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Characteristics of high-precipitation events in Dronning Maud Land, Antarctica

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[1] High-resolution Antarctic Mesoscale Prediction System archive data were used to investigate high-precipitation events at the deep ice core drilling site Kohnen Station, Dronning Maud Land, Antarctica, during the period 2001–2006. The precipitation is found to be highly episodic, with, on average, approximately eight high-precipitation events per year that can bring more than half of the total annual accumulation. The duration of the events varies between 1 day and about 1 week. On most days in the remaining time of the year, however, daily precipitation sums are about one order of magnitude smaller than that for the high-precipitation events. Synoptic weather patterns causing these events were directly connected to frontal systems of cyclones in only 20% of the 51 investigated cases. The majority of the events occurred in connection with (blocking) anticyclones and correspondingly amplified Rossby waves, which lead to advection of warm, moist air from relatively low latitudes. Possible changes in the seasonality and frequency of these events in a different climate can lead to a bias in ice core properties and might also strongly influence the mass balance of the Antarctic continent and thus global sea level change.

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1. Introduction

[2] Even with modern techniques, measuring Antarctic precipitation is a challenging task because of the remoteness and cold of the continent combined with the aridity of the interior and the prevailing strong winds in coastal areas that make it difficult to distinguish between real precipitation and blowing or drifting snow. However, a thorough knowledge of the Antarctic precipitation regime is important for the following two reasons: (1) snowfall is the largest positive component of the Antarctic mass balance and its behavior in a changing climate influences global sea level change, and (2) for a correct interpretation of ice cores (one of the most important information sources in paleoclimatology), knowledge about the seasonality of accumulation and possible changes in that seasonality during climatic change is a basic requirement.

[3] In Dronning Maud Land (DML), in the Atlantic sector of Antarctica, two deep ice cores were recently drilled: one in the framework of the European Project for Ice Coring in Antarctica (EPICA), at Kohnen Station [75.00°S, 0.50°E, 2892 m above sea level (asl)] [*Oerter et al.*, 2004], and one at Dome Fuji (77.32°S, 39.7°E, 3810 m asl) [*Horiuchi et al.*, 2008]. Both cores reached bedrock and, together with the second core drilled within EPICA, Dome C, yielded information about the climate of the past 800 kyr [*European Project for Ice Coring in Antarctica* (*EPICA*) *Community Members*, 2004]. Of special interest for ice core interpretation is the investigation of the occurrence of high precipitation compared to diamond dust, also called “clear-sky precipitation” (even though it also occurs under overcast conditions beneath a cloud layer; G. Birnbaum, personal communication). Diamond dust, which is formed from in situ nucleation of ice crystals in the extremely cold air [*King and Turner*, 1997], is assumed to show some seasonal variations but basically occurs in each month. Episodically occurring, synoptically induced high-precipitation events are rare in the interior of the continent, but a few events per year can bring a large percentage of the total annual precipitation. A possible tendency of those events to occur in certain seasons could lead to a strong bias in ice core properties [*Noone and Simmonds*, 1998; *Jouzel et al.*, 1997, 2003; *Schlosser*, 1999], in particular in the stable isotope ratio, which is used to derive paleotemperatures, but also in various chemical properties. A possible over-representation of summer snow, for instance, would lead to a higher stable isotope ratio and, thus, to a seemingly higher temperature, even if the mean annual temperature had not changed at all. Therefore, a thorough understanding of precipitation processes is needed for a correct interpretation. For Kohnen Station, because it is a summer ice core drilling

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station, daily precipitation observations are available only for a restricted time period. However, model results show for the majority of the time very small daily precipitation sums. Unlike at Dome C or Dome Fuji, which are both situated at higher altitudes and larger distances from the coast than Kohnen Station, these small precipitation amounts are not necessarily attributed to diamond dust formation; they can also be attributed to a weak synoptic influence. However, both types seem to be fairly evenly distributed over the year and, thus, do not lead to a bias in the ice core properties.

[4] Climate model simulations have shown a poleward shift of Southern Hemispheric storm tracks in a warmer climate, which means significant changes in the spatial precipitation distribution [*Bengtsson et al.*, 2006]. This supports the hypothesis of systematic changes in cyclone behavior between glacial and interglacial time periods, which must be considered for interpretation of ice core properties.

[5] In this study, an investigation of "high-precipitation events" at Kohnen Station, the EPICA drilling site in western Dronning Maud Land, is presented. The study is based mainly on the high-resolution Antarctic Mesoscale Prediction System (AMPS) archive data, but it also draws on some temporally restricted observational data from Kohnen Station [*Birnbaum et al.*, 2006] and Dome Fuji [*Fujita and Abe*, 2006]. Typical synoptic patterns connected to high-precipitation events are classified, and their frequency and seasonality is investigated. The corresponding precipitation amounts are compared to estimated amounts during periods with diamond dust. An overview of previous studies of Antarctic precipitation and the synoptics involved is given in section 2, and AMPS is described in section 3. In section 4 the synoptic patterns for high-precipitation events are introduced and, in section 5, frequency distribution and seasonality of these events are discussed. After a short consideration of diamond dust (section 6), a summary and conclusions are presented in section 7.

2. Previous Work

[6] Different types of models and reanalyses have been used to study Antarctic precipitation and the synoptic patterns involved. Whereas at the coastal stations cyclones with frontal systems in the circumpolar trough are the main cause of precipitation, in the dry interior of the continent these systems play only a minor role. However, *Sinclair* [1981] has already shown that low-pressure systems can penetrate deeply into the interior of the continent and are usually accompanied by a large increase in temperature and wind speed.

[7] Until the pre-site survey expeditions for EPICA, DML was poorly investigated and covered only by general studies of Antarctic mass balance. With EPICA, several automatic weather stations (AWSs) were set up, and various model studies also were performed to get a better picture of conditions at the planned drilling site.

[8] *Noone et al.* [1999] used European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data and ECMWF operational archive data for a comprehensive study of DML precipitation. The data showed several synoptically induced precipitation events per year that brought exceptionally high precipitation to the high Antarctic plateau. Two case studies revealed that the high precipitation amounts were caused by amplification of upper level planetary waves directing warm, moist air from lower latitudes toward the interior of the continent.

[9] These results were confirmed by *Reijmer and Van den Broeke* [2003], who found that accumulation at several AWSs in DML occurred in many small and a few large precipitation events per year, with those few large events accounting for up to 50% of the total annual accumulation. Usually air temperature and wind speed increased considerably during the large events [*Reijmer and Van den Broeke*, 2001]. This had also been found by *Noone and Simmonds* [1998], who used a general circulation model (GCM) to investigate the synoptic patterns that cause unusually high precipitation in Antarctica.

[10] At Kohnen Station, *Birnbaum et al.* [2006] investigated the weather patterns that led to high precipitation amounts during several summer seasons. They studied a set of visual observational data and the corresponding ECMWF operational analyses. For the summer they identified three typical categories of weather situations that brought exceptionally high snowfall: (1) occluding fronts from eastward moving low-pressure systems, (2) large-scale lifting processes caused by an upper-air low west of Kohnen Station, and (3) retrograde lows or secondary lows with frontal systems. The second category, an upper air low west of the base, leads to a northwesterly flow over DML that can be fairly stable over several days in the case of a blocking anticyclone above eastern DML. Such blocking high-pressure systems were also studied by *Enomoto et al.* [1998] for Dome Fuji, where they observed an extreme winter warming connected to a blocking high that persisted for several weeks and involved the aforementioned advection of warm, moist air. Owing to the extremely high altitude of Dome Fuji (3810 m asl), the air is often not moist enough to produce precipitation, but the corresponding cloud cover changes the radiation conditions, namely the longwave radiation balance. This, together with increasing wind speeds, leads to a breakdown of the surface temperature inversion layer and can bring dramatic temperature increases of up to 40°C within 2 days [*Hirasawa et al.*, 2000]. *Van As et al.* [2007] described similar results in a study of a blocking event at Kohnen Station in 2002. Another study of significant precipitation events in East Antarctica using EMCWF analyses, supplemented by satellite passive microwave data (Special Sensor Microwave Imager), was carried out by *Massom et al.* [2004]. They stated that such events play a key role in delivering substantial snowfall as far south as at least 75°S (the latitude of both Kohnen Station and Dome C) on the central East Antarctic ice sheet with the corresponding moisture originating from as far north as 35°S to 40°S.

[11] *Marshal* [2009] investigated the annual and semiannual cycles of Antarctic precipitation using ECMWF reanalysis data (ERA-40). He found a marked change in precipitation seasonality between the 1980s and the 1990s in the Peninsula area, which can be related to the El Niño-Southern Oscillation (ENSO) and which, according to his estimate, would lead to an apparent warming of approxi-

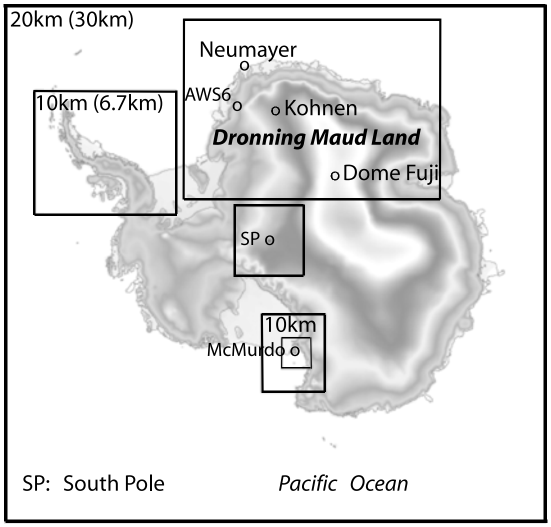

Figure 1. AMPS grids during 2001–2006: Outer frame, 30 km domain (20 km since September 2005); 10 km (6.7 km) domain over Antarctic Peninsula, South Pole, and western Ross Sea, 3.3 km (2.2 km) domain over Ross Island (McMurdo). An outer domain of 90 km (60 km) (not shown) extended to New Zealand, Australia, South Africa, and South America. (see text for the grids used at present).

mately 0.6°C in the mean annual temperature derived from oxygen isotope measurements in an ice core.

3. Antarctic Mesoscale Prediction System

[12] The AMPS [*Bromwich et al.*, 2005; *Powers et al.*, 2003] was developed by the National Center for Atmospheric Research (NCAR) and the Polar Meteorology Group of the Byrd Polar Research Center of The Ohio State University to provide high-resolution model guidance for Antarctic forecasts, particularly for the McMurdo Station region, in support of scientific activities and flight operations of the U.S. Antarctic Program. The AMPS model output has been archived since 2001. These archives have also been used for scientific studies. Currently, AMPS employs the Weather Research and Forecasting model [*Skamarock et al.*, 2008]. During the time period used for this study (2001–2006), AMPS used a polar-modified version of the Fifth-Generation Pennsylvania State University/NCAR Mesoscale Model (MM5), which was optimized for use over extensive ice sheets and high latitudes. The polar modifications include (1) representation of fractional sea ice coverage in grid cells, (2) accounting for sea ice with specified thermal properties, (3) modified properties of snow and ice, (4) use of latent heat of sublimation for calculation of latent heat flux over ice surfaces, and (5) additional levels in the MM5's soil model for a better representation of heat transfer through ice sheets [*Bromwich et al.*, 2001; *Cassano et al.*, 2001].

[13] Figure 1 shows the different domains of AMPS. The current AMPS setup has six grids, with horizontal spacings of 45, 15, 5 (three grids), and 1.67 km. For the investigated period, the resolution of these grids was lower; however, until September 2005 the corresponding grid spacings were 90, 30, 10, and 3.3 km, and afterwards 60, 20, 6.7, and 2.2 km, respectively.

[14] To represent various physical processes in the atmosphere, the Polar MM5 was configured with a suite of schemes and parameterizations. The Reisner microphysics scheme [*Reisner et al.*, 1998] was used for grid-scale cloud and precipitation processes. The Grell cumulus parameterization [*Grell et al.*, 1994] treated subgrid-scale convective cloud processes, which produce only minimal convective precipitation south of 60°S and over Antarctica because of the lack of tropospheric conditions sufficient for convective triggering (e.g., instability, moisture, and convective available potential energy). For boundary-layer processes, the Eta planetary boundary layer scheme was used [*Janjic*, 1994].

[15] The AMPS archive data have been used for both model performance studies [*Bromwich et al.*, 2005] and climatological investigations [*Monaghan et al.*, 2005; *Schlosser et al.*, 2008; *Uotila et al.*, 2009]. Additionally, case studies of weather events have been carried out [*Bromwich et al.*, 2003; *Powers*, 2007; *Schlosser et al.*, 2010].

[16] Compared to GCMs and the most commonly used reanalysis data (e.g., ERA-40, National Centers for Environmental Prediction), AMPS shows a better performance because of higher spatial and temporal resolution and the use of polar optimized physical parameterizations, in particular the representation of sea ice [*Uotila et al.*, 2009]. The higher spatial resolution especially means that the topography of the ice sheet is much better resolved and, thus, allows a more accurate simulation of the impact of steep slopes on the inland moisture transport. Lee effects, which play an important role in the spatial accumulation distribution, are clearly evident in the model precipitation fields [*Schlosser et al.*, 2008]. Thus, it provides a highly valuable tool for investigating Antarctic regions with poor data coverage.

4. Synoptic Patterns for High-Precipitation Events

[17] At Kohnen Station, daily precipitation amounts are very small for the majority of the time (see Figure 2). Of all days, 77% have precipitation sums smaller than the mean value of 0.29 mm. However, precipitation events with considerably higher precipitation amounts, which are clearly connected to synoptic activity in the circumpolar trough, occur several times a year. These events, even though only a few per year, can bring a large amount of the total annual precipitation. Figure 2 shows AMPS daily precipitation sums at Kohnen Station for the years 2001–2006. The high-precipitation events can be clearly distinguished from the usual weak precipitation.

[18] The long-term annual accumulation at Kohnen Station amounts to 62 mm [*Oerter et al.*, 2000]. Daily precipitation sums derived from AMPS vary between a few tenths of a millimeter and several millimeters. The highest daily values reach almost 10 mm, with the highest total sums for one event (over several days) amounting to 10–15 mm (e.g., for an extreme precipitation event in February 2003 [*Schlosser et al.*, 2010]). The mean daily precipitation in the investigated period 2001–2006 is 0.294 mm with a standard deviation σ of 0.672 mm. This yields a mean annual precipitation of 107 mm, a value considerably higher than the

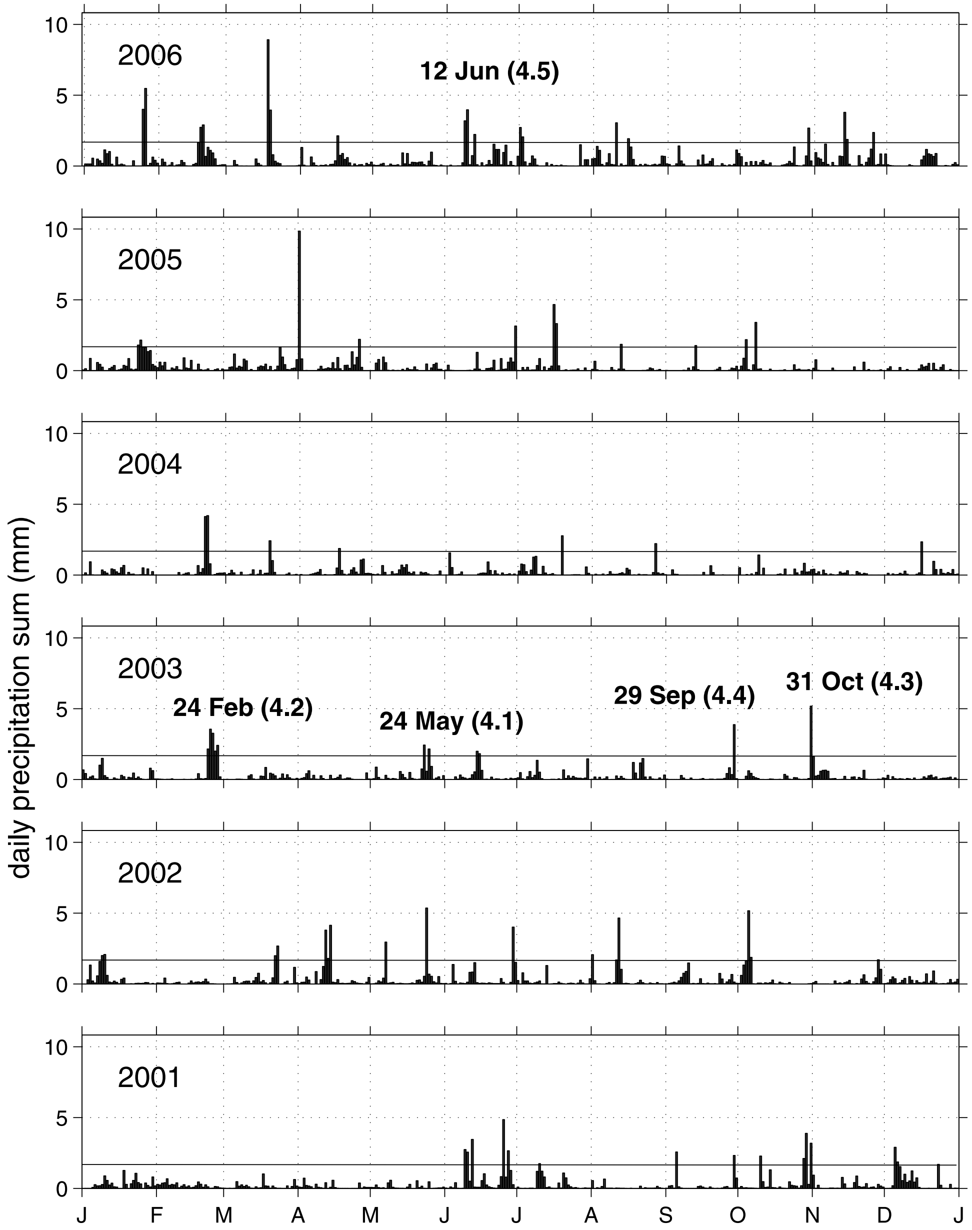

Figure 2. Daily precipitation sums derived from AMPS for Kohnen Station, 2001–2006. The straight line indicates the threshold of ($p_{\text{mean}} + 2\sigma_{\text{daily precipitation}}$) used for definition of a high-precipitation event. The numbers 4.1 to 4.5 refer to the sections in text that describe the typical weather sitations.

glaciologically derived accumulation. It is not possible to compare accumulation and precipitation directly, because accumulation is the sum of precipitation, sublimation and deposition, and erosion and deposition of snow from wind influence. *Van den Broeke et al.* [2004] estimated that the mass loss owing to sublimation from both the surface and drifting snow is about 6% of the annual accumulation at Kohnen Station. This is not enough to explain the observed difference between accumulation and precipitation. The remaining difference is from wind erosion, model errors, and measurement errors, which cannot be quantified.

[19] To define a "high-precipitation event," a threshold of the mean value plus twice the standard deviation (i.e., $p_{\text{threshold}} = p_{\text{mean}} + 2\sigma_{\text{daily precipitation}}$) was chosen. This yields a value of 1.638 mm (indicated by a straight line in Figure 2), which is a rather high value and ensures that only synoptically induced precipitation cases are considered here. Of all days studied, 4% have precipitation sums above this threshold. In spite of precipitation distributions being typically non-Gaussian, this methodology (rather than considering percentiles) was chosen for consistency with that of *Fujita and Abe* [2006]. It identifies the upper fourth percentile of events, which adequately represent precipitation extremes.

[20] During the time period 2001–2006, at Kohnen Station 51 such events were identified in the AMPS data. The synoptic patterns for all these events were investigated. Five frequently recurring weather situations were found to represent 82% of all cases. In the following, typical examples for those weather situations are presented. Figures 3–7 show

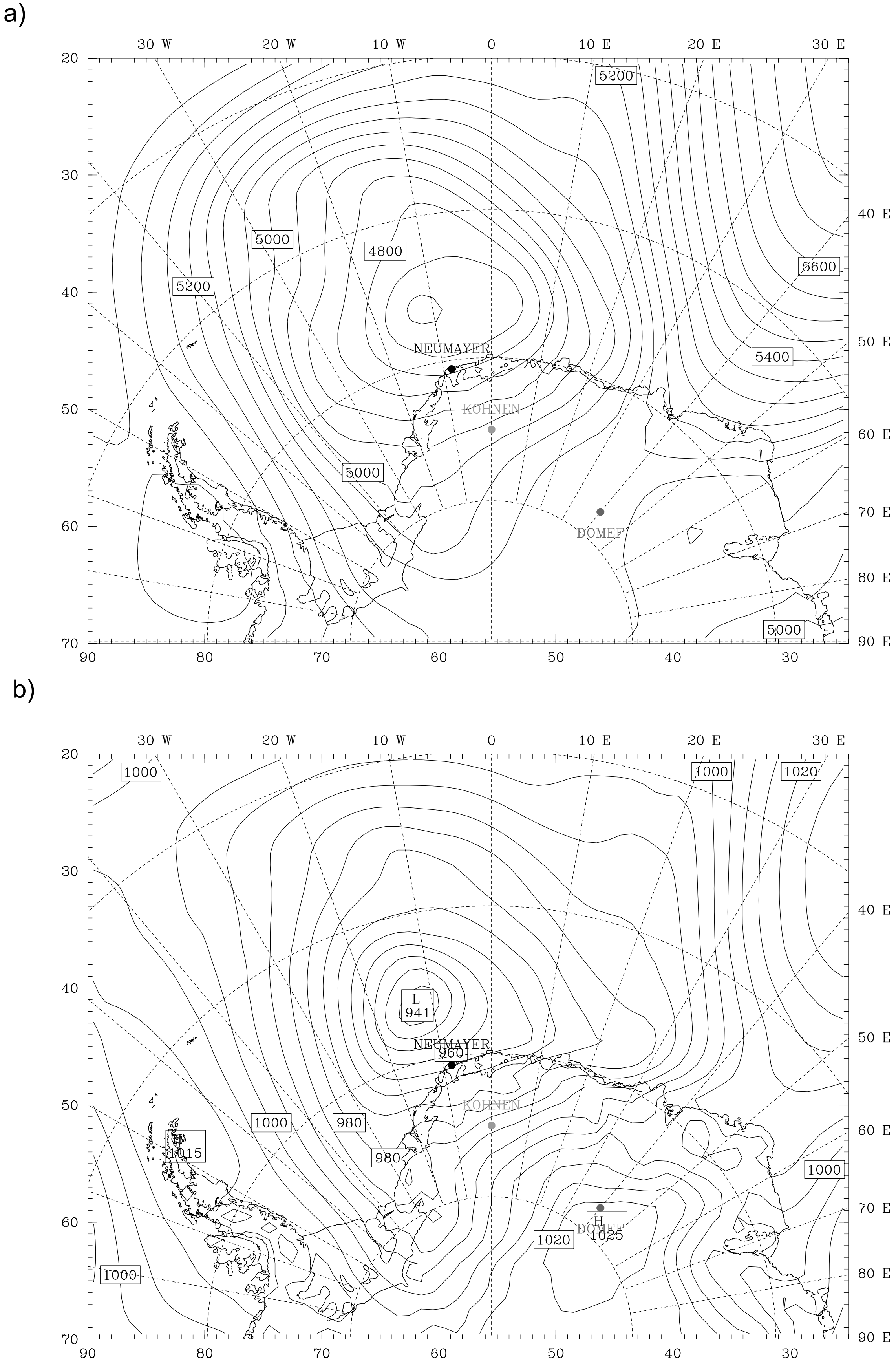

Figure 3. AMPS 500 hPa (a) geopotential height and (b) surface pressure for example in section 4.1: strong, deep cyclone over and north of Kohnen Station (24 May 2003).

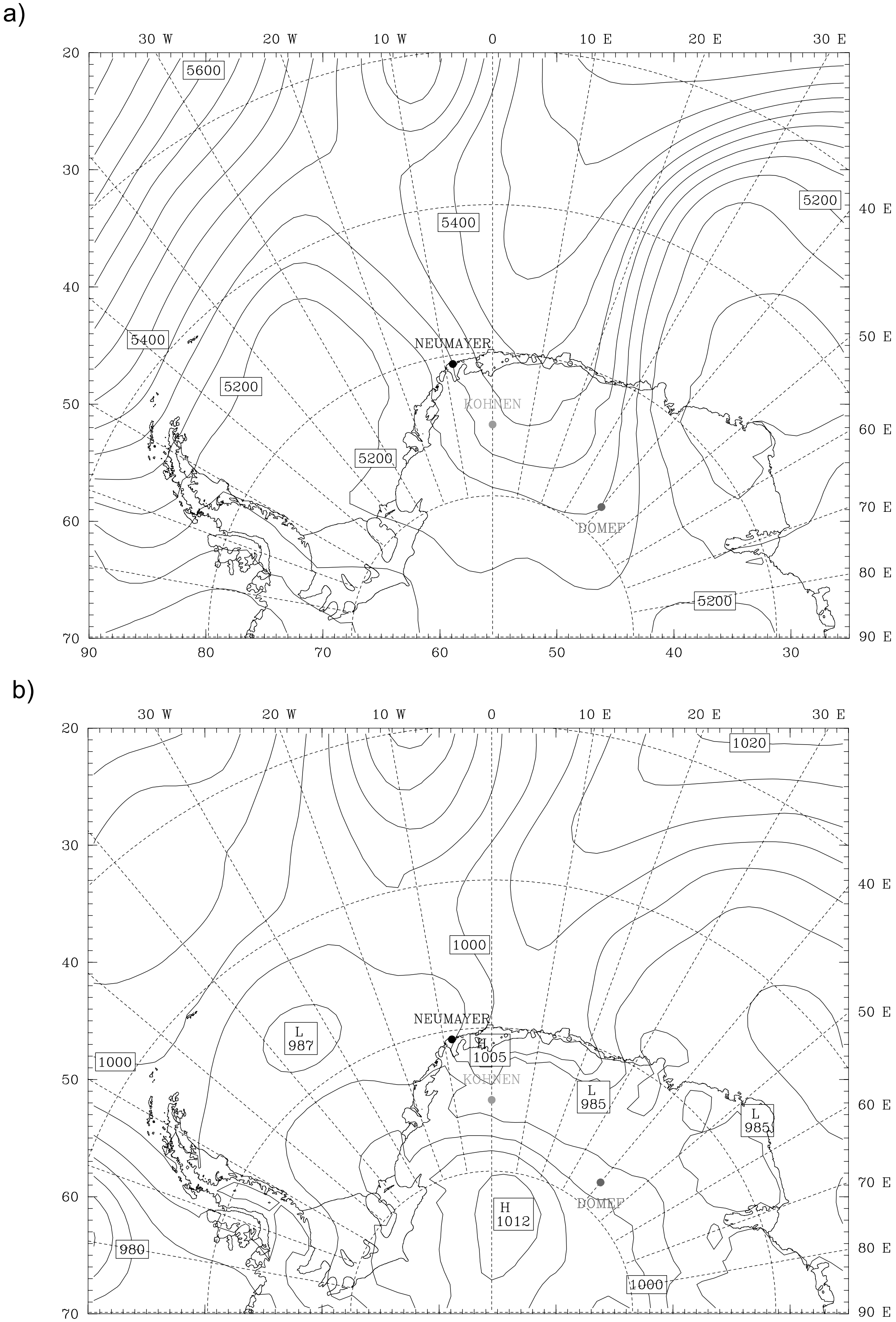

Figure 4. AMPS 500 hPa (a) geopotential height and (b) surface pressure for example in section 4.2: blocking high east of Kohnen Station with northwesterly flow (24 February 2003).

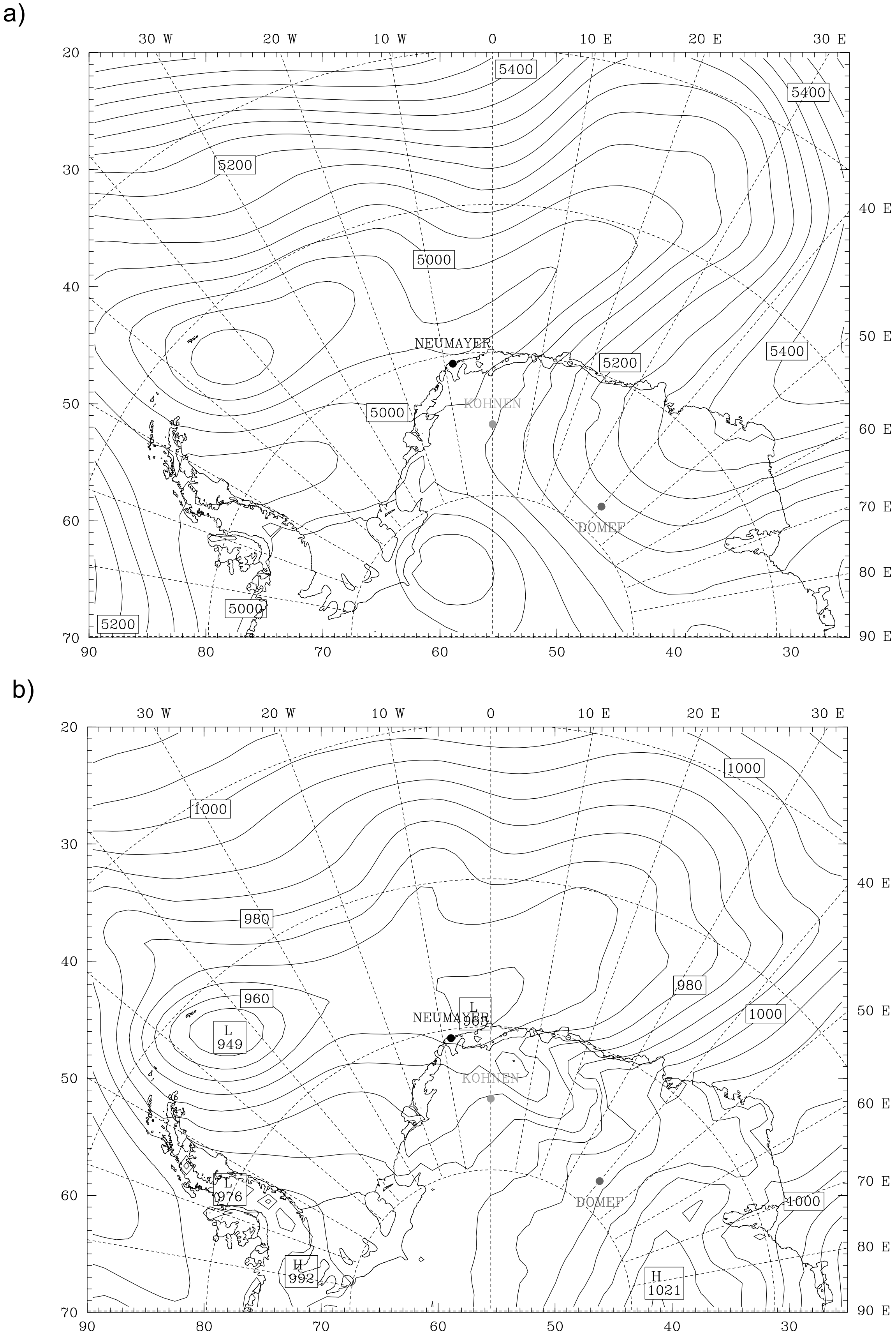

Figure 5. AMPS 500 hPa (a) geopotential height and (b) surface pressure for example in section 4.3: blocking high east of Kohnen Station with northeasterly flow (31 October 2003).

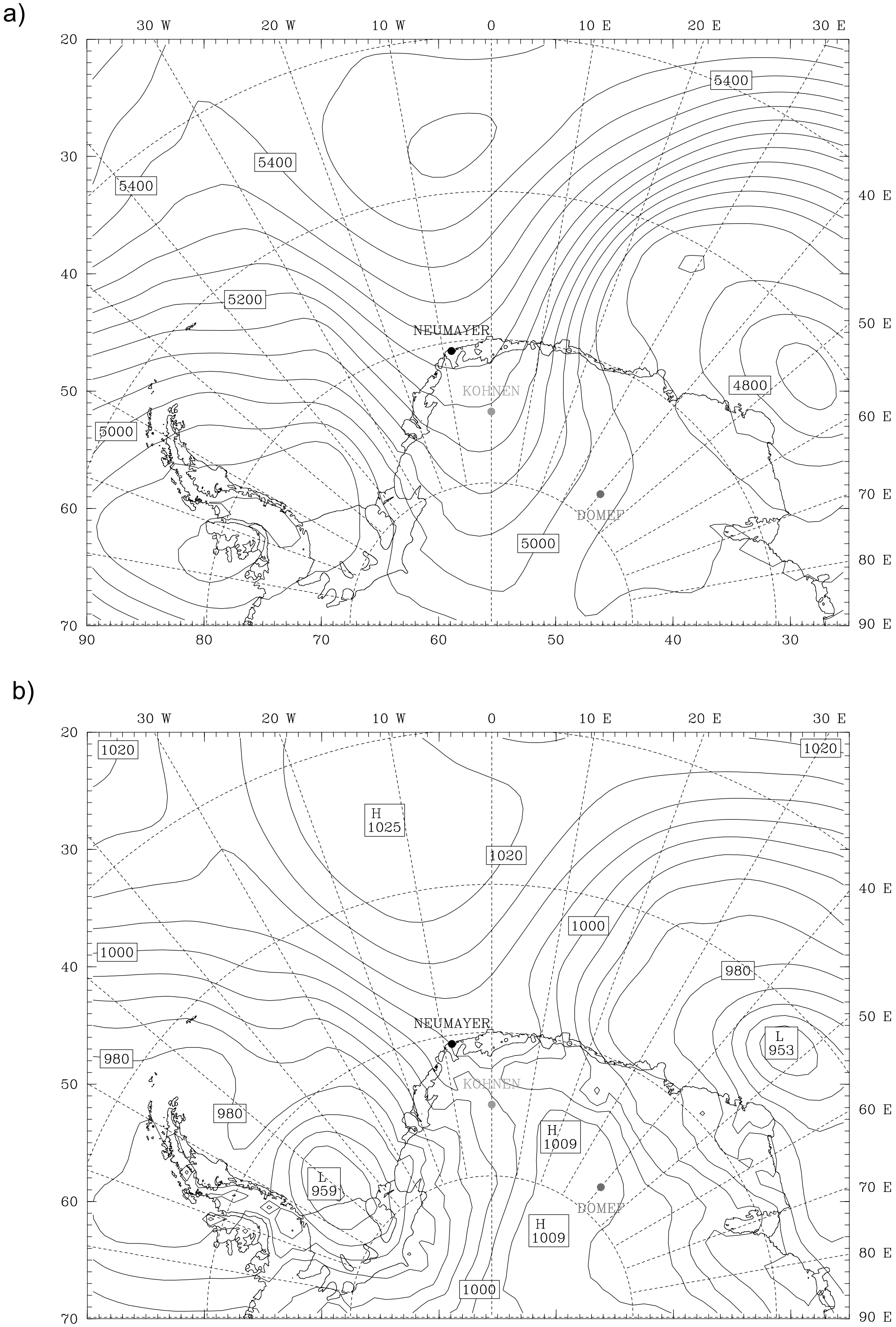

Figure 6. AMPS 500 hPa (a) geopotential height and (b) surface pressure for example in section 4.4: (weak) ridge above Kohnen Station (29 September 2003).

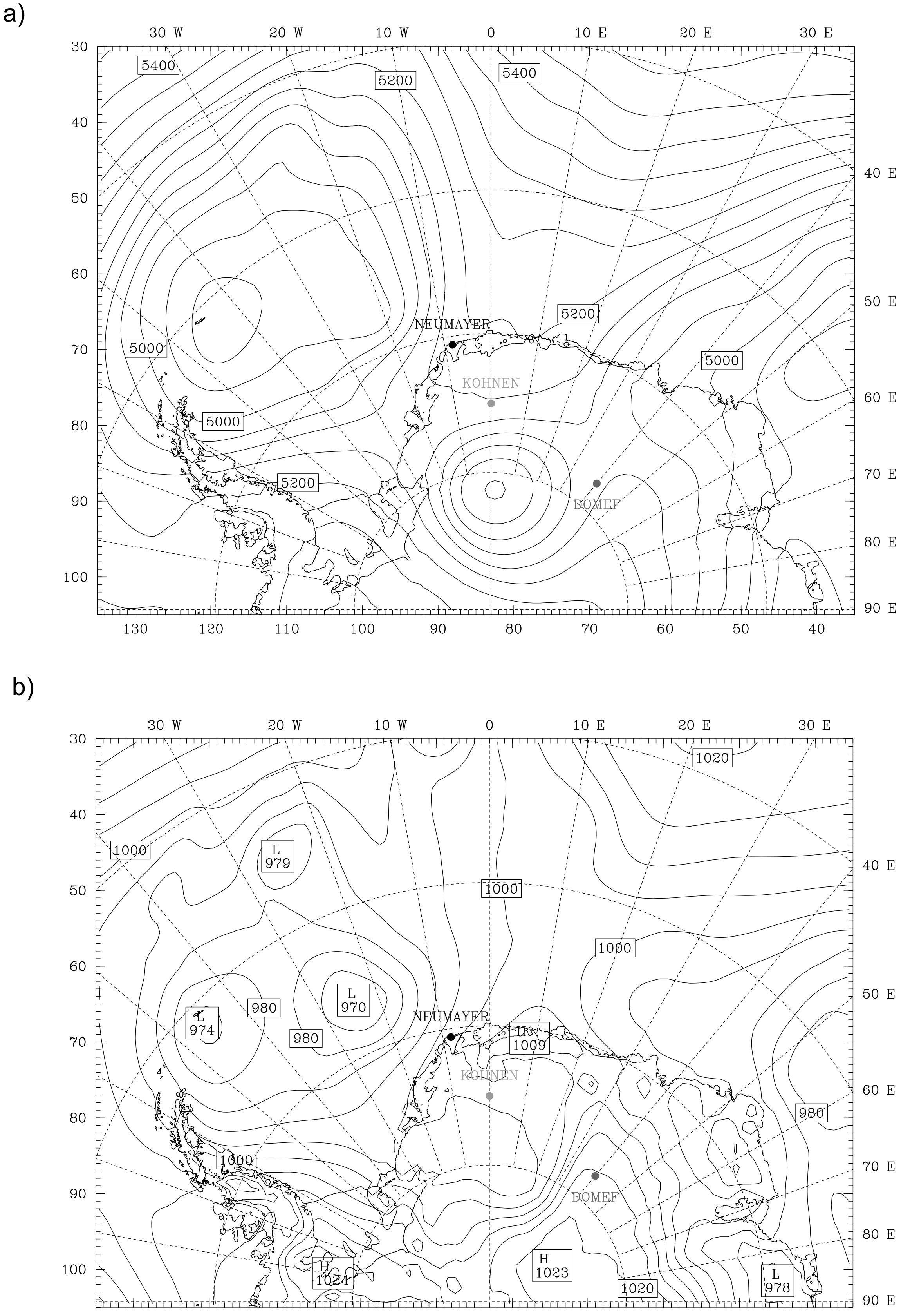

Figure 7. AMPS 500hPa (a) geopotential height and (b) surface pressure for example in section 4.5: upper air low south of Kohnen Station (12 June 2006).

the 500 hPa geopotential height fields and the sea level pressure fields for these five situations (AMPS 12 h forecasts). Note that sea level pressure is not reliable in the interior of the continent; reduction of surface pressure to sea level is problematic because of the strong surface inversions and the high terrain elevation. In Figures 8a–8e, the five typical corresponding precipitation fields (precipitation sums for the 12 h time interval following the dates above) are shown.

4.1 Strong, Deep Cyclone Over and North of Kohnen Station (Figures 3 and 8a)

[21] For the first pattern (e.g., 24 May 2003), a strong surface low and the corresponding upper air low are centered approximately 40 km northeast of Neumayer Station. In this example, the central surface pressure is 941 hPa, which is close to the minimum pressure values measured in the circumpolar trough. The system is extensive and covers the area between the western Weddell Sea and central Dronning Maud Land, with the north-south extent amounting to about 40° latitude. Kohnen Station, about 550 km southeast of Neumayer Station, is influenced by precipitation associated with the frontal system of the cyclone.

[22] This synoptic pattern is related to Birnbaum et al.'s category 1 (occluding fronts from eastward moving low-pressure systems). However, because they investigated only events that occurred in summer when the circumpolar trough is shifted to its northernmost position, the low-pressure systems in their investigation were weaker and situated farther north than in the present example. A strong, active cyclone as described here occurring in summer would represent a rare exception.

4.2. Blocking High East of Kohnen Station with Northwesterly Flow (Figures 4 and 8b)

[23] In this situation (e.g., 24 February 2003), Kohnen Station is situated at the western side of a well-developed ridge above central and eastern DML in a northwesterly flow that persists for several days connected to advection of relatively warm and moist air from latitudes as low as north of 50°S. Orographic lifting of this air leads to exceptional precipitation at Kohnen Station. In the example shown here, the precipitation even reaches Dome Fuji. A detailed case study of this event is given by *Schlosser et al.* [2010]. Blocking anticyclones such as this are also found farther east, which brings Dome Fuji in a similar warm-moist northwesterly flow. However, in the investigation presented here, it was found only twice that the same blocking high caused precipitation at both Kohnen Station and Dome Fuji. The highest precipitation values are found on the windward slope northwest of Kohnen Station.

4.3. Blocking High East of Kohnen Station with Northeasterly Flow (Figures 5 and 8c)

[24] A similar blocking anticyclone (e.g., 31 October 2003) can cause a completely different spatial distribution of precipitation when Kohnen Station lies in a northeasterly flow. The topography of the coastal areas and the escarpment is clearly mirrored in the precipitation field, with precipitation maxima at the northeastern slopes and minima at the western (leeward) slopes. The precipitation almost reaches Dome Fuji also, but because its altitude is almost 1000 m higher than that of Kohnen Station, the humidity is in most cases not sufficient to yield precipitation.

4.4 (Weak) Ridge Above Kohnen Station (Figures 6 and 8d)

[25] Usually a moderate or weak ridge above Kohnen Station (e.g., 29 September 2003) is, similarly to the case in section 4.2, connected to a northwesterly flow; thus, there is advection and orographic lifting of warm and moist air, which leads to precipitation at the station. Amounts are usually smaller than in the case of a blocking anticyclone, because the duration of the corresponding synoptic pattern is smaller than in the situation described in sections 4.2 and 4.3 and the ridge does not extend as far to lower latitudes as in the case of a blocking high. The spatial precipitation distribution is similar to that of the situation in section 4.2. Weaker ridges are usually not connected to a northeasterly flow because the amplification of the Rossby waves is not as strong and no omega-blocking situations are seen. This synoptic pattern is related to category 2 in the study by *Birnbaum et al.* [2006].

4.5 Upper Air Low South of Kohnen Station (Figures 7 and 8e)

[26] The last frequently recurring situation involves an upper air low south or southwest of Kohnen Station (e.g., 12 June 2006), leading to a southwesterly or westerly flow that brings moisture from the Weddell Sea to the continental plateau. The different cases categorized in this pattern were not quite as uniform as in the situations of sections 4.1–4.4, but they were similar enough to define them as a typical class. Precipitation is observed mainly west and south of Kohnen Station.

5. Frequency Distribution and Seasonality

[27] Figure 9 shows the frequency distribution of the typical weather patterns described in section 4. Only 20% of the cases are connected to the direct influence of cyclones and their frontal systems, while more than half of the cases are related to anticyclones and the corresponding flow patterns. The blocking situations especially require a strong cyclogenesis in the Weddell Sea or the ocean north of western DML; however, the precipitation is related not to the frontal systems of these lows but to orographic lifting of the moist and relatively warm air that is advected in the northwest to northeasterly flow between the low and the ridge. In some cases, Kohnen Station is situated exactly beneath the ridge axis at the time of the precipitation. The cases of a blocking anticyclone with northwesterly or northeasterly flow together represent almost 25% of all cases, the weak ridge situation slightly more than 25%, and the situation of southwesterly flow due to cutoff lows south or southwest of the station is the least frequent group with only about 10%. Of the cases investigated, 18% could not be clearly classified as belonging to one of the five classes, and there were not enough cases with similar weather patterns that were sufficient to define a sixth class.

[28] The number of investigated cases is too small to get any statistically significant results concerning seasonality of the extremes. However, it seems that the warm season months of November until March are less favored for the

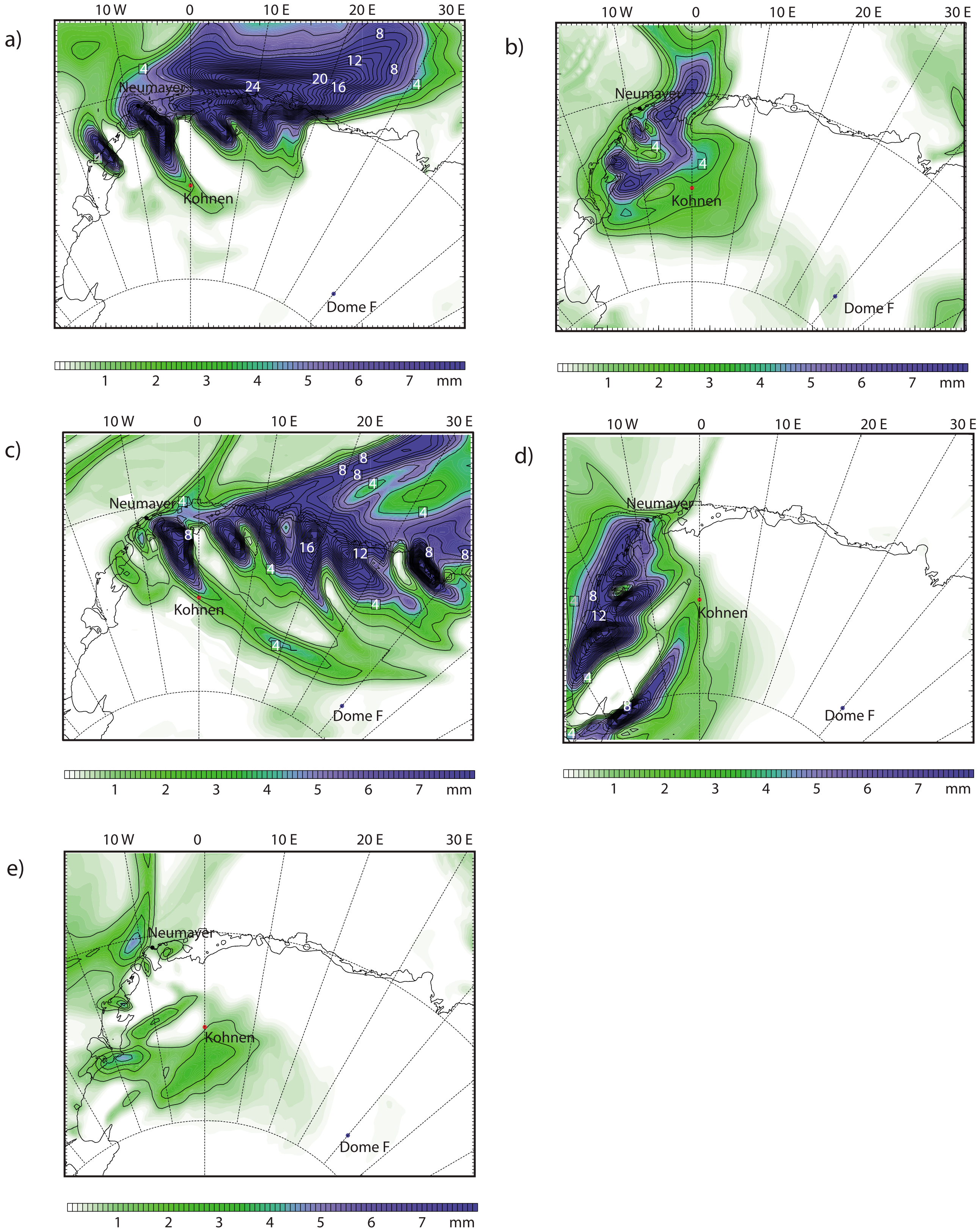

Figure 8. AMPS 12 h precipitation sums for the synoptic situations described in Figures (a) 3, (b) 4, (c) 5, (d) 6, and (e) 7.

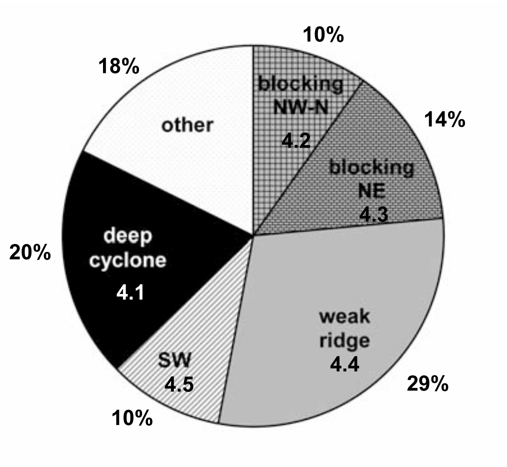

Figure 9. Frequency distribution of different synoptic patterns for high-precipitation events. Numbers below pattern names refer to the sections in the text where the respective synoptic situation is described.

aforementioned weather situations than the rest of the year. In each of these months, only three high-precipitation events were found between 2001 and 2006. October was the month with the maximum number of events (seven), followed by August and June with six events each. The number of events per year varied between 5 (2003) and 11 (2006) (see Figure 2). A longer investigation period is required to get statistically significant numbers.

6. Diamond Dust

[29] Although the model does not explicitly treat diamond dust, a rough estimate of the fraction of diamond dust or low-amount precipitation compared to the high-precipitation events has been calculated. For our purposes, it is not necessary to physically distinguish between diamond dust and low-amount synoptic precipitation, because neither shows a strong seasonality that could affect ice core interpretation. It is assumed that all daily precipitation values smaller than the mean (p_{mean}) plus the twofold standard deviation ($\sigma_{\mathrm{daily\ precipitation}}$) are diamond dust or low-amount precipitation, while all amounts larger than this threshold are caused by synoptically induced high-precipitation events. This is, of course, a strong simplification; thus, the results can only be treated as estimates. *Fujita and Abe* [2006] measured daily precipitation at Dome Fuji between February 2003 and January 2004. They estimated the amount of diamond dust at Dome Fuji during this period as 53% using a threshold of $p_{\mathrm{mean}} + 1\sigma_{\mathrm{daily\ precipitation}}$. For the same time period and threshold, AMPS gives a value of 55%. For 2001–2006, the AMPS data yield a value between 55% and 72%, using a threshold of ($p_{\mathrm{mean}} + 1\sigma_{\mathrm{daily\ precipitation}}$) and ($p_{\mathrm{mean}} + 2\sigma_{\mathrm{daily\ precipitation}}$), respectively. Because it is impossible to determine one threshold that distinguishes exactly between diamond dust/low-amount precipitation and high-precipitation events, an estimate for the threshold range between ($p_{\mathrm{mean}} + 1\sigma_{\mathrm{daily\ precipitation}}$) and ($p_{\mathrm{mean}} + 2\sigma_{\mathrm{daily\ precipitation}}$), respectively, is given. During the period measured by *Fujita and Abe* [2006], synoptically induced precipitation occurred only 5% of the time but brought 47% of the total accumulation. The choice of a threshold of ($p_{\mathrm{mean}} + 2\sigma_{\mathrm{daily\ precipitation}}$) would yield non-diamond dust precipitation on 3% of the days, bringing 40% of the total precipitation during the period February 2003 to January 2004.

[30] For Kohnen Station, a threshold between ($p_{\mathrm{mean}} + 1\sigma_{\mathrm{daily\ precipitation}}$) and ($p_{\mathrm{mean}} + 2\sigma_{\mathrm{daily\ precipitation}}$) yields a percentage of event-type precipitation of 40% to 54%. Observational data from Kohnen Station for one summer season (19 November 2005 to 1 February 2006) reveal nine events with measurable precipitation (fresh snow depth larger than 1 mm), which were all represented by AMPS; 2006 was the year with the highest number of high-precipitation events. However, only three of those nine events brought precipitation larger than the threshold of 1.64 mm ($p_{\mathrm{mean}} + 2\sigma_{\mathrm{daily\ precipitation}}$) chosen for the definition of high-precipitation events in this study. Additionally, on 23 occasions, non-diamond dust snowfall was observed with fresh snow accumulations that were so little as to not have been measured. This shows that, at Kohnen Station, only a part of the low-amount precipitation is really diamond dust. In summer, observations show that the diamond dust formation was often related to sublimation-deposition cycles; for the wintertime, no observations are available. A quantification of errors for the preceding estimates is not possible because of the very small precipitation amounts and uncertainties in both the model and the measurements that cannot be quantified.

7. Discussion and Conclusion

[31] Although on most days of the year low-amount precipitation caused by diamond dust formation or a weak synoptic influence is the prevailing type of precipitation at Kohnen Station, on average approximately eight precipitation events with significantly higher precipitation amounts occur per year that account for more than half of the total annual accumulation. The episodic nature of such precipitation events in the interior of the Antarctic continent, in particular at Kohnen Station, DML, is found in the majority of the cases to be connected to the amplification of upper level planetary waves. This leads to a meridional flow, in contrast to the typical zonal flow, which means advection of relatively warm and moist air from lower latitudes to the interior of the continent. This moist air is being orographically lifted, leading to condensation and cloud formation and, in many cases, to precipitation. Only 20% of the 51 investigated high-precipitation cases between 2001 and 2006 were directly connected to the influence of low-pressure systems and frontal activity, whereas 53% of the cases were connected to high-pressure systems and the corresponding flow patterns.

[32] Thus, even though frontal systems seldom reach the Antarctic plateau, the dynamic processes connected to the circumpolar trough play an important role for precipitation processes in the interior. Climate variability in the Southern Ocean has recently often been described by the Southern Annular Mode (SAM) [*Marshall*, 2003]. The amplification of the long atmospheric waves mentioned earlier is usually observed during the negative phase of the SAM, meaning a decreased pressure gradient (compared to the long-term mean) between middle and high southern lati-

tudes corresponding to weaker westerlies. The SAM, in turn, is connected to ENSO variability in a highly complex, nonlinear way [e.g., *Turner*, 2004] that is not fully understood yet. *Divine et al.* [2009] investigated the relationship between ENSO and stable isotope records in Antarctic ice cores from Dronning Maud Land. Our understanding of the complex relationship between Antarctic climate and ENSO is still fairly incomplete because of the nonlinearity of this relationship. While ice cores may be helpful to improve our understanding of the teleconnections in the Southern Hemisphere, the SAM trends and corresponding changes in precipitation seasonality have to be considered for a correct ice core interpretation. This mutual influence further increases the complexity of the problem.

[33] Further research employing mesoscale models over an extended time period will help to increase our knowledge of seasonal and interannual changes in the occurrence of high-precipitation events in the interior of Antarctica. The possibility of a higher frequency of such events due to a smaller sea ice extent [*Simmonds and Wu*, 1993] combined with higher moisture content in a warmer climate could significantly influence Antarctic precipitation and, thus, the mass balance of the continent. This might enhance Antarctica's role in the mitigation of sea level rise.

[34] In ice core studies, the observed increase in near-surface wind speed and temperature during high-precipitation events has to be taken into account. Additionally, the seasonality of such events in former climates must be known for a correct climatic interpretation of ice core properties, such as water stable isotope ratios and chemical species. However, because such information is not directly available, it remains an unsolved problem that might be addressed in the future by combining modeling efforts, namely mesoscale atmospheric modeling and isotope modeling, with both modern and paleoclimatological data.

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