A&A 385, 328–336 (2002)
DOI: 10.1051/0004-6361:20020132

Astronomy & Astrophysics

Astronomical seeing from the summits of the Antarctic plateau*

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Received 12 November 2001 / Accepted 10 January 2002

Abstract. From the South Pole, microthermal turbulence within a narrow surface boundary layer some 200 m thick provides the dominant contribution to the astronomical seeing. We present results for the seeing at a wavelength of 2.4 μm. The narrow turbulence layer above the site, confined close to the surface, provides greatly superior conditions for adaptive optics correction than do temperate latitude sites. An analysis of the available meteorological data for the Antarctic plateau suggests that sites on its summit, such as Domes A and C, probably experience significantly better boundary layer seeing than does the South Pole. In addition, the inversion layers may be significantly narrower, lending the sites even further to adaptive optics correction than does the Pole.

Key words. atmospheric effects – site testing – methods: observational

1. Introduction

The effect of atmospheric turbulence on astronomical image quality, or “seeing”, has been studied at the South Pole through measurement of the microthermal fluctuations associated with the turbulence (Marks et al. 1996 – Paper I, Marks et al. 1999 – Paper II). The seeing was found to be dominated by the contributions from a narrow but turbulent boundary layer, with a minimal contribution from the free atmosphere above it. This suggests that, if the effects of the surface boundary layer over the Antarctic plateau can be mitigated, superb seeing conditions might be obtained. Since the boundary layer seeing is strongly influenced by the inversion wind, it is possible that exceptionally good seeing may occur at the surface from other locations on the plateau away from the South Pole, where this wind is reduced. Such sites may be the high points of the Antarctic plateau – Domes A and C – where the inversion wind is almost non-existent. Little direct evidence is available on seeing conditions for these sites. Some clues, however, are available from meteorological records. We examine these in this paper, and discuss the implications for future astronomical observatories in Antarctica.

While the South Pole is convenient location, in the sense that it is populated all year-round, it is generally agreed that there are other sites where the observing conditions are potentially much better, in terms of atmospheric transmission, humidity and weather, in addition to the seeing. The South Pole lies some 1000 km away from Dome A, the highest point on the plateau at about 4200 m. Much of the boundary layer turbulence at the Pole is associated with the inversion winds which consist of cold air rolling gradually down the slope from the highest regions of the plateau, picking up speed as they go, before finally turning into the violent katabatic winds that are such a well-known feature of the weather along the Antarctic coastline. It is quite possible that the boundary layer seeing at Dome A is much lower than at the South Pole since, although the temperature inversion is still present, the calm winds close to the surface mean that the mechanical mixing of the different temperature layers is minimised.

Since Dome A still remains almost totally inaccessible it is fortunate that there are other sites for which similar comments apply. Potential candidates include Vostok and Dome C. Dome C has the further advantage that the infrastructure will soon be in place at this site to support a large observatory, with construction of the year-round Franco-Italian *Concordia Station*, expected to be completed by 2004. Obviously, direct measurements need to be made at these sites; however the sparse information available at this stage does allow some general comments

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[*] Rodney Marks died tragically at the South Pole in May 2000. This paper presents the most significant previously unpublished results from his Ph.D. Thesis: “Antarctic site testing: measurement of optical seeing at the South Pole” (Marks 2001).

to be made about the likely seeing conditions at the higher plateau sites, given the results from the South Pole.

2. Super deeing on the antarctic plateau?

The upper-atmosphere jet streams that are common in temperate locations are associated with the upper boundary of the troposphere, at an altitude of around 10–12 km. The winds can be very strong, averaging over $40\,\mathrm{m\,s^{-1}}$ in some places (e.g. McIlveen 1992). In contrast, such high-altitude winds are very much weaker in the polar regions, and the tropopause is relatively low (7–8 km) and less marked. In such conditions, the free atmosphere is expected to be very stable, with smooth wind and temperature gradients leading to exceptionally good seeing. Since the upper atmosphere turbulence is a significant component of the seeing at many locations, the lack of indicators for such turbulence on the Antarctic plateau have led to the coining of the phrase "Super Seeing" (Gillingham 1993) to describe conditions that may well be superior to any other region on earth.

Mitigating against good seeing from the surface, however, is an intense temperature inversion, pervasive over the plateau during the winter months, and often exceeding $0.1°\mathrm{C\ m^{-1}}$ averaged over the entire boundary layer. The limited data available on boundary layer turbulence on the plateau (Neff 1981) indicates that some very intense optical turbulence, concentrated in quite narrow layers, extends throughout the lower parts of the inversion layer. It has a vertical extent of some 300–500 m.

On the other hand, the fact that this atmospheric disturbance is concentrated so close to the surface, in comparison to the turbulence at other sites, might well have its own advantages. Most large optical/IR telescopes employ some form of real-time image correction technique, which broadly come under the title of "adaptive optics". The effectiveness of such methods is severely restricted by angular and temporal limitations set by the nature of the atmospheric turbulence. In general, the scale of these parameters is inversely proportional to the altitude of the turbulent layers, and hence high-altitude turbulence is much more difficult to correct than low-altitude disturbances (see, for example, Cowie & Songaila 1988; Olivier 1993). Hence, even if the boundary-layer seeing is poor, it may be relatively easy to eliminate this component over larger areas than is possible at other sites. A similar altitude dependence also applies to the scintillation of stellar sources caused by atmospheric turbulence. The vertical structure of the atmospheric turbulence over the Antarctica plateau should therefore lend itself to more accurate photometry, which is especially important in astroseismology and the study of variable stars, including planetary occultations. Another field where the Antarctic plateau offers outstanding opportunities is that of astrometric interferometry (e.g. see Lloyd et al. 2002). This is because the measurement error in the spatial position of a source made using this technique is proportional to h^2, where h is the height above the telescope where microthermal fluctuations occur. On the Antarctic plateau, where these are confined to the surface boundary layer, this factor is much smaller than at temperate-latitude sites, where they arise from the high-altitude jet stream.

3. South pole seeing conditions

We undertook a site-testing campaign during nighttime (i.e. in winter) at the South Pole over two years; during the first, the contribution of the lower boundary layer was examined (Marks et al. 1996 – Paper I) and in the second year this was extended to 15 km altitude (Marks et al. 1999 – Paper II). The atmosphere was found to show a marked division into two characteristic regions: (i) a highly turbulent boundary layer (0–220 m), with a strong temperature inversion and wind shear, and (ii) a very stable free atmosphere. The mean visual seeing over 15 balloon flights in 1997 was measured to be $1.86''$, of which the free atmosphere component was only $0.37''$. Direct measurements of the seeing with a differential image-motion monitor (DIMM) by Loewenstein et al. (1998) are consistent with these values.

The $\sim$220 m height of the boundary layer at the South Pole, in terms of the micro-turbulence, is much lower than the 300–500 m temperature inversion that usually is regarded as defining the boundary layer depth. This is due to the fact that the optical turbulence intensity depends strongly on the vertical gradients of the wind velocity and temperature inversion. Near the top of the boundary layer, the inversion begins to flatten out at around 200–250 m, at which point the microthermal turbulence becomes quiet, even though the inversion continues weakly for a further 100 m or more.

In contrast to the severe optical turbulence present in the boundary layer, the free atmosphere is very quiescent in comparison with other sites. The inversion that often occurs in the tropopause at mid-latitudes does not exist in Antarctica. Instead, the temperature profile generally levels off weakly and smoothly.

These are quite different characteristics to those at temperate latitude sites. The Chilean observatory sites, in particular, tend to have a high proportion of the seeing caused by turbulence in a boundary layer extending up to about 1000–2000 m, with a relatively quiescent tropopause. This is in marked contrast to Mauna Kea, which at 4200 m is high enough to avoid boundary layer effects almost completely (Bely 1987). Here, however, an upper level jet stream greatly increases the high-altitude component of the seeing, so that, overall, the site quality is no better than the high desert sites in Chile.

3.1. Infrared seeing at the south pole

In Paper II we calculated the seeing profiles at optical wavelengths, $\lambda = 5000\,\text{Å}$. Here, we show the values in the near–IR, $\lambda = 2.4\ \mu$m, a wavelength of particular interest because of the particularly low value for the sky background there in Antarctica (e.g. Ashley et al. 1995).

Table 1. Integrated seeing and boundary layer contributions at 2.4 μm for the South Pole, determined from 15 balloon launches between 20 June and 18 August 1995. The "free atmosphere" refers to the entire atmosphere, excluding the boundary layer.

Measurement	Mean	Std. Dev.	Median	Best 25%	Best	Worst
Seeing (arcseconds)						
–*total*	1.36	0.55	1.2	0.7	0.6	2.3
–*free atmosphere*	0.27	0.05	0.23	0.21	0.17	0.38
r_0 (cm)						
–*total*	36	22	42	65	81	22
–*free atmosphere*	179	47	185	228	293	153

These profiles are calculated assuming that the Fried parameter, r_0, scales as $\lambda^{6/5}$ and the seeing, ε, as $\lambda^{-1/5}$ (see Paper II).

The FWHM seeing and r_0 values at 2.4 μm are shown in Table 1. Figure 1 shows a comparison between the seeing profiles at Paranal and the South Pole at 2.4 μm. Every tenth of an arcsecond gain is increasingly significant at IR wavelengths, as the seeing reaches very low levels. The free atmosphere seeing at the South Pole approaches $0.2''$, while the Paranal curve remains at around $0.4''$. While the free atmosphere seeing at the South Pole is still about 65% of that at Paranal from the same level, in terms of the actual values the difference between the sites is probably more notable here than in the visible.

The adaptive optics parameters also register a corresponding improvement, scaling as they do with r_0. Assuming a Kolmogorov spectrum, these values for optical wavelengths (Paper II) are increased by a factor of $(2.4/0.5)^{6/5} = 6.6$ when observing at 2.4 μm. Hence, the isoplanatic angles, $\theta_{\rm AO,SI}$ (AO, SI = adaptive optics, speckle interferometry – see Paper II), over the entire atmosphere, are around 18–$20''$, while coherence times $\tau_{\rm AO,SI}$ increase to 10–100 ms. Angles obtained if boundary layer correction is applied increase to very significant values of around 7–$12'$. This is large enough to give close to 100% sky coverage for finding suitable stars for use in wavefront correction, up to at least $m_{\rm K} = 10$. The results are shown in Fig. 2.

3.2. Forecasting the seeing

A striking feature of our data (Paper II) was that the boundary layer turbulence structure is not evenly spread throughout the inversion layer but, rather, is concentrated in anywhere from one to half a dozen narrow strips, generally 10–20 m in depth. They are almost always associated with a sharp peak in either the potential temperature or wind velocity gradient, or both. Quite often, the strongest turbulence above the surface layer appears close to the top of the boundary layer (~200 m).

It would appear that the Richardson number, $R_i = \frac{g}{\theta}\frac{({\rm d}\theta/{\rm d}z)}{({\rm d}\boldsymbol{U}/{\rm d}z)^2}$, is a reasonable indicator of upper-air turbulence in the atmosphere at the South Pole (see Paper II). Here ${\rm d}\theta/{\rm d}z$ is the potential temperature gradient, with $\theta(z) = T(z)\left(\frac{P(z)}{1000}\right)^{-0.286}$, such that the value of θ corresponds to the temperature of the air adjusted adiabatically to a standard pressure of 1000 hPa. ${\rm d}U/{\rm d}z$ is the wind velocity gradient, $T(z)$ the temperature, $P(z)$ the air pressure, g the acceleration due to gravity and z the height above sea level. When $R_i < \frac{1}{4}$, relatively strong upper-air turbulence can be expected. This suggests that it may be possible to determine the frequency of very good free atmosphere seeing at the site by analysis of historic and ongoing meteorological records. The importance of this is that if, in practice, it is possible to correct for the boundary layer turbulence by the use of adaptive optics, then the free atmosphere component of the seeing will be the limiting factor in large telescope image resolution at the site. One could then hope to forecast, or at least "nowcast" (Murtagh & Sarazin 1993, 1995), seeing conditions in terms of just a few parameters easily obtainable from standard balloon launches performed daily by the Meteorology department. The infrequent formation of the shear layers described above could perhaps be reported some time in advance, depending on their typical lifetime, and then be used to generate an approximate value for the upper atmosphere seeing at that time.

4. Implications for adaptive optics wavefront correction

The turbulence structure of the atmosphere also has implications for the feasibility of image correction techniques such as adaptive optics and speckle interferometry. In particular, the isoplanatic angle and wavefront coherence time – the main spatial and temporal parameters limiting any image correction system – are highly dependent on the altitude of the strongest turbulent layers, and can be calculated from the known $C_{\rm N}^2$ profiles at a given site (e.g. Vernin & Muñon-Tuñóz 1994; Fuchs 1995). A turbulence profile showing a higher proportion of boundary layer turbulence, with a relatively clear free atmosphere, will be much more tractable for a low-order adaptive optics system than one with, for example, strong jet stream-related turbulence in the tropopause. Most of the new generation

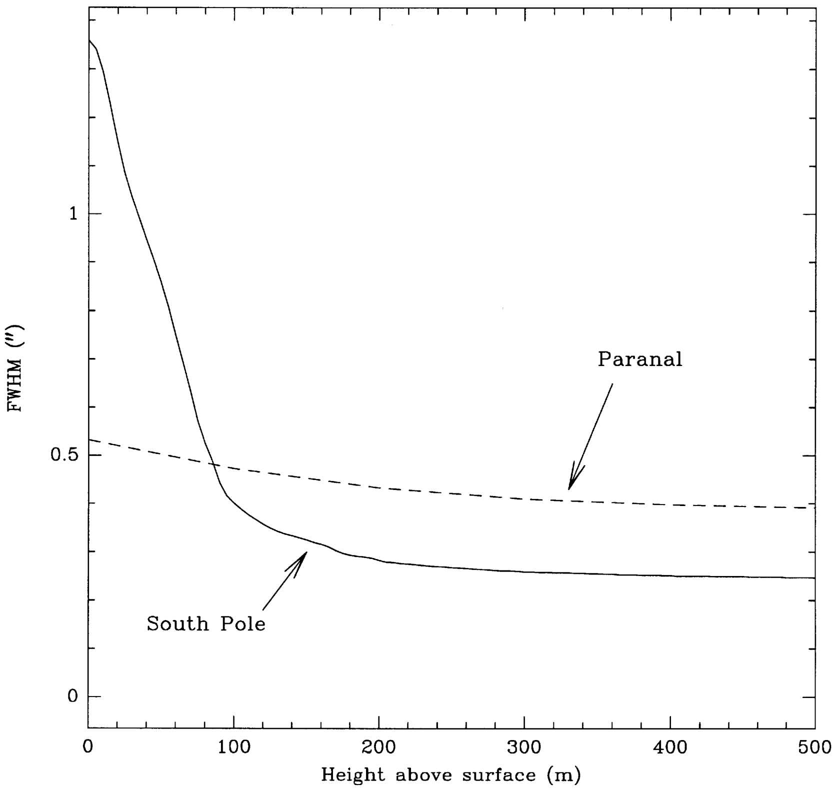

Fig. 1. Seeing as a function of height of telescope above the surface, compared between the South Pole and Cerro Paranal in Chile, for a wavelength of 2.4 μm. The solid line represents the results from balloon launches at the South Pole (Paper II), and the dashed line a summary of a similar experiment performed at the ESO–VLT site in Paranal (Fuchs 1995).

of large telescopes are utilising some form of image correction of this type, and so the vertical profile becomes even more important with these considerations in mind.

The limiting factors in any adaptive optics method are the spatial and temporal coherence of the wavefront that one is trying to correct. In general, the high-altitude turbulence that forms a large proportion of the seeing at many mid-latitude sites is very difficult to correct, and sophisticated methods are usually required to extract much improvement in image quality (e.g. Cowie & Songaila 1988), since it is isoplanatic over an angular scale of only a few arcseconds. However, over the Antarctic plateau we have the exact opposite scenario, where a large proportion of the turbulence is produced very close to the aperture of the telescope, and so the isoplanatic angle should be much larger. Indeed, considering the single large turbulent cells that were often observed (Paper I), we might reasonably expect that the South Pole should be almost the ideal site for the application of relatively simple low-order image correction methods, even despite the large amplitude of the fluctuations observed.

The concentration of the bulk of the seeing in the lower boundary layer means that a low-order, turbulence conjugated, adaptive optics system should be able to remove the large majority of the seeing over very wide angles. The small free atmosphere component would remain uncorrected in this scenario, and hence the possibility of predicting the rare occurrences of poor (0.4–0.5″) free atmosphere seeing would be very helpful (see Sect. 3.2).

Clearly the tight limitations on the isoplanatic angle and coherence time, θ and τ (see Sect. 3), mean that the ideal of perfect image correction of turbulence-distorted images is extremely difficult to achieve at any site, including the South Pole. A large number of independent submirrors is required to correct the wavefront errors over the full field of view of the telescope. The strategy at other sites has generally been to settle for varying degrees of partial image correction, usually by ignoring the higher orders of the perturbations of the wavefront, and thus making the corrections applicable over a larger area. The aim is to make the maximum gains possible in image quality with a relatively simple and inexpensive system such as a tip-tilt mirror (i.e. first-order corrections). Evidently, the maximum “reconstruction angle” (the term coined by Cowie & Songaila 1988) depends on the precision required in the corrections, and there is a trade-off between image quality and sky coverage.

These ideas are particularly important in relation to the situation at the South Pole since high-altitude turbulence has a higher spatial frequency, when viewed from ground-level, than turbulence close to the surface. We may expect, therefore, that a low-order adaptive optics system that corrects the boundary layer component of the seeing, leaving the upper atmosphere uncorrected, would be

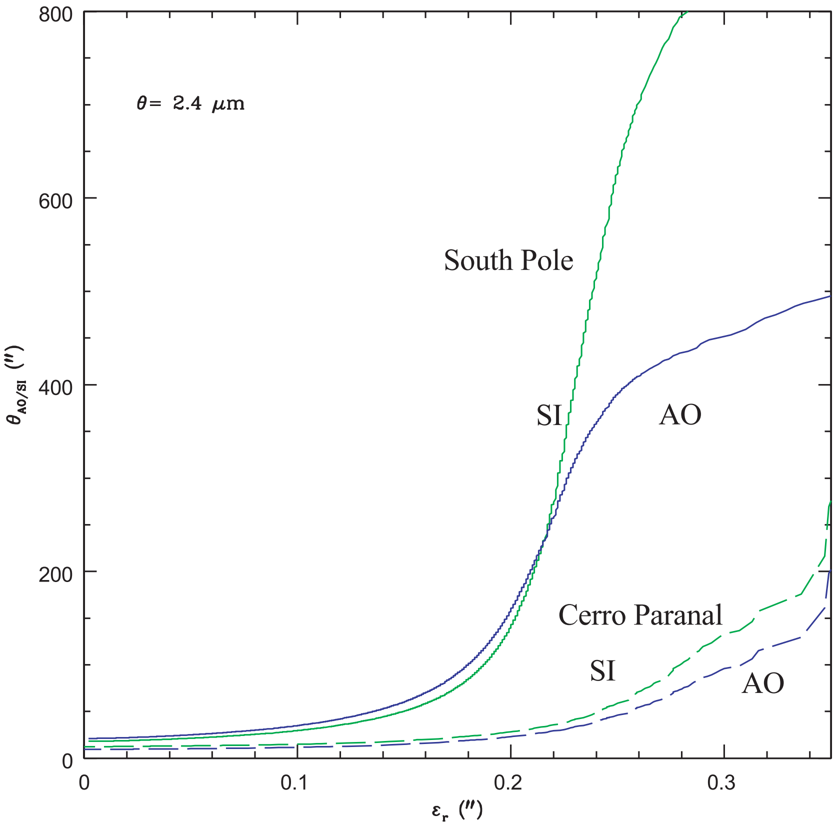

Fig. 2. Isoplanatic angles, θ_{AO} and θ_{SI}, as a function of the residual seeing, ε_r, in arcseconds for $\lambda = 2.4$ μm. Solid lines are derived from the average C_{N}^2 profile at the South Pole, and dashed lines are from Cerro Paranal data. The dark lines refer to adaptive optics (AO) correction, and the light lines to speckle interferometry (SI).

effective over a substantially greater area of the sky at the South Pole than a similar system operating at the best mid-latitude sites. A glance at Fig. 2 indicates that image resolution of 0.2–0.3″ should be obtainable over much larger angles at the South Pole than at Cerro Paranal.

Although no vertical C_{N}^2 profiles were available from other mid-latitude sites for analysis, the comparison should be much the same as Paranal. Indeed, it may be even more favourable in comparison with Mauna Kea, where a much greater proportion of the seeing is due to upper atmosphere turbulence.

It is worth also mentioning some of the methods used for correction of higher-order components of the wavefront phase fluctuation. With a characteristic coherence length of r_0, the number of independent elements required for full image correction is on the order of $(D/r_0)^2$, for corrections made in planes conjugate to the telescope aperture. Such a project is not expected to be any easier at the South Pole than other sites.

A "multiconjugate" approach (e.g. Tallon et al. 1992) requires, in principle, a single correction element for each turbulent layer, which, at any site, is likely to result in a less complex system than the usual aperture-conjugated case. It is a particularly powerful method in situations where the bulk of the image degradation is produced by a small number of turbulent layers. This is clearly the case at the South Pole, where the boundary layer seeing usually consists of 2–4 intense layers, with a similar number, or less, of much weaker layers in the free atmosphere. It is likely, therefore, that the South Pole represents a particularly good site for higher-order corrections using such a technique.

5. Prospects for "super seeing" from the summits of the plateau

In the broadest sense, the aim of the site-testing campaign underway in Antarctica (e.g. Storey et al. 1995) is to find the best site for astronomy in Antarctica. Given that the only measurements of site conditions available at this point are from the South Pole, it is important to use the results of this experiment to attempt to draw some conclusions about the likely seeing conditions elsewhere on the high plateau. It is generally agreed that the South Pole is almost certainly not the best site for astronomy in Antarctica. Indeed, the only reason for choosing this location for the experiments conducted so far is that it has been the only place on the plateau that has been easily accessible. In any case, the conditions there should provide a good indication of the magnitude of the improvements that might be expected from the very best sites, from infrared to millimetre wavelengths.

Table 2. Comparison of weather parameters at all sites on the high plateau for which information is available. Data on Dome C are taken from Keller et al. (1991, 1993, 1995), values for for Plateau and Vostok stations are from Schwerdtfeger (1984). "Years" denotes the length of time for which records are available, "δT_{BL}" is the temperature change across the boundary layer, 'Slope' is the mean slope of the surface, "$\bar{V}$" is the mean surface wind speed, "Constancy" is ratio of the average wind velocity to the average wind speed, "$V_{\max}$" is the maximum wind speed ever recorded, and "Cloud" gives the percentage of time in winter where the cloud cover is less than 30%. Where no data is available the entry is indicated with a "–".

	South Pole	Vostok	Plateau	Dome C	Dome A
Years	26 (40)	24	3	8	–
Altitude (m)	2835	3488	3625	3280	4200
Latitude (°S)	90	78.5	79.2	74.5	82
Yearly Mean Temperature (°C)	−49.3	−55.4	−56.4	−50.6	∼−60
Coldest Monthly Mean	−59.9	−68.3	−71.4	−61.7	–
Temperature (°C)	(Jul.)	(Aug.)	(Aug.)	(Aug.)	–
δT_{BL} (°C)	20	23	∼20	∼20	> 25
Slope (degrees)	1.0×10^{-3}	1.3×10^{-3}	0.8×10^{-3}	∼0	∼0
$\bar{V}$ ($\mathrm{m\,s^{-1}}$)	5.8	5.1	–	2.8	–
Constancy	0.79	0.81	0.67	0.53	–
Calm (%)	2	1	–	10	–
$V_{\max}$ ($\mathrm{m\,s^{-1}}$)	24	25	–	16	–
Cloud $< \frac{3}{10}$ (winter) (%)	63	56	65	–	–

The South Pole lies a long way off the central "ridge" that marks the highest elevations on the plateau. The implications of this are quite obvious if we consider the three key words: "high", "cold" and "dry". Dome A (82° S, 80° E), at 4200 m, and some 1000 km from the South Pole, is the highest point on the plateau. Although no data are available from Dome A (in fact, it is uncertain whether anyone has ever set foot there), indications from the closest stations are that it should be at least 10°C colder than the South Pole on average. Given the enormous difference between the South Pole and the best mid-latitude sites in the thermal infrared (Chamberlain et al. 2000; Phillips et al. 1999; Nguyen et al. 1996), we might expect further reductions again in the thermal background from Dome A. In addition, the thinner atmosphere (∼5000 m physiological altitude at the surface) and lower temperature should result in even lower water vapour content than the South Pole, which is already a factor five times lower than Mauna Kea.

These ideas are widely known now. What is less certain is the quality of the seeing we might expect higher on the plateau. Since the seeing depends on a more complex interplay of atmospheric conditions, it is not as easy to predict any improvements, let alone what the scale of those improvements might be. In this section we examine the available data from elsewhere in East Antarctica, and compare this with what we have discovered at the South Pole, in an attempt to give some indication of what we might expect to find at the higher elevations.

The paucity of information about atmospheric conditions over East Antarctica make this a difficult task. Reasonably continuous, long-term records of both surface and upper air meteorology parameters are available from only two places: the South Pole and Vostok (of which only the South Pole has continuously maintained a winter crew in recent years). These have been supplemented by a few Automatic Weather Stations (AWS), successfully deployed at other locations above 3000 m for periods of a few years at a time, which provide some valuable additional information about surface conditions. Overall, we have access to data from no more than four or five places, in an area half the size of Australia. Many of the results are discussed in the book of Schwerdtfeger (1984), and it is from this source that much of the weather information used here has been gleaned. Table 2 is a summary of all the measurements that could be found that are in some way related to the seeing (in particular, the boundary layer seeing). Some of the numbers quoted are based on no more than a couple of years data, especially from the AWSs, and so any conclusions made here on the basis of these figures should be treated with caution.

The boundary layer seeing at the South Pole is generally intense, but highly variable and critically dependent upon the interplay of the temperature gradient and inversion wind, in particular any vertical irregularities that occur. The C_{N}^2 signal tends to be most intense close to the surface. Above the boundary layer, the free atmosphere is in general exceptionally calm and clear. Whilst no microthermal data are available from any of the sites listed in Table 2, aside from the Pole, these meteorological parameters may offer some clues as to the likely structure of the boundary layer at these sites.

One factor that does differ from the South Pole to the other sites is diurnal variation. At Plateau Station over a 24 hour period the depth of the temperature inversion falls from around 15° at night to <5° during the day (Schwerdtfeger 1984). Although the diurnal changes appear to be mostly restricted to the lowest 10–15 m, according to the data from the South Pole, this is probably the most turbulent region in the whole boundary layer. Given that the winds at surface level at a site such as Plateau Station are driven by the inversion, it is likely that these too undergo some diurnal variation. The impact of this on the stability of the boundary layer in terms of turbulence is not clear, but certainly, at mid-latitude sites, it is a general rule that the best seeing is observed later in the evenings, when the boundary layer has stabilised. Such temperature variations are likely to have some minor effect in Antarctica, increasing as the latitude of the site decreases. Since all of the highest sites are south of 75° S, there are at least a few months everywhere during the winter when the Sun doesn't rise, and little or no diurnal effect would be noticed during this period.

The increasing strength of the inversion at higher altitudes means that, in fact, the temperature of the warmest layer above the site is very similar from place to place. Comparison of weather balloon data from the South Pole and Vostok show that the temperatures at the 500 hPa level at each station in winter differ by less than a degree, with the South Pole being slightly warmer. The temperature inversion at the South Pole is about 400 m high, according to the temperature data from our microthermal balloon sondes (in terms of C_N^2, it levels off at about 200–220 m). While no information is available regarding the vertical extent of the inversion at Vostok, it is likely that it is slightly narrower at the higher altitude site, given that it reaches almost the same temperature at the same pressure altitude. If the temperature layers are to some degree stratified across the plateau, according to pressure altitude, then it may be that Dome C also has a somewhat narrower inversion, while at Dome A it could be significantly narrower again.

Without discussing wind characteristics at each site for a moment, the results of our C_N^2 measurements of boundary layer turbulence at the South Pole are clearly associated with vertical fluctuations in $\mathrm{d}T/\mathrm{d}z$ in the boundary layer. The seeing contributions are generally proportional to the magnitude of the temperature fluctuations, for a given strength of wind shear. This indicates that individual turbulent disturbances in the boundary layer at higher sites may be greater in magnitude than those observed at the South Pole due to the combined effect of both of these differences: a stronger inversion, extending over a smaller vertical distance, means that the temperature *gradient* may be significantly steeper, especially close to the surface. Any mechanical turbulence, then, of a similar sort to that experienced at the South Pole would naturally produce more intense turbulent cells, in terms of C_N^2.

A narrower inversion also has implications from the point of view of image correction techniques. We now know that the concentration of optical turbulence at the South Pole very close to the surface leads to very favourable conditions for the application of adaptive optics. If the boundary layer at the higher sites does turn out to extend over a shorter distance, this argument applies even more forcefully, regardless of the baseline seeing. Our conclusion for the South Pole was that a system designed to correct only the boundary layer seeing would be applicable over a characteristic angle of about 1–2′ in the visible. Hence, any significant reduction of the height of the boundary layer at a place like Vostok or Dome C could result in a large increase in the angular scale, and hence the sky coverage, of adaptive optics-type image correction techniques.

What is hoped for, of course, is that the natural seeing will be better at other sites on the plateau, and the wind conditions must be considered before this possibility can be dismissed. A conclusion that came through strongly from our South Pole data was that fairly strong wind shears within the boundary layer are a necessary ingredient for strong optical turbulence. It is possible to have clear seeing through a deep inversion if there are no strong wind shear regions; peaks in $\mathrm{d}T/\mathrm{d}z$ will not do the damage on their own. The available wind data from other sites on the plateau suggest that, here too, the effect on the seeing is likely to be somewhat different to that observed at the South Pole.

South Pole Station is located well down from the peak of the plateau, and lies on a gentle slope with a gradient of approximately 1 part in 10^3. This is roughly the same as Vostok and Plateau stations. These gentle slopes are enough to generate an inversion wind with an average speed of just over $5\,\mathrm{m\,s^{-1}}$ at both the South Pole and Vostok (see Table 2). The directional constancy is very high: around 0.8 at Pole and Vostok, slightly lower at Plateau, with the vectored average wind blowing in a direction oriented at about 30° to the fall line of the terrain. This is an indication that the ubiquitous inversion wind dominates the surface flow, but is modified in direction, to some extent, by the lesser effects of synoptic air flows and the coriolis effect. The calculated average flow lines for the surface winds across the continent (see Fig. 3 from Paper II) illustrate the importance of the local topography on the wind characteristics at any given location.

Since the geostrophic winds above the boundary layer do not generally blow from the same direction as the inversion wind, at the South Pole at least, there are inevitably shear layers in the boundary layer, where the winds change both speed and direction. One of our main conclusions was that virtually all of the turbulence responsible for the seeing occurs in layers where wind shear causes disturbances in the vertical temperature gradient. This statement describes almost all of the observed optical turbulence at the

South Pole, and explains why the overwhelming majority of the seeing arises from the boundary layer.

The situation at Dome C is rather different. Here, the terrain is almost perfectly flat, and the inversion wind is negligible. Wind speeds are generally much lower ($2.8\,\mathrm{m\,s^{-1}}$ on average), with a lower constancy factor (about 0.5), reflecting the fact that the wind direction is determined by weather patterns rather than the slope of the terrain. A more detailed study of some of the monthly AWS data reveals that Dome C enjoys winds of less than $2\,\mathrm{m\,s^{-1}}$ roughly 50% of the time during winter, and below $4\,\mathrm{m\,s^{-1}}$ up to 80% of the time. This compares with approximate figures of 10% and 50%, respectively, at the South Pole. Dome C is a very calm site.

The absence of an inversion wind means that this source of turbulence, at least, can be discounted. The kinds of wind shear layers observed at the South Pole ought not exist. There may be other sources of vertical wind gradients, such as those observed occasionally in the free atmosphere over the South Pole. There is, however, a possibility that there is in fact no significant source of mechanical turbulence in the boundary layer, in which case the seeing could be very good from ground level. Dome C, along with Dome A, may be an oasis of calm in the turbulent inversion layer stretching right across the plateau.

Another feature of the South Pole seeing is the remarkably quiescent free atmosphere. Upper-level jet streams associated with the tropopause are virtually absent in the data, and very few other significant sources of turbulence were observed. From the long-term records, the strong upper-troposphere winds (jet streams) that limit the seeing at mid-latitude sites are virtually absent. At the 300 hPa level (about 10 km altitude at the South Pole), winds of over $30\,\mathrm{m\,s^{-1}}$ occur 5% of the time, and over $40\,\mathrm{m\,s^{-1}}$ a mere 1%. This is compared with 14%/3% at Byrd Station (80° S), and larger values further north. So it would appear that the free atmosphere is somewhat less stable as one moves out from the centre of the polar vortex, and there would probably be a corresponding increase in upper-atmosphere turbulence. Hence the average free atmosphere may be somewhat worse than the very low value of around $0.3''$ (upward from 200 m) measured at the South Pole.

6. Summary

To summarise our results, the microthermal turbulence at the South Pole is concentrated much closer to the surface than at the best mid-latitude sites. So, while the integrated seeing from surface level is poor, the free atmosphere is quieter than at these other sites. This has the result that the seeing contribution above about 200 m (the depth of the South Pole boundary layer) is significantly less than at any temperate latitude site.

The available evidence also suggests that the high-altitude sites such as Domes A and C probably experience better boundary layer seeing than the South Pole. Given that this is by far the dominant source of image degradation at the Pole, this is a very important result. The conclusion is based on the absence of the inversion winds that generate much of the wind shear responsible for the mechanical turbulence.

In addition, the inversion layers themselves may be significantly narrower at the higher sites. The narrow turbulent region at the South Pole, relative to mid-latitude sites, greatly increases the characteristic angles over which image correction techniques can be applied. The higher sites may also, therefore, be significantly better in terms of their potential for adaptive optics.

Acknowledgements. This paper is an edited version of unpublished results from Rodney Marks' PhD thesis, prepared by Michael Burton, with assistance from Michael Ashley and John Storey from the University of New South Wales and Darryn Schneider from the Antarctic Muon and Neutrino Detector Array (AMANDA) project. This research was supported by an Australian Postgraduate Award and by grants from the Australian Research Council and the Australian Department of Industry, Science and Technology. Rodney worked closely during his PhD with Jean Vernin and others from the University of Nice, Bob Pernic and colleagues from the US Center for Astrophysical Research in Antarctica, and with many colleagues from the University of New South Wales. Astronomy is much richer for the spirit of international cooperation that Rodney fostered through these collaborations.

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