Mon. Not. R. Astron. Soc. **387,** 1499–1510 (2008) doi:10.1111/j.1365-2966.2008.13361.x

Comparison of the atmosphere above the South Pole, Dome C and Dome A: first attempt

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Accepted 2008 April 17. Received 2008 April 3; in original form 2007 November 14

ABSTRACT

The atmospheric properties above three sites (Dome C, Dome A and the South Pole) on the Internal Antarctic Plateau are investigated for astronomical applications using the monthly median of the analyses from ECMWF (the European Centre for Medium-Range Weather Forecasts). Radiosoundings extended on a yearly time-scale at the South Pole and Dome C are used to quantify the reliability of the ECMWF analyses in the free atmosphere as well as in the boundary and surface layers, and to characterize the median wind speed in the first 100 m above the two sites. Thermodynamic instability properties in the free atmosphere above the three sites are quantified with monthly median values of the Richardson number. We find that the probability to trigger thermodynamic instabilities above 100 m is smaller on the Internal Antarctic Plateau than on mid-latitude sites. In spite of the generally more stable atmospheric conditions of the Antarctic sites compared to mid-latitude sites, Dome C shows worse thermodynamic instability conditions than those predicted above the South Pole and Dome A above 100 m. A rank of the Antarctic sites done with respect to the strength of the wind speed in the free atmosphere (ECMWF analyses) as well as the wind shear in the surface layer (radiosoundings) is presented.

Key words: turbulence – atmospheric effects – site testing.

1 INTRODUCTION

The summits of the Antarctic Plateau are of particular interest for ground-based astronomy because the optical turbulence appears to be confined to a narrow layer close to the ground (Marks et al. 1999; Lawrence et al. 2004; Agabi et al. 2006). Above this layer the atmosphere is exceptionally clear and the turbulence weak (0.27 arcsec Lawrence et al. (2004), 0.36 arcsec Agabi et al. (2006) at Dome C). Measurements have shown that the height of the turbulent layer above the summits is much lower than above other sites on the Plateau (Marks et al. 1996, 1999; Marks 2002; Lawrence et al. 2004). More precisely, the height of this layer is much larger above the South Pole [220 m (Marks 2002) or 270 m (Travouillon et al. 2003)], which lies on a slope, than above Dome C [36 ±10 m (Agabi et al. 2006)]. Above Dome A the turbulence is expected to be even weaker.

The surface winds of Antarctica are among the principal sources of turbulence near the ground. The dominant source of the surface winds is the sloping terrain and the radiative cooling of the surface (Schwerdtfeger 1984). The radiative cooling produces a temperature inversion that together with the sloping terrain cause a horizontal temperature gradient. This triggers a surface wind alongside the slope of the terrain. Strong wind shears can therefore occur in the boundary between the surface winds and the winds in the free atmosphere, which in general are geostrophic. This is the main source of instability under conditions of extreme stability, as is the case of the Antarctic atmosphere in winter. Above the summits of the Internal Antarctic Plateau the surface winds should be much weaker than elsewhere on the Plateau due to a lack of the principal cause triggering them: a sloping terrain.

These elements justify the enthusiastic interest of astronomers for this site (Storey et al. 2003; Fossat 2005). Studies of the atmospheric properties of these regions are fundamental for applications to ground-based astronomy. However, we need a better quantification of these characteristics, using instruments and measurements as well as models and simulations, in order to fill the gaps of uncertainties or doubts that still remain (Masciadri et al. 2006), extending our attention to a comparative analysis of different sites of the Internal Antarctic Plateau.

It is important to produce statistical estimate of meteorological parameters at all heights from the ground to verify if atmospheric conditions are *always* advantageous for astronomical applications. Indeed, it has recently been shown (Geissler & Masciadri 2006), using European Centre for Medium-Range Weather Forecasts (ECMWF) analyses, that in winter the wind speed grows monotonically above

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~10 km a.s.l. (above sea level), achieving median values of the order of ~30 m s^{-1} at 25 km a.s.l. At this height a variation of ~20 m s^{-1} has been estimated between summer and winter. Such a strong wind might trigger an important decrease of the wavefront coherence time, even in presence of a weak turbulence (see discussion in Geissler & Masciadri 2006) and, as a consequence, the potentiality of these sites might vanish. It should be therefore interesting to better quantify the median wind speed profile on other sites (with astronomical interest) of the Internal Antarctic Plateau or to retrieve some general indication of the wind speed in the free atmosphere above the Internal Antarctic Plateau.

Besides that, the employment of ECMWF analyses for characterization of the surface layer requires a deeper analysis. Geissler & Masciadri (2006) concentrated their study at heights greater than 30 m thus excluding the surface contribution, assuming that the ECMWF analyses are not optimized for the atmospheric flow near the surface. More recently, studies (Sadibekova et al. 2006) appeared claiming that the ECMWF analyses can be used to quantify and characterize the atmospheric properties with a good level of accuracy down to the surface level. In spite of our conviction that this conclusion is the result of a partial analysis (only summer data) we admit that in Geissler & Masciadri (2006) the authors *assumed* (and they did not proved) the limits of the ECMWF for the surface layer. We therefore think that is time to provide a dedicated analysis on this subject to know the limit within which we can achieve reliable estimates with general circulation models (GCM), i.e. with ECMWF analyses and to identify the domains in which one is forced to employ mesoscale models. The latter are in principle more suitable to better resolve phenomena happening at smaller spatial and temporal scales.

The usefulness of mesoscale models depends on the limitations imposed by the products of the GCMs (that means the ECMWF analyses). It is obvious that, the usefulness of mesoscale models would not be justified for wind speed if ECWMF products could provide answers with a sufficient good accuracy.

Our group is involved in a long-term study made with mesoscale models for the simulation of the optical turbulence on the whole troposphere and low stratosphere using the technique described in Masciadri, Avila & Sanchez (2004) above the Internal Antarctic Plateau.[1] This study is therefore propedeutic to researches done with such a typology of models.

It is therefore fundamental to provide a clear picture of the limitations of the ECMWF products and at the same time, to try to retrieve the maximum number of useful information we can get from such a kind of products.

In this paper we try a first attempt to quantify, above the three sites with some astronomic interests (the South Pole, Dome C and Dome A), the differences of some critical meteorologic parameters that are directly, or indirectly, related to the characteristics of atmospheric turbulence. We expressly select two sites (South Pole and Dome C) for which measurements are available and one site (Dome A) for which no measurements are available. The reasons for this choice are explained later on (paper's scientific goals).

We use data from the MARS catalogue of the ECMWF and radiosoundings from the South Pole[2] and Dome C.[3] Analyses data are extracted from the three grid points that are nearest to the sites of interest, i.e. Dome A, Dome C and the South Pole. The coordinates of the sites are given in Table 1. We extracted analyses data from MARS at 00:00 UTC for the whole year of 2005 to assure a complete statistical sample covering all seasons. A more detailed description of the analyses data set is given by Geissler & Masciadri (2006).

Table 1. The geographic coordinates of the sites and the closest grid points from which the ECMWF analyses are extracted.

Site	Latitude	Longitude
Dome A[a]	80°22′00″S	77°21′11″E
	80°30′00″S	77°30′00″E
Dome C[b]	75°06′04″S	123°20′48″E
	75°00′00″S	123°30′00″E
South Pole	90°00′00″S	0°00′00″E
	90°00′00″S	0°00′00″E

[a]Measured with GPS by Dr X. Cui (private communication).[b]Measured with GPS by Professor J. Storey (private communication).

The scientific goals of this paper are as follows.

(1) To carry out a detailed comparison of radiosoundings/analyses of the wind speed and the potential temperature (the main critical parameters defining the stability of the atmosphere) near the surface (the first 150 m) for winter as well as summer above Dome C and the South Pole. This will permit us to quantify the uncertainty between measurements and ECMWF analyses in this vertical slab. The idea is therefore to define the conditions in which the ECMWF analyses can be used to characterize, with a good level of reliability and accuracy, some atmospheric parameters and to use this tool to characterize a site for which no measurements are available. This is of course the interest for a model. Depending on the results of this analysis we will perform comparisons of meteorologic parameters above the South Pole, Dome C and Dome A using ECMWF analyses (Section 2).

(2) Using radiosoundings we will estimate the statistic median values of the wind speed in the first tens of metres above the South Pole and Dome C extended from April to November. We will therefore be able to quantify which site shows the better characteristics for nightly astronomical applications (Section 3).

(3) We extend the study developed by Geissler & Masciadri (2006) above Dome C for the ECMWF wind speed also to the South Pole and Dome A, both located on the Internal Antarctic Plateau but at different latitude and longitude. In this way, we intend to quantify which site is the best for astronomical applications. Results of this analysis are fundamental to confirm or see in the right perspective the potentialities of Dome C.

(4) We extend the analysis of the Richardson number done by Geissler & Masciadri (2006) for Dome C for heights above 30 m to the three sites (South Pole, Dome C and Dome A) in order to quantify the regions and the periods that are less favourable for the triggering of optical turbulence and to identify the site with the best characteristics (Section 5). This result should represent the first estimate of potentialities of Dome A for astronomical applications and this should mean that we are able to provide some reliable results and conclusions even before some measurements are done on that site. This study has therefore a double interest. First the intrinsic result itself. Secondly, this analysis should open the path to a different approach for a fast and reliable classification of potential astronomical sites.

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[1] Some attempts have been done in the past (Swain & Gallée 2006) even if with different scientific goals.

[2] ftp://amrc.ssec.wisc.edu/pub/southpole/radiosonde.

[3] http://www.climantartide.it.

2 ECMWF ANALYSES VERSUS RADIOSOUNDINGS

In this section the ECMWF analyses are compared to radiosoundings from Dome C and the South Pole in order to investigate the reliability of the ECMWF data over an Antarctic site. The radiosoundings and the ECMWF analyses used for this comparison refer to the year 2006. This year was chosen because of the richer sample of available radiosoundings. The reason why the comparison of analyses from different sites, discussed later on in this paper, are from 2005 is because we wish to investigate a homogeneous data set. In 2006 February the number of vertical levels in the ECMWF model changed from 60 to 91.

When studying the difference between radiosoundings and analyses particular interest is paid to the first tens of metres since this is where we expect the largest turbulent activity and this range was not studied by Geissler & Masciadri (2006). The median of the difference in wind speed and temperature between ECMWF analyses and radiosoundings, for summer (December, January and February) and winter (June, July and August) are shown in Fig. 1. A total number of 73 nights has been used in summer and 75 in winter. In the free atmosphere we observe that the radiosoundings do not reach as high altitudes in winter as they do in summer. A similar effect has been observed above the South Pole in our previous study (Geissler & Masciadri 2006). This effect makes it difficult to study the reliability of the ECMWF data at high altitudes in winter. In this season the balloons frequently explode. This happens, highly probably, because, due to the low pressure in the high part of the atmosphere, the balloons increase their size and they finally explode. The elastic material of the balloons is much more fragile in winter, when the temperature is much lower than in summer in the high part of the atmosphere.

In local summer the median difference in the wind speed never exceeds 1 m s^{-1}. Closest to the ground the difference is even smaller, below 1 m s^{-1}. During local winter the median difference in wind speed never exceeds 0.5 m s^{-1} in the upper atmosphere, though the radiosoundings only reach ∼10 km above the ground. The median difference is larger closest to the ground (∼3 m s^{-1}) in winter.

The median absolute temperature difference in summer is below 2 K throughout the whole 20 km. In the proximity of the surface this difference is of the order of 1 K, closest to the surface even less. During the winter the median difference is similar to that of the summer in the high part of the atmosphere. In the first 100 m the median difference is significantly larger, more than 6 K nearest the surface.

Fig. 2 shows the same outputs of Fig. 1 but calculated for South Pole. We report just the first 150 m because we had already calculated (Geissler & Masciadri 2006) the difference ECMWF analyses/radiosoundings above 150 m at South Pole. For the wind speed the conclusion is similar to what observed at Dome C. The wind speed difference remains within 1 m s^{-1} in the first 150 m in summer. However, analyses show a tendency in overestimating (∼2 m s^{-1}) the wind speed in the very low levels in winter even if this effect is slightly weaker than above Dome C. The median absolute temperature difference in summer is similar to what observed above Dome C and contained within ∼1 K. Near the ground the ECMWF analyses are almost 2 K warmer than the radiosoundings. This same trend is observed also in winter. However, in this season, the

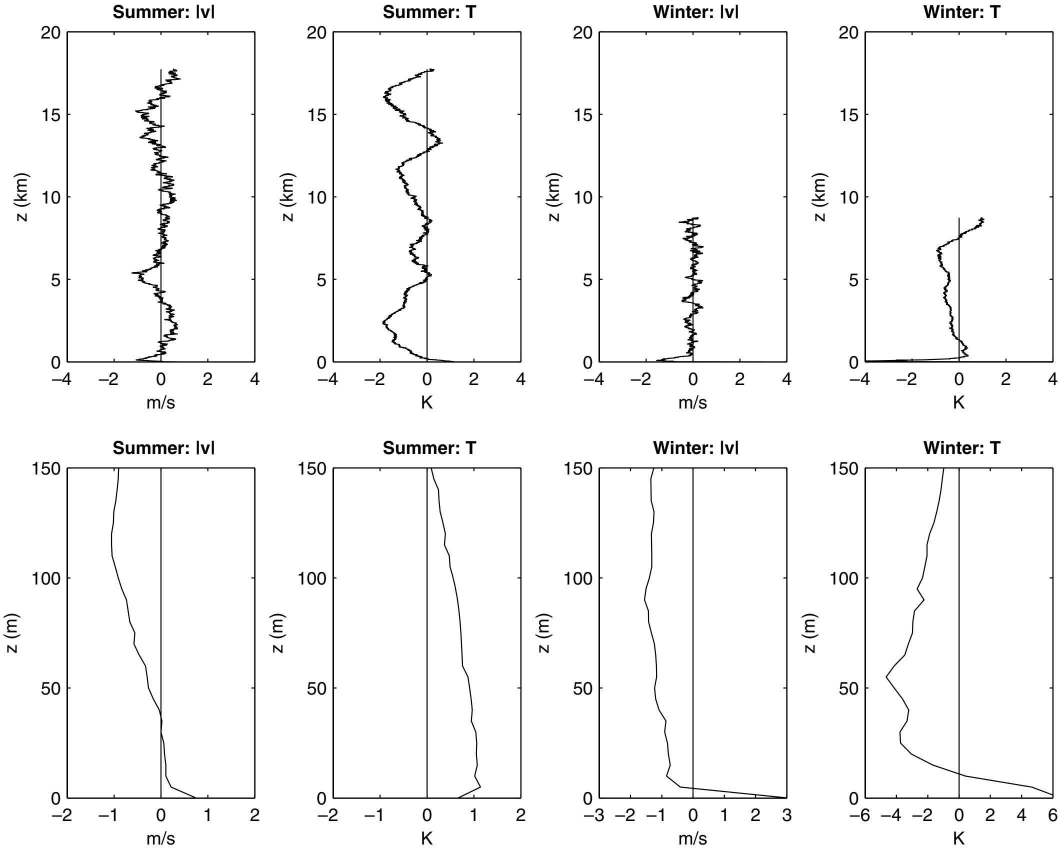

Figure 1. The median of the difference of the absolute temperature and the wind speed between ECMWF analyses and radiosoundings (ECMWF – radiosoundings) for summer (December, January, February) and winter (June, July, August) at Dome C in 2006.

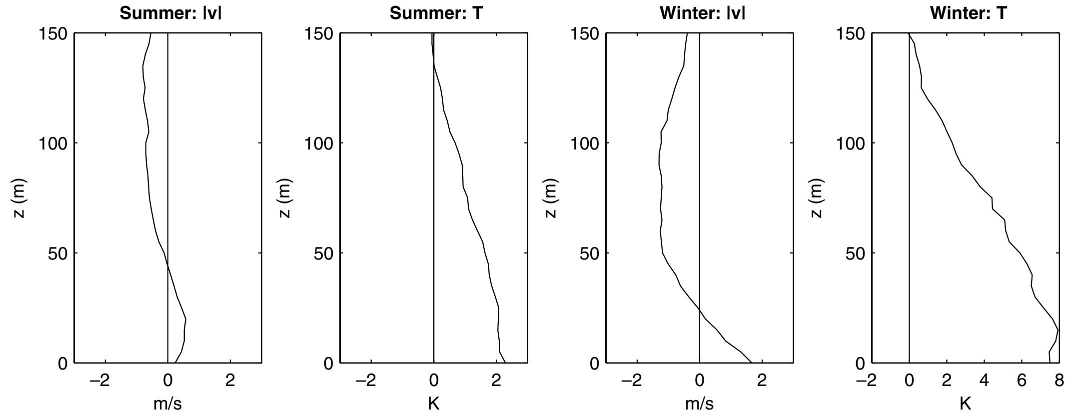

Figure 2. The median of the difference of the absolute temperature and the wind speed between ECMWF analyses and radiosoundings (ECMWF – radiosoundings) for summer (December, January, February) and winter (June, July, August) at South Pole in 2006.

analyses are visibly much warmer (∼6 K) than the radiosoundings near the surface. The statistic uncertainty $\sigma/\sqrt{N}$ for the wind speed is of the order of 0.2 m s^{-1} all along the 20 km with a maximum of 0.4 m s^{-1} at 5 km in summer. The statistic uncertainty for the absolute temperature is of the order of 0.3 K and slightly larger (∼0.6 K) in the first 30 m in winter. The precision of the temperature provided by radiosoundings is ∼0.2 K in the boundary layer and ∼0.4 K in the free atmosphere while the precision of the wind speed[4] is of the order of 0.15 m s^{-1}.

Summarizing, we should say that the wind speed is almost well reconstructed by the ECMWF analyses with exception of the surface in winter where ECMWF analyses show a tendency in overestimating of 2–3 m s^{-1}. For a typical wind speed of 3 m s^{-1} this corresponds to a large discrepancy. The absolute temperature is in general warmer from the ECMWF analyses than from the radiosoundings near the surface in winter achieving a difference of the order of ∼6 K. The wind speed and temperature show similar trends above the two sites with exception of the absolute temperature in winter. At South Pole, the temperature from ECMWF analyses appears warmer on the whole 150 m while, at Dome C, only in the first 20 m.

To check if any biases are present in the measurement provided by radiosoundings in the first vertical grid point (critical region for radiosoundings) we calculated (Table 2) the median values of wind speed and absolute temperature in the three central winter months obtained from the Automatic Weather Station (AWS).[5] An automatic weather station is an automated version of the traditional weather station, to enable measurements from remote areas and we compared these outputs with those obtained from radiosoundings in the first grid point. Data of 2004 are used for South Pole because no AWS data from 2006 were available. The median wind speed from radiosoundings in first vertical grid point is 2.8 and 5.7 m s^{-1}, respectively, at Dome C and South Pole. These values match in excellent way with AWS measurements: 3 and 5.7 m s^{-1}, respectively, at Dome C and South Pole in the same periods. We conclude therefore that the measurement of the first grid point from the radiosoundings are reliable because perfectly in agreement with AWS measurements. We note that a similar median wind speed of 2.6 m s^{-1} has been calculated at Dome C on a climatologic scale (1984–2003) by Aristidi et al. (2005) in winter. Hudson & Brandt (2005) calculated at the South Pole a median wind speed of ∼5 m s^{-1} in winter on a climatologic scale (1994–2003). The median values calculated in our paper on a time-scale of 1 yr have therefore almost no climatologic trends. If we look at the absolute temperature in Table 2 we conclude that the radiosoundings are ∼1 K colder than the AWS at Dome C and ∼2 K at South Pole.

Going back to Figs 1 and 2, this conclusion supports and confirms the thesis that we are in front of an overestimate produced by the ECMWF analysis and not to an artefact in the measurements (radiosoundings). However, the overestimate is slightly smaller than what predicted for the temperature. This means an overestimate of 4–5 K instead of 6 K.

Figs 1 and 2 therefore indicate that the ECMWF analyses accurately describe the state of the free atmosphere above Dome C and the South Pole. In the boundary layer, the ECMWF data shows a tendency in overestimating the wind speed and the absolute temperature, particularly in winter. Results we obtained indicated that ECMWF analyses should be treated with more caution.

These conclusions also confirmed the thesis we had expressed in Section 1 concerning the Sadibekova et al. (2006) paper who claimed for a good agreement between radiosoundings and ECMWF analyses even near the surface.

In spite of the fact that they used ERA-reanalyses (a product having a lower resolution than the MARS catalogue used in our study) the agreement between radiosoundings and analyses in their data matches well with our findings and predict a good agreement between radiosoundings and ECMWF analyses in summer. Our analysis, extended to winter, reveals that, in this season, the agreement is far from being good and the sharp changes in wind speed and temperature closest to the surface measured by the radiosoundings are not well reconstructed by the ECMWF analyses data.

To provide the most comprehensive and compact comparison of ECMWF analyses and radiosoundings above Dome C and the South Pole in the proximity of the surface we prefer to focus now on the two key parameters defining the thermodynamic stability, i.e. the gradients of the potential temperature and of the wind speed. Indeed, only a study of the simultaneous systematic effects on both quantities can tell us if we can use ECMWF analyses to quantify the thermodynamic stability in the surface layer.

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[4] More precisely, the velocity uncertainty is defined in the technical specification as the standard deviation of the differences in twin soundings.

[5] http://amrc.ssec.wisc.edu/realtime.html.

Table 2. The median wind speed and absolute temperature for the winter months (JJA) from the lowest level of the radiosoundings compared to values obtained with AWS. First and third quartile are also given.

	v_0 (ms^{-1}) First quartile	v_0 (ms^{-1}) Median	v_0 (ms^{-1}) Third quartile	T_0 (K) First quartile	T_0 (K) Median	T_0 (K) Third quartile
		Radiosoundings			Radiosoundings	
Dome C (2006)	1.5	2.8	3.8	204.4	208.3	213.1
South Pole (2004)	4.6	5.7	7.2	205.8	209.7	213.6
		AWS			AWS	
Dome C (2006)	2.0	3.0	4.5	204.8	209.0	213.6
South Pole (2004)	3.6	5.7	7.4	206.7	211.4	215.0

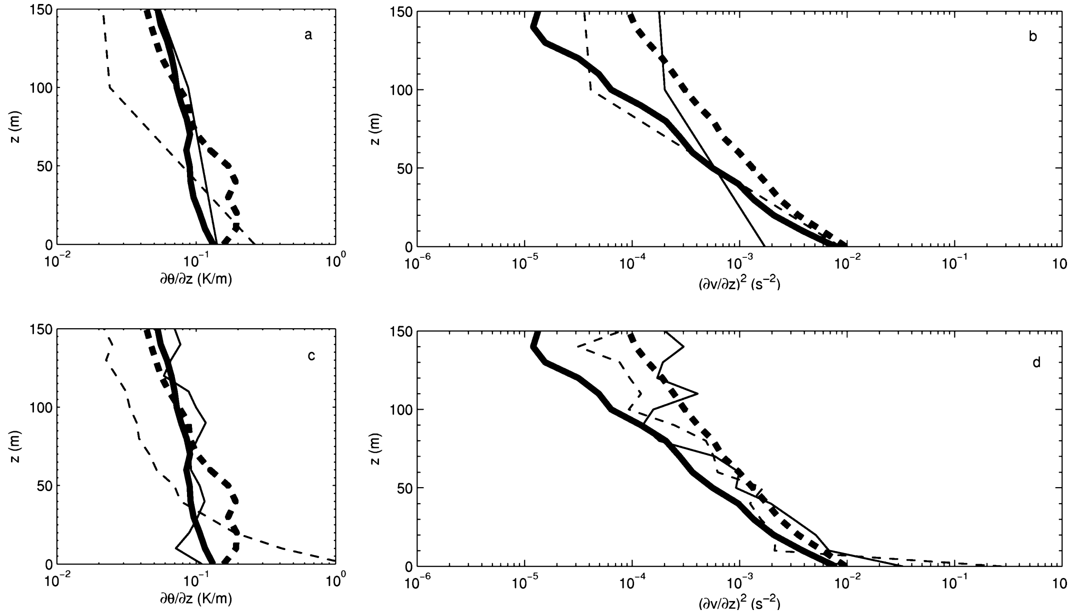

Figure 3. The gradients of the potential temperature and the wind speed near the surface for Dome C and the South Pole in 2006 July. The dashed lines refer to Dome C and the solid lines refer to the South Pole. Thick lines are ECMWF analyses and thin lines are radiosoundings. In the top plots (a and b) the radiosoundings are interpolated with a step of 100 m, in the bottom plots (c and d) the step is 10 m.

Fig. 3 shows the median gradient of the potential temperature (left-hand panels) and the median of the square of the gradient of the wind speed (right-hand panels) in the first 150 m with a vertical resolution of 100 m (a and b) and of 10 m (c and d). As we can expect, the radiosoundings show a sharper gradient than the analyses near the surface. We can observe that the ECMWF analyses are able to identify that the gradients above Dome C are larger than above South Pole. Unfortunately, a precise quantification is missing and, even in the case of the best vertical resolution (cases c and d), the offset produced by analyses with respect to radiosoundings on the two parameters [$\partial\theta/\partial z$ and $(\partial v/\partial z)^2$] is not comparable above the two sites (Dome C and the South Pole). This implies that the ECMWF analyses do not smooth out the potential temperature and wind speed gradients in a similar way above the two sites.

Knowing that the Richardson number depends on the ratio of $\partial\theta/\partial z$ and $(\partial v/\partial z)^2$ we conclude that it is pretty risky to draw any conclusion on a comparative analyses of the Richardson number in the surface layer between different sites calculated with the ECMWF analyses. As a consequence we can state that we can retrieve a ranking of the three sites with respect to the thermal and the dynamic gradient in an independent way but we cannot retrieve a ranking of the three sites with respect to the Richardson number in the surface layer using ECMWF analyses. We have therefore to limit us to a comparative analysis of the $\partial\theta/\partial z$ and $(\partial v/\partial z)^2$. In section 5 we will perform the Richardson number comparison in the free atmosphere where we showed the ECMWF analyses are reliable.

For a reliable study of the Richardson number in the surface layer we need, at present, radiosoundings. A forthcoming paper on this topic is in preparation.

2.1 $\partial\theta/\partial z$ and $(\partial v/\partial z)^2$ at the South Pole, Dome C and Dome A

As a consequence of the conclusions obtained in the previous section, we present here the ‘thermal’ and ‘dynamic’ properties of the surface layer in an independent way.

The change of the potential temperature with height indicates the thermal stability of the atmosphere. A positive gradient is defined as stable conditions, the vertical displacement of air is suppressed and thus is the production of dynamic turbulence.

The absence of sunlight in the Antarctic night and the consequent radiative cooling of the snow surface create a strong temperature inversion close to the ground. The monthly median of the gradient of the potential temperature in the first 150 m for the three sites,

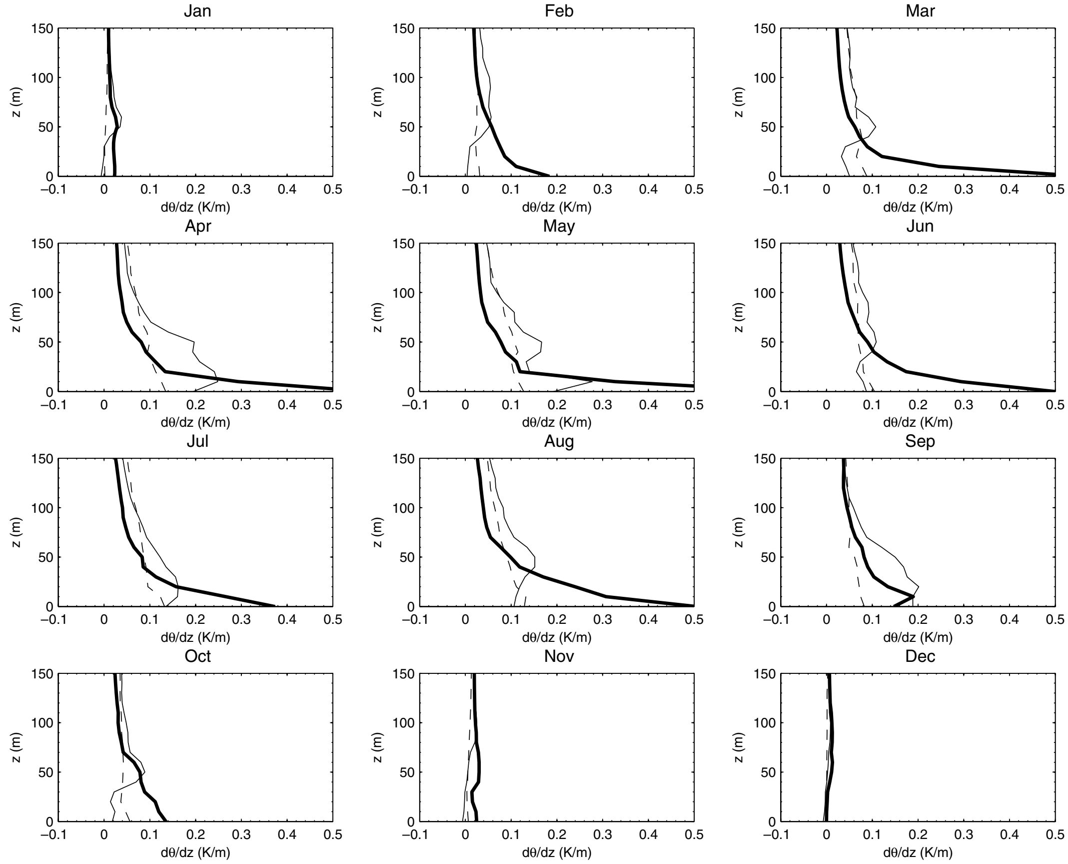

Figure 4. The monthly median of the gradient of the potential temperature for 2005, Dome A (thick lines), Dome C (thin lines) and the South Pole (dashed lines).

calculated with the ECMWF analyses, is shown in Fig. 4. From February to October all the gradients are positive and indicate a thermally stable stratified atmosphere near the surface. The inversion above Dome A (thick lines) is particularly intense when compared to Dome C (thin lines) and to the South Pole (dashed lines) during these months. The value of the gradient at the lowest level is significantly larger for Dome A almost all the year. From March to August there is a very sharp change in the slope of the gradient of Dome A at around 20 m above the surface.

During the summer months all three sites have a neutral stratification near the surface, i.e. $\partial\theta/\partial z \approx 0$. Vertical motion of the air is not suppressed but neither is it encouraged. A small perturbation can trigger dynamic turbulence.

The median of the gradient of the square of the wind speed in the first 50 m above the ground is shown in Fig. 5. The gradient of the wind speed at the lowest level is largest at Dome A for every month (except in June when it is slightly larger above Dome C).

3 RADIOSOUNDINGS: THE SURFACE WIND SPEED

Above the summits of the Internal Antarctic Plateau the surface winds are expected to be weaker than elsewhere on the Plateau. Fig. 6 shows the median wind speed near the surface measured with radiosoundings at the South Pole (dashed lines) and Dome C (solid lines) from April to November. We observed that while it is true that the wind speed at the very lowest level is weaker at the peak (Dome C) than at the slope (South Pole), there is a sharp increase in the wind speed above Dome C in the first few tens of metres. At the height of 10/20 m, from May to November, i.e. in the winter, the wind speed is higher above Dome C than above South Pole. Above this height the wind speed at Dome C is either higher than or very similar to the one observed above the South Pole.

In the centre of the winter (June, July and August), the wind speed above Dome C reaches the 8 m s^{-1} at 20 m and 9 m s^{-1} at 30 m. The sharp change of the wind speed in the first 10/20 m matches with our expectations of a large wind speed gradient. This is indeed a necessary condition to justify the presence of optical turbulence in the surface (Agabi et al. 2006) in spite of very stable thermal conditions (i.e. a positive gradient of the potential temperature).

Trinquet et al. (2008), in a small sample of radiosoundings in winter, observed a wind speed of 5 m s^{-1} at 20 m and 8 m s^{-1} only at 70 m. Our results, obtained with a complete statistical sample in winter, tell us that the Trinquet et al. estimate is too optimistic and we should expect a larger wind speed at low heights.

We conclude that in the first 10/20 m the mechanical vibrations, which might be derived from the impact of the atmospheric flow, flowing at 8–9 m s^{-1} on a telescope structure, are probably more critical above Dome C than above the South Pole and should be carefully taken into account in the design of astronomical facilities.

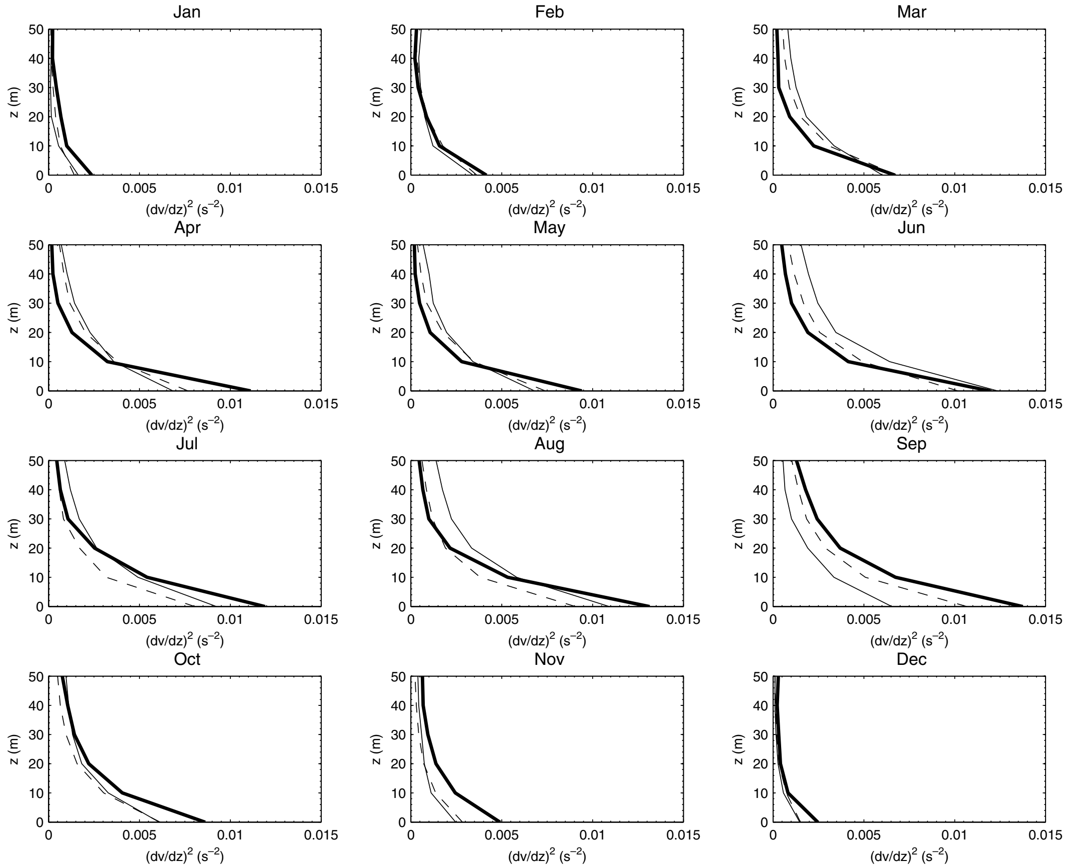

Figure 5. The monthly median of the square of the gradient of the wind speed in the first 50 m for the year 2005. Dome A (thick lines), Dome C (thin lines) and the South Pole (dashed lines).

4 ECMWF ANALYSES: THE WEAKEST WIND SPEED IN THE TROPOSPHERE AND THE LOWER STRATOSPHERE

Fig. 7 shows the monthly median of the wind speed from ground level up to 25 km a.s.l. for Dome A (blue lines), Dome C (green lines) and the South Pole (red lines). During summer the wind speed is quite weak in the upper part of the atmosphere for all three sites. A maximum is observed at roughly 8 km a.s.l. From December to March the median wind speed is never larger than 15 m s^{-1} in the whole 20 km and above all the sites. As the winter approaches the wind speed in the upper atmosphere increases. From April to November the wind speed increases monotonically above 10 km a.s.l. and the highest wind speed is more likely to be located in the highest part of the atmosphere. However, the rate at which the wind speed grows is not the same above the three sites. The smallest increase rate is observed at the South Pole and the maximum rate is found above Dome C. Differences are far from being negligible. In this slab the median wind speed is, at Dome C, almost twice that of Dome A or the South Pole.

Geissler & Masciadri (2006) found in their investigation a similar wind speed trend above Dome C from ECMWF analyses for the years 2003 and 2004. The wind speed trend above Dome C is therefore confirmed in different years. However, as announced in Section 1, the goal in our paper is the comparison of Dome C with other sites to evaluate which are the best for astronomical applications.

The different wind speed gradient rate observed in Fig. 7 above different sites is highly probable related to the synoptic circulation of the Antarctic regions. Indeed, the jet stream, that characterizes the vertical wind speed profile of mid-latitude sites at the tropopause level, is absent here. On the other hand, the polar vortex creates strong high-altitude winds surrounding the polar high in winter (Schwerdtfeger 1984). Wind speed increases monotonically above 10 km. The result observed in Fig. 7 can be explained with the fact that the South Pole is located near the centre of the polar vortex and consequently the influence of the polar vortex is weak at this site. Dome A and Dome C are situated further from the centre of the continent, and thus from the centre of the polar vortex. It is to be expected that the wind speed is larger above these sites. The farther from the polar high (centre of the polar vortex) is the site, the greater is the wind speed strength above 10 km.

According to this explanation the wind speed strength in the upper atmosphere should be related to the distance of the site from the centre of the polar vortex. If we could know the exact position of the polar high we would have a perfect tool to identify, a priori, the site with the weakest wind speed above 10 km in winter. Unfortunately the polar vortex is not a perfect cone and the centre of the vortex is not located at the same coordinates at all heights. To verify the sensitivity to this effect we included in our sample a further site (Dome F, (77.31 S, 39.7 E), $h = 3810$ m) and we added the median wind speed in the same Fig. 7. In this picture it is evident that South Pole and Dome C have, respectively, the weakest and the greatest wind speed above 10 km. The wind speed above Dome A and Dome

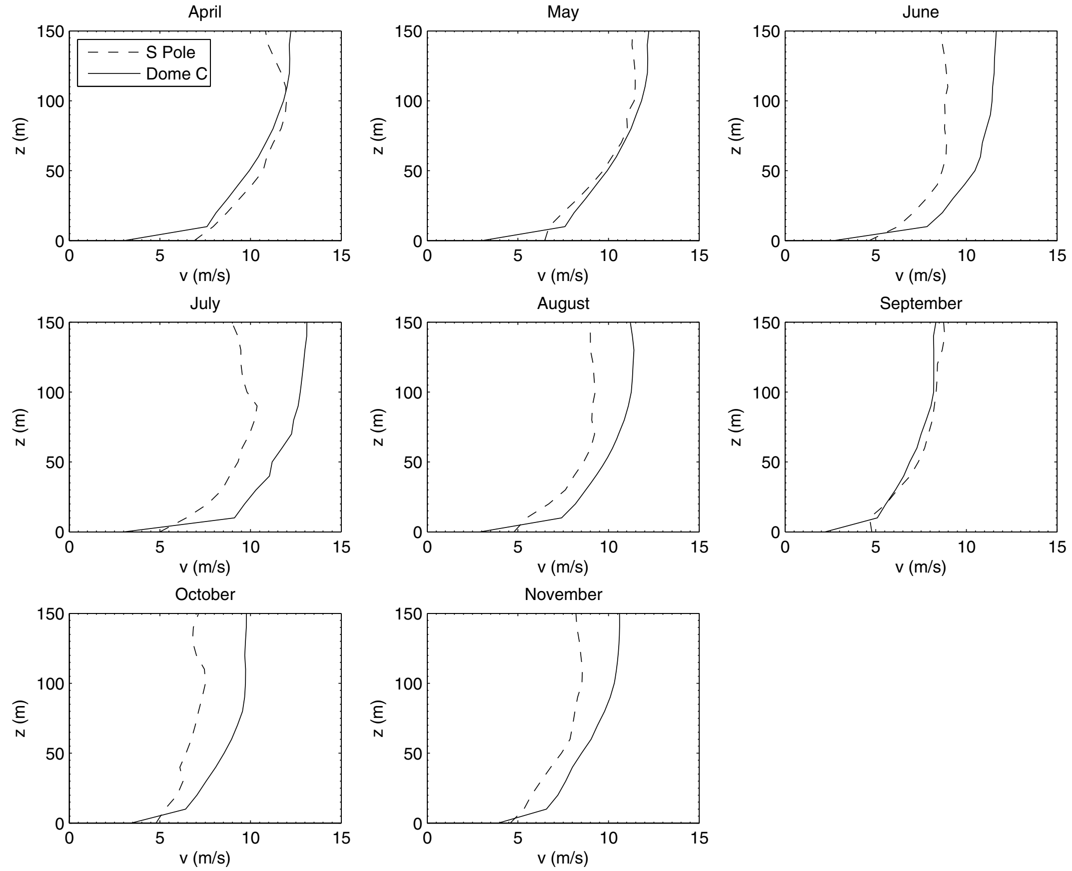

Figure 6. The wind speed near the ground at Dome C (solid lines) and the South Pole (dashed lines), 2006 April to November.

F is mostly comparable and it is more difficult to state which site has the weakest wind speed. Dome A is slightly better if we consider a statistical analysis of the whole year but the difference is not so important. This indicates that the polar high fluctuates probably in a region located between the South Pole, Dome A and Dome F as indicates the dashed region in Fig. 8.

5 THE RICHARDSON NUMBER FOR THE SOUTH POLE, DOME C AND DOME A

The Richardson number is an indicator of the stability of the atmosphere:

$$\mathrm{Ri} = \frac{g}{\theta} \frac{\partial\theta/\partial z}{(\partial v/\partial z)^2}, \qquad (1)$$

where g is the gravitational acceleration (9.8 m s^{-2}), θ is the potential temperature and v is the wind speed. The atmosphere is considered to have a stable stratification when the Richardson number is larger than a critical value, typically 0.25. If the Richardson number is less than the critical value the stratification is classified as unstable. The smaller the Richardson number is the higher is the probability of triggering of turbulence.

The comparison of the Richardson number above different sites allows us to make a relative estimate of which site is characterized by a higher or lower probability to trigger turbulence. In Geissler & Masciadri (2006) (fig. 14), the median of the inverse of the Richardson number for Dome C are shown in different slabs and periods of the year. From such results it is possible to retrieve a comparative analysis that necessarily is qualitative. In other words we can say if a region shows a higher or smaller probability to trigger turbulence but we do not have a reference to quantify these differences nor can we conclude whether these differences are negligible or not. In order to provide insights on this question we calculated (Fig. 9) the median of the inverse of the Richardson number (1/Ri) from Dome C (thick lines) and from Mt Graham (thin lines), taken as an example of a typical mid-latitude site, for each month during the whole year 2005. The inverse of the Richardson number is shown instead of the Richardson number itself because the inverse shows a better dynamic. The smaller 1/Ri is, the more stable is the atmosphere. The 1/Ri is smaller above Dome C than above Mt Graham almost everywhere. This result is coherent with the optical turbulence measurements observed above the two sites (Agabi et al. 2006; Egner, Masciadri & McKenna 2007) and for this reason it definitely confirms the method proposed by Geissler & Masciadri (2006) to study 1/Ri as a qualitative relative indicator to rank sites with respect to the probability to trigger turbulence. During September and October, when the median wind speed is remarkably strong at high altitudes at Dome C (see Fig. 7), 1/Ri is actually larger than for the mid-latitude site. This confirms, from a qualitative and quantitative point of view, that the high part of the atmosphere in September and October is a region to be monitored carefully because the probability to trigger instabilities is comparable and even larger than above mid-latitude sites. A strong increase in the wind speed is most certainly the cause of the high 1/Ri over Dome C at such altitudes.

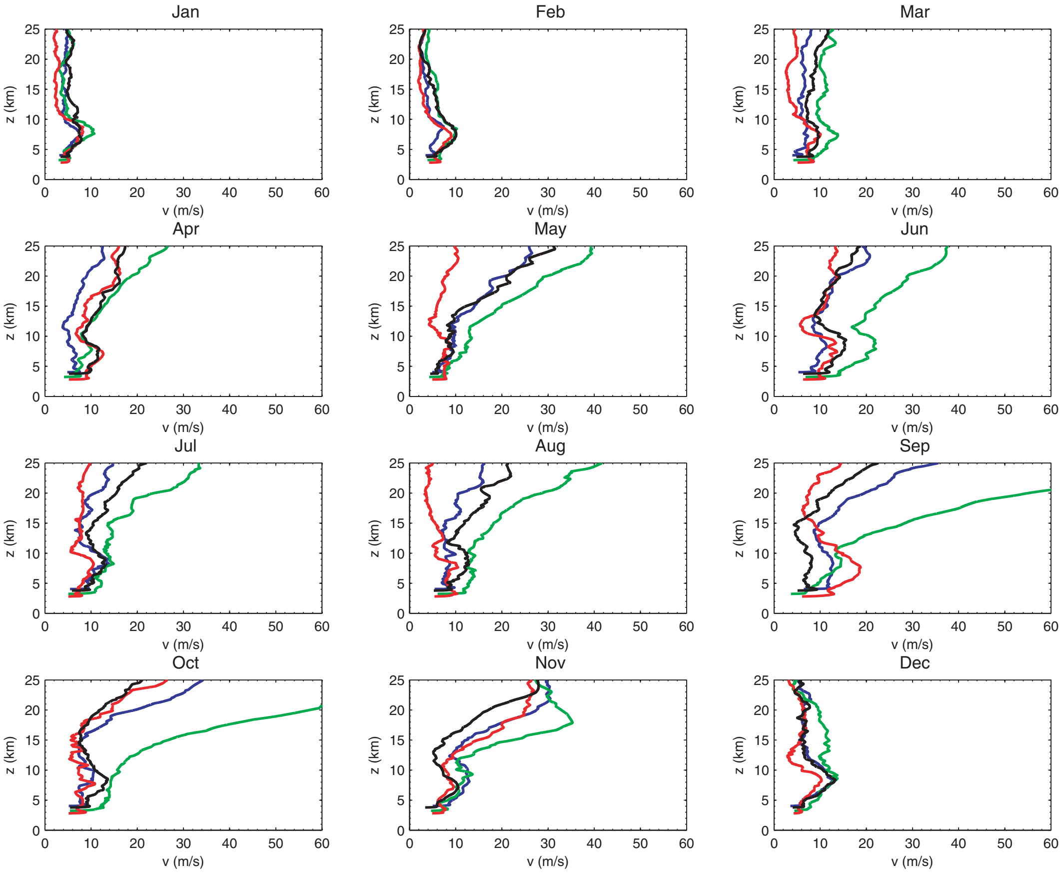

Figure 7. The monthly median wind speed for 2005. Dome A (blue line), Dome C (green line), South Pole (red line) and Dome F (black line).

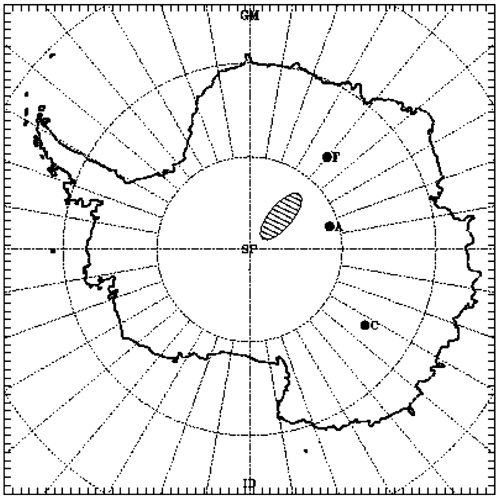

Figure 8. Antarctica map. The sites of South Pole, Dome A, Dome C and Dome F are labelled with a black point. The dashed region indicates the 'position space' of the polar high at different heights as retrieved from the Fig. 7.

The vertical median profiles of 1/Ri for the three Antarctic sites (Dome A, Dome C and the South Pole) are shown in Fig. 10. In local summer the profiles from the different sites are similar to each other. The 1/Ri has a maximum at ground level and a smaller peak somewhere slightly above 6 km a.s.l. Above 10 km a.s.l. the atmosphere is very stable for all the three sites. From April/May the instability above 10 km increases. At the end of the winter (September and October) the instability in the upper part of the atmosphere is even larger than the maximum value observed near 6 km for Domes A and C. The instability of Dome C is more pronounced than that of Dome A. Above the South Pole 1/Ri shows the best conditions (i.e. the most stable) over the whole year.

6 CONCLUSIONS

In this paper we provide a first comparison of the atmospheric characteristics above three different sites on the Internal Antarctic Plateau: Dome C, Dome A and the South Pole. More precisely we try to answer the specific questions defined in Section 1.

(1) The comparison of the ECMWF analyses with the radiosoundings shows that the analyses can accurately describe the atmosphere above the Internal Antarctic Plateau in the whole range from 10 m to 20 km above the surface. During no season does the median difference of the wind speed exceed 1 m s^{-1} above the first 10 m. The median difference of the absolute temperature is within 2 K in the same vertical slab. In the surface layer the wind speed discrepancy between analyses and radiosoundings is slightly larger (2–3 m s^{-1}) while ECMWF analyses show a tendency to overestimate the absolute temperature measured by radiosoundings in the lowest level in winter ($\Delta T \sim$4–5 K). A statistic analysis reveals that most of the radiosoundings explode in winter at about 10–12 km. This does not allow us to estimate the reliability of the ECMWF analyses at these high altitudes.

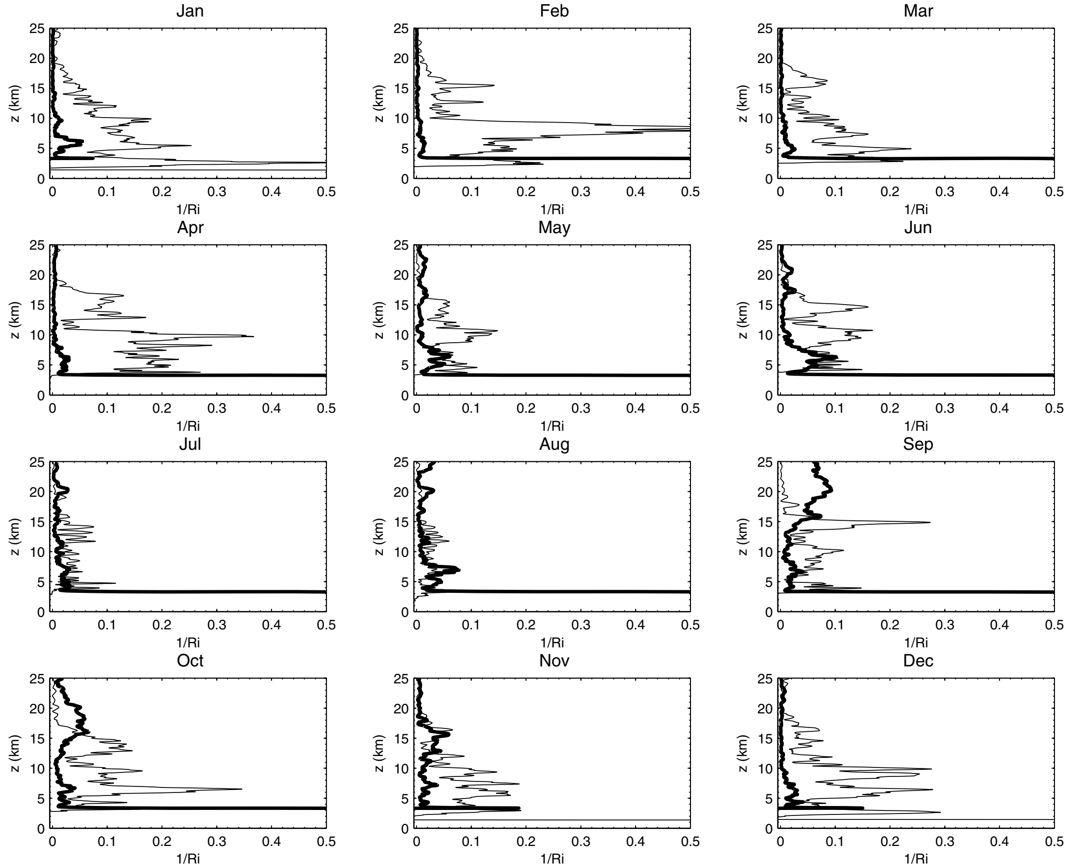

Figure 9. The monthly median for 2005 of the inverse of the Richardson number (1/Ri) for Dome C (thick lines) and Mt Graham (thin lines).

(2) We proved that the ECMWF analyses do not produce accurate estimates in the surface layers confirming what was only assumed by Geissler & Masciadri (2006). This result represents an answer to our original question expressed in Section 1. The ECMWF intrinsically have limitations for the characterization of the atmospheric flow in this vertical slab. This justifies the employment of mesoscale models but, at the same time, also tells us that it will be fundamental to prove that mesoscale models can do better than GCM in this vertical slab.

(3) We could conclude that above all the three sites the potential temperature in the surface layer is extremely stable even if the ECMWF analyses generally underestimate its gradient when compared to measurements obtained by radiosoundings. Such an effect is particularly evident in winter. Dome A is by far the site with the steepest gradient of potential temperature and wind speed if compared to the South Pole and Dome C.

(4) We proved that the median wind speed in the first metres above the ground is weaker at Dome C than at the South Pole from April to November. However, the wind shear in the surface layer at Dome C is much larger than at the South Pole achieving at 10–20 m a wind speed of 8–9 m s^{-1} in winter. Such a strong wind shear combined with a stable stratification of the air in this layer is most likely to be the cause of the intense optical turbulence that has been measured in the first tens of metres at Dome C (Agabi et al. 2006). Such a strong wind speed at this height might be a source of vibrations produced by the impact of the atmospheric flow on telescope structures and should therefore be taken into account in the conception and design of astronomic facilities.

(5) Median monthly values of the inverse of the Richardson number (1/Ri) indicate that the probability to trigger instabilities is larger above a mid-latitude site (for which we have a reliable characterization of the optical turbulence) than above any of the three sites on the Internal Antarctic Plateau. Above all the three Antarctic sites 1/Ri is visibly smaller than that measured above Mt Graham (selected as representative of mid-latitude sites). This is the first time that such a conclusion has been achieved and it definitely proves that the method presented in Geissler & Masciadri (2006) is reliable.

(6) Moreover, our analysis permitted us also a more sophisticated discrimination between the quality of the 1/Ri above the three sites. Dome A and the South Pole show, indeed, more stable conditions than Dome C above the first 100 m. This is probably due to the polar vortex which, producing an increase of the wind speed in the upper atmosphere, also increases the probability to trigger thermodynamic instabilities.

(7) We showed that it is risky to retrieve estimates of the Richardson number in the surface layer (Fig. 3) because we did not find an equivalent smoothing effect of the ECMWF analyses for the gradient of the potential temperature nor for the gradient of the wind speed above different sites.

(8) In the free atmosphere, above the first 10 km, the polar vortex induces a monotonic increase of the wind speed in winter that is proportional to the distance of the site to the polar high. Dome C therefore shows the largest wind speed above 10 km in winter. At Dome C the wind speed at 15 km can easily be almost twice that of Dome A and even thrice the wind speed at the South Pole in winter. The wind speed above the South Pole is the weakest among the three

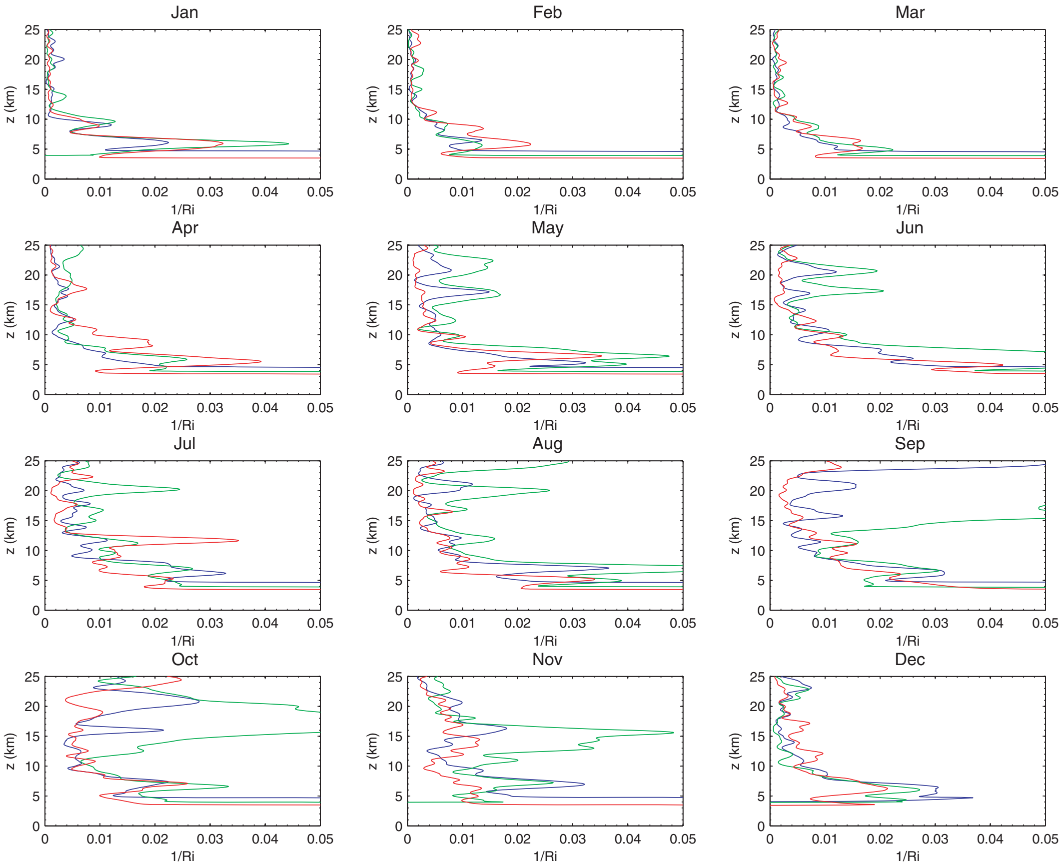

Figure 10. The monthly median for 2005 of the inverse of the Richardson number (1/Ri) for Dome A (blue lines), Dome C (green lines) and the South Pole (red lines).

sites on the whole 20 km in all seasons. This conclusion therefore puts fundamental warnings for astronomical applications.

(9) This study allowed us to draw a first comprehensive picture of the atmospheric properties above the Internal Antarctic Plateau. In spite of the presence of generally good conditions for astronomical applications, Dome C does not appear to be the best site with respect to the wind speed, in the free atmosphere as well as in the surface layer. Both the South Pole and Dome A show a weaker wind speed in the free atmosphere. Estimates related to the surface layer need to be taken with precaution. ECMWF analyses cannot be used to draw definitive conclusions on comparisons of the three sites in this vertical slab due to their limited reliability in this thin atmospheric slab (see Section 5) and radiosoundings are available only for Dome C and the South Pole. Above Dome A the gradient of the potential temperature is particularly large in the very near surface layer indicating conditions of extreme thermal stability that might be associated to a strong value of the optical turbulence in this vertical range when a thermodynamic instability occurs (possibly even larger than above Dome C). However, our study showed that to predict the thickness of such a layer we should need measurements or simulations with atmospheric mesoscale model with a higher spatial resolution near the ground that is able to better resolve the evolution of the atmospheric flow. This is a part of our forthcoming activities.

In conclusion, at present, the real solid and unique argument that makes Dome C preferable to the South Pole for astronomical applications is the extreme thinness of the optical turbulence surface layer. We expect at Dome A comparable or even larger optical turbulence values with respect to Dome C in the surface layer. We cannot conclude if the surface layer at Dome A is thinner than that observed above Dome C. However, our study clearly indicates that Dome C is not the best site on the Internal Antarctic Plateau with respect to the wind speed in the free atmosphere as well as in the surface layer nor is it the site with the most stable conditions in the free atmosphere. Both Dome A and the South Pole show more stable conditions in the free atmosphere.

ACKNOWLEDGMENTS

This study has been carried out using radiosoundings from the AMRC (Antarctic Meteorological Research Centre, University of Wisconsin, Madison, ftp://amrc.ssec.wisc.edu/pub/southpole/radiosonde) and from the Progetto di Ricerca 'Osservatorio Meteo Climatologico' of the Programma Nazionale di Ricerche in Antartide (PNRA), http://www.climantartide.it. ECMWF products are extracted from the Catalogue MARS, http://www.ecmwf.int. This study has been funded by the Marie Curie Excellence Grant (FOROT) – MEXT-CT-2005-023878.

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