Climate and surface mass balance of the polar ice sheets in ERA40/ERA15

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1. Introduction

The density of meteorological observations in the polar regions, including the polar ice sheets, is comparatively low. There is thus great hope that, by making optimized use of the few available observations, meteorological analyses and forecasts can provide a wide and relatively reliable picture of the climate of the polar ice sheets. However, because observational control is limited, the performances of the assimilation and modeling tools must be very good. Unfortunately, the polar regions are not the regions which in the past have benefited the largest development and validation efforts. ERA15, the first ECMWF reanalysis product, has proved very useful for polar climate research in various ways (e.g., for a variety of applications over the polar ice sheets, Genthon and Krinner [1998], Bromwich et al. [2000], Genthon et al. [2001], Hanna and Valdes [2001], etc.), yet hampered by a number of first order problems, like large errors in prescribed surface elevation at the assimilation [Bromwich et al. 2000] and modeling [Genthon and Braun 1995] steps. Inappropriate model physics, e.g. inadequate parameterizations of stable boundary layers [Viterbo et al. 1999], has also adversely affected the results of ERA15 over the ice sheets. Identified problems of ERA15 are expected to be corrected in the new reanalysis in production, ERA40, and there are thus great expectations that, besides a longer time sample, the quality of ERA40 will allow further advances in polar climate research.

Some aspects of the climate and surface mass balance of the polar ice sheets in ERA40, with large emphasis on the Antarctic ice sheet, are discussed here. Following recommendations by ECMWF (Sakari Uppala, ECMWF, personal communication), the years 1989 to 1992 from Stream 1 (as of October 2001) are evaluated. This is compared with the same period in ERA15, and with observations or other estimations when available. The polar ice sheets play an important role in the global climate balance and have complex interactions with the other components of the climate system. The surface is more accessible for meteorological and atmospheric environment monitoring, but exchange with the free and large scale atmosphere is controlled by an atypical, often very stable boundary layer. Among the consequences, strong temperature inversions and strong surface (catabatic) winds are typical features of surface climate of the polar ice sheets, particularly Antarctica. On average, Greenland and Antarctica together recycle water to the equivalent of 6.5 mm of sea-level every year. A change of one of the component of the overall mass balance of the polar ice sheets can thus significantly affect the global environment through sea-level. The component which is determined by meteorology, and thus which can be evaluated in meteorological analyses and forecasts, is the surface mass balance (SMB). A 40-year (or more) reanalysis series offers nice prospects of analyzing variability and trends in ice sheet SMB, if the SMB is reliably reproduced. This is, to some extent, evaluated in section 2. A very limited evaluation of other aspects of the climate over the Antarctic ice sheet, including a note on the assimilation of Antarctic weather station data, is given in section 3.

2. Components of the surface mass balance (SMB)

2.1. The SMB

The SMB of an ice sheet is defined as the net moisture budget at the surface. The components of the budget are: the precipitation *P*; the evaporation or sublimation *E*; the gravitational export *R* (runoff) of liquid water across the boundaries of the ice sheet. Negative sublimation (water vapor directly freezing onto the surface) is not exceptional, so the sign of *E* is variable. Liquid water that runs off can be either rain-water or melted ice. Liquid water does not necessarily all run off. A large part may be trapped in the snow/ice and (re)frozen. Whether blowing snow significantly contributes to the SMB of an ice sheet, either through enhanced sublimation or by exporting solid snow across ice sheet boundaries, is a currently debated subject.

None of the components of the SMB are analyzed at ECMWF at this time, but they are predicted. The predictions provide estimates of *P*, *E* and *R*. Surface freezing/melting and runoff of liquid water in soils are calculated. However, it appears that snow and ice are not properly treated as «soil» types in the reanalyses, and that the partitioning of running/frozen water in the ice is not correct (all liquid water runs off, see section 2.3). Blowing snow and its possible consequences on the SMB are not predicted.

Although surface melting occurs, runoff is supposed to be a very weak contribution to the SMB of Antarctica, except possibly in the northernmost parts of the Peninsula. This is unlike Greenland, where the mean quantity of water that runs off at the periphery is about half the average precipitation on the whole ice sheet.

The mean SMB is the positive component of the overall mass balance of an ice sheet. The other components include ice flowing into the ocean and either forming floating ice shelves or directly calving as icebergs. The SMB instantly responds to climate whereas ice flow exhibits some delay. The mean SBM, responding to climate change, can thus contribute to fast sea-level change. However, verifying the ability of models used to predict climate and environment changes requires checking how they succeed in reproducing not only the mean SMB, but also its spatial distribution, components, seasonality and variability, etc., for which very few observational data exist. Meteorological forecasts, which benefit from some observational control on the atmospheric dynamics, heat and moisture content, might be expected to produce useful information in this respect.

All units here are given in thickness of equivalent liquid water per unit time, e.g. mm/day or cm/year.

2.2. Annual mean SMB components

2.2.1. Prediction lead-time and spin-up

In ERA15 (and in some operational analyses), the predicted hydrology has proved to somewhat vary with the prediction lead-time, including over Antarctica. This has been interpreted as the signature of inconsistencies between the initial conditions from analyses and the meteorological model physics. At the beginning of each forecast, the analyzed hydrology thus needs adjusts to the model physics. As a consequence, even though predictions are expected to deteriorate with lead-time, the shortest term (6h) is not necessarily the preferred lead-time. Rather, data users have exploited the 12h or 24h predictions, in some cases even substracting the earliest 6h forecasts from these to minimize spin-up contamination [Genthon and Krinner, 1998].

Table 1 gives the annual mean precipitation, evaporation and runoff averaged over the grounded (i.e. excluding the floating shelves) Antarctic ice sheet, in ERA15 and in ERA40 at 6, 12 and 24h lead-time.

	ERA15			**ERA40**		
Lead time	6h	12h	24h	6h	12h	24h
Prec	0.34	0.36	0.38	0.41	0.43	0.44
Evap	0.027	0.026	0.024	0.063	0.064	0.064
Roff	0.097	0.097	0.097	0.033	0.034	0.035

Table 1: Annual mean predicted SMB components over the grounded Antarctic ice sheet, in mm/day

In ERA15, the mean precipitation increases with lead-time by more than 10% from 6h to 24h. The increase is slightly less but still not negligible in ERA40. A 10% uncertainty on the SMB of Antarctica translates into a 0.5 mm/year of sea-level uncertainty. It is thus still recommended that, with ERA40 as it stands now, the 6h-forecast is not used. Evaporation, which is also affected in ERA15 (12% increase from 6 to 24h lead-time), is much less sensitive to lead-time in ERA40. Runoff is little affected by lead-time. Figure 1 shows the mean precipitation minus evaporation (*P-E*) and the 24h-6h difference for ERA15 and ERA40. This indicates that the spin-up problem is not uniformly distributed and that it more strongly affects the driest, and also the coldest, interior parts of the Antarctic ice sheet. *P-E* is thus particularly poorly determined (up to and more than 100% change from 6h to 24h lead-time) on the East Antarctic plateau. At a few places in Antarctica, and over larger chunks of the circum-Antarctic seas, *P-E* actually decreases with lead-time.

At Vostok (78^{o}27'S, 106^{o}52'E), Dome C (75^{o}06', 123^{o}23'E) and South Pole (90^{o}S), fairly reliable glaciological measurements indicate that the mean SMB, or *P-E* since there is clearly no runoff, is 2, 3.2 and 8.5 cm/year, respectively. The 6h ERA40 forecast yields 0.2, 0.7 and 4.5 cm/year only. The 24h forecast is still much too dry (0.9, 1.3 and 5.2 cm/year) but quite closer to the observation. Clearly, the 24h forecast or even may be (at least at Vostok and to some extent Dome C) the 24h-12h forecast should be preferred.

Figure 1 shows a remarkable change of spin-up between ERA15 and ERA40 in the vicinity of Vostok. With South Pole, Vostok is the only meteorological station in the interior of the ice sheet that, during the period analyzed here, carried out and reported soundings through the atmosphere (Vostok is no longer operational, and only South Pole currently reports observations above the surface). It should be interesting to see if and how the Vostok reports of moisture are differently used in the two reanalyses. Moisture measurements in very cold and dry atmospheres are reputedly unreliable [King and Turner, 1997], so the use of Vostok observations may be delicate and suspect in this respect. It is not clear how the information from observations elsewhere in Antarctica (at South Pole and at the coasts) propagate and result in largest spin-up biases on the Est Antarctic plateau.

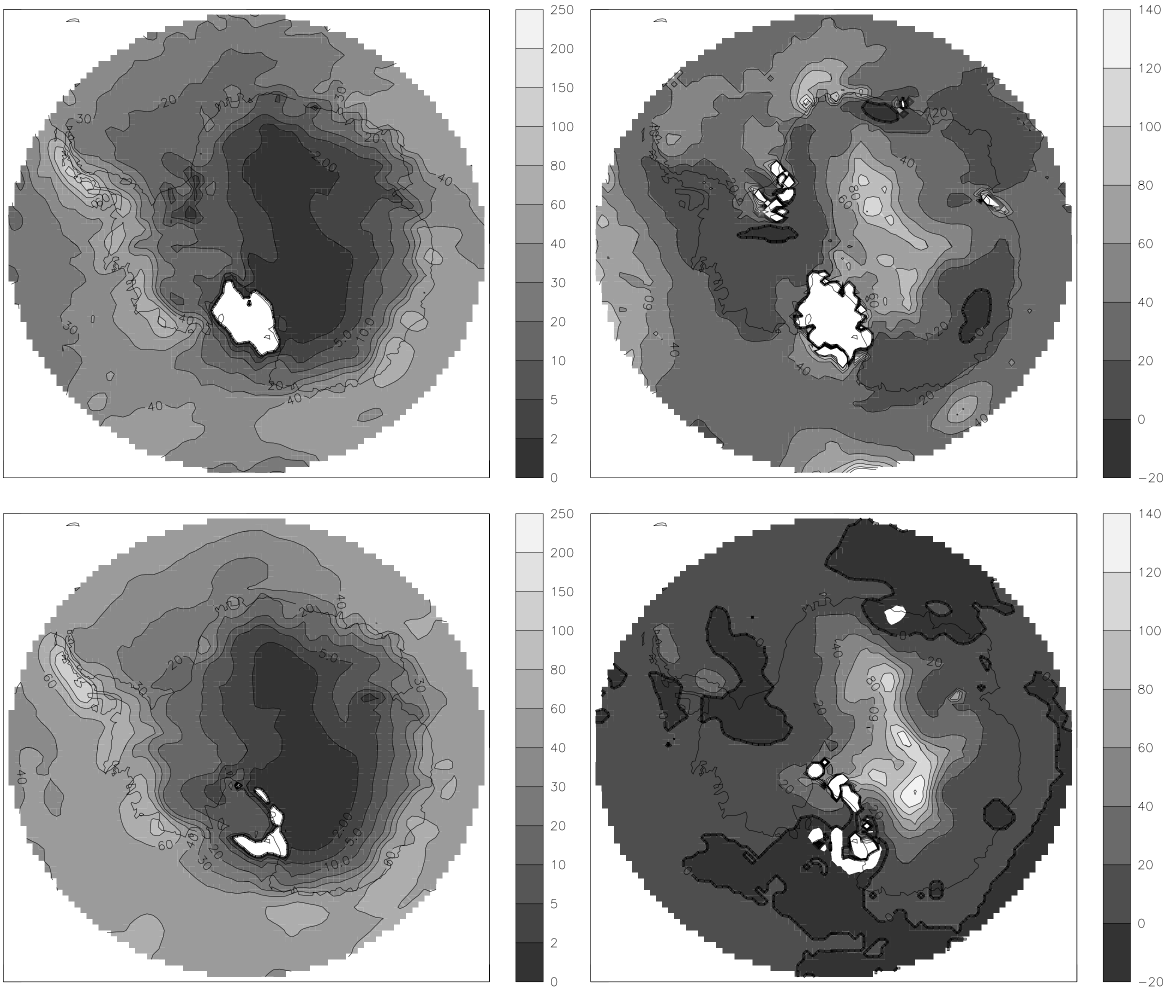

Figure 1: Mean P-E (left, averaged over 6h and 24h lead-time, in cm/year) and percentage change of P-E between 6h and 24h lead-time (right, in %), for the Antarctic region in ERA15 (upper) and ERA40 (lower plots).

	ERA15			**ERA40**		
Lead time	6h	12h	24h	6h	12h	24h
Prec	0.77	0.82	0.88	0.94	0.97	0.98
Evap	0.058	0.058	0.055	0.077	0.077	0.074
Roff	0.58	0.58	0.58	0.74	0.74	0.76

Table 2: Annual mean predicted SMB components over the Greenland ice sheet, in mm/day

Over Greenland, table 2 shows an even stronger precipitation spin-up in ERA15 (14% increase from 6h to 24h lead-time) than over Antarctica. This problem is again reduced in ERA40 but not eliminated, and again the 6h forecast should be considered with suspicion. Evaporation is again less affected. In fact, it is stable from 6 to 12h, then decreases from 12 to 24h, possibly suggesting that there is no significant spin up but a loss of predictive capability as early as one day ahead in time. Runoff is little affected by spin-up. As for Antarctica, the spatial distribution of spin-up (not shown) is not uniform with, broadly (but not systematically), larger effects in the driest regions

2.2.2. Mean SMB and SMB components versus observations

There are few direct reliable observations of the separate components of the SMB of the ice sheets, including of precipitation. On the other hand, quite a few glaciological estimates of the mean SMB have been performed. They are not all equally reliable, their spatial and temporal significance varies, and there are still large gaps in the available network of such observations. Genthon and Krinner [2001] have shown that general circulations models (GCM) display a number of common biases in their reconstructions of the SMB of Antarctica when compared to the latest compilation and interpolation of the available glaciological observations [Vaughan et al., 1999]. They suggest that, if some of the biases may be due to systematic shortcomings of the models (e.g., no a ccount of blowing/drifting snow), others are more likely to reflect problems with the observations and interpolations. They also show that ECMWF operational as well as ERA15 forecasts of the SMB of Antarctica are equally affected. Figure 2 compares ERA15 and ERA40 (24h forecast) biases with respect to Vaughan et al. [1999] mean SMB map. The predicted SMB is taken as *P-E*, since runoff is generally considered a negligible component. Incidentally, this is not confirmed by table 1, which indicates that the predicted runoff is of a same order or even larger than evaporation/sublimation. This is clearly an overestimation, although Antarctic runoff may not have been seriously enough addressed so far.

The major and most robust (i.e. those that show in all or most models) coastal biases identified in ERA15 and in a number of GCMs by Genthon and Krinner [2001] still show in ERA40. However, in regions where the biases are less robust, there is a better agreement of ERA40 than ERA15 with Vaughan et al. [1999]. This confirms that the less robust biases are not systematic, thus unlikely to result from common shortcomings in models or from observation deficiencies, and that ERA40 performs better than ERA15.

Because the Antarctic SMB generally decreases rapidly with distance from the coast, difference maps are not very appropriate to discuss biases both at the coasts and in the interior. To highlight the interior, figure 3 shows SMB ratios, rather than differences. As anticipated (section 2.2.1), the reanalysis-based forecasts are too dry on the high eastern plateau, and this does not improve in ERA40, compared to ERA15. In both reanalyses, the strongest biases are found in Victoria Land, east of the Ross ice shelf. However, there is a tendency in other models, not as strong as here though, to also underestimate the SMB in this region. Some of the problem may thus, as in some coastal regions, reveal unreliable observations.

According to Vaughan et al. [1999], the mean SMB of Antarctica (grounded ice) is almost 15 cm/year. Table 3 gives the Antarctic SMB from ERA15 and ERA40 24h forecasts. Even if runoff is not considered, and

SMB	**P-E**	**P-E-R**
ERA15	13.1	9.50
ERA40	13.7	12.4
Vaughan et al.	~15	

Table 3: Antarctic SMB, 24h forecasts, in cm/year

consistent with previous discussions, both reanalyses are too dry. ERA40 is in slightly better agreement with observation. Runoff is clearly overestimated and will no longer be considered part of the Antarctic SMB in the reanalyses.

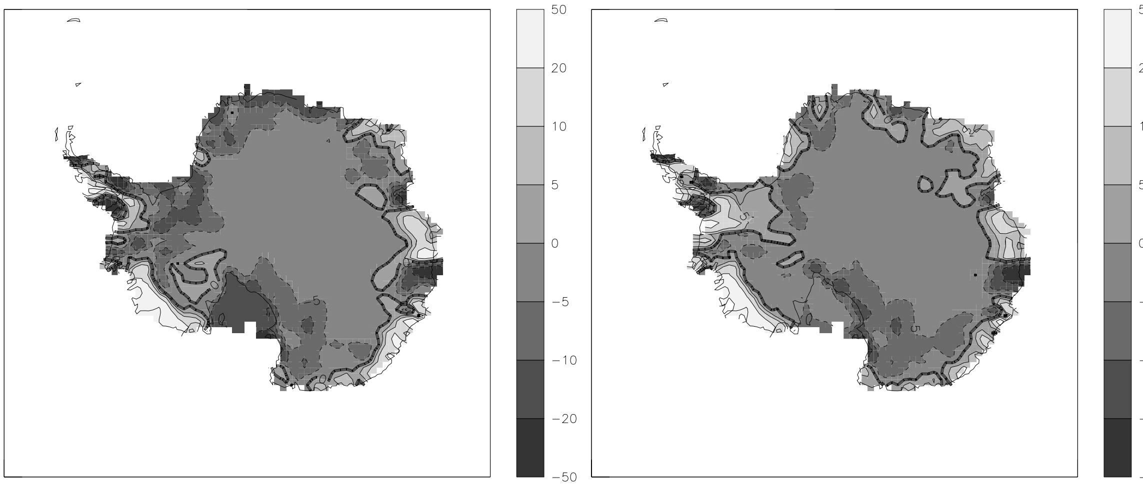

Figure 2: Mean ERA15 (left) and ERA40 (right) SMB biases with respect to Vaughan et al. [1999], in cm/ year.

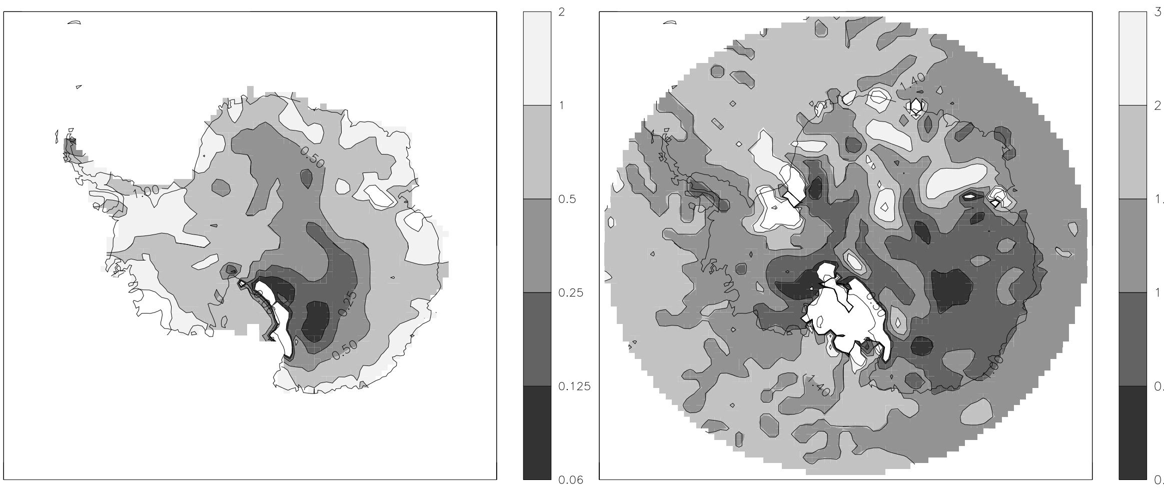

Figure 3: ERA40 (24h-forecast) SMB ratio with respect to Vaughan et al. [1999] (left) and with respect to ERA15 (right). No unit.

Measurements of evaporation/sublimation are too scarce to draw a global picture on the ice sheet. Models suggest that annual sublimation can return from ~5 to ~20% of the Antarctic precipitation to the atmosphere (Genthon and Braun [1995], van den Broeke [1997], Genthon and Krinner [2001]). Table 1 indicates that evaporation is in this range for both ERA15 and ERA40, but it is 2.5 time larger in the latter than in the former reanalysis. Figure 4 shows the distribution of annual evaporation in the Antarctic region. For ERA40, this is in relatively good agreement with a map reported by van den Broeke [1997] for the ECHAM3 GCM, except on the ice shelves where evaporation is significantly lower in the reanalysis. Interestingly, figure 4 shows an evolution of the evaporation in the reanalyses, from ERA15 to ERA40, which is just opposite to the evolution in the ECHAM model, from ECHAM3 to ECHAM4 [Genthon and Krinner, 2001]. Specifically, evaporation is negative (i.e. deposition) on the high plateau in ERA15 and ECHAM4, but not in ERA40 and ECHAM3. Although the quantities involved are not negligible compared to local precipitation (e.g. at Vostok: only ~20 mm/yr), they are small (less than 5 mm/yr) and thus hard to measure, and it is not clear whether negative sublimation over such large region is correct or not. Some of the observations compiled by van den Broeke [1997] suggest that annual mean deposition is not unrealistic.

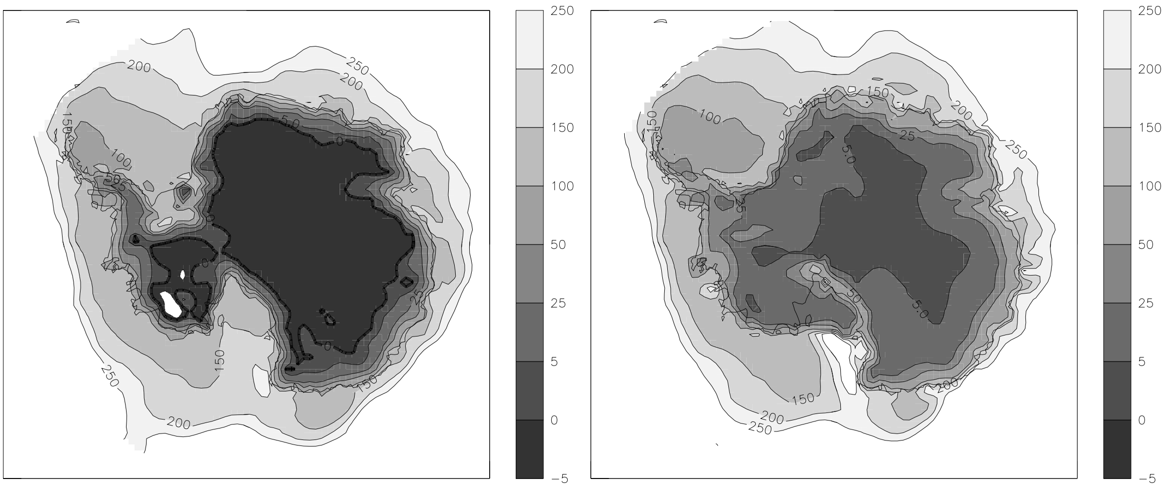

Figure 4: 24h forecast of evaporation/sublimation in ERA15 (left) and ERA40 (right), in mm/yr.

The ice shelves are other areas where evaporation/sublimation is very different in ERA15 and ERA40. This is probably in relation with a change of the prescribed nature of the ice shelves, from sea-ice in ERA15 (thus allowing significant heat flux from or to the ocean, e.g. Genthon and Krinner [1998]) to land-ice in ERA40. From a thermal point of view, shelves (which are hundreds of meter thick slabs of floating meteoric ice) are indeed much closer to land-ice than to sea-ice. Compared to observations on the Ross ice shelf [Stearns and Weidner, 1993], evaporation appears too strong in ERA15 but too weak in ERA40.

According to Ohmura et al. [1999], the mean SMB of Greenland is slightly less than 10 cm/yr. For the 24h forecasts, table 2 indicates a value of 9 and 5.4 cm/yr for ERA15 and ERA40, respectively, suggesting a deteriorating performance from the former to the latter reanalysis. Ohmura et al. [1999] suggest that mean runoff is about 20 cm/yr (but this may well be an overestimation), a value with which ERA15 agrees relatively well (21 cm/yr) but which ERA40 overestimates (28 cm/yr). In fact, there are at least two reasons why direct estimates of runoff from analyses (or from climate models) may be strongly biased over ice sheets. One is related to spatial resolution, which is insufficient to resolve the narrow regions (a few tens of km) over which summer melt occurs. The other is related to the disposal of liquid water (ice melt or liquid precipitation) in the model, a sizeable fraction of which (of the order of 50% for Greenland, probably close to 100% in Antarctica), in the real world, may percolate and refreeze within the snow or ice, rather than run off the ice sheet. Runoff is thus fortuitously better estimated in ERA15 than in ERA40. Mean precipitation, 34 cm/yr according to Ohmura et al. [1999], is slightly underestimated by ERA15 (32 cm/year) and overestimated by ERA40 (36 cm/yr) but this is probably within observation uncertainty. The difference of mean evaporation/sublimation between ERA15 and ERA40 is also certainly within uncertainties. There is thus no clear indication of a superiority of either ERA15 or ERA40 in reproducing the mean components of the SMB of Greenland.

2.3 Seasonality and variability of SMB components

Figure 5 shows the monthly time series of the mean components of the grounded Antarctic SMB. The variability of the SMB itself (excluding runoff, that is *P-E*) is very similar in ERA15 and ERA40 (correlation r=0.95). The variability of precipitation alone differs more (r=0.84 only). Evaporation/sublimation, although much stronger in ERA40, is very coherent in the two reanalyses because it is tightly paced by temperature. In fact, there is very little seasonality in the precipitation series, and evaporation/sublimation is responsible for the seasonality and higher coherence of the SMB [Genthon and Krinner, 1998]. This is a result also found in some climate models but which cannot be verified in the real world. Remarkably, both the precipitation and the evaporation of the two reanalyses differ more in (austral) summer than in winter, in ways that almost exactly compensate and result in very little seasonality of the (small) differences in the SMB. It may be postulated that higher summer precipitation in ERA40 is associated with higher temperatures which contribute to higher evaporation.

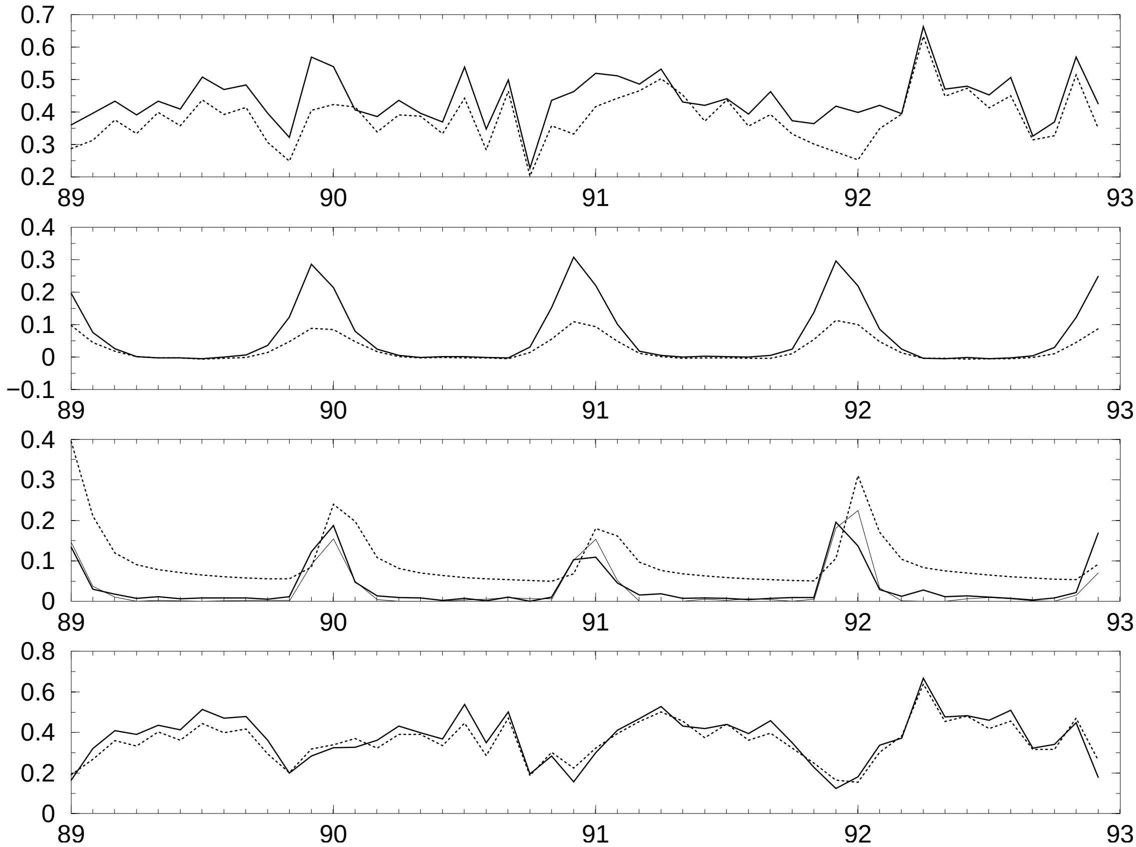

Figure 5: Monthly series of (from top to bottom) Antarctic-mean precipitation, evaporation/sublimation, runoff, and SMB (P-E only) from 24h forecasts of ERA40 (solid line) and ERA15 (dotted line). Unit: mm/day. For runoff, a thin line shows the monthly mean surface affected by melting (arbitrary unit scaled to approximately fit ERA40 runoff), as seen by satellite microwave sensors [Torinesi et al., 2001].

Larger evaporation/sublimation in ERA40 (Table 2) is confirmed by figure 5. In summer, evaporation is ~3 times larger in ERA40 than ERA15. Van den Broeke [1997] reports observations of summer surface latent heat flux at a few coastal sites which are in the range 20 to 50 W/m^2. ERA15 is below that range at the same sites (not shown). ERA40 is in better agreement with the observation, although still at the lower limit of the range.

Runoff is clearly unrealistic in ERA15 since it does not reduce to near zero even in full (austral) winter. This is because all liquid water (liquid precipitation + melting, essentially in summer) percolates without refreezing to the lowest soil layer in the model, then runs off as deep, very slow drainage. In ERA40, the ice is impermeable to liquid water, which runs off immediately as surface drainage (Pedro Viterbo, ECMWF, personal communication). The thin line superposed to runoff on figure 5 shows the monthly mean Antarctic surface affected by melting. This can be obtained by satellite microwave sensors [Torinesi et al., 2001] because even tiny amounts of liquid water strongly increase the microwave emissivity of the surface. Although melting surface does not necessarily linearly relate to meltwater quantity or to runoff, the phasing between melting surface from satellite and ERA40 runoff is quite good. The fact that runoff begins and peaks ~1 month later in ERA15 and ERA40 probably simply reflects a delayed deep drainage.

Figure 6 shows the monthly time series of SMB components for Greenland. The correlation between ERA15 and ERA40 for precipitation is better than in Antarctica. For evaporation, there is also more agreement as far as quantities are concerned, but less agreement for timing: Maximum evaporation occurs 1 month later in ERA15 (July) than in ERA40 (June). Consistent with Antarctic results and deep drainage in ERA15 versus surface drainage in ERA40, the early summer onset of runoff is delayed by a month or so. Both reanalyses

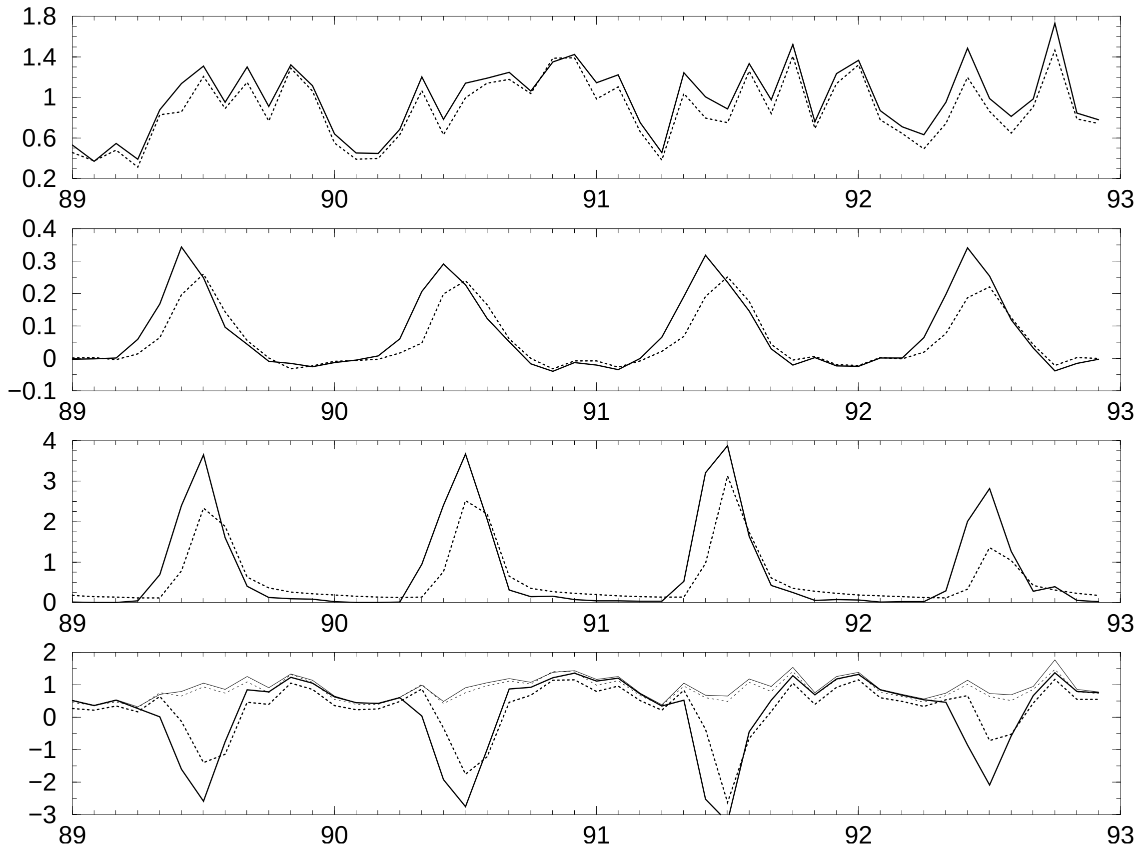

Figure 6: Monthly series of (from top to bottom) Greenland-mean precipitation, evaporation/sublimation, runoff, and SMB (thick line: P-E-R; thin line: P-E only) from 24h forecasts of ERA40 (solid line) and ERA15 (dotted line). Unit: mm/day.

suggest less runoff in the summer of 1992 than in the other years. Satellite observations do suggest that 1992 is a low runoff year. For Greenland, runoff is the component that introduces the largest differences of SMB between the two reanalyses.

3. Additional aspects of the Antarctic climate

3.1. Surface temperature

There are large differences in analyzed surface temperature between ERA15 and ERA40. Figure 7 illustrates that some of these differences are associated with differences in surface elevation. The prescribed Antarctic surface elevation in ERA15 was outdated and in error of, locally, more than 1000 m [Genthon and Braun, 1995]. The new topography in ERA40 is based on recent satellite altimeter measurements [Bamber et al., 1994] and probably accurate within a few tens of meters, except possibly in the coastal regions [Genthon and Krinner, 2001]. However, figure 7 shows that most of the temperature difference between ERA15 and ERA40 is not related to surface elevation errors in the former reanalysis. The largest temperature difference, about 18^{o}C in western Queen Maud Land, does coincide with a large elevation error in ERA15, about 1000 m, but a simple lapse rate is not sufficient to explain the temperature difference. In fact, the temperature is lower in ERA15 than in ERA40, even where the surface elevation is lower, e.g. in eastern Queen Maud Land. Only on the shelves is ERA15 surface temperature higher. This is, as previously mentioned (section 2.2.2), because the «soil» nature has been changed from sea-ice in ERA15 to land-ice in ERA40.

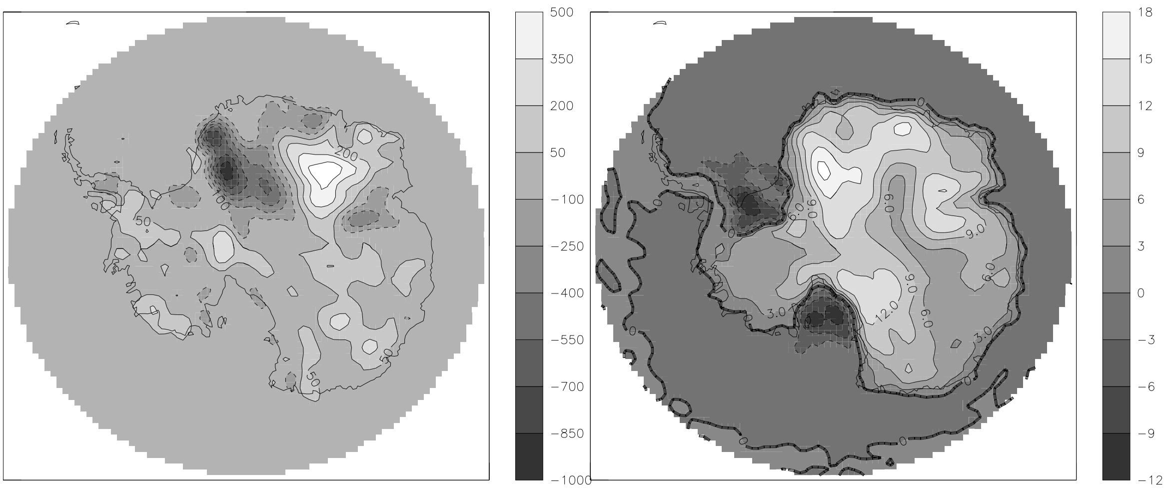

Figure 7: Change from ERA15 to ERA40 (ERA40-ERA15) of prescribed surface elevation (left, in m) and annual-mean analyzed atmospheric (2-m) surface temperature (right, in ^{o}C).

Figure 8 shows the annual mean analyzed surface temperature in ERA15 and ERA40. This can be compared with glaciological measurements (i.e. 10-m deep snow temperature, King and Turner [1997]). The general shape of the isotherms on the East Antarctic plateau is in much better agreement with observation in ERA40, most likely thanks to an updated Antarctic orography, but temperature is too warm by ~5^{o}C. Temperature is too cold by almost the same amount on the East plateau in ERA15. On the shelves, the temperature is more correct in ERA40 than in ERA15 (too warm in the latter).

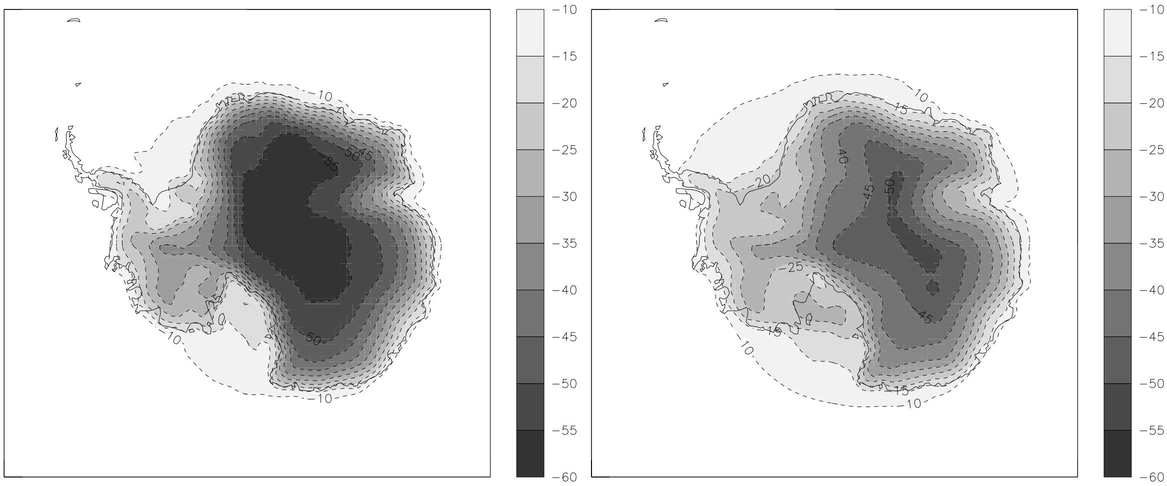

Figure 8: Annual-mean analyzed surface (2-m) atmospheric temperature in ERA15 (left) and ERA40 (right). Unit: ^{o}C.

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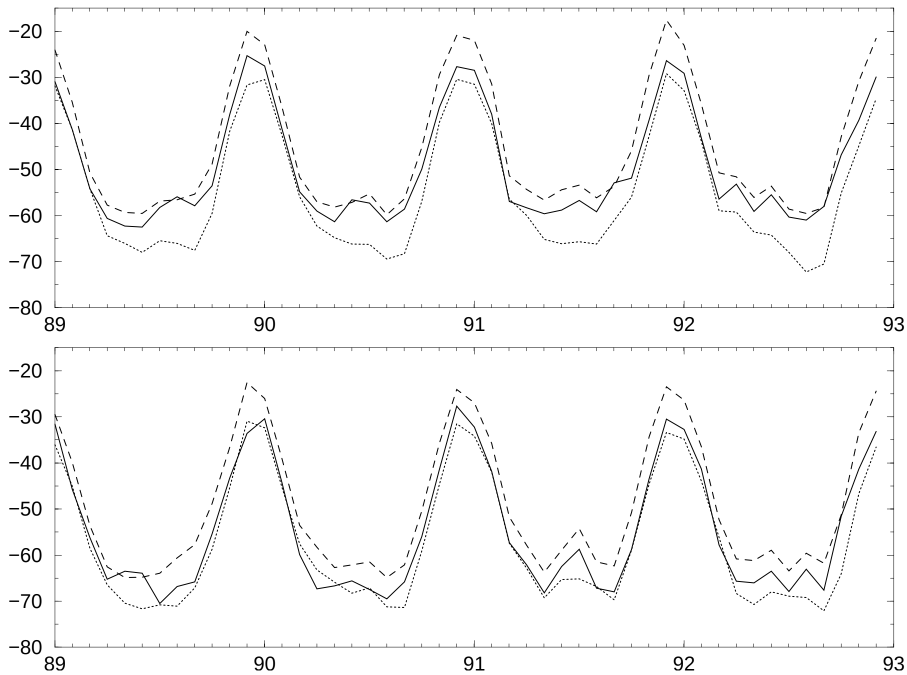


Figure 9: Monthly-mean surface (2-m) atmospheric temperature at South Pole (upper plot) and Vostok (lower plot), observed (solid line), ERA15 (dotted line), and ERA40 (dashed line). Unit: ^{o}C.

Figure 9. shows the monthly series of surface temperature at 2 interior stations, South Pole (90^{o}S) and Vostok (78^{o}27'S, 106^{o}52'E), where the elevation in the 2 reanalyses differs by a few tens of meters only (and thus, temperature differences may not be due to surface elevation differences). This confirms a warm (cold) bias in ERA40 (ERA15, respectively). However, figure 9 also indicates that the temperature bias in stronger in (austral) winter in ERA15, whereas it hardly varies with season in ERA40, and that chronological

variability in winter is generally more realistic in ERA40 than in ERA15. At both South Pole and Vostok, in winter, the surface temperature inversion strengthen to more than 20^{o}C. Winter surface temperature deficiencies are likely to be related to deficiencies of the surface and boundary layer flux parameterizations in ERA15 [Viterbo et al., 1999]. This appears to be efficiently corrected in ERA40. It is not clear yet why ERA40 is too warm all year-long though.

3.2. 500 hPa geopotential

A major deficiency of the 500 hPa geopotential over Antarctica was identified by Bromwich et al. [2000] and associated with ~70 m error on the elevation attributed to the Vostok weather station when assimilating the observations. The assimilation error at Vostok was corrected in ERA40, and figure 10 does shows a large 500 hPa geopotential height difference between the two reanalyses on the East Antarctic plateau. However, surprisingly, the maximum change is not located right on Vostok, but it rather extends largely westward towards a region devoid of observation on the field. Figure 10 also shows that much of the 500 hPa geopotential change, from ERA15 to ERA40, occurs over the polar oceans. This is further evaluated by Bromwich et al. [2001]. Also, the results of Bromwich et al. [2000] and Genthon et al. [2001] suggest that ERA15 has, along with the low geopotential bias in the interior of Antarctica, a high bias in the Ross and Bellingshausen regions. Bromwich et al. [2000] explicitly state that the Vostok assimilation deficiency in ERA15 has adversely affected the climate of the Ross area. Figure 10 does show a large subsidence of the 500 hPa geopotential in this region in ERA40, compared to ERA15.

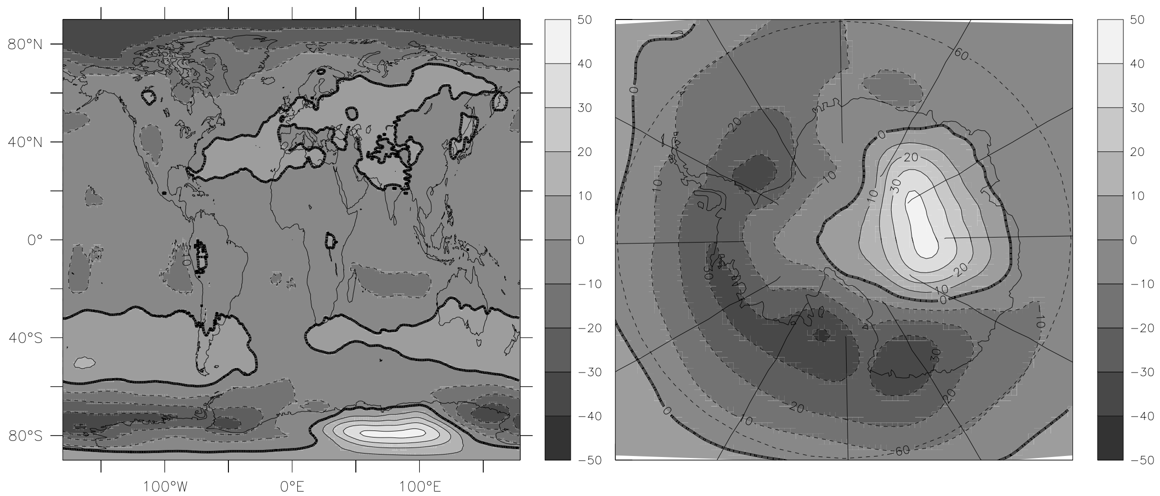


Figure 10: Change from ERA15 to ERA40 (ERA40 - ERA15) of annual-mean analyzed 500 hPa geopotential height, globally (left) and over the Antarctic region (right). Unit: m.

The 500 hPa geopotential is also lower in ERA40 over Oates and George V Lands. In fact, figure 11 indicates that in this region, the (negative) geopotential change has increased through the years, apparently shifting the (Vostok related) positive change to the west, further westward. Figure 12 shows little particular change in this area through the years in ERA40. On the other hand, figure 13 displays a rather dramatic change from 1989-90 to 1991-92 in ERA15. In addition, this temporal change in ERA15, which is very localized and thus very unlikely to be natural variability, shows in the interior of Wilkes Land. On the other hand, in figure 11, it comes out closer to the coast, as if the ERA15 temporal change and the ERA40/ERA15 Vostok-related change «pushed» each other apart.

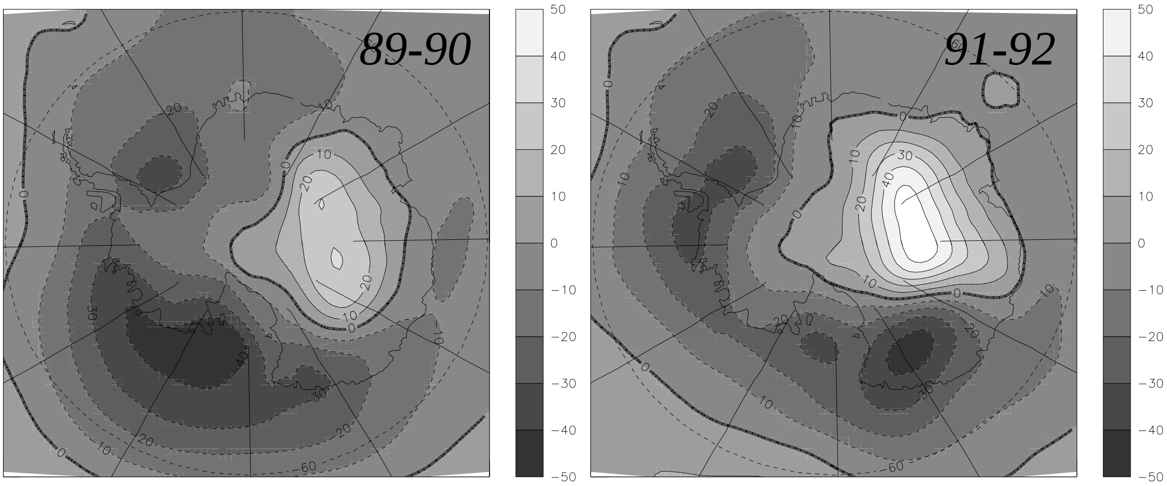
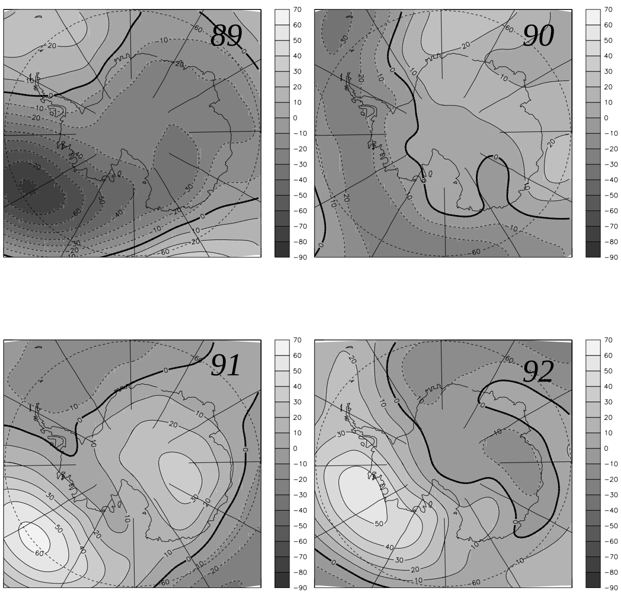


Figure 11: Change from ERA15 to ERA40 (ERA40 - ERA15) of annual-mean analyzed 500 hPa geopotential height, separately for 1989-90 and for 1991-92. Unit: m.



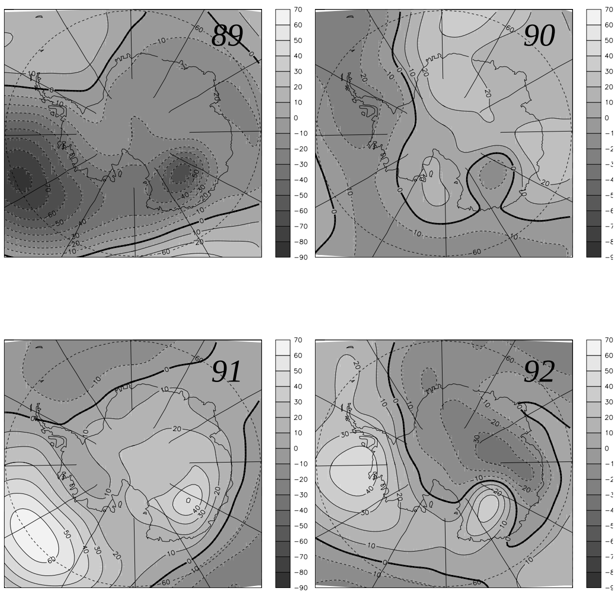


Figure 12: ERA40 500 hPa annual geopotential anomaly with respect to the 89-92 mean. Unit: m.

Figure 13: ERA15 500 hPa annual geopotential anomaly with respect to the 89-92 mean. Unit: m.

In fact, the temporal change in ERA15 is located right over the Dome C (now called Dome Concordia), in the vicinity of which an University of Wisconsin Automatic Weather Station (AWS) has been (more or less continuously) operating since early 1980. Only surface measurements are made at the station, but this includes surface pressure which directly affects geopotential height higher in the atmosphere. Figure 13 strongly suggests that the assimilation of the Dome C station data has changed some time around the 1990. This is confirmed at ECMWF (Sakari Uppala, ECMWF, personal communication): Dome C data prior to October 1990 were not used in the ERA15 analyses. Figure 12 suggests more time consistency in the use of the Dome C observations in ERA40.

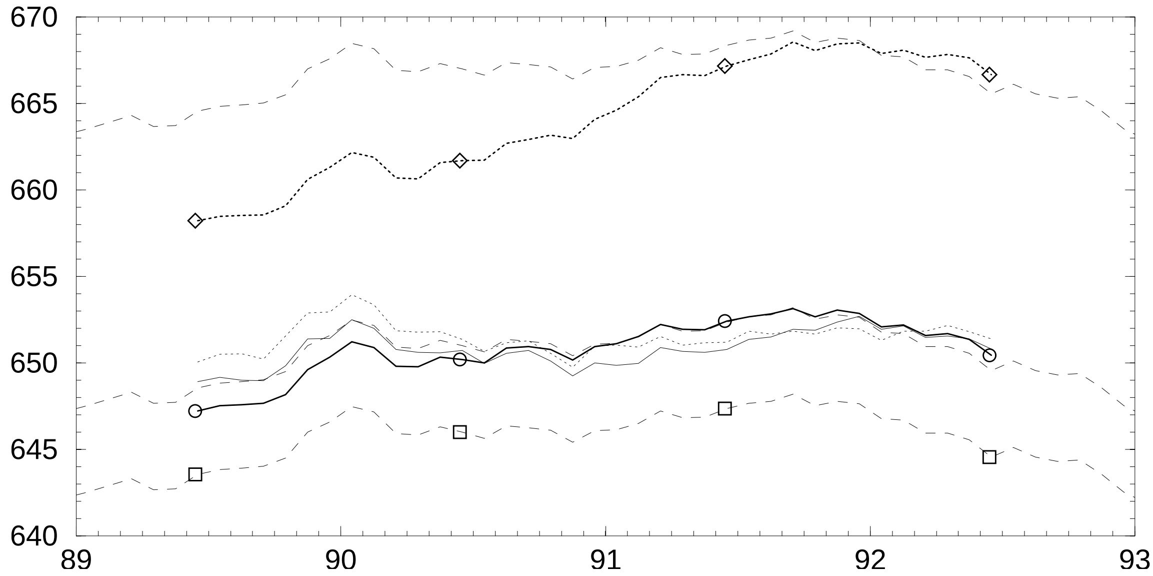


Figure 14: Smoothed (12-month running-mean) series of surface pressure at Dome C in the ERA40 (solid thick) and ERA15 (dotted thick) reanalyses, observed by the AWS (dashed), and from the LMDZ GCM nudged at 60^{o}S with ERA40 (solid thin) and ERA15 (dotted thin) surface pressure and winds [Genthon et al., 2001]. The observations are reproduced 3 times, the actual values (lower dashed) being shifted twice for better comparison with the other series. Symbols mark annual means. Unit: hPa.

This is also confirmed by figure 14, which compares the interannual evolution of reanalyzed versus observed surface pressure at the first (in operation until 1995) Dome C AWS at (74^{o}30'S, 123^{o}E). Incidentally, figure 14 shows that ERA15 reproduces the smoothed short term variability seen in the observations, even before the observations are used in the reanalyses. Experiments with a laterally-nudged GCM [Genthon et al., 2001] show that, in fact, much of this variability is determined by the circum-polar Antarctic circulation (figure 14) which, in the reanalyses, is efficiently constrained by a number of coastal observations.

3.3. A note on the elevation of weather stations in Antarctica

Because of model limited spatial resolution or simply due to a wrong prescribed orography in the model, station and model elevation at a given site differ. Observations must thus be corrected for this difference to be adequately assimilated. However, if the actual Vostok station height is underestimated (section 3.2), the elevation correction (z_{model} - $z_{station}$) at Vostok contains a spurious positive component, which results in a negative surface pressure or 500 hPa geopotential bias in the analyses. This problem was identified in ERA15 and corrected on ERA40 (section 3.2). Only recently has accurate mapping of the surface elevation of full Antarctica been possible, thanks to the use of GPS, radar altimetry, and other airborne and spaceborne technics (e.g., Bamber [1994], Remy et al. [1999]). The orography of the Antarctic continent which is prescribed in the ECMWF model was erroneous in ERA15 but updated in ERA40 (section 3.1, figure 7.). It remains to be verified that the station height attributed to all Antarctic weather stations used to produce the reanalyses is also updated and correct.

Figure 14 suggests that the mean analyzed surface pressure at Dome C in ERA15 has increased by ~5 hPa when the Dome C AWS observations have been used. It is very possible that, before the Dome C AWS observations were taken into account, the consequences of an elevation error at Vostok have laterally propagated to Dome C. However, it also turns out that the first Dome C AWS (operating through 1980-95) was attributed a wrong, overestimated height. In the University of Wisconsin AWS data base (http://uwamrc.ssec.wisc.edu/aws/awsdata.html) as well as in the ECMWF archive (Sakari Uppala, ECMWF, personal communication), the elevation of the first Dome C AWS is 3280 m. The elevation of the top of Dome C has recently been accurately determined to be 3270m (plus or minus a couple of meters) (Christian Vincent, LGGE topographer, personal communication). Because the top of the dome is the highest point within several hundreds of km around, the elevation attributed to the first Dome C AWS is too high by at least 10 m. In fact, the latest surface topography maps from satellite altimeter, combined with GPS and DORIS measurements (e.g. Remy and Tabacco [2000]), indicate that the first Dome C AWS was about 25 m below the top of the dome. As of now, a best estimate for the height of the first Dome C AWS is 3245 m, that is 35 m less than currently figured at ECMWF (an improved calculation and mapping of the geoid under the Antarctic ice sheet should soon become available, to possibly further refine this number). At Dome C, a 35 m altitude error results in a ~3 hPa surface pressure error, which can account for a large fraction of the 1989-92 pressure rise at Dome C in ERA15 (the other few hPa possibly to be blamed on the Vostok error).

In 1996, the first Dome C AWS was decommissioned and replaced by a new station, generally designed as the Dome C II AWS (see http://uwamrc.ssec.wisc.edu/aws/aws/data.html). In addition, at the same time, the AWS was moved by a few tens of km, from (74^{o}30'S, 123^{o}E) to (75^{o}07'S, 123^{o}22'E), closer to the top of Dome C and thus at higher elevation. In fact, the altitude of the Dome C II AWS is only a couple of meter below the top, that is about 3268 m above the geoid (a figure again to be refined when an up-to-date geoid is available). However, both the University of Wisconsin AWS data base and the ECMWF archive log a station elevation of 3250 m only. This is an almost 20 m error. More importantly, combined with the error on the first AWS, this will result in a drop of station elevation of 30 m in 1996, instead of an actual rise by more than 20 m. Unless corrected by 1996, an elevation change error of more than 50 m may be expected to result in a spurious surface pressure drop of ~5 hPa, when the observations shift from the first station to the Dome C II AWS in the assimilation process. The time consistency of the analyses in a significant part of Antarctica may be affected.

In fact, an update of the surface elevation of all weather stations in the interior of the Antarctic ice sheet, taking account of the latest and most accurate surface topography and geoid maps now or soon to be available, is probably recommended for the production of ERA40.

4. Summary

A preliminary evaluation of ERA40 analyses and forecasts over the polar ice sheets shows that:

- The ERA40 forecasts of precipitation and to some extent evaporation at the surface of the polar ice sheets are still affected by spin-up problems, although somewhat less than in ERA15. The shorter term (6h, possibly even 12h) forecasts should still be avoided. The spin-up bias is stronger in the interior, drier parts of the ice sheets.

- The annual-mean Antarctic SMB (Surface Mass Balance), although probably slightly better reproduced in the forecasts of ERA40, is still affected by regional biases. In particular, it is too dry on the east Antarctic plateau. On average over the grounded ice sheet, the SMB is somewhat too low, but less so in ERA40 than in ERA15.

- The mean Antarctic evaporation/sublimation is quite different in the two reanalyses, ERA40 probably being more realistic in the coastal regions and on the ice shelves. On average over the ice sheet, evaporation is about 2.5 times larger in ERA40 than in ERA15. Precipitation is also significantly larger in ERA40. Observations are insufficient to assess which reanalysis is more realistic in these respects.

- Runoff is not properly handled in the models and consequently (mostly largely) overestimated.

- The mean precipitation and evaporation averaged over the Greenland ice sheet are within observational uncertainties, both for ERA15 and ERA40. Because runoff is incorrect, the mean Greenland SMB cannot be evaluated. Spatial distribution has not been (but should be) verified.

- The monthly and seasonal variability (including chronological variability) of the components of the SMB of the two polar ice sheets are at least qualitatively similar in the two reanalyses. The onset of spring evaporation on Greenland is delayed by a month in ERA15, compared to ERA40. It is not clear whether there are observations to assess which reanalysis is more realistic. The fact that runoff is also delayed (over Antarctica as well) is obviously a result of different, but equally inadequate, handling of soil water over ice sheets in the reanalyses.

- The analyzed Antarctic surface temperature has a cold, mainly winter bias in ERA15, but a warm permanent bias in ERA40. The origin of the ERA40 warm bias has not been identified and should be looked for in the surface energy budget.

- The largest differences of 500 hPa geopotential height between the two reanalyses are found in the polar regions. Over the Antarctic plateau, a large ERA15/ERA40 geopotential rise is apparently related to the update of the Vostok weather station elevation in the data assimilation to produce ERA40 analyses.

- A temporal change of geopotential in ERA15 over Dome C hints at an other weather station height problem in this region. The latest topographic measurements in the Dome C area confirm this problem. If this is not corrected in time, a spurious circulation jump in 1996 is predicted in ERA40, due to a change of the Dome C weather station. A systematic reevaluation of the elevation of weather stations in the interior of Antarctica is recommended for optimal use of the not-too-numerous available observations in the assimilation process.

Produced on a longer time scale, with a more up-to-date numerical package, after correction of a number of identified problems in ERA15, ERA40 is expected to be an improved source of information on the meteorology and climate of the polar ice sheet. However, a preliminary examination of ERA40 results leaves somewhat mixed feelings. Except possibly for summer mean temperature, there is no deterioration of the performances compared to ERA15. In fact, in a number of respects, ERA40 appears to do better than ERA15 but it is still affected by similar problems, e.g. spin-up, dry bias, etc. At last, circulation problems associated with erroneous assimilation of the few available observations on the ice sheets need to be further looked into.

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