HOW CAN WE UNDERSTAND THE ANTARCTIC ATMOSPHERE?

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The Antarctic Plateau offers many benefits to astronomers, including dark and transparent infrared skies, long periods of uninterrupted observations, and very low levels of atmospheric turbulence. Efforts to quantify these benefits are ongoing. Characterizing the turbulence is particularly challenging, and requires a different approach to that commonly used at temperate sites. First, the atmosphere has two quite distinct regimes: a free atmosphere that is largely devoid of turbulence, and a thin but highly turbulent stable boundary layer. Second, if heat is used to avoid frost formation on optical surfaces, local turbulence might inadvertently be created by the instrument trying to measure it. In this paper we review the work that has been performed to date, and discuss what is required to advance our understanding of the Antarctic atmosphere.

1. Introduction

The Antarctic plateau, a vast area of several million square kilometers at an elevation of over 3000m, presents astronomers with a remarkable opportunity to build new ground-based telescopes with greatly superior performance to any currently existing [1]. The most promising Antarctic sites are those that are at local maxima in elevation—Dome A, Dome C and Dome F—together with the geographic South Pole which also offers its own set of unique advantages. Characterising these sites is therefore a very high priority. Because of the difficulty of access, and the importance of obtaining good statistics, robotic instruments are greatly preferable to those that require human operators and/or constant maintenance.

For astronomy, the extreme cold, low absolute humidity and highly transparent atmosphere lead directly to improved sensitivity in the infrared and sub-millimetre. Measurement of the sky brightness at unattended sites can be performed with robotic instruments, which can also return estimates of cloud cover throughout the year. At optical wavelengths, CCD cameras are used [2, 3] and these can self-calibrate using known stars in the field of view. In the IR and sub-mm, the “sky-dip” principle is generally used, together with reference hot and cold loads of known temperature [4, 5, 6]. The precipitable water vapour

(PWV) is perhaps the most important single parameter to be derived from these longer wavelength measurements, as it can then be fed into model atmospheres to estimate the atmospheric transmission across the entire spectrum [7].

The second major advantage of the Antarctic plateau stems from the very low levels of atmospheric turbulence. The free atmosphere is largely free from the high-altitude jet-stream winds that dominate mid-latitude sites, leading to improved image quality, lower scintillation, and large isoplanatic angles and coherence time. However, as suggested by Gillingham [8], the excellent free-atmosphere conditions will almost always be compromised by an intense but relatively thin boundary layer that results from the strong temperature inversion in the lowest few tens of metres of the atmosphere. Unlike the situation that prevails at all temperate sites, where the boundary layer contributes an inevitable component to the seeing, over much of the Antarctic plateau the boundary layer is sufficiently thin that it is feasible to avoid it by simply placing the telescope above it; for example on a small tower. Characterising the atmospheric turbulence in Antarctica must therefore take into account the two very different regimes—a generally excellent free atmosphere and a generally highly turbulent boundary layer. This ideally requires using one technique that can characterize the free atmosphere uncontaminated by the boundary layer, and a second technique that measures the height of the boundary layer.

The difficulty of making turbulence observations in Antarctica is further complicated by the surprisingly high relative humidity within the boundary layer [9]. Any exposed optical surface will develop a layer of frost on it unless heated a few degrees above ambient. While this gentle heating is of little consequence for instruments measuring sky brightness or transparency, it is clearly important to implement telescope and mirror heating schemes with caution when making accurate measurements of the turbulence.

2. Techniques to measure the free atmosphere

While the first question many observational astronomers ask about a site is *"What is the seeing like?"* in Antarctica this is the wrong question. The seeing from ground level is poor. The true benefits of Antarctica become apparent when the atmosphere is characterized not just in terms of natural seeing, but when all the parameters such as ε_0, τ_0, θ_0, and L_0 of most importance to adaptive optics and interferometry are known, and are measured not just as whole-atmosphere averages but as a function of altitude throughout the atmosphere.

2.1. *DIMM*

Traditionally, the DIMM (Differential Image-Motion Monitor) has been the "gold standard" for characterizing atmospheric turbulence. It is a relatively simple instrument, and returns an apparently unambiguous measurement of the parameter most familiar to astronomers, the "seeing", or FWHM of stellar images. At a traditional temperate site, a DIMM, if carefully calibrated [10, 11] gives a very useful indication of the relative merits of competing sites.

In Antarctica, however, the vast bulk of the atmospheric turbulence is located close to the ground, and this turbulent boundary layer is usually present throughout all of the (interesting) night-time. Thus, any technique that measures the integrated atmospheric turbulence will register poor seeing, most of the time. This was confirmed by the first DIMM measurements at the South Pole [12, 13].

However, during the summer the surface inversion layer is periodically removed by the solar heating, leading to the possibility of exceptionally good seeing even at ground level. Using a DIMM, Agabi *et al.* [14] found that at Dome C the summer-time seeing goes through a daily cycle with minimum levels well below that observed at any other site on earth. This is important not just for solar astronomy, but also for mid-IR observations with telescopes large enough to take advantage of the achievable image quality. The same team has also shown that it is possible to derive an estimate of free-atmosphere seeing statistics and boundary-layer height by using multiple DIMMs at various heights [15], although this technique is very costly in terms of both time and resources.

2.2. *Balloons*

Direct measurement of C_T^2 is possible by using microthermal sensors flown on a meteorological balloon [16]. This technique has been used with great success, both at temperate sites and in Antarctica, but has the disadvantage that a balloon and electronics package must be expended for every measurement. In addition, a minimum amount of wind shear is needed to ensure that the package is free from the balloon wake. Other issues, including the possibility of ice accumulation and a fluctuating radiation load on the sensor, complicate this otherwise very straightforward technique.

In Antarctica, there is a further problem that the balloons have a tendency to burst at a lower altitude than is desirable if the whole atmosphere turbulence profile is to be properly sampled. Nevertheless, balloon-borne microthermal campaigns have already made major contributions to our understanding of the free atmosphere at the South Pole [17] and Dome C [18].

2.3. *Double-star scintillation techniques*

A variety of triangulation techniques (e.g., SCIDAR, SLODAR) have been developed for use at temperate sites to derive an atmospheric turbulence profile. Such techniques can be "generalized" by conjugating the detector to different levels, thereby providing some information about the boundary layer [19]. In general, a larger telescope is required than can conveniently be deployed to a remote site. In this context, the development of a Single-Star SCIDAR [20] that can potentially work with a smaller telescope may prove to be an important development for Antarctica, where at this stage in the development of permanent plateau stations the emphasis must be on small, robotic instruments.

2.4. *MASS*

The Multi-Aperture Scintillation Sensor (MASS) was developed by Tokovinin *et al.* [21]. By correlating the scintillation noise observed in a series of concentric apertures, it is possible to derive a crude turbulence profile. Despite its simplicity, the technique has several powerful advantages that make it ideal for Antarctic deployment: only a single star is required, and only a small (~100 mm) telescope is needed. Most importantly, the technique is tolerant of poor image quality and is largely insensitive to turbulence below about 500 m. The telescope and its housing can therefore be kept warm, and hence frost-free, without compromising the measurements [22]. A robotic MASS operating at Dome C through the first half of 2004 demonstrated that the site could deliver superb image quality, with unprecedented low levels of free-atmosphere seeing [23] and scintillation [24].

2.5. *Modelling*

An alternative to the direct measurement of atmospheric turbulence is to calculate the stability of the atmosphere using, for example, reanalysis of data from the European Centre for Medium-Range Weather Forecasts (ECMWF). This is a particularly valuable way to investigate potential new sites, and to develop an understanding of the reasons for the differences between known sites [25]. Similarly, Swain and Gallée [26] have shown that regional climate models can be used to estimate the boundary layer thickness across the entire plateau.

3. Techniques to measure the boundary layer

As discussed above, Antarctica is unique in possessing a stable boundary layer that persists throughout most of the winter. This boundary layer is strongly turbulent. However, turbulence in stable boundary layers is very poorly understood. The more stable the boundary layer, the greater the probability that the turbulence will be intermittent or sporadic, and that rather than having a fully-developed Kolmogorov character will consist of Kelvin-Helmholtz instabilities, gravity waves, low-level jets and meandering motions. Almost all turbulence-monitoring techniques used by astronomers measure only a single turbulence length scale, and then assume a Kolmogorov distribution; this is likely to be a poor approximation at best in the boundary layer.

3.1. *Tower microthermals*

By placing microthermal sensors at various heights on a tower it is possible to measure the turbulence at intervals from ground level to the top of the tower. This was the technique used by Marks *et al.* [27] to characterize the boundary layer at the South Pole. Unfortunately, the supersaturated atmosphere results in ice accumulation on the sensors, making this a very labour-intensive technique that does not lend itself readily to automation. To address this problem, Travouillon *et al.* [28] have pioneered the use of sonic anemometers in Antarctica. These sensors are very robust and can be heated between measurements to remove the ice. Although a considerable amount of power is required to keep the sensors defrosted, this method appears to be a very valuable way to probe the boundary layer.

3.2. *SHABAR*

A simple yet elegant way to probe the turbulence profile of the lower atmosphere is to observe the scintillation of an extended object such as the sun or moon with an array of photo-detectors [29]. This is known as a SHABAR, for SHAdow BAnd Radiometer. Recently, Tokovinin *et al.* [30] and Hickson and Lanzetta [31] have developed practical lunar scintillometers, extending the application of the technique to night-time site characterization. Like the MASS, the SHABAR is relatively insensitive to image quality and is insensitive to turbulence that is close to the sensors—simplifying defrosting. Its usefulness is of course limited to those times when the moon is well above the horizon and reasonable full. A prototype lunar scintillometer has been installed at Dome C by Moore *et al.* [32].

3.3. *Acoustic radar*

Acoustic radars, or sonic radars (SODARs) have been used in Antarctica for many years by atmospheric physicists [33, 34]. Early measurements by Travouillon *et al.* [35] at the South Pole showed that SODARs are an excellent tool for astronomers in Antarctica, where the low altitude of the boundary layer places it easily within range. In addition, because it is a non-optical technique and does not rely on fine sensors, it is relatively impervious to snow and frosting. Measurements at Dome C with a Remtech PA1 SODAR subsequently demonstrated that, during the night-time, the boundary layer had a typical vertical extent of 30 m or less. However, the limited vertical resolution of this particular model make it unsuitable for a detailed study of boundary-layer height variations.

A new, high-resolution SODAR has therefore been developed by Bonner *et al.* [36] and optimized for Antarctic conditions. This instrument has a vertical resolution of better than 1 metre, and can measure turbulence from within a few metres of the ground to about 100 m. It has been deployed successfully to Dome A, and may be eventually deployed to other sites such as Dome C in future. This instrument can operate over a wide range of frequencies, leading to the possibility of probing a range of turbulence scales in order to explore the various structures within the stable boundary layer [37].

4. The future

New telescopes on the Antarctic plateau have the potential to change the way we do astronomy. The success of the South Pole Telescope [38] is a particularly good example of what can be achieved. Each of the various Dome sites, plus the South Pole, offers major advantages over existing temperate sites. The costs of building and operating scientific research infrastructure on the plateau are well known, as the US has operated a permanent station (Amundsen-Scott) at the geographic South Pole since 1957. These costs are surprisingly modest.

To fully realize the potential offered by Antarctica, the wider astronomical community and the funding agencies must be presented with clear evidence of the excellence of the sites. It is therefore essential that the site characterisation be carried out as fully and as rigorously as possible. Site testing of any kind requires the acquisition of properly calibrated data over a number of years, in order to understand the effects of year-to-year climatic variations. However, the investment in rigorously carrying out these site-testing studies is repaid many times over when the data result in new telescopes being placed at the best sites, to perform the best science they are capable of. It is important to make measurements in Antarctica that can be directly compared to those from temperate observatories. Ideally, a common suite of instruments would be used.

Measurements of the sky brightness and transparency, PWV and cloud cover have so far revealed few surprises—the Antarctic plateau appears to live up to the high expectations that astronomers are placing on it. Understanding the turbulence structure of the atmosphere is more challenging. Neither the free atmosphere nor the stable boundary layer is well understood at present, with the latter presenting a particularly fascinating theoretical and technical problem. Progress in understanding atmospheric turbulence will thus be most rapid in future if there is close collaboration between astronomers and meteorologists.

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