ECMWF Analyses and Predictions of the Surface Climate of Greenland and Antarctica

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ABSTRACT

Major weather forecast centers produce physically based large-scale climate analyses and predictions that can be used as proxies for missing observations and thus as full-coverage climatologies. Because of this, a global reanalysis of recent climate is being carried out at the European Centre for Medium-Range Weather Forecasts (ECMWF). At the surface of the polar ice sheets (the atmospheric boundary condition for ice evolution), observations of climate are particularly scarce. To estimate how the new ECMWF climatology might help provide climate data over the polar ice sheets, the authors present 6 years of previously analyzed surface temperature and predicted precipitation for both Greenland and Antarctica. Analyses are the result of 6-h forecasts corrected to fit with reports from weather stations. Predicted variables are not corrected but the observation-constrained analyzed fields are used to initialize forecasting cycles. In spite of a sparse coverage of the observation network, the analyzed temperature, including seasonality, is very reasonable. Interannual variability, however, appears greater than suggested by satellite observation. Mean annual precipitation in Antarctica is fairly well represented, but it is difficult to determine whether a lack of seasonality on the plateau is reasonable or not. Precipitation in coastal Greenland is often too high, and accumulation might be low inland. Mean predicted accumulations, 1594×10^{12} and 539×10^{12} kg yr^{-1}, over the Antarctic and Greenland ice sheets, respectively, are in good agreement with previous estimates. It is reasonable to expect that the reanalysis will largely satisfy the need for a full-coverage gridded climatology of the two polar ice sheets.

1. Introduction

The atmosphere, mainly through temperature and water exchange at the surface, exerts a strong control on the evolution of ice sheets and on the balance of water between the oceans and the cryosphere. Climate change is likely to perturb this balance (Houghton et al. 1990), and therefore adequate modeling of climate over ice sheets is important. To check and improve models, there is a need for a climatology with extensive spatial and temporal coverage, which is not available from field observations.

The distribution of annual mean surface temperature over much of Greenland and Antarctica is fairly well known from field measurements (Giovinetto et al. 1990; Fortuin and Oerlemans 1990; Ohmura 1987, and references therein), but the estimation of seasonal cycles is more speculative. Remote sensing can provide estimates of the amplitude of the seasonal cycles and of extreme temperatures in the many areas distant from currently or previously operating weather stations. At present, this approach provides encouraging results over ice sheets (e.g., Comiso 1994) that should be confirmed. For precipitation, even the annual mean is not well measured at weather stations (Bromwhich 1988; Genthon 1993). There are many field observations of the long-term mean surface mass balance, but they are not all reliable (Giovinetto et al. 1989), and the latest estimates of the distribution of accumulation at the surface of the polar ice sheets (Giovinetto and Bentley 1985; Ohmura and Reeh 1991) are still subject to some uncertainties.

Meanwhile, major weather-forecasting centers currently provide "analyses" of the climate observed at weather stations and analysis-initialized model predictions. Analyses and predictions can be used as physically based proxies for climate information in regions where observations are missing, for example, the polar ice sheets. At the European Centre for Medium-Range Weather Forecasts (ECMWF), the analyses are, in fact, atmospheric General Circulation Model (GCM) simulations corrected every 6 h to fit with observations reported by weather stations and other operational means of weather monitoring.

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The GCM, a spectral model, is fully described in technical notes by the ECMWF (ECMWF 1988, 1991). Because it is used in weather-prediction mode, the model is a pure atmosphere and atmosphere-surface exchange model (that is, ocean and sea ice are prescribed), and initialization (every 6 h) is more important than boundary conditions. Otherwise, the ECMWF model is very similar to other GCMs designed for climate studies. Atmospheric dynamics, but also diabatic physics, hydrologic cycle including cloud cover, and radiation transfer are computed using numerical formulations and parameterizations subject to defects as in any other GCM. However, on average, the consequences of these defects on the simulated atmospheric circulation is more limited than in climate models because of the periodical relaxation of the analyzed variables to values reported by the weather-observation network.

Indeed, the ECMWF-analyzed fields are distributed and often used as full-coverage gridded climatologies (e.g., Schubert et al. 1990). The product includes temperature, atmospheric moisture, geopotential, and winds at the surface and through the depth of the atmosphere. Sea level pressure and total cloud cover are also available. Over Greenland and Antarctica, most of the weather stations that operate full-time are coastal stations and, thus, much of the control of observations on analyses is at the coasts.

Precipitation and moisture surface fluxes (evaporation–sublimation and dew–frost) are not analyzed since they are not observed and reported by the world meteorological network. However, the ECMWF GCM simulates these variables, which are thus available as "predictions" only. Predictions are certainly more model dependent than analyses. However, atmospheric moisture, temperature, and transport are analyzed and, thus, are controlled near observation sites. One may expect that such control helps with the prediction of precipitation as well.

In this paper, we present and discuss the ECMWF-analyzed surface temperature and predicted precipitation and net atmosphere–surface water balance (accumulation) for 6 years of the ECMWF archive (from May 1985 to April 1991). Over this time period, the model spectral truncation was T106 (about 1.125° × 1.125°) horizontally. Such high resolution would be fairly exceptional for a GCM used in climate mode, but it is now customary for models operating in prediction mode (the ECMWF model currently produces analyses at T213 spectral truncation, or about 0.55° × 0.55°, which is very attractive for future research). Resolution is a very important parameter of climate modeling over regions with large variations of surface elevation, like the ice sheets (Genthon et al. 1994).

2. The surface temperature

Figure 1 shows the annual mean temperature at the surface of Greenland and Antarctica, averaged over the 0000, 0600, 1200, and 1800 (UTC) analyzed ground surface temperature for 6 years. Atmospheric surface temperature, extrapolated 2 m above the surface, is also available from ECMWF. Differences between annual-mean ground and atmospheric surface temperatures of the order of 1°C (up to 3°C locally) are commonly observed in Antarctica (Giovinetto et al. 1990) and are also found in the model. Because these differences are small and we compare model results with field and satellite measurements of the surface snow temperature, we present and discuss only the ground temperature.

The ECMWF-analyzed temperature distributions are similar to the climatologies compiled by Ohmura (1987) and Giovinetto and Bentley (1985). In Greenland, the observations suggest that the −30°C isoline reaches 80°N. This is not reproduced by the analysis, but the other isolines look quite good considering that the smallest-scale features of Ohmura's estimate cannot be captured at the model resolution. The analyzed isotherm distribution is also fairly satisfactory over Antarctica, and a small spot of coldest temperatures (<−60°C) is even reproduced in central East Antarctica. Queen Maud Land near the 0° meridian appears too cold. This is discussed later.

Figures 2a and 2b show the mean January and July surface temperature averaged over the six available model years. Ohmura (1987) provides an estimate of these fields over Greenland based on weather reports, whereas Comiso (1994) shows for both Greenland and Antarctica six different years of satellite-sensed infrared radiation converted to surface temperature. For January over Greenland, there is again good consistency between model results and Ohmura's climatology. The model is slightly colder but Comiso's data show that temperature can decrease below −40°C in some years. Agreement is also better with Comiso's data in July, since above 75°N the model is warmer than Ohmura's map suggests.

Over Antarctica, the January and July model temperatures have the main characteristics of the annual mean; the range of temperature is correct, but the distribution appears flawed in some areas. For instance, the western part of Queen Maud Land is colder than suggested by Comiso's results, an apparent flaw already mentioned for the annual mean. Inadequate topography is certainly largely responsible for this deficiency since the ECMWF orography is up to 1000 m too high in this region (Fig. 3). This confirms the suggestion by Genthon (1994) that some of the global topography databases most widely used to set surface elevation in GCMs are deficient over Antarctica, with obvious consequences for surface temperatures. In addition, the ECMWF model uses an "envelope" topography, so that the surface elevation in each grid cell is the maximum rather than the mean of the real elevation in the area covered by the cell.

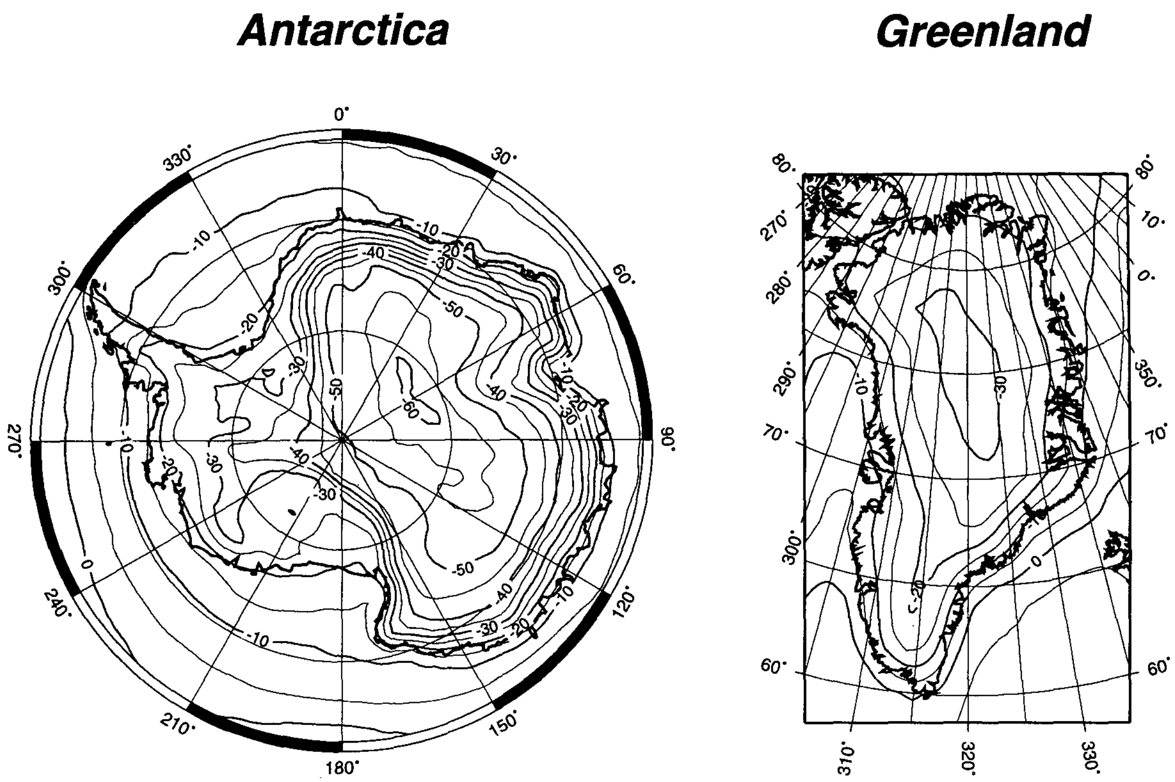


FIG. 1. ECMWF analyzed annual-mean (May 1985–April 1991) surface temperature. Units are in degrees Celsius. Latitude circles every 10° from 90°S.

Comiso's (1994) data show fairly high interannual variability in both seasons and over both ice sheets. It is unfortunate that the Comiso (1980–1985) and ECMWF (1985–1991) year ranges have almost no intersection, so that the substantial year to year differences in the model can only qualitatively be compared with satellite observations. Model variability over central Greenland reaches 8°C in July and more than 12°C in January, which is higher than satellite data suggest. It is more moderate, up to 8°C, over central Antarctica, and this is more consistent with the observation. It must be stressed that some of this variability might be a result of changes in the model design during the time period covered, as the GCM is constantly being improved. Also, the set of weather station observations that are taken into account in the analyses can vary in time, as some stations close, others open, and some do not consistently provide good observations in time.

3. Precipitation and accumulation

The precipitation and accumulation from the model shown here are predicted, not analyzed. A 24-h mean value is computed every day as the difference between the cumulated predictions 6 h and 30 h ahead in time. Daily values are then averaged over the six available years to provide monthly and annual means.

Figure 4 presents the annual mean simulated and observed precipitation in millimeters of equivalent water per year at a selection of weather stations in Greenland and Antarctica. The observed data (Dolgina and Petrova 1977; Ohmura and Reeh 1991) are from gauge precipitation measurements that, although empirically corrected for such effects, are in some cases strongly affected by bias due to strong winds and freezing of the measuring devices. Also, precipitation has a high interannual variability in these regions, and the years of observations do not coincide (and are much more numerous) than the years of modeling. Indeed, at Vostok and Amundsen–Scott South Pole stations in central Antarctica, accumulation (i.e., precipitation minus evaporation–sublimation) measured by stakes or ice-core analyses (darkest bar on the Antarctic bar plot, stations 1 and 2) does not coincide with direct precipitation measurements. Ice measurements are certainly more reliable, and away from the coast accumulation and precipitation are little different. Considering all these potential sources of uncertainty, one finds that the agreement between the predictions and the observations is good in many cases.

The agreement is particularly good in Antarctica. However, the model does not systematically reproduce the measured seasonal cycles. As an example, Fig. 5 compares the observed and simulated seasonal cycles

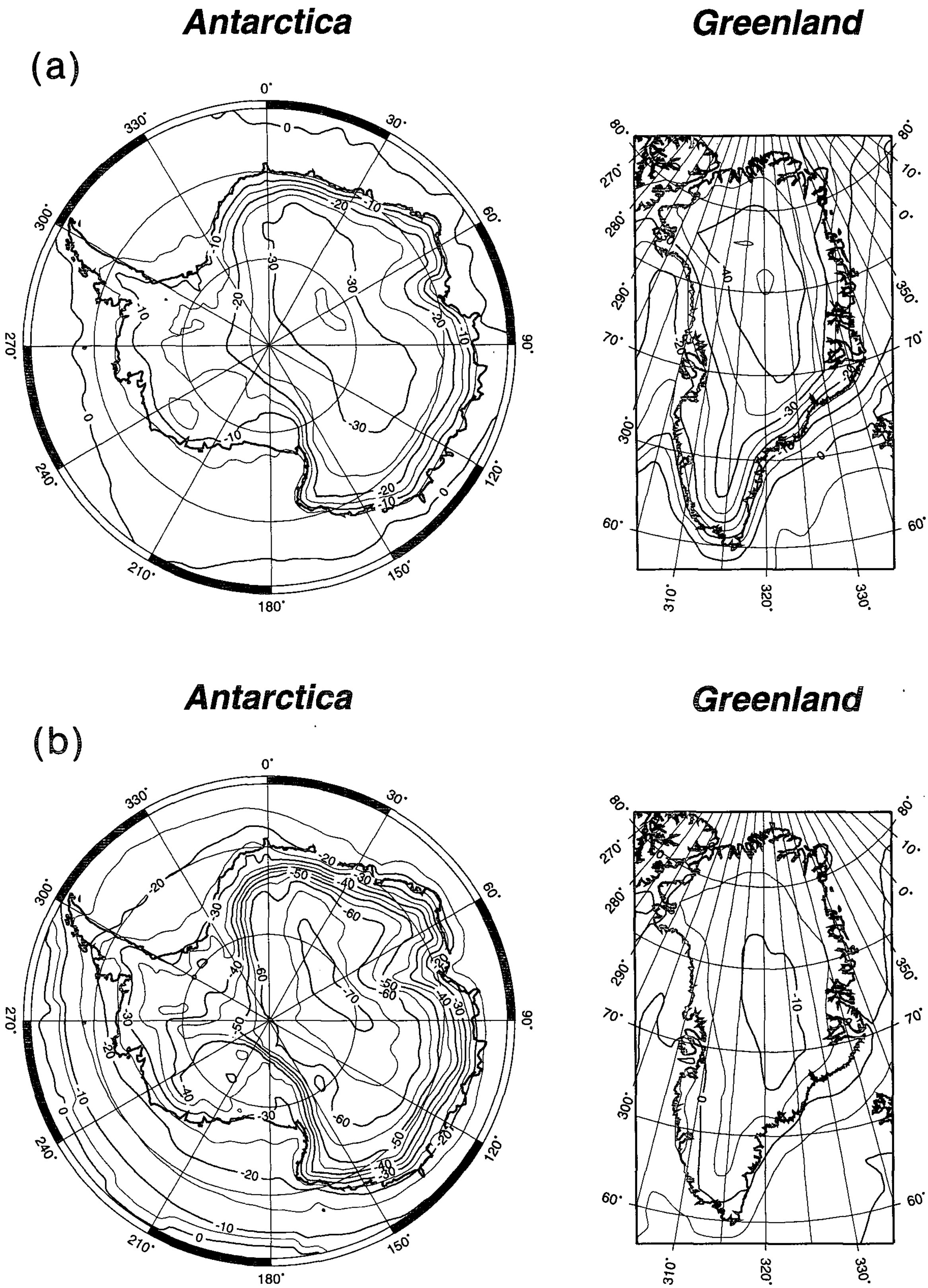


FIG. 2. ECMWF-analyzed mean surface temperature for (a) January (1986 to 1991) and (b) July (1985 to 1990). Units are in degrees Celsius.

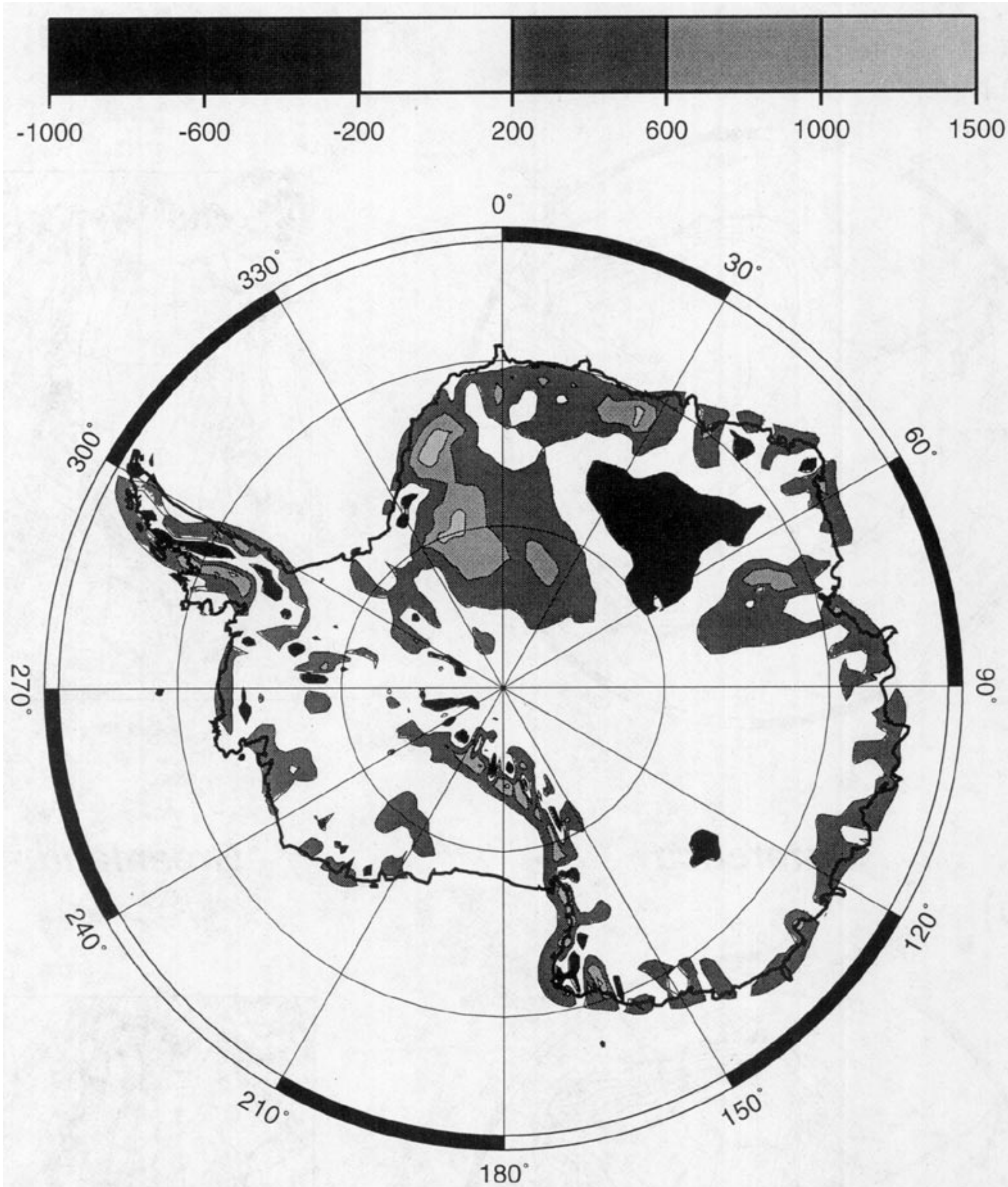
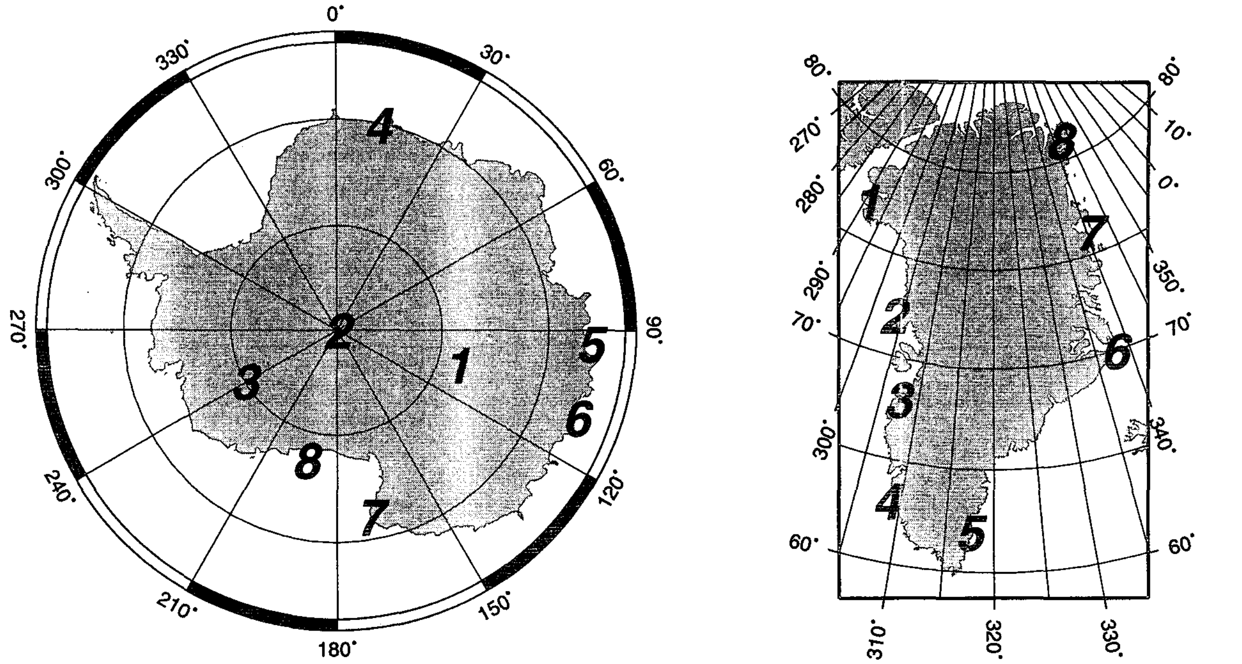


FIG. 3. Difference between the surface topography of Antarctica in use in the ECMWF model and a compilation of the most recent atlases and databases (British Antarctic Survey et al. 1993). Units are in meters. In coastal and mountainous regions, the differences are mainly due to model resolution, otherwise (e.g., Queen Maud Land) they also exist in the comparatively old orography database used to set surface elevation in the model.

at Wilkes (66°15′ S, 110°13′ E, Antarctic station 6 of Fig. 4), where the model is rather successful, and at Vostok (78°27′ S, 106°52′ E, station 2), where it appears much poorer. Yet again, particularly where precipitation rates are very low (e.g., Vostok), observation is largely questionable (Bromwich 1988). In coastal Greenland, mean precipitation is generally overestimated by the model. On the other hand, inland and at high elevation, the model accumulation is sometimes low compared to ice observations (e.g., 150 mm yr^{-1} versus 230 mm yr^{-1} observed at the summit of Greenland).

Figure 6 shows the ECMWF annual mean surface accumulation over the two ice sheets. Runoff, which can be an important component of accumulation at the coasts of Greenland, is not taken into account in these maps. According to Giovinetto and Bentley (1985), a large fraction of East Antarctica is a desert with accumulation below 5 cm yr^{-1}, and in some places below 2 cm yr^{-1}. This is rather adequately re-



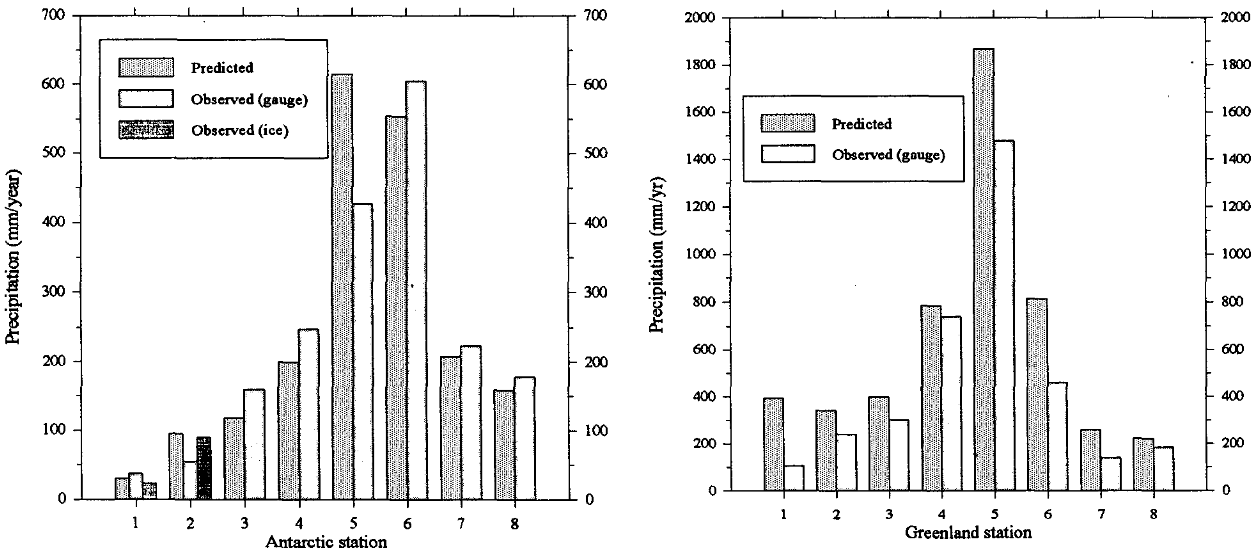


FIG. 4. Predicted (light gray) and gauge-measured (medium gray) precipitation and ice-measured accumulation (dark gray, Antarctic stations 1 and 2 only) at stations in Antarctica and Greenland. Units are in millimeters of equivalent water per year. Each digit is centered on the corresponding station. Antarctica: 1 = Vostok, 2 = Amundsen–Scott South Pole, 3 = Byrd, 4 = Novolazarevskaja, 5 = Mirny, 6 = Wilkes, 7 = Hallet, 8 = McMurdo. Greenland: 1 = Thule, 2 = Upernavik, 3 = Egedesminde, 4 = Faeringehavn, 5 = Tingmiarmiut, 6 = Kap Tobin, 7 = Danmarkshavn, 8 = Nord.

produced by the model, although many small-scale features do not spatially coincide with their counterparts in the observations. The relative aridity over the two ice shelves and the sharp increase of accumulation farther south over West Antarctica, particularly along the Peninsula, are well simulated. However, a thin line of locally maximum accumulation (15 to 20 cm yr^{-1}), which runs along the Transantarctic Mountains and

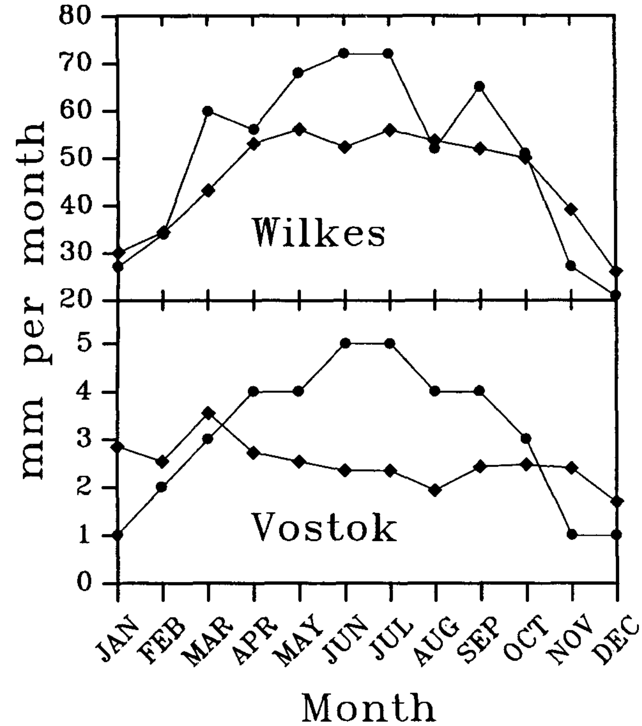


FIG. 5. ECMWF analyzed (diamonds) and observed (dots) mean seasonal cycle of precipitation at Wilkes and Vostok, Antarctica.

separates the East and West Antarcticas, is not properly reproduced.

Over Greenland, a number of features, including small scales, are in good agreement with the estimation by Ohmura and Reeh (1991). The region of highest precipitation in the southeast, with a "hooked" extension west and north, is nicely reproduced. The belt of relatively high accumulation along the west flank of the Greenland ice sheet is also present, but it is displaced slightly west. The envelope topography used in the ECMWF model might be responsible for this flaw because it may force the elevation of moist air advected from the west, and consequent condensation, to occur too early. The lowest accumulation is correctly simulated in the far northeast, but the less than 10 cm yr^{-1} region probably extends too far south.

The surface-integrated predicted precipitation is 1808 10^{12} and 609 10^{12} kg yr^{-1} over Antarctica (excluding the ice shelves) and Greenland (excluding the ice-free margins), respectively. The corresponding numbers for evaporation–sublimation are 214 10^{12} and 70.5 10^{12} kg yr^{-1}. In published observation-based estimates of the components of ice sheets mass balance, it is not always clear whether evaporation–sublimation is accounted for in the accumulation or the ablation term. In the interior of ice sheets, accumulation is generally estimated from ice (not gauge precipitation) measurements and, thus, it necessarily includes evaporation–sublimation. Yet, Houghton et al. (1990) compile and list estimates for accumulation and ablation, the latter being defined as melting and runoff plus evaporation. Evaporation–sublimation is generally considered negligible in Antarctica [e.g., as mentioned in Houghton et al. (1990)], but in the model it represents more than 10% of the precipitation.

The ECMWF Antarctic accumulation (1594 10^{12} kg yr^{-1}) is quite low compared to the best estimate compiled by Houghton et al. (2200 10^{12} kg yr^{-1}, but with a 30% uncertainty). However, Giovinetto and Bentley (1985), whose observation-based accumulation map is probably the most reliable to date, calculate a significantly smaller number. If the fraction of the Antarctic peninsula not connected to the main ice sheet is excluded, then the ECMWF-predicted accumulation is 1420 10^{12} kg yr^{-1}, in very good agreement with the corresponding estimate by Giovinetto and Bentley (1466 10^{12} kg yr^{-1}). Over Greenland, the predicted accumulation (539 10^{12} kg yr^{-1}) almost exactly coincides with the 535 10^{12} kg yr^{-1} reported by Houghton et al. (1990). It is also very close to the 520 10^{12} kg yr^{-1} estimated by Ohmura and Reeh (1991). Such a good agreement is certainly partly fortuitous—the regions where accumulation is too low compensating for the high coastal precipitation—yet it supports that the ECMWF model does a fairly good job with atmosphere–surface water exchange over ice sheets.

4. Discussion and conclusions

The ECMWF surface temperature, precipitation, and accumulation distributions over the Greenland and Antarctic ice sheets, obtained using a high-resolution GCM in analysis and prediction modes, are in good agreement with available observations. Even precipitation, a variable that is highly sensitive to GCM flaws and less directly constrained by observations than temperature, appears fairly reasonable. The ECMWF-analyzed atmospheric component of the mass balance of the two ice sheets is within the uncertainty estimates of the observations.

However, Connolley and Cattle (1994) and Genthon et al. (1994) display results from two different GCMs used in pure climate mode (i.e., not constrained by observations), with horizontal resolutions significantly coarser than that of the ECMWF model and which, on average, reproduce the accumulation over Antarctica as realistically as the ECMWF predictions. In some respects, the accumulation over Greenland simulated by the model with the finest resolution presented in Genthon et al. (1994) appears even better than the ECMWF predictions (e.g., the positioning of the western high-accumulation belt). Therefore, even if the observation control on ECMWF analyses over ice sheets is not increased, the ECMWF product can improve in time through GCM adjustment and refining. In addition, new conventional weather stations, more operational existing ones, new means of observation

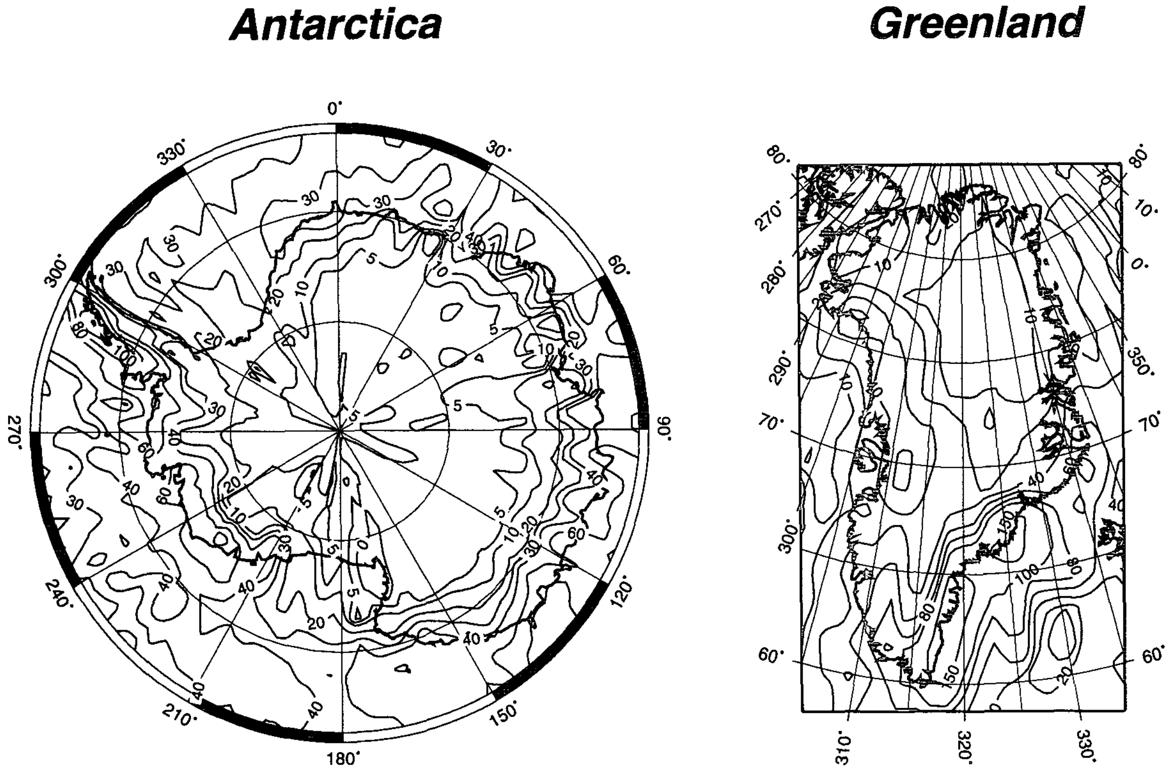


FIG. 6. ECMWF predicted annual mean (May 1985–April 1991) accumulation (precipitation minus evaporation or sublimation). Units are in centimeters of equivalent water per year.

(e.g., satellites, automatic weather stations) and improved analysis schemes can also contribute to make such product even more convincing and thus widely used in the future.

The real climate over the ice sheets is not very well known, and it cannot be excluded that some of the discrepancies between ECMWF (and other models) and observations are, in fact, the signature of imperfections in the latter. We certainly do not conclude that model results should be systematically trusted more than observations. However, in several instances the analyses and predictions appear to fall within observation uncertainties. In specific regions where field measurements are particularly scarce or doubtful and where models and observations consistently disagree, model results such as provided by the ECMWF could be taken into account in the estimation of an uncertainty range.

The ECMWF data presented here were produced in real time along with the weather forecasts, and they cover only a 6-yr period. ECMWF is currently rerunning these and other analyses and predictions using the observations available at the time the original product was made, plus other observations that came late and could not be used at that time. The reanalysis also uses updated versions of the ECMWF GCM and analysis scheme, thus probably providing a better product and definitely a product that is more consistent over time. Even a moderate improvement over the currently available product will yield a much needed, easy to use, full-coverage, gridded climatology of the climate over Greenland and Antarctica.

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