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Precipitation regime of Dronning Maud Land, Antarctica, derived from Antarctic Mesoscale Prediction System (AMPS) archive data

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[1] The precipitation regime of Dronning Maud Land (DML), Antarctica, was studied using Antarctic Mesoscale Prediction System (AMPS) archive data. Precipitation is the most important component of the mass balance of the Antarctic ice sheet. Precipitation studies of DML are particularly important because two deep ice core drilling sites, Kohnen Station and Dome Fuji, are located in this region. For the correct interpretation of the ice core properties a thorough understanding of the precipitation regime is necessary. We used the high-resolution AMPS archive data for the years 2001–2006 to investigate the temporal and spatial distribution of precipitation. The results were compared to a recently published mass balance map derived from glaciological data of western DML. The mass balance map and the AMPS mean annual precipitation field show fairly similar patterns, which are mostly related to topography and prevailing wind systems. Precipitation is found to generally decrease from the coast to the inland plateau. Along the escarpment between the low-altitude coastal areas and the interior plateau, local minima and maxima in precipitation correspond to the leeward and windward sides of topographical ridges. Interannual variability of monthly sums of precipitation is fairly high owing to the influence of cyclone activity on precipitation, which affects not only the coastal regions, but also the interior of the continent more than previously thought.

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1. Introduction

[2] In the ongoing discussion about climate change the mass balance of Antarctica is one of the crucial points for the calculation of global sea level rise. The most important component of the Antarctic mass balance is precipitation. Thus, for estimates of the mass balance of Antarctica it is necessary to know Antarctic precipitation amounts and distribution as accurately as possible.

[3] For the investigation of the Earth's climate and discussing possible future climate changes on a scientific basis, we need to understand the climate system and thus also the past climate changes as completely as possible. Valuable paleoclimatic information is derived from ice cores drilled on the large ice sheets of Greenland and Antarctica. However, for a correct climatic interpretation of the ice core properties, we have to know the regime of the precipitation that forms the ice found in the cores [*Jouzel et al.*, 2003]. Recently, two deep drillings have been carried out in Dronning Maud Land (DML), Antarctica. In the context of the European drilling project EPICA (European Project for Ice Coring in Antarctica), the so-called EPICA-DML core, drilled at Kohnen Station (75°S, 0°E), western DML, was finished in 2005/2006 [*EPICA community members*, 2006]; a second deep core has been obtained by Japanese scientists at Dome Fuji (77°S, 40°E), eastern DML [*Watanabe et al.*, 2003]. Kohnen Station was chosen as a drilling site because it is a location with relatively high accumulation rates (62 kg m^{-2} a^{-1} [*Oerter et al.*, 2000]) in DML. An additional reason for this choice is that precipitation at this site is influenced by the Atlantic Ocean, a valuable consideration, since the Atlantic is thought to be an important link between Antarctic and Greenland climate records [*Stocker*, 1999].

[4] One important factor that influences ice core properties is the seasonal distribution of precipitation [*Jouzel et al.*, 1997; *Noone and Simmonds*, 1998; *Schlosser*, 1999]. Especially for the derivation of paleotemperatures from the stable isotope ratio of the ice, it is a necessary precondition that precipitation is evenly distributed over all seasons, otherwise there will be a strong bias in the core. Until recently, it has always been assumed that precipitation on the Antarctic Plateau, where most deep drillings have been carried out, is almost entirely clear-sky precipitation, which forms from

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in situ nucleation of ice crystals in the extremely cold air without any synoptic dynamical forcing [*Bromwich*, 1988; *King and Turner*, 1997; *Roe*, 2005]. (Here, the term "diamond dust" is preferred to "clear-sky precipitation," because this kind of precipitation can also form in lower layers when there is a cloud cover above.) While this assumption is still correct in terms of number of days with diamond dust compared to number of days with "normal" precipitation, it is incorrect in terms of amount of precipitation. Automatic weather stations and model investigations indicate that several precipitation events occur per year that can bring up to 60–80% of the total annual precipitation [*Reijmer*, 2001]. An important question, however, is: Have these precipitation events always been randomly distributed over the year, or were there changes in the general atmospheric circulation that systematically altered the temporal (seasonal) and/or spatial precipitation distribution during past climate cycles? As a first step to answer this question, this study investigates the present-day precipitation regime of DML using a high-resolution mesoscale model. The results of this study will be later combined with a study of more than 60 firn cores drilled in DML.

[5] DML is situated in the Atlantic sector of Antarctica, extending from approximately 30°W (Coats Land) to 50°E (Enderby Land), including New Schwabenland. Until the presite survey expeditions for EPICA the largest part of DML was poorly investigated. Members of the Schwabenland Expedition in 1938/1939 investigated an area of 360,000 km^2 using aerial photography [*Klebelsberg*, 1942]. The British-Norwegian-Swedish Expedition 1949–1952 established the first wintering base on Quarisen, at the coast of DML [*Swithinbank*, 1957]. Today the following wintering bases, mostly at the coast of DML, are in operation: Halley (UK), Neumayer (Germany), SANAE (South Africa), Novolazarevskaya (Russia), Maitri (India), and Syowa (Japan). In the context of EPICA, an extensive presite survey program was initiated in DML in 1995/1996, during which accumulation and ice thickness distribution were determined, as well as isotope ratios and concentration of the main ions of the snow. Shallow firn cores were drilled in order to get information about the temporal and spatial variations of these properties for the last 200 years. Additionally, several automatic weather stations were set up by Dutch scientists [*Reijmer*, 2001]; one of them is still in operation today.

[6] In this study we present the first detailed precipitation map for DML derived from a mesoscale weather forecast model. We discuss the spatial and temporal variability of precipitation using AMPS (Antarctic Mesoscale Prediction System) archive data. The results are compared to a recently published mass balance map of Western DML based on glaciological measurements. Section 2 of this paper gives a short overview of previous investigations of Antarctic precipitation, while section 3 describes AMPS. In Section 4 we discuss the spatial and temporal variability of precipitation, and in section 5 we compare the AMPS results with a glaciologically derived mass balance map of western DML [*Rotschky et al.*, 2007]. Section 6 presents a summary, conclusion, and outlook.

2. Previous Work

[7] Measuring precipitation in Antarctica is a problem still unsolved. One of the main reasons for this is the problem of differentiating between blowing snow and falling precipitation. Conventional precipitation gauges have been found to give poor results due to the strong winds prevailing in many parts of the continent. The winds also cause snow drift from the ground, which makes it impossible to measure fresh snow depth. Thus, other methods for determining the accumulation need to be employed, such as accumulation/ablation stakes or counting annual layers in snow pits and firn cores, where the annual layers are found by crystal stratigraphy and by seasonal variations of stable oxygen/hydrogen isotopes and/or chemical properties of the snow/ice [e.g., *King and Turner*, 1997]. On a continental scale, precipitation has also been estimated from water vapor fluxes derived from radiosondes launched at coastal stations around the continent [*Bromwich*, 1988; *Connolley and King*, 1993; *Bromwich et al.*, 1995]. More recently, different types of models have been used to investigate Antarctic precipitation. *Bromwich et al.* [2004] used the mesoscale model MM5 as well as the so-called dynamic retrieval method (DRM) to study spatial and temporal variability of Antarctic precipitation. They also estimated redistribution of snow by snow drift using MM5 surface wind fields. *Cullather et al.* [1998] compared the spatial and temporal variability of net precipitation (precipitation minus evaporation/sublimation) derived from ECMWF operational analysis data with a variety of glaciological and meteorological observations and data sets.

[8] Glaciological estimates of Antarctic mass balance have been done repeatedly; over the last four decades about 22 such compilations have been presented, with continuously increasing number of data and using increasingly sophisticated methods. A widely used compilation was that of *Giovinetto and Bentley* [1985]. *Vaughan et al.* [1999] used in situ measurements of surface mass balance combined with a new elevation model derived from ERS-1 satellite altimetry for a reassessment of Antarctic mass balance. Uncertainties are decreasing, but still large enough to leave the errors in estimations of the contribution of Antarctica to sea level change fairly high [*Vaughan et al.*, 1999]. Although considerable differences in the results of regional investigations exist, most studies agree that there has been a slight increase in Antarctic precipitation/accumulation during the past decades [*Lemke et al.*, 2007]. However, *Monaghan et al.* [2006] derived a 50-year time series of snowfall accumulation over the Antarctic continent by combining model simulations and observations primarily from ice cores. They found that there has been no significant change in snowfall since the 1950s, which indicated that Antarctic precipitation is not mitigating global sea level rise as expected. A study with a stretched-grid atmospheric general circulation model (GCM) by *Krinner et al.* [2007] yields the scenario of an increase in Antarctic mass balance of 32 mm w.e. until the end of the 21st century.

3. Antarctic Mesoscale Prediction System

[9] The Antarctic Mesoscale Prediction System (AMPS) [*Bromwich et al.*, 2005; *Powers et al.*, 2003] provides numerical forecasts over Antarctica, in particular for the McMurdo Station region, in support of flight operations and scientific activities of the United States Antarctic Program (USAP). These forecasts, produced since September 2000, are archived and have been used for research

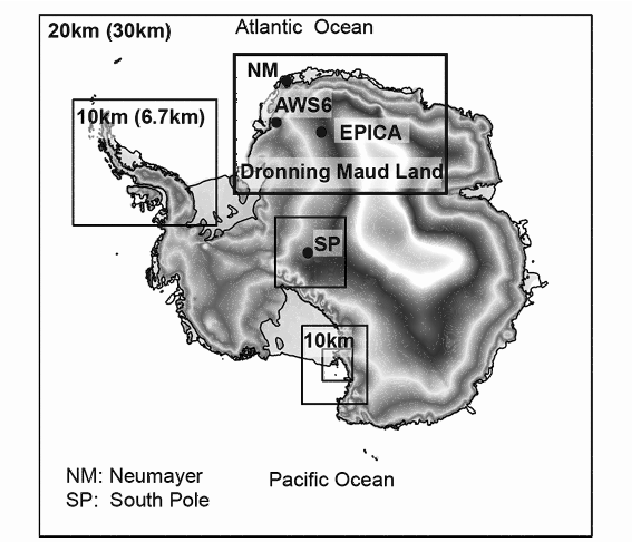

Figure 1. AMPS grids. Outer frame: domain 2 (20 km, 30 km until September 2005, used in this study); inner frames: over Antarctic Peninsula, South Pole (SP), and western Ross Sea: domain 3 (6.7 km/10 km) and domain 4: frame within western Ross Sea grid over Ross Island (2.2 km/3.3 km). Domain 1 (60 km/90 km), which is not shown here, includes New Zealand and parts of Australia, South Africa, and South America. Gray shades refer to model topography, which is shown in detail for DML in Figures 2 and 3.

purposes. AMPS was developed by the National Center of Atmospheric Research (NCAR) and the Polar Meteorology Group of Byrd Polar Research Center (BPRC) of The Ohio State University. AMPS employs the Polar MM5, a version of the Fifth-Generation Pennsylvania State University/NCAR Mesoscale Model that has been optimized for use over ice sheets. The modifications include: (1) accounting for sea ice with specified thermal properties, (2) representing fractional sea ice coverage in grid cells, (3) using the latent heat of sublimation for calculation of latent heat flux over ice surfaces, (4) modified properties of snow and ice, and (5) additional levels in the MM5's soil model in order to better represent heat transfer through ice sheets. Figure 1 shows the different domains of AMPS. The current AMPS setup has six grids, with horizontal spacings of 60 km, 20 km, 6.7 km (two grids), and 2.2 km. These grids were of lower resolution originally, and from September 2000 to September 2005 had grid sizes of 90 km, 30 km, 10 km, and 3.3 km, respectively. In this study data from the second domain, covering the Antarctic continent, were used. As indicated, this grid had a resolution of 30 km until September 2005, and 20 km afterward. Gray shades refer to topography, which is shown in detail for DML in Figures 2 and 3. For model topography, the RADARSAT Antarctic Mapping Project digital elevation model (Version 2) ("RAMP2") [*Liu et al.*, 2001] has been used since 2005. The horizontal resolution is 200 m, and vertical accuracy ranges from ±1 m over ice shelves to ±100 m over rugged mountains; for latitudes south of $-81.5°$, the DEM is accurate to within 50 m in the vertical.

[10] The MM5 in AMPS is configured with a suite of schemes and parameterizations to represent various physical processes in the atmosphere. The Reisner scheme [*Reisner et al.*, 1998] is used to represent the grid-scale cloud and precipitation processes, and the Grell cumulus parameterization [*Grell et al.*, 1994] is employed to handle subgrid-scale convective cloud processes. With respect to the latter, however, it is found that very little cumulus scheme precipitation is produced over Antarctica owing to the lack of tropospheric characteristics sufficient to trigger the parameterization (e.g., instability, moisture, convective available potential energy (CAPE)). Since 2005, AMPS has also been running the Advanced Research WRF (Weather Research and Forecasting) model [*Skamarock et al.*, 2005]. To maintain consistency, in this study only the archived MM5 data are used. However, since AMPS's inception the system has been regularly upgraded in response to the continuous testing and research done at NCAR and Ohio State University. Several improvements have been made to the model during the study period, including adding model grids, increasing of the resolution of the model grids, raising the model top, and adding additional vertical layers. Whereas so far AMPS archive data have been used for performance reviews [*Bromwich et al.*, 2005; *Powers*, 2007] or short-term climatological investigations [*Monaghan et al.*, 2005], this is the first time that the full archive has been analyzed. Using this data set for the time period 2001–2006, a comprehensive investigation of the precipitation regime of Dronning Maud Land is here carried out. Although it is recognized that 6 years is too short for a true climatological study, the AMPS forecasts can serve as a unique tool for investigating the spatial and temporal distribution of precipitation in DML with a high spatial resolution data set.

4. AMPS Precipitation

4.1. Spatial Variability of Precipitation

[11] Figure 2 shows the mean annual precipitation for DML for 2001–2006 as calculated from the AMPS archive. Additionally, AMPS topography (contour lines) is shown. The 12–36 h sums of precipitation (rather than 0–24 h) were used, in order to allow for model spin up of clouds and microphysical fields. The time period of 12 h is considered sufficient for moist process spinup, and *Bromwich et al.* [2005] used the same period in their study of an evaluation of AMPS forecasts over 2 years. A longer time allowance for spinup would result in unnecessarily longer-forecast output with, on average, larger error. As mentioned above, several changes have been made to the model grid, so for calculation of the annual means, all precipitation fields were interpolated to the earliest (coarsest) grid in domain 2. This was done using bilinear interpolation from the actual grid onto every grid point in the earliest grid. Generally, precipitation decreases with distance from the coast and with increasing elevation, both being connected to dryer and colder air. The limiting factor for precipitation is the saturation vapor pressure of air at low temperatures. On the high plateau around the Japanese drilling site Dome Fuji, the values are less than 20 mm per year, which might be a slight underestimate since the model does not represent diamond dust formation. *Fujita and Abe* [2006] created a unique data set of daily precipitation measurements at Dome Fuji for the year 2003. They observed precipitation

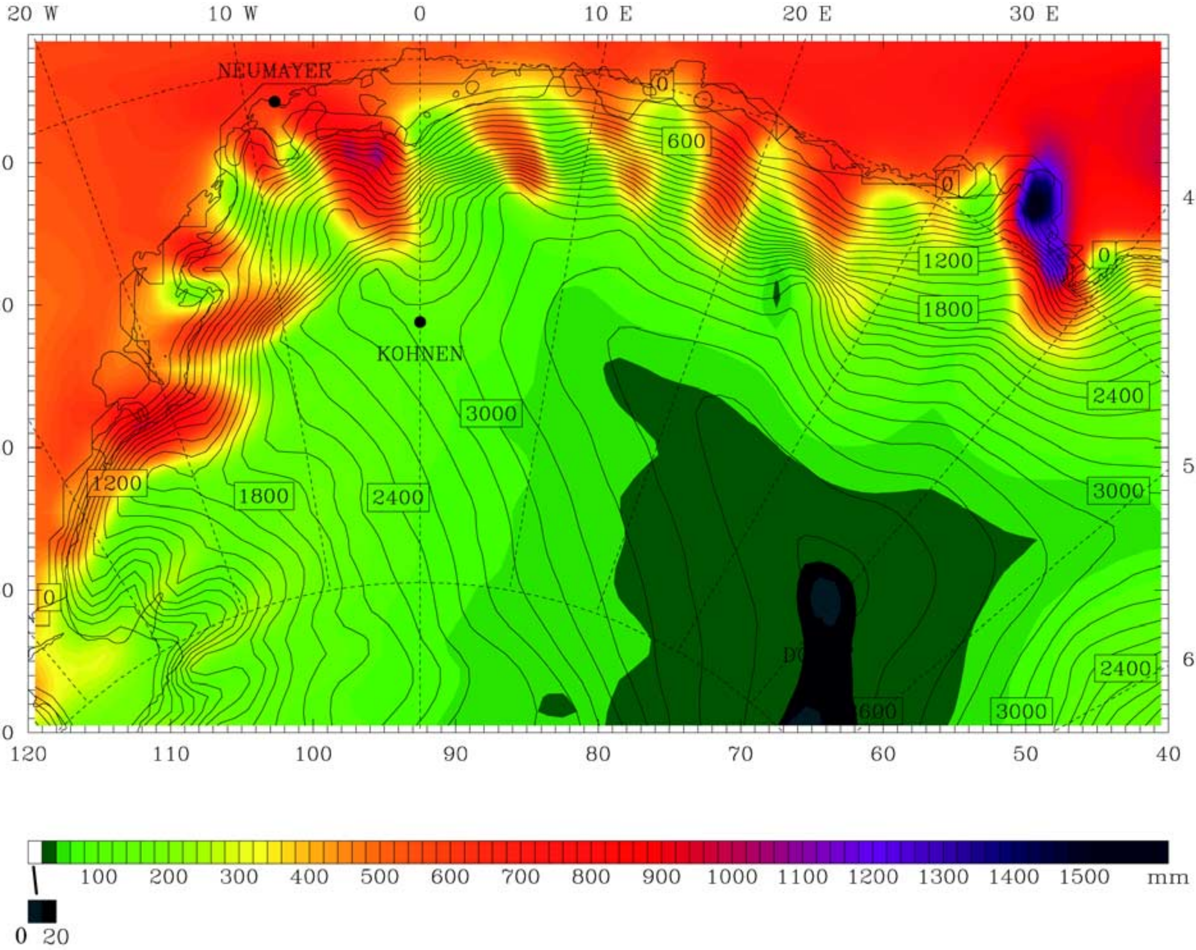

Figure 2. Mean annual precipitation 2001–2006 for Dronning Maud Land derived from AMPS. Model topography is also shown with 150-m contour intervals.

almost daily, with only 18 days of non-diamond-dust precipitation during an observation period of 349 days. Glaciological estimates of the mass balance at Dome Fuji give values of 27 ± 1.5 kg m a^{-1} [*Kameda et al.*, 2008] between 1995 and 2006; a part of the difference can be explained by evaporation/sublimation, which can mean loss or gain, respectively, and cannot be quantified here.

[12] Precipitation at the escarpment, the transition zone between the coast and the plateau, is highly influenced by a combination of topography and winds. Figure 3 shows the

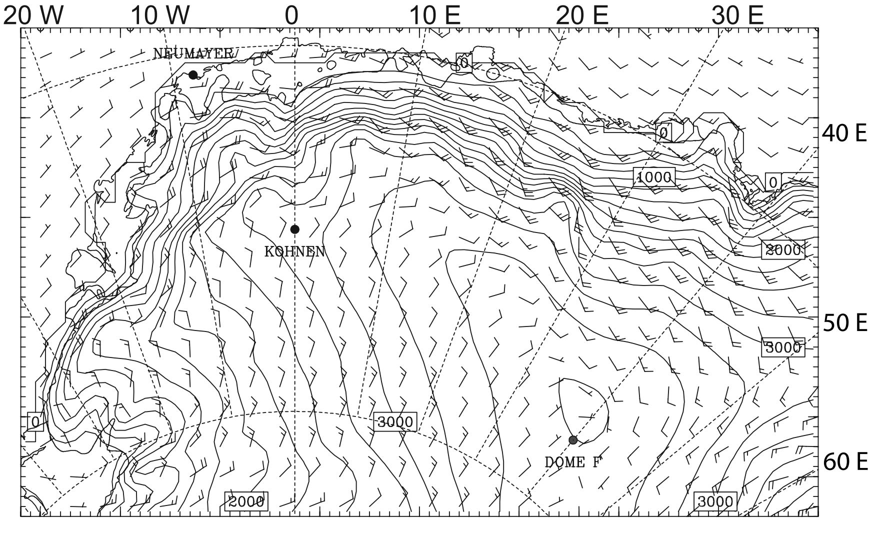

Figure 3. Annual mean AMPS near-surface winds 2001 for DML.

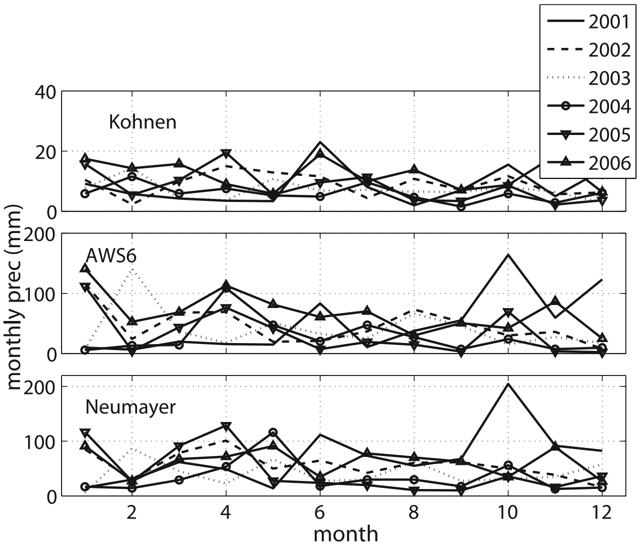

Figure 4. Monthly sums of AMPS precipitation for 2001–2006 for Neumayer, AWS6, and Kohnen Station.

annual mean near-surface wind (horizontal wind at the lowest model half-sigma level, corresponding to about 12 m to 14 m above the ground) in 2001 for DML, derived from the AMPS archive. The mean wind fields are computed by averaging the 3-hourly forecast fields from the 12-h, 15-h, 18-h, and 21-h forecasts initialized 0000 and 1200 UTC. (The annual means of surface winds for single years did not show significant interannual differences, except some different patterns over the oceans, which depend on the synoptic situations in the corresponding year. Thus we prefer to show a single year here rather than compute an average over the whole study period 2001–2006, which would require both horizontal and vertical interpolation due to the changes in the model grids and number of vertical layers.) Generally, the surface winds can be explained by katabatic outflow of cold air toward lower altitudes, diverted to the left by the Coriolis force and merging with coastal easterlies caused by low-pressure systems in the circumpolar trough. This leads to predominantly easterly winds in most parts of the escarpment. Maxima of precipitation (Figure 2) are found on the upstream sides of ridges, minima on the leeward side. The low-pressure systems that usually move eastward north of the coast lead to easterly or northeasterly winds; (details about cyclone behavior around Antarctica given by *Simmonds et al.* [2003], who used NCEP-NCAR reanalysis data for an investigation of cyclone density, intensity, and storm tracks.) At the eastern sides of these cyclones, north to northeasterly winds prevail, which means an onshore flow of relatively moist air that is orographically lifted and cooled. This also causes fairly high precipitation values. In particular, at the Riiser-Larsen Peninsula (about 35°E), northeasterly winds combined with a relatively steep slope lead to the highest precipitation values found in DML, a result which is confirmed by a study of *Yamanuchi and Wada* [1992].

4.2. Temporal Variability of Precipitation

[13] To assess how representative the 6-year average of precipitation is, the temporal variability of precipitation was analyzed. Figure 4 shows the monthly sums of precipitation derived from AMPS for three different locations: Kohnen Station (75°S, 0°E, 2892 m a.s.l.), on the Antarctic Plateau; AWS6 (74°S, 12°W, 1160 m a.s.l.), one of the automatic weather stations at the slope of the escarpment; and Neumayer (70°S, 8°W, 15 m a.s.l.), the German wintering base at the coast. The temporal variability of precipitation is fairly high. Figure 5 shows the mean monthly sums of precipitation for 2001–2006 for the same three locations as in Figure 4. Note that there are different scales for precipitation for each station. The error bars represent two times the standard deviation. By comparing Figure 4 to Figure 5 it is evident that the relative maxima of precipitation in October and April for all stations and in June for Kohnen are clearly related to high monthly sums in single years; for example, October 2001 shows exceedingly high values for all three stations, which is reflected in the mean over the 6 years. The temporal variability of precipitation is too high to know for sure the reason for the precipitation maxima at Neumayer and AWS6 in April and October, but a plausible explanation would be the semiannual oscillation of the circumpolar trough [*van Loon*, 1967]. The trough is deepest and closest to the coast during the equinoctial seasons, which means highest cyclonic activity and thus highest precipitation at that time [e.g., *Simmonds and Jones*, 1998]. However, the number and strength of cyclonic systems connected to the circumpolar trough was found to show considerable interannual variability [*Simmonds*, 2003]. Stations in the interior would be less influenced by this.

[14] To investigate the reasons for this high temporal variability, the time series of daily AMPS precipitation from 2001–2006 for the locations of thirty different firn cores and AWSs distributed all over DML, covering a range from the coast (70°S, 15 m a.s.l.) to Dome Fuji (77°S, 3810 m a.s.l.) (not shown here) have been examined. Those sites were chosen with respect to later examination of the firn cores and comparison of AWS to AMPS data. However, for this study, it was preferred to use the AMPS precipitation data rather than the AWS accumulation data, since it was found that the wind influence is fairly high and the accumulation amounts derived from the change of the height of a sensor above the snow surface have to be regarded cautiously.

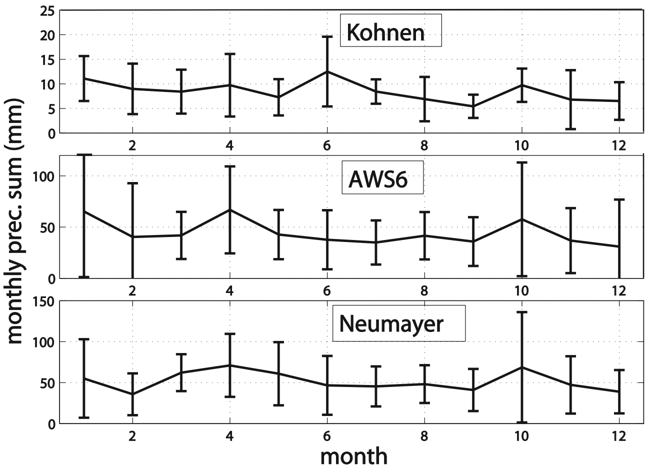

Figure 5. Monthly mean sums 2001–2006 of AMPS precipitation for Neumayer, AWS6, and Kohnen Station. The error bars represent the double standard deviation.

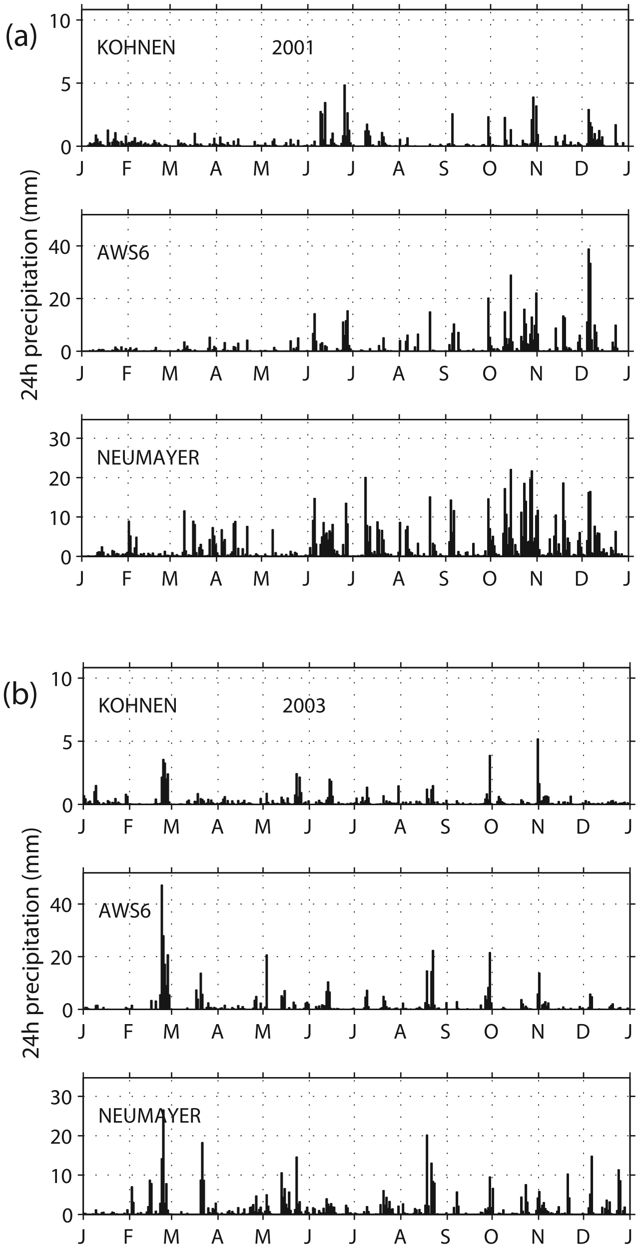

Figure 6. Daily sums of precipitation for Neumayer, AWS6, and Kohnen for (a) 2001 and (b) 2003.

[15] As an example, Figure 6 shows the daily sums of precipitation at Neumayer, AWS6, and Kohnen Station for the years 2001 (Figure 6a) and 2003 (Figure 6b). Many of the larger precipitation events observed at the coastal station Neumayer, which are usually related to cyclone activity in the circumpolar trough [*King and Turner*, 1997], can be seen at almost all other stations, including Kohnen Station, the drilling station on the high plateau, and some even at Dome Fuji at 3810 m elevation, which is supposed to have the most continental climate of all locations shown here. Usually a small amount of precipitation (less than 0.5 mm) is calculated for Dome Fuji and Kohnen Stations on days with no obvious synoptic influence. These very small daily precipitation amounts are thus considered as diamond dust. The exceedingly high monthly precipitation sum of February 2003 can be clearly attributed to one precipitation event at the end of the month, which is visible at all locations, including Dome Fuji (not shown here). Also, the high October 2001 value can be explained by the time series, which show a number of precipitation events in this month at all sites. This parallel occurrence of precipitation peaks at the coast and further inland means that the temporal distribution of precipitation is mainly determined by the synoptic activity in the circumpolar trough, which varies considerably from year to year. By "synoptic activity," we refer not only to the penetration of frontal systems into the interior of the continent. In cases of amplification of the long atmospheric waves, relatively stable synoptic patterns can be established, with a blocking high and a consistent flow of relatively warm, moist air from the northwest that yields relatively high precipitation amounts for the region between trough and ridge [e.g., *Enomoto et al.*, 1998; *Massom et al.*, 2004; see also *Hirasawa et al.*, 2000]. Other mechanisms that bring precipitation to Kohnen Station include occluding fronts of eastward-moving cyclones and retrograde movement of lows formed east of the Greenwich Meridian [*Birnbaum et al.*, 2006]. However, it appears that all of Dronning Maud Land is affected by the described precipitation events in a similar way, so that the spatial patterns are fairly stable over longer time periods.

5. Comparison of AMPS Precipitation to Mass Balance Derived From Glaciological Data

[16] *Rotschky et al.* [2007] did a comprehensive study of the mass balance of western DML using all available glaciological data, namely stake measurements, snow pits, and firn/ice cores. In total, 111 records from different countries gained during 20 different Antarctic field campaigns, held over a period of about four decades, were investigated. No trend in accumulation was found over these 40 years, which justifies taking records covering different time periods for calculation of a mean spatial distribution of mass balance. In contrast to earlier Antarctic mass balance estimates [e.g., *Giovinetto and Bentley*, 1985; *Vaughan et al.*, 1999], which used a uniform interpolation scheme for the whole continent [*Rotschky et al.*, 2007], divided DML into two different mass balance regimes, the coastal area and the inland plateau, which are separated by mountain/nunatak ranges (Heimefrontfjella, Kirvanveggen, and Muehlig-Hoffmann-Gebirge). They determined the mass balance for western DML using different interpolation schemes for the two regimes, thus creating the first detailed accumulation map of DML.

[17] Figure 7 shows the accumulation map by *Rotschky et al.* [2007] and the mean annual precipitation derived from AMPS. For easier comparison, the AMPS precipitation is shown for exactly the same area as the accumulation map. It is recognized that precipitation is only a part of the mass balance, and evaporation/sublimation and redistribution of snow by wind can create large differences between precipitation and mass balance. Evaporation can amount to up to about 40% of precipitation, especially in the coastal areas [*Bromwich et al.*, 2004]. Redistribution of snow after the snowfall is an important factor for mass balance estimates, too, since it can mean either positive or negative contributions to the mass balance of a given area. However, there are

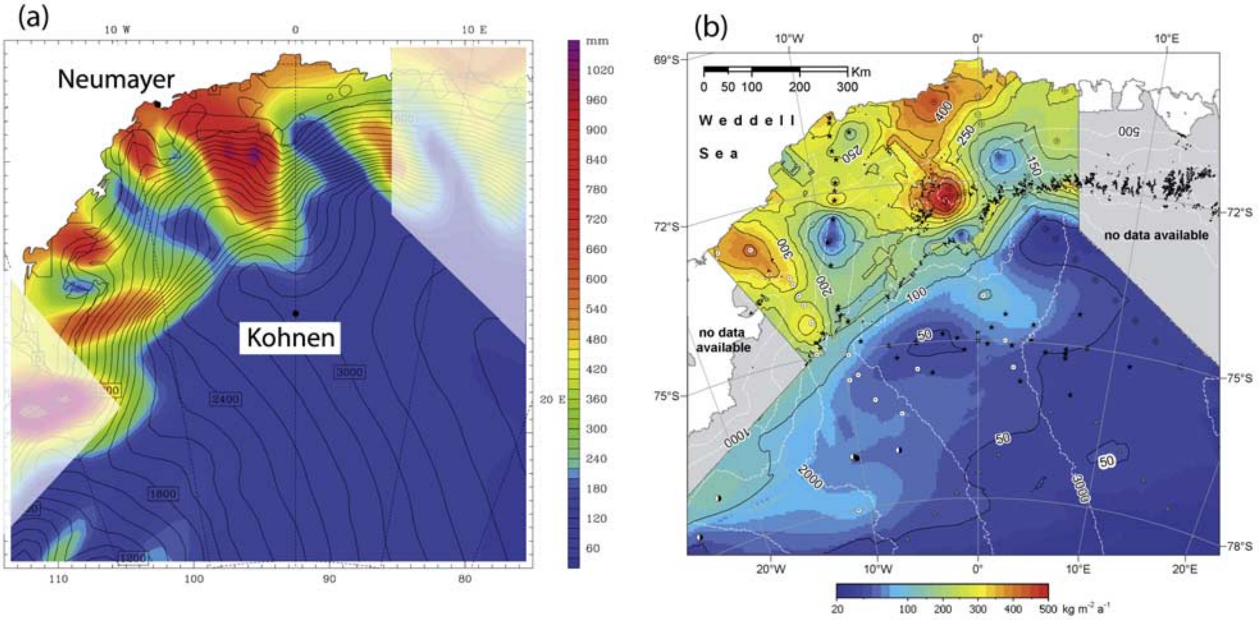

Figure 7. Comparison of (a) AMPS mean annual precipitation 2001–2006 with (b) accumulation map from glaciological data for western DML [*Rotschky et al.*, 2007].

no means to quantify this mass balance component. *Rotschky et al.* [2007] use the term accumulation with the same meaning as "net accumulation." To be exact, the mass balance is the sum of accumulation and ablation, where accumulation is the sum of precipitation, deposition of hoarfrost, and deposition of snow due to snowdrift, whereas ablation is the sum of sublimation and erosion due to snowdrift. Evaporation can occur during snowfall and snowdrift as well as after the snowfall, which is important for comparison with precipitation, although the first (evaporation during snowfall or snowdrift) is actually not a component of the mass balance as is evaporation after the snowfall directly from the snow surface. Evaporation from the snow/ice surface is not available in the AMPS archive. It could be derived from the latent heat flux, as has been done by *Bromwich et al.* [2004], who used the Polar MM5 (which is also used in AMPS) to calculate P-E for Antarctica for a 3-year period. However, since it is known that surface temperatures are overestimated by the model owing to the strong inversions and owing to the fact that the lowest model level is not close enough to the surface, the error in evaporation is considered to be higher than in precipitation and it is difficult to quantify. Thus it is preferred here to consider only the precipitation fields rather then P-E with the combined errors of both variables.

[18] Melting does not play a role here, since even in the coastal areas of DML, where melting does occur in summer, the meltwater is not removed from the snow cover by runoff, but remains in the annual layer and thus does not represent a mass loss.

[19] Because of these differences in the compared variables used for these studies, the comparison has to be done in a qualitative way, and, considering the uncertainties in both the model results and the mass balance calculation, the agreement is highly satisfactory. The model precipitation is much smoother than the interpolated accumulation, but the general features, especially the distinct maximum southeast of Neumayer, as well as the other topographically forced minima and maxima along the escarpment, are basically the same in both maps. (Uncertainties in the accumulation map by *Rotschky et al.* [2007] are largest at the borders where not enough data for interpolation are available.) Also the gradual decrease of precipitation from the coast to the high plateau is similar in both maps. It is thus concluded that the 6-year mean of precipitation is representative for the spatial distribution on a climatological timescale (defined as at least three decades) or, representative for the present climate. Furthermore, also reasonable are the AMPS results for Eastern DML, for which, until now, no detailed precipitation/accumulation map has existed. Thus, the new map should also be useful for interpretation of the data from the Japanese ice core drilling program at Dome Fuji.

6. Discussion and Conclusions

[20] The precipitation regime of Dronning Maud Land has been studied using mesoscale atmospheric forecast model output from the AMPS archive. Comparison with a recently derived accumulation map for Western Dronning Maud Land shows good qualitative agreement with the precipitation data. Differences in the absolute values of precipitation and accumulation are partly due to the influence of evaporation and redistribution. They also depend on the model's accuracy in producing the actual precipitation amounts. However, the similar spatial patterns of precipitation and accumulation imply that redistribution of snow by wind influence is only important on a local scale.

[21] The influence of cyclonic activity in the circumpolar trough on precipitation in the interior of the continent is larger than previously thought [e.g., *King and Turner*, 1997]. In spite of high temporal variability of precipitation due to this influence, the spatial distribution of precipitation was found to be fairly stable. The annual mean precipitation

sums for each year between 2001 and 2006, from which Figure 2 was compiled, look fairly similar. Considering the high temporal variability of precipitation (Figure 4), at first sight, this is a bit surprising. However, the time series of the thirty investigated locations show basically the same precipitation events, with slight delays in case of eastward moving systems. Most of these high-precipitation events are caused by low-pressure systems in coastal areas, which were found to affect also the precipitation amounts in the interior of the continent. The relative spatial differences between the different locations, however, seem to be constant. Further investigation of these events and the synoptic patterns prevailing during precipitation is necessary and will be done in a subsequent study. For a correct interpretation of ice core data it is necessary to know whether the seasonal distribution of such events differed between glacial and interglacial periods. As long as these events are evenly distributed over the whole year, it can be assumed that the ice cores yield information equally from all seasons. However, if, owing to a changed general atmospheric circulation in a different climate, one season is preferred or underrepresented, the temperatures derived from the stable isotope ratios do not represent the annual mean temperature, but only the mean of the seasons that get a fairly high amount of precipitation by the events described above.

[22] Changes in the seasonal distribution might be different for different areas, possibly related to sea ice extent, as the sea ice influences cyclogenesis and storm tracks. The sea ice edge, as the zone with the largest meridional temperature gradient and thus highest baroclinicity, is supposed to be a preferred region for cyclogenesis [*King and Turner*, 1997; *Watkins and Simmonds*, 1995]. Therefore sea ice distribution and concentration strongly influence the development and behavior of low-pressure systems within the circumpolar trough [*Simmonds and Wu*, 1993]. Sea ice also acts as a highly efficient insulator between ocean and atmosphere, which affects the formation of clouds, the stability of the atmosphere and therefore precipitation [*King and Turner*, 1997]. By influencing the turbulent fluxes and thus vertical transports above the ice pack, sea ice affects also the long-range transports to the interior of the continent, as was found by *Noone and Simmonds* [2004], in a GCM study. Chances in sea ice distribution also directly influence stable isotope ratios by changing the location of possible moisture sources [*Noone and Simmonds*, 2004]. To answer the question, whether the seasonal distribution of precipitation has changed or not, is beyond the scope of this paper. It should be addressed interdisciplinarily by a combination of modeling and a longer-period study of glaciological and meteorological data.

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