Interactive comment on "Characterization of the boundary layer at Dome C (East Antarctica) during the OPALE summer campaign" by H. Gallée et al.

Anonymous Referee #1 , Received and published: 11 January 2015

General

This is a comprehensive description of the application of the MAR model to the OPALE experimental period. The model suffers limitations as do other models in the polar regions of not accurately producing cloud structures (often of mixed phase nature) and the associated surface radiative balance. The authors document this well. Comparisons of wind speed and direction and friction velocity are quite reasonable. The model shows a cold bias in general at nighttime: the temperature in shallow stable layers may be important to the chemistry and a comment on its importance or lack thereof should be made.

1.1. The following sentence is added in the « discussion and conclusion section » en p.33104, line 3: « *Note that, since underestimation will induce also an error in the modelled temperatures measured temperatures were used when interpreting the chemistry (Preunkert et al., 2014)* »

Only a single 3-day example of model boundary layer depth estimates compared with high resolution sodar data is shown. A critical missing piece in the paper is a detailed comparison between the model and sodar depth measurements for the entire period broken into stable and unstable periods, particularly for the early period when surface snow nitrate and associated fluxes were large. Documenting model performance during the collapse of the daytime convective layer is essential to understanding the ensuing chemistry where past research has indicated the possibility of non-linearity in the HOx-NOx chemical system. I have noted below that in the paper by Frey et al., they eliminate 22% of the NOx flux values (∼five hours per day on average) when the boundary layer depth is less than 10 m: This would eliminate a substantial portion of the evening transition chemistry.

1.2. The height of the BL is not used as an input variable of the 1D box models used by Legrand et al. (2014), Kukui et al. (2014), and Preunkert et al. (2014). It is a diagnostic variable generated by MAR and illustrating the behavior of simulated turbulence. Rather the turbulent diffusion coefficients generated by MAR are used as the input variable of the 1D box models.

Frey et al. (2014) decide to not use MOST when BL height is lower than 10 m.

The comparison between MAR BL height and sodar measurements helps us in evaluating the model. A comparison between the model and sodar measurements is possible for a few days only during the period of interest, which lasts from 4 December 2011 to 11 January 2012 in Legrand et al. (2014), from 19 December to 9 January in Kukui et al. (2014), from 14 December to 11 January in Preunkert et al. (2014), and from 23 November to 12 January in Frey et al. (2014). Sodar data are available only on 12, 13, 18, 21, 26, 27, 28 December 2011 and on 3, and 4 January 2012. Among those days MAR underestimates DLW radiation significantly on 18 December in the evening, and on 21 December. Although the possibility exists to make a comparison between MAR, sodar measurements and other meteorological measurements on 12 and 13 December 2011, the best period for such a comparison is on 26 – 27 – 28 December 2011, since this period is the longest and it is analyzed by the above-mentioned authors. It will be mentioned on p.33100, line 20.

Simulated (observed) minimum and maximum heights of the BL are 3.4 and 224 m (10 m and 150 m) on 12 December and 3.6 and 251 m on 13 December (5 m and 125 m).

I also feel there was inadequate crosslinking to the other papers in this special issue: the authors could easily point out and reference how their model results are used. For example, Frey et al show the only period of NOx profiles on 9 January: the detailed behavior of the boundary layer in this period from the model (and sodar) perspective could be quite valuable. Another curiosity is the burst of NOx around 2300: Is this a boundary layer effect? Similarly, Kukui et al use a 1-D chemistry-transport box model to get the vertical distribution of HONO using the MAR boundary layer depth data: this is an example of the type of use that should be referenced in this paper and how the modeling effort should be an essential part of the OPALE collection of papers.

1.3. Unfortunately MAR significantly underestimates DLW radiation on 9 January and the period after that day, so that a comparison of MAR simulation with observations on that day is not relevant. In the same way it is not possible to interpret the burst of NOx around 23h00 in Figure 2 of Frey et al. (2014) with MAR simulation.

The following details about how MAR outputs are used in other OPALE studies are given on p. 33092, line 27:

MAR turbulent vertical diffusion coefficients Kz are used by Preunkert et al. (2014) and the uncertainty of the later on HCHO mixing ratios is discussed. Legrand et al. (2014) also use the same MAR outputs in their 1D box model of HONO mixing ratio. Kukui et al. (2014) performed similar calculations using the same MAR output. On the other hand BL heights are not strictly needed since they are redundant with Kz. Frey et al. (2014) use MAR BL heights to determine when they may apply the Monin–Obukhov similarity theory for calculating the turbulent fluxes of NOx in the SBL.

Cross-linking is also made on p. 33100, line 12.

Specific

33091, lines 1-2: If “observation and modelling of the boundary layer has already been performed” at Dome C there should be references here.

1.4. References have been included.

33091, line 1-16: This is all quite general and doesn’t bring out the challenges of modeling the boundary layer at Concordia. A critical feature of the boundary layer at Concordia in the summer is the rapid collapse of a convective BL to a very stable shallow one. In this respect, the authors neglect one the first papers to point this out, namely: King, J. C., S. A. Argentini, and P. S. Anderson (2006), Contrasts between the summertime surface energy balance and boundary layer structure at Dome C and Halley stations, Antarctica, Journal of Geophysical Research-Atmospheres, 111(D2).

1.5. The critical feature is the generation of a very stable BL after sunset. Rapid collapse of the convective BL at the end of the day is observed at other latitudes. King et al. (2006) paper was already cited in the companion paper of this issue (Gallée et al. 2014) in order to explain the role of sensible heat fluxes at Dome C which are responsible for a strong diurnal cycle of turbulence. It is now also cited in the present paper on p. 33091 line 20.

33092-93: If “situations with an overcast sky were not considered” give a brief reason here. I realize you come back to this later but the question is whether MAR is not useful in interpreting chemical processes under cloudy sky conditions or whether the chemistry analyses were not carried out for cloudy conditions (it seems like the contrast in photochemistry would be important). It would be useful to identify the percentage of time clouds are present during the experimental period (e.g. 10% or 90% would make a big difference.)

1.6.1. Sentence starting on p.33092 line 28 is rewritten with more details: Observations during bad weather conditions are often discarded when the air (containing contaminants) comes from the station. Bad weather conditions also often occur simultaneously with a significant advection of chemical species, a situation that was discarded in the studies cited above. Finally clear sky conditions were preferred since the assumption of a similar DSW radiation from sunny day to sunny day may be done. These criteria allow us to avoid most of the situations for which clouds are underestimated leading to an erroneous behavior of the surface energy budget, as explained by Legrand et al. (2014).

Another factor with respect to clouds is that they are often associated with periods of the warming of the surface (increased LWD and warm advection): the subsequent boundary layer evolution under clearing skies would be preconditioned by this effect. Was this examined in the model evaluation?

1.6.2. The boundary layer evolution under clearing skies was not compared with the observations since the model underestimates cloud cover, so that the timing of clearing skies is not the same in the model and in the observations. Also note from the detailed analysis of the 26 – 28 December period that the response of the model could differ depending on the time of the day at which a covered sky occurs (compare the biases of the model on 26 December and 27 December).

33095, line 12: “similarity”

1.7. Correction is made.

33095. Section 3: Does Genthon et al 2013 or Gallée and Gorodetskaya (2008) describe MAR in enough detail especially the high resolution aspect in the boundary layer [. . .a long-term simulation of MAR with ECMWF analyses, showing the interest to represent the atmosphere with a fine vertical resolution (Genthon et al., 2013)]. If this is the case, it seems efficient to refer to other summaries of the properties of MAR and only point out the unique properties here that affect boundary layer structure and associated interpretative demands posed by the need to interpret the chemistry in OPALE.

The description of the roughness could have been removed from the description of MAR since observations of roughness length were not done at Dome C during OPALE. Nevertheless a blowing snow event is simulated on 29 December and could help in analyzing the sensitivity of the model. Indeed it is responsible for a change of the roughness length from almost constant values around 0.05 mm before the event to 2 mm after the event at Dome C. No significant sensitivity to this change may be found in the behavior of MAR variables near the surface from a look to Fig. 3. Some information about that point is given on p. 33100 line 6.

33096, line 10: Given the strong diurnal temperature range, does SISVAT account for subsurface heat storage during the day and conduction back for radiative loss at night? Were there any firn temperature measurements during OPALE that might indicate whether this is important or not?

1.9. SISVAT is a multi-layer snow model, and each snow layer has its own heat capacity and conduction coefficient. Firn temperature measurements were done during summer 2009 – 2010 (Brun et al. 2011) but not during OPALE.

33096, line 26: Would the orientation of the sastrugi relative to sun orientation also affect the albedo? I think there was a paper by Gerd Wendler in the 1980s on this.

1.10. Indeed the effect of sastrugi is not included in MAR and this now mentioned on p. 33096, line 26. Influence of sastrugi on snow albedo is mentioned on p. 33097, line 21.

33099, lines 27-28: Note there is a subtle consideration with "winds from the south": these lie along terrain contours (compare the 120oE meridian with the 3250m contour). Winds from the southwest might be from the "ocean" namely the Ross Sea region although the origin of trajectories are rarely related to local wind directions. Something that would greatly add to the analysis would be using the high resolution of MAR to present some trajectory clusters for various key periods during OPALE. Another concern is that the plateau area to the south is often a region of high photochemical production (Slusher et al 2010). Whether this impacts Concordia may be a good question.

1.11. Indeed, transport of chemical species in the BL may not be neglected when the wind comes from the ocean. Oceanic influences are typically arriving (from the 1000 km far away northern coast) at Dome C under northerly wind conditions. In addition chemical measurements were made a few hundred meters southwards from the main Station of Dome C. This is why northerly wind situations were not considered during OPALE.

Concerning potential southerly wind advections with potential enriched photochemical produced species, this was not considered in the actual chemistry manuscripts since they treat actually species with a rather short atmospheric lifetime. This should be the purpose of a future study when examining for example the ozone budget at Dome C. Neglecting situations with advection is mentioned in p.33092 line 28 and following.

33100, lines 20-21: Focusing the discussion on 26-28 December because of intensive observation of chemical species is "interesting." However, in looking through the other papers submitted to the OPALE special issue I didn't find this period called out (although there was a lot to look through and I might have missed it.) More interesting meteorology, as far as the behavior of the HOx-NOx system goes, falls in the period 1-18 December with high winds (above the threshold for blowing snow) that precede a dramatic increase in surface nitrate (Berhanu, OPALE special issue) around 4-9 December. A future research question could well be modeling these types of meteorology and chemistry and whether blowing snow is related in increases in surface nitrate. This surface nitrate increase is followed by followed by large increases in atmospheric Nox concentrations (which appear to depend on wind speed) and surface to atmosphere NOx fluxes until 20 December. As snow nitrate and atmospheric concentrations decline could the MAR model be used to quantify the export of NOx, OH and other radicals?

This should be the purpose of a future study, for example by activating the transport of tracers and possibly the generic chemical model of MAR.

Remember there is an "E" in OPALE. Also of interest is 9 January which is described in Frey et al (special issue): in this case the shallow boundary layer modeling is really critical to evaluate to compare with the profile measurements of NOx.

1.12. The reason for choosing 26 – 28 December is given on p. 33100 line 20.

Blowing snow may have occurred during OPALE but we have no observations of that phenomenon. MAR simulated a blowing snow event on 29 December. Influence of blowing snow could be considered in a future study also taking into account the influence of transport.

As already explained it was not possible to compare MAR to the observations on 9 January.

33101, lines 19-22: With respect to Fig. 4b, the authors refer to an underestimation of temperature (cold bias) in the morning (27 and 28 December) although this bias starts in the evening with the collapse of the daytime boundary layer and intensifies as the model wind speed drops during the night. Should not this cold bias influence calculation of the boundary layer depth? Also when the boundary layer is at or below 10m does MOST still work? In Frey et al, they report that when the boundary layer is less than 10m they remove all the NOx flux data from the analysis (the inlet is at 1m which would be 10% of the depth). It would have been useful to have statistics from model-sodar comparisons for boundary layer depth for the entire experimental period, by time of day, rather than just one example. Frey et al show a time series of modeled boundary layer depth for the entire experimental period. Unfortunately, shallow boundary layer periods are not resolvable in their figure. However, in Kukui et al., they show a high resolution figure (their Fig. 1) with boundary layer depths that are effectively zero even though u* never goes to zero. Is it possible that the model is better than assumed with Frey et al.'s 10-m cutoff. After comparison with sodar data this would be extremely important to assess in diagnosing surface chemistry after the collapse of the daytime convective boundary layer. This assumes that a sodar minimum range of 2m was used (the sodar's mode 2: Argentini et al. 2013), As Davis et al. 2008 have pointed out the HOx-NOx system can become very non-linear under conditions of both low OH production and shallow boundary layers that allow NOx concentrations to exceed 250 pptv in a non-linear fashion. Of note, Frey et al show values right after 11/12/11of NOx exceeding 2500 pptv.

1.13.0. p.33101 line 19 is reworded and a sentence is added about the starting time of the underestimation.

1.13.1. The underestimation of turbulence by the K-e model during night-time is explained in p.33101 lines 28-29. Of course this could lead to an underestimation of the BL height. This detail is added on p.33102, line 4.

1.13.2. The BL height is a diagnostic from the turbulence model of MAR. It is never smaller than the height of the lowest level of the model. Unfortunately we do not have continuous sodar measurements to get a comprehensive comparison between the simulated and observed BL height. The period from 26 to 28 December was also chosen to evaluate MAR since it is the longest period for which we have continuous sodar measurements together with other meteorological observations.

1.13.3. MOST could be responsible for the cold bias but as explained on p. 33101 lines 24 – 25 the downward turbulent heat flux is well simulated. Looking at the experiment with 1 m resolution it is found that the weakening of the turbulent fluxes from 1 to 2 m amounts to slightly more than 20%, a value that is larger than the usual departure from constancy generally accepted (10%). More generally temperature and wind speed at 2 m in the simulations with 1 m and 2 m resolution near the surface have been compared. It has been found that when clear sky is observed they are not sensitive (differences no larger than 1.5°C to 2°C or 1 m/sec) to the vertical resolution even when in the simulation with 1 m resolution the turbulent fluxes between 1 m and 2 m depart from the constancy by 30%. These additional explanations have been included after p.33101 line 27.

1.13.4. Note also that a cold bias near the surface is simulated since simulated turbulence does not shut down. Rather a decoupling of the lowest layers of the model with the surface would have lead to a warm bias.

Figure 3. It would be useful for cross-referencing the chemistry papers to the model results to highlight (say using light gray shading) periods called out in other papers. For example, in Frey et al. 9 January was a special case (their Figure 2) where balloon profiles were made. The authors should

probably call out other specific cases discussed in the OPALE papers. In 9-January case, MAR significantly underestimates the 3-m temperature at night but appears to overestimate wind speed if I am interpreting dates correctly (it would be useful in these plots to have a vertical grid lines). In the lower right of the figure, for friction velocity it would be useful to plot the MAR simulation over the BAS observations because the magenta area covers up the comparison with MAR.
In this case it would be useful to see whether the friction velocity or the more rapid cooling in MAR is more important to the calculation of the boundary layer depth. In the wind direction plot, it would be useful to have the ordinate divided for the cardinal and ordinal directions (90 and 45 degree intervals).

1.14. Grey shading is used for cloudy periods (DLW assumed to be higher than 130 W/m2). MAR simulation of friction velocity is plotted over the BAS observations. Ordinate are divided in cardinal and ordinal direction in wind direction plot.
Unfortunately MAR works wrong on 9 January 2012.

Figure 6: The black model line should be plotted on top of the blue sodar stars. Can you explain why the sodar reveals an earlier peak and fall-off in boundary layer depth than does the model? Is this some combination of radiative balance, wind speed, surface heat flux or something else?

1.15. The earlier peak and fall-off in boundary layer depth is marked on 26 December and is due to the presence of clouds, which are not simukated. This is indicated on p.33103, line 14.

Anonymous Referee #2 . Received and published: 25 January 2015

General assessment

This paper describes the performance of a mesoscale atmosphere model when applied to summertime conditions over Dome C, East Antarctica. In general a good agreement is found for wind speed and wind direction, but important deviations are found in simulated shortwave/longwave radiation components and near-surface temperatures. The paper is reasonably well written, but the English needs improving by the editorial staff.
Here I only provide textual comments when a formulation may cause confusion. The figures are generally of good quality. The added value of the science requires better motivation. All in all the paper requires major revisions, see below.

Major comments

The introduction must be restructured and rewritten so as to include more specific information how mesoscale models like MAR can assist in the interpretation of the chemical composition of the Antarctic boundary layer. The current model does not have a chemical routine, so please explain explicitly how the current results are of value for OPALE. Can the results be used to drive an offline chemistry module? It must also become clear what this study adds to previous knowledge on the ABL structure over Dome C, since quite a number of observational studies have been published on that topic recently.

2.1.1. More information on how mesoscale models can assist in the interpretation of the chemical composition of the Antarctic boundary layer is included in the introduction on p.33092 line 17.

2.1.2. Other papers of the special issue use MAR BL height and eddy diffusivity to drive chemical 1D box models (see Legrand et al., 2014, Kukui et al., 2014 and Preunkert et al., 2014). Frey et al. (2014) uses simulated BL height to decide if the conditions to use the Monin-Obukhov Similarity Theory (MOST) are met. More details is included in the paper about what and how model data are used in other papers on p.33092, line 27.

2.1.3. The purpose of the paper is also to analyze the impact of MAR turbulence on the vertical profile of meteorological variables. Such a work has not yet performed with so much details.

Page 33096: An elaborate description is given on the parameterizations of surface and surface layer processes, e.g. z0 as a function of sastrugi formation and decay and the interaction of blowing snow with the vertical transport of radiation; disappointingly little of the influence of these elaborate parameterizations on the model results is found back in the discussion of the results. How important are these model adjustments for the final results at Dome C? For instance, it would be nice to discuss a time series of z0. Was blowing snow a common occurrence during the campaign? If so, was this simulated by the model? Etc.

2.2. Parameterization of z0 was not modified since the study on blowing snow by Gallée et al. (2013). Observations of blowing snow and roughness length were not done at Dome C during OPALE. Nevertheless the simulation of a blowing snow event on 29 December is responsible for a change of the roughness length from almost constant values of 0.05 mm to 2 mm at Dome C. No significant sensitivity to this change may be found from a look to Fig. 3. Some information about that point is given on p. 33100 line 6.

Same page: how is the calibration (line 27) performed? How did MAR perform in terms of 3 m wind speed before this calibration was performed?

2.3. The calibration of the roughness length is performed from observation made near the coast of Adélie Land (see Gallée et al., 2013). No changes have been made for this study since observations were not available. See also p. 33100 line 6.

Table 1: It is remarkable that both LWd and SWd are underestimated. When cloud cover is underestimated in the model, as is suspected, one would expect SWd to be overestimated. Any thoughts?

2.4. We use the solar routine developed by ECMWF. One could expect that SWd is larger than expected when cloud cover is underestimated but this does not preclude the solar routine to underestimate SWd under clear sky situations.

p. 33090, l. 24: the model used by Van As and others (2006) had very high vertical resolution, in the cm range near the surface; in terms of physics, it was not simpler, just 1D. How important are 3D (advection) effects over Dome C, in other words, what is the added effect of performing 3D simulations?

2.5. Advection effects and changes in the pressure gradient force (PGF) are handled in a more realistic way with a 3D model than with a 1D model, since both processes are highly non linear in the real atmosphere. Furthermore Dome C is surrounded by slopes, so that atmospheric dynamics there are characterized by mass divergence when downslope flows occur (usually during night for clear sky conditions). Mass divergence may be responsible for a thinning of the BL at Dome C. Finally as the aim is to use a 3D model in future studies, we prefer to use it and compare it with the observations rather than developing a new 1D model. The additional knowledge of MAR we gain from this study will help us for future studies including e.g., the transport of chemical species.

Another important difference between Van As and others (2006) and this study is that Kohnen is situated on a ridge with surface slope, generating a mixture of inertial oscillations and katabatic winds, while Dome C has no or very little slope, deleting the impact of katabatic forcing. This is supported by the absence of a nocturnal wind speed maximum. Please add a brief discussion along these lines (difference between climate of the ice shelves, the ice sheet slopes and the interior domes) in the introduction, and how these differences in e.g. daily cycles could impact the chemistry of the boundary later.

2.6. Low level jet may be responsible for a nocturnal wind speed maximum just above the BL at Dome C. This point was mentioned on p.33102 line 27 and detailed in a companion paper by Gallée et al. (2014).

The very low air temperatures at Dome C strongly limits latent heat fluxes at Dome C so that the conditions for developing a well mixed layer during daytime are optimal, in contrast to the situation over the ice shelf, as at Halley, for example. This is mentioned on p. 33091 line 20.

Also the Antarctic plateau is far away from the coast, so that the chemical properties of the air masses coming from the Antarctic interior at Dome C are rather homogeneous. This is mentioned on p.33092, line 28.

p. 33103, l. 3: "... while the pressure gradient force (PGF) still contributes to an increase of the wind speed after that time..." but the supergeostrophic wind speeds in the nocturnal jet are caused by a combination of (frictionless) inertia and the Coriolis effect, and do not require changes in the geostrophic wind speed.

2.7. Wind speed (and not geostrophic wind speed) is mentioned in the sentence. Simulated wind speed is smaller than geostrophic wind speed during daytime and does not become supergeostrophic immediately after turbulence shuts down. Rather it tends to become supergeostrophic after some time and then to come back to the geostrophic equilibrium, causing an inertial wave.

Minor and textual comments

p. 33090, l. 17: preferably use 'evaluation' instead of 'validation' when it concerns models

2.8. OK

p. 33090, l. 20: for -> in

2.9. OK

p. 33090, l. 22: remove 'circulation'

2.10. OK

p. 33090, l. 23: an approach ...done -> a study...performed

2.11. OK

p. 33091, l. 13: able -> enable

2.12. OK

p. 33092, l. 27: "...the low troposphere..." perhaps leave out 'low' for a site > 3000 m asl

2.13. OK

p. 33093, l. 26: the sensors used in the K&Z CNR1 are CG3 pyrgeometers and CM3 pyranometers (I may be wrong, please check). Please state their accuracy; if I remember well, measurement error maybe substantial for these sensors and may explain part of the obs-model bias.

2.14. The reviewer is right, the sensor used is a Kipp & Zonen CNR1 which combines two CM3 pyranometers for downward and upward broadband shortwave radiation flux (spectral range 305–2800 nm) and two CG3 pyrgeometers for downward and upward broadband longwave radiation flux (spectral range 5– 50 µm). The K&Z CM3 pyranometer is a thermopile type pyranometer, covered by a single glass dome, which complies with ISO 9060 second-class specifications (estimated accuracy for daily totals ±10%). The K&Z CG3 pyrgeometer consists of a thermopile sensor covered by a silicon window that is transparent for far-infrared radiation but absorbs solar radiation. The factory-provided estimated accuracy of the K&Z CG3 for daily totals is also ±10%.

Errors which may affect the SHW radiation in Antarctica: 1) Icing of the sensor dome, 2) Rime formation on the sensor Dome, 3) Low sun Angle, 4) Sensor tilt, 5) High surface albedo.

Errors which may affect the LW radiation: 1) Window heating offset, 2) Riming of the upward-facing pyrgeometer window, 3) Riming of the downward-facing pyrgeometer window.

Van den Broeke et al. 2004a [Surface Radiation balance in Antarctica as measured with automatic weather stations. M. Van den Broeke, C. Reijmer, and Roderik van de Wal, Journal of Geophysical Research Vol. 109, D09103 doi:10.1029/2003JD004394, 2004] compared radiation measurements of the K&Z CNR1 with radiation data collected at Neumayer station, a BSRN station (70.7°S, 8.4°W, 50 m asl) for a 10-day period in February 2001. At Neumayer, the radiation instruments (K&Z CM11 for shortwave radiation and Eppley PIR for longwave radiation) are ventilated with slightly heated air to prevent rime formation. The comparison yielded a root mean square difference of 2.7% (4.8 W m−2) for daily mean SHWdown and 1.2% (2.7 W m−2) for daily mean LWdown. This shows that under controlled conditions the K&Z CM3 and CG3 perform much better than the listed specifications. Similar results were found by Van den Broeke et al. 2004b (Assessing and improving the quality of unattended Radiation Observations in Antarctica, M. Van den Broeke, D. Van As, C. Reijmer, and Roderik van de Wal, Journal of Atmospheric and Oceanic Technology, 2004).

p. 33095, l. 7: in the absence of a significant surface slope at Dome C and the fact that it is the highest point of the region, I do not expect drainage flow but rather radially diverging flow away from the dome, see major comment above.

2.15. The simulation is 3D and not 1D. Drainage winds will be simulated everywhere over the domain except probably over the Dome.

Characterization of the boundary layer at Dome C (East Antarctica) during the OPALE summer campaign

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Abstract

The regional climate model MAR (Modèle Atmosphérique Régional) was run for the region of Dome C located on the East Antarctic plateau, during Antarctic summer 2011 – 2012, in order to refine our understanding of meteorological conditions during the ~~OPALE observation~~tropospheric chemistry campaign OPALE. A very high vertical resolution is set up in the lower troposphere, with a grid spacing of roughly 2 m. Model output is compared with ~~Comparisons are made with observed~~ temperatures and winds observed near the surface and from a 45 m high tower as well as sodar and radiation data. MAR is generally in very good agreement with the observations but sometimes underestimates cloud formation, leading to an underestimation of the simulated downward long-wave radiation. Absorbed short-wave radiation may also be slightly overestimated due to an underestimation of the snow albedo and this influences the surface energy budget and atmospheric turbulence. Nevertheless the model provides sufficiently reliable information ~~that represent~~about ~~and~~surface turbulent fluxes, vertical profiles of vertical diffusion coefficients and boundary layer height ~~key parameters~~ when discussing the representativeness of chemical

measurements made nearby the ground surface during field campaigns conducted at ~~the~~ Concordia ~~site~~ station located at Dome C (3233 m above sea level).

1. Introduction

The aim of this paper is to ~~valid~~evaluate MAR (Modèle Atmosphérique Régional) simulations ~~covering~~ during the OPALE ~~summer~~ campaign~~, which took place~~ at ~~Conco~~Dome C~~rdia~~ ~~during~~ in austral summer 2011 – 2012 (from late November 2011 to mid-January 2012), ~~for use~~to support ~~for~~in the interpretation of ~~the chemistry~~ observations ~~carried out during the campaign~~of tropospheric chemistry. ~~It is intended in~~ A particular purpose is to characterize the behaviour and the vertical structure of the boundary layer ~~circulation~~ at Dome C during this period.

A similar study has been ~~performed has been already donestudySuch an approach~~carried out previously above~~ over~~ the East ~~a~~Antarctic plateau, based on summer time observations at Kohnen station in Dronning Maud land, albeit only with a ~~but with a~~ more simpl~~er~~istic ~~vertical~~ 1-~~d~~D model~~, which has been evaluated from observations during summertime at Kohnen base, in Dronning Maud Land~~ (Van As et al., 2006).

Dome C is an area where observation and modelling of the boundary layer has already been performed due to its particular location (Swain and Gallée, 2006, Sadibekova et al., 2006, King et al., *2006*, Gallée and Gorodetskaya, 2010, Genthon et al., 2010, 2013, Brun et al., 2011, Lascaux et al., 2011, Argentini et al. 2013, Pietroni et al. , 2014)~~ belowetails on that point are given and d~~. Furthermore ~~due to an already available set of observations, Dome~~, 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). In spite of its remote location Concordia station, operated year-round, is logistically well supported due to a number of reasons. ~~Indeed, despite the harsh environment of Antarctica it is well supplied by~~

~~logistics for many reasons. It is a dome on the East Antarctic plateau and~~Dome C ha~~s~~d been chosen as part of ~~in the framework of~~ the EPICA project for drilling the ice core with the longest climate chronology ever recorded, allowing to study the climate of the last eight glacial cycles (EPICA community members, 2004). The EPICA project initiated extensive meteorological observations at Dome C, in order to establish~~ firmly~~, among others, the relationship between ~~Dome C~~local ~~climate~~ and global climate. ~~So the set up of~~Therefore setting up a regional model at the Dome C drilling site enables (i) to assimilate large scale meteorological conditions and (ii) to simulate local atmospheric conditions, which ~~may be helpful~~contributes ~~in~~to establishing this relationship. The good management of logistics between the Concordia station and the Antarctic coast (Terre Adélie) and the low optical turbulence at Dome C also promoted the site for astronomical observations (see e.g., Swain and Gallée, 2006, Sadibekova et al., 2006). The main characteristic of meteorological conditions at Dome C is that turbulent conditions in the ~~low trop~~near-surface atmosphere are only effective in a rather shallow layer~~ only~~, especially during night-time (Pietroni et al. , 2014). During day-time the sensible heat fluxes are much larger than the latent heat fluxes, because of ~~the~~ low temperatures and ~~the~~ subsequently very low ~~capacity of the~~ atmospheric moisture content ~~e to contain water~~ (~~see e.g.,~~ *King et al., 2006*). Consequently the conditions for develop~~ing~~ment of a well mixed layer during daytime are optimal, in contrast to the situation ~~on the ice shelf~~in coastal Antarctica such as Halley station ~~, as at Halley for example~~(King et al., 2006). This means that the simulation of summer case studies at Dome C ~~could help a lot~~will be very useful in validating the turbulence scheme of ~~an~~ atmospheric models. Sodar ~~measurement~~ and sonic anemometer measurements w~~h~~ere done at the Concordia station to monitor the turbulent structure of the planetary boundary layer (PBL) in connection with the temperature inversion and estimate the PBL height in the frame of the ABLCLIMAT (Atmospheric Boundary Layer Climate) project (Argentini et al. 2013).

The 45 m high tower built up at Concordia is also a very useful tool for observing such conditions (Genthon et al., 2010, 2013). Short-term meteorological simulations have already been done over Dome C with a coupled atmosphere – snow model, focusing on the behaviour of the snow model (Brun et al., 2011). Long term simulations ~~(i.e., without any reinitialisation of meteorological variables)~~ of the Antarctic climate have also been done, with a focus on their behaviour at Dome C. Swain and Gallée (2006) and Lascaux et al. (2011) used respectively the limited area models MAR (without any reinitialisation of meteorological variables) and Meso-NH to compare the optical properties of the atmosphere at Dome C with those of other potential Antarctic sites for astronomical observations using a large telescope. Gallée and Gorodetskaya (2010) validated MAR for winter conditions, emphasizing~~stressing on~~ the difficulty to accurately simulate the downward long-wave radiation and proposing to include the influence of small airborne snow particles in the parameterization of the radiation transfer. MAR has also been used for providing information on the atmospheric turbulence at Dome C in summer, which appears to very significantly control the vertical ~~distribution~~ flux and concentration profiles~~s~~ of numerous atmospheric chemical species (Legrand et al., 2009, Kerbrat et al., 2012; Dommergue et al., 2012, Frey et al., 2013). Finally two years of observations at the Dome C tower were used to compare a long-term simulation of MAR with ECMWF analyses, showing the interest to represent the atmosphere with a fine vertical resolution (Genthon et al., 2013). Here we go a step further by ~~validating~~evaluating in detail the model for summer conditions ~~in the frame of the~~during the OPALE campaign ~~which took place during Austral summer 2011 – 2012~~.

The ~~main~~general ~~objective~~ motivation of the ~~paper~~present research is to provide tools from a meteorological point of view for future campaigns dedicated to ~~document~~ investigate the chemical composition of the Antarctic boundary layer ~~of~~ above the East Antarctic plateau. Thus, the first objective of this paper is to evaluate a meteorological model that is capable of simulating transport and that can be coupled to a chemical routine. ~~To reach that goal a meteorological model that could simulate transport and be coupled to a chemical routine must be evaluated. This is the main objective of the paper.~~

The second objective of the paper is to provide ~~()~~ key physical parameters of the atmospheric boundary layer ~~as well as~~ for the interpretation of~~ng~~ data gained during the OPALE campaign~~s~~ as detailed in companion papers (see Legrand et al., 2014; Kukui et al., 2014; Frey et al., 2014, and Preunkert et al., 2014). Transport processes are not considered during the 2011-2012 OPALE campaign and we will focus on situations characterized by an atmospheric circulation localized over the Antarctic plateau, where chemical properties of the air are rather homogeneous from one point to another. ~~More precisely~~This means that from a meteorological point of view atmospheric turbulence plays ~~an~~the most important role in the ~~evolution~~ fate of atmospheric NO_x, HONO, HCHO, or H_2O_2 emitted by the snow pack. Key parameters are surface turbulent fluxes and the height of the boundary layer, which is determined by vertical turbulent diffusion. These parameters are used in companion papers to determine the contribution of turbulence to the concentration of key atmospheric species emitted from the surface, driving the oxidant budget in the ~~low trop~~near-surface atmosphere at Dome C. ~~More precisely~~ MAR turbulent vertical diffusion coefficients are used by Preunkert et al. (2014) and the uncertainty of the later on HCHO mixing ratios is discussed. Legrand et al. (2014) also use the same MAR outputs to force their 1-D box model to simulate ~~of~~ HONO mixing ratios. Kukui et al. (2014) performed similar calculations using the same MAR output. Frey et al. (2014) use MAR boundary layer heights to determine when they may apply the Monin–Obukhov similarity theory for calculating the turbulent fluxes of NOx in the surface boundary layer. Other parameters like cloud cover and wind direction are ~~also~~ considered for chemical analyses. For example situations with an overcast sky were not considered nor situations for which the wind direction is from Concordia station, since the air is then contaminated by pollutants emitted by the station. ~~in conjunction with an atmospheric circulation which is not localized only on the Antarctic Plateau and is responsible forOPALE~~ ~~Also~~Sunny sky conditions were preferred since the assumption of a similar downward shortwave (DSW) radiation from sunny day to sunny day may be done. From a meteorological point of view these criteria also allow us to avoid most of the situations for which clouds are underestimated by MAR leading to an erroneous behaviour of the surface energy budget, and subsequently of atmospheric turbulence, as explained by Legrand et al. (2014). Fortunately such a behaviour of MAR allows us to analyze the best part of the simulation which corresponds to the same days for which the analysis of chemical species is the easiest.

The remaining of the paper is divided in 4 parts. The experimental set-up and the main characteristics of the MAR model are described in sections 2 and 3. The fourth section is dedicated to the evaluation of the model, looking in particular ~~to the consequences~~at the impact of the simulated radiative transfer on the surface atmospheric energy budget and atmospheric turbulence.

2. Meteorological observations

2.1. ISAC (Istituto di Scienze dell' Atmosfera e del Clima)

One-year in situ turbulence and radiation measurements, as well as ~~SL~~ sodar observations, were carried out at the Concordia station from December 2011 up to December 2012 ~~in the frame~~as part of the *ABLCLIMAT* ~~*(Atmospheric Boundary Layer Climate)*~~ project (Argentini et al., 2013).

The SL-sodar (Surface Layer sodar, Argentini et al., 2011) is an improved version of the sodar described by Argentini and Pietroni (2010), with the possibility of zooming ~~within~~ into the atmospheric surface-layer thermal turbulent structure. With the SL-Sodar, the PBL height *h* is estimated following Casasanta et al. (2014). During convective conditions *h* was determined as the height above the zone of weak backscattered intensity of the acoustic waves emitted by the sodar. Under stable conditions, *h* was retrieved either from the minimum of the first derivative of the backscattered signal, ~~either~~ or from its maximum curvature.

Measurements of turbulence we~~a~~re made with a Metek USA-1, a three-axes sonic thermo-anemometer (sampling frequency of 10 Hz) installed on a 3.5 m mast. The heat and momentum fluxes are estimated using the eddy covariance method. ~~The longwave and shortwave radiation components (up and down) were measured using Kipp & Zonen CNR1 pyrgeometers and pyranometers installed 1.5 m above the snow surface.~~ The longwave and shortwave radiation components (up and down) were measured with a ~~using~~ Kipp & Zonen CNR1 radiation sensor. This instrument combined two CM3 pyranometers for downward and upward broadband shortwave radiation flux (spectral range 305–2800 nm) and two CG3 pyrgeometers for downward and upward broadband longwave radiation flux (spectral range 5– 50 µm). Pyrgeometers and pyranometers were installed 1.5 m above the snow surface.

2.2. LGGE (Laboratoire de Glaciologie et de Géophysque de l'Environnement)

Meteorological ~~profiling is carried out along~~measuremen~~s~~ts were made on a 45-m tower at Dome C since 2008 (Genthon et al. 2010). Wind, temperature and moisture are monitored at six levels from the near surface (3.5 m) to near the top of the tower (42.1 m). The instruments occasionally fail due to the extreme weather conditions at Dome C (extreme low temperatures, frost deposition), however the data record is almost continuous since 2009 and the instruments work ~~perform~~ generally quite well in summer (Genthon et al. 2013). Genthon et al. (2011) have demonstrated that a ~~warm~~ bias to warmer temperatures affects ~~temperature~~ measurements in Antarctica in~~s~~ cases of weak winds if conventional passively (wind) ventilated radiation shields are used to protect solid state thermometers (e.g. the ubiquitously used platinum thermistors) from solar radiation. To overcome this problem the temperature measurements on the tower at Dome C are made in aspirated shields. ~~At Dome C, only the temperature measurements on the tower are made in aspirated shield and bias free.~~ Further details of the profiling set up, instrumentation and results obtained so far can be found in Genthon et al. (2010, 2013).

2.3. BAS (British Antarctic Survey)

Measurements of turbulence are made with a Metek USA-1, a three-axes sonic thermo-anemometer (sampling frequency of 25 Hz) -mounted on a mast 4 m above the snow surface. The mast was set up in the clean-air sector at about 1.2 km distance from the 45-m meteorology tower (map in Frey et al., 2013), at the site where the chemical ~~co-located with OPALE detectors of chemical~~ trace gas species were measured during the OPALE campaign ~~in the clean air sector at about 1.2 km distance from the 45-m meteorology tower (map in Frey et al., 2013)~~. Atmospheric boundary layer parameters such as friction velocity u_* and Monin-Obukhov Length were computed from the three-dimensional wind components (u, v, w) and temperature (Frey et al., 2014, this issue). Processing in 10-min blocks included temperature cross-wind correction and a double coordinate rotation to force mean w to zero (Kaimal and Finnigan, 1994; Van Dijk et al., 2006).

3. Description of MAR

An overview of the regional climate model MAR is given here, focused on the description of the turbulence scheme. A more complete description can be found in Gallée and Schayes (1994), Gallée (1995) and Gallée et al. (2013).

MAR atmospheric dynamics are based on the hydrostatic approximation of the primitive equations. This approximation is correct when the vertical extent of the circulation (here the drainage flow) remains much smaller than the size of the grid (here 20 km). Nevertheless, it should be noted that non-hydrostatic processes may be responsible for a weak deceleration of the katabatic flow (Cassano and Parish, 2000). The vertical coordinate is the normalized pressure, with the model top situated at the 1 Pa pressure level. Parameterization of turbulence in the surface boundary layer~~ (SBL)~~ is based on the Monin-Obukhov simi~~u~~larity theory (MOST) and is completed by taking into account the stabilization effect by the blowing snow flux, as in Gallée et al. (2001) (see also Wamser and Lykossov, 1995). Turbulence above the ~~SBL~~suface boundary layer is parameterized using the local E - ε model, consisting in two prognostic equations for turbulent kinetic energy and its dissipation. The prognostic equation of dissipation allows to relate the mixing length to local sources of turbulence and not only to the surface. The E - ε model used here has been adapted to neutral and stable conditions by Duynkerke (1988) and revised by Bintanja (2000), who included a parameterization of the turbulent transport of snow particles that is consistent with classical parameterizations of their sedimentation velocity. The influence of changes in the water phase on the turbulence is included following Duynkerke and Driedonks (1987). The relationship between the turbulent diffusion coefficient for momentum and scalars (Prandtl number) is dependant on the Richardson number, according to Sukoriansky et al. (2005).

Prognostic equations are used to describe five water related parameters ~~, as in (~~Gallée, ~~(~~1995): specific humidity, cloud droplets and ice crystals, raindrops and snow particles. A sixth equation has been added describing the number of ice crystals, and the influence of hydrometeors on air specific mass is included in the model ~~as in (~~Gallée et al. (2001). This allows us to account for the influence of the weight of eroded particles on atmospheric flow dynamics by representing the pressure gradient force as a function of air density rather than of potential temperature only.

The radiative transfer through the atmosphere is parameterized following Morcrette (2002) and is the same as the one ~~at~~ used in ERA-40 re-analyses. As blowing snow particles are small (Walden at al., 2003), they may have an impact on the radiative transfer. Influence of snow particles on atmospheric optical depth is also included in the MAR model (Gallée and Gorodetskaya, 2010).

Surface processes are modelled using the “soil-ice-snow-vegetation-atmosphere transfer” scheme (SISVAT, De Ridder and Gallée, 1998, Gallée et al., 2001, Lefebre at al., 2005, Fettweis et al., 2005). ~~In particular, the snow surface albedo depends on the snow properties (dendricity, sphericity and size of the snow particles).~~ The influence of snow erosion / deposition on surface roughness (z_0) is taken into account by allowing the aerodynamic roughness length to increase linearly as a function of the wind speed at 10 m above the ground level (a.g.l.) (V_{10}), when V_{10} > 6 m s^{-1}. The time scale for sastrugi formation is assumed to be half a day, as suggested by Andreas (1995), and the asymptotic value of the surface roughness length z_0 may increase linearly as a function of the wind speed V ($z_{0,lim}$ = 1.5 mm for V = 10 m s^{-1}; note that the friction velocity corresponding to V = 10 m

s^{-1} is generally slightly greater than 0.5 m s^{-1}). z_0 is allowed to decrease when precipitation occurs without wind ~~no~~ erosion of the snow ~~by the wind~~. Indeed the newly deposited snow progressively buries the sastrugi. Andreas et al. (2005~~, their Fig. 1~~) found values of z_0 ranging between approximately 10^{-4} and 100 mm, for friction velocities no greater than 0.6 m s^{-1}. ~~Also observations by~~ King and Anderson (1994) observed at Halley for compacted, sintered firn with some sastrugi , i.e. for ~~with~~ similar snow properties as encountered at Dome C,~~,~~ a ~~being compacted, sintered firn with some sastrugi revealed~~ z_0 value of (5.6 ± 0.6) × 10^{-5} m. The scatter of z_0 is~~is~~ very high and is explained by the high dependency of z_0 on sastrugi history. Our parameterization includes that effect in a simple way, and is calibrated to obtain the best simulation of the wind speed. Note that the snow surface albedo depends on the snow properties (dendricity, sphericity and size of the snow particles) and solar zenithal distance, but not on sastrugi nor sastrugi orientation.

4. Evaluation of MAR

We here used the 3-D version of MAR in order to take into account the influence of drainage winds on mass divergence at Dome C and consequently on subsidence and thinning of the boundary layer at the dome. ~~Also it would~~In addition this allows also to ~~take into~~ account for a possible influence of the inversion wind circulation over the Dome C area, as suggested by Pietroni et al. (2014). The MAR domain is represented in Fig. 1. The horizontal grid size is 20 km and the vertical discretization in the lower troposphere is 2 m, with 60 levels. The vertical resolution 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. In parallel MAR was also run ~~A simulation~~ with a vertical grid spacing of 1 m in the lower levels, ~~has also been done,~~ without any significant change in the results. Taking advantage of the higher vertical resolution near the surface the output of this latter model run was used~~The results obtained with this 1 m vertical grid have been used~~ to discuss the behaviour (in particular the diurnal cycles) of different atmospheric components as e.g. HONO, ROH, NOx, and HCHO, ~~chemical species~~measured near the surface during the OPALE campaign~~,~~ ~~in particular their diurnal cycles, as presented in other papers of this issue~~ (Legrand et al., 2014; Kukui et al., 2014; Frey et al., 2014; and Preunkert et al., 2014).

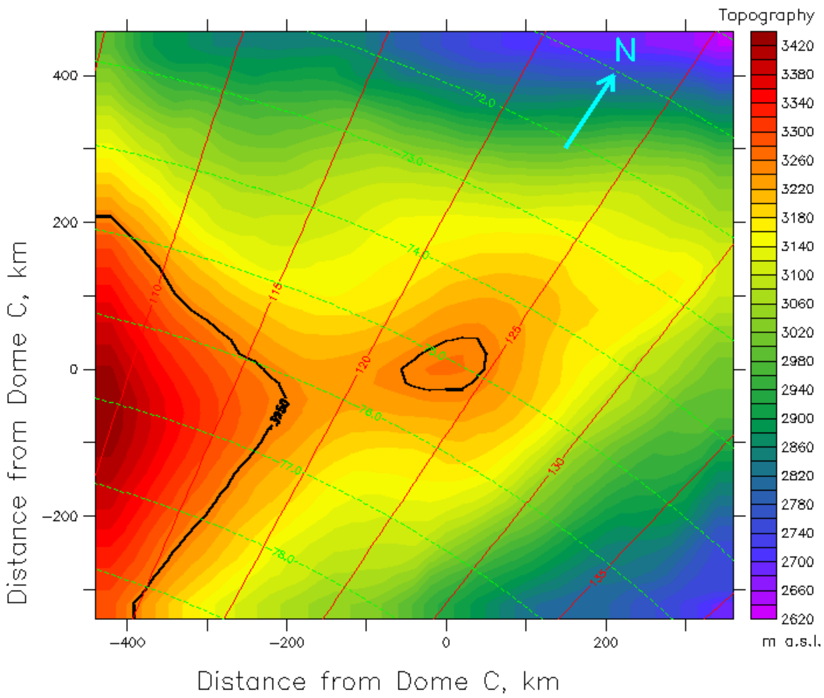


Fig. 1. The MAR integration domain and topography. The solid line refers to the 3250 m isocontour.

The MAR model is nested into the European re-analyses ERA-Interim (Dee et al., 2011). A relaxation zone of 5 grid points is prescribed at each lateral boundary (Marbaix et al., 2003) and model variables are nudged to the re-analysed variables in the upper 6 layers, i.e., above 13 km a.g.l. at Dome C. As the OPALE campaign took place from early December 2011 until mid January 2012, ~~the~~ MAR was run over ~~simulations were covering~~ 3 months (from 1 November 2011 until 31 January 2012). The model variables are assumed to adapt to Dome C conditions during the first simulated month (i.e., November 2011). The snow pack is initialized with a density of 300 kg m^{-3} and the assumption ~~and~~ of the ~~assuming the~~ presence of small grains, what results in a ~~giving a~~ slightly decreased ~~too low~~ initial albedo (close to 0.79 at noon), compared to the value (0.80-0.81) ~~while its value is~~ estimated by Brun et al. (2011). ~~in the range of 0.80-0.81 (Brun et al., 2011).~~ Note that the albedo would have been more underestimated if sastrugi orientation had been taken into account (Wendler and Kelley, 1988). ~~Nevertheless~~However no observation of sastrugi has been made during the OPALE campaign. Our analysis focuses on the period between 12 December 2011 and 14 January 2012, when most of the OPALE observations were made.

4.1. Cloud cover and surface energy budget

A problem already encountered when running the model over Adélie Land (East Antarctica) ~~was~~ is an underestimation of the cloud cover (but not always) and the subsequent underestimation (overestimation) of the downward long-wave (shortwave) radiation. As a consequence, a~~A~~n underestimation (overestimation) of air temperatures near the surface during night-time (day-time) results (Gallée et al., 2013). ~~Note however that the underestimation of the cloud cover is generally not critical since situations with an overcast sky are discarded when interpretating atmospheric chemistry measurements.~~

In the following we will investigate in how far this shortcoming occurs ~~Here we consider the possibility that this problem could also occur~~ also in the MAR simulations at Dome C. We note first that MAR generally underestimates both the short-wave and long-wave downward radiations, with a bias of about 24.3 W m^{-2} and 20.8 W m^{-2}, respectively (Table 1). The influence of the former on the surface energy budget is nevertheless less important than that of the latter, because of the high value of the snow albedo.

MAR		ISAC	ISAC 3 m	Tower 3 m	BAS 4 m
SWD	Bias	-24.3 W m^{-2}			
SWA	Bias	3.4 W m^{-2}			
LWD	Bias	-20.8 W m^{-2}			
Temperature	Corr. Coef.		0.981	0.912	0.973
	Bias		-0.387 °C	-0.642 °C	-0.551 °C
	RMSE		2.408 °C	2.778 °C	2.735 °C
	E		0.958	0.751	0.933
Wind Speed	Corr. Coeff.		0.865	0.872	0.856
	Bias		-0.227 m/s	-0.105 m/s	0.440 m/s
	RMSE		1.057 m/s	0.949 m/s	1.089 m/s
	E		0.737	0.752	0.677

Table 1. *Correlation coefficient, bias, RMSE (root mean square error) and efficiency statistical test of the simulated short-wave downward radiation (SWD), the short-wave absorbed radiation by the surface (SWA), the long-wave downward radiation (LWD), the temperature and the wind speed when compared to the observations made by ISAC (Istituto di Scienze dell' Atmosfera e del Clima) (3 rd and 4 th column), by LGGE (Laboratoire de Glaciologie et de Géophysique de l'Environnement) (at the tower, 5 th column) and by BAS (British Antarctic Survey) (6 th column). Data were averaged over an interval of 30 minutes.*

Let us now examine the downward long-wave radiation and the air temperature near the surface (Fig. 2). Both observations and simulation exhibit rapid variations in the long-wave downward radiation (LWD) (Fig. 2a). The correlation coefficient between the simulated LWD and cloud optical thickness is 0.79 for a 10 minutes time interval between each value of these variables, suggesting that cloud cover changes are responsible for most of these variations.

Fig. 2b compares the daily averaged bias (simulation minus observation) in the long-wave downward radiations (LWD) and air temperatures near the surface at Dome C. The former is generally underestimated, leading to the underestimation of the latter (see also Table 1). A significant correlation may be seen between both biases, even when the temperature bias may be positive while the long-wave downward radiation bias remains negative. But the latter bias is partially compensated by a slight positive bias in the absorbed solar radiation (Table 1), probably because of an underestimation of MAR snow surface albedo.

In contrast, the bias in the absorbed solar radiation may become negative, for example on 10 and 11 January 2012, when the bias in the long-wave downward radiation is almost zero and significant snowfall is simulated. The positive temperature bias on 31 December 2011 is probably due to an overestimation of the long-wave downward radiation by MAR.

Thus, as already observed along the Adélie Land Coast (see Gallée et al., 2013), MAR underestimates cloud cover at Dome C, but not always. ~~Note that this is also the case along the Adélie Land Coast (see Gallée et al., 2013).~~ This underestimation is responsible for an underestimation of the downward long-wave radiation. As long-wave downward radiation plays a key role in the surface energy budget and the subsequent behaviour of turbulence near the surface, this point will be considered in the remaining of the paper. Concerning the application of MAR for the interpretation of the atmospheric chemistry measured during OPALE, the underestimation of the cloud cover is generally not critical since situations with an overcast sky were not considered in these model applications.

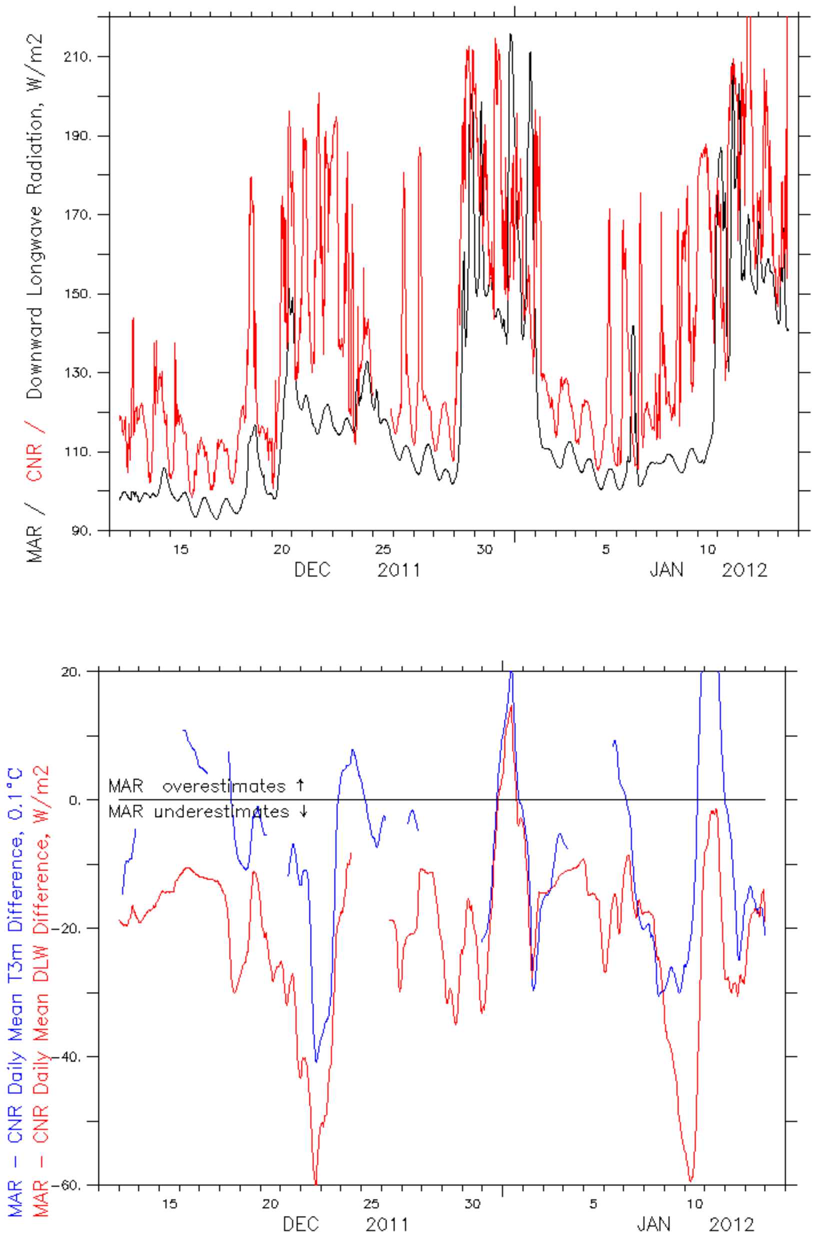


Fig. 2. *Top : Long-wave Downward radiation (LWD, W/m2) : simulation (dark line) and observation (red line). Data were averaged over an interval of 30 minutes. Bottom : comparison between the daily averaged LWD bias (red line) and air temperature bias (blue line, units : 0.1°C). Observations are those of the ISAC. MAR temperatures are averaged between 2 m and 4 m a.g.l. Gaps correspond to the absence of observations.*

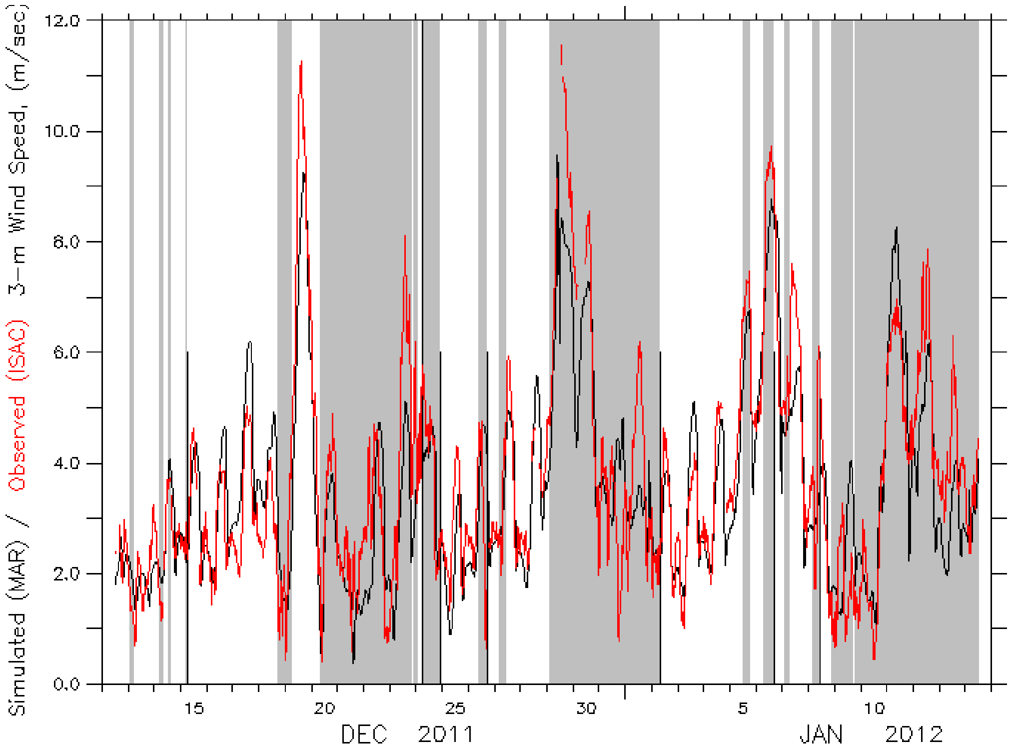
4.2. Wind and Temperature near the surface

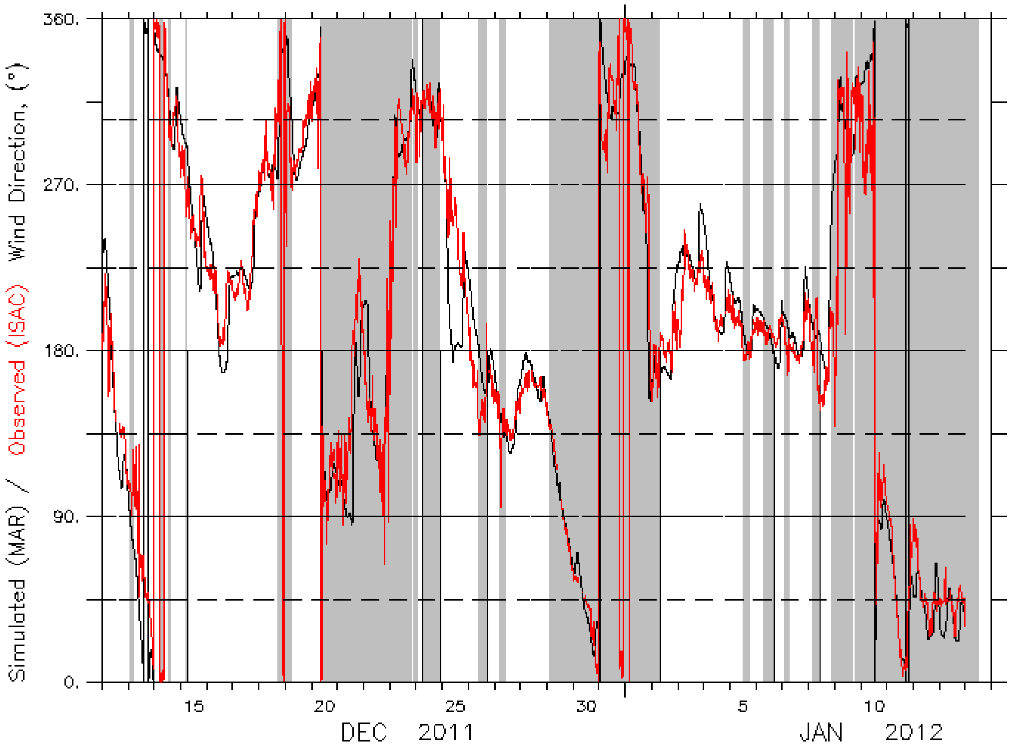
~~Next we look at the main meteorological variables (wind speed, temperature) near the surface.~~ The performances of the simulated temperature and wind speed are summarized in Table 1 by the correlation between simulation and observation, the bias (simulation minus observation), the root mean square error (RMSE) and the efficiency statistical test (*E*) proposed by Nash and Sutcliffe (1970):

$$E = 1 - RMSE^2 / s^2 \qquad (2)$$

where *s* and *RMSE* are respectively the standard deviation of the observations and the root-mean-square error of the simulated variable. Note that *RMSE = 0* implies *E = 1*. An efficiency index greater than *0* also means that comparing the simulated variable with the corresponding observation provides a lower *RMSE* than that obtained when comparing it with its time average. A negative efficiency index means that the *RMSE* is higher than the standard deviation of the observations. Finally, t~~T~~his then suggests that a detailed model would not improve the results when compared to a simpler model providing an estimation of the variable averaged over the time period concerned.

It is found that the efficiency statistical test for temperature and wind speed is not ~~o~~ lower~~smaller~~ than 0.677 for all comparisons (Table 1)~~,~~ giving us confidence ~~not only~~ into the respective ~~-~~time averages as well as ~~but also~~ into the fluctuations of these simulated variables~~model~~.


12.0
10.0
8.0
6.0
4.0
2.0
0.0
Simulated (MAR) / Observed (ISAC) 3-m Wind Speed, (m/sec)
15
20
25
30
5
10
DEC 2011
JAN 2012


360.
270.
180.
90.
0.
Simulated (MAR) / Observed (ISAC) Wind Direction, (°)
15
20
25
30
5
10
DEC 2011
JAN 2012

800

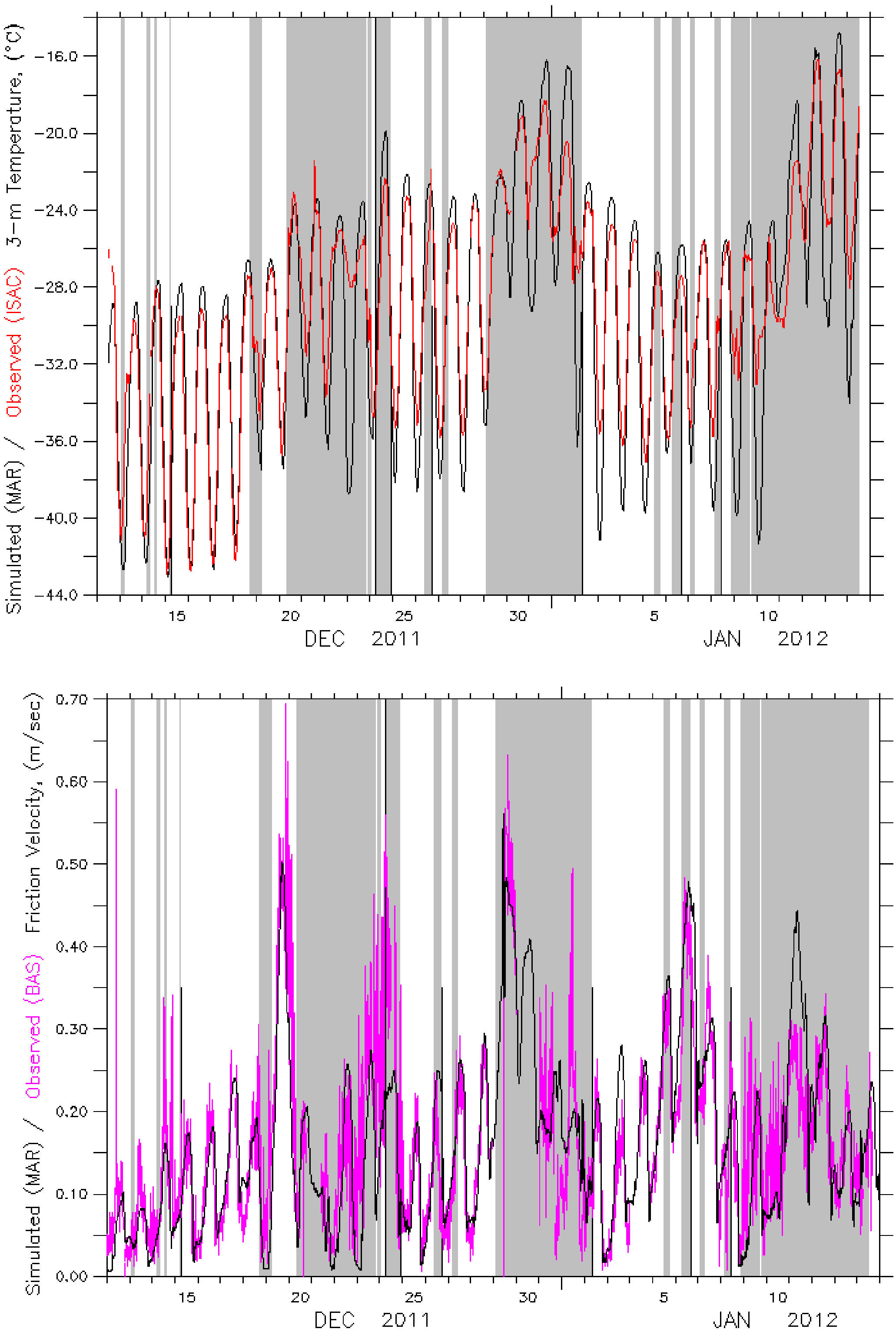


Fig. 3. *Simulation (dark line) of wind speed (top left), wind direction (top right), and air temperature (bottom left) at Dome C, 3 m a.s.l., compared with ISAC observations. Bottom right: simulation of friction velocity (dark line) compared with BAS observations (magenta line). Data were averaged over an interval of 30 minutes. Shaded area indicate periods with DLW > 130 Wm^{-2}*

For a more detailed examination ~~We here examine in more details~~of wind speed and temperature, t~~. T~~he comparison between simulated and observed wind speeds at ~~–~~3 m above the surface is shown in figure 3a. The agreement is good, as also quantified by the efficiency (0.737, Table 1). As it can be seen in Fig. 3b t~~T~~he agreement between the simulated and observed wind direction is also excellent.~~, as it can be seen by eye (Fig. 3b).~~ This behaviour indicates that the model is able to capture the atmospheric circulation at Dome C at the synoptic scale and is able to simulate the local circulation. Both, observation and simulation reveal two preferential wind directions, one from the plateau (southerly winds) and the other from the ocean (northerly winds). A well-marked diurnal cycle is generally found in the wind speed but does not exist in the wind direction. Wind speed peaks during the afternoon, when turbulent fluxes in the well mixed layer are able to transport momentum downwards more efficiently. Wind speed is also generally stronger and may be larger than 6 m s^{-1} in case of wind blowing from the North, except on 5 – 7 January 2012, when wind was blowing from the South. Note that the simulation of a blowing snow event on 29 December is responsible for an increase of the simulated roughness length from an almost constant in time value of 0.05 mm to an almost constant in time value of 2 mm. No significant change in the agreement between simulation and observations of the wind speed or of the friction velocity after this increase may be deduced from a look to Fig. 3. Consequently it is difficult to determine if the parameterization of the roughness length at Dome C is important for the~~is~~ simulation.

The ~~behaviour of the~~ simulated air temperature is also in good agreement with ~~good~~observations (Fig. 3c), although the simulated diurnal cycle is generally more ~~marked~~ pronounced than the observed one, especially for night-time (not shown for tower and BAS observations). The largest differences are found when simulations are compared~~ing~~ with the observations made at the tower. Note that, t~~T~~ower temperature measurements ~~observations~~ are performed~~made~~ in aspirated shields which have been demonstrated to avoid large warm biases with the most often used passively ventilated shields in cases of weak winds (Genthon et al. 2011). Since these ~~These~~ are the only temperature measurements ~~of temperature at Dome C~~ carried out in aspirated shields at Dome C, they are ~~and thus~~ (except of~~for~~ sonic measurements) the only ones which are unaffected by radiations biases.

Finally the good behaviour of the simulated friction velocity (Fig. 3d) suggests that MAR simulates surface meteorological variables ~~for the right reasons~~without compensating errors. From the previous analysis we have some confidence on the behaviour of the model in the surface boundary layer at Dome C during the OPALE observation period, but some discrepancies with the observations are found, even for sunny days.

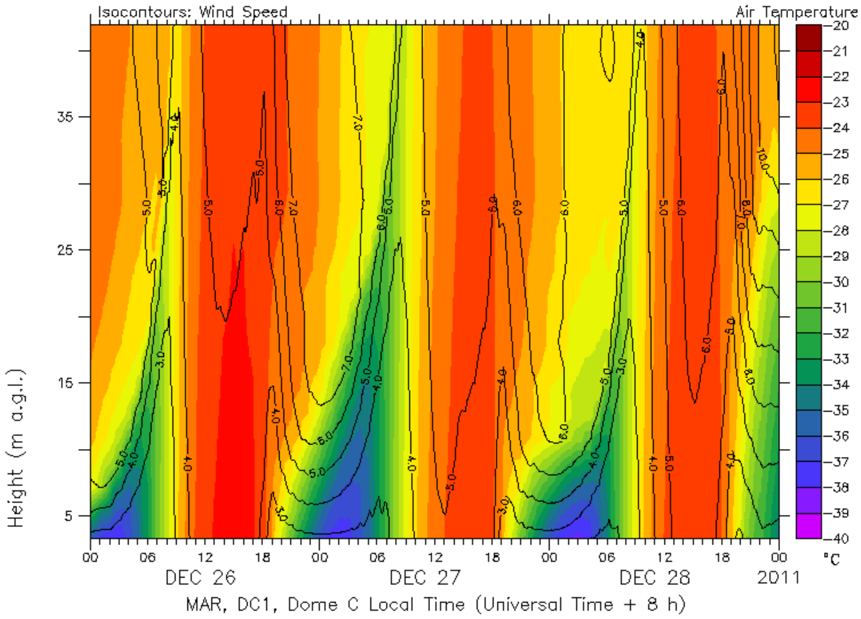
4.3. Period between 26 and 28 December 2011

In the following ~~We here~~ we will focus on the period between 26 and 28 December 2011, which is ~~a period of intensive observations of chemical species~~ also included in the studies of Legrand et al. (2014), Kukui et al. (2014), Preunkert et al. (2014), and Frey et al. (2014). Moreover this is the longest period for which we have estimations of the ~~PBL~~boundary layer height from sodar measurements. This period is characterized by winds coming from the high East Antarctic plateau and by an absence of clouds except between 9 h LT and 15 h LT on 26 December and between 4 h LT and 11 h LT on 27 December, when the downward long-wave flux (LWD) is relatively large in the observations. Unfortunately MAR underestimates LWD at those times (see section 4.1 and Fig. 2a).

~~We show i~~In Fig. 4a we report the behaviour of the simulated temperature and wind speed at the tower, between 3.5 and 42.1 m a.g.l. The simulation exhibits a marked diurnal cycle, with a strong temperature inversion during night-time and a well mixed layer during day-time. During night-time a close link exists between the vertical temperature gradient and the vertical wind speed gradient.

The ~~latter~~vertical wind speed gradient is the highest where temperature increase with height is the strongest and associated vertical stability is the largest ~~associated with temperature increasing strongly with height is the largest~~. Such a behaviour is often referred to as a decoupling between the cold air near the surface and the warmer air above. This decoupling is also found in a change of the wind direction just above the turbulent layer. Convective mixing during day-time precludes this behaviour, and the vertical gradients of both temperature and wind speed are much smaller. Night-time decoupling and day-time mixing are also found in the observations, but with some differences due to the presence of clouds that the model was not able to simulate.

It is seen in Fig. 4b that the model ~~indicates~~ simulates a warm bias on 26 December 2011 until 18 h LT, except below 10 m a.g.l. until 6 h LT. Probably the absence of simulated clouds is responsible for an overestimation of the surface absorbed solar radiation and the subsequent heating of the surface. The heat excess is then transferred to the atmosphere through turbulent mixing. Note that the marked overestimation ~~by the model~~ of the simulated absorbed solar radiation and air temperature are not repeated on 27 and 28 December 2011 in spite of the presence of clouds on December 27 in the morning. Nevertheless temperature maxima are overestimated by roughly 1 to 1.5°C, both at the surface (not shown) and above.



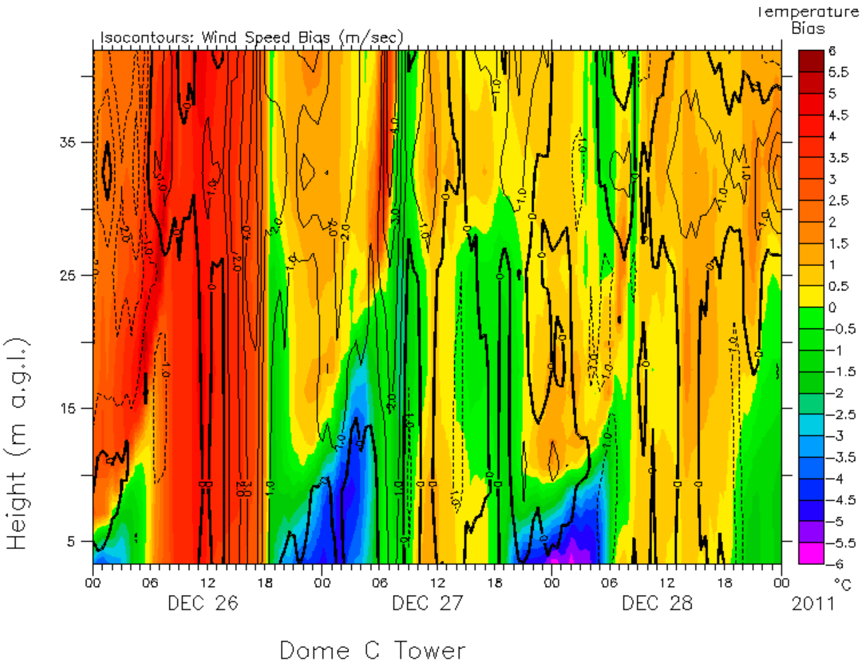


***Fig**. 4. Temperature (color) and wind speed (isocontours) at the Dome C tower, as a function of Local Time LT (Universal Time UT + 8 h) and height above the surface. (a) refers to MAR simulation, (b) to simulation minus observation.*

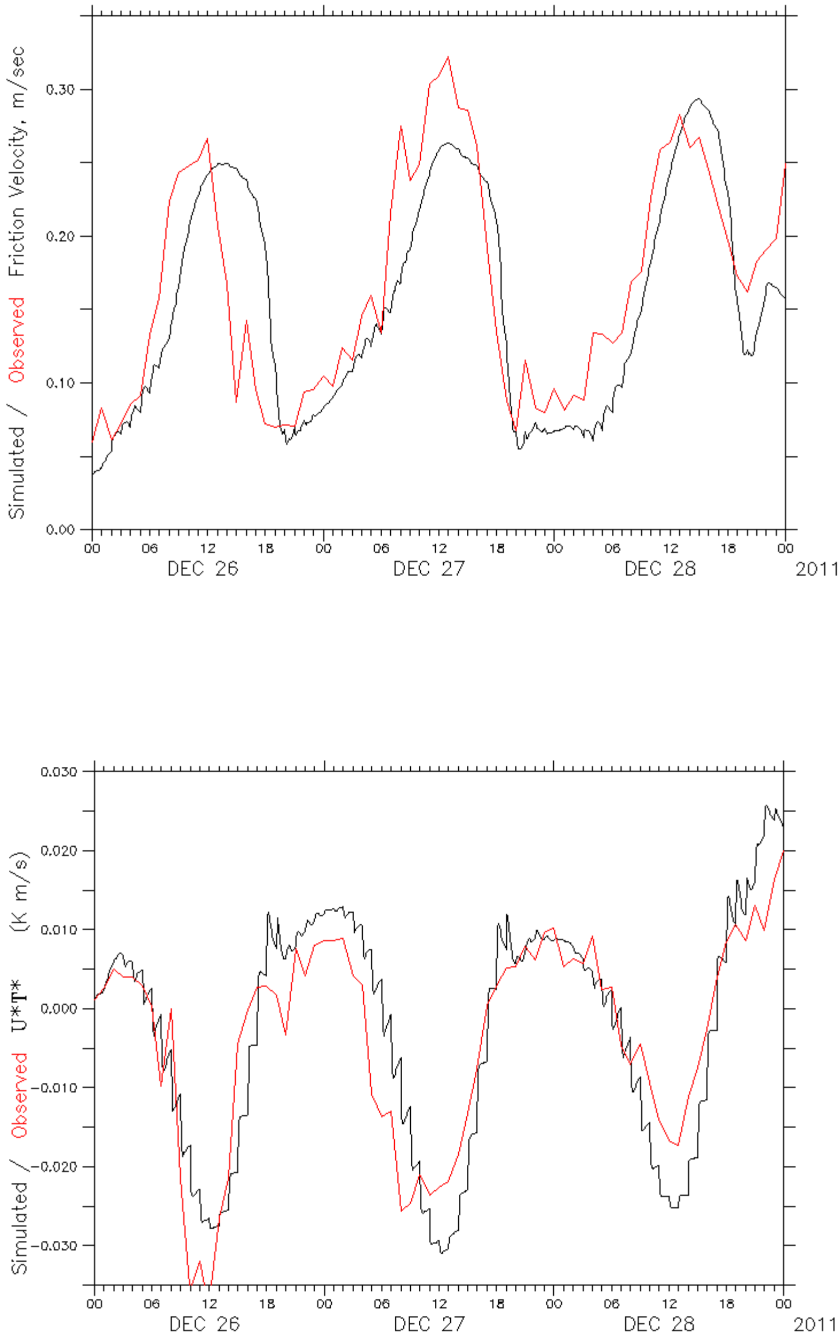


Fig. 5. *Surface turbulent fluxes at the Dome C tower, as a function of Local Time LT (Universal Time UT + 8 h). The panel a refers to the friction Velocity, the panel b to the sensible Heat Flux u*T*. The dark line is the MAR simulation, the red line the ISAC observations.*

Air temperatures on 27 and 28 December in the morning are significantly underestimated in the MAR simulations, especially on 28 December. The underestimation starts previous day around 18 LT. An underestimation of about 10 W m^{-2} or more is also found in the downward long-wave radiation (LWD), even in the absence of clouds (Fig. 2a). Simulated and observed turbulent fluxes are compared in Fig. 5. The simulated friction velocity is slightly underestimated by the MAR model during night-time, especially on 28 December, while the simulated downward turbulent heat flux is comparable to the observations or slightly overestimated. Possibly the simulated surface turbulent heat flux would have been larger if the friction velocity had not been underestimated by the model at that time. Thus Monin-Obukhov Similarity Theory is not a good candidate for explaining the underestimation of temperature near the surface. More precisely looking at the experiment with 1 m resolution it is found that the weakening of the turbulent fluxes from 1 to 2 m amounts to slightly more than 20%, a value that is larger than the usual departure from constancy generally accepted (10%). More generally temperature and wind speed at 2 m in the simulations with 1 m and 2 m resolution near the surface have been compared. It has been found that when clear sky is observed they are not sensitive (differences no larger than 1.5°C to 2°C or 1 m/sec) to the vertical resolution even when in the simulation with 1 m resolution the turbulent fluxes between 1 m and 2 m depart from the constancy by 30%. ~~Furthermore, the~~In contrast a slight overestimation of the air temperature above 10 – 15 m a.g.l. (Fig. 4b) could also result from an insufficient turbulent mixing by the *E* - *ε* model during night-time, explaining also partly the underestimation of the air temperature near the surface. ~~Thus~~Finally it could be argued that an initial underestimation of the air temperature near the surface may be responsible for an increased vertical stability above the surface boundary layer, reinforcing the decoupling between the lower troposphere and the atmosphere above, and being responsible for a possible underestimation of the boundary layer height.~~,~~ ~~but a~~A possible leading role of an underestimation of LWD must be firmly established.

From Fig. 5 it is also found that MAR underestimates the upward turbulent heat flux during day-time, when observed clouds were not simulated (on 26 December around noon and on 27 December in the morning) while it overestimates it when clouds are not present nor in the observation nor in the simulation (on 27 and 28 December during day-time). No definite explanation was found about the underestimation but the overestimation may be related to a too large heating of the surface and an overestimation of the air temperature by the model (see Fig. 4b), suggesting that the overestimation of air temperature at that time is driven by the surface.

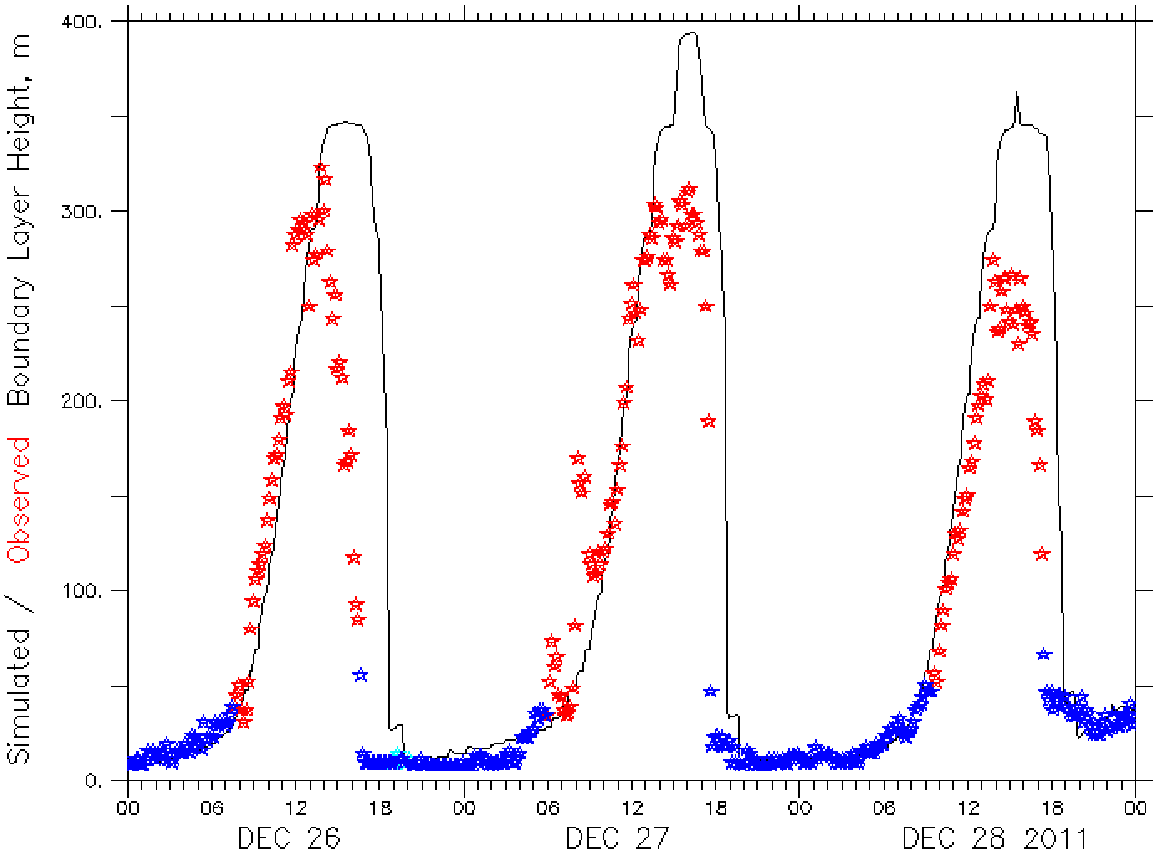


***Fig.** 6. The boundary layer height at Dome C as a function of Local Time LT (Universal Time UT + 8 h). Red (blue) stars: SODAR observations during convective (stable) situations (Argentini et al., 2013). Dark line : MAR mixed layer depth, computed as the level where the turbulent kinetic energy amounts to 5 % of the turbulent kinetic energy in the lowest layer of the model.*

Biases in the simulated wind speed could be sometimes linked to biases in the simulated air temperature~~,~~ but not always. An example of such a link in Fig. 4b is a positive wind speed bias simulated between 15 h and 18 h LT on 26 December 2011. It could be associated with the positive bias in the downward short-wave radiation. At that time the overestimated turbulent mixing could lead to an overestimated height of the turbulent layer and an overestimated downward transfer of momentum. Indeed simulated wind speeds are larger than observations at the upper levels of the tower at that time (Fig. 4a) and the model overestimates the height of the well-mixed layer (Fig. 6). The bias in the wind speed decreases after 18 h LT especially below 25 m a.g.l. This is due to an increasing stability near the surface and the subsequent decoupling between the layer of air near the surface and the layer above. Wind speeds are still overestimated above up to the highest level of the tower, possibly because of an overestimated vertical extent of the residual mixed layer at that time.

Observations suggest the onset of a nocturnal jet after 18 h LT, with a maximum of 7 m s^{-1} around 20 m a.g.l. around 22 h LT. MAR also simulates a nocturnal jet at that time but around 140 m a.g.l., and with a slightly stronger wind speed (8 m s^{-1}) (not shown). This occurrence is consistent with a higher extent of the residual layer and may be the consequence of the sudden shut down of the turbulent mixing at 18 h LT at 140 m a.g.l.~~that level~~ in the model (not shown), while the pressure gradient force (PGF) still contributes to an increase of the wind speed after that time. Such an evolution is typical for a convective mixed layer at the end of day-time, and is also observed at lower latitudes. The contribution of PGF to the acceleration of the wind starts to decrease after 20h30 LT. ~~In fact~~Since -nocturnal low level jets arrived ~~have been so~~ frequently during OPALE ~~that~~ the analysis of this process deserves some attention. Therefore, t~~T~~his topic will be addressed in a companion note by analysing a case study which is well simulated by the model (Gallée et al., 2014, this issue).

A small positive temperature ~~positive~~ bias seems also to occur on 6 h LT on 27 December 2011 above 25 m a.g.l. Its behaviour is similar to that of 26 December and it occurs also in conjunction with an underestimation of the cloud cover by the model and an earlier deepening of the well-mixed layer~~, but it is less marked~~.

Finally the sodar reveals an earlier peak and fall-off in boundary layer depth on 26 December than does the model (Fig. 6). This is due to clouds which are responsible for a strong decrease of SWD, while clouds are not simulated.

5. Discussion and conclusion

The MAR model has been set up over a domain covering Dome C during the OPALE campaign. The size of the domain is much smaller than the internal radius of deformation. As a consequence~~Such choice~~ ~~constrains~~ the model solution is constrained in the free atmosphere by ~~by~~ the one of the ~~that of the host model (here the~~ European re-analyses ERA-Interim~~)~~ but, as already pointed out by Lefebre et al. (2005), it allows ~~it~~ to develop its own solution in the boundary layer. The simulation is characterized by a positive efficiency of wind and temperature over Dome C, given us confidence in its behaviour. In certain situations, MAR underestimates the downward long-wave radiation~~, but not always~~. When this problem occurs~~it occurs this problem~~ it is often linked ~~is probably caused~~ to ~~by~~ an underestimation of the cloud cover, and is one ~~may be one of the causes~~ of the reasons ~~being~~ , which leads to an ~~responsible for an~~ overestimation of the simulated amplitude of the diurnal cycle of air temperature~~s by the model~~. An other possible cause of this overestimation ~~Other possible causes are an~~is the underestimation of heat transfer in the snow pack and an amplification of the subsequent decoupling between the atmosphere and the surface initiated by the underestimated LWD and heat conduction. Indeed surface turbulent fluxes are well simulated, but discrepancies with the observations are found when the simulated downward long-wave flux is underestimated. *Note that, since this underestimation of the LWD will induce also an error in the modelled temperatures measured temperatures, which were available through all the OPALE campaign were used when interpreting the chemistry data (e.g. Preunkert et al., 2014).* On the other hand the simulated wind speed in the surface boundary layer is in good agreement with the observations. It may consequently be argued that the turbulence schemes used in MAR (Monin-Obukhov similarity theory and E - ε model) are valid for the OPALE period. However, t~~T~~he question ~~of wether~~whether this keeps true also ~~it remains valid, especially~~ under strong~~er~~ ~~winter~~ radiational cooling as encounterd during winter at Dome C is still open.

Consequently model outputs and especially its turbulent characteristic are useful when interpreting the observations made in case of observed clear sky during OPALE. Indeed clear sky conditions, i.e. situations for which the model simulation is in excellent agreement with available observations, are more adequate when discussing measurements of species involved in photochemical processes. In particular the good behaviour of the simulated surface turbulent fluxes allows us to use the associated turbulent eddy diffusivity coefficient to evaluate the impact of turbulent transport on NO_x, HONO and HCHO emitted from snow. In addition the simulated boundary layer height ~~indicates over~~indicates over which thickness of the atmosphere these chemical species are diluted. In brief, the use of such a model will allow us to optimize the experimental set- up for future campaign aiming to characterize the low troposphere chemistry at Dome C.

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Characterization of the boundary layer at Dome C (East Antarctica) during the OPALE summer campaign

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Abstract

The regional climate model MAR (Modèle Atmosphérique Régional) was run for the region of Dome C located on the East Antarctic plateau, during Antarctic summer 2011 – 2012, in order to refine our understanding of meteorological conditions during the tropospheric chemistry campaign OPALE. A very high vertical resolution is set up in the lower troposphere, with a grid spacing of roughly 2 m. Model output is compared with temperatures and winds observed near the surface and from a 45 m high tower as well as sodar and radiation data. MAR is generally in very good agreement with the observations but sometimes underestimates cloud formation, leading to an underestimation of the simulated downward long-wave radiation. Absorbed short-wave radiation may also be slightly overestimated due to an underestimation of the snow albedo and this influences the surface energy budget and atmospheric turbulence. Nevertheless the model provides sufficiently reliable information about surface turbulent fluxes, vertical profiles of vertical diffusion coefficients and boundary layer height when discussing the representativeness of chemical measurements made nearby the ground surface during field campaigns conducted at Concordia station located at Dome C (3233 m above sea level).

1. Introduction

The aim of this paper is to evaluate MAR (Modèle Atmosphérique Régional) simulations during the OPALE campaign at Dome C in austral summer 2011 – 2012 (from late November 2011 to mid-January 2012), to support the interpretation of observations of tropospheric chemistry. A particular purpose is to characterize the behaviour and the vertical structure of the boundary layer at Dome C during this period.

A similar study has been carried out previously above the East Antarctic plateau, based on summer time observations at Kohnen station in Dronning Maud land, albeit only with a more simplistic 1-D model (Van As et al., 2006).

Dome C is an area where observation and modelling of the boundary layer has already been performed due to its particular location (Swain and Gallée, 2006, Sadibekova et al., 2006, King et al., *2006*, Gallée and Gorodetskaya, 2010, Genthon et al., 2010, 2013, Brun et al., 2011, Lascaux et al., 2011, Argentini et al. 2013, Pietroni et al. , 2014). Furthermore , 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). In spite of its remote location Concordia station, operated year-round, is logistically well supported due to a number of reasons. Dome C had been chosen as part of the EPICA project for drilling the ice core with the longest climate chronology ever recorded, allowing to study the climate of the last eight glacial cycles (EPICA community members, 2004). The EPICA project initiated extensive meteorological observations at Dome C, in order to establish, among others, the relationship between local and global climate. Therefore setting up a regional model at the Dome C drilling site enables (i) to assimilate large scale meteorological conditions and (ii) to simulate local atmospheric conditions, which contributes to establishing this relationship. The good management of logistics between the Concordia station and the Antarctic coast (Terre Adélie) and the low

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optical turbulence at Dome C also promoted the site for astronomical observations (see e.g., Swain and Gallée, 2006, Sadibekova et al., 2006). The main characteristic of meteorological conditions at Dome C is that turbulent conditions in the near-surface atmosphere are only effective in a rather shallow layer, especially during night-time (Pietroni et al. , 2014). During day-time the sensible heat fluxes are much larger than the latent heat fluxes, because of low temperatures and subsequently very low atmospheric moisture content (*King et al., 2006*). Consequently the conditions for development of a well mixed layer during daytime are optimal, in contrast to the situation in coastal Antarctica such as Halley station (King et al., 2006). This means that the simulation of summer case studies at Dome C will be very useful in validating the turbulence scheme of atmospheric models. Sodar and sonic anemometer measurements were done at the Concordia station to monitor the turbulent structure of the planetary boundary layer (PBL) in connection with the temperature inversion and estimate the PBL height in the frame of the ABLCLIMAT (Atmospheric Boundary Layer Climate) project (Argentini et al. 2013).

Comment [7]: Rev. 1.5
Rev. 2.6

The 45 m high tower built up at Concordia is also a very useful tool for observing such conditions (Genthon et al., 2010, 2013). Short-term meteorological simulations have already been done over Dome C with a coupled atmosphere – snow model, focusing on the behaviour of the snow model (Brun et al., 2011). Long term simulations of the Antarctic climate have also been done, with a focus on their behaviour at Dome C. Swain and Gallée (2006) and Lascaux et al. (2011) used respectively the limited area models MAR (without any reinitialisation of meteorological variables) and Meso-NH to compare the optical properties of the atmosphere at Dome C with those of other potential Antarctic sites for astronomical observations using a large telescope. Gallée and Gorodetskaya (2010) validated MAR for winter conditions, emphasizing the difficulty to accurately simulate the downward long-wave radiation and proposing to include the influence of small airborne snow particles in the parameterization of the radiation transfer. MAR has also been used for providing information on the atmospheric turbulence at Dome C in summer, which appears to very significantly control the vertical flux and concentration profiles of numerous atmospheric chemical species (Legrand et al., 2009, Kerbrat et al., 2012; Dommergue et al., 2012, Frey et al., 2013). Finally two years of observations at the Dome C tower were used to compare a long-term simulation of MAR with ECMWF analyses, showing the interest to represent the atmosphere with a fine vertical resolution (Genthon et al., 2013). Here we go a step further by evaluating in detail the model for summer conditions during the OPALE campaign.

The general motivation of the present research is to provide tools from a meteorological point of view for future campaigns dedicated to investigate the chemical composition of the Antarctic boundary layer above the East Antarctic plateau. Thus, the first objective of this paper is to evaluate a meteorological model that is capable of simulating transport and that can be coupled to a chemical routine.

The second objective of the paper is to provide key physical parameters of the atmospheric boundary layer for the interpretation of data gained during the OPALE campaign as detailed in companion papers (see Legrand et al., 2014; Kukui et al., 2014; Frey et al., 2014, and Preunkert et al., 2014). Transport processes are not considered during the 2011-2012 OPALE campaign and we will focus on situations characterized by an atmospheric circulation localized over the Antarctic plateau, where chemical properties of the air are rather homogeneous from one point to another. This means that from a meteorological point of view atmospheric turbulence plays the most important role in the fate of atmospheric NO_x, HONO, HCHO, or H_2O_2 emitted by the snow pack. Key parameters are surface turbulent fluxes and the height of the boundary layer, which is determined by vertical turbulent diffusion. These parameters are used in companion papers to determine the contribution of turbulence to the concentration of key atmospheric species emitted from the surface, driving the oxidant budget in the near-surface atmosphere at Dome C. MAR

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turbulent vertical diffusion coefficients are used by Preunkert et al. (2014) and the uncertainty of the later on HCHO mixing ratios is discussed. Legrand et al. (2014) also use the same MAR outputs to force their 1-D box model to simulate HONO mixing ratios. Kukui et al. (2014) performed similar calculations using the same MAR output. Frey et al. (2014) use MAR boundary layer heights to determine when they may apply the Monin–Obukhov similarity theory for calculating the turbulent fluxes of NOx in the surface boundary layer. Other parameters like cloud cover and wind direction are considered for chemical analyses. For example situations with an overcast sky were not considered nor situations for which the wind direction is from Concordia station, since the air is then contaminated by pollutants emitted by the station. Sunny sky conditions were preferred since the assumption of a similar downward shortwave (DSW) radiation from sunny day to sunny day may be done. From a meteorological point of view these criteria also allow us to avoid most of the situations for which clouds are underestimated by MAR leading to an erroneous behaviour of the surface energy budget, and subsequently of atmospheric turbulence, as explained by Legrand et al. (2014). Fortunately such a behaviour of MAR allows us to analyze the best part of the simulation which corresponds to the same days for which the analysis of chemical species is the easiest.

Comment [10]: Rev. 1.3.
Rev. 2.1.2

Comment [11]: Rev.1.6.1
Rev.1.11

The remaining of the paper is divided in 4 parts. The experimental set-up and the main characteristics of the MAR model are described in sections 2 and 3. The fourth section is dedicated to the evaluation of the model, looking in particular at the impact of the simulated radiative transfer on the surface atmospheric energy budget and atmospheric turbulence.

2. Meteorological observations

2.1. ISAC (Istituto di Scienze dell' Atmosfera e del Clima)

One-year in situ turbulence and radiation measurements, as well as sodar observations, were carried out at the Concordia station from December 2011 up to December 2012 as part of the *ABLCLIMAT* project (Argentini et al., 2013).

The SL-sodar (Surface Layer sodar, Argentini et al., 2011) is an improved version of the sodar described by Argentini and Pietroni (2010), with the possibility of zooming into the atmospheric surface-layer thermal turbulent structure. With the SL-Sodar, the PBL height *h* is estimated following Casasanta et al. (2014). During convective conditions *h* was determined as the height above the zone of weak backscattered intensity of the acoustic waves emitted by the sodar. Under stable conditions, *h* was retrieved either from the minimum of the first derivative of the backscattered signal, or from its maximum curvature.

Measurements of turbulence were made with a Metek USA-1, a three-axes sonic thermo-anemometer (sampling frequency of 10 Hz) installed on a 3.5 m mast. The heat and momentum fluxes are estimated using the eddy covariance method. The longwave and shortwave radiation components (up and down) were measured with a Kipp & Zonen CNR1 radiation sensor. This instrument combined two CM3 pyranometers for downward and upward broadband shortwave radiation flux (spectral range 305–2800 nm) and two CG3 pyrgeometers for downward and upward broadband longwave radiation flux (spectral range 5– 50 µm). Pyrgeometers and pyranometers were installed 1.5 m above the snow surface.

2.2. LGGE (Laboratoire de Glaciologie et de Géophysque de l'Environnement)

Meteorological measurements were made on a 45-m tower at Dome C since 2008 (Genthon et al. 2010). Wind, temperature and moisture are monitored at six levels from the near surface (3.5 m) to near the top of the tower (42.1 m). The instruments occasionally fail due to the extreme weather conditions at Dome C (extreme low temperatures, frost deposition), however the data record is almost continuous since 2009 and the instruments work generally quite well in summer (Genthon et al. 2013). Genthon et al. (2011) have demonstrated that a bias to warmer temperatures affects measurements in Antarctica in cases of weak winds if conventional passively (wind) ventilated radiation shields are used to protect solid state thermometers (e.g. the ubiquitously used platinum thermistors) from solar radiation. To overcome this problem the temperature measurements on the tower at Dome C are made in aspirated shields. Further details of the profiling set up, instrumentation and results obtained so far can be found in Genthon et al. (2010, 2013).

2.3. BAS (British Antarctic Survey)

Measurements of turbulence are made with a Metek USA-1, a three-axes sonic thermo-anemometer (sampling frequency of 25 Hz) mounted on a mast 4 m above the snow surface. The mast was set up in the clean-air sector at about 1.2 km distance from the 45-m meteorology tower (map in Frey et al., 2013), at the site where the chemical trace gas species were measured during the OPALE campaign. Atmospheric boundary layer parameters such as friction velocity u_* and

Monin-Obukhov Length were computed from the three-dimensional wind components (u, v, w) and temperature (Frey et al., 2014, this issue). Processing in 10-min blocks included temperature cross-wind correction and a double coordinate rotation to force mean w to zero (Kaimal and Finnigan, 1994; Van Dijk et al., 2006).

3. Description of MAR

An overview of the regional climate model MAR is given here, focused on the description of the turbulence scheme. A more complete description can be found in Gallée and Schayes (1994), Gallée (1995) and Gallée et al. (2013).

MAR atmospheric dynamics are based on the hydrostatic approximation of the primitive equations. This approximation is correct when the vertical extent of the circulation (here the drainage flow) remains much smaller than the size of the grid (here 20 km). Nevertheless, it should be noted that non-hydrostatic processes may be responsible for a weak deceleration of the katabatic flow (Cassano and Parish, 2000). The vertical coordinate is the normalized pressure, with the model top situated at the 1 Pa pressure level. Parameterization of turbulence in the surface boundary layer is based on the Monin-Obukhov similarity theory (MOST) and is completed by taking into account the stabilization effect by the blowing snow flux, as in Gallée et al. (2001) (see also Wamser and Lykossov, 1995). Turbulence above the suface boundary layer is parameterized using the local *E* - *ε* model, consisting in two prognostic equations for turbulent kinetic energy and its dissipation. The prognostic equation of dissipation allows to relate the mixing length to local sources of turbulence and not only to the surface. The *E* - *ε* model used here has been adapted to neutral and stable conditions by Duynkerke (1988) and revised by Bintanja (2000), who included a parameterization of the turbulent transport of snow particles that is consistent with classical

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parameterizations of their sedimentation velocity. The influence of changes in the water phase on the turbulence is included following Duynkerke and Driedonks (1987). The relationship between the turbulent diffusion coefficient for momentum and scalars (Prandtl number) is dependant on the Richardson number, according to Sukoriansky et al. (2005).

Prognostic equations are used to describe five water related parameters (Gallée, 1995): specific humidity, cloud droplets and ice crystals, raindrops and snow particles. A sixth equation has been added describing the number of ice crystals, and the influence of hydrometeors on air specific mass is included in the model (Gallée et al. (2001). This allows us to account for the influence of the weight of eroded particles on atmospheric flow dynamics by representing the pressure gradient force as a function of air density rather than of potential temperature only.

The radiative transfer through the atmosphere is parameterized following Morcrette (2002) and is the same as the one used in ERA-40 re-analyses. As blowing snow particles are small (Walden at al., 2003), they may have an impact on the radiative transfer. Influence of snow particles on atmospheric optical depth is also included in the MAR model (Gallée and Gorodetskaya, 2010).

Surface processes are modelled using the “soil-ice-snow-vegetation-atmosphere transfer” scheme (SISVAT, De Ridder and Gallée, 1998, Gallée et al., 2001, Lefebre at al., 2005, Fettweis et al., 2005). The influence of snow erosion / deposition on surface roughness (z_0) is taken into account by allowing the aerodynamic roughness length to increase linearly as a function of the wind speed at 10 m above the ground level (a.g.l.) (V_{10}), when V_{10} > 6 m s^{-1}. The time scale for sastrugi formation is assumed to be half a day, as suggested by Andreas (1995), and the asymptotic value of the surface roughness length z_0 may increase linearly as a function of the wind speed V ($z_{0,lim}$ = 1.5 mm for V = 10 m s^{-1}; note that the friction velocity corresponding to V = 10 m s^{-1} is generally slightly greater than 0.5 m s^{-1}). z_0 is allowed to decrease when precipitation occurs without wind erosion of the snow. Indeed the newly deposited snow progressively buries the sastrugi. Andreas et al. (2005) found values of z_0 ranging between approximately 10^{-4} and 100 mm, for friction velocities no greater than 0.6 m s^{-1}. King and Anderson (1994) observed at Halley for compacted, sintered firn with some sastrugi , i.e. for similar snow properties as encountered at Dome C, a z_0 value of $(5.6 \pm 0.6) \times 10^{-5}$ m. The scatter of z_0 is very high and is explained by the high dependency of z_0 on sastrugi history. Our parameterization includes that effect in a simple way, and is calibrated to obtain the best simulation of the wind speed. Note that the snow surface albedo depends on the snow properties (dendricity, sphericity and size of the snow particles) and solar zenithal distance, but not on sastrugi nor sastrugi orientation.

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4. Evaluation of MAR

We here used the 3-D version of MAR in order to take into account the influence of drainage winds on mass divergence at Dome C and consequently on subsidence and thinning of the boundary layer at the dome. In addition this allows also to account for a possible influence of the inversion wind circulation over the Dome C area, as suggested by Pietroni et al. (2014). The MAR domain is represented in Fig. 1. The horizontal grid size is 20 km and the vertical discretization in the lower troposphere is 2 m, with 60 levels. The vertical resolution 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. In parallel MAR was also run with a vertical grid spacing of 1 m in the lower levels, without any significant change in the results.

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Taking advantage of the higher vertical resolution near the surface the output of this latter model run was used to discuss the behaviour (in particular the diurnal cycles) of different atmospheric components as e.g. HONO, ROH, NOx, and HCHO, measured near the surface during the OPALE campaign (Legrand et al., 2014; Kukui et al., 2014; Frey et al., 2014; and Preunkert et al., 2014).

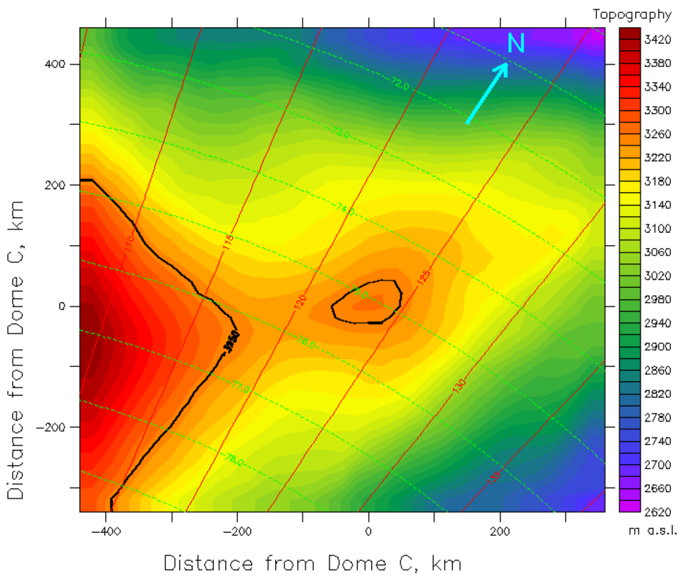

***Fig. 1**. The MAR integration domain and topography. The solid line refers to the 3250 m isocontour.*

The MAR model is nested into the European re-analyses ERA-Interim (Dee et al., 2011). A relaxation zone of 5 grid points is prescribed at each lateral boundary (Marbaix et al., 2003) and model variables are nudged to the re-analysed variables in the upper 6 layers, i.e., above 13 km a.g.l. at Dome C. As the OPALE campaign took place from early December 2011 until mid January 2012, MAR was run over 3 months (from 1 November 2011 until 31 January 2012). The model variables are assumed to adapt to Dome C conditions during the first simulated month (i.e., November 2011). The snow pack is initialized with a density of 300 kg m^{-3} and the assumption of the presence of small grains, what results in a slightly decreased initial albedo (close to 0.79 at noon), compared to the value (0.80-0.81) estimated by Brun et al. (2011). Note that the albedo would have been more underestimated if sastrugi orientation had been taken into account (Wendler and Kelley, 1988). However no observation of sastrugi has been made during the OPALE campaign. Our analysis focuses on the period between 12 December 2011 and 14 January 2012, when most of the OPALE observations were made.

Comment [16]: Rev.1.10

4.1. Cloud cover and surface energy budget

A problem already encountered when running the model over Adélie Land (East Antarctica) is an underestimation of the cloud cover (but not always) and the subsequent underestimation (overestimation) of the downward long-wave (shortwave) radiation. As a consequence, an underestimation (overestimation) of air temperatures near the surface during night-time (day-time) results (Gallée et al., 2013).

In the following we will investigate in how far this shortcoming occurs also in the MAR simulations at Dome C. We note first that MAR generally underestimates both the short-wave and long-wave downward radiations, with a bias of about 24.3 W m^{-2} and 20.8 W m^{-2}, respectively (Table 1). The influence of the former on the surface energy budget is nevertheless less important than that of the latter, because of the high value of the snow albedo.

MAR		ISAC	ISAC 3 m	Tower 3 m	BAS 4 m

SWD	Bias	-24.3 W m^{-2}			
SWA	Bias	3.4 W m^{-2}			
LWD	Bias	-20.8 W m^{-2}			
Temperature	Corr. Coef.		0.981	0.912	0.973
	Bias		-0.387 °C	-0.642 °C	-0.551 °C
	RMSE		2.408 °C	2.778 °C	2.735 °C
	E		0.958	0.751	0.933
Wind Speed	Corr. Coeff.		0.865	0.872	0.856
	Bias		-0.227 m/s	-0.105 m/s	0.440 m/s
	RMSE		1.057 m/s	0.949 m/s	1.089 m/s
	E		0.737	0.752	0.677

Table 1. *Correlation coefficient, bias, RMSE (root mean square error) and efficiency statistical test of the simulated short-wave downward radiation (SWD), the short-wave absorbed radiation by the surface (SWA), the long-wave downward radiation (LWD), the temperature and the wind speed when compared to the observations made by ISAC (Istituto di Scienze dell' Atmosfera e del Clima) (3 rd and 4 th column), by LGGE (Laboratoire de Glaciologie et de Géophysique de l'Environnement) (at the tower, 5 th column) and by BAS (British Antarctic Survey) (6 th column). Data were averaged over an interval of 30 minutes.*

Let us now examine the downward long-wave radiation and the air temperature near the surface (Fig. 2). Both observations and simulation exhibit rapid variations in the long-wave downward radiation (LWD) (Fig. 2a). The correlation coefficient between the simulated LWD and cloud optical thickness is 0.79 for a 10 minutes time interval between each value of these variables, suggesting that cloud cover changes are responsible for most of these variations.

Fig. 2b compares the daily averaged bias (simulation minus observation) in the long-wave downward radiations (LWD) and air temperatures near the surface at Dome C. The former is generally underestimated, leading to the underestimation of the latter (see also Table 1). A significant correlation may be seen between both biases, even when the temperature bias may be positive while the long-wave downward radiation bias remains negative. But the latter bias is partially compensated by a slight positive bias in the absorbed solar radiation (Table 1), probably because of an underestimation of MAR snow surface albedo.

In contrast, the bias in the absorbed solar radiation may become negative, for example on 10 and 11 January 2012, when the bias in the long-wave downward radiation is almost zero and significant snowfall is simulated. The positive temperature bias on 31 December 2011 is probably due to an overestimation of the long-wave downward radiation by MAR.

Thus, as already observed along the Adélie Land Coast (see Gallée et al., 2013), MAR underestimates cloud cover at Dome C, but not always. This underestimation is responsible for an underestimation of the downward long-wave radiation. As long-wave downward radiation plays a key role in the surface energy budget and the subsequent behaviour of turbulence near the surface, this point will be considered in the remaining of the paper. Concerning the application of MAR for the interpretation of the atmospheric chemistry measured during OPALE, the underestimation of the cloud cover is generally not critical since situations with an overcast sky were not considered in these model applications.

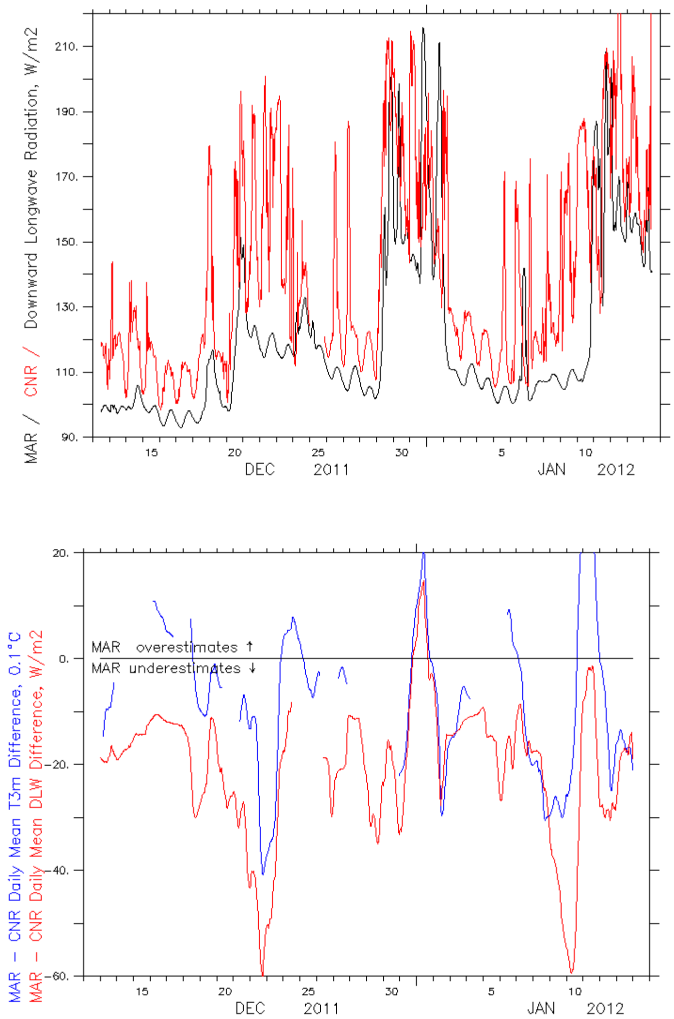

Fig. 2. *Top : Long-wave Downward radiation (LWD, W/m2) : simulation (dark line) and observation (red line). Data were averaged over an interval of 30 minutes. Bottom : comparison between the daily averaged LWD bias (red line) and air temperature bias (blue line, units : 0.1°C). Observations are those of the ISAC. MAR temperatures are averaged between 2 m and 4 m a.g.l. Gaps correspond to the absence of observations.*

4.2. Wind and Temperature near the surface

The performances of the simulated temperature and wind speed are summarized in Table 1 by the correlation between simulation and observation, the bias (simulation minus observation), the root mean square error (RMSE) and the efficiency statistical test (*E*) proposed by Nash and Sutcliffe (1970):

$$E = 1 - RMSE^2 / s^2 \qquad (2)$$

where *s* and *RMSE* are respectively the standard deviation of the observations and the root-mean-square error of the simulated variable. Note that *RMSE = 0* implies *E = 1*. An efficiency index greater than *0* also means that comparing the simulated variable with the corresponding observation provides a lower *RMSE* than that obtained when comparing it with its time average. A negative efficiency index means that the *RMSE* is higher than the standard deviation of the observations. Finally, this then suggests that a detailed model would not improve the results when compared to a simpler model providing an estimation of the variable averaged over the time period concerned.

It is found that the efficiency statistical test for temperature and wind speed is not lower than 0.677 for all comparisons (Table 1) giving us confidence into the respective time averages as well as into the fluctuations of these simulated variables.

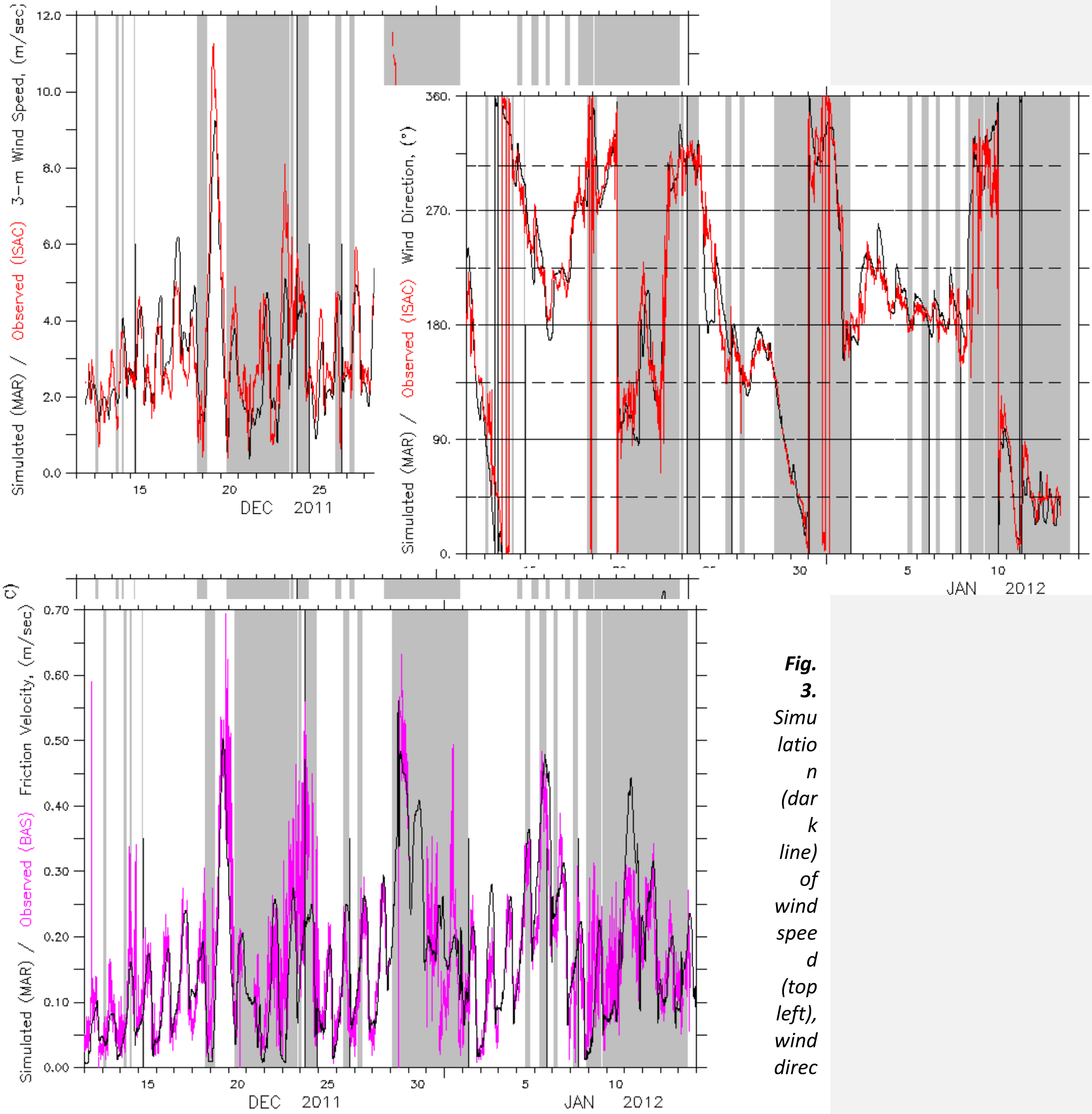

Fig. 3. *Simulation (dark line) of wind speed (top left), wind direction (top right), and air temperature (bottom left) at Dome C, 3 m a.s.l., compared with ISAC observations. Bottom right: simulation of friction velocity (dark line) compared with BAS observations (magenta line). Data were averaged over an interval of 30 minutes. Shaded area indicate periods with DLW > 130 Wm^{-2}*

For a more detailed examination of wind speed and temperature, the comparison between simulated and observed wind speeds at 3 m above the surface is shown in figure 3a. The agreement is good, as also quantified by the efficiency (0.737, Table 1). As it can be seen in Fig. 3b the agreement between the simulated and observed wind direction is also excellent. This behaviour indicates that the model is able to capture the atmospheric circulation at Dome C at the synoptic scale and is able to simulate the local circulation. Both, observation and simulation reveal two preferential wind directions, one from the plateau (southerly winds) and the other from the ocean (northerly winds). A well-marked diurnal cycle is generally found in the wind speed but does not exist in the wind direction. Wind speed peaks during the afternoon, when turbulent fluxes in the well mixed layer are able to transport momentum downwards more efficiently. Wind speed is also generally stronger and may be larger than 6 m s^{-1} in case of wind blowing from the North, except on 5 – 7 January 2012, when wind was blowing from the South. Note that the simulation of a blowing snow event on 29 December is responsible for an increase of the simulated roughness length from an almost constant in time value of 0.05 mm to an almost constant in time value of 2 mm. No significant change in the agreement between simulation and observations of the wind speed or of the friction velocity after this increase may be deduced from a look to Fig. 3. Consequently it is difficult to determine if the parameterization of the roughness length at Dome C is important for the simulation.

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Rev. 2.3

The simulated air temperature is also in good agreement with observations (Fig. 3c), although the simulated diurnal cycle is generally more pronounced than the observed one, especially for night-time (not shown for tower and BAS observations). The largest differences are found when simulations are compared with the observations made at the tower. Note that, tower temperature measurements are performed in aspirated shields which have been demonstrated to avoid large warm biases with the most often used passively ventilated shields in cases of weak winds (Genthon et al. 2011). Since these are the only temperature measurements carried out in aspirated shields at Dome C, they are (except of sonic measurements) the only ones which are unaffected by radiations biases.

Finally the good behaviour of the simulated friction velocity (Fig. 3d) suggests that MAR simulates surface meteorological variables without compensating errors. From the previous analysis we have some confidence on the behaviour of the model in the surface boundary layer at Dome C during the OPALE observation period, but some discrepancies with the observations are found, even for sunny days.

4.3. Period between 26 and 28 December 2011

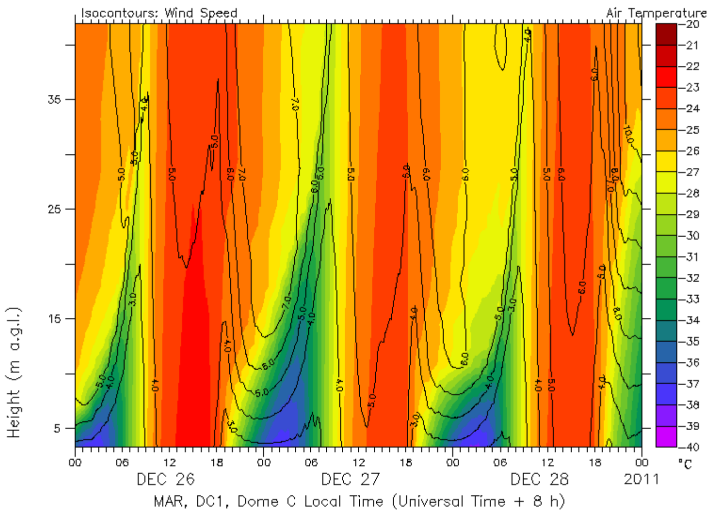
In the following we will focus on the period between 26 and 28 December 2011, which is also included in the studies of Legrand et al. (2014), Kukui et al. (2014), Preunkert et al. (2014), and Frey et al. (2014). Moreover this is the longest period for which we have estimations of the boundary layer height from sodar measurements. This period is characterized by winds coming from the high East Antarctic plateau and by an absence of clouds except between 9 h LT and 15 h LT on 26 December and between 4 h LT and 11 h LT on 27 December, when the downward long-wave flux (LWD) is relatively large in the observations. Unfortunately MAR underestimates LWD at those times (see section 4.1 and Fig. 2a).

Comment [18]: Exp.1.3. Additional cross-linking with other OPALE studies

Comment [19]: Exp.1.2. Sodar Measurements.

In Fig. 4a we report the behaviour of the simulated temperature and wind speed at the tower, between 3.5 and 42.1 m a.g.l. The simulation exhibits a marked diurnal cycle, with a strong temperature inversion during night-time and a well mixed layer during day-time. During night-time a close link exists between the vertical temperature gradient and the vertical wind speed gradient. The vertical wind speed gradient is the highest where temperature increase with height is the strongest and associated vertical stability is the largest . Such a behaviour is often referred to as a decoupling between the cold air near the surface and the warmer air above. This decoupling is also found in a change of the wind direction just above the turbulent layer. Convective mixing during day-time precludes this behaviour, and the vertical gradients of both temperature and wind speed are much smaller. Night-time decoupling and day-time mixing are also found in the observations, but with some differences due to the presence of clouds that the model was not able to simulate.

It is seen in Fig. 4b that the model simulates a warm bias on 26 December 2011 until 18 h LT, except below 10 m a.g.l. until 6 h LT. Probably the absence of simulated clouds is responsible for an overestimation of the surface absorbed solar radiation and the subsequent heating of the surface. The heat excess is then transferred to the atmosphere through turbulent mixing. Note that the marked overestimation of the simulated absorbed solar radiation and air temperature are not repeated on 27 and 28 December 2011 in spite of the presence of clouds on December 27 in the morning. Nevertheless temperature maxima are overestimated by roughly 1 to 1.5°C, both at



the surface (not shown) and above.

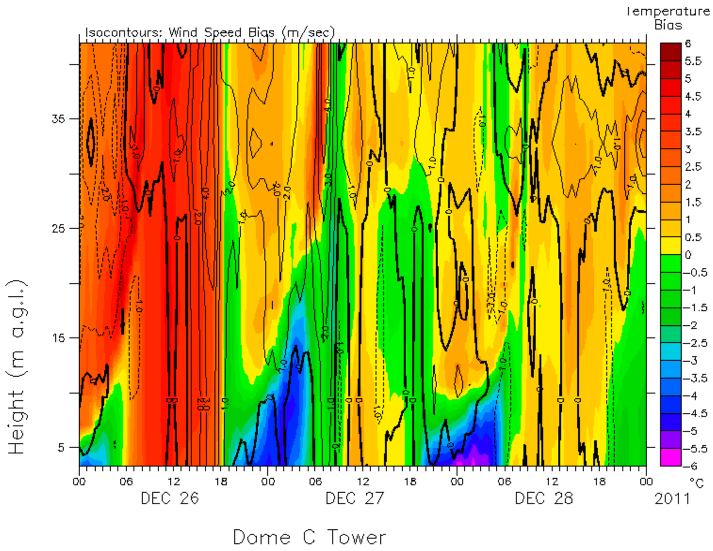
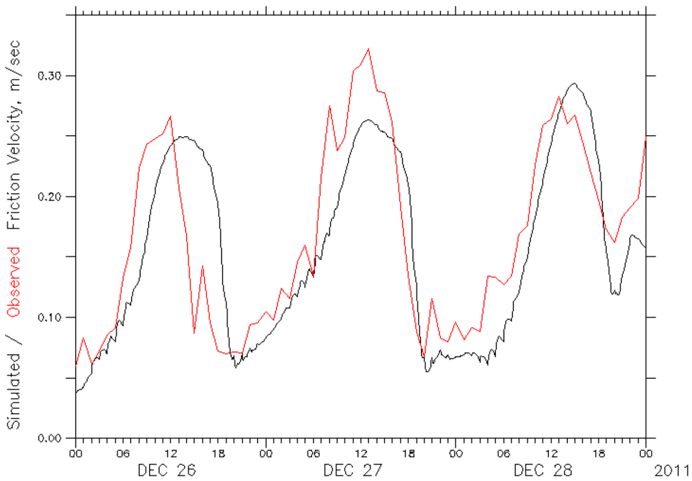


Fig. *4. Temperature (color) and wind speed (isocontours) at the Dome C tower, as a function of Local Time LT (Universal Time UT + 8 h) and height above the surface. (a) refers to MAR simulation, (b) to simulation minus observation.*



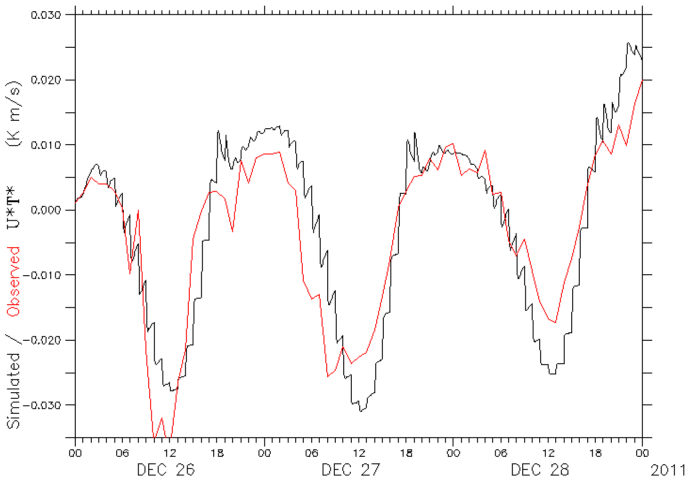


Fig. 5. Surf*ace turbulent fluxes at the Dome C tower, as a function of Local Time LT (Universal Time UT + 8 h). The panel a refers to the friction Velocity, the panel b to the sensible Heat Flux u*T*. The dark line is the MAR simulation, the red line the ISAC observations.*

Air temperatures on 27 and 28 December in the morning are significantly underestimated in the MAR simulations, especially on 28 December. The underestimation starts previous day around 18 LT. An underestimation of about 10 W m^{-2} or more is also found in the downward long-wave radiation (LWD), even in the absence of clouds (Fig. 2a). Simulated and observed turbulent fluxes are compared in Fig. 5. The simulated friction velocity is slightly underestimated by the MAR model during night-time, especially on 28 December, while the simulated downward turbulent heat flux is comparable to the observations or slightly overestimated. Possibly the simulated surface turbulent heat flux would have been larger if the friction velocity had not been underestimated by the model at that time. Thus Monin-Obukhov Similarity Theory is not a good candidate for explaining the underestimation of temperature near the surface. More precisely

Comment [20]: Rev.1.13.0

looking at the experiment with 1 m resolution it is found that the weakening of the turbulent fluxes from 1 to 2 m amounts to slightly more than 20%, a value that is larger than the usual departure from constancy generally accepted (10%). More generally temperature and wind speed at 2 m in the simulations with 1 m and 2 m resolution near the surface have been compared. It has been found that when clear sky is observed they are not sensitive (differences no larger than 1.5°C to 2°C or 1 m/sec) to the vertical resolution even when in the simulation with 1 m resolution the turbulent fluxes between 1 m and 2 m depart from the constancy by 30%. In contrast a slight overestimation of the air temperature above 10 – 15 m a.g.l. (Fig. 4b) could also result from an insufficient turbulent mixing by the E - ε model during night-time, explaining also partly the underestimation of the air temperature near the surface. Finally it could be argued that an initial underestimation of the air temperature near the surface may be responsible for an increased vertical stability above the surface boundary layer, reinforcing the decoupling between the lower troposphere and the atmosphere above, and being responsible for a possible underestimation of the boundary layer height. A possible leading role of an underestimation of LWD must be firmly established.

Comment [21]: Rev. 1.13.3

Comment [22]: Rev.1.13.1

From Fig. 5 it is also found that MAR underestimates the upward turbulent heat flux during day-time, when observed clouds were not simulated (on 26 December around noon and on 27 December in the morning) while it overestimates it when clouds are not present nor in the observation nor in the simulation (on 27 and 28 December during day-time). No definite explanation was found about the underestimation but the overestimation may be related to a too large heating of the surface and an overestimation of the air temperature by the model (see Fig. 4b), suggesting that the overestimation of air temperature at that time is driven by the surface.

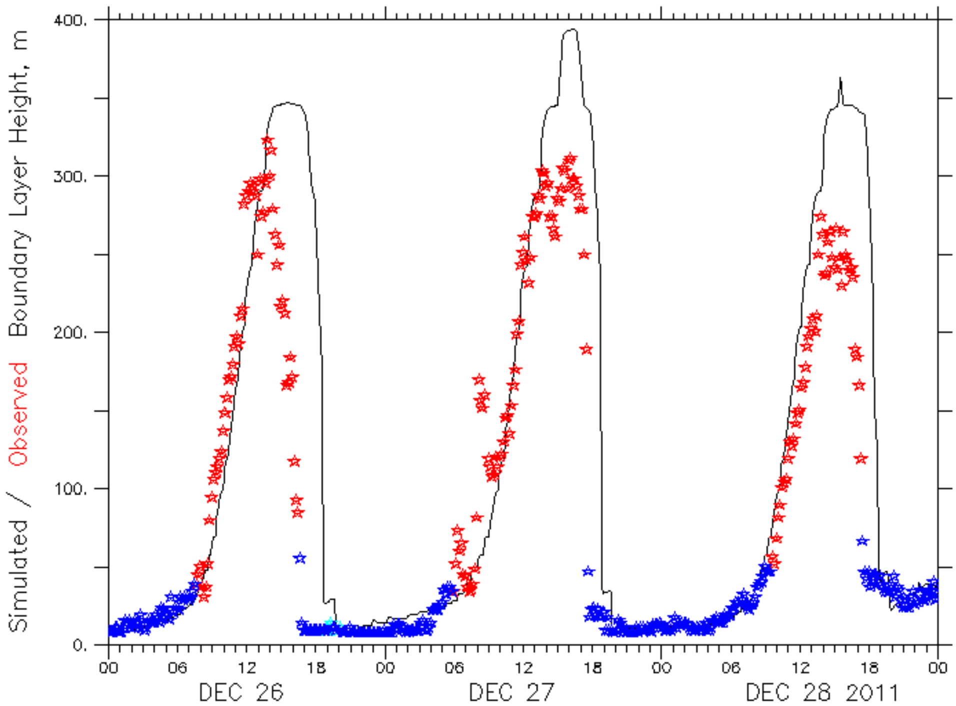


Fig. *6. The boundary layer height at Dome C as a function of Local Time LT (Universal Time UT + 8 h). Red (blue) stars: SODAR observations during convective (stable) situations (Argentini et al., 2013). Dark line : MAR mixed layer depth, computed as the level where the turbulent kinetic energy amounts to 5 % of the turbulent kinetic energy in the lowest layer of the model.*

Biases in the simulated wind speed could be sometimes linked to biases in the simulated air temperature but not always. An example of such a link in Fig. 4b is a positive wind speed bias simulated between 15 h and 18 h LT on 26 December 2011. It could be associated with the positive bias in the downward short-wave radiation. At that time the overestimated turbulent mixing could lead to an overestimated height of the turbulent layer and an overestimated downward transfer of momentum. Indeed simulated wind speeds are larger than observations at the upper levels of the tower at that time (Fig. 4a) and the model overestimates the height of the well-mixed layer (Fig. 6). The bias in the wind speed decreases after 18 h LT especially below 25 m a.g.l. This is due to an increasing stability near the surface and the subsequent decoupling between the layer of air near the surface and the layer above. Wind speeds are still overestimated above up to the highest level of the tower, possibly because of an overestimated vertical extent of the residual mixed layer at that time.

Observations suggest the onset of a nocturnal jet after 18 h LT, with a maximum of 7 m s^{-1} around 20 m a.g.l. around 22 h LT. MAR also simulates a nocturnal jet at that time but around 140 m a.g.l., and with a slightly stronger wind speed (8 m s^{-1}) (not shown). This occurrence is consistent with a higher extent of the residual layer and may be the consequence of the sudden shut down of the turbulent mixing at 18 h LT at 140 m a.g.l. in the model (not shown), while the pressure gradient force (PGF) still contributes to an increase of the wind speed after that time. Such an evolution is typical for a convective mixed layer at the end of day-time, and is also observed at lower latitudes. The contribution of PGF to the acceleration of the wind starts to decrease after 20h30 LT. Since nocturnal low level jets arrived frequently during OPALE the analysis of this process deserves some attention. Therefore, this topic will be addressed in a companion note by analysing a case study which is well simulated by the model (Gallée et al., 2014, this issue).

A small positive temperature bias seems also to occur on 6 h LT on 27 December 2011 above 25 m a.g.l. Its behaviour is similar to that of 26 December and it occurs also in conjunction with an underestimation of the cloud cover by the model and an earlier deepening of the well-mixed layer.

Finally the sodar reveals an earlier peak and fall-off in boundary layer depth on 26 December than does the model (Fig. 6). This is due to clouds which are responsible for a strong decrease of SWD, while clouds are not simulated.

Comment [23]: Rev. 1.15.

5. Discussion and conclusion

The MAR model has been set up over a domain covering Dome C during the OPALE campaign. The size of the domain is much smaller than the internal radius of deformation. As a consequence the model solution is constrained in the free atmosphere by the one of the European re-analyses ERA-Interim but, as already pointed out by Lefebre et al. (2005), it allows to develop its own solution in the boundary layer. The simulation is characterized by a positive efficiency of wind and temperature over Dome C, given us confidence in its behaviour. In certain situations, MAR underestimates the downward long-wave radiation. When this problem occurs it is often linked to an underestimation of the cloud cover, and is one of the reasons , which leads to an overestimation of the simulated amplitude of the diurnal cycle of air temperatures. An other possible cause of this overestimation is the underestimation of heat transfer in the snow pack and an amplification of the subsequent decoupling between the atmosphere and the surface initiated by the underestimated LWD and heat conduction. Indeed surface turbulent fluxes are well simulated, but discrepancies with the observations are found when the simulated downward long-wave flux is underestimated. *Note that, since this underestimation of the LWD will induce also an error in the modelled temperatures measured temperatures, which were available through all the OPALE campaign were used when interpreting the chemistry data (e.g. Preunkert et al., 2014).* On the other hand the simulated wind speed in the surface boundary layer is in good agreement with the observations. It may consequently be argued that the turbulence schemes used in MAR (Monin-Obukhov similarity theory and E - ε model) are valid for the OPALE period. However, the question whether this keeps true also under strong radiational cooling as encounterd during winter at Dome C is still open.

Comment [24]: Rev. 1.1

Consequently model outputs and especially its turbulent characteristic are useful when interpreting the observations made in case of observed clear sky during OPALE. Indeed clear sky conditions, i.e. situations for which the model simulation is in excellent agreement with available observations, are more adequate when discussing measurements of species involved in photochemical processes. In particular the good behaviour of the simulated surface turbulent fluxes allows us to use the associated turbulent eddy diffusivity coefficient to evaluate the impact of turbulent transport on NO_x, HONO and HCHO emitted from snow. In addition the simulated boundary layer height indicates over which thickness of the atmosphere these chemical species are diluted. In brief, the use of such a model will allow us to optimize the experimental set- up for future campaign aiming to characterize the low troposphere chemistry at Dome C.

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