Lambert Glacier Basin Outflow across the Amery Ice Shelf, East Antarctica

Scott Carpentier
Bureau of Meteorology, Tasmanian and Antarctica Region, GPO box 727 Hobart, Tasmania, 7001, Australia.
e-mail: s.carpentier@bom.gov.au

Abstract

The Lambert Glacier basin (LGB) forms a significant embayment in the Antarctic continent. The shape of the embayment causes cyclonic turning of the winds from the surface up to the middle troposphere (500 hPa). This trough is apparent in all seasons and is connected with the high directional constancy of the wind field across the LGB. Katabatic winds and Coriolis turning cause the coldest air of the LGB to accumulate along the western margin of the Amery Ice shelf (AIS), where the large scale pressure field and barrier wind effects then drive the LGB outflow further northward towards the circumpolar trough. The western AIS outflow is a primary region for the transport of the antarctic atmospheric boundary layer away from the high southern latitudes. A case study is presented where the western AIS outflow is blocked during a period when the large scale pressure gradient is weak in the region, causing cold air to accumulate over the AIS and the surface trough to shift eastward. These events are highly correlated with record cold temperatures at Davis station, located to the near northeast of the AIS.

1. Introduction

Davis station is situated to the near northeast of the Amery Ice shelf within the Lambert Glacier basin, on a westward facing section of coastline (Ingrid Christensen coast) along the shores of Prydz Bay. It's on the seaward side of the Vestfold Hills, a roughly 400 km^2 triangular area of ice free islands and peninsulas, which through summer can reach 2m temperatures extremes of 10 ^{o}C. Fixed wing aircraft accessing Davis station utilise the recently built WoopWoop skiway, located at 550 m above sea level, about 37 km further inland on the permanent ice sheet (Fig.1).

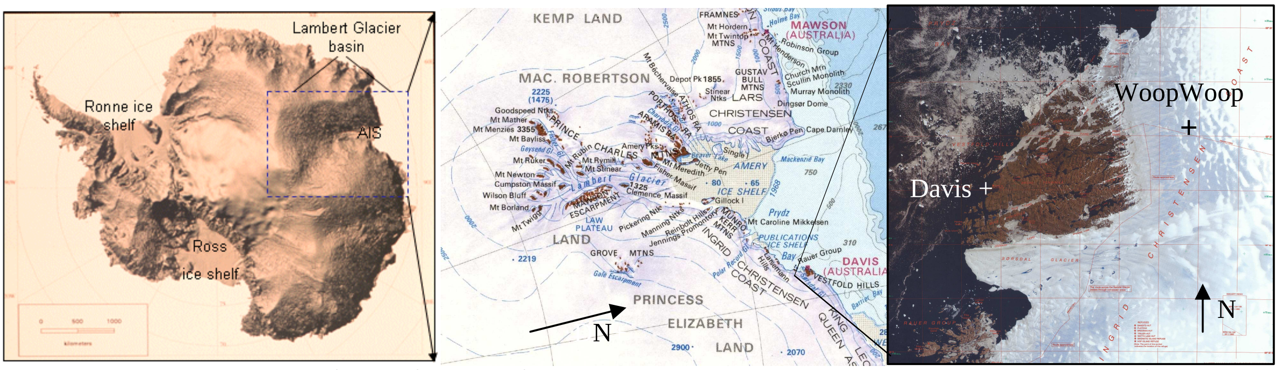


Figure 1. Shaded relief image of Antarctica from United States Geological Survey digital elevation model (DEM) (left). LGB with topographical contours in metres (center). Landsat TM image of Vestfold Hills (right). DEM procured from http://terraweb.wr.usgs.gov/projects/Antarctica/antdemsr.html#nuvu. Centre and right images published by Australian Antarctic Division.

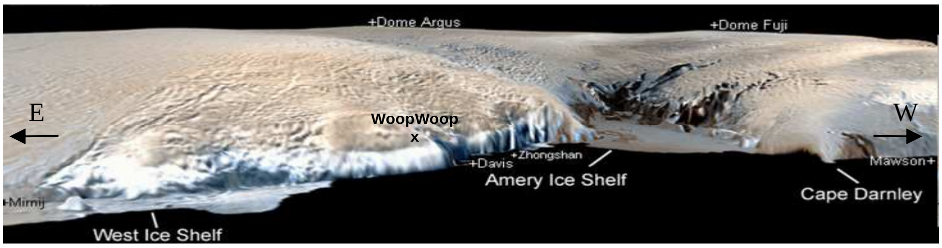
Observations from the automatic weather station at WoopWoop prompted a reassessment of the nature of afternoon onshore winds that develop regularly over the Vestfold Hills in summer. What had been considered a simple sea breeze circulation forced by the contrasting heating rates between Prydz Bay and the adjacent ice free Vestfold Hills is no longer a sufficiently complete explanation, given that even in the absence of synoptic scale forcing, WoopWoop will at times also shift “onshore” in the afternoon.

Using numerical weather prediction (NWP) forecasts from the 27.5 km resolution Australian Antarctic polar-stereographic Limited Area Prediction System (polarLaps, Adams 2006), a case study involving the competing forces from the Ingrid Christensen coast outflow against the more voluminous Lambert Glacier/Prince Charles Mountains outflow is presented. From the case study, a conceptual model is developed that is specific to the unique form of the LGB, but which draws on the earlier concepts developed by Gallee and Schayes (1992); that is “*cold air at rest over an ice covered ocean can generate a pressure gradient force sufficiently large to stop the katabatic flow over the slope*”.

2. Characteristics of the Atmospheric Boundary Layer in the LGB

The main feature of the Antarctic atmospheric boundary layer (ABL), particularly in winter, is a persistent temperature deficit compared to the free atmosphere (Connolley, 1996). Along the sloping ice sheet, this sets up a horizontal pressure gradient force directed downslope, resulting in the katabatic wind. The Coriolis effect deflects the katabatic winds to the left of the topographic fall line, though surface drag maintains a downslope component in a shallow layer below the wind speed maximum (van den Broeke et al. 2002). Using the Antarctic Mesoscale Prediction System (AMPS), Parish and Bromwich (2007) calculated the mean streamlines over Antarctica at approximately 100 m above ground level (AGL) for a 1 year period in 2003-2004 (Fig. 2c). Their work highlights the “drainage” character of the ABL; and in the LGB region, this is characterised by the confluence of cold continental air onto the AIS. Due to Coriolis turning, the bulk of this drainage flow is banked up against the Prince Charles Mountains region along the western AIS, resulting in the generation of a barrier wind. In concert with the large scale pressure gradient force, the barrier wind effect continues to drive the drainage flow northward, until the topographic barrier ceases at Cape Darnley, after which the ABL slumps westward towards the Mawson coast.

The accumulation of cold air along the western AIS is evident in the work of van de Berg et al. (2008). Using the Regional Atmospheric Climate Model RACMO2/ANT, they calculated the average wintertime ABL depth as less than 250 m in the eastern AIS, and greater than 1km in the western AIS (Fig. 2b, reproduced from their Fig. 4b). Their work also illustrates the sharp westward turning of the ABL as it moves past Cape Darnley and slumps into the coastal easterlies, towards the Mawson coast (Fig. 2d, reproduced from their Fig. 8a).



A. Lambert Glacier basin perspective view (expanded in vertical)
from USGS digital elevation model (http://terraweb.wr.usgs.gov/projects/Antarctica/antdemsr.html#nuvu)

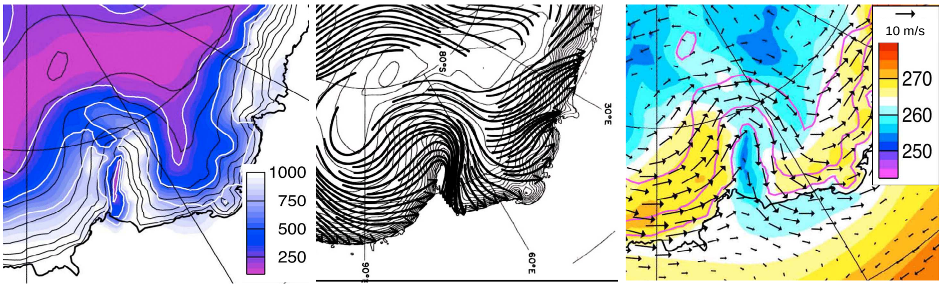


Figure 2

B. Average wintertime ABL depth in m
From fig. 4b of Van de Berg et al 2008

C. Mean streamlines at 100 m AGL
From fig. 3 Parish and Bromwhich, 2007

D. ABL mean potential temperature (K) and wind
From fig. 8a of Van de Berg et al 2008

The LGB is bounded by some of the highest topography in the Antarctic, with its southern ridgeline extending from Dome Fuji at 3810m (average station level pressure (SLP) approximately 592hPa) through Dome Argus at 4093m (average SLP of 574hPa, calculated from SCAR READER database: http://www.antarctica.ac.uk/met/READER). Antarctic orography has been shown to constrain the large scale pressure field in the atmosphere, which establishes a wind regime qualitatively similar to that produced by diabatic cooling of the terrain slopes (van den Broeke et al. 2002, Parish and Cassano, 2003). Thus the surface trough established at the convergence of katabatic winds along the eastern AIS (Figs. 2c and 2d) extends vertically well above the effects of katabatic forcing, sloping to the centre of the embayment with height (an example is shown in the case study section). In winter, a significant trough is apparent over the LGB in 500hPa height contours (for example, see Fig. 5 of van den Broeke and van Lipzig, 2003). In summer, mean 500hPa heights are more zonal over the LGB (see Fig. 14 of van den Broeke and van Lipzig, 2003), though Keable et al. (2002) report a 500 hPa cyclone density maxima over the LGB in all seasons (see their Fig. 2).

The combination of the large scale pressure gradient force and katabatic flow acting in similar directions maintains a high directional constancy of the near surface flow over the LGB (Fig. 3). This results in a near continuous outflow of cold continental air along the western AIS, past Cape Darnley, even in summer when katabatic forcing is weaker and diurnal.

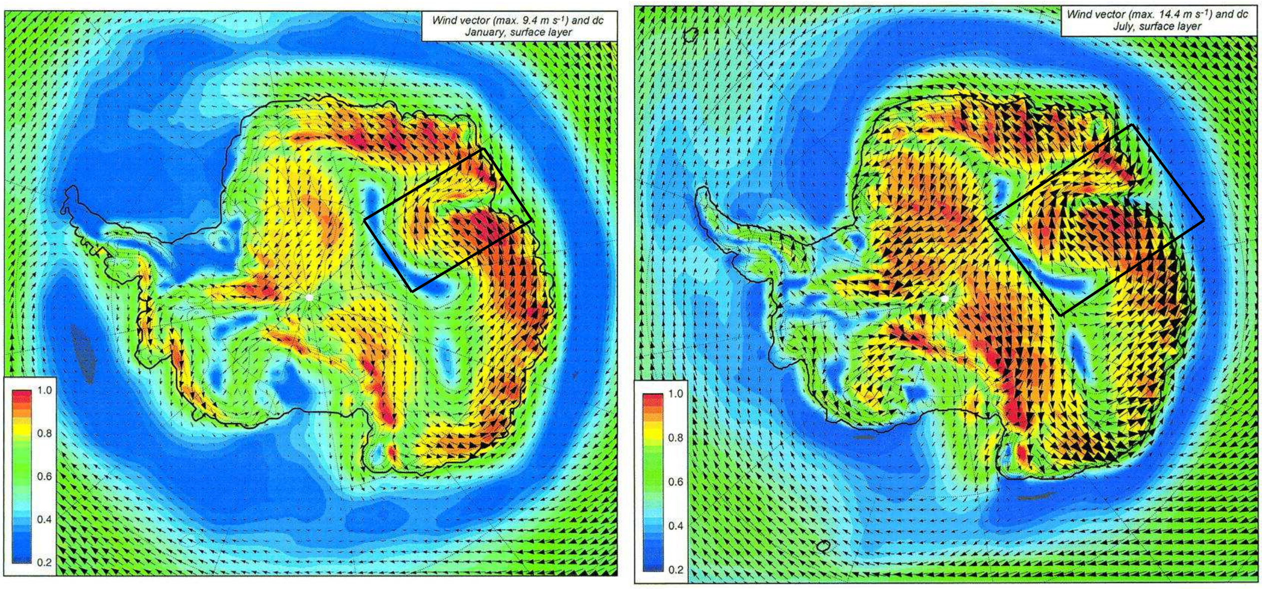
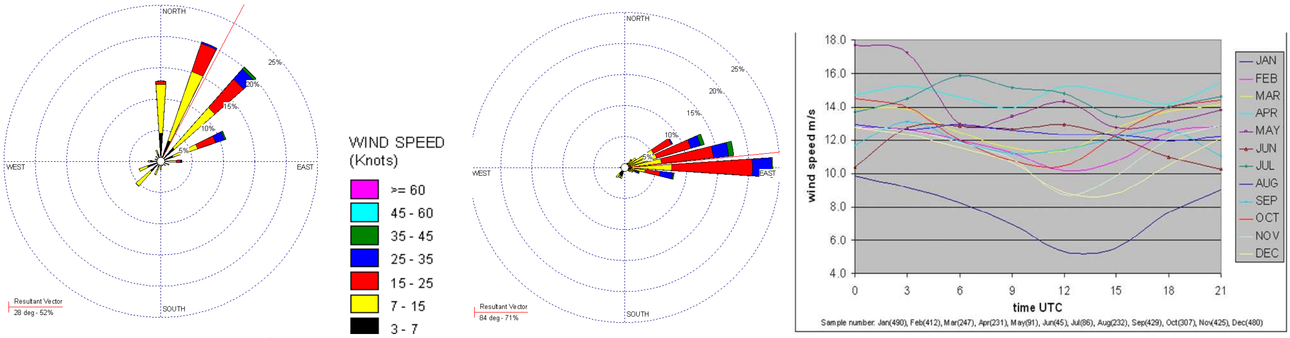


Figure 3. Average January (left) and July (right) RACMO2/ANT surface layer wind vector (arrows) and directional constancy (colors) for the period 1980–93 (reproduced from figures 2 and 13 of van den Broeke and van Lipzig, 2003). Black rectangle represents LGB region.

The Davis and WoopWoop historical 10 m wind roses for January highlight the directional constancy in the region (Fig. 4a-b). Because it is situated on the continental slope, WoopWoop is subject to stronger easterly winds (ie. downslope) due to katabatic forcing. In January, the katabatic regime at WoopWoop is diurnal (Fig. 4c), peaking between 21-03UTC (1am-7am solar time). The easterly katabatic regime is mostly eroded by the Vestfold Hills, so it is not so evident at Davis through summer.

The variation of winds within the northeast quadrant occurs with the passage of synoptic scale systems over the Southern Ocean. The little variation that is shown in direction highlights the ability of the Antarctic orography to constrain the large scale pressure field. Both Davis and WoopWoop wind roses are bi-modal in direction, with an infrequent secondary tendency for southwesterly winds, generally below 15 knots. Given the mild afternoon climate over the Vestfold Hills in summer, it is likely that many of the southwesterly events at Davis occur through the development of a sea breeze circulation. However, a sea breeze would not be expected to reach WoopWoop skiway, situated well up on the permanent ice sheet. It is hypothesised here that in weak katabatic and large scale pressure regimes, the wall of cold air banked up along the western AIS collapses eastward, causing southwest winds to develop at WoopWoop skiway. The eastward advection of cold air should also occur in large scale westerly regimes (ie. strong polar vortex).



a. Davis

b. WoopWoop

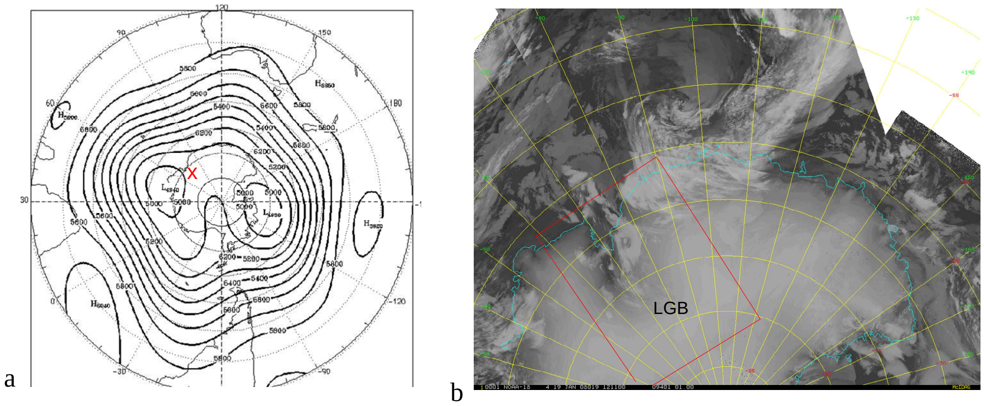
c. Diurnal cycle of winds at WoopWoop

Figure 4. Davis 1957-2009 (left) and WoopWoop skiway 2008-09 (centre) January 10 m wind roses in knots. WoopWoop 2007-2009 (right) average monthly wind speeds (ms^{-1}) through the day (UTC) with sample numbers at bottom of graph showing fewer observations in Winter months.

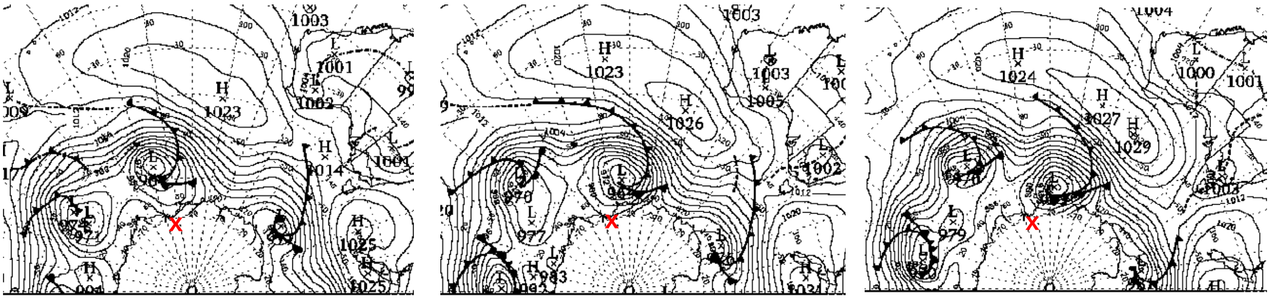
3. Case study: Southwesterly at WoopWoop skiway 18-20th January 2008

During the period 18th-20th January 2008, a long wave trough was located to the near west of the LGB (60°E), directing a series of mature transient low pressure systems onto the Antarctic coast between 80-110°E (Fig. 5).

Figure 5
(a) 500 hPa long wave analysis derived from Global Assimilation Analysis and Prediction model (GASP): x marks the LGB region.
(b) NOAA 18 band 4 image at 19th January 12 UTC



The mean sea level pressure (MSLP) sequence over the period showed a 964 hPa low and associated warm front crashing onto the Antarctic coast near 90°E (Fig. 6). A narrow ridge of high pressure extending from the mid latitudes followed in its wake.



18th Jan 12 UTC

19th Jan 00UTC

19th Jan 12UTC

Figure 6. Australian Bureau of Meteorology MSLP analysis. LGB region marked with red x. 18-19 January, 2008

At WoopWoop skiway, SLP slowly decreased and bottomed out at 18UTC on 19th January, following the onset of a southwest 5 ms^{-1} wind change (Fig. 7).

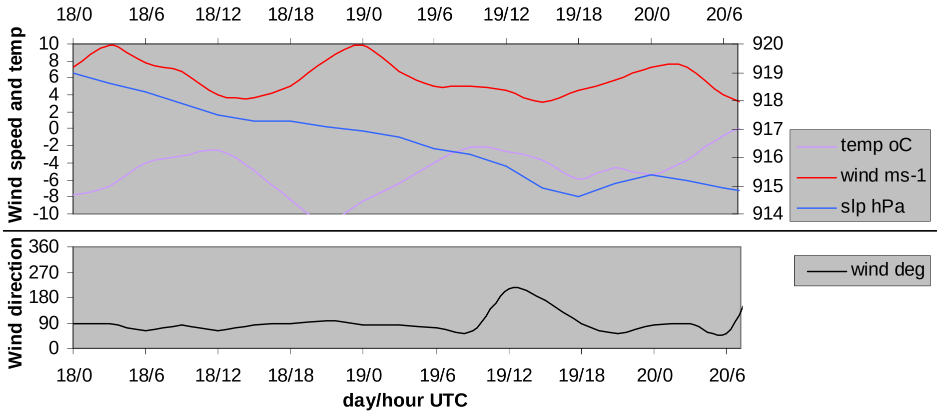


Figure 7.
WoopWoop skiway 3 hourly observations for the period 18-20 January 2008. SLP on secondary y axis.

Radiosonde flights released at Davis over the period showed relatively high moisture and N/NE winds through the troposphere before 12UTC 19th January (Fig. 8 a-c). At 12 UTC on 18th January, a weak westerly was observed at Davis (Fig. 8b), but did not reach WoopWoop (Fig. 7). However, at 12 UTC 19th January (Fig. 8d), the Davis radiosonde flight showed more light and variable winds through the troposphere, associated with a weak large scale pressure gradient, and on this occasion southwest winds developed near the surface at both Davis and WoopWoop (Fig. 7).

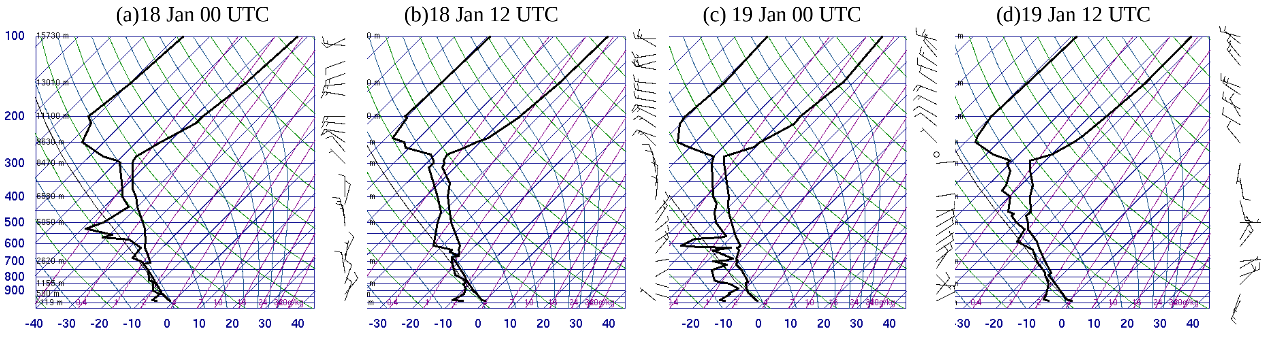

(a)18 Jan 00 UTC (b)18 Jan 12 UTC (c) 19 Jan 00 UTC (d)19 Jan 12 UTC

Figure 8. Davis skew Temp/-log Pressure graphs of wind (knots), temperature (^{o}C) and dew point from sonde flights 18-20th January 2008

A sequence over the same period of west-east cross sections over the northern AIS (along approximately 68.6^{o}S) is shown in figure 9. The top half of these panels shows potential temperature (θ in K) and wind component (knots) along the section. A plan view of the near surface wind and cross section track is shown at the bottom of each panel, stamped with solar time (about UTC +5). The cross sections are developed from polarLaps 27.5 km resolution data (Adams 2009), nested in the National Centre for Environmental Prediction NCEP2 reanalysis (Kalnay et al. 1996).

In Fig. 9a (5pm solar time), a typical outflow regime from the Lambert Glacier and Prince Charles mountains along the western AIS can be seen, with the coldest air banked up against the rising continental slope. At this time (afternoon), the katabatic forcing is negligible and the surface trough extends along the coastline of the eastern AIS, with the trough shifting to the centre of the LGB embayment with height (convergence of winds apparent in top panel).

In Fig. 9b-c it was night time, the depth of cold air (ie. <274 K) had thickened over the AIS and katabatic regimes had developed along both slopes of the embayment. The surface trough was pushed slightly westward and off the east coast by the katabatic winds flowing down from the continental slope along the Ingrid Christensen coast. The sequence so far showed the typical summertime diurnal trend.

In Fig. 9d-e it was daytime and warming of the Ingrid Christensen coast boundary layer was observed. There was little change in the temperature field along the western AIS, possibly due to the continued replenishment of cold air from the Lambert Glacier catchment.

In Fig. 9e-i a westerly change, associated with the approach from the northwest of a high pressure ridge of mid-latitude origin, passes to the north of the embayment. This had the effect of advecting the northwestern AIS outflow eastward . By Fig. 9h, the mid latitude ridge axis lied near the centre of the AIS, causing a weak cyclone to form over the AIS and effectively halting any further release of cold air from the area. Through this period, an accumulation of cold air over the AIS was observed, particularly in the eastern section. Also through this period, the surface trough had shifted eastward and was located near WoopWoop, at the very eastern end of the cross section.

From the case study it can be surmised that the position of the AIS surface trough is dependent on the competing forces from the Ingrid Christensen coast outflow against the more voluminous Lambert Glacier/Prince Charles Mountains outflow. When the western AIS outflow was halted by the passage of a mid latitude ridge, the wall of cold air piled against the western AIS slumped eastward, thereby advecting the surface trough onto the Ingrid Christensen coast. The large scale continental wind, which is mostly constrained by the orography, is also likely to play a role in maintaining the position of the surface trough through downward momentum transfer, particularly when the winds are strong.

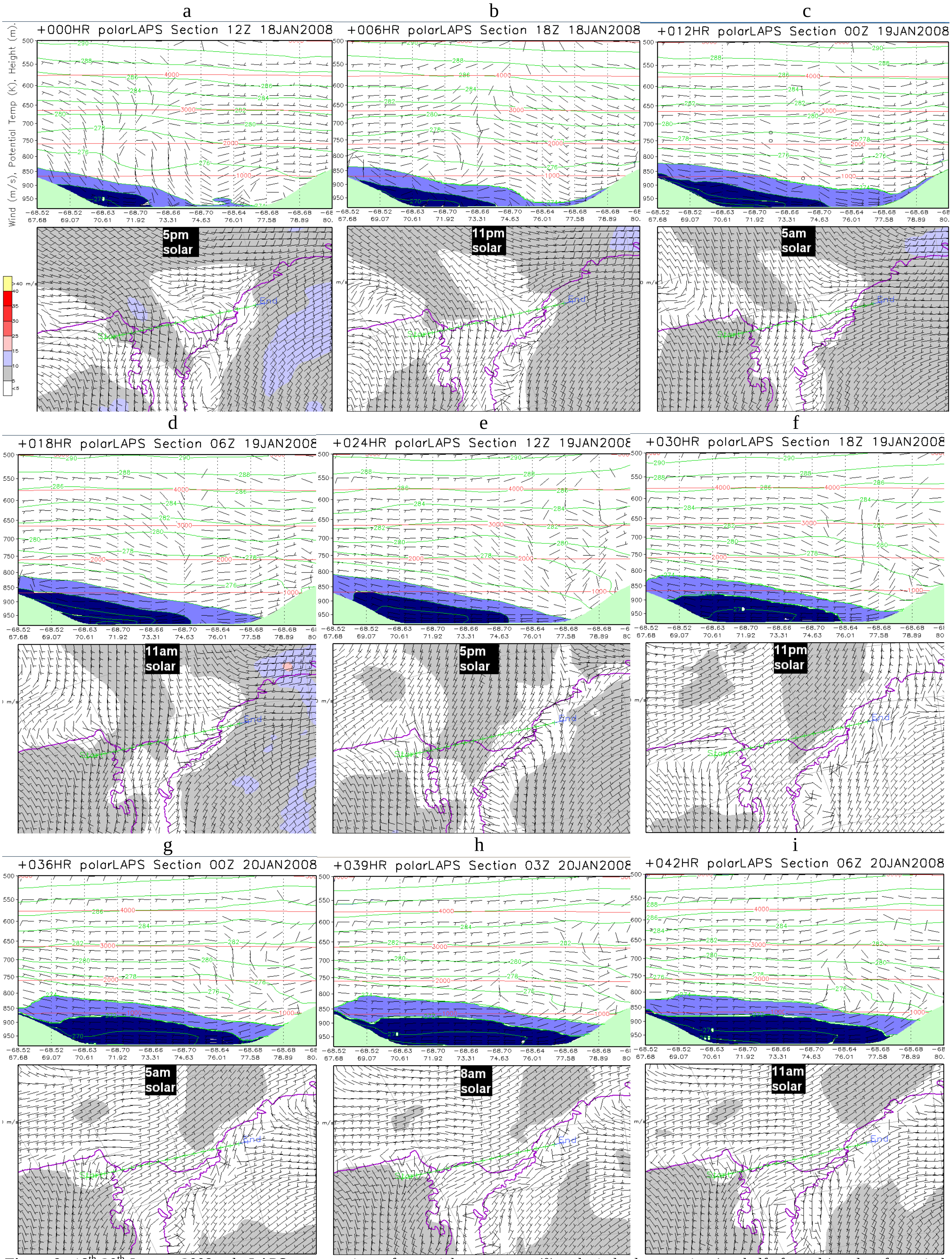


Figure 9. 18th-20th January 2008 polarLAPS cross-sections of potential temperature (θ) and winds along section (top half of panels) and surface winds in plan view (bottom half of panels). Section track is denoted by green line, along approximately 68.6°S. Solar time at the LGB is about +5 UTC. Land is light green. Coastline and edge of the AIS is violet. Dark blue denotes θ < 272 K. Light blue 272k < θ < 274 K. Wind speed scale is on first panel.

4. Discussion on the links between the wind and temperature fields

Parish and Bromwich (2007) calculated the mean meridional mass flux in the lowest 1500m AGL around the Antarctic margin from the June 2003 to May 2004 AMPS archive (Fig. 10, reproduced from their Fig. 8). At 67.5°S, the central axis of the LGB embayment is near 77°E. Their figure highlights how significant the western AIS region is in the transport of the ABL away from the high southern latitudes. Other regions of primary northward mass transport are located at Adelie Land, the eastern side of the Transantarctic Mountains and the eastern side of the Antarctic Peninsula.

Van den Broeke and van Lipzig (2002) investigated how wintertime low level winds and temperatures in East Antarctica respond to variations in the polar vortex. Using output from their regional climate model RACMO/ANT1, they found that when a strong vortex extended far to the south and to relatively low atmospheric levels (ie. positive SAM index), there was a reduction in the strength and directional constancy of the low-level easterlies south of the circumpolar trough, which resulted in reduced meridional air exchange. This had the effect of both reducing the incursion of relatively warmer airmasses of mid latitude origin over the continent and also of weakening subsidence over the continent, thus reducing warming by adiabatic compression.

This case study has demonstrated that a hemispheric wide contraction of the polar vortex is not necessary for inhibiting the outflow of a major Antarctic basin: for the LGB, a narrow ridge of high pressure extending from the mid latitudes was sufficient. However the passage of a narrow ridge may not necessarily affect the average temperatures across the wider East Antarctic expanse. For example, in this case study while there is significant cooling over the LGB there is also strong warm air advection onto the continent between 80-110^{o}E (Fig 5b).

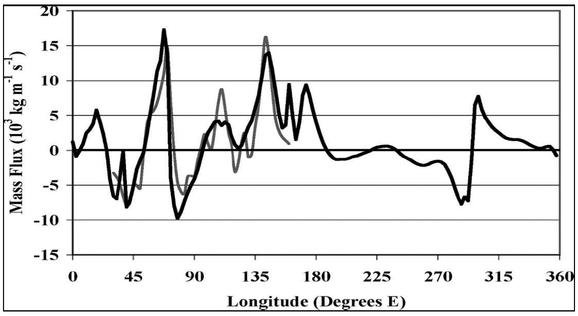


Figure 10.
Mean meridional mass flux (northward is positive) in lowest 1500 m AGL at 67.5°S (thin line) and 70°S (thick line) from the June 2003–May 2004 AMPS archive. At 67.5^{o}S, the LGB embayment is centered near 77^{o}E. (Reproduced from Fig. 5 of Parish and Bromwich 2007).

Preliminary investigations of the 2 coldest temperature events per calendar month across the Davis temperature record (since 1957) suggest little correlation with monthly SAM, Indian Ocean Dipole (IOD) and Southern Oscillation (SOI) indices. This is not surprising as most cold events are of less than a week in duration. However, daily Davis radiosonde profiles and daily southern hemisphere MSLP and 500 hPa geopotential height analyses suggest that record cold events at Davis occur when the wind profile aloft of the station is contrary to the near constant climatological mean: that is the winds are either weak or west to southwesterly, with the latter being characteristic of a strong polar vortex. The majority of these events coincide with deep low pressure/height anomalies located near Dronning Maud to Enderby Land (0-60^{o}E) and at Queen Mary/Wilkes Land (80-120^{o}E), with a high pressure ridge or col located near the AIS. This setup suggests that anomalously cold air over the LGB is draining onto the AIS, with the mid latitude ridge positioned so as to promote an eastward displacement of the AIS surface trough, thereby producing the necessary conditions for record cold temperatures, namely light surface winds and the coldest and driest airmass possible aloft.

Acknowledgments. Thank you Neil Adams for providing polarLAPS data for the case study and for supporting this research in general, it is greatly appreciated.

5. References

Adams N., 2006 Continued Developments in Numerical Weather Prediction and Weather Forecasting in Support of the Australian Antarctic Program The Antarctic Meteorological Observations, Modeling and Forecasting Workshop (Boulder CO., USA) June 13-15 2006

Adams N., 2009 Output from an eleven year climate run of a regional Antarctic Numerical Weather prediction System MOCA-09: IAMAS - IAPSO - IACS Joint Assembly, Montreal, July 19 - 29 2009

Connolley,W. M., 1996. The Antarctic temperature inversion. International Journal of Climatology. **16**, 1333–1342.

Gallee, H. and G. Schayes, 1992. Dynamical aspects of katabatic winds evolution in the Antarctic coastal zone. Boundary Layer Meteorology, **59**, 141-161.

Kalnay E. et al. 1996 Bull. Amer. Meteor. Soc., **77,** 437-70

Keable M., I. Simmonds and K. Keay, 2002. Distribution and temporal variability of 500 hPa cyclone characteristics in the Southern Hemisphere. International Journal of Climatology, **2**, 131-150

Parish T.R and D.H. Bromwich, 2007. Reexamination of the near-surface airflow over the Antarctic Continent and Implications on Atmospheric Circulations at High Southern Latitudes. Monthly Weather Review. **135**. 1961-1973.

Parish T.R. and J.J. Cassano, 2003. The role of katabatic winds on the Antarctic surface wind regime. Monthly Weather Review, **131**, 317-333.

van de Berg, W. J., M.R. van den Broeke and E. van Meijgaard, 2008. Spatial structures in the heat budget of the Antarctic atmospheric boundary layer, The Cryosphere, **2**, 1-12.

van den Broeke M.R. and N.P.M. van Lipzig, 2002. Impact of Polar vortex variability on the wintertime low-level climate of East Antarctica: results of a regional climate model. Tellus, **54A**, 485-496.

van den Broeke, M.R. and N. P. M. van Lipzig, 2003. Factors Controlling the Near-Surface Wind Field in Antarctica. Monthly Weather Review, **131**, 733–743.

van den Broeke M.R., N.P.M. van Lipzig and E. van Meijgaard, 2002. Momentum Budget of the East Antarctic Boundary Layer: results of a regional climate model. Journal of Atmospheric Sciences. **59**. 3117-3129