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A case study of a low level jet during OPALE

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Abstract

A case study of a low level jet during the OPALE (Oxidant Production over Antarctic Land and its Export) summer campaign is presented. It has been observed at Dome C (East Antarctica) and is simulated accurately by the three-dimensional version of the Modèle Atmosphérique Régional (MAR). It is found that this low level jet is not related to an episode of thermal wind, conforting that Dome C may be a place where turbulence on flat terrain can be studied.

1 Introduction

Low Level Jets (LLJs) have been observed and studied for a long time (see e.g., Cuxart and Jimenez, 2006; Banta et al., 2003). Their interest may be related to the need of a better understanding of the atmospheric boundary layer. On one hand they are suspected to generate additional turbulence. On the other hand their behaviour may have an impact among others on the management of wind turbines, birds migration studies. Following Blackadar (1957) and Van de Wiel et al. (2010) LLJs may be due to the onset of an inertial oscillation when the turbulence force suddenly decreases at the end of day-time. In this note we consider a case study of a low level jet happening at Dome C during the night of 16–17 December 2011 (during OPALE campaign) and accurately simulated by MAR. The model has been satisfactorily validated for the OPALE campaign in Gallée et al. (2014, this issue). The objective here is to focus on the driving forces of a LLJ at Dome C.

2 The model

The model used is MAR (Modèle Atmosphérique Régional). It is described and set up as in Gallée et al. (2014, this issue). A summary is given here.

MAR is a hydrostatic primitive equations model using finite differences schemes (Gallée and Schayes, 1994). The terrain following normalized pressure is used to take into account topography. Turbulence is parametrized by using two prognostic equations for turbulent kinetic energy and its dissipation (Duynkerke, 1988; Bintanja, 2000). The prognostic equation of dissipation allows to relate the mixing length to local sources of turbulence and not only to the surface. Finally the relationship between the turbulent diffusion coefficient for momentum and scalars (Prandtl number) is dependant on the Richardson number, according to Sukorianski et al. (2005). An explicit cloud microphysical scheme describes exchanges between water vapor, cloud droplets, cloud ice crystals (concentration and number), snow particles and rain drops (Gallée, 1995).

The horizontal domain covers an area of about 800 km × 800 km surrounding Dome C. The x axis of MAR domain is directed from the south-west to the north-east (see Fig. 1 – see also Fig. 3 for a localisation of Dome C over the Antarctic ice sheet). Horizontal grid size is 20 km. There are 60 levels, with a vertical discretization in the lower troposphere of 2 m. It decreases with altitude above 32 m a.g.l., reaching 50 m at 300 m a.g.l. and 400 m at 3000 m a.g.l.

3 The low level jet

We consider the same experiment as in Gallée et al. (2014, this issue) and the observations which have been performed on a 45 m tower with 6 levels of measurement (Genthon et al., 2010, 2013). The situation of 16–17 December 2011 has been chosen because the model simulates a low level jet at a height where it has been observed. An other case study occurring on 26 December 2011 evening is presented in Gallée et al. (2014, this issue). In that case the model overestimates significantly the height at which the LLJ is observed, mainly because it fails in simulating the surface energy balance during day-time, in conjunction with an underestimation of the cloud cover by the model. In contrast the simulated surface energy balance is much better simulated by MAR on 16 December, when the downward longwave radiation flux (DLW) is only slightly underestimated.

MAR simulation for 16–17 December 2011 is compared with observation on Fig. 2. The low level jet is simulated at 01:00 LT on 17 December at 14 m a.g.l. This height is comparable to that found in the observations (18 ± 4 m) as we have observations at 9, 18 and 25.5 m a.g.l. Both simulation and observation show a strong wind shear beneath the jet and almost no wind shear above. The temperature profiles are similar, with the same evolution of the intensity and depth of the inversion, although the depth is slightly underestimated.

The behaviour of MAR turbulent scheme is discussed in Gallée et al. (2014, this issue) with the conclusion that the underestimation of turbulence may be partly due to the underestimation of DLW, which is responsible for an overestimation of the vertical stability near the surface during night-time.

We now have a look to the general conditions prevailing during this LLJ.

The synoptic scale situation prevailing on 16–17 December in the vicinity of Dome C and illustrated by the 500 hPa geopotential map consists in a low pressure center situated on the Ross ice Shelf, with a secondary minimum on Adélie Land (see Fig. 3 for the situation at 12:00 UT on 16 December). Intensity of both diminishes with time while they remain stationary. Consequently the synoptic scale pressure gradient force is directed from the southwest to the northeast at Dome C while synoptic scale (geostrophic) winds blow from the Antarctic plateau towards Dome C during this period.

Lets now look at the simulation along the slope (x axis) and consider the pressure gradient force (PGF). Rather than representing the norm of the PGF horizontal vector ($\mathrm{PGF}_u, \mathrm{PGF}_v$) we represent the contribution of the PGF to the wind speed intensity (V). This allows us to get more insight into the role of the different forces in accelerating the wind speed at the end of day-time. This contribution may be obtained by multiplying the equations for u and v by u and v respectively and summing them in order to obtain an equation for the local variation of the kinetic energy with time.

We get (see appendix for more details):

$$\frac{\partial V}{\partial t} = \underbrace{\frac{u}{V}\mathrm{ADV}_u + \frac{v}{V}\mathrm{ADV}_v}_{\text{Advection Contribution}} + \underbrace{\frac{u}{V}\mathrm{PGF}_u + \frac{v}{V}\mathrm{PGF}_v}_{\text{PGF Contribution}} + \underbrace{\frac{u}{V}F_u + \frac{v}{V}F_v}_{\text{Turbulence Contribution}} \tag{1}$$

where ADV_u and ADV_v are the contributions from advection to u and v respectively. Similarly F_u and F_v are the contribution from turbulence. Of course the contribution of the Coriolis force to the kinetic energy is zero and so it is the same for the wind speed. Note also that a zero PGF contribution to the wind speed evolution should be related to the fact that the PGF vector is orthogonal to the wind vector.

The wind speed V, the wind direction, the contribution of the pressure gradient force (PGF) to the wind speed and the direction of the PGF vector (PGF_u, PGF_v) simulated by the model are shown on Fig. 4a (day-time) and b (night-time). The (PGF contribution to the) wind speed and the direction of the wind speed (direction of the PGF vector) are shown respectively by contour lines and by colours.

A positive PGF contribution to the wind speed, as defined in Eq. (1), means that the PGF is responsible for an acceleration of the wind speed. The wind is roughly from the south-south-east during day-time (Fig. 4a, 16:00 LT). It comes from a slightly more southerly direction only above the jet level (14 m a.g.l.) during night-time (Fig. 4b, 24:00 LT) and blows from the south-west below. The changes in the wind direction between 16:00 and 24:00 LT result from a change in the direction of the synoptic scale PGF vector ($\mathrm{PGF}_{u,\mathrm{syn}}$, $\mathrm{PGF}_{v,\mathrm{syn}}$) from south-westerly to westerly. The wind direction well above the jet level 14 m a.g.l. was influenced by turbulence at 16:00 LT, with a direction between the direction of the geostrophic wind (south-easterly) and that of the PGF vector (south-westerly). At 24:00 LT, it is no more influenced above the jet level by turbulence and comes in the geostrophic wind direction (southerly at that time), while below the jet level it is still influenced by turbulence and comes between the geostrophic wind direction and the PGF vector direction (westerly).

The reason why the PGF contributes to an acceleration of the wind speed up to 14 m a.g.l. at Dome C (isocontours of Fig. 4b, lower panel, at 24:00 LT and $x = 0$ km) comes from the fact that the wind direction is not geostrophic, because it is influenced by turbulence generated by surface friction up to this height. In fact turbulence deflects the wind vector, forcing it to blow from a direction in which it may be accelerated by the PGF. The acceleration occurs when turbulence shuts down at the end of the day. Then the increasing wind speed is responsible for an increase of the Coriolis force and the wind starts to turn to the left (anti-clokwise rotation). This is not the case above 14 m, where the wind direction is close to be geostrophic, i.e., the wind vector is roughly perpendicular to the PGF vector.

Note on Fig. 4b the weakening of the wind speed below the jet level (14 m a.g.l.) from day to night, which is due to a strong weakening of turbulence led by a strong increase of the vertical stability of the atmosphere. In contrast the onset of a low level jet is responsible for an increase of the vertical wind shear between the ground and 14 m a.g.l., so that the weakening of turbulence from day to night may be slightly limited. In fact a possible contribution of the low level jet to turbulence in our case seems not significant. Rather turbulence during night-time on 16–17 December 2014 is essentially generated by the surface friction. Also the strong stabillity of the atmosphere at Dome C during night-time explains why the LLJ is situated very close to the surface and may be observed over a relatively short tower.

Note also the occurrence of the wind speed maxima with downslope wind direction just above 14 m a.g.l. at 24:00 LT (see e.g., Fig. 4b, top panel, $x = -200$ km and $x = 130$ km). These maxima may correspond to an acceleration of the wind when turbulence in the boundary layer weakens, so that the downslope flow behaves like an advective-gravity flow (see Mahrt, 1982).

The component of the PGF along the x axis (PGF_u) on 16 December at 24:00 LT is compared to the temperature on Fig. 5a. It is found that PGF_u intensifies below 14 m a.g.l. except between −150 and 0 km, where the local slope is in the opposite direction of its general direction. The variations of PGF_u along the x axis below 14 m a.g.l. occur in conjunction with a strong inversion, suggesting that they are associated with a downslope pressure gradient force. The variations of PGF_u also influence the variations of the contribution of the PGF to the wind speed (Fig. 4b, bottom). Nevertheless neither the wind speed nor the wind direction are strongly affected by these variations (Fig. 4b, top). In fact PGF_u is relatively homogeneous up to 2500 m a.g.l., suggesting that the synoptic scale pressure gradient force is responsible for the general direction and intensity of the wind during that time. In other words the inversion winds are not responsible for the wind field at Dome C during the LLJ case of 16–17 December 2014.

Note that the height of the strong inversion layer is the smallest and the inversion the strongest over the Dome (Fig. 5), probably because of a progressive weakening of the flow which is counteracted upstream by the downlope contribution of the PGF along the x axis, leading to a minimum in the wind speed and subsequently in the turbulent kinetic energy there.

The contribution of the PGF to the wind speed is also compared with the air temperature on Fig. 5b. From the discussion above it appears that the change of sign of this contribution at Dome C (i.e., a change in the PGF contribution from an acceleration of the wind speed below 14 m a.g.l. to a slight deceleration above – pay attention to the colour scale) is not fortuitous. The 14 m a.g.l. level at Dome C is situated just below the sign reversal, i.e., where PGF still contributes to an acceleration of the wind speed. As the turbulence has already shut down there (see Fig. 6), we get good conditions for the formation of a low level jet.

In fact the coincidence between the height of the change of sign of PGF contribution to the wind speed and the top of the inversion layer during night-time may be due to a wind vector no longer orthogonal to the PGF in the inversion layer, but partly directed in the same direction as the wind vector. This is because turbulence there is generated by surface friction (Ekman Wind) at that time. As a remnant of the wind direction change due to turbulence still exists in the upper part of the inversion layer, while turbulence contribution has already shut down, the PGF is in position to accelerate the wind speed there.

Figure 6 illustrates the sudden shut-down of turbulence 14 m a.g.l. at Dome C after 19:00 LT, while the PGF is sustained. Such a situation has already been described by Blackadar (1957) as a source of an inertial oscillation. Indeed it is found that the wind vector at 14 m a.g.l. initiates a counter clock-wise rotation typical of an inertial oscillation until midnight-time (Fig. 7). This inertial oscillation is initiated by the sudden acceleration of the wind speed arising in conjunction with the sudden shut-down of turbulence. Contrary to the observations the inertial oscillation vanishes around 01:30 LT in the model. A possible cause is that turbulence is again active at that time (Fig. 6). Another possible explanation is that the horizontal diffusion of the model damps the inertial oscillation as it does above 14 m a.g.l.

4 Conclusions

MAR simulates a low level jet at Dome C on 16–17 December 2011, as in the observations. It is the first time that a 3-D simulation of such a low level jet (LLJ) over an ice sheet is performed. The good behaviour of the model allows us to perform an analysis of the dynamical contributions (PGF, turbulence, advection) to the simulated wind speed.

It appears that the low level jet (LLJ) is generated when turbulence shuts down at the end of day-time, just above the turbulent layer, where the flow is still deflected from the geostrophic wind direction, blowing from higher to lower pressures. The low level jet seems not to be due to inversion winds over Dome C, but a reinforced low level jet is simulated by the model over the slopes near Dome C, where and when the downslope PGF reinforces the synoptic scale PGF. In contrast the model is not able to simulate the inertial oscillation after 01:30 LT. The cause is not yet firmly identified and this would be the subject of future work.

Finally the height of the LLJ at Dome C is strongly dependant on the height of the turbulent layer and thus its simulation is an indicator of the success or not of a model in simulating the intensity of turbulence under stable conditions. Barral et al. (2014) show that a model overestimating turbulence overestimates the height of the LLJ. Here a slight underestimation of turbulence by MAR possibly due to a slight underestimation of the downward long-wave radiation flux during night-time is responsible for a possible slight underestimation of the LLJ height. Vertical stratification of the atmosphere is strongly stable at Dome C during night-time, even in summer. During day-time the sensible heat fluxes are much larger than the latent heat fluxes, because of the low temperature and the subsequent very low capacity of the atmosphere to contain water (see e.g., King et al., 2006). Consequently the conditions for developing a well mixed layer during day-time are optimal. This means that the simulation of summer case studies at Dome C could help a lot in validating the turbulence scheme of an atmospheric model. Due to its particular location and available set of observations, Dome C was recently selected as the test site for the next Gewex Atmospheric Boundary Layer Studies (GABLS4) model intercomparison (see http://www.cnrm.meteo.fr/aladin/meshtml/GABLS4/GABLS4.html).

Appendix A: Contributions to the wind speed

Equations of horizontal motion in MAR read (Gallée and Schayes, 1994):

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - \dot{\sigma}\frac{\partial u}{\partial \sigma} + fv - \left.\frac{\partial \phi}{\partial x}\right|_p + F_u \tag{A1}$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - \dot{\sigma}\frac{\partial v}{\partial \sigma} - fu - \left.\frac{\partial \phi}{\partial y}\right|_p + F_v \tag{A2}$$

where f is the Coriolis parameter, $\phi = gz$ is the geopotential, and F_u and F_v are the contributions of turbulence to the wind components u and v respectively. Writing

$$\mathrm{ADV}_u = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - \dot{\sigma}\frac{\partial u}{\partial \sigma}$$

$$\mathrm{ADV}_v = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - \dot{\sigma}\frac{\partial v}{\partial \sigma}$$

$$\mathrm{PGF}_u = -\left.\frac{\partial \phi}{\partial x}\right|_p$$

$$\mathrm{PGF}_v = -\left.\frac{\partial \phi}{\partial y}\right|_p$$

and multiplying the first equation by u and the second by v one gets the equation for the horizontal kinetic energy

$$u\frac{\partial u}{\partial t} + v\frac{\partial v}{\partial t} = u\mathrm{ADV}_u + v\mathrm{ADV}_v + u\mathrm{PGF}_u + v\mathrm{PGF}_v + uF_u + vF_v \tag{A3}$$

where

$$u\frac{\partial u}{\partial t} + v\frac{\partial v}{\partial t} = V\frac{\partial V}{\partial t}$$

dividing both members of the equation for the horizontal kinetic energy by V one gets

$$\frac{\partial V}{\partial t} = \underbrace{\frac{u}{V}\mathrm{ADV}_u + \frac{v}{V}\mathrm{ADV}_v}_{\text{Advection Contribution}} + \underbrace{\frac{u}{V}\mathrm{PGF}_u + \frac{v}{V}\mathrm{PGF}_v}_{\text{PGF Contribution}} + \underbrace{\frac{u}{V}F_u + \frac{v}{V}F_v}_{\text{Turbulence Contribution}} \tag{A4}$$

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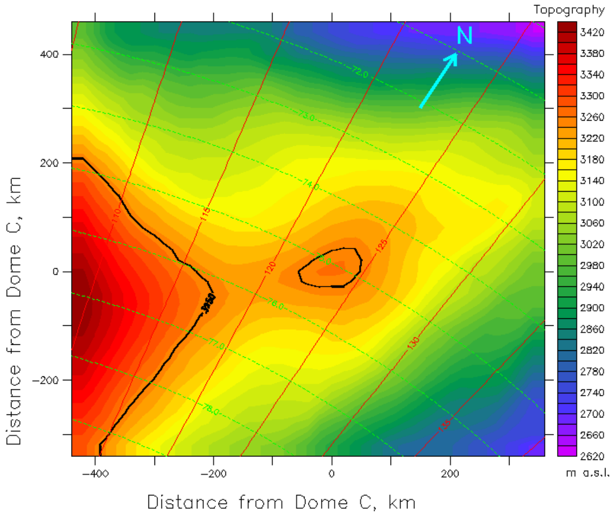

Figure 1. MAR integration domain and topography (color). Solid line represents the 3250 m isocontour.

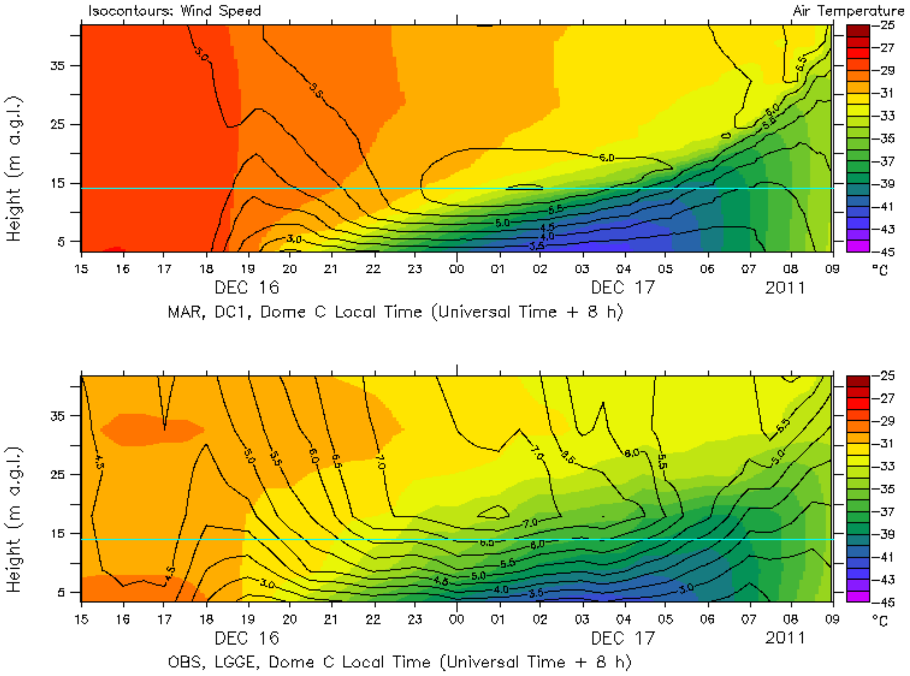

Figure 2. Temperature (color) and wind speed (isocontours) at Dome C tower, simulated by MAR on 16–17 December 2011 (upper panel) and observed (lower panel). Local Time LT (Universal Time UT + 8 h) is used. The simulated jet level is at $z = 14$ m a.g.l. (shown by a cyan line in both panels).

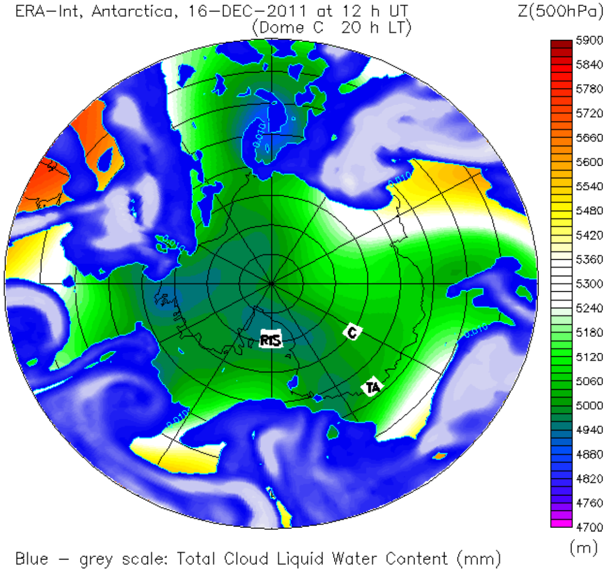

Figure 3. 500 hPa geopotential (m) over Antarctica on 16 December 2011 at 12:00 UT (color key to the right). Total cloud liquid water content (TCLW), from 0.01 (dark blue) to 1.2 mm (grey) is also shown. TCLW 0.01 mm isocontour is also represented by cyan line. Dome C is indicated by letter C. Terre Adélie and the Ross Ice Shelf are indicated respectively by “TA” and “RIS”.

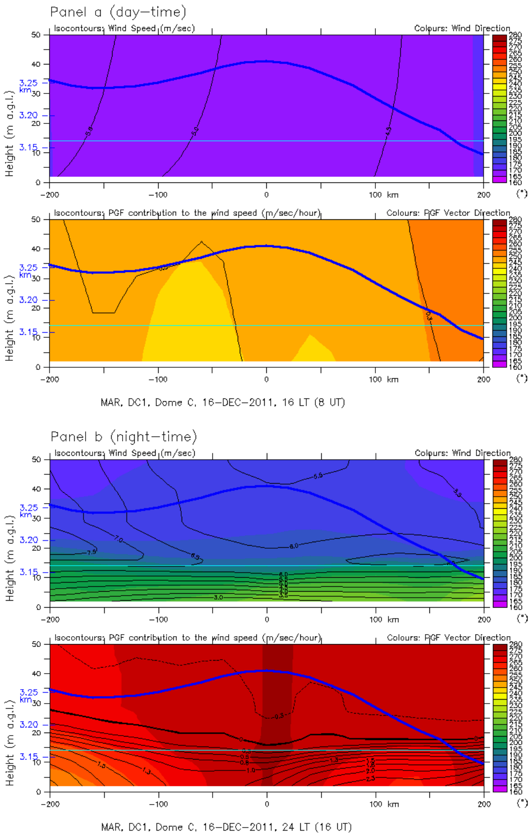

Figure 4. (a) Wind (top) and PGF(bottom) at the end of day-time (16:00 LT), along the x axis. The PGF contribution to the wind speed is defined in Eq. (1). PGF Vector refers to (PGF_u, PGF_v). Domain topography is shown by the thick blue line. Distance from Dome C is in km. The simulated jet level is at $z = 14$ m a.g.l. (cyan line). **(b)** same as in **(a)**, but at midnight.

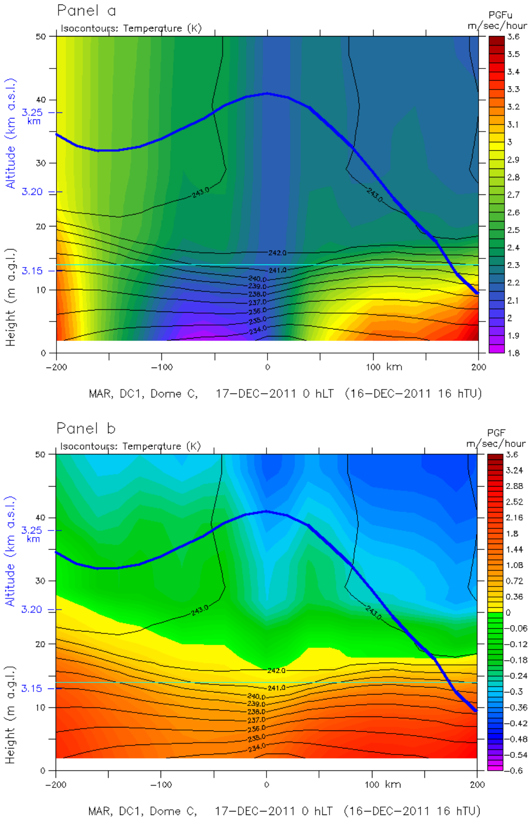

Figure 5. (a) Temperature and PGF_u at midnight, along the x axis. Distance is from Dome C. **(b)** Temperature and PGF, at midnight, along the x axis. Distance is from Dome C.

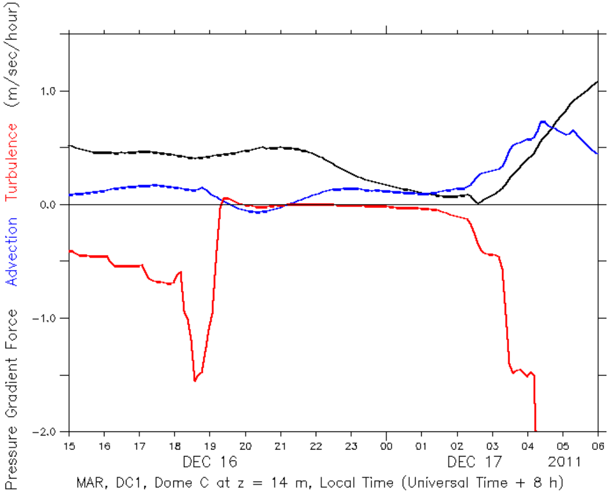

Figure 6. Simulated contribution of the forces to the wind speed, 14 m a.g.l. at Dome C on 16–17 December 2011. Local Time LT (Universal Time UT + 8 h) is used. The shutdown of turbulence occurs at 19:00 LT.

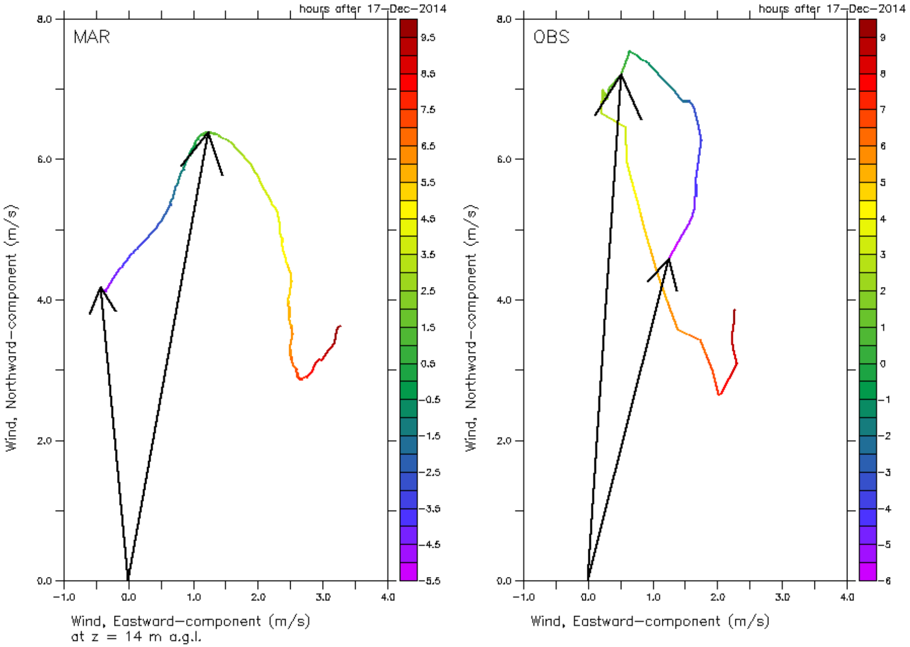

Figure 7. Wind hodograph at Dome C between 16 December 2011 19:00 LT and 17 December 2011 10:00 LT. Colours represent time in hours before/after 17 December midnight (negative/positive values). Arrows are plotted for 16 December 2011 19:00 LT and 17 December 2011 01:30 LT. Panel labeled "MAR": simulation at $z = 14$ m a.g.l. Panel labeled "OBS": observations at level 3 of the tower ($z = 17.9$ m a.g.l.).