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Eastern Antarctic Peninsula precipitation delivery mechanisms: process studies and back trajectory evaluation

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Abstract

The atmospheric circulation patterns that result in precipitation events at a site on the eastern Antarctic Peninsula (AP) are investigated using back trajectories (BTs) driven by ERA-40 data. Moisture delivery occurs from the east and west depending on the location of blocking events in the South Atlantic and Pacific Oceans. Observations are sparse in this region, so our process studies compare the trajectories (and the ERA-40 fields from which they were derived) with advanced very high resolution radiometer (AVHRR) satellite images. It is found that the trajectories represent these transport mechanisms very well and that they are relatively insensitive to the initial trajectory elevation. Copyright © 2008 Royal Meteorological Society

Keywords: **moisture transport; ERA-40; Dolleman Island**

1. Introduction

The atmospheric circulation patterns that deliver precipitation to the eastern Antarctic Peninsula (AP) have been examined only recently in any depth; Russell *et al*. (2004, 2006) have performed a cluster analysis on back trajectories (BTs) for an eastern AP site (Dolleman Island, hereafter DI, 70.3 °S, 60.5 °W) to classify climatological precipitation delivery mechanisms. Unusually, for a coastal Antarctic site, which tend to be dominated by circumpolar westerlies (Simmonds *et al*. 2005), DI receives precipitation from the east fairly regularly (∼43% of events). This ratio is strongly dependant on the phase/strength of ENSO and Southern Hemisphere annular mode (SAM), which determine the propagation of high-pressure anomalies to the high southern latitudes and the strength/location of the circumpolar westerlies, respectively. In this article, we examine individual events from the clusters identified by Russell *et al*. (2006) in order to understand these precipitation delivery mechanisms in more depth. Such a study will also help in the effort to understand the factors controlling the composition of Antarctic surface snow (Masson-Delmotte *et al*. 2008).

Several BT analyses have been used in many meteorological investigations to determine the origin of atmospheric air parcels. They are particularly useful in the southern high latitudes where observations are sparse and re-analyses and derived products, such as BTs, are invaluable. For example, Harris (1992); Reijmer *et al*. (2002) and Simmonds *et al*. (2003) have all used BTs to identify the source of precipitation at a number of Antarctic sites. However, the assessment of BT models and their output is relatively limited in the scientific literature. Pickering *et al*. (1996) have demonstrated that BT model input data can be more important, with respect to trajectory reliability, than the model itself. More generally, Stohl (1998) reviewed works using trajectory analyses and the different trajectory models themselves, including their structure, sources of error and different calculation techniques. One of his most important conclusions, which was expanded upon by Stohl and Seibert (1998), was that three-dimensional trajectory models are more accurate than other methods (e.g. isentropic or isobaric). Specific Northern Hemisphere mid-latitude cases have been assessed by Baumann and Stohl (1997), Stohl *et al*. (2001) and Riddle *et al*. (2006), who used altitude-controlled balloons released from the eastern United States and, of particular relevance here, found that the modelled trajectories were sensitive to the presence of a narrow jet, but no such assessment has been performed for the high southern latitudes. Our second aim, therefore, is to add to these studies by presenting a qualitative assessment of BTs for their representation of the precipitation delivery mechanisms to DI.

2. Data and methodology

The trajectory model used was provided by the British Atmospheric Data Centre (www.badc.rl.ac.uk). This derives three-dimensional air parcel paths from six hourly ECMWF re-analysis data (ERA-40) wind components (u, v, $omega$) held on a $2.5° \times 2.5°$ latitude–longitude grid. This choice of input data was deemed best, as ERA-40 has been shown to be particularly skilful in this region compared to other re-analyses in the post-satellite era (Bromwich *et al.*, 2007). The model used a parcel advection scheme summarised by Dritschel (1989) and Norton (1994). The vertical component of the trajectory is linearly interpolated between the pressure levels of ERA-40, which decrease in resolution with increasing height. The BTs were initiated from 850 hPa at 1200 UTC from DI and data was output at six hourly intervals for 5 days before the precipitation event. The initial level choice of 850 hPa is discussed further.

Advanced very high resolution radiometer (AVHRR) satellite infrared (IR) imagery is used to understand the circulation characteristics and validate the trajectories. The images, which were taken by instruments on the NOAA weather satellites, have been archived at Rothera (67.6 °S, 68.1 °W) since mid-1993. These polar orbiting satellites make around 14 orbits per day and data is downloaded when a satellite passes within a 3000-km radius of Rothera, which is a very well located collection point, given the location of DI. The images archived are sporadic, both temporally and spatially, but are frequent enough to be of significant use. This IR imagery is particularly powerful in presenting cloud formations and height: high (low) cloud is generally cold (warm) and appears brightest (darkest) on the images.

In the following sections, we present case studies for five of the seven BT patterns (two easterly; one northerly; four westerly) associated with the significant precipitation events (i.e. greater than 3.6 mm day^{-1}), as identified by Russell *et al.* (2006) using daily ERA-40 precipitation fields, which are calculated as a forecast for a 24-h period (00-00 UTC) in the model. The reliability of the ERA-40 precipitation data is an issue as there is very limited data with which to verify it. However, it is relatively well-correlated with the DI ice core accumulation (Russell *et al.* 2004) and there is no better alternative. The precipitation events chosen for these studies were included because of the availability and quality of the AVHRR images. These cases have been shown to be representative of the circulation characteristics in further investigations by Russell (2005).

Figure 1 gives a preliminary view of the BTs associated with these five significant precipitation events and shows that they are relatively insensitive to initial elevation. With the exception of the blue BTs, which are dealt with later, the patterns are very similar for the initial half of the BTs. After this, they do tend to diverge a little, most likely because of

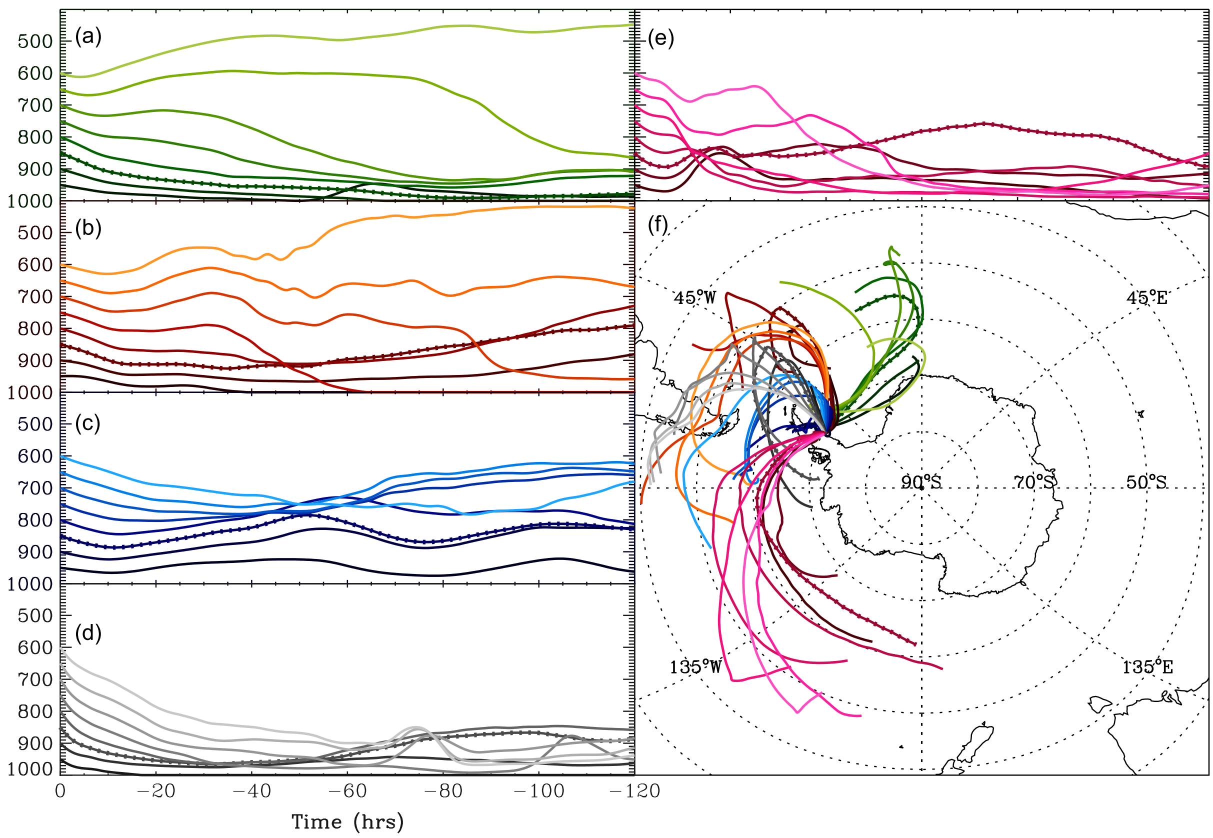

Figure 1. Sensitivity analysis of the BTs to the initial height level. (a–e) show the BT height for the 5 days before BT initiation at 950, 900, 850, 800, 750, 700, 650 and 600 hPa for the five events analysed in Section 3. (f) shows these BTs plotted in plan form with the 850 hPa BT dotted as this is the one analysed in Section 3. The colours [darker shades indicate higher (lower) initial pressure (elevation)] are consistent for (a–e) and (f), i.e. the same colour shows the same BT in plan and profile form.

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the slant of the weather systems with altitude. In this respect, the initial elevation that we choose is not so important, although we do wish to use a level quite close to the surface so that we are tracing the flow of moist air parcels but above the elevation of DI (398 m). However, as we are performing this analysis near to the Peninsula (which is smoothed in the ERA-40 model), it would be best to pick a level that is close to the maximum elevation of the Peninsula in reality (around 1.5 km) as some of the behaviour below this may be unrealistic in the BT model; 850 hPa is a good level to use with this goal in mind. The blue BTs shown in Figure 1(c) represent somewhat a special case, as 850 hPa is still a good initial level to choose but for a different reason. In this case, as shown in Section 3.3, the lowermost BTs move slowly over the AP and develop on the lee side whilst the higher BTs flow around the AP from the north. These are important characteristics of lee cyclogenesis events that sometimes deliver precipitation to DI. By contrast, the BTs that come furthest from the west (Figure 1(e)) travel much faster and can flow over the orography much easier.

3. Case studies of precipitation delivery mechanisms

3.1. Precipitation from the east (Figure 2)

- Date: 3 January 2001
- Precipitation total: 8.7 mm
- Climatological mechanism frequency: 15%
- BT origin: 57.8 °S, 5.7 °W (29 December 2000)
- Other events in this range: 2 January 2001 (5.4 mm) also from E

The mean sea level pressure (MSLP) for 12 UTC 29 December 2000 shows a low of 980 hPa to the north-east of the AP at approximately 58 °S, 45 °W. This is reflected in the AVHRR image with a developing low-pressure system in the same position. The low deepened to 964 hPa on 30 December 2000 and the centre moved east by 5°. The satellite image displays a clear comma-shaped structure associated with this depression. This low drew moisture in from the South Atlantic as a ridge of high pressure pushed southwards at around 5 °W, similar to patterns observed by Noone *et al.* (1999). On 31 December 2000, the low over the Weddell Sea (east of the AP) moved south and further east and remained relatively deep (968 hPa). The ridge remained largely in the same position. The development of the cyclonic system can be seen in the AVHRR images as well as a calm region immediately to the east of the AP, which relates to another tongue of relatively high pressure. The depression deepened to 964 hPa on 1 January 2001 and moved west to about 57 °S, 40 °W. It then appears to have remained largely stationary as a result of blocking extending from the South Atlantic (now 1024 hPa at 35 °S, 10 °E). The BT, MSLP and relative humidity (RH) patterns now indicate that moist air flowed directly to DI from the east. The depression attained its lowest pressure (960 hPa) on 2 January 2001 and moved back east to 60 °S, 10 °W. By 3 January 2001, the low started to fill and dissipate, as reflected in the satellite imagery. Despite this, the system was still established enough to have brought precipitation to DI, as the ERA-40 MSLP and RH data imply.

The BT replicates the flow of moist air seen in the AVHRR images very well. Meteorologically, whilst the low is essential in driving the moisture delivery from the east of the AP, it is the blocking to the east

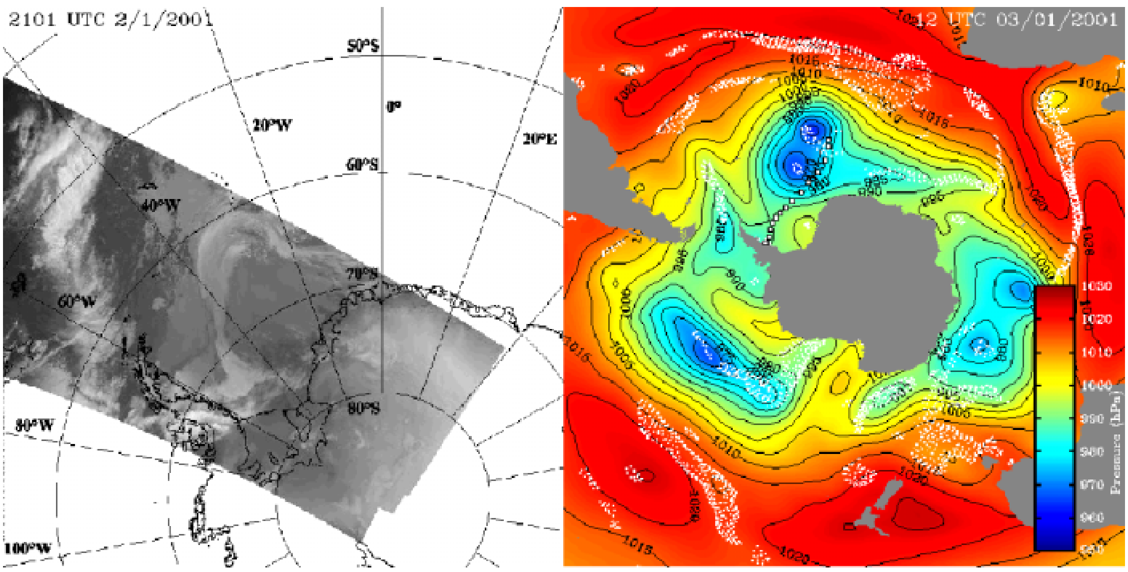

Figure 2. Animation of atmospheric conditions for the 5 days leading to the precipitation event on 3 January 2001. The left panel shows IR images from the AVHRR data at sporadic intervals (between around 6 and 12 h depending on satellite pass time). The shading and contours on the right panel show MSLP (contour interval: 5 hPa) from ERA-40 every 6 h. The right panel also includes regions of high (>95%) relative humidity (RH; white stippling) at 1000 hPa and the BT co-ordinates every 6 h (white squares). The still image shows the final time step of the animation.

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of the Weddell Sea that forces the low and moisture to stall in this region.

3.2. Precipitation from the north-east (Figure 3)

- Date: 12 February 2001
- Precipitation total: 9.7 mm
- Climatological mechanism frequency: 28%
- BT origin: 60.0 °S, 44.7 °W (7 February 2001)
- Other events in this range: 10 February 2001 (6.1 mm) and 11 February 2001 (4.0 mm) both also from NE

There are two features worthy of note on 6 February 2001: firstly, a low (58 °S, 40 °W) over the Weddell Sea; and a second low (62 °S, 110 °W) over the Amundsen–Bellingshausen Sea (west of the AP; hereafter ABS). Both had central pressures of 972 hPa. The eastern-most end of the depression over the ABS, with the cloud patterns resembling a baroclinic leaf (i.e. early development of a comma-shaped cyclone), can be seen in the AVHRR images. Both systems moved east on 7 February 2001, with the Weddell Sea system filling (980 hPa) and the ABS low remaining at 972 hPa. The AVHRR images show that the ABS depression developed a clearly cyclonic structure and there is evidence of calm conditions over the Weddell Sea. On 8 February 2001 the ABS system was deepening (960 hPa) and continuing eastward. The low initially over the Weddell Sea had no further influence over the eastern AP, as the appearance of a ridge of high pressure over the western Weddell Sea prevented this. The calm conditions associated with this high can be appreciated from the nature of the satellite image. The progression of the ridge continued on 9 February 2001, having now reached 1004 hPa as far south as 68 °S. This had an impact on the ABS system, now having filled to 984 hPa, which stopped moving eastward and spread north along the Peninsula. The satellite images show some movement of air towards the northern tip of the Peninsula consistent with the isobars parallel to the Peninsula on its eastern side. The low re-deepened to 972 hPa and moved to the east and north (58 °S, 58 °W) on 10 February 2001, which created a strong east–west pressure gradient from the South Atlantic to the eastern AP. The AVHRR images show high cloud to the north-east of the Peninsula, which had taken on a cyclonic structure. There are also distinctive patterns of shower clouds, indicating the advection of moist air around the depression, which reached 960 hPa on 11 February 2001 and moved east whilst the ridge moved northward by a few degrees. The AVHRR image from 1832 UTC on this day may represent the system at its peak of precipitation delivery to DI as it shows a well-developed cyclone to the north-east of the Peninsula 'pumping' moist air towards DI, as manifest in the MSLP and RH data. On 12 February 2001, the low remained deep (960 hPa) and moved about 5° to the east, as the high pressure retreated north allowing the westerly regime to dominate once more, but the satellite imagery still shows that moist air was being transported from the north-east towards DI.

As with the previous case, this event clearly shows the importance of a low-pressure system and a blocking high to the east to allow the system to remain in the AP region and also shows that the BT model can represent the patterns seen in the AVHRR images very well. The orography and a region of high pressure over the South Pacific also played important roles in slowing the circumpolar flow.

3.3. Precipitation from the north-west (Figure 4)

- Date: 17 January 2001
- Precipitation total: 5.1 mm

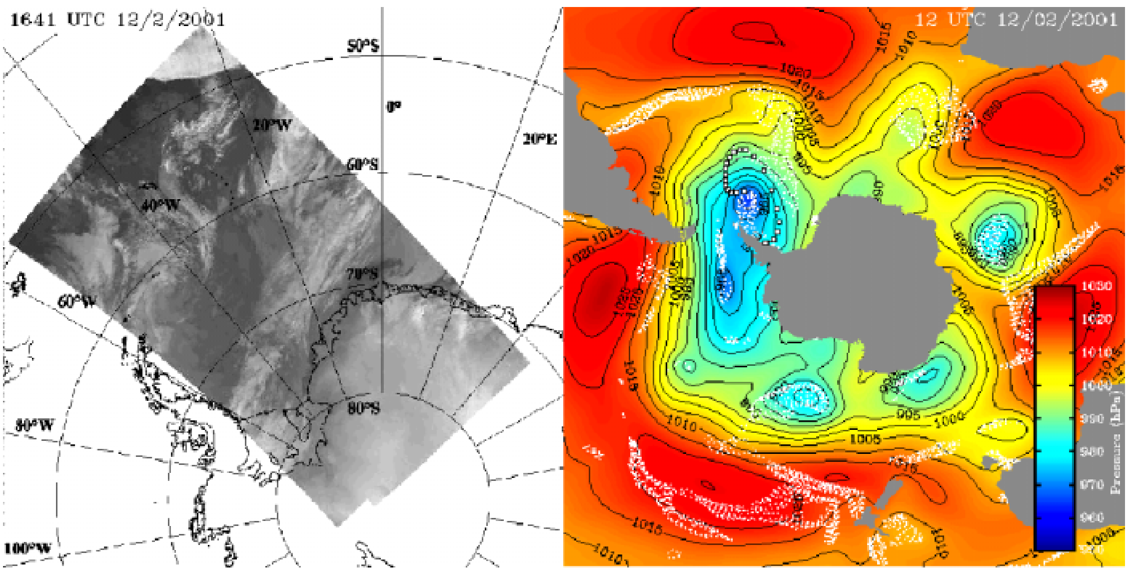

Figure 3. Animation of atmospheric conditions for the 5 days leading to the precipitation event on 12 February 2001. See the caption of Figure 2 for plot details.

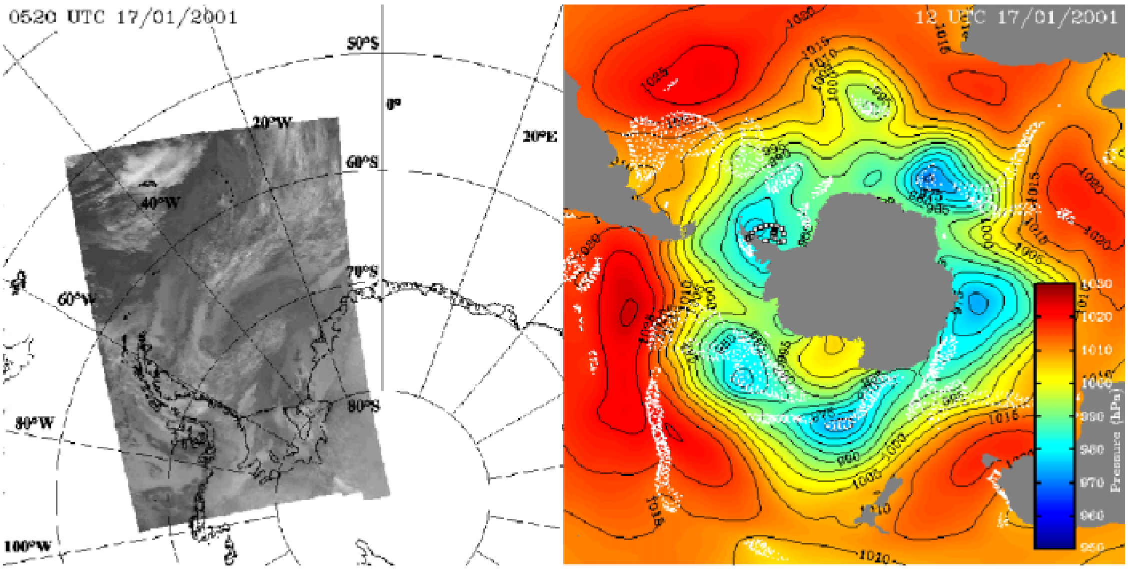

Figure 4. Animation of atmospheric conditions for the 5 days leading to the precipitation event on 17 January 2001. See the caption of Figure 2 for plot details.

- Climatological mechanism frequency: 15%
- BT origin: 66.7 °S, 64.0 °W (12 January 2001)
- Other events in this range: 15 January 2001 (4.9 mm) also from NW

This case focuses on a low of 972 hPa initially (11 January 2001) centred on 62 °S, 120 °W, which continued to move eastwards and fill slowly on 12 to 13 January 2001. On this latter date, the development of a low-pressure centre (984 hPa) can be seen in the lee of the peninsula alongside observations of warm low-level cloud starting to appear on the AVHRR image at the same time. A ridge of high pressure developed over the South Atlantic on 14 January 2001 – this slowed the eastward progression of the low (now at 972 hPa), which in fact moved westward (54 °S, 90 °W). The low pressure in the lee of the Peninsula filled slightly (988 hPa), but the alignment of isobars suggests that air was flowing perpendicularly towards and over the western side of the Peninsula enhancing the lee cyclogenesis – there is evidence in the AVHRR images of a small cyclone in the southern Weddell Sea to support this. The low over the ABS moved east again (60 °S, 70 °W) on 15 January 2001 and the lee side low developed a defined centre of 980 hPa just to the east of the Peninsula. The significant precipitation event on this day is likely to be related to this lee side low and it is an interesting observation, especially as such events are likely to become more common as the SAM index becomes more positive. More importantly, the RH data shows the flow of moisture from the south-east Pacific towards the AP. The lee-side low moved towards the southern Weddell Sea on 16 January 2001 and the low over the Bellingshausen Sea moved east and south to sit over the tip of the Peninsula. The low-pressure centre (now at 976 hPa) moved over the AP towards the Weddell Sea on 17 January 2001, thus, allowing the atmospheric flow to loop around the AP and towards DI as seen in the BT and AVHRR images. The high pressure over the South Pacific again slowed the circumpolar progression of lows influencing the AP region.

3.4. Precipitation from the east and then west (Figure 5)

- Date: 28 November 1998 from E
- Precipitation total: 24.9 mm
- BT origin: 70.4 °S, 37.0 °W (23 November 1998)
- Other events in this range: 29 November 1998 (16.2 mm) and 30 November 1998 (6.2 mm), both from W

This case shows a period, where significant precipitation events are grouped into different classes by Russell *et al.* (2006), which occurred within 2 days of each other. With the AVHRR images, we aim to show whether this is realistic.

In the early stages of this case (23 November 1998), a deep low (960 hPa) was observed at 59 °S, 170 °W. This low moved east on 28 November 1998 (62 °S, 160 °W) and a new low-pressure centre of 976 hPa (63 °S, 100 °W) was also developing/splitting from the eastern-most end of the depression over the ABS. The low-pressure centre furthest west started to dissipate (968 hPa) on 26 November 1998 and the new centre over the ABS (now at 63 °S, 85 °W) deepened to that same pressure. The AVHRR images show that the new low had a well-developed cyclonic structure and was moving towards the Peninsula. It continued to deepen on 27 November 1998 and moved eastwards. The penetration of a blocking high over the Weddell Sea, synonymous with precipitation delivery to the eastern Peninsula, as seen in Sections 3.1 and 3.2, occurred on this day whilst the satellite images show the cyclone starting to cross the Peninsula and the bright-white cloud signature – the high cloud – implies that

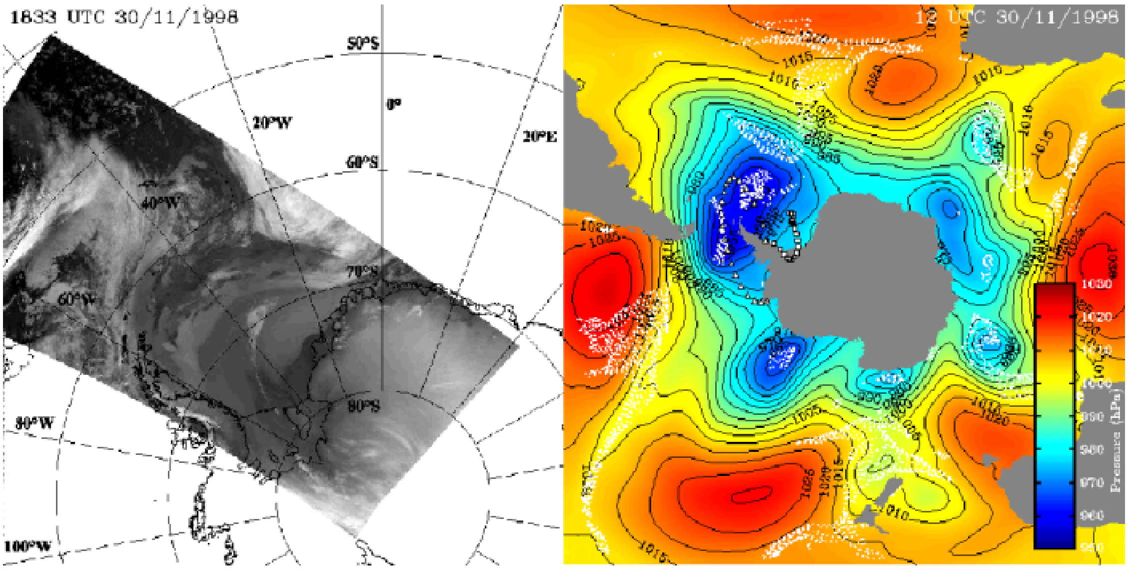

Figure 5. Animation of atmospheric conditions for the 7 days leading to the precipitation events on 28 November 1998 (BT shown in white squares) and 30 November 1998 (BT shown in white triangles). See the caption of Figure 2 for plot details.

the orography of the Peninsula, in turn, started to impact the cyclone and provide conditions for a large precipitation event to occur. On 28 November 1998, the low moved directly over the Peninsula and continued to deepen (956 hPa). The ERA-40 precipitation total for this day was 24.9 mm and, given the combination of the deep low, the blocking high and the orographic forcing, an event of this size is feasible. Indeed, the RH data shows very moist air moving in from the central South Pacific and then down the east coast of the AP. This evidence supports the occurrence of a large precipitation event at DI. However, the BT for this day originates from the southern Weddell Sea, not from the north-west as the RH and AVHRR data show. This contradiction is caused by the low temporal resolution of the precipitation data (24 h), as the large event appears to happen towards the end of 28 November 1998 (see the AVHRR images), it is grouped with the easterly BT of that day, whereas it should have been grouped with the westerlies, which arrive the following day, as described further later. This is an issue with the precipitation data rather than the BTs.

The low moved right across the Peninsula on 29 November 1998 and the accompanying satellite images corroborate this. This led to a precipitation event where the moisture was drawn largely from the north-west of DI, as we discussed earlier, and the flow from the west continued on 30 November 1998.

3.5. Precipitation from the west (Figure 6)

- Date: 2 October 1995
- Precipitation total: 4.4 mm
- Climatological mechanism frequency: 42%
- BT origin: 63.1 °S, 139.6 °W (27 September 1995)

There was a deep cyclone (948 hPa) to the west of DI at 62 °S, 10 °W on 28 September 1995 and there was an unbroken circumpolar flow, including flow through the Drake Passage. This pattern resulted from several low-pressure systems close to the Antarctic continent and some well-defined high-pressure centres further north. The low to the west of the Peninsula advanced south and east to 67 °S, 105 °W and deepened to 944 hPa on 29 September 1995 when it began to span the Peninsula. The AVHRR images show a small but well-defined cyclone to the west of the Peninsula and an interesting formation of very high/cold cloud along the eastern coast driven by the cyclonic flow of air around the low. By 30 September 1995, the depression appeared to have crossed the Peninsula and the centre was over the Weddell Sea with a minimum pressure of 968 hPa. Most of the high cloud and motion of air also appears to be over the Weddell Sea area, as seen in the satellite images. There was still a well-defined circumpolar flow maintained with the presence of low pressure at high latitudes and high pressure over the mid-latitudes. The depressions over the ABS and the Weddell Sea were starting to show less well defined structures by 1 October 1995. Despite this, the satellite imagery shows a cyclonic system to the west of the Peninsula and a clear flow of cumulus from the west to the centre of cyclone. The pattern of circumpolar isobars also remained strong. On the day of the significant precipitation event (2 October 1995), there was evidence of some frontal interaction between the air flowing over the Peninsula and the colder, stationary air over the Weddell Sea. This led to precipitation in the area and some of this was delivered to DI.

In summary, there is a remarkable visible correlation between the orientation of the isobars over the ABS (as also inferred from the AVHRR images) and the BT path. It appears that this precipitation delivery mechanism relies on a strong north-westerly flow of air over the Peninsula to DI.

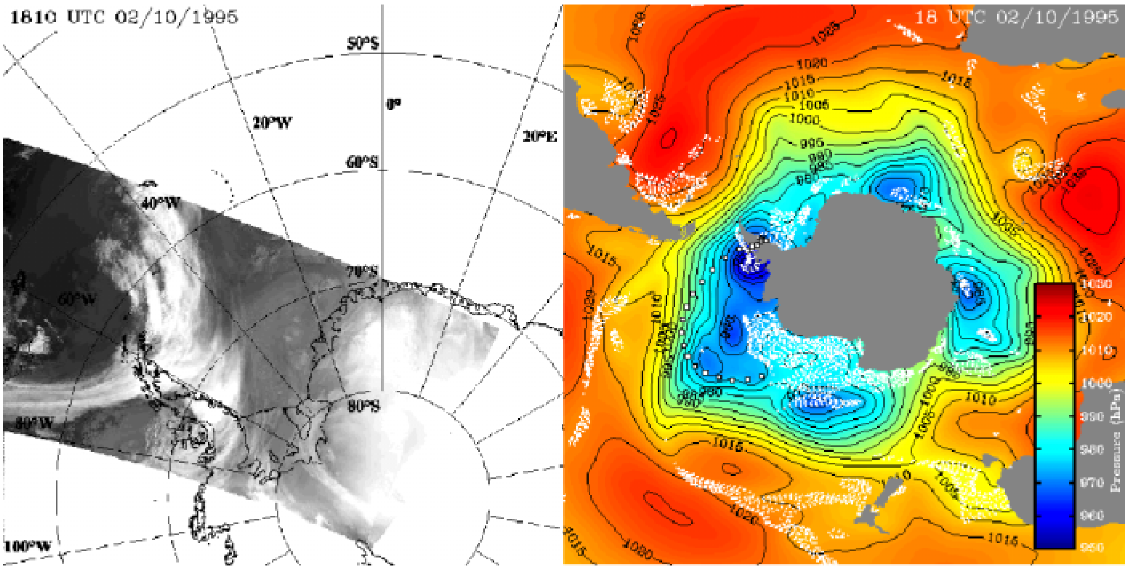

Figure 6. Animation of atmospheric conditions for the 5 days leading to the precipitation event on 2 October 1995. See the caption of Figure 2 for plot details.

4. Conclusions

We have presented a number of process studies of significant precipitation events at an eastern AP site with a view to: assessing the accuracy and sensitivity to the initial level of BTs that were run; identifying the moisture source of the precipitation; and describe the meteorology of this region in more detail. Given the evidence here, we have every reason to recommend the quality of the ERA-40 data and the accuracy of BTs derived therefrom in the post-satellite era examined here. Furthermore, sensitivity studies show that, for BTs initiated near the AP, 850 hPa is a good initial level to allow the BTs to interact realistically with the topography. However, in studies examining precipitation events, the reliability of the precipitation data needs careful consideration.

From a meteorological point of view, the AVHRR images have corroborated the climatological findings of Russell *et al.* (2004, 2006) on an individual case basis (i.e. precipitation events can be forced from the east and west of the site). In particular, the importance of blocking on both sides of the AP was highlighted as well as the orographic barrier of the AP itself, which was only penetrated in one BT class.

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References

Baumann K, Stohl A. 1997. Validation of a long-range trajectory model using gas balloon tracks from the Gordon Bennett Cup 95. *Journal of Applied Meteorology* **36**: 711–720.

Bromwich DH, Fogt RL, Hodges KI, Walsh JE. 2007. A tropospheric assessment of the ERA-40, NCEP, and JRA-25 global reanalyses in the polar regions. *Journal of Geophysical Research* **112**: D10111, DOI:10.1029/2006JD007859.

Dritschel DG. 1989. Contour dynamics and contour surgery: numerical algorithms for extended, high-resolution modelling of vortex dynamics in two-dimensional, inviscid, incompressible flows. *Computer Physics Reports* **10**: 77–146.

Harris JM. 1992. An analysis of 5-day midtropospheric flow patterns for the South Pole: 1985–1989. *Tellus* **44B**: 409–421.

Masson-Delmotte V, Hou S, Ekaykin A, Jouzel J, Aristarain A, Bernardo RT, Bromwich DH, Cattani O, Delmotte M, Falourd S, Frezzotti M, Gallée H, Genoni L, Isaksson E, Landais A, Helsen MM, Hoffmann G, Lopez J, Morgan V, Motoyama H, Noone D, Oerter H, Petit JR, Royer A, Uemura R, Schmidt GA, Schosser E, Simões J, Steig E, Stenni B, Stievenard M, van den Broeke MR, van de Wal RSW, van de Berg WJ, Vimeux F, White JWC. 2008. A review of Antarctic surface snow isotopic composition: observations, atmospheric circulation and isotopic modelling. *Journal of Climate* in press.

Noone D, Turner J, Mulvaney R. 1999. Atmospheric signals and characteristics of accumulation in Dronning Maud Land, Antarctica. *Journal of Geophysical Research* **104**: 19191–19211.

Norton WA. 1994. Breaking Rossby waves in a model stratosphere diagnosed by a vortex-following coordinate system and a technique for advecting material contours. *Journal of the Atmospheric Sciences* **51**: 654–673.

Pickering KE, Thompson AM, McNamara DP, Schoelberg MR, Fuelberg HE, Loring RO Jr, Watson MV, Fakhruzzaman K, Bachmeier AS. 1996. TRACE a trajectory intercomparison. 1. Effects of different input analyses. *Journal of Geophysical Research* **101**(D19): 23903–23925.

Reijmer CH, van den Broeke MR, Scheele MP. 2002. Air parcel trajectories and snowfall related to five deep drilling locations in Antarctica based on the ERA-15 dataset. *Journal of Climate* **15**: 1957–1968.

Riddle EE, Voss PB, Stohl A, Holcomb D, Maczka D, Washburn K, Talbot RW. 2006. Trajectory model validation using newly developed altitude-controlled balloons during the International Consortium for Atmospheric Research on Transport and Transformations 2004 campaign. *Journal of Geophysical Research* **111**: D23S57, DOI:10.1029/2006JD007456.

Russell A. 2005. Southern Hemisphere atmospheric circulation impacts on eastern Antarctic Peninsula precipitation. PhD thesis, University of Birmingham.

Russell A, McGregor GR, Marshall GJ. 2004. An examination of the precipitation delivery mechanisms for Dolleman Island, eastern Antarctic Peninsula. *Tellus* **56A**: 501–513.

Russell A, McGregor GR, Marshall GJ. 2006. 340 years of atmospheric circulation characteristics reconstructed from an eastern Antarctic Peninsula ice core. *Geophysical Research Letters* **33**: L08702, DOI:10.1029/2006GL025899.

Simmonds I, Keay K, Lim E-P. 2003. Synoptic activity in the seas around Antarctica. *Monthly Weather Review* **131**: 272–288.

Simmonds I, Rafter A, Cowan T, Watkins A, Keay K. 2005. Large-scale vertical momentum, kinetic energy and moisture fluxes in the Antarctic sea-ice region. *Boundary-Layer Meteorology* **117**: 149–177.

Stohl A. 1998. Computation, accuracy and applications of trajectories – a review and bibliography. *Atmospheric Environment* **32**: 947–966.

Stohl A, Haimberger L, Scheele MP, Wernli H. 2001. An intercomparison of results from three trajectory models. *Meteorological Applications* **8**: 127–135.

Stohl A, Seibert P. 1998. Accuracy of trajectories as determined from the conservation of meteorological tracers. *Quarterly Journal of the Royal Meteorological Society* **124**: 1465–1484.

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