 8c) and GMAO systems (Fig 8c) are considerably larger. For each model the largest variance is found generally in the zone between 50°S and 70°S, and regional maxima of variance within this latitude belt in the south Indian ocean and south Pacific ocean. Given the similarity in location of the static-time variance pattern in each model, it appears likely that this is accounted for by general properties of atmospheric dynamics and the global observing system. That is, the largest static-time variance in 500 hPa height analyses is found in the southern sub-Antarctic oceanic region, where there are strong atmospheric dynamics, rapid forecast error growth, and fewer upper air wind observation data to constrain the analyses. The larger static-time variance in NRL and GMAO systems is essentially an enhancement of the variance pattern seen in the ECMWF and Météo-France analyses, but implies the NRL and GMAO 500hPa analyses are less reliable, since they consistently have greater departures from a consensus (average) analysis.

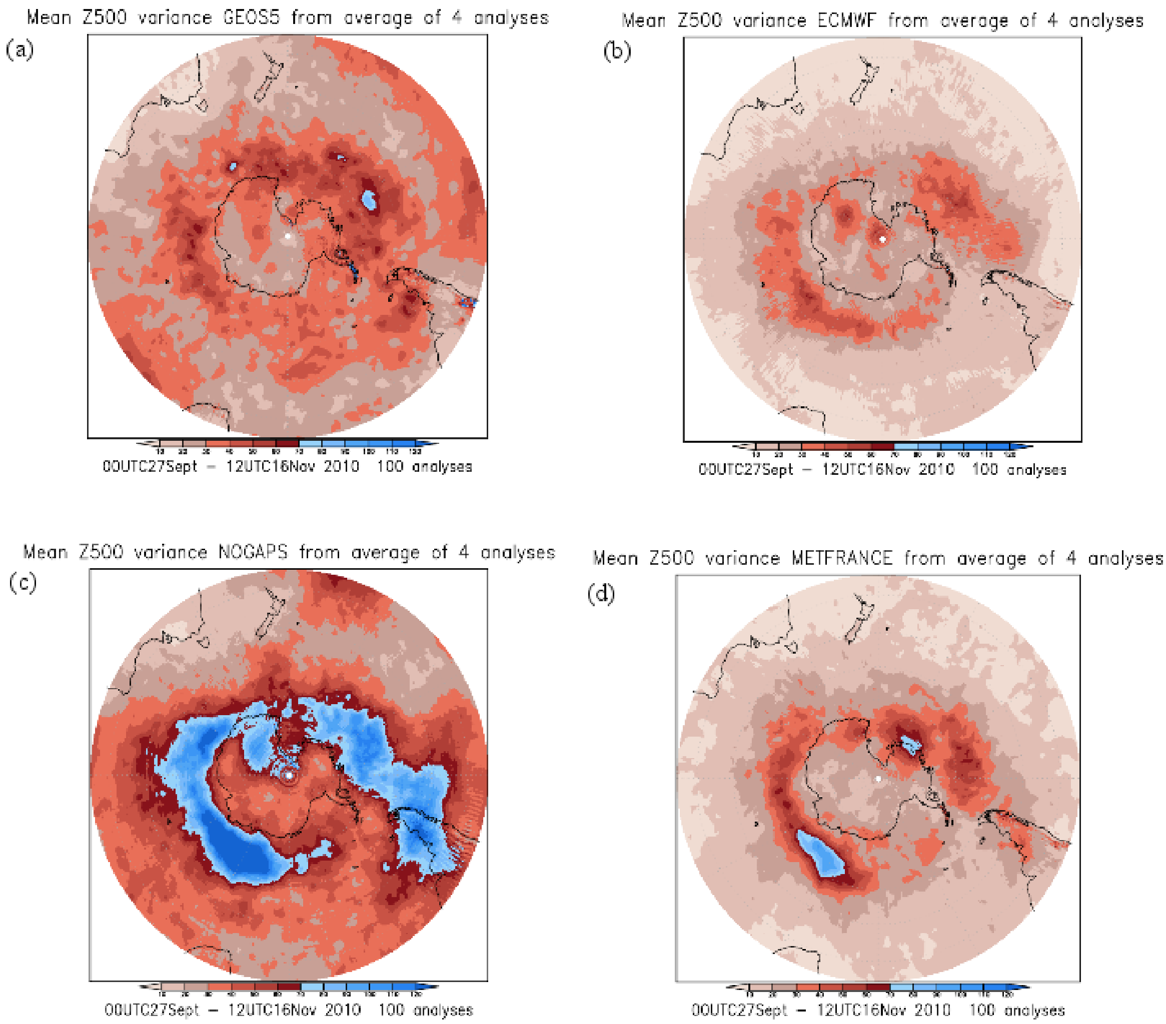

Figure 8: As in Fig. 6, except showing separately the mean variance of analyzed 500 hPa geopotential height for each model from the average analysed height field. a) GMAO, b) ECMWF, c) NRL, d) Météo-France. Units are m^2.

3 Data impact with the adjoint sensitivity tool

3.1 Model descriptions and impact calculation

The technique used to measure observation impact in this study is based on variants of the method proposed by Langland and Baker (2004). It uses the adjoint of a data assimilation system to estimate the impact of individual observations on an energy-based measure of forecast error:

$$e = (x^f - x^t)^T P^T C P (x^f - x^t), \qquad (1)$$

where x^f is a 24-h forecast state, x^t is the verifying analysis corresponding to x^f , C is a diagonal matrix of weights that gives units of energy per unit mass (Talagrand, 1981), P is a spatial projection operator that measures *e* only within a specified region of interest and the superscript T denotes the transpose operation.

For the NRL, the impacts shown here are derived from the operational run of its global data assimilation system (NAVDAS-AR, Xu et al. 2005) and forecast model (NOGAPS, Peng et al. 2004). NAVDAS-AR uses four-dimensional variational assimilation (4D-Var) to produce analyses at 00, 06, 12, 18 UTC, with observations assimilated during 6 hour time windows using an inner-loop resolution of T119L42. The NOGAPS forecast model and its adjoint are both run at T319L42. Observation impact is measured using a moist total energy norm evaluated over the global domain from the surface to approximately 150hPa in the form

$$\delta e = \left\langle K^T g, d \right\rangle, \qquad (2)$$

where K^T is the adjoint of the analysis scheme, d are the observation-minus-background departures (innovations) and g is a vector in model space given by

$$g = M_b^T P^T CP(x_b^f - x^t) + M_a^T P^T CP(x_a^f - x^t), \qquad (3)$$

where M_b^T and M_a^T represent the adjoint of the forecast model evaluated along the forecast trajectories initialized from the background and analysis states, respectively. Equation (2) provides a non-linear (essentially third-order) approximation of δe in terms of d (Errico 2007).

Météo-France has conducted two global simulations with the 2010 version (cycle 36t1) of the French global model, Action Research Small Scale Large Scale (ARPEGE) (Fourrié et al. 2006) developed in collaboration with ECMWF. It uses 4D-Var and data are assimilated at 00, 06, 12, 18 UTC with 6 hour-time windows. Experiments were performed on a period from September to mid-November 2010 that covers the field campaign. A control experiment without the additional observations from Concordiasi was run, as well as one in which all additional observations from Concordiasi were assimilated. The stretched geometry of the model was adapted to have a better spatial resolution of about 10 km over the Antarctic and 60 km on the opposite side of the globe. Observation impacts were computed at T107 resolution based on a dry energy norm from the surface to the top of the model using (2), with g replaced by

$$g' = M_a^T P^T C P(x_b^f - x^t) + M_b^T P^T C P(x_a^f - x^t), \qquad (4)$$

Note that (4) is similar to (3) except that the adjoint of the forecast model linearized about the forecast started from x_a is applied to the error measure evaluated for the forecast started from x_b , and vice versa. This corresponds to a second-order approximation of δe in terms of d (Errico 2007), but for the measure (1) provides essentially the same accuracy as the third-order form (3) (Gelaro et al. 2007).

The GMAO produced a global simulation and observation impacts including Concordiasi dropsonde observations using a reduced-resolution version of the Goddard Earth Observing System-5 (GEOS-5) atmospheric data assimilation system (Rienecker et al. 2007). The background forecasts and analysis increments were produced at 0.5° resolution with 72 vertical levels using the GEOS-5 forecast model and Gridpoint Statistical Interpolation (GSI, Wu et al. 2002) analysis scheme, respectively. The GSI adjoint was run at 0.5° resolution, while the GEOS-5 adjoint model was run at 1° resolution. The GSI was run in a 3D-Var configuration with a 6-hour update cycle. Observation impacts were computed at 00 and 12 UTC (although Concordiasi observations were assimilated in all cycles) based on a dry energy norm defined poleward of 60° S and from the surface to 150 hPa. The impacts were computed using a variant of the third-order approximation (2) which takes partial account of the multiple outer loops used to produce the forward analysis in GEOS-5, as in Gelaro et al. (2010).

At ECMWF, OSEs were performed to assess the analysis and forecast impact of the Concordiasi campaign. In particular, the period chosen is from 2010/09/28 to 2010/11/16 in which a maximum number of dropsondes were released. The experiment were performed using the operational IFS cycle 36R4 at the resolution T799 for the model trajectory (and forecast) with three inner loops at T159, T255, T255 for the analysis resolution. The reference experiment contains all the operation data plus the dropsondes observations.

The ECMWF operational forecast sensitivity adjoint technique uses a third order sensitivity gradient as Langland and Baker (2004) but on a 12 hour assimilation period. The sensitivity gradients (3) are therefore valid at the starting time of the 4D-Var assimilation window (0900 and 2100 UTC). The forecast sensitivity runs the model trajectory at the T1279 resolution whilst the linear system is solved at T255 resolution.

3.2 Influence of polar observations in different analysis and forecast systems

Figure 9 represents the percentage in terms of reduction of forecast error (total energy) of polar observations, namely observations polarwards of 60° latitude. The total, which is different for each centre as the computation of the sensitivity of forecast error to observation is not the same, has been brought back to 100 %. This measure does not account for the number of observations except through the impact they infer.

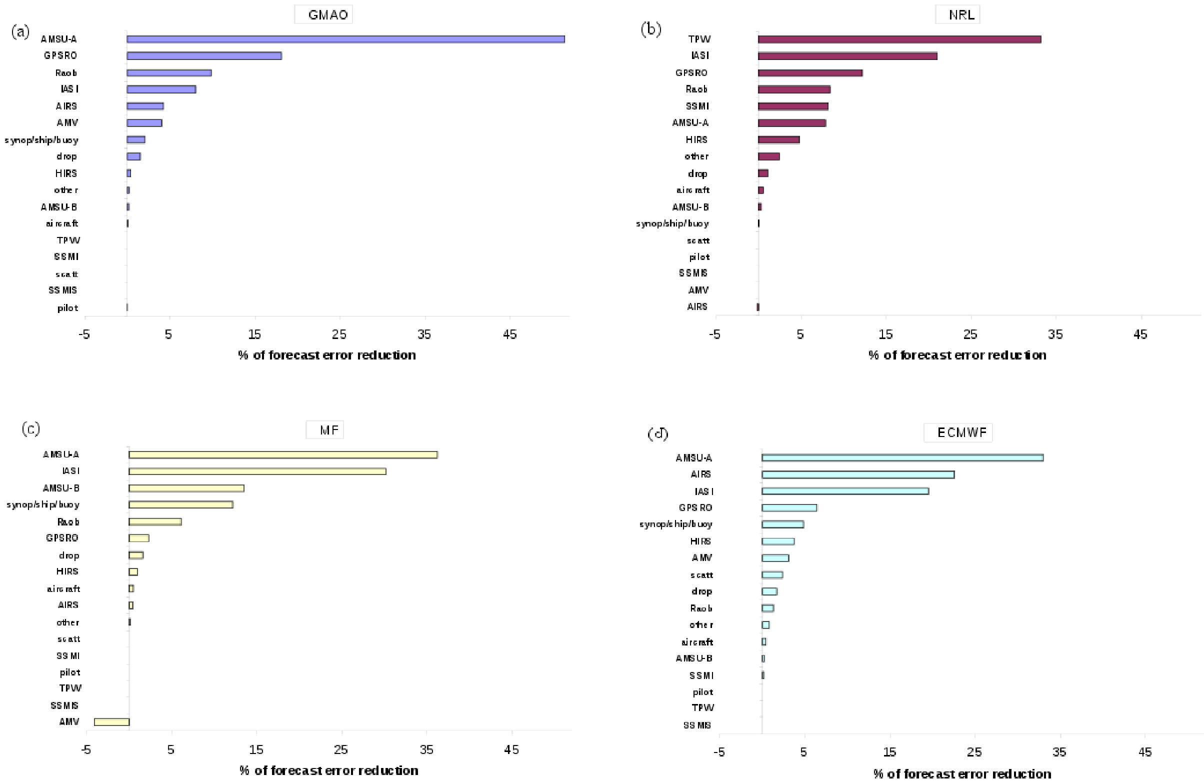

Figure 9: Normalised impact on the 24-hour forecast of different observation groups in the polar domain for (a) GMAO, (b) NRL, (c) Météo-France and (d) ECMWF systems in decreasing order.

The impact of the different observation groups is not distributed similarly for every system. 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 more-evenly distributed among 6 of them. AMVs in the NRL system have the largest impact on forecast error reduction in the south polar region due to the assimilation of a larger number of MODIS and AVHRR wind data in this particular system and an elaborate pre-processing and data selection. This case notwithstanding, microwave radiances of AMSU-A and infrared radiances of IASI have a good impact in all systems, representing around 60 % of the total contribution (except for NRL, for which it is 33%).

The results obtained for each system reflect different assimilation strategies. Météo-France shows detrimental impact of AMVs in this region, which should be investigated further (it is not generally the case, for other areas and/or other periods). AMSU-B microwave radiances account for more than 13 % of total forecast error reduction in the Météo-France system only. Efforts have been made in recent years to assimilate more AMSU-A and AMSU-B radiances, particularly over land and sea ice. This is why AMSU-B impact is very important in this particular case of polar observations. As explained in Karbou et al (2013), the method involves estimating emissivity from the surface sensitive observations by inverting the radiative transfer equation and assigning it to other sounding channels.

For ECMWF and Météo-France, in-situ 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 infrared 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%), this kind of observations have a good impact. Météo-France is the only system 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. This vertical thinning is not applied in the other systems. Since then, some experiments have taken place to test the assimilation of GPSRO without any vertical thinning. This processing, which multiplies the number of assimilated observations by 5 and increase their impact, was subsequently implemented in operations. SSMI/S data have a relatively good impact in the NRL system (8.4%), the only system that assimilated them in this experiment.

3.3 Impact of the choice of domain for observations and norm definition

Depending on the model used, the calculation of the impact of observations was performed by calculating J on the whole globe or by limiting the area of interest to the South pole, between 60 and 90 degrees southern latitude. In this section, we investigate how the choice of the total norm affects the impact result of an observing system. For the ARPEGE model, the calculation of the impact of observations on forecast error reduction was repeated using two different norms for the cost function calculation, a polar norm on the one hand, where J is calculated between 60 and 90 degrees south, and a global norm on the other hand, calculated on the whole globe. This additional computation was made on a shorter period going from 8 to 31 October 2010. The impact of polar observations in the two cases, over the same short period, is shown in Figure 10a.

Depending on the norm used, the absolute values are not the same. However, the relative influence of each observation group is similar and almost in the same order. This shows that whichever the norm is used, the relative influence of each observation group is similar for polar observations, which explains why we could compare the various systems in the previous section. The differences obtained using the global norm instead of the polar norm can be interpreted as the influence of polar observations that spreads beyond their original area to the neighbouring regions in 24 hours. In general, polar observations also contribute to improve forecasts in other areas.

Conversely, we can show the influence of extra-polar observations on the reduction of forecast error in the polar area. Figure 10b shows the forecast error reduction in the Météo-France system computed only in the polar area but for all observations on one hand, and for polar observations on the other hand. Here, the relative influence of each observation group is not the same because the ocean surrounding the Antarctic area is denser in observations. Observations outside of the polar area contribute to reducing the forecast error in this area, especially AMSU-A, IASI, synop, and buoys (exhibiting the largest differences between the two calculations in figure 10b).

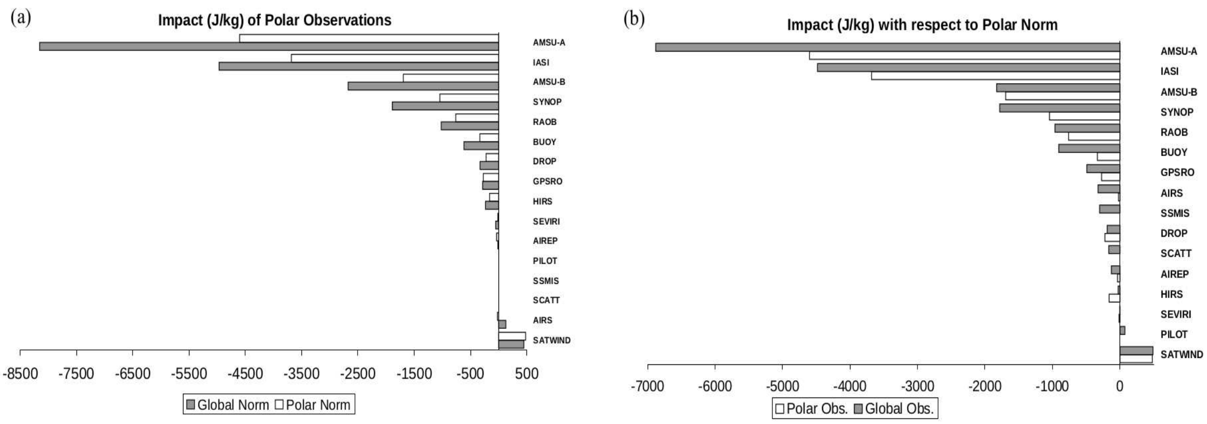

Figure 10: (a) Impact of polar observations (60S – 90S) separated by observation groups when the cost function J is computed on the globe (global norm) or on the polar area (polar norm). (b) Impact of polar observations (white) and global observations (grey) using the polar norm (J computed over the polar area 60S-90S only). Both are valid for Météo-France system. [8-31 Oct. 2010] in J.kg^{-1}.

Although observations from outside the southern polar zone have an impact on the 24-hour forecast in the polar region, polar observations are the most important to reduce the forecast error in this region which justifies our choice to focus this paper on these particular observations, south of 60S, which we call “polar observations”.

To finish with, it seemed relevant to compare the impact of polar observations to the general impact of global observations. In order to compare the global observing system to what we can call the polar observing system, we show in Figure 11 the impact in the Météo-France system of different observation systems computed with different norms: global norm computed for global observations and polar norm computed only between 60 and 90 degrees South for the polar observations.

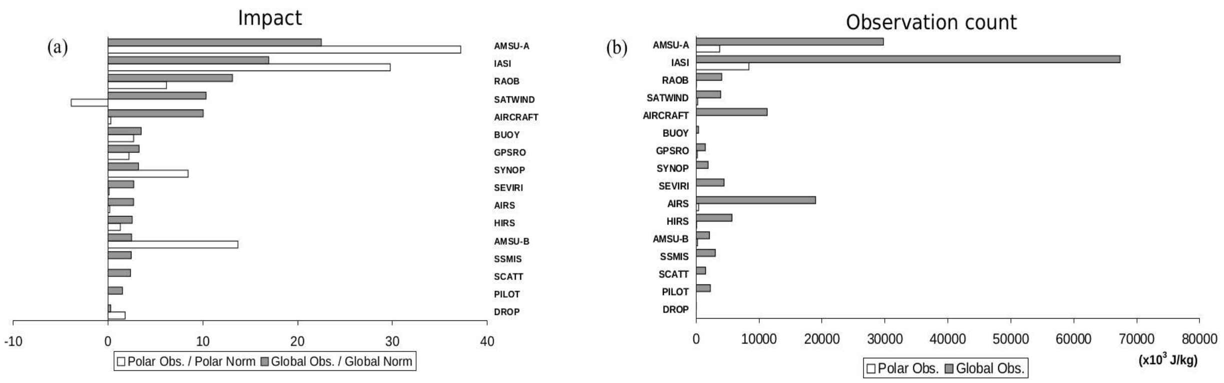

Figure 11: (a) Impact of different observation groups in Météo-France system for the polar observations using the polar norm (in white) and global observations using the global norm (in grey) computed in percentage and (b) observation counts for each case.

In the global context (impact of global observation system computed with the global norm), satellite observations have the largest impact, and contribute for more than 68 % to the global impact. This is not surprising as they represent more than 87 % of the total number of observations assimilated in this experiment. Conventional observations play also an important part and contribute to improve forecast skill. If we look more closely to the ranking, AMSU-A contribute the most, followed by IASI, radiosondes, AMVs from geostationary or polar satellites, aircraft, buoys, and radio-occultation data based on the global positioning system (GPSRO). This is not a specific result for this assimilation and forecast system. Although the impact of any one data type depends on the mix of other data types, there is a broad consensus amongst the global numerical weather prediction (NWP) centres that these observation types are the biggest contributors to forecast skill, as noted in the Final report of the fifth WMO workshop on the impact of various observing systems on numerical weather prediction, 2012.

If we focus now on the Antarctic region, we can see different features. In situ measurements are rare due to the hostile environment for both manual and automatic systems. In this context, satellite observations represent nearly 99 % of the observations assimilated, and dominate the impact. IASI and AMSU-A still represent the most important contributors to the forecast error reduction, but here, the influence of AMSU-B is relatively important. AMSU-B improve the forecast in Météo-France system as some recent progress has been made in assimilating observations over sea ice as discussed earlier. Although measurement stations are not numerous and observation numbers are low (0.17% and 0.44% of the total respectively), synop and radiosondes have a good impact. Most of these measurements are made along the coast except for Amundsen-Scott at the South Pole and Concordia on the Plateau at Dome C. Drifting buoys around Antarctica also have a good impact on improving the forecast on the area. Dropsondes improve the forecast skill. Their influence in the global context is limited to 0.3%. In the polar context, it represents nearly 2% of the total. The low number of observations coming from aircrafts explain their small influence here. The radiances from the Seviri instrument onboard the geostationary satellite Meteosat Second Generation (MSG) has little influence in polar regions as they are not numerous below 60° South. There are no PILOT, scatterometter and SSMI/S observations assimilated in the Météo-France system in the region, mainly covered by land, sea ice or snow and not much open sea. Surprisingly, AMVs which are one of the biggest contributors in the global context, degrade (slightly) the Météo-France forecast in the polar context during this study period. AIRS is not assimilated over sea ice, neither over land for the moment (even though some stratospheric and upper tropospheric channels could be assimilated). Considering HIRS observations over the South Pole area (land), Météo-France system assimilates data from only a single water vapour channel if the altitude is less than 1500 meters. Over sea, observations too far from the guess for one surface channel are discarded. On the contrary, GPSRO measurements are independent from the surface type, cloud or particles in the air and so bring a contribution commensurate with their number.

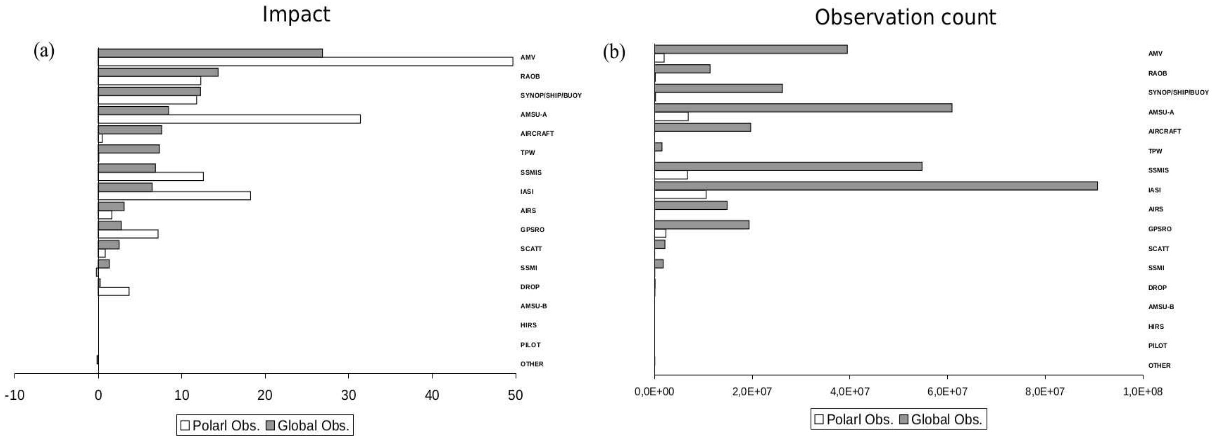

Figure 12: As Figure 11 but for NRL system.

Similarly, figure 12 shows observation impact results obtained in the NRL system. Here, in a global context, AMVs have more impact than other observation types. This may be explained largely by the greater number of AMV data assimilated. Compared to other systems, more wind observations are assimilated. Another explanation may be more-optimal assimilation of AMVs using the NRL super observation procedure. In the polar domain, AMVs wind data (MODIS) still provide the largest forecast error reduction, followed by satellite radiances, including AMSU-A and IASI, and in situ measurements such as radiosondes, land-surface observations and dropsondes profiles.

3.4 Dropsonde impact in the southern polar region

During the 2010 campaign, an important effort was made to evaluate the impact of dropsonde observations. In this section, we detail the forecast improvements that dropsondes brought as part of the observing system. The impact of temperature, humidity and wind measurements are investigated as well as the impact of the location of these data.

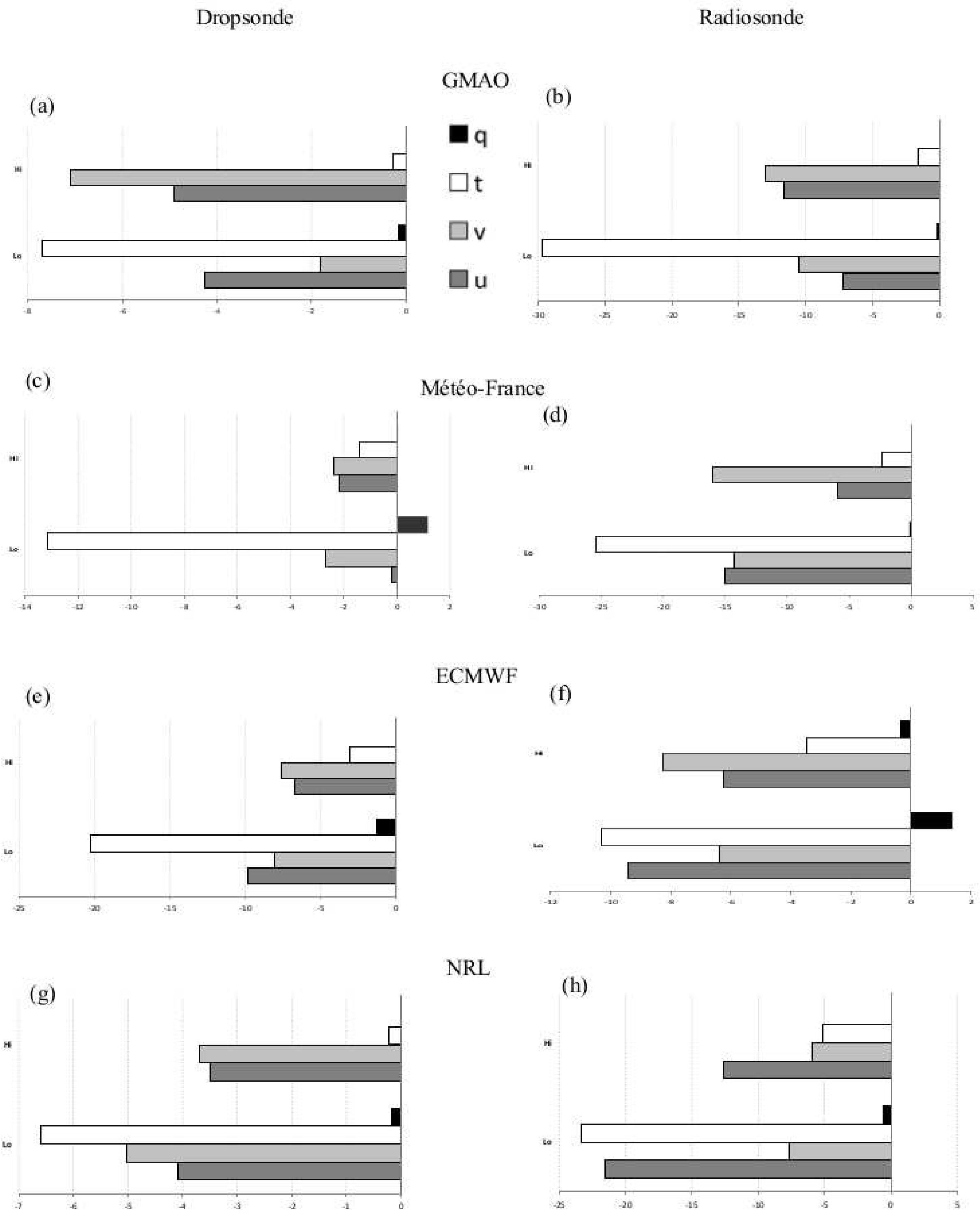

Figure 13: Impact of dropsondes (left) and radiosonde (right) data by parameter (U, V, T, Q) and layer (Hi, Lo). The low layer (Lo) is for pressure larger than 400 hPa and the high layer (Hi) is for pressure less than 400 hPa in different systems : (a) and (b) GMAO, (c) and (d) Météo-France, (e) and (f) ECMWF, (g) and (h) NRL. Negative values correspond to a reduction in forecast error. Impact values on the abscissa have been normalised so that the total impact of dropsondes and radiosondes is 100 J/kg for each centre.

Although the dropsonde impact is relatively small compared to satellite data such as AMSU-A, IASI or GPSRO, it is interesting to evaluate the impact of this relatively uniform source of atmospheric profiles in the region and to compare it with the impact provided by radiosondes over Antarctica. Figure 13 shows the dropsonde impact for each measured parameter at low and high levels (below and above 400hPa). For dropsondes at high levels, wind measurements have the largest impact, whereas temperature measurements have a large impact at lower levels. This is particularly evident in the Météo-France system, where the influence of temperature measurements collected from dropsondes in low levels is nearly four times bigger than the influence of the wind measurements. The impact of temperature observations at high levels in GMAO and NRL systems is quite small compared to that provided by wind observations. Humidity measurements have globally a smaller impact, and a detrimental impact is seen at low levels for dropsonde humidity in the Météo-France model and for radiosonde humidity in the ECMWF model.

Technically, radiosonde and dropsonde are similar as they vertically sample the atmosphere, from the bottom up for radiosondes and conversely for dropsondes. Radiosoundings are made routinely at fixed stations whereas dropsondes are launched on demand, meaning that their location and time are not fixed. For these two profiling methods, we can see similar features for each centre. The impact of radiosondes at low levels in the Météo-France system is more evenly distributed among temperature and wind measurements than for dropsondes. Temperature measurements at high levels in NRL system have a bigger impact than for dropsondes.

Most radiosondes in Antarctica are launched along the coast, except for the Amundsen-Scott station at the South pole and Concordia station at Dome C. In contrast, dropsondes were deployed in many different locations, some of them over the surrounding oceans, others over the Antarctic continent. This allowed sampling of the atmosphere at latitudes usually poorly covered by in situ observations. One can notice that overall the results confirm the impact of radiosondes.

In order to further investigate the improvement brought by dropsondes over Antarctica, impacts of individual observations have been computed and results have been gathered in three latitude bands of 10 degrees each between 60 and 90° South. The result for each centre is shown in Figure 14.

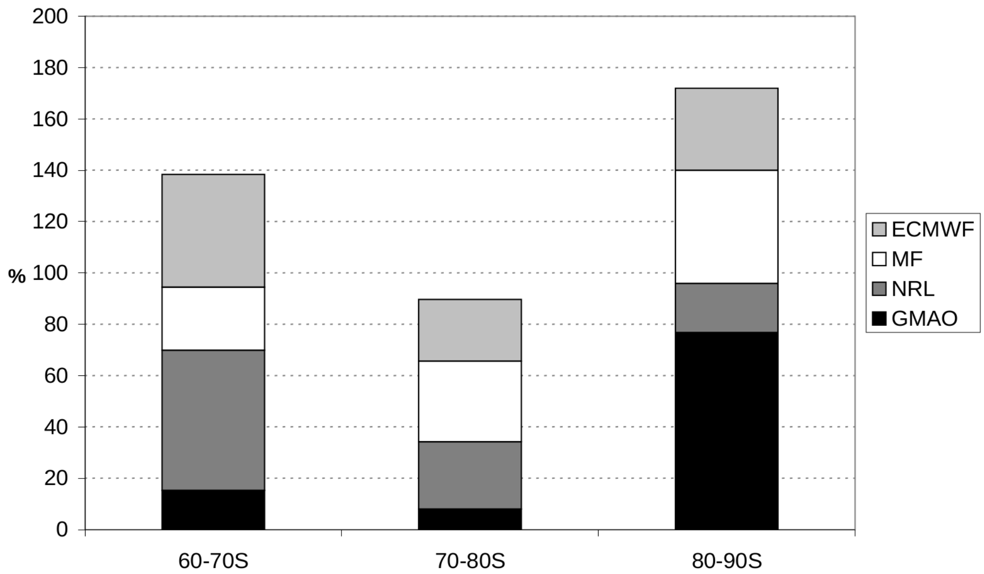

Figure 14: Impact per observation of dropsonde data in different systems by latitude band 10 degrees large. Impacts are normalised for each system (GMAO, NRL, Météo-France and ECMWF) for the sum of 3 columns to be 100 % for each centre over the polar area (60-90S).

In the GMAO and Météo-France systems, individual observations have the largest impact when located near the South Pole. For the ECMWF and the NRL system, observations located on a ring between 60 and 70° South participate more in reducing the forecast error. The intermediate ring between 70 and 80° South seems to be the location where observations have the smallest impact without being negligible. These differences may be explained by several considerations. Weather regimes are different depending on latitude. Between 60 and 70° South, more low-pressure systems are active than southwards. These challenging forecast areas may benefit from the dropsondes as additional data to improve the analysis. Closer to the pole, the large impact of dropsondes may be explained by the lack of other data. For the GMAO and Météo-France systems, the domain used to compute the impact of the observations is the Southern polar area, which might explain the relatively larger values for the higher latitudes. On the contrary, the domain used to compute the impact of the observations in the ECMWF and NRL systems is global, which might explain the larger values for the lower latitude bands for these two systems.

4 Observing system experiments

At both ECMWF and Météo-France, observing system experiments were performed to document further the impact of the Concordiasi dropsondes. Experiments with and without the dropsonde data were run from the end of September to mid-November, when most of the 644 dropsondes were available. The examination of analysis differences showed that, as anticipated from the results described in the previous section, these data provide most of the impact in winds at higher altitudes and temperature at lowest altitudes. An example is shown in Figure 15, for the analysis temperature differences at 700 hPa, applied to both Météo-France and ECMWF, for both averaged differences and standard-deviations of differences.

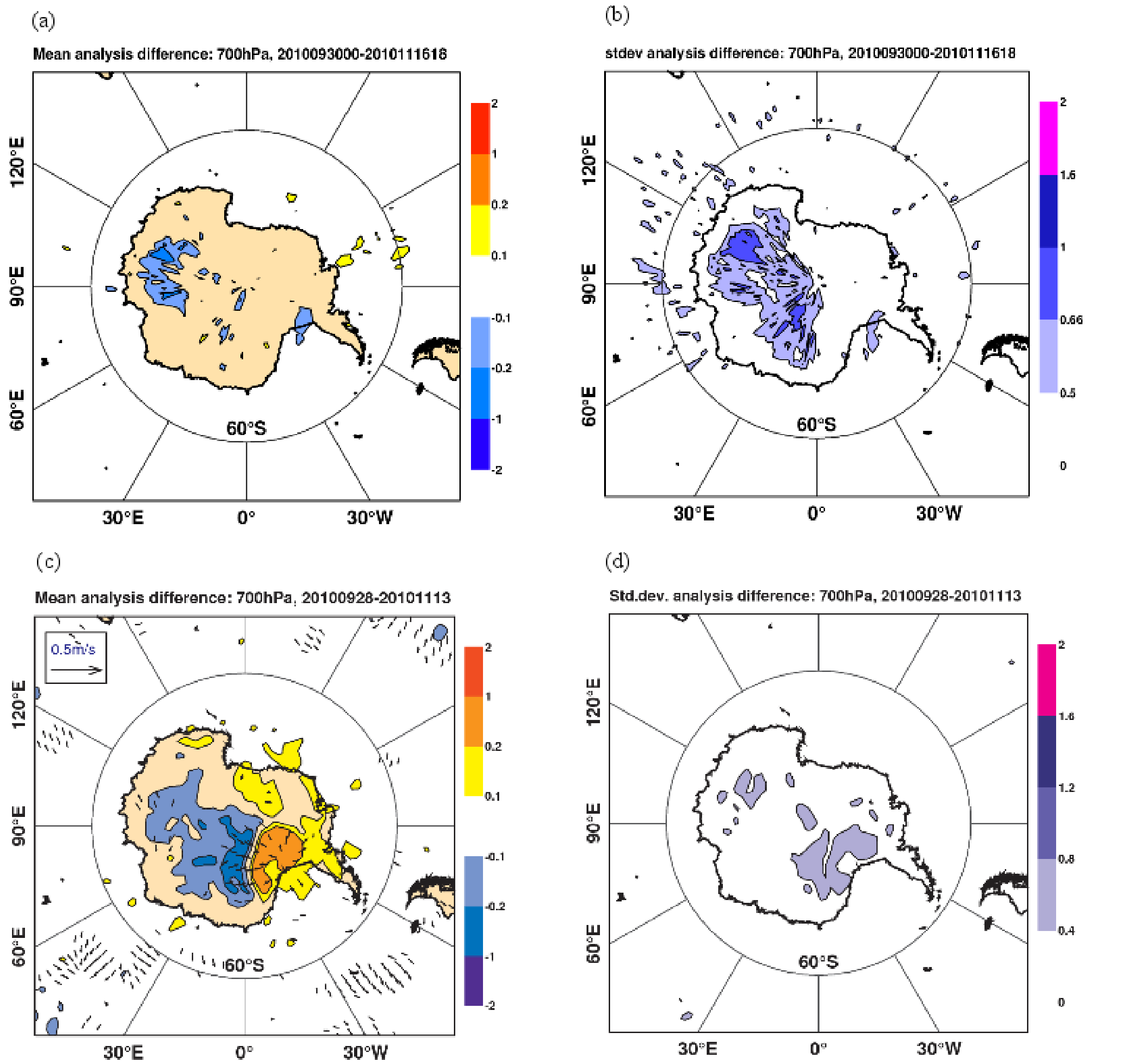

Figure 15: Temperature (control - dropsonde denial) difference fields at 700 hPa for Météo-France (a) mean analysis difference, (b) standard deviation analysis difference and for ECMWF (c) mean analysis difference for temperature and wind and (d) standard deviation.

The changes to the analysis from the dropsondes are not in the areas with large uncertainty of analysed height (Fig. 6) or with large Singular Vector amplitude (Fig. 7). Also, ECMWF has larger analysis differences (Fig 15c), which is consistent with Fig. 13. The average impact over the Antarctic plateau is to lower the temperature, which is consistent with a compensation of the model biases (Cohn et al, 2013, Rabier et al, 2013b). The models are not cold enough over the plateau and the dropsondes manage to correct part of this bias. Inland Antarctica is also the place where the analysis differences have the largest standard-deviations. This shows that at this relatively low level, the dropsondes mainly introduce differences over inland Antarctica.

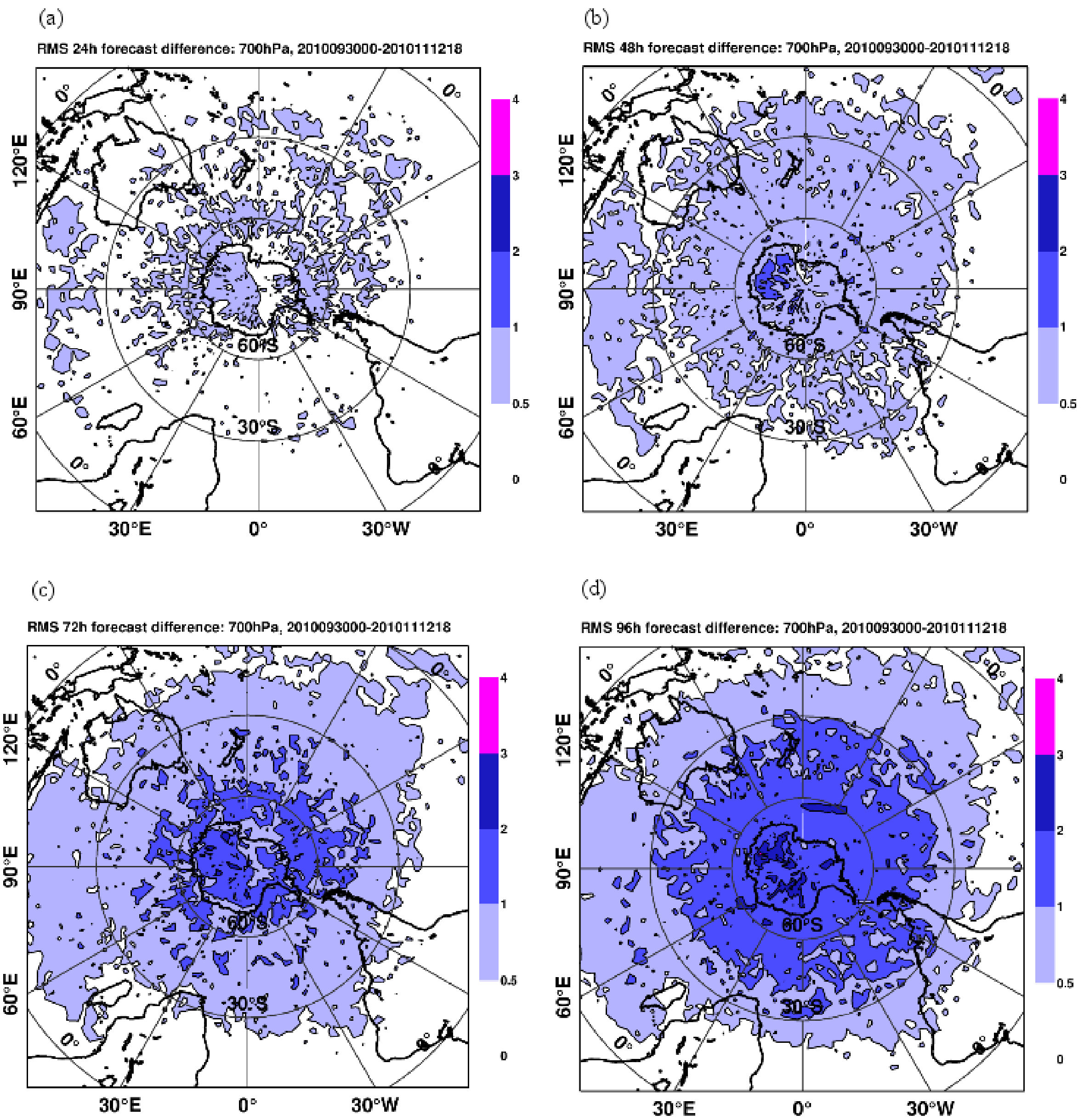

Figure 16: Météo-France temperature difference (control-denial) fields at 700 hPa (a) RMS of 24h forecast difference, (b) RMS of 48h forecast difference, (c) RMS of 72h forecast difference, (d) RMS of 96h forecast difference.

One can investigate how this analysis impact translates into a forecast impact. The RMS of the differences between the experiments with and without the dropsondes are plotted in Figure 16 for the Météo-France experiment at forecast ranges from 1 to 4 days. One can see how the initial differences grow in time to extend to lower latitudes. Although the largest forecast impact remains over inland Antarctica, it is also significant around 60 South for most of the forecast ranges.

5 Conclusion

In this article, the impact of observations on analysis uncertainty and forecast performance was investigated for Austral Spring 2010 over the Southern polar area for four different systems (NRL, GMAO, ECMWF and Météo-France). The period of interest was chosen so as to coincide with the main field observation campaign of the Concordiasi project, providing more than 600 additional dropsonde atmospheric profiles over the area. Examination of the observation coverage and analysis differences between the four centres point out an area of poor data density and maximum analysis uncertainty over the Southern ocean at latitudes ranging from 50 to 70° South. This is also an area with large flow instability as shown by the singular vectors. The impact of observations was then calculated with the adjoint method and shows similarities between the four systems. The most important players are AMSU, IASI, AIRS, GPS-RO, RAOB, surface and AMV data. The exact ranking varies among centres due to their data assimilation system specifications. The NRL shows a particularly strong impact of AMV data, not surprisingly as this centre uses more of these particular observations than the other centres. The Météo-France assimilation exhibits a large impact of AMSU-B data, following some research developments to be able to use these data over sea-ice. Compared to the global context, there is generally more impact of satellite data and less impact of conventional observations. This would be slightly different over the Northern polar area, where radiosondes and aircraft also play a more prominent role (not shown). 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. In terms of impact by latitude band, both the area near to the pole and the latitudes around 60° South where dynamic instability prevails show a large impact. Indeed, Observing System Experiments using the Concordiasi dropsondes show a large impact of the observations over the Antarctic plateau extending to lower latitudes with the increasing forecast range, with a large impact around 60° South.

This study was primarily aimed at documenting data impact over the Southern polar area to highlight the importance of certain data types and point to the use of additional observations. In particular, it seems that one should progress in the use of satellite data over snow and sea-ice to better control temperature at low altitudes. One could also think of exploiting the occasional aircraft flying to Antarctica in order to fill the data gap over the ocean. Another promising data source is the AMVs provided by a combination of geostationary and polar-orbiting satellites, which are precisely located in the "ring of uncertainty" between 50 and 70° South.

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