

Interactive comment on “A case study of a low level jet during OPALE” by H. Gallée et al. **Anonymous Referee #1** , Received and published: 12 January 2015

This is an interesting case where the wind at the top of the boundary layer accelerates in response to the cutoff of convective mixing in the boundary layer. It is mentioned in a MAR focused paper by Gallée in the OPALE collection. In that discussion it is noted that such events were frequent during the OAPLE experiment. In such cases with the simplest dynamics, there is an ageostrophic component of the wind that rotates inertially: That was not found here. However, there are other observations and modeling with similar dynamics involved, associated with seabreezes which were found to rotate both clockwise and anticlockwise, counter to expectations. The authors may want to consult Atmos. Chem. Phys., 14, 13471– 13481, 2014 doi:10.5194/acp-14-13471- 2014, Dynamical analysis of seabreeze hodograph rotation in Sardinia. I am sure there are other examples in the literature. At this point I do not feel that the analysis is complete enough to justify publication as a stand-alone paper in the OPALE collection.

1.1. Dynamics of sea-breeze winds and low level jets (LLJ) are not similar, in particular when one consider the rotation of the winds. Although the Coriolis force plays a central role in the rotation of the wind speed, the rotation occurs in the bulk of the boundary layer of the sea breeze and is observed near the surface. The LLJ simulated in the present paper is supergeostrophic and results from an inertial oscillation occurring above the boundary layer. Another point is that our paper does not compare differences between two observations but differences between the observation and a simulation: anticlockwise rotation is observed while the model simulates an anticlockwise rotation followed by a clockwise rotation.

The study of Andreas, E.L., Claffey, K.J., and Makshtas, A.P. (2000, “Low-level atmospheric jets and inversions over the western Weddel Sea” BLM 97, pp. 459 - 486) is an exemple of a case study observed over the Weddel Sea and a simulation made with a simplified 1D atmospheric model. It is mentioned on p.31092 line 16.

Two alternatives might be considered:

1) Include a figure showing the development of the LLJ from model and observations in the primary paper in this collection, and/or 2) because these are frequent, develop more statistics on their occurrence and behavior and, hopefully, determine if there is a related signature in the surface chemistry (the was some work done as part of the ANTCI program at the South Pole that showed a LLJ and elucidated the mixing processes below the wind maximum and the effect on the vertical profile of NO_x.)

1.2. To the authors knowledge this is the first time that a so shallow LLJ is simulated by a 3D meteorological model.

Observation				Simulation			
Date		h (m)	LLJ (m/s)	Date		h (m)	LLJ (m/s)
12 Dec	21h00	18.2	4.33	13 Dec	00h00	08.0	4.34
14 Dec	03h30	18.2	3.26	14 Dec	04h30	10.0	3.80
15 Dec	00h00	25.6	5.40	15 Dec	01h00	10.0	5.44
16 Dec	01h00	18.2	5.59	16 Dec	01h00	08.0	4.83
17 Dec	01h00	18.2	7.56	17 Dec	02h00	14.0	6.52
17 Dec	23 h 30	32.9	8.53	18 Dec	00h30	22.0	8.26
22 Dec	05h30	25.6	6.40	22 Dec	05h30	14.0	4.22
22 Dec	00h30	18.2	1.02	22 Dec	23h30	10.0	3.68
25 Dec	00h00	18.2	6.47	25 Dec	00h00	16.0	6.85
26 Dec	04h30	25.6	7.70	26 Dec	04h30	16.0	5.72
26 Dec	06h00	25.6	6.14				
27 Dec	00h30	18.2	6.59				
28 Dec	02h30	32.9	7.12				
28 Dec	04h00	18.2	6.72				
29 Dec	04h30	25.6	10.6				

Table 1: Observed and simulated LLJs at Dome C during OPALE. h is the height of the LLJ.

It was possible to observe LLJ occurring only at a height below the top of the tower. As LLJs occur where turbulence shuts down this means that in these cases stabilization of the vertical column of air is strong, i.e., when the wind shear is not too large and a strong radiational cooling of the surface occurs.

Observed and simulated LLJs during the OPALE period (12 December 2011 - 14 January 2012) are listed in table 1. They are obtained by searching from below the lowest wind speed maximum below the highest level of the tower. Note that the vertical resolution of the model (2 m) is higher than that of the observations (6 levels, respectively at 3.5 m, 10.8 m, 18.2 m, 25.6 m, 32.9 m and 42.1 m). Consequently the estimation of the height of the LLJ in the observations may be very crude. No LLJ is simulated nor observed in January 2012, but no observations at the tower were made between 1 and 9 January and generally we did not get clear sky conditions in the first half of January 2012 (see e.g. fig. 2a of the companion paper - Gallée et al., 2014). MAR simulated a LLJ on 15 December below the top of the tower while it was very weak in the observation. No LLJ was simulated below the top of the tower on 26, 27 and 28 December, when MAR underestimated cloud cover and consequently overestimated day-time solar warming the day before. This caused an overestimation of turbulence and precluded the formation of a shallow inversion layer during night-time. In short the good simulation of a LLJ by MAR

or not in December 2011 was mainly the result of the good behavior of turbulence or not in the model, which itself results mainly from a good behavior or not of the simulated cloud cover. LLJs are more sensitive to turbulence than the winds simulated near the surface. Consequently the evaluation of their behavior may help us in evaluating vertical mixing of chemical species. Of course a longer time serie must be analysed in order to confirm this result. Hereafter we focus on a well marked case study which is accurately simulated, in order to infer in a deeper way how to evaluate the simulation of a LLJ by a 3D model.

Section 3 is divided in two subsections and this discussion is included as the first subsection on p. 31093, line 18. We mention also that statistics of observed LLJs at Dome C are already given in Barral et al. (2014).

1.3. A wind speed maximum near the surface has also been observed at South Pole during ANTCI (Neff et al., 2008). In constrast with the LLJs observed at Dome C it is associated to events of inversion winds. Indeed South Pole is situated on a slope, while Dome C is not. The LLJ at Dome C is related to the PGF extending well above the BL while at South Pole the wind speed maximum is caused by the downslope pressure gradient force (PGF) developing only in the bulk of the inversion winds layer. Another difference is that there is no diurnal cycle at South Pole. Consequently a LLJ could not develop there at the end of day-time, when turbulence shuts down. Possibly a LLJ could develop at South Pole with a rapid stabilization of the atmosphere associated with changes in synoptic scale conditions. A consequence of the absence of a diurnal cycle is that turbulence in the stable boundary layer of South Pole may reach an equilibrium, while this is not the case at Dome C. Note that Neff et al. (2008) mention that the behavior of NO below the wind speed maximum they observe is not fully understood since it could depend (but not always) on an accumulation process of NO over a thin drainage flow which thickness increases gradually before it reaches South Pole. In our case no drainage flow reaches Dome C so that the above-mentioned accumulation process does not exist.

A common point between our simulation and the observations of Neff et al. (2008) is that the wind shear is zero at the jet maximum, so that turbulent transport could not exist through the jet core (gradient Richardson number is “infinite” there). Note however that the LLJ at Dome C forms at a height where turbulence has already shut down, so that the LLJ is not strictly necessary for precluding vertical turbulent transport there. In contrast the wind speed maximum at South Pole is associated to the turbulent inversion winds, and probably plays a more important role in causing the shutdown of turbulence.

Finally the shutdown of turbulence by a wind speed maximum remains an open question. Indeed turbulence bursts have been simulated through a jet core in a LES by Cuxart and Jiménez (2007), but only when the wind and air temperature near the surface are prescribed in their model.

This discussion is included on p. 31092, line 16.

Anonymous Referee #2 , Received and published: 15 January 2015

The paper describes, with the model MAR, the acceleration of the wind (Low Level jet) in the PBL due to the cut-off of the turbulence. The subject is very interesting especially the connection between in the inertial oscillation and turbulence. Nevertheless, the lector would like probably to have more diagnostics and analysis.

In Fig2: the wind speed increases from 5m/s to 7m/s at 25m and above in the observations, it is less in MAR. Some comments ?

2.1. The model also simulates a wind speed maximum which is weaker than the observed one. In fact the night-time wind speed maximum is weaker in the simulation than in the observation at and above the level of the jet core. Possibly horizontal diffusion in the model may be responsible for such a weaker LLJ and the weaker wind speed above.

See more details in the response 2.6.

Could you also explain when the model start the simulation at 00Utc 16th December or at 12UTC ? forecast length ? The initial condition ?

2.2. The simulation is started on 1 November 2011 and the model is not reinitialized until the end of the experiment (end of January 2012). Thus the simulation is sufficiently long to allow the influence of lateral boundary conditions to reach the central part of the domain, in contrast to what happens in a simulation starting from prescribed initial conditions, and lasting of few hours or days only. As lateral boundary conditions are over-specified in a limited area model, they may distort the solution of the model and cause some differences between the simulation and the observation (see also response 2.4 for an exemple of this behavior).

Clarification is included in the section 2 about the model, on p. 31093, after line 16.

A mean (30mn or 1h) vertical profile with the observed value along the mast and the model for theta, U and V at 16LT and 24LT would be interesting.

2.3. Vertical profiles of simulated temperatures, wind speeds and wind directions are compared on (a new) Figure (referred to here as Fig. 1) to the observations made at the tower for 16 h LT and 24 h LT. Temperatures are overestimated during day-time and overestimated above the LLJ during night-time. The overestimation above the LLJ during night-time may be due to an underestimation of turbulence by the E – e model. Similarly momentum mixing seems to be well simulated during day-time but the wind speed is underestimated at midnight above the LLJ, as the temperature. Possibly this is linked to the representation of large scale winds in the model (see Fig. 2 at the end of this note and response 2.4). Wind direction seems to be well simulated.

The new figure (referred to here as Fig. 1) is included at the end of the present note and in the paper. The above-mentioned comment on it is included in the text on p. 31094, line 9.

In general concerning the wind and the geostrophic wind above the mast, is it possible to have some information about the “reality” with sounding data or analysis from ECMWF or NCEP ?

2.4. It appears that the model captures reasonably well the wind vector above the tower, as it can be seen from a comparison with the forcing (ERA-Interim) at 100 and 300 m a.g.l. The error in the wind speed and direction may amount respectively to 1.5 m/sec and 30° (see Fig. 2 at the end of the note). Note that universal time is used and that the crude time discretisation of ERA forcing (data provided each 6 hours only) influences strongly the time evolution of the simulated wind speed and direction. Indeed MAR data are provided with a time resolution of 10 min but exhibit significant changes only each 6 hours.

This is mentioned on p. 31094, after line 21.

Line 85: The underestimation of the downward LW probably generates too cold surface temperature and then an overestimation of the vertical stability. This case was selected (line 67) because the surface energy balance was much better so the surface temperature is well simulated ? It is possible to prescribe the surface temperature in MAR ?

2.5. I would prefer to say “better” than “well” since a model is not correct by construction. Surface temperature is better simulated when simulated DLW radiation is better simulated. Nevertheless it seems that simulated surface temperature is still underestimated during night-time, as it can be deduced from the underestimation of air temperature near the surface (compare lower and upper panels in Figure 2 of the manuscript). It should be possible to prescribe surface temperature in a future 1D version of the model but not in the 3D version since observations of surface temperature are available at Dome C only. Here the use of the 3D version allows us to fully represent the non-linearity of atmospheric dynamics, including the sinking of air over the Dome caused by the divergence of mass due to downslope winds around the Dome. Such a sinking could be responsible for a thinning of the BL, as it could be inferred from temperature isocontours in Figure 5.

I am interesting to see the vertical profile of the wind budget (up to 100m) of the three contributions at 16LT and 24LT, in particular the advection and the PGF contribution.

2.6. Vertical profiles of advection, PGF, the contribution of turbulence and horizontal diffusion, and their sum at 16 h LT and 24 h LT are shown in (a new) Figure (referred to here as Fig. 3). The last is interpreted as the tendency of the wind speed. These profiles are roughly homogeneous along the vertical during daytime (16 h LT), with PGF counterbalancing roughly the turbulent contribution. A similar equilibrium between PGF and turbulent contribution exists at midnight but their absolute values are reinforced. The contribution of turbulence is zero at the level of the LLJ and just above, where turbulence production by the wind shear is almost zero. Horizontal diffusion contributes negatively (positively) below

(above) the height of the jet core. The negative contribution in the bulk of the boundary layer could be related to the weakening of the wind speed on the slope directed towards negative values along the x axis during night-time. The maximum in the wind speed tendency results from the dominant contribution of the PGF just above the boundary layer, i.e., where the contribution of turbulence cancels.

The new figure (referred to here as Fig. 3) is included at the end of the present note and in the paper. A comment on it is included in the text on p. 31095, line 7.

In your plot PGFu is only $-\text{d}\phi/\text{d}x$? so it is not really the term used in the budget equation ? It is the same legend for 5a and 5b ? 5a it is PFGu and 5b PGF ? Line 200 Figure 5a ? PGFu is only $-\text{d}\phi/\text{d}x$ as shown in the appendix. 5a it is PFGu and 5b PGF

2.7. PGFu = $-\text{d}\phi/\text{d}x$ is plotted on Figure 5a, while PGF = (u/V) PGFu + (v/V) PGFv is plotted on Figure 5b. Caption of Figure 5a is correct in the discussion paper, but not in the manuscript you received before publication in acpd.

I don't really understand line 195-198

2.8. Inversion winds are generated by the downslope pressure gradient force. The thickness of the layer over which such a circulation occurs is generally no larger than a few tens of meters. Here the pressure gradient force is homogeneous along the vertical up to 2500 m a.g.l.

Clarification is included in the discussion paper on p.31097, line 4.

Fig6: Could you add the tendency of the wind speed ? Could you also comment the change in the advection between 19LT and 23LT ? Is it local ? Is it the same above at 25m ?

2.9. Advection weakens between 18 h LT and 21 h LT and recovers after that time. The weakening of advection occurs mainly below 20 m a.g.l. and decreases progressively upwards. It is found that turbulence is larger to the South of (upstream) Dome C than at Dome C at 14 m a.g.l. (height of the jet core) and at 19 h LT, while this is not the case at 22 h LT. Also at 19 h LT the wind speed is larger upstream Dome C than at Dome C. But at 17 h LT the contribution of turbulence is smaller everywhere at 14 m a.g.l. while the wind speed is already larger upstream Dome C. A possible mechanism upstream Dome C could be a slight reinforcement of the wind speed during day-time by an upslope PGF, leading to a larger wind shear and turbulence there at the end of the day. While the inertial oscillation starts at Dome C due to the shutdown of turbulence, this is not yet the case upstream. Turbulence shuts down there only a few hours later. Consequently the advection of momentum at Dome C could be weaker during a few hours at the end at the day. In short if surface temperature is overestimated by the model the

reinforcement of the wind speed and turbulence upstream Dome C during day-time could be overestimated by the model, and could lead to an overestimation of turbulence during a few hours at the end of day-time, a subsequent underestimation of advection at Dome C at the height of the LLJ and an underestimation of its strength.

This discussion is included on p. 31098, line 8. New Figure 6 (referred to here as Fig.4) is added at the end of the present note.

Line 270: The IO disappears at 1h30 in the model, and as you said the turbulence is one possibility, advection also? The turbulence starts with the SW, in the model and in the reality, but may be too active in the beginning or it is not the reason of disappearance of the IO in the model. Do you see also the IO in the observation below 14m and above at 25m? The wind vector in the model is significantly different to the observed one around 4LT.

2.10. About a possible role of advection, see response 2.9 above. An IO is observed below 14 m and above 25 m but it is not simulated.

This is mentioned on p. 31098, line 6.

Cuxart et al (2006) with the GABLS1 case explain clearly the problem of the overestimation of the turbulence and the LLJ.

2.11. LLJ is not mentioned by Cuxart et al (2006, BLM 118: 273–303). Possibly the reviewer would mention the wind speed maximum observed and sometimes simulated in the frame of this intercomparison experiment.

The study of Cuxart et al (2006) is mentioned on p. 31098 line 25.

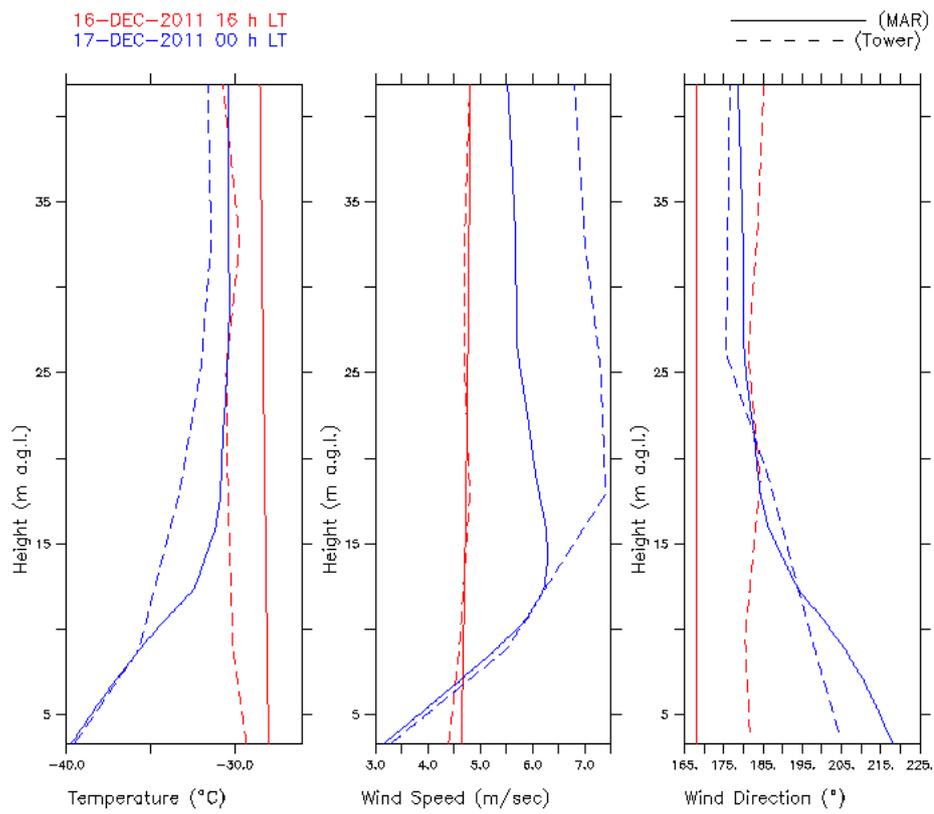


Figure 1: Vertical profiles of simulated temperatures, wind speeds and wind directions on 16 December 2011 at 16 h LT and midnight.

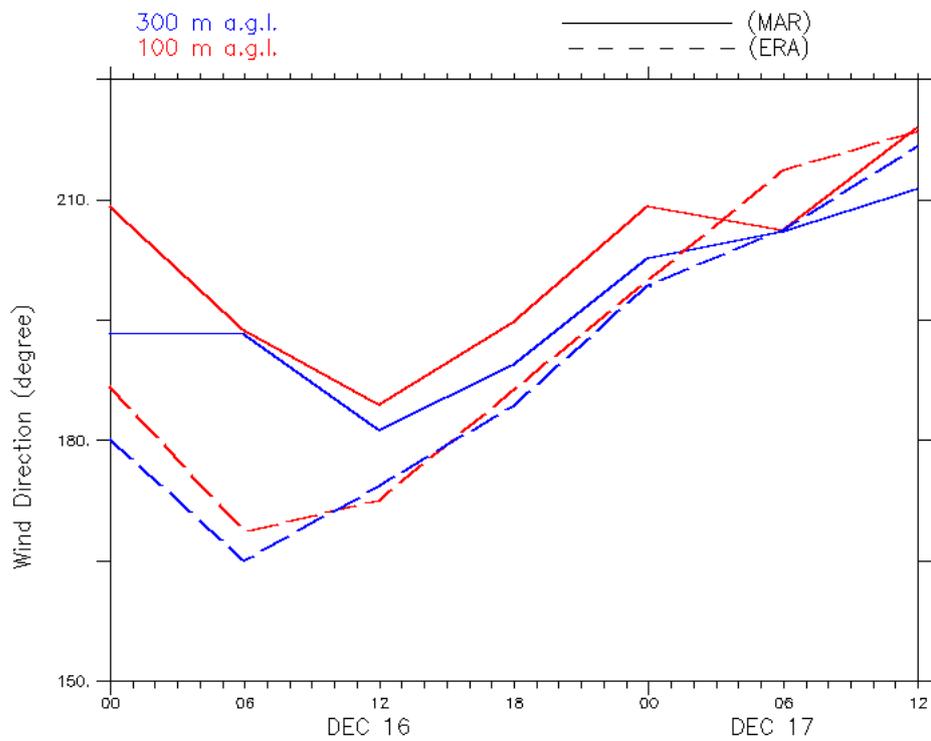
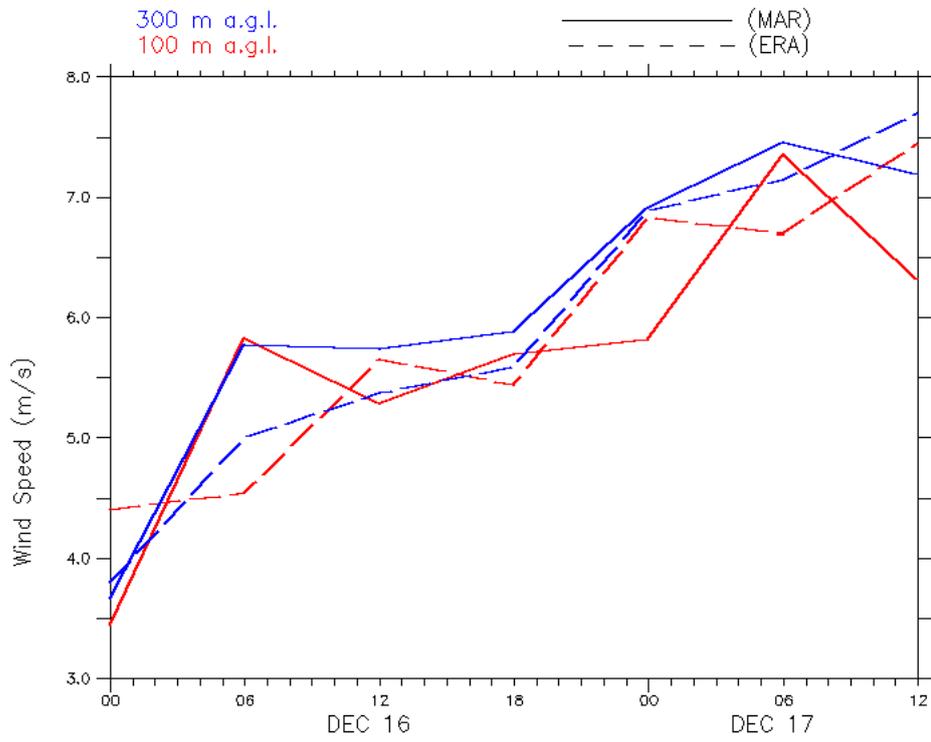


Figure 2: Comparison between the analysed wind speed (top) and direction (bottom) and the simulation, at 100 m a.g.l. and 300 m a.g.l. Note that universal time is used.

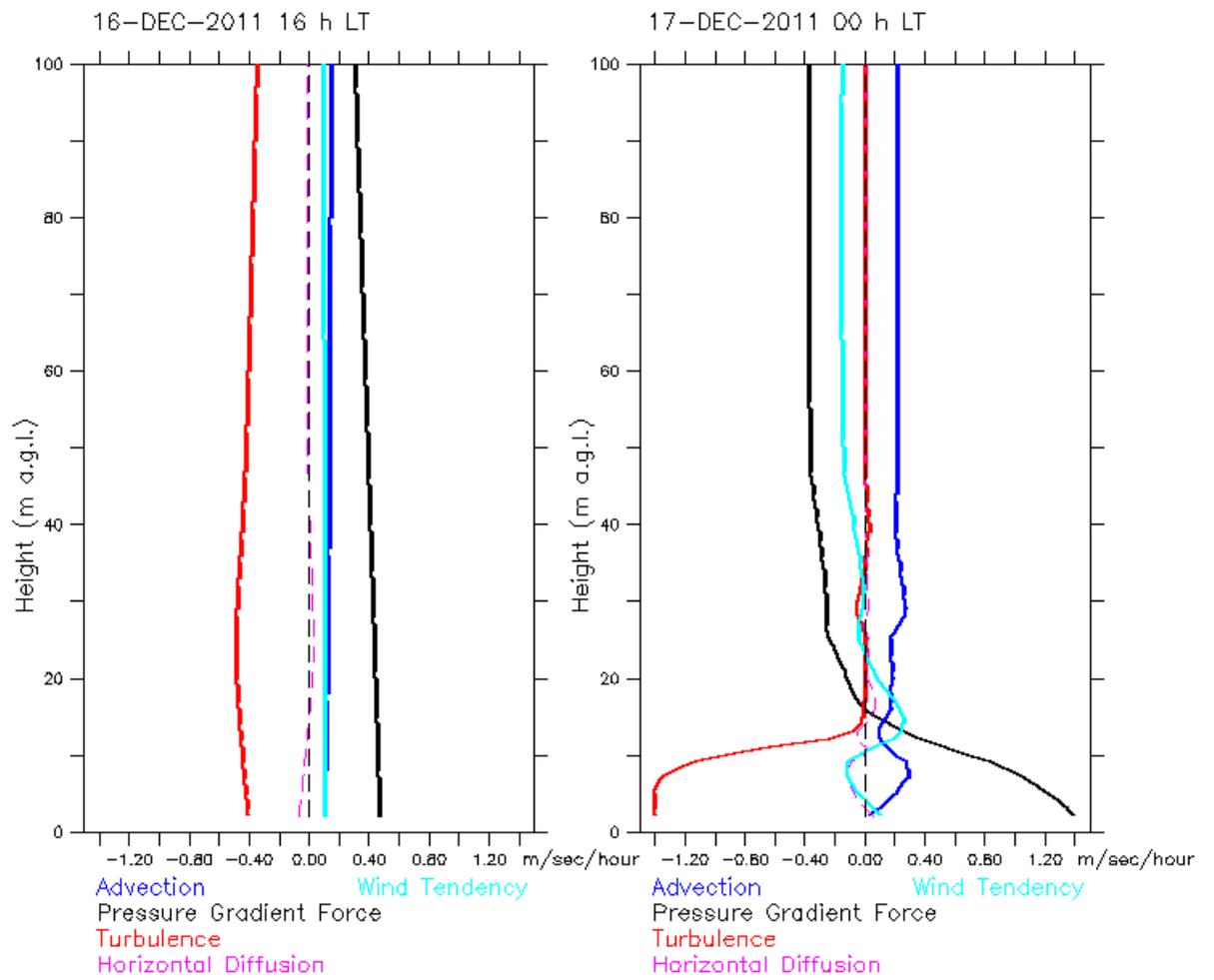


Figure 3: Vertical profiles of the contributions to the wind speed of PGF, advection, turbulence and horizontal diffusion.

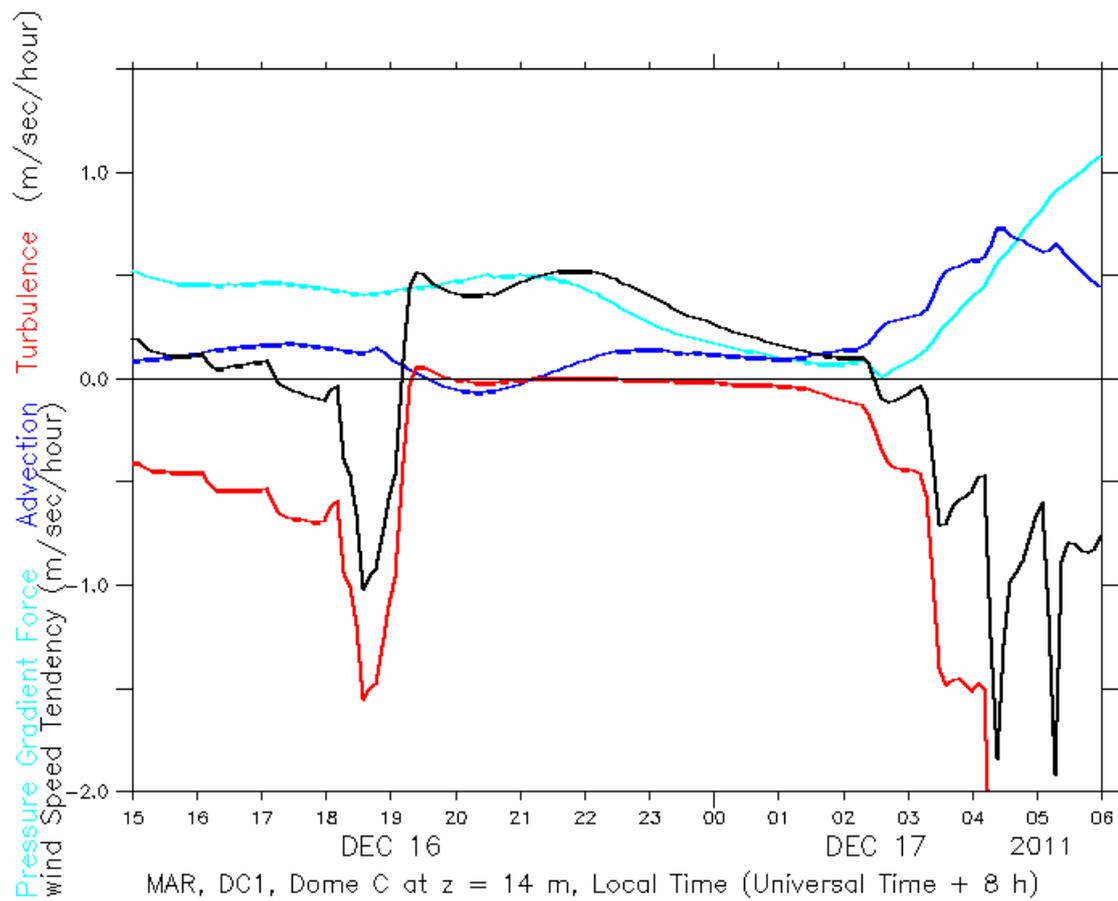


Figure 4: Simulated wind tendency and contribution of the forces to the wind speed, 14 m a.g.l. at Dome C on 16 \textendash{} 17 December 2011. Local Time LT (Universal Time UT + 8 h) is used. The shutdown of turbulence occurs at 19h LT.

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

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, confornting 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.

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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 (Duynderke, 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 micro-physical 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 x 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. \uparrow

3 ~~The low level jet~~

3.1 ~~Overview~~ \uparrow

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

3.2 ~~The case study~~

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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 (PGF_u, 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.

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We get (see appendix for more details):

$$\frac{\partial V}{\partial t} = \underbrace{\frac{u}{V}ADV_u + \frac{v}{V}ADV_v + \frac{u}{V}PGF_u + \frac{v}{V}PGF_v}_{\text{PGF Contribution}} + \underbrace{\frac{u}{V}F_u + \frac{v}{V}F_v}_{\text{Turbulence Contribution}} \quad (1)$$

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.

Fig. 2.6 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 ($PGF_{u,syn}$, $PGF_{v,syn}$) 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

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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-clockwise 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 stability 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 varia-

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tions 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

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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 under-

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estimation 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>).

5

10

Appendix A: Contributions to the wind speed

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

$$\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - \sigma \frac{\partial u}{\partial \sigma} + f v - \frac{\partial \phi}{\partial x} \Big|_p + F_u \quad (\text{A1})$$

$$\frac{\partial v}{\partial t} = -u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - \sigma \frac{\partial v}{\partial \sigma} - f u - \frac{\partial \phi}{\partial y} \Big|_p + F_v \quad (\text{A2})$$

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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

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

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

$$5 \quad \text{PGF}_u = - \left. \frac{\partial \phi}{\partial x} \right|_{\rho}$$

$$\text{PGF}_v = - \left. \frac{\partial \phi}{\partial y} \right|_{\rho}$$

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

$$u \frac{\partial u}{\partial t} + v \frac{\partial v}{\partial t} = u \text{ADV}_u + v \text{ADV}_v + u \text{PGF}_u + v \text{PGF}_v + u F_u + v F_v \quad (\text{A3})$$

10 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

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

Acknowledgements. The OPALE project was funded by the ANR (Agence National de Recherche) contract ANR-09-BLAN-0226.

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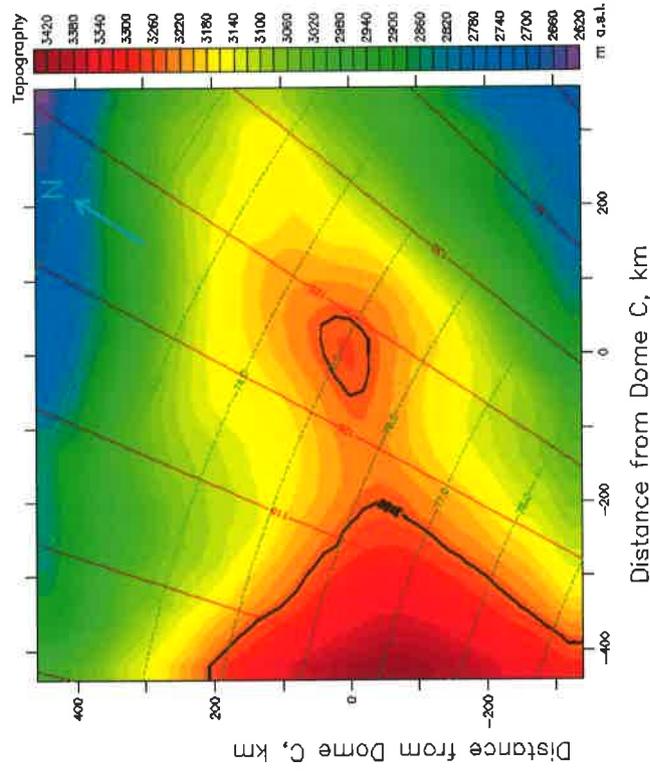


Figure 1. MAR integration domain and topography (color). Solid line represents the 3250 m isocontour.

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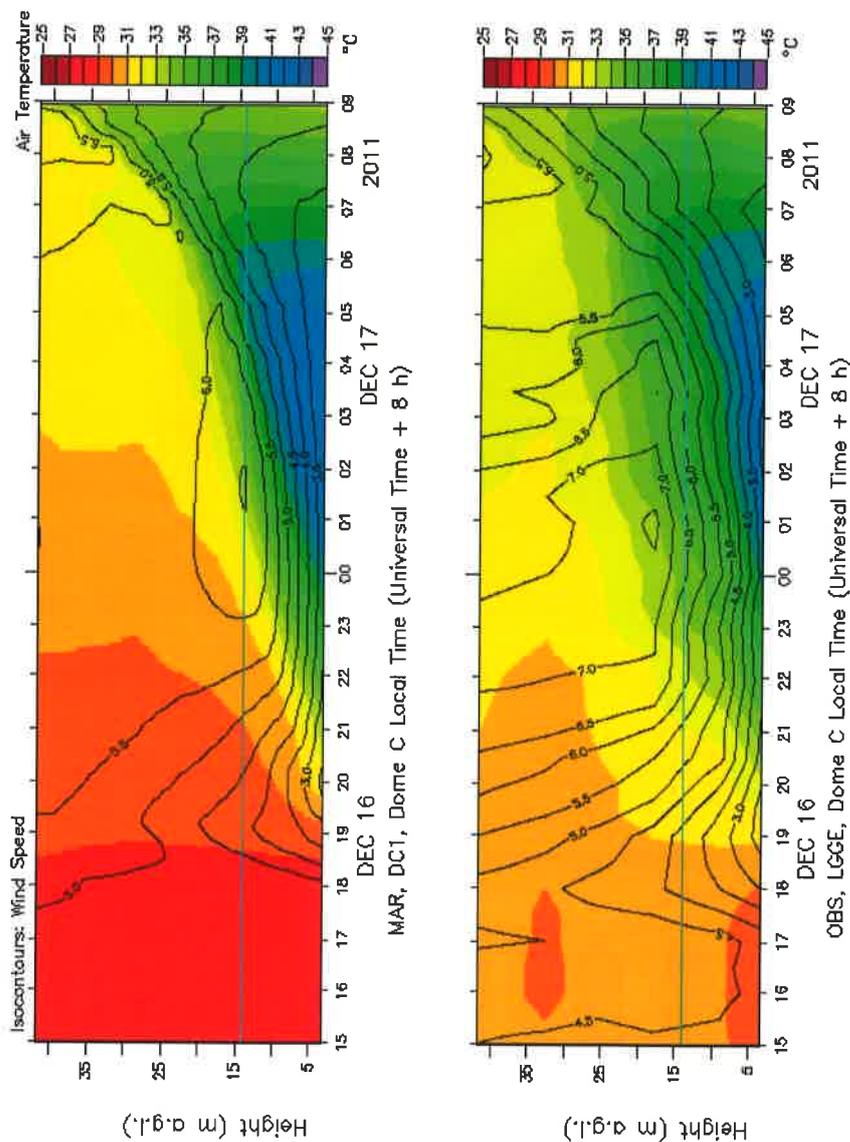


Figure 2. Temperature (color) and wind speed (isocontours) at Dome C tower, simulated by MAR on 16–17 December 2011 (upper panel) and observed (lower panel). Local Time LT (Universal Time UT + 8 h) is used. The simulated jet level is at $z = 14$ m a.g.l. (shown by a cyan line in both panels).

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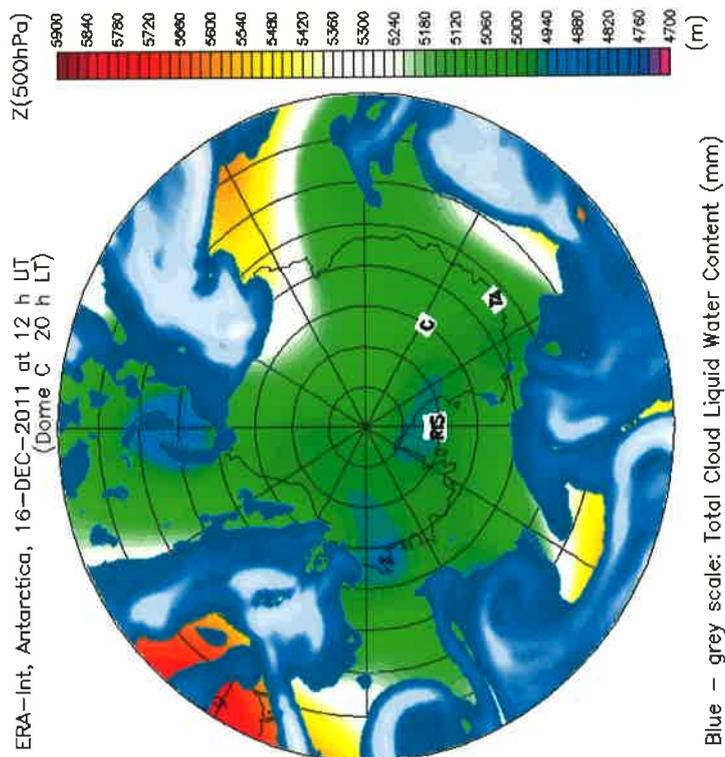


Figure 3. 500 hPa geopotential (m) over Antarctica on 16 December 2011 at 12:00 UT (color key to the right). Total cloud liquid water content (TCLW), from 0.01 (dark blue) to 1.2 mm (grey) is also shown. TCLW 0.01 mm isocontour is also represented by cyan line. Dome C is indicated by letter C. Terre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

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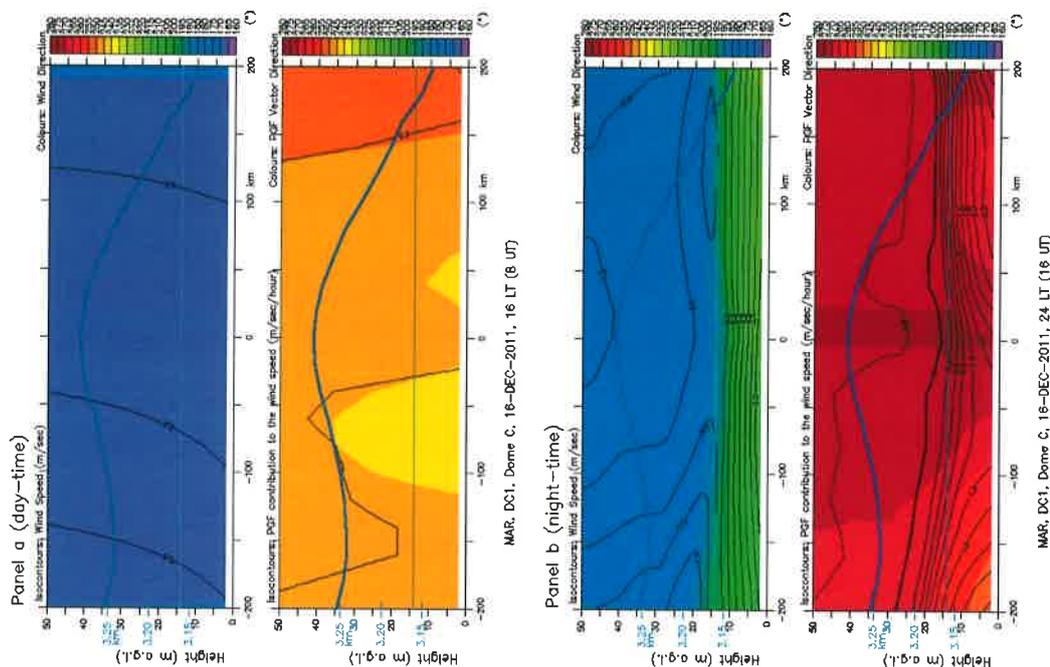


Figure 4. (a) Wind (top) and PGF(bottom) at the end of day-time (16:00 LT), along the x axis. The PGF contribution to the wind speed is defined in Eq. (1). PGF Vector refers to (PGF_u, PGF_v) . Domain topography is shown by the thick blue line. Distance from Dome C is in km. The simulated jet level is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

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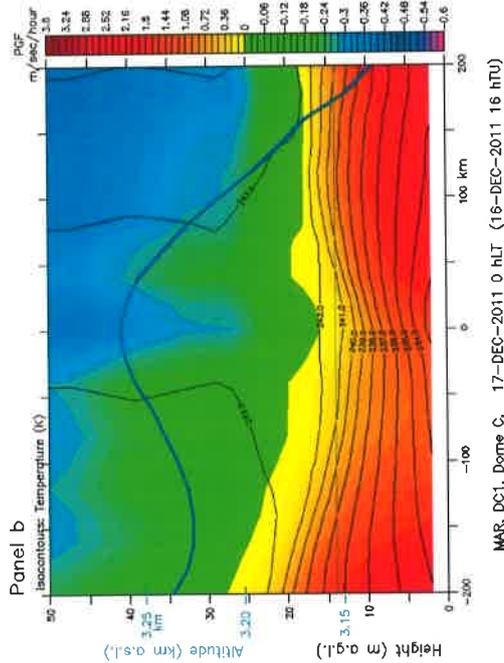
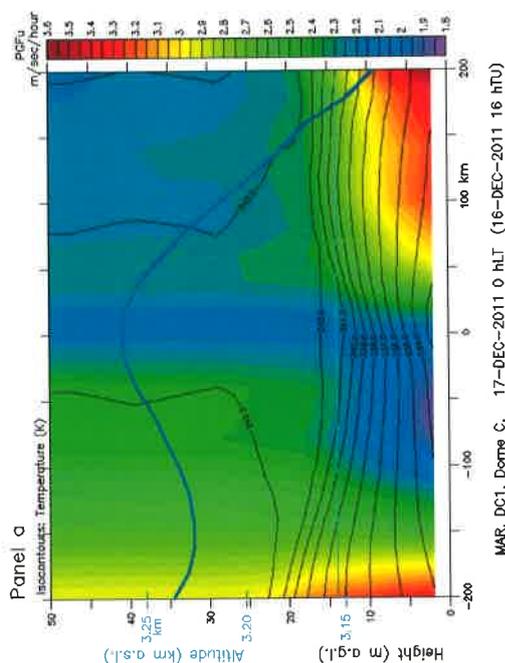


Figure 5. (a) Temperature and PGF_y at midnight, along the x axis. Distance is from Dome C. (b) Temperature and PGF, at midnight, along the x axis. Distance is from Dome C.

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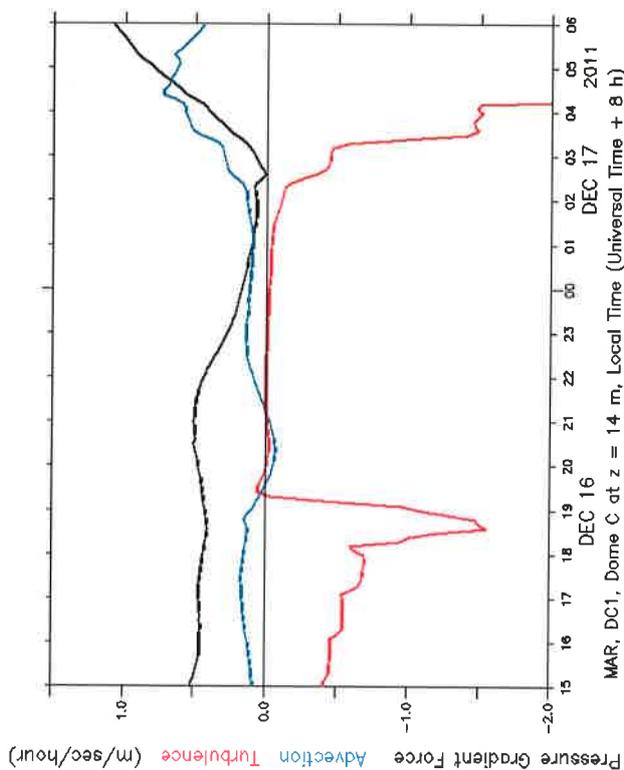


Figure 6. Simulated contribution of the forces to the wind speed, 14 m.a.g.l. at Dome C on 16–17 December 2011. Local Time LT (Universal Time UT + 8 h) is used. The shutdown of turbulence occurs at 19:00 LT.

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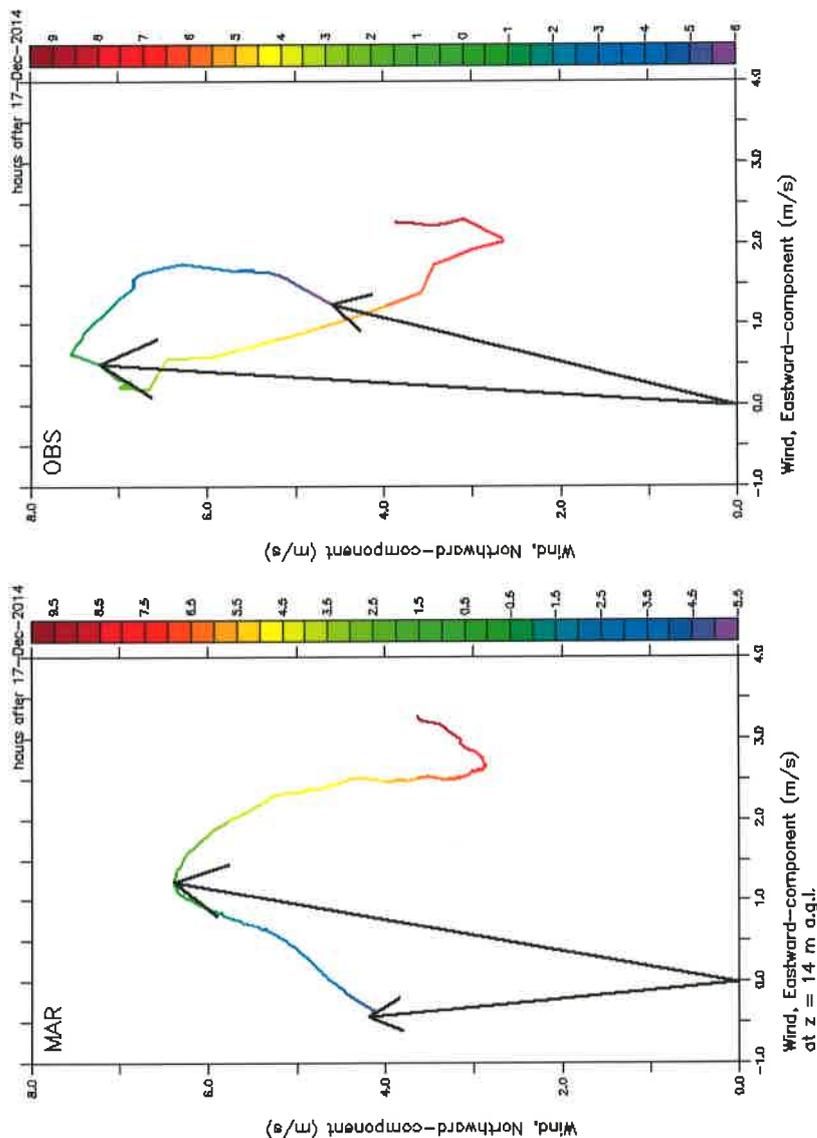


Figure 7. Wind hodograph at Dome C between 16 December 2011 19:00 LT and 17 December 2011 10:00 LT. Colours represent time in hours before/after 17 December midnight (negative/positive values). Arrows are plotted for 16 December 2011 19:00 LT and 17 December 2011 01:30 LT. Panel labeled “MAR”: simulation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

