An extreme precipitation event in Dronning Maud Land, Antarctica: a case study with the Antarctic Mesoscale Prediction System

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Abstract

An extreme precipitation event that influenced almost the whole polar plateau of Dronning Maud Land, Antarctica, is investigated using Antarctic Mesoscale Prediction System archive data. For the first time a high-resolution atmospheric model especially adapted for polar regions was used for such a study in Dronning Maud Land. The outstanding event of 21–25 February 2003 was connected to a strong north-westerly flow, caused by a blocking high above eastern Dronning Maud Land, that persisted for several days and brought unusually large levels of moisture to the Antarctic Plateau. This weather situation is most effective in bringing precipitation to high-altitude interior Antarctic ice-core drilling sites, where precipitation in the form of diamond dust usually dominates. However, a few such precipitation events per year can account for a large percentage of the annual accumulation, which can cause a strong bias in ice-core data. Additionally, increased temperatures and wind speeds during these events need to be taken into account for the correct climatic interpretation of ice cores. A better understanding of the frequency of occurrence of intermittent precipitation in the interior of Antarctica in past and future climates is necessary for both palaeoclimatological studies and estimates of future sea-level change.

The mass balance of Antarctica has received increasing attention in recent years in discussions of climate change, as its response to global warming can significantly influence sea-level change. Possibly increased precipitation in a warmer climate would mean storage of a larger volume of water in the Antarctic ice sheet, thus mitigating the sea-level rise resulting from the thermal expansion of the ocean. For estimates of the Antarctic mass balance it is necessary to know the most important component, namely precipitation, as accurately as possible. The huge ice sheet of Antarctica is also a highly valuable climate archive: data from deep ice cores yield information about palaeotemperatures, as well as the composition of the palaeoatmosphere from studies of the air bubbles included in the ice. However, for a correct interpretation of ice-core properties, it is important to know the regime of precipitation that forms the ice in the cores. But measurements of precipitation in Antarctica are sparse and difficult to carry out, because of the remoteness and size of the continent and its climatic extremes. Although precipitation rates are relatively high in the coastal areas, measurements are problematic because precipitation events are usually accompanied by strong winds that make it impossible to differentiate between blowing snow and falling precipitation. Standard precipitation gauges fail, and so far no satisfactory method for measuring precipitation under such conditions has been developed (King & Turner 1997). At high-altitude inland stations (e.g., Dome Fuji), the level of precipitation is so low that measurements of high-temporal resolution are also extremely difficult. Thus, only a few data sets for relatively short time periods exist (e.g., Fujita & Abe 2006; Braaten 2000). In light of the lack of observations, atmospheric models are useful tools to investigate the spatial and temporal variability of Antarctic precipitation, and to estimate the precipitation distribution.

For a long time it had been assumed that whereas precipitation in the coastal regions of Antarctica is mainly caused by frontal systems connected to synoptic activity in the circumpolar trough, at higher elevations precipitation usually falls as diamond dust that forms as a result of radiative cooling of the air under clear-sky conditions, as low-pressure systems do not penetrate into the interior of the continent. Thus, contributions from all seasons are assumed to be found in the ice cores, an assumption that is a necessary precondition for non-biased information from ice-core proxy data (Jouzel et al. 1997; Jouzel et al. 2003). However, both observations (e.g., Reijmer & van den Broeke 2003) and model studies (Noone & Simmonds 1998; Noone et al. 1999; Braaten 2000; Schlosser et al. 2008) have shown that the interior plateau is influenced by the synoptic conditions in the coastal areas more strongly than previously thought.

In Dronning Maud Land (DML), extending from approximately 30°W to 50°E and from 70° to 80°S, two deep ice cores have recently been retrieved: the first drilling was carried out in the frame of the European Project for Ice Coring in Antarctica (EPICA) at Kohnen Station (0.50°E, 75.00°S; 2892 m a.s.l.) (Oerter et al. 2004; EPICA community members 2006). The second core was taken by Japanese scientists in eastern DML at Dome Fuji (77.32°S, 39.7°E; 3810 m a.s.l.) (Watanabe et al. 2003; Horiuchi et al. 2008). With the goal of ultimately assisting in the analysis of such cores, in this study we shall concentrate on the precipitation regime of DML. In order to document the scenario that appears to provide a large part of the annual precipitation in the interior of DML, an extreme precipitation event that affected most of DML, including the high-altitude plateau, is investigated, using model forecast output from Antarctic Mesoscale Prediction System (AMPS) archive data. Thus, for the first time, a high-resolution mesoscale atmospheric model especially adapted for polar regions is used for the detailed diagnosis of conditions responsible for such an event in DML.

Background

Early studies of Antarctic precipitation (e.g., Bromwich 1988) estimated its level on a continental scale from water vapour fluxes derived from radiosondes launched at coastal stations around the continent (Bromwich 1988; Connolley & King 1993; Bromwich et al. 1995). More recently, different types of numerical atmospheric models have been employed for Antarctic precipitation studies. Cullather et al. (1998) investigated the temporal and spatial variability of net precipitation (precipitation minus evaporation) using European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis data, and compared their results with various glaciological and meteorological observational data sets. Bromwich et al. (2004) studied Antarctic precipitation variability using the mesoscale model MM5 as well as the so-called dynamic retrieval method. Numerous mass-balance estimates for Antarctica have been calculated over the past decades, using increasing numbers of observational data and increasingly sophisticated methods (e.g., Giovinetto & Bentley 1985; Vaughan et al. 1999; van de Berg et al. 2006). However, results of different studies still do not entirely agree, particularly concerning trends in accumulation. For example, Monaghan et al. (2006) combined model simulations and observations, primarily from ice cores, to derive a 50-year time series of snowfall over the Antarctic continent, and found no significant trend over the past 50 years, which suggests that global sea-level rise is not mitigated by the storage of more water in the Antarctic ice sheet. Antarctica at present contributes to global sea-level rise by an increase in ice discharge, mainly from the West Antarctic ice sheet (Rignot et al. 2008).

Although Sinclair (1981) had shown as early as 1981 that low pressure systems do penetrate deeply into the interior of the continent, for a long time it was assumed that this was the exception to the rule, and that in central Antarctica clear-sky precipitation was the dominant factor in accumulation (e.g., Bromwich 1988). Only in the past decade have several studies shown a different picture. Noone & Simmonds (1998) looked at the synoptic patterns causing unusually high precipitation in Antarctica using data from a general circulation model. They stressed that such precipitation events are usually accompanied by unusually high temperatures, leading to a strong bias in temperatures derived from ice cores. This bias is already included in empirical relationships between temperature and isotope ratios; however, the bias might be different for different climates.

A comprehensive study of DML precipitation was carried out by Noone et al. (1999) using ECMWF re-analysis data. They also found that a few synoptically induced precipitation events per year can yield a large part of the total annual accumulation. A changed seasonality of the occurrence of such events between the present and former climate can lead to a bias in ice-core properties that is much more difficult to account for (Jouzel et al. 1997; Schlosser 1999). Two case studies showed that the high precipitation levels were caused by amplification of upper-level planetary waves directing warm, moist air masses to the interior of the continent.

Reijmer & van den Broeke (2003) showed that accumulation at several automatic weather stations (AWSs) in DML occurs in many small, and a few large, events per year, with those few large events accounting for up to 50% of the total annual accumulation. Air temperatures and wind speeds during such events are usually exceptionally high (Reijmer & van den Broeke 2001). Braaten (2000) studied accumulation using snow stakes, tracer material and an acoustic depth gauge at a site on the Antarctic plateau between the South Pole and the Filchner–Ronne Ice shelf, which is also influenced by low-pressure systems above the Weddell Sea. He also found that few large events per year brought much accumulation. He did not always observe a temperature increase during those events: a slight decrease in temperature was possible, too.

Birnbaum et al. (2006) investigated synoptic situations causing high precipitation rates on the Antarctic Plateau using observations from Kohnen Station and ECMWF operational analyses. They defined three categories of weather situations that led to high precipitation levels at Kohnen Station: (1) occluding fronts from eastward-moving low-pressure systems; (2) frontal clouds of retrograde lows or secondary lows; and (3) large-scale lifting processes resulting from an upper-air low, west of Kohnen Station. Their analysis is restricted to the summer months, for which visual observations were available. An upper-air low, west of Kohnen, leads to a north-westerly flow over DML that can be fairly stable over several days as a result of blocking a high-pressure system further eastwards. Such blocking anticyclones were also investigated by Enomoto et al. (1998), who observed an extreme winter warming around Dome Fuji connected to a blocking high that persisted for several weeks, and brought relatively warm air deep into the interior of the continent. At Dome Fuji, the moisture content of the warm air is not always sufficient to produce precipitation, but dramatic changes in meteorological conditions are observed. Hirasawa et al. (2000) studied a blocking event that lasted for only 2 days. Orographic lifting of the moist air led to the formation of relatively thick clouds in the area around Dome Fuji, which increased the downward long-wave radiation. Together with increasing wind speeds that enhanced vertical mixing, this broke up the surface temperature inversion, yielding a temperature increase of almost 40°C within 2 days (also see van As et al. 2007).

Massom et al. (2004) used both satellite passive microwave data (SSM/I) and numerical weather prediction model analyses (ECMWF) to investigate the episodic occurrence of significant precipitation events on the East Antarctic ice sheet, and related them to blocking high activity in the South Tasman Sea. They found that such events play a key role in delivering substantial snowfall as far south as at least 75°S on the central East Antarctic ice sheet. The corresponding moisture originates from as far north as 35–40°S.

Whereas Noone et al. (1999) used a general atmospheric model with a horizontal resolution of about 100 km, in this investigation, for the first time, a mesoscale model specifically modified for Antarctic application is used at a much higher horizontal resolution across the continent (30-km grid spacing). In particular, the topography of the ice sheet is much better resolved, and thus allows a more accurate simulation of the impact of the steep slopes on the inland moisture transport. Lee effects are clearly evident in the model precipitation fields (Schlosser et al. 2008), and this is important when individual high-precipitation events show prevailing wind directions that are different from the climatological mean. Also, in contrast to Noone et al. (1999), we investigate an extensive area including two interior deep-drilling sites: Kohnen Station and Dome Fuji.

The Antarctic Mesoscale Prediction System

The AMPS (Powers et al. 2003; Bromwich et al. 2005) provides numerical forecasts for Antarctica, especially for the McMurdo Station region, to support flight operations and scientific activities of the United States Antarctic Program. These forecasts have been produced since 2000, and archived since 2001, and have also been used for scientific investigations. AMPS was developed by the National Center of Atmospheric Research and the Polar Meteorology Group of the Byrd Polar Research Center at the Ohio State University. Whereas AMPS currently employs the Weather Research and Forecasting model (Skamarock et al. 2008), at the time of the case investigated here AMPS used a polar-modified version of the MM5 (5th-Generation Pennsylvania State University/ National Center of Atmospheric Research Mesoscale Model). This version was optimized for use over high latitudes and extensive ice sheets, and 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 soil model for a better representation of heat transfer through ice sheets.

Figure 1 shows the different domains used in AMPS as well as the locations mentioned in this study. The current AMPS set-up has six grids, with horizontal spacings of 45, 15, 5 (three grids) and 1.67 km. These grids had been of lower resolution at the time of the February 2003 event: 90, 30, 10 and 3.3 km, respectively. Thus, the latter spacings apply to the case study of February 2003, which will be presented in the next section. For this study, data from the 30-km domain covering the continent were used.

For representing physical processes in the atmosphere, the MM5 in AMPS is configured with a suite of schemes and parameterizations. For the case study the key

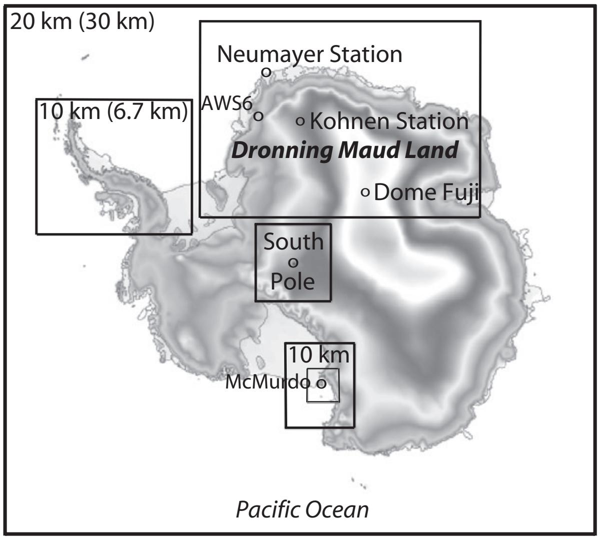

Fig. 1 Antarctic Mesoscale Prediction System grids: outer frame, 30-km domain (20 km since September 2005); 10-/6.7-km domains over Antarctic Peninsula, South Pole and western Ross Sea; 3.3-/2.2-km domain over Ross Island. An outer domain of 90/60 km (not shown) extends to New Zealand, Australia, South Africa and South America. Grey shades refer to model topography, which is shown in detail for Dronning Maud Land in Fig. 5. Locations mentioned in the text are also shown.

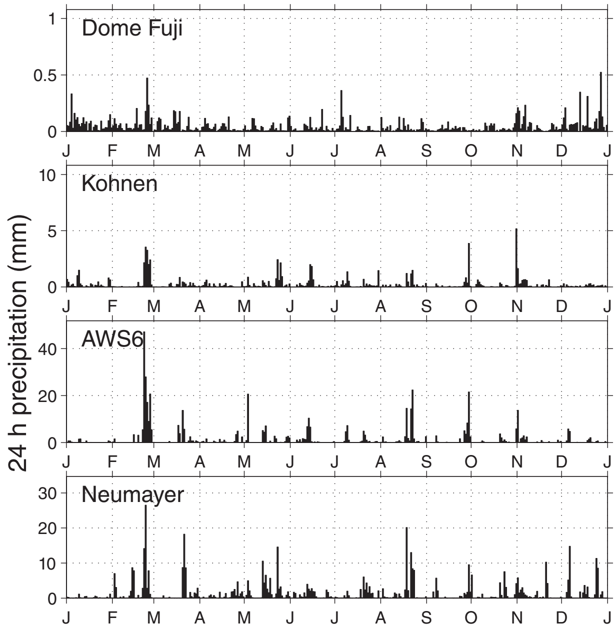

Fig. 2 Daily sums of precipitation for 2003 derived from the Antarctic Mesoscale Prediction System for Neumayer Station, AWS6, Kohnen Station and Dome Fuji.

schemes operating were as follows: the Reisner microphysics scheme was used for grid-scale cloud and precipitation processes (Reisner et al. 1998), whereas the Grell cumulus parameterization handled subgrid-scale convective cloud processes (Grell et al. 1994). Note that the cumulus parameterization is minimally active, and produces 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). The Eta planetary boundary layer scheme (Janjic 1994) was used for boundary layer processes. AMPS has previously been analysed in forecast performance reviews (e.g., Bromwich et al. 2005), and has been applied in climatological investigations (Monaghan et al. 2005; Schlosser et al. 2008) and weather event case studies (Bromwich et al. 2003; Powers 2007).

The precipitation event of February 2003

This study analyses a high precipitation event occurring in February 2003 that was observed over a broad area of DML, bringing unusually high precipitation levels to the two inland drilling sites mentioned above (Kohnen Station and Dome Fuji). For the 24-h precipitation levels examined, the model output from the 12–36-h forecast period is used to account for the model spin-up of clouds and microphysical fields. For all other parameters shown here the 12-h forecasts for the event period are analysed.

Figure 2 presents the daily sums of precipitation for the year 2003 derived from AMPS forecasts for four different locations: the coastal Neumayer Station (70.71°S, 8.42°W), an AWS location further inland at an altitude of 1160 m a.s.l. (AWS6, 74°29′S, 11°31′W), Kohnen Station (0.50°E, 75.00°S; 2892 m a.s.l.) and Dome Fuji (77.32°S, 39.7°E; 3810 m a.s.l.). For comparisons at the observation locations considered here, corresponding model values have been derived from a linear interpolation from the four closest grid points. Note that the precipitation scale is different for each location. At all four stations, this event, seen as the signal at the end of February, brought the largest precipitation sums of the year. Forecast precipitation maxima for the 24-h periods analysed in the event were approximately 0.5 mm for Dome Fuji, 3.5 mm for Kohnen, 46 mm for AWS6 and 26 mm for Neumayer. The total forecast precipitation for each site was greater than this, as the episode continued for more than one day.

Synoptic evolution

The synoptic evolution of the event is analysed to understand and document an event that appears to be typical of those that account for so much of the annual precipitation in the interior of DML. It is important to know the conditions of such events, as they can have a strong influence on the interpretation of ice cores from these regions. The frequency and occurrence of such events influence the temporal and spatial distribution of precipitation, which must be taken into account for a correct ice-core interpretation. Usually they occur more frequently during the negative phase of the Southern Annular Mode, which means weaker-than-average circumpolar westerlies.

Figure 3 shows the 12-h AMPS sea-level pressure forecasts for 22–25 February 2003, 12:00 UTC. Figure 4 presents the corresponding AMPS 500-hPa geopotential heights. On 22 February 2003 (Fig. 3a), a surface low is situated in the western Weddell Sea, whereas a ridge extends north of Neumayer. A broad upper-level trough covers the Antarctic Peninsula and the Weddell Sea, and east of it a ridge extends south to about 80°S, which brings a westerly flow to Kohnen Station (Fig. 4a). Dome Fuji is not yet influenced by these features. On 23 February 2003 (Fig. 3b), the surface low has moved to the Filchner–Ronne ice shelf. The upper-level ridge has intensified, and reaches south to latitudes beyond 80°S (Fig. 4b). Between the trough and the ridge, Kohnen Station is situated in a strong north-westerly flow, with Dome Fuji in a weak southerly flow. On 24 February 2003 (Fig. 3c), the surface low has almost disappeared, and a high-pressure ridge extends southwards to the South Pole. The upper level ridge has moved slightly eastwards, and also extends farther south than the preceding day (Fig. 4c). Kohnen is still experiencing a strong north-westerly flow aloft, with Dome Fuji experiencing southerly flow at higher levels. On 25 February 2003 (Fig. 3d), the surface low above the Filchner–Ronne ice

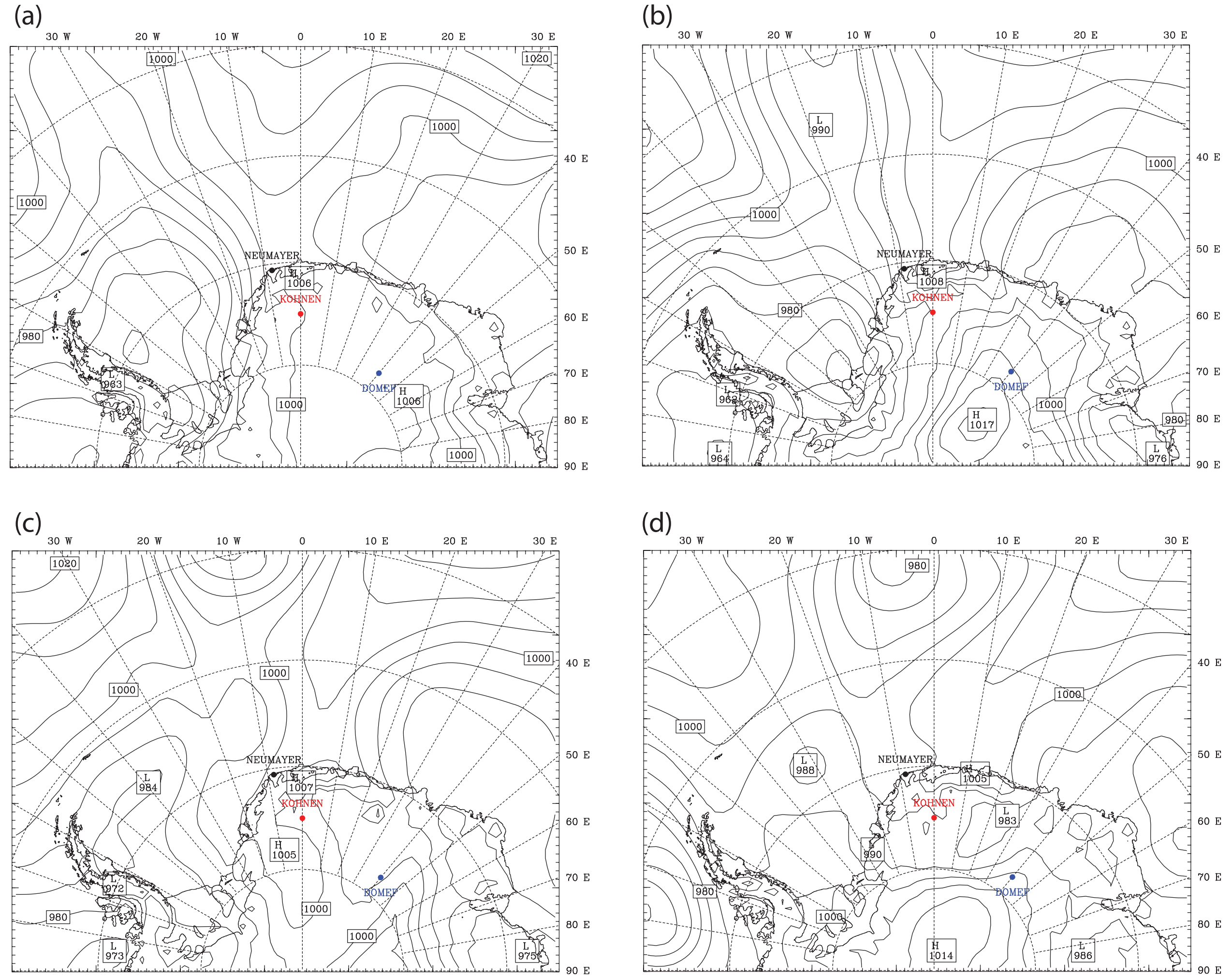

Fig. 3 Antarctic Mesoscale Prediction System surface pressure for (a) 22 February 2003, (b) 23 February 2003, (c) 24 February 2003 and (d) 25 Febuary 2003; 12:00 GMT.

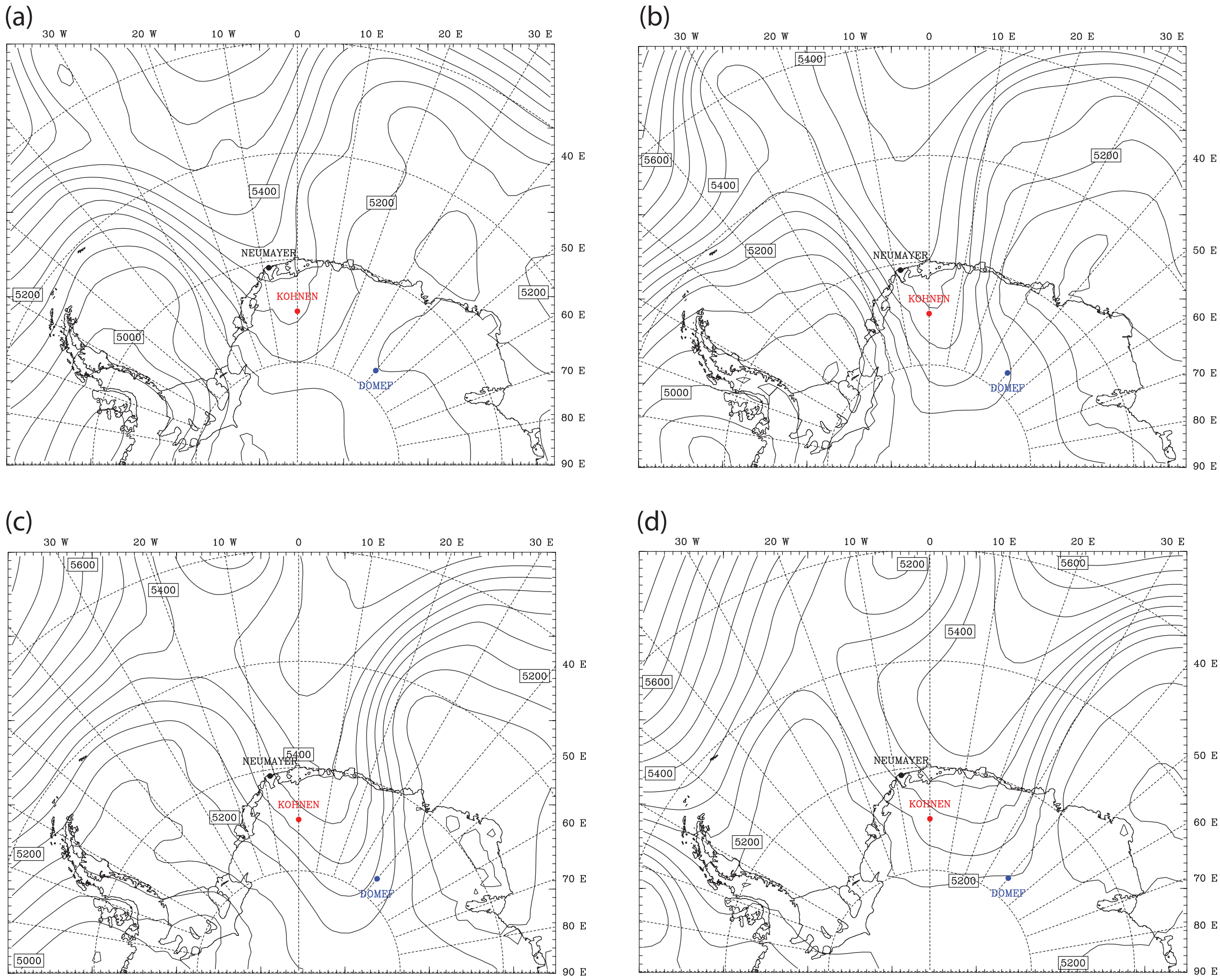

Fig. 4 Antarctic Mesoscale Prediction System 500-hPa geopotential height for (a) 22 February 2003, (b) 23 February 2003, (c) 24 February 2003 and (d) 25 Febuary 2003; 12:00 GMT.

shelf has dissipated, whereas a weak low is in the Weddell Sea. An anticyclone is found over the high plateau south of Kohnen Station. The north-westerly flow at the 500-hPa level has become weaker (Fig. 4d).

In Fig. 5 the surface wind for the event period (dates/times as in Figs. 3, 4) is shown together with the model topography. The contour intervals for the terrain are 200 m. The terrain is marked by a relatively steep slope southwards of the coast: the so-called escarpment. About 300–400 km inland, the polar plateau begins at an altitude of roughly 2500 m a.s.l. The plateau then gradually rises further to its highest point in DML, of almost 3900 m a.s.l., at Dome Fuji. The slope of the plateau is very small, however, leading to only weak katabatic winds that blow downslope, but are deflected to the left by Coriolis force. On 22 February 2003 (Fig. 5a), Neumayer Station is situated in a diffluence zone with weak winds. Kohnen, however, already shows winds of 3–5 ms^{-1} from the NNW, which are not katabatically induced. Around Dome Fuji, weak katabatic winds of 3–5 ms^{-1} from a north to north-easterly direction prevail. On the following day (Fig. 5b), wind speeds have increased considerably at Neumayer Station, with values of up to 15 ms^{-1} from the ENE observed. At Kohnen Station, winds have increased to 10–13 ms^{-1} from NNE, whereas Dome Fuji is still under katabatic influence. On 24 February 2003 (Fig. 5c), wind speeds have decreased at Neumayer Station, and at Kohnen Station they have decreased to about 8 ms^{-1} from the north. In contrast, Dome Fuji shows an increase of wind speed to 8 ms^{-1}, and a change of direction to west to south-west, which is related to the upper-level flow around the ridge. On the next day (Fig. 5d), higher wind speeds are found again at Neumayer, whereas winds have decreased at both

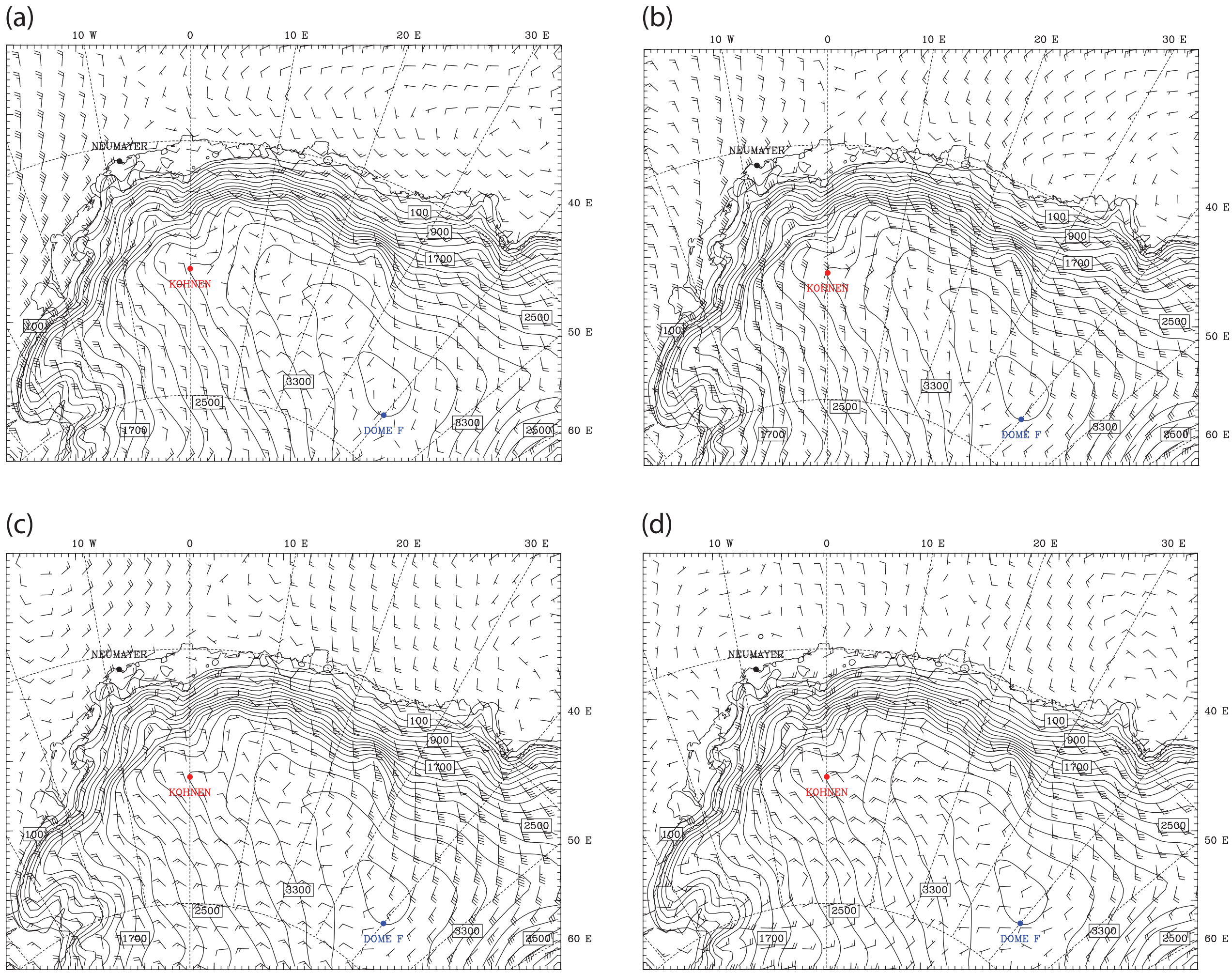

Fig. 5 Antarctic Mesoscale Prediction System surface winds for (a) 22 February 2003, (b) 23 February 2003, (c) 24 February 2003 and (d) 25 Febuary 2003; 12:00 GMT.

Kohnen and Dome Fuji, with the wind direction having shifted to north-westerly and westerly, respectively.

Figure 6 presents the forecasts of AMPS 12-h accumulated precipitation for 22–25 February 2003, 00:00–12:00 UTC. On 22 February 2003 (Fig. 6a), an area of heavy precipitation is situated west of Neumayer Station: it reaches as far south as about 80°S. On the following day (Fig. 6b), the precipitation has intensified, and the precipitation area has moved south and slightly east, now bringing accumulation to both Neumayer and Kohnen stations. On 24 February 2003 (Fig. 6c), the heaviest precipitation can be seen at Neumayer Station and south of it, whereas around Kohnen Station a secondary maximum is found; further south the precipitation increases again. Between the coast and Kohnen Station, a north-westerly flow means orographic lifting and cooling of the moist air masses, whereas beyond Kohnen Station the flow is almost parallel with the isohypses of the terrain. Later, when the flow changes to westerly to south-westerly to southerly, it moves slightly upslope again towards Dome Fuji, where precipitation is seen for the first time on this day. For 25 February 2003 (Fig. 6d), the main precipitation has passed Neumayer Station. The area around Kohnen Station shows precipitation that reaches south only to about 77°S, whereas south-west of this field almost no precipitation is seen. Dome Fuji is still receiving weak precipitation in this period. This is one of only three cases in the entire period 2001–06 for which the synoptic situation described here caused precipitation not only at Kohnen Station but also at Dome Fuji. Usually Dome Fuji is influenced by blocking situations situated further east, rather than by cyclogenesis above the Weddell Sea (although the two are not necessarily independent).

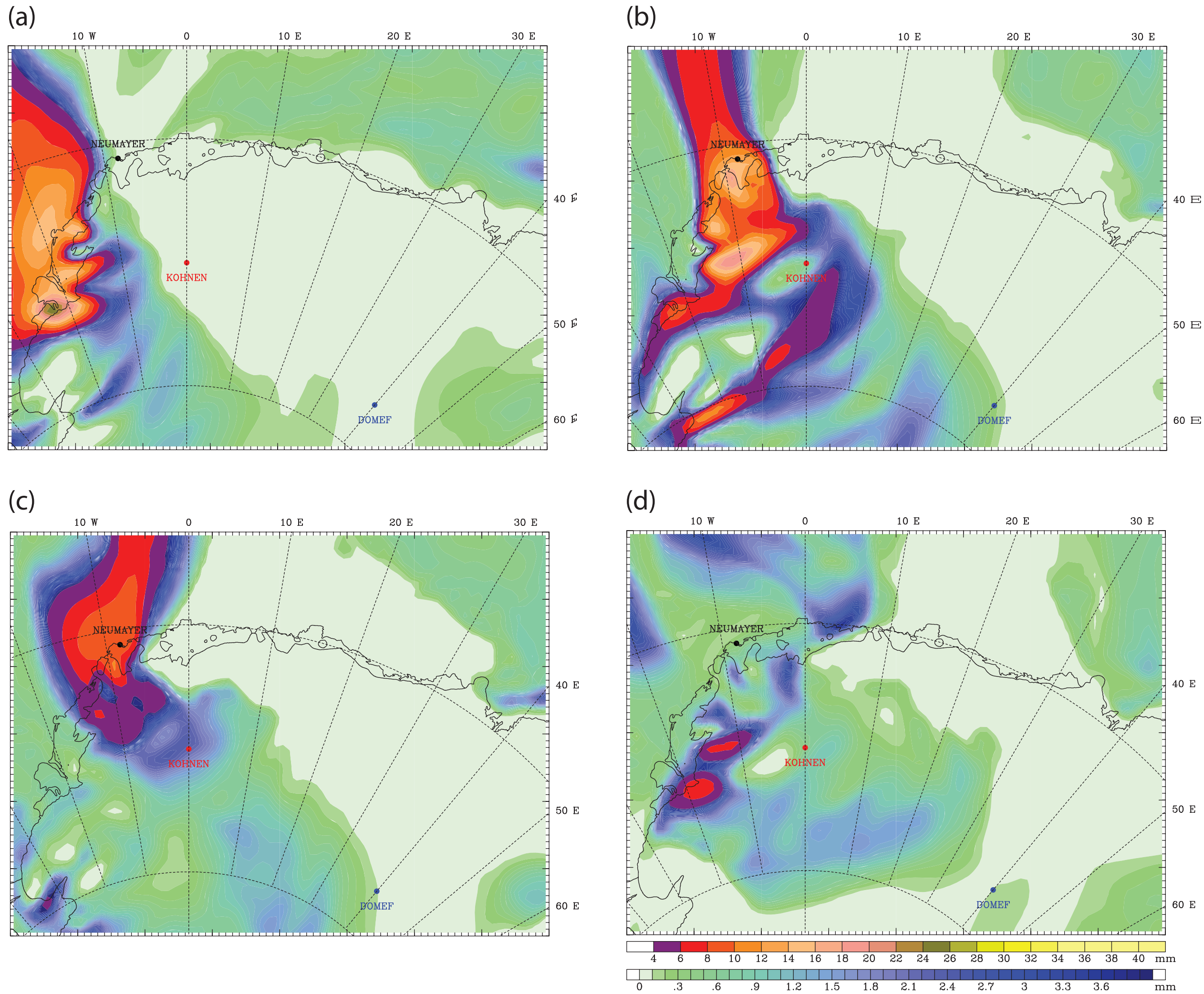

Fig. 6 Antarctic Mesoscale Prediction System precipitation for (a) 22 February 2003, (b) 23 February 2003, (c) 24 February 2003 and (d) 25 Febuary 2003; 12:00 GMT.

In Fig. 7, infrared satellite composites of Antarctica are shown for 23–24 February 2003 (Lazzara et al. 2003). The cloud band associated with the precipitation at 00:00 UTC on 23 February 2003 can be seen above western coastal DML in Fig. 7a. By 00:00 UTC on 24 February 2003 it has moved eastwards (Fig. 7b), whereas at 15:00 UTC on 24 February 2003 (Fig. 7c) only less-pronounced cloud formations remain above DML.

Figure 8 presents the AMPS surface temperatures for the dates/times shown in Figs. 3 and 4. Figure 8a shows a relatively undisturbed spatial temperature distribution, with coastal temperatures around 0°C and increasing temperatures towards the interior, more or less reflecting the topography. In Fig. 8b the Kohnen temperature has considerably increased, whereas at Dome Fuji only a slight increase is observed. Figure 8c,d shows warm air progressively intruding from west to east and from north to south: the levels of temperature change are discussed below in relation to Figs. 9–11. Warmer air means higher saturation vapour pressure, thus more potential for precipitation, no matter whether the cause is orographic lifting or radiative cooling.

Figures 9–11 show AMPS surface temperature, surface pressure, surface winds and precipitation for the period 20 February–2 March 2003 for Neumayer Station, Kohnen Station and Dome Fuji. Additionally, for Neumayer Station and Kohnen Station observational data are shown (surface synoptic observations for Neumayer; AWS data for Kohnen). Precipitation data are only shown from AMPS, because accumulation is only measured on a weekly basis at Neumayer, and the snow height changes measured at the AWS cannot be transferred to a

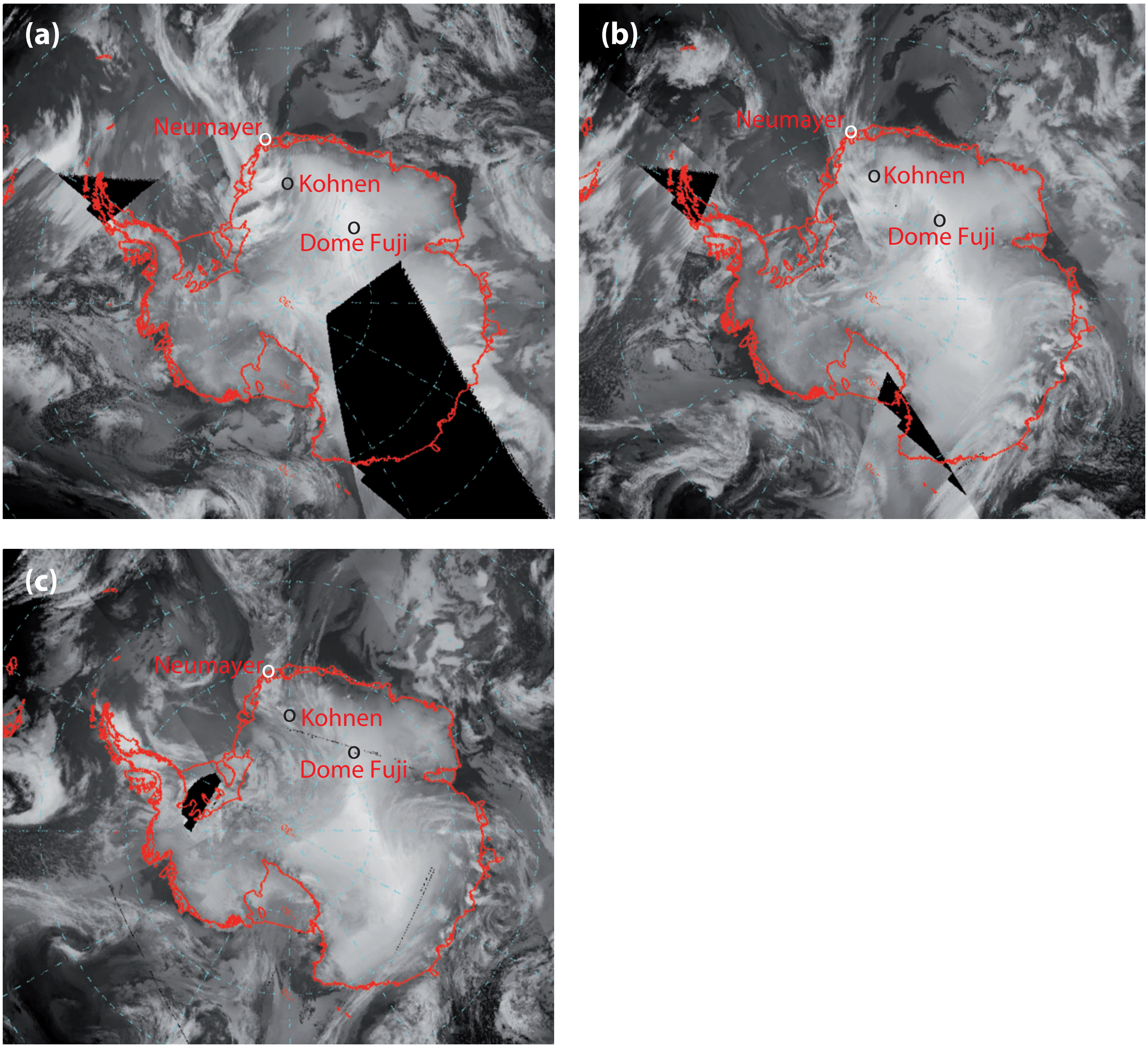

Fig. 7 Infrared composite satellite images for (a) 22 February 2003, (b) 23 February 2003, (c) 24 February 2003 and (d) 25 Febuary 2003, 15:00 GMT.

reasonable precipitation value here because of the strong influence of the wind, which led to both accumulation and erosion during the precipitation event at the measuring site.

At all three stations, both wind speed and temperature increase during the precipitation event. Temperature increases during the period reach about 10°C at Neumayer, 15°C at Kohnen and 20°C at Dome Fuji. Neumayer observational temperatures are about 5–10°C lower than the AMPS temperatures at the beginning of the event, whereas later on the inversion was removed because of high wind speeds, and a fairly good agreement between AMPS and Neumayer observational data is found. At Kohnen Station, the correlation between AMPS and AWS data is very good for surface pressure, fairly good for wind speed and less good for temperature, even though the general course of air temperature during the event is captured well, including the slight cooling on 25 February 2003. Slight differences in the absolute value of surface pressure are caused by differences between the model topography and the real topography. It should be noted that the values from the Polar MM5 in AMPS presented here will often show a warmer near-surface temperature than the observations, because of the lowest model vertical half-level (used here) being at about 14 m above the ground, whereas air

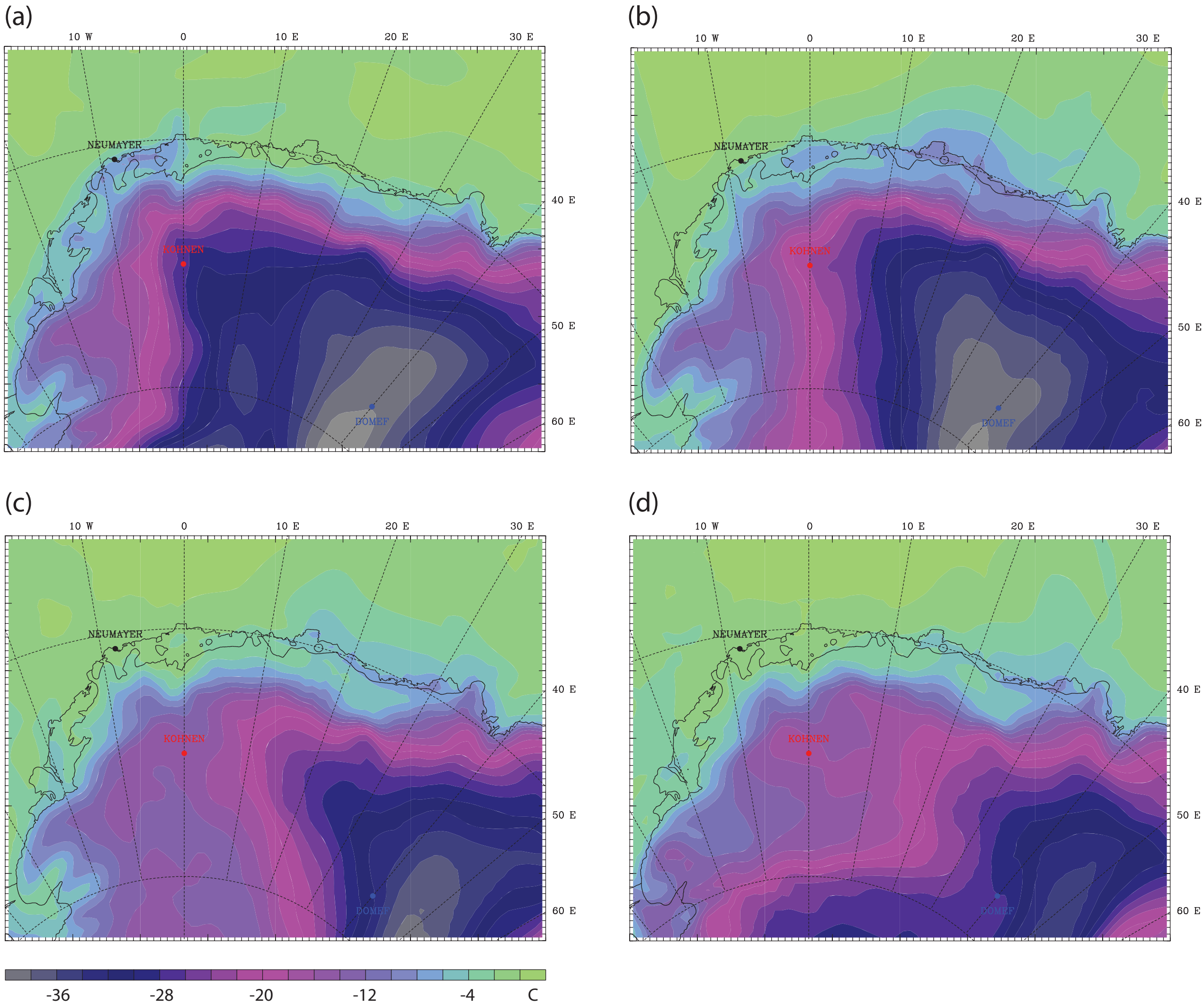

Fig. 8 Antarctic Mesoscale Prediction System surface temperature for (a) 22 February 2003, (b) 23 February 2003, (c) 24 February 2003 and (d) 25 Febuary 2003; 12:00 GMT.

temperatures are usually measured at a height of 2–3 m. This can mean differences result from the strong surface temperature inversions commonly present. Thus, the real temperature increase near the surface is most likely to be even higher in the entire DML, as is shown here for the two stations. It can also be considerably higher in winter (June/July/August), when the surface inversion is stronger. On 27 February 2003, temperatures began to fall, and the temperature inversion was re-established. The surface pressure shows no decrease at Kohnen Station and Dome Fuji, as the precipitation is not connected to frontal system passage. At Neumayer Station, a pressure fall in the forecast is seen on 24 February 2003 in both model and observational data. At all three locations, the surface pressure increases at the beginning of the precipitation event (from 21 to 22 February 2003), and remains relatively high for several days thereafter. Neumayer surface synoptic observations show heavy snowfall at noon on the 23rd, decreasing to light snowfall at 12:00 UTC on the 24th, and then increasing to moderate snowfall again on the 25th, which is forecast well by the model.

The further development of the synoptic situation is presented in Fig. 12, which shows the 500-hPa geopotential height for 26 February, 28 February and 2 March 2003, together with the 12-h precipitation levels for the periods beginning at these times. On 26 February 2003 (Fig. 12a), an upper-level low centred at approximately 55°S, 0°E, has developed, and the corresponding surface low has a central pressure of 975 hPa (not shown).

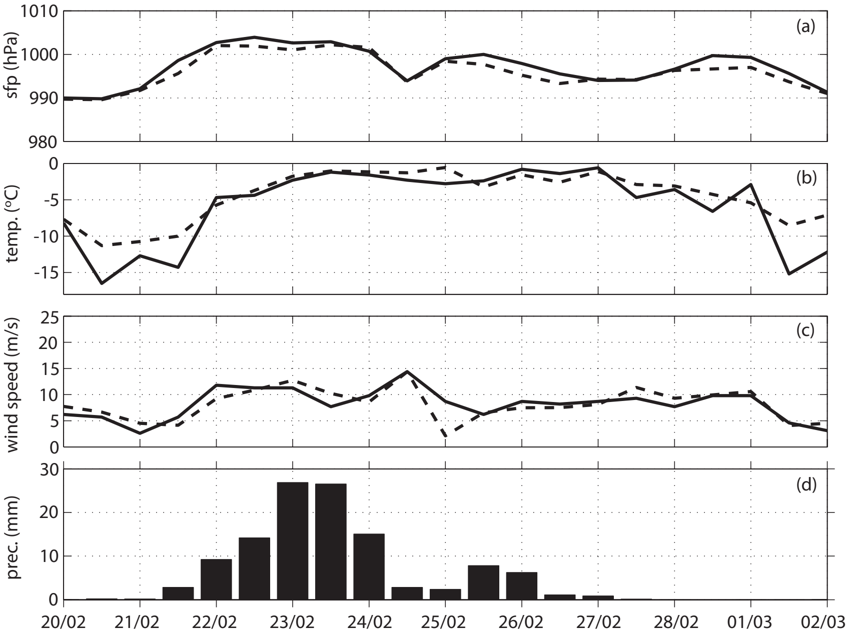

Fig. 9 (a) Surface pressure, (b) surface temperature, (c) surface winds from Antarctic Mesoscale Prediction System (dashed line) and surface synoptic observations (solid line) data, and (d) Antarctic Mesoscale Prediction System daily precipitation for Neumayer Station, from 20 February to 12 March 2003.

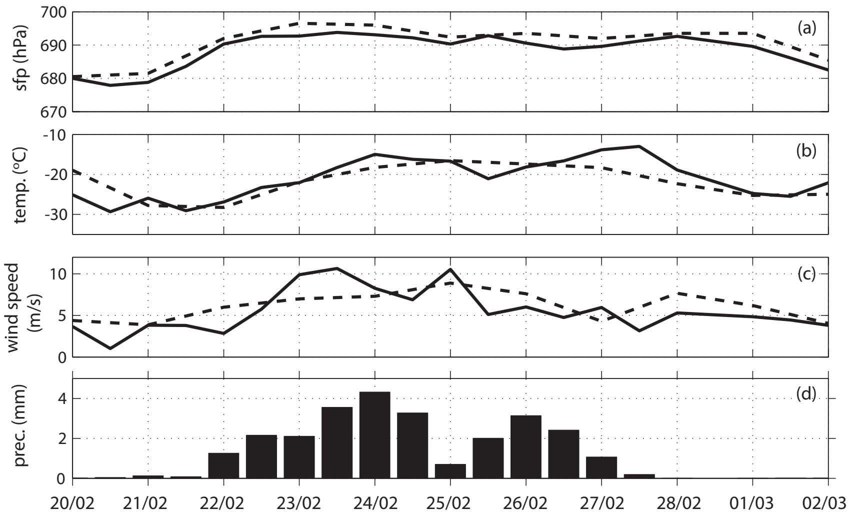

Fig. 10 (a) Surface pressure, (b) surface temperature, (c) surface winds from Antarctic Mesoscale Prediction System (dashed line) and automatic weather station (solid line) data, and (d) Antarctic Mesoscale Prediction System daily precipitation for Kohnen Station, from 20 February to 12 March 2003.

The axis of the upper-level ridge has shifted to a north-easterly–south-westerly orientation. The main precipitation area is still over Neumayer and Kohnen, whereas a lighter precipitation area is situated south of a line from Kohnen to Dome Fuji. On 28 February 2003 (Fig. 12b), the upper-level ridge has become a cut-off high, and thus the continent is isolated from the moist north-westerly flow. The zonal westerly flow started to become re-established at about 60°S. The precipitation area is restricted to a region around 80°S, with Dome Fuji on its north-eastern edge. On 2 March 2003 (Fig. 12c), the zonal flow was re-established, and no further precipitation was observed in DML.

Discussion and conclusions

Intrusions of heat and moisture deep into the interior of the Antarctic continent had been undetected for a long time, mainly because of the scarcity of weather stations, the difficulty of resolving these features in numerical models and difficulties in distinguishing cloud signatures associated with these events from the underlying snow/ice surface, because of similarities in their optical and thermal signatures. The snowfall period during the last week of February 2003 was an event that stood out in the 2001–06 AMPS precipitation forecasts for DML discussed in Schlosser et al. (2008). However, as has been seen in a

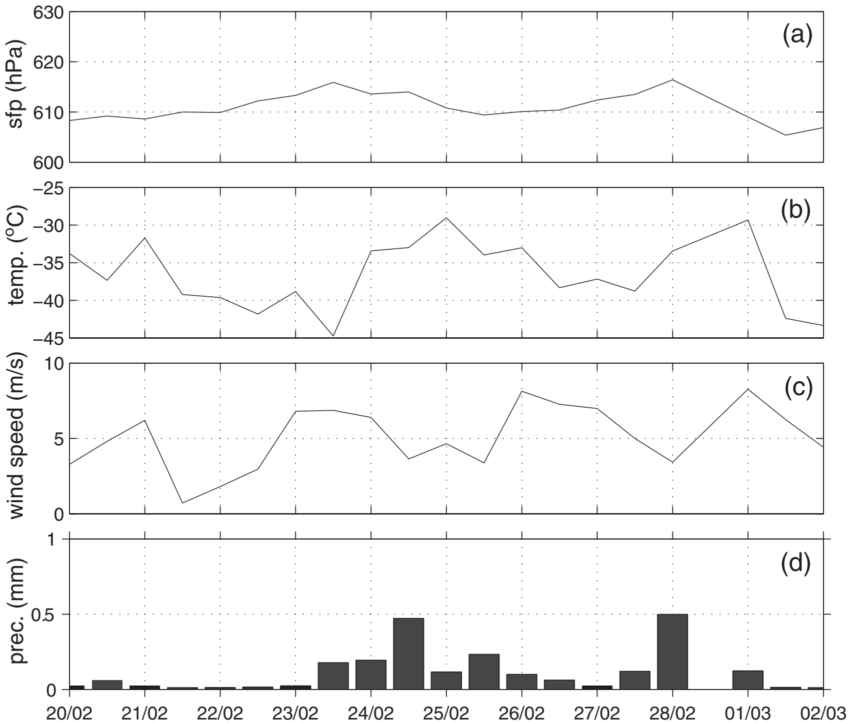

Fig. 11 Antarctic Mesoscale Prediction System (a) surface pressure, (b) surface temperature, (c) surface winds and (d) daily precipitation for Dome Fuji, from 20 February to 12 March 2003.

couple of earlier studies (Reijmer & van den Broeke 2003; Schlosser et al. 2008), such high-precipitation events influencing the interior of the Antarctic continent occur several times per year, and bring a large percentage of the total annual accumulation of the region. Whereas different synoptic situations can lead to those events (Birnbaum et al. 2006), the synoptic pattern described in this study, with a strong north-westerly flow at the western boundary of a blocking high, is the most effective mechanism for yielding large levels of precipitation at high-latitude/high-elevation Antarctic ice-core drilling sites, as it entails the advection of warm, humid air masses from lower-latitude oceanic regions. Such amplifications of the long atmospheric waves are usually observed during the negative phase of the Southern Annular Mode (Marshall 2003), which in turn is linked to the El Niño–Southern Oscillation variability (e.g., Turner 2004). First attempts have already been made to investigate the relationship between the El Niño–Southern Oscillation and stable isotope records in Antarctic ice cores (Divine et al. 2009). Our understanding of the complex relationship between Antarctic climate and the role of the El Niño–Southern Oscillation is still incomplete because of the non-linearity and complex nature of this relationship. However, ice cores may be helpful to improve our understanding of the teleconnections in the Southern Hemisphere; on the other hand, information about Southern Annular Mode trends and seasonality from other sources may be helpful for correct ice-core interpretation.

Further research is needed to increase our knowledge of seasonal and interannual changes of blocking highs, and related precipitation events, in Antarctica. Possible changes in the frequency and/or seasonality could significantly influence Antarctic precipitation/accumulation, and thus the mass balance of the continent. The possibility of a higher frequency of such events because of less sea ice in a warmer climate (Simmonds & Wu 1993), combined with higher moisture contents caused by higher surface temperatures, might enhance the role of Antarctica in mitigating sea-level rise. This, however, cannot be quantified without more thorough investigations combined with climate modelling.

For the correct climatic interpretation of ice cores it is desirable to have information about the seasonality of such events in former climates, during both glacial periods and warm periods. This is especially true during the warm periods before 400 000 years B.P., which were cooler and lasted longer than the warm periods in the following 400 000 years (EPICA community members 2004). Seasonality of precipitation and/or its changes on different time scales can lead to strong bias in parameters derived from ice cores. Efforts have been made to take precipitation seasonality into account (Masson-Delmotte et al. 2005) by combining results from palaeoclimate models with data from Greenlandic ice cores and marine

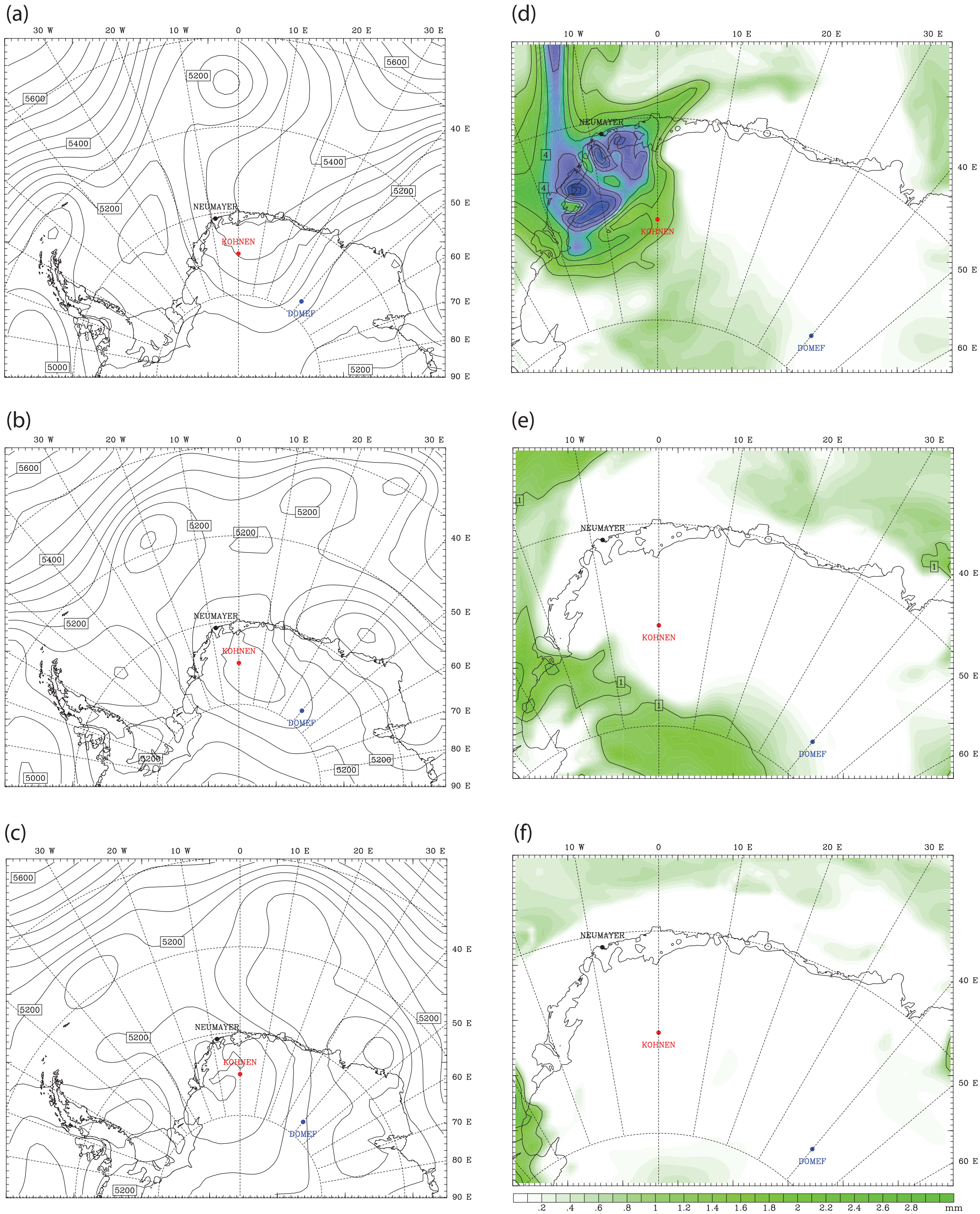

Fig. 12 Antarctic Mesoscale Prediction System 500-hPa geopotential height for 26 February at 12:00 GMT, 28 February at 12:00 GMT and 2 March 00:00 GMT, and Antarctic Mesoscale Prediction System 12-h precipitation sums for the corresponding 12-h time intervals following the dates above.

benthic isotope data, relating circulation patterns to the presence and size of the Laurentide Ice Sheet. However, correcting the effects of precipitation seasonality for ice-core properties remains a complex problem, one not yet solved for Antarctica.

Apart from precipitation seasonality, the observed increase in near-surface wind speed and temperature during high-precipitation events in interior high-elevation Antarctic areas must be taken into consideration for ice-core interpretation, as the removal of the otherwise prevailing surface-based temperature inversion leads to temperatures that are atypically high. The synoptic/mesoscale flow patterns, namely the advection of moist air from relatively low latitudes (30–50°S), also have consequences for the transport and deposition of aerosols and chemical species measured in ice cores. It is suggested that previous common assumptions underlying aspects of ice-core analysis should be revisited in the context of the study and use of cores from DML.

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