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On the atmosphere for astronomers above Dome C, Antarctica

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Abstract: This paper describes a comparison between balloon radio-soundings made in summer at the Concordia station, Dome C, Antarctica and coincident model-based meteorological analyses. The comparison allows the assessment of the reliability of the analyses in summer. This allows the use of the winter analyses within an estimated range of uncertainty, while the first *in situ* measurements are just becoming available. The astronomical interest is to produce an estimate of atmospheric turbulence during the Antarctic winter at this very promising site. For this work the 6-hourly ECMWF operational analyses were used, concurrently with the data obtained *in situ* by the radio-sounding made at Concordia with standard meteorological balloons and sondes during four summer seasons (November–January), from December 2000 to the end of January 2004.

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Key words: Antarctic plateau, ECMWF analyses, optical turbulence, radio-soundings, site testing, temperature gradient, wind gradient

Introduction

Dome C, one of the summits of the Antarctic plateau (75°S, 123°E), was originally selected for the glaciological ice core programmes because glacier motions are minimal around a dome. Katabatic winds follow more or less the sFurface slopes, so that they are minimized near the domes, an *a priori* very favourable situation for astronomers. The local altitude is about 3260 m, but because of the low temperature, the surface pressure is equivalent to the surface pressure at an altitude of 3700 to 3800 m at more usual latitudes. Today, astronomy seems very likely to be among the major scientific activities to be intensely developed at Concordia in the future. At the Amundsen-Scott South Pole station, astronomy started a long time ago, and many site testing programs have been undertaken in optical and IR astronomy (see e.g. Pomerantz 1986). In 1991–92 Gillingham suggested that exceptionally good seeing could be expected above the high part of the Antarctic Polar Plateau. A preliminary site testing campaign was done at Dome C in 1996 (Marks *et al*. 1999).

Then, during each summer campaign since 2000, with the construction of the permanent station, an astronomical site testing program has been implemented step by step, to be ready for operation during this first winter. It contains three DIMM (Differential Image Motion Monitor) telescopes (Aristidi *et al.* 2005a), one of them on top of a 5 m high platform, and the other two at the snow surface level, being operated together in the GSM (Grating Scale Monitor) mode (Ziad *et al.* 2000). Scintillation and isoplanatic angle measurements are also carried out. Temperature sensors have been installed on the 32 m high metallic mast for *in situ* measurements of the air turbulence in the ground based inversion layer. Meteorological balloons specially equipped with similar micro-thermal sensors are launched twice per week, for probing the turbulence up to the higher atmospheric layers (Azouit & Vernin 2005)

The first seeing winter measurements was done in 2004 by the Automatic Astrophysical Site Testing International Observatory (AASTINO), installed at Dome C in 2003 by Australian team of University of New South Wales (Lawrence *et al.* 2004). From a combination of SODAR and MASS data, a mean seeing value of 0.27 arcsec was obtained during the autumn season (23 March–5 May), the measurements being sensitive to atmospheric layer above 30 m.

In 2005, the first over-wintering team made it possible to run the site testing program during the whole winter. The DIMM instruments showed a regular deterioration of the ground based seeing quality with the decreasing winter temperature. On the other hand 30 radio-sounding during the dark time have shown a ground inversion layer that is very turbulent, with a thickness of 20–50 m (Agabi *et al.* 2006)

During the four previous summers (mid-November to early February), 200 meteorological balloons equipped with standard meteo radiosondes were been launched (Aristidi *et al.* 2005b). They provide the following parameters: altitude, temperature, pressure, humidity, wind speed and direction, up to altitudes generally between 20 and 25 km, and sometimes slightly higher. One of the first astronomically interesting results of these summer radio-soundings has been the confirmation that wind speed above the site is low. The ground wind speed was already known to be among the slowest on Earth in year-round average. At higher altitudes, there is generally a wind increase around the tropopause (8–9 km a.s.l., and sometimes another increase at much higher altitudes, above 20 km. But these wind speeds are often less than 10 m s^{-1}, and essentially never faster than 20 m s^{-1}. Indeed, the air density becomes faint enough there to imply negligible effects on the refraction index. Of course, wind speed alone is not sufficient for estimating the turbulence conditions. The other important parameter is the temperature stratification, and especially its vertical derivative. Indeed, the occurrence of optical turbulence depends on the vertical gradient of the potential temperature δθ/δz and on the vertical wind shear δυ/δz. Physically, the potential temperature of an air parcel is the temperature the parcel would have if it were brought adiabatically to the standard pressure p_o; generally we take p_o = 1000 hPa. The potential temperature is a conserved quantity for an air parcel in adiabatic motion, i.e. motion in which there are no heat sources or sinks. It is defined by

$$\theta = T\left(\frac{p_o}{p}\right)^{\gamma},$$

where T is the temperature in K, p is the pressure and γ is

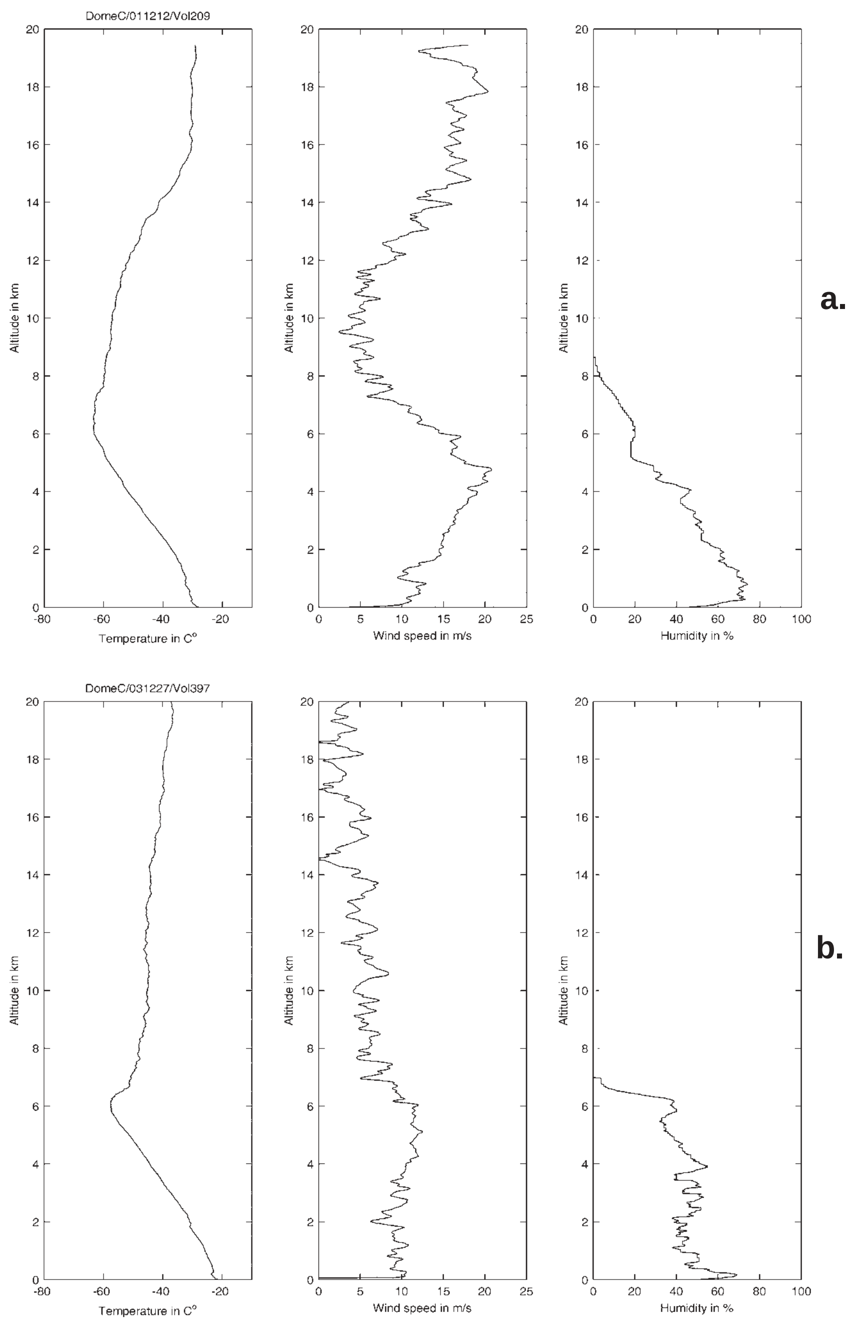

Fig. 1. Comparison between temperature, wind speed and humidity measurements (thin line) and interpolated model (bold line) profiles. **a.** is an illustration (12 December 2001) with the RS-80 radiosonde, **b.** is another one (27 December 2003) with RS-90 radiosonde. (Altitude above the ground)

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R_d/c_p, the ratio of the gas constant and specific heats of dry air ($\gamma = 0.286$).

The radio-soundings made in summer do not provide any information on the winter atmospheric conditions. Before having access to winter measurements on the site, a two-step strategy was developed. First to compare the radio-sounding datasets with model-based meteorological analyses. This will define the quantitative confidence of the analyses in summer. Then, assuming a similar level of confidence, the winter analyses can be used for a first estimate of the winter parameters relevant for astronomers. The identification of the layers with a possible risk of optical turbulence is of particular interest.

Data and meteorological analyses

The stratospheric balloons launched between 2000 and 2004 were generally equipped with Vaisala radiosondes model RS-80. During the last summer season, about half of the sondes were of the model RS-90 instead, which are supposed to provide more accurate temperature and humidity values. This has proved to be especially true for the humidity.

The ECMWF (European Center for Medium-range Weather Forecasts) produces 6-hourly operational meteorological analyses to initialize short - and medium-range weather forecast. The analyses are the results of the assimilation of real-time observations, where and when available, into a meteorological model. In Antarctica, most of the *in situ* observations are made at weather stations scattered at the periphery of the ice sheet. Automatic weather stations, including one at Dome C, also provide basic surface information for the interior of the ice sheet, but there is currently no radio-sounding done on the East Antarctic plateau and reported for analyses, except for Amundsen-Scott South Pole station. None of the radio-soundings mentioned above have been used in the analyses, so the observations provide an independent evaluation of the analyses capabilities. However, polar-orbiting meteorological satellites provide all-season downward-looking sounder information. Further information on the ECMWF system can be found at http://www.ecmwf.int. The 6-hourly profiles have been interpolated to the Dome C coordinates (rounded to 75°S, 125°E) from the original spectral archives with a nominal spatial resolution is ~75 km. There are 60 levels unevenly distributed along the vertical from the surface to 0.1 hPa, with typical resolution 2–3 hPa in the lowest levels.

Comparison and model validation

For a comparison between radiosonde data and analyses, it is necessary to have simultaneous values on one hand, and the same vertical sampling on the other hand. Two different interpolations have then been processed on the atmospheric model data:

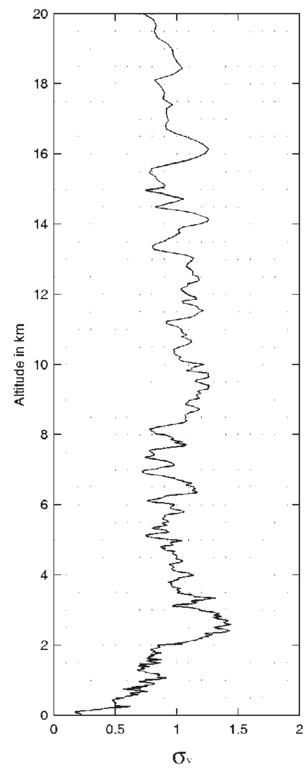

Fig. 2. Variance of the wind speed difference (measurements and analyses) that shows a rms difference of the order of 1m s^{-1} at all altitudes. (Altitude above the ground)

1) Starting from the 60 pressure levels of the model, a vertical spline interpolation provides pressure levels accordingly to each individual radiosonde measurement.

2) As there is generally only one radiosonde launched each day, while the analyses are computed four times per day, the model value is then linearly interpolated between the two closest computations.

Figure 1 shows two examples of comparison for the three parameters temperature, wind speed and relative humidity. The first example corresponds to a RS-80 radiosonde, while the second is visibly more precise on the humidity parameter, with a RS-90.

A detailed comparison of the RS-80 and RS-90 radiosonde performances is described in Luers 1997. Additional information can also be found in an annual report of the Met Office (Smout *et al.* 2000). Following Luers 1997, the RS-90 temperature sensor is shown to be superior to its RS-80 predecessor, the difference being often of the order of 0.5°C. During day time, the temperature difference RS-90–RS-80 increases with altitude from 0.03°C at sea level to 0.42°C at 35 km. As to wind speed measurements, it is made independently by GPS position.

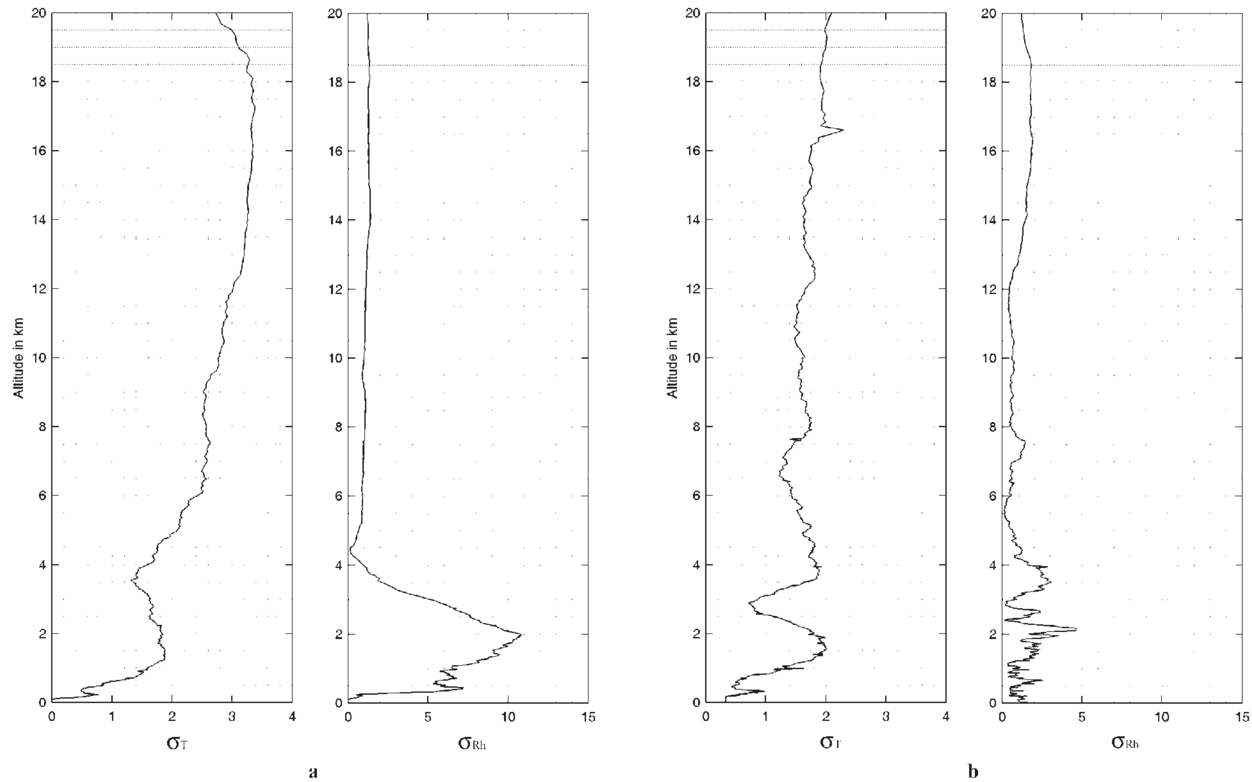

Fig. 3. The same variance for temperature and relative humidity differences shows the better quality of **b.** RS-90 radiosondes against **a.** RS-80. The rms differences are then about 1–1.5°C in temperature and 1–2% in relative humidity. (Altitude above the ground)

Such comparisons were made on a total of 120 balloons with RS-80 and 48 with RS-90. Figure 2 gives the root mean square error (RMSE) of the simulated wind speeds, using all the 168 selected radio-soundings (this parameter does not depend on the radiosonde model). It shows that this difference is of the order of 1 m s^{-1} at one sigma. For the other two parameters, temperature and relative humidity, the statistics is computed separately for the two radiosonde models. The standard deviations are shown on Fig. 3a (RS-80) & 3b (RS-90). The fact that the meteorological analyses compare more favourably to the RS-90 soundings therefore indicates that these analyses are certainly better than what could be thought when using all radio-soundings: A part of the error comes from the radiosondes themselves, especially with the RS-80 model. This is encouraging for using the analyses in assessing winter atmospheric conditions.

Optical turbulence conditions study at Dome C

Taking the RMSE of the analyses as a rough estimate of the model reliability during the summer season (in fact it has to be at least a little better, since the standard deviations contains both the model errors and also the measurement errors that cannot be zero, even with the best radiosondes), we will now assume that this reliability is of the same order all year. We can then have a look at the main characteristics of the winter atmosphere above Dome C. For astronomers, these atmospheric main properties can be used as a first approach toward an estimate of the atmospheric turbulence, which is one of the main limiting factors of ground based astronomical observations (apart from cloudiness of

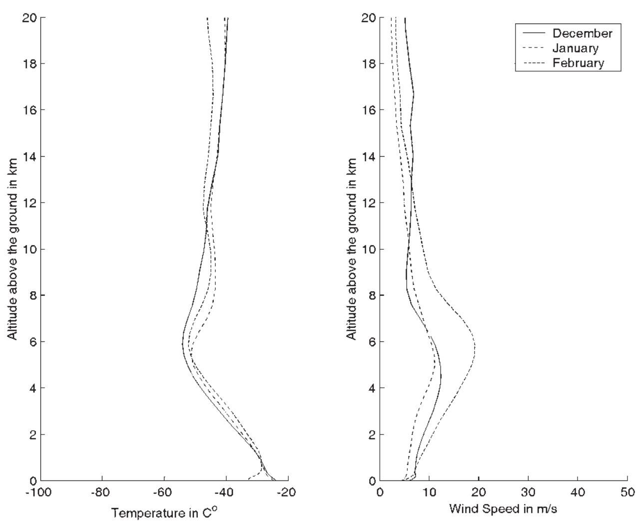

Fig. 4. Summer monthly mean temperature and wind speed profiles at 6UT given by the ECMWF for 2003. The tropopause is visible at 5–6 km by the inversion of the temperature gradient and a maximum of wind speed.

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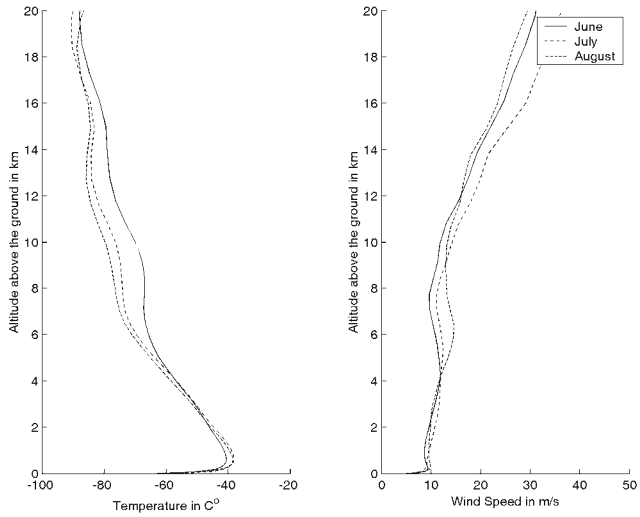

Fig. 5. Winter monthly mean temperature and wind speed profiles at 6UT given by the ECMWF for 2003. Note the disappearance of the tropopause, both the temperature minimum and the wind speed maximum. Also note the very strong ground based inversion layer of the temperature.

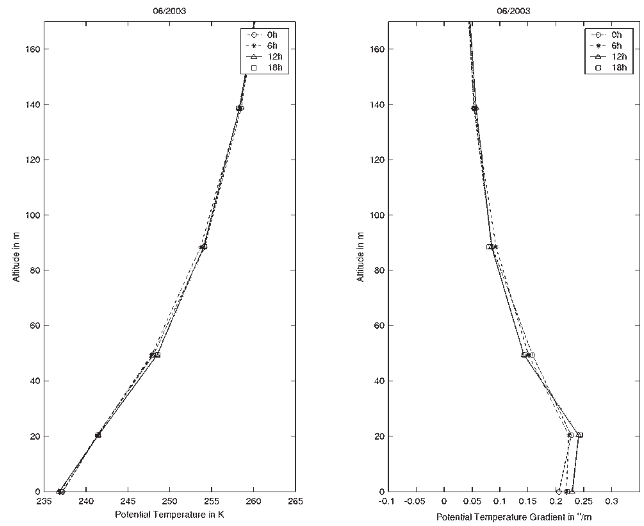

Fig. 6. The potential temperature (left) and its gradient (right) on the first 170 m above snow surface. Monthly mean in winter month of June 2003. As must be expected in permanent darkness, there is no more dependence on local time.

course).

Broadly speaking, high altitude atmospheric turbulent layers are mostly producing stellar scintillation, while low altitude layers are rather producing scatter and motions of stellar images at the focus of a telescope.

For many photometric measurements, stellar scintillation is one of the most important factors, together with the sky transparency. In the summer atmosphere, the tropopause altitude around 8–9 km (5 or 6 above the surface), is presumably contributing most to scintillation. Indeed, it corresponds both to an inversion of the temperature gradient, with the frequent occurrence of a wind speed maximum (Fig. 4). However, during the night time, the inversion of the temperature disappears, as shown by Fig. 5. The slight wind speed increase corresponds then to a very small or slightly decreasing temperature gradient. One can thus expect a lower amplitude of the stellar scintillation.

Table I. Monthly average wind speed given by the first three sampled values of the ECMWF model. They are at the ground level, then 20 and 50 m above. The turbulent layer of about 30 m is located inside this strong gradient (around 40 to 50% wind speed increase in 50 m in winter). Averages computed on the two years 2003 and 2004.

Altitude levels	1 level Ground level	2-level (20 m (20 m above ground level)	3-level (50 m (50 m above ground level)
January	3.8	4.4	4.9
February	4.2	5.1	5.7
March	4.0	4.9	5.5
April	5.1	6.3	7.3
May	5.1	6.3	7.3
June	5.5	6.8	7.8
July	4.8	6.0	6.9
August	5.9	7.3	8.4
September	5.3	6.5	7.4
October	4.5	5.5	6.2
November	4.7	5.6	6.2
December	4.3	5.0	5.5
Annual average (m s^{-1})	4.8	5.8	6.6

The story is very different at low altitude, near the ground. As can be seen on the same Figs 4 & 5, there is a strong inversion of temperature gradient, of the order of 20°C in 100 m. With the shortage of sunlight during the transition and winter periods, the air temperature goes down but the temperature of the snow surface is always below the ground layer air temperature. During the winter, in the absence of sunlight, the snow surface is cooled by radiation, whereas the air in the ground layer has permanent circulation and maintains some interaction with air streams brought to the interior of the continent by motions created by deep depressions all around the Antarctic coast. Figure 6 shows the mean value of the temperature gradient in the first 170 m above the ground in June 2003. The right side shows indeed a very strong positive gradient in the lowest layers. Such a positive gradient is convectively stable, but as it is combined with an important vertical gradient of the wind speed, it must indeed create vertical motions of temperature inhomogeneities, which in turn create the unwanted optical turbulence.

Also, near-surface wind speed varies monthly and it increases in winter and transit seasons. Table I gives the monthly averages of wind speed at the first three altitude levels calculated from ECMWF data for two years (2003, 2004). The model surface level wind speed attains 4 m s^{-1} during the summer and 5 m s^{-1} during winter. In (Aristidi *et al.* 2005c) average near-surface wind speed measured by AWS permanent meteo-station at Concordia is 2.9 m s^{-1}.

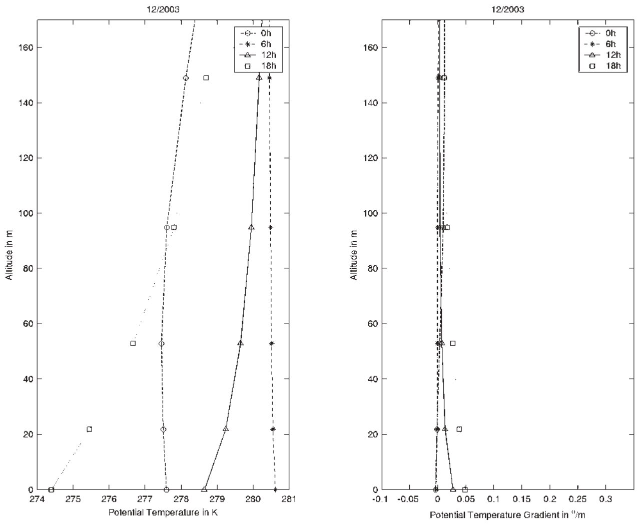

Fig. 7. Same as Fig. 6 for the summer month of December 2003. A strong time dependence is clearly visible, as the sun moves up and down in summer.

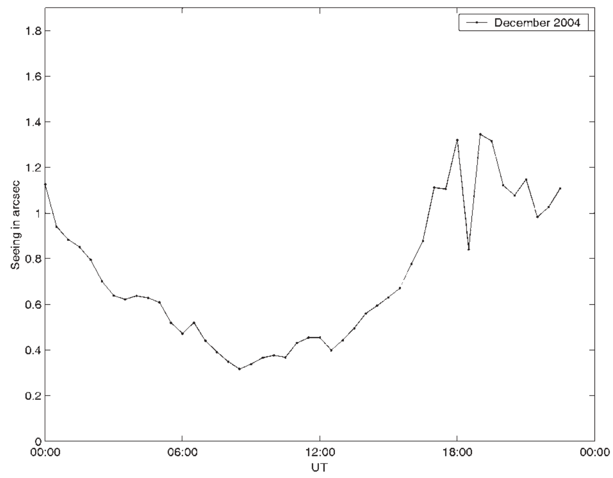

Fig. 8. Mean astronomical seeing in December 2004, as a function of the time, UT. The best condition is observed around 9UT, and corresponds to local afternoon, 17LT.

Unfortunately, the model has a resolution not better than 20 m just above the ground, the next sampled value being around 50 m high. One can then only suspect that a turbulent layer of at least 20 m but presumably less than 50 m thick must exist above the ground. The two gradients decrease very quickly above 50 m.

In this respect, however, is has to be kept in mind that the parameterizations of stable boundary layer turbulence in climate models suffers from severe theoretical limitations (Krinner *et al.* 1997, Zilitinkevich & Calanca 2000).

This is confirmed by the first set of C_n^2 balloons equipped with microthermal sensors launched at Dome C during the first over-wintering season (March–August 2005). They show that largest part of the optical turbulence is generally confined in the first 36m (Agabi *et al.* 2006). Probably, such a turbulent inversion layer must be present everywhere on the polar plateau, during all winter, with a thickness that must depend on the katabatic winds and on the penetration in the continent of coastal air streams. A more detailed and more finely sampled model or the atmospheric lower layers is required for a better understanding of these turbulent properties. More radio-soundings with C_n^2 balloons will also provide the required statistics.

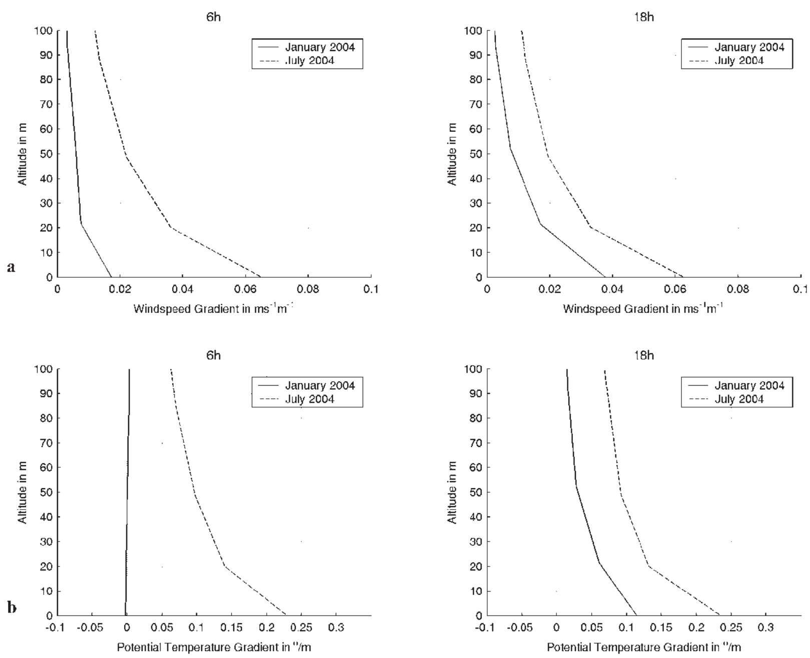

Fig. 9. a. Monthly average wind speed gradient at 6UT and 18UT in January and July 2004, **b.** monthly average potential temperature gradient at 6UT and 18UT in January and July 2004.

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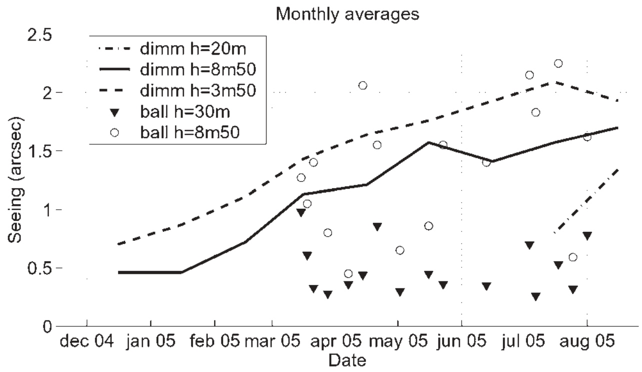

Fig. 10. Monthly averaged ground seeing from the monitors located at elevations h = 3.5 m, h = 8.5 m, and h = 20 m. Individual points are balloon-based estimations at h = 8.5 m and h = 30 m (Agabi *et al.* 2006).

An interesting fact is correlation of the seeing with the potential temperature gradient behaviour in the ground layer during the summer months. At 6UT (14LT), the potential temperature is essentially constant (Fig. 7). Seeing measurements (Aristidi *et al.* 2005a) have found the best seeing values around 9UT (17LT). Figure 8 shows, as an example and as a function of time, UT, the mean seeing in December 2004. The best values are clearly obtained between 6h and 13UT, when the potential temperature gradient is essentially zero, while the worst seeing is measured around 18UT, when the gradient is maximum in a 30–50 m thick surface layer, making this ground based inversion layer looking like the winter situation. This scenario is repeated almost every day during the whole summer season, from mid November to early February (Aristidi *et al.* 2005a).

The wind gradient has been mentioned previously, as it clearly plays a role in the turbulent behaviour of the temperature inversion layer. Figure 9a shows two examples of this gradient, in summer (mean values of January 2004) and in winter (mean values of July 2004), and compared to the potential temperature gradient (Fig. 9b) itself on the first 170 m. One can note an important correlation between these two gradients. In summer the wind speed gradient is much lower at 6UT (14LT), while the temperature gradient is essentially flat all afternoon, and the best seeing is measured at 17LT. This reduced wind gradient in the afternoon, apparently a thermal effect, helps explaining why the best astronomical seeing obtained in the summer (Fig. 10). In winter (from March to October) this daily wind speed gradient variation disappears, and the gradient remains permanently and much stronger near to the ground. The resulting shears, combined with the very strong temperature gradient in the same layers, are clearly responsible for the optical turbulence observed in the first 30 m (Agabi *et al.* 2006).

Conclusion and prospects

Although weakly constrained by *in situ* observations, the ECMWF meteorological analyses reproduce remarkably well the summer observations from Dome C radio-soundings, at least for temperature and wind speed which most directly impact on optical seeing for astronomy. It is very likely that satellite data, which are provided all-year-round on a continuous basis and assimilated in the ECMWF metrological analyses, contribute to these results. Thus, although still to be verified with actual observations, the assumption that winter analysed profiles can be confidently used to evaluate the Dome C site as an all-year astronomical observatory does not seem unreasonable. However, besides uncertainties on winter findings, there are some limits to the conclusions which can be drawn from the ECMWF analyses alone. The vertical resolution in the lowest layers, although quite fine by meteorological standards, is insufficient to accurately assess the role of the boundary layer, and the height above which boundary layer turbulence is avoided. Further modelling and theoretical developments, a well as simulations with improved vertical resolution, are necessary for a better assessment. Such developments may actually provide a direct quantification of turbulence, information which is calculated but not appropriately recorded and archived by ECMWF, or even of seeing. On the other hand, there are several decades of analyses in store at ECMWF and at other weather research and operation centres, which could be used to produce a first climatology of atmospheric properties for astronomical observations in Antarctica, in the line of the work carried out here for the single Dome C site. An interesting point is of course the model capability of predicting atmospheric turbulence a few hours in advance. Given the apparent reliability of the ECMWF model when compared with radio-sounding, this bonus can probably be regarded with some optimism.

It seems now very likely that extraordinary seeing encountered in summer afternoons will be present, almost always, above the ground based inversion layer. If this layer appears to be an excessively difficult obstacle at the South Pole site, with a thickness of more than 200 m (Marks *et al.* 1996, 1999), its much reduced thickness at Dome C (around 30 m, as it appears now both from models and from measurements) makes it a real difficulty, but not an insurmountable problem. Different strategies must be studied to make it possible to exploit the unique seeing encountered up there, either to set up the most demanding instruments at 30 m, or to use highly performing adaptive optics that must solve an unusual but probably not so difficult problem with a unique turbulent layer located extremely close (Travouillon *et al.* 2004, LeLouarn & Hubin 2006). The technical studies at Dome C seem worth being undertaken when keeping in mind all the other unique astronomical properties of the site, regarding the clear sky

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statistics, the infrared transparency (Ashley *et al.* 1996, Storey *et al.* 1999), the lower scintillation, the long day and night, and also the 6-hour per day of unique seeing at ground level during summer, that can be exploited not only by solar astronomers, but possibly also in thermal infrared where the day time sky brightness becomes dark enough.

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