Night-time measurements of astronomical seeing at Dome A in Antarctica

To measure the seeing directly at Dome A, the location of Kunlun Station (see Extended Data Fig. 1), we developed the KunLun Differential Image Motion Monitors (KL-DIMMs)\(^{17}\). They were designed to operate automatically at temperatures as low as −80 °C. In January 2019, the 35th Chinese National Antarctic Research Expedition installed two KL-DIMMs on a tower 8 m high. The KL-DIMM provided a seeing measurement every minute. In total, we obtained 45,930 valid seeing values during the polar night from 11 April to 4 August 2019. These values were corrected to the zenith and a wavelength of 500 nm, as is standard. During observations, frost and snow accumulated on the two wedges that form the sub-apertures. The frost reduced not only the signal but also the effective diameters of the sub-apertures. We decided to use a fixed diameter value of 3 cm for all seeing estimates. Thus, the derived seeing values are upper limits; the true values are likely to be 10–20% lower (see Methods).

Figure 1 shows the histogram of seeing from Dome A during the polar night in 2019. The distribution consists of a strikingly sharp peak that has a mode value of 0.31 arcsec, as well as a long tail of poor seeing extending beyond 3 arcsec. In total, the peak at 0.31 arcsec is on the order of the expected free-atmosphere seeing, so it is reasonable to attribute the times of superb and poor seeing to the cases when the boundary layer was entirely below or extended above the telescope, respectively. In addition, we expect an intermediate case when there is a transition phase of the boundary-layer thickness varying across the apertures of the KL-DIMM, or a secondary turbulent layer above the surface layer. We therefore fit the histogram with three log-normal components\(^{10}\), corresponding to the free-atmosphere, intermediate and boundary-layer components, as shown in Fig. 1. The fraction of free-atmosphere seeing is consistent with the results from the sonic radar\(^{16}\).

We compare the statistics of seeing from Dome A with those from Dome C\(^{10}\) and the mid-latitude sites in Table 1. For the height of 8 m, the seeing statistics at Dome A are much better than those at the same height from Dome C, and are comparable to those at a height of 20 m from Dome C. This is because the fraction of free-atmosphere seeing is higher at Dome A, although the free-atmosphere seeing values are similar. The comparison confirms that the boundary layer at Dome A is much thinner, and more turbulent, than at Dome C, as was predicted by models\(^{7}\). We therefore expect that on a tower that is higher than 8 m at Dome A, superb seeing will be more frequent while poor seeing will be reduced in both frequency and value, as is the case at Dome C. At the best mid-latitude sites, the boundary layer contributes less to the seeing, but it has a thickness that can be hundreds of metres and therefore cannot be avoided. In Antarctica, a telescope on an adequate tower would be affected by the free atmosphere only, enabling high-resolution wide-field observations.

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To estimate the seeing at other heights, we can correlate the seeing, or boundary-layer thickness, with near-ground meteorological parameters, since most turbulence resides within a few tens of metres of the snow surface. In 2019 the expedition installed a new second-generation Kunlun Automated Weather Station, which measured temperature, wind speed and wind direction every 2 m from the snow surface up to a height of 14 m, as well as air pressure and relative humidity. However, we have only 1.5 months of simultaneous data with KL-DIMM, mainly during the polar day, up until 15 March 2019.

A comparison of seeing and weather data (see Methods) reveals that the best seeing occurs when the temperature gradient is large. In a temperature inversion, warm air overlies cooler air, resulting in a stable atmosphere. However, wind shear may generate turbulence. The relative importance of buoyancy and wind shear is quantified by a dimensionless ratio, Ri, the Richardson number. If Ri is below the critical value of 0.25, turbulence develops. Even for 0.25 < Ri < 1, residual turbulence may remain for some time during the transition from turbulent to laminar flow.

In Fig. 2a, it can be seen that the seeing at the height of 8 m depends strongly on the temperature difference between heights of 8 m and 0 m (surface), $T_h - T_0$, which dominates Ri at 8 m. Three regions of different behaviour can be identified: (1) for $T_h - T_0 < 1$ K, Ri = 0, the median seeing increases from 1 arcsec to 1.5 arcsec; (2) as $T_h - T_0$ increases from 1 K to 10 K, the median Ri increases from 0 to 0.8, and the median seeing decreases from 1.5 arcsec to 0.3 arcsec; and (3) for $T_h - T_0 > 10$ K, Ri > 0.8, seeing remains constant at about 0.3 arcsec for most data but with a small fraction having seeing of about 1 arcsec.

Because seeing close to 0.3 arcsec suggests that the KL-DIMM is above the boundary layer, the dependence of seeing on $T_h - T_0$ reflects the height variation of the boundary layer. Similar dependence at Dome C is also reported. As $T_h - T_0$ increases, so does Ri. The turbulence intensity then rapidly decreases with height and the boundary layer becomes thinner. Consequently, the seeing at 8 m improves until the boundary layer is below 8 m, when the seeing is determined only by the free atmosphere. The seeing has little dependence on $T_h - T_0$, beyond 10 K, which is the critical value when the thickness of the boundary layer is about 8 m. Occasionally, when extra high-altitude turbulence occurs, the seeing is degraded to about 1 arcsec, which is also observed at Dome C.

Although the seeing is correlated mainly with $T_h - T_0$, the scatter is quite large (around 0.2 dex). From Fig. 2b, we see that the wind speed at 8 m, $U_8$, also plays a part. There is a clear trend of improved seeing with decreasing $U_8$ for small $T_h - T_0$. Good seeing and large $T_h - T_0$ never occur when $U_8 > 7$ m s$^{-1}$. Modelling also indicates that the surface wind speed is an indicator for boundary-layer thickness and seeing.

To infer the dependence of the boundary layer on meteorological parameters during the polar night, we analysed historical weather data. Figure 3a shows the same plot as Fig. 2b, but for the winter period from April to August 2015. The two regimes with large and small $T_h - T_0$ correspond to the thin and thick boundary-layer cases, respectively. Also, the fraction of large $T_h - T_0$ increases substantially compared to the polar daytime data. Strikingly, the greatest $U_8 - U_f$ does not occur with the greatest $U_f$, but occurs during the transitional phase with moderate $U_f$. The meteorological data from Dome C show a similar pattern, and two regimes separated by a $U_f$ threshold have been proposed. However, our results prefer the temperature difference as an indicator to distinguish the two regimes (or boundary-layer thickness).

In principle, the temperature difference, $T_h - T_0$, between the height $h$ and the surface could be used to estimate the fraction of time with good seeing at $h$. Then, one could optimize the height for the installation of a large telescope, balancing the seeing quality and the difficulty of construction. In Fig. 3b, we plot the histograms of $T_h - T_0$ for $h = 4$ m, 8 m and 14 m, respectively, for the polar night in 2015. The distributions are bimodal, corresponding to the boundary layer below and above $h$. The condition $T_h - T_0 > 10$ K, suggesting that the free-atmosphere seeing would be obtained at an 8 m height, occurred 38% of the time. This agrees with the KL-DIMM result for the polar night in 2019. For $h = 14$ m, the two peaks of the histogram are larger than those for 8 m by less than 1 K. Thus, we set the threshold for $T_h - T_0$ to be approximately 11 K, which is 1 K greater than that for $T_h - T_0$. The fraction of time with $T_h - T_0 > 11$ K, when the boundary-layer thickness is expected to be lower than 14 m, was 49% in 2015. This is also consistent with previous measurements.

In conclusion, the exceptional seeing, in combination with clear and dark sky, and the low thermal-infrared background from the cold atmosphere, would greatly improve both angular resolutions and limiting factors.
magnitudes of optical/infrared telescopes at Dome A. The proposed 2.5-m Kunlun Dark Universe Survey Telescope (KDUST26) would be able to compete with 6-m class telescopes at the best mid-latitude sites. In addition, Dome A is a natural laboratory for studies of the formation and dissipation of turbulence within the boundary layer. Future measurements of weather, seeing and the low-altitude turbulence profile could contribute to a better understanding of the Antarctic atmosphere.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-020-2489-0.

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**Fig. 2** | The correlations between seeing and meteorological parameters.

**a**, The strong correlation between seeing and $T_8 - T_0$. The colour scale indicates Ri. The solid line is the median seeing for each 0.5-K bin of $T_8 - T_0$, and the dashed line indicates $T_8 - T_0 = 10$ K. **b**, $T_8 - T_0$ versus wind speed at 8 m, $U_8$, with the colour scale indicating seeing.

**Fig. 3** | The statistics of polar-night weather data in 2015. **a**, $T_8 - T_0$ plotted against $U_8$ as in Fig. 2b, with the colour scale indicating the wind speed difference between 8 m and 2 m, $U_8 - U_2$. The data points concentrate in two horizontal regimes: large $T_8 - T_0$ with $U_8 \approx 7$ m s$^{-1}$, and small $T_8 - T_0$ values with $U_8$ mostly in the range 3–15 m s$^{-1}$. Also, they are connected by a vertical zone where $U_8 = 6$ m s$^{-1}$. **b**, The histograms of temperature differences between $T_h$ at the height of $h$ and $T_0$ at the surface, for $h = 14$, 8 and 4 m, respectively.
which we have a valid temperature measurement (the sensor at 14 m showed little diurnal trend. These two heights are adopted because T after sunset. Smaller variations are seen in the temperatures presented in Extended Data Fig. 2. The seeing shows a strong diurnal variation, ranging from around 0.3 arcsec at local midnight and around 0.9 arcsec at noon. Sporadic bursts of seeing variations are also apparent.

An example of seeing and weather data from 4 to 5 March 2019 is presented in Extended Data Fig. 2. The seeing shows a strong diurnal variation, ranging from around 0.3 arcsec at local midnight and around 1 arcsec at noon. Sporadic bursts of seeing variations are also apparent on timescales as short as 1 h. On these days, the air temperature at the snow surface, T_air, also varied diurnally. It was about $-55^\circ$C at night, rising quickly to about $-45^\circ$C after sunrise, then falling again to $-55^\circ$C after sunset. Smaller variations are seen in the temperatures T_8 and T_12 at 8 m and 12 m heights, which were typically close to $-40^\circ$C and showed little diurnal trend. These two heights are adopted because 8 m is the height of the KL-DIMM and 12 m is the highest height for which we have a valid temperature measurement (the sensor at 14 m was faulty). A strong temperature inversion developed rapidly at night, with the temperature difference between 8 m and the snow surface (T_8 − T_air) often exceeding 15°C. The temperature gradient generally decreased rapidly with height. The inversion decreased or even disappeared during the day, owing to solar heating. Yet the temperature inversion was not always strong at night. For instance, on the night of 5 March when T_air decreased rapidly, T_8 and T_12 also decreased, owing to the strong wind and wind speed gradient. At that time, the seeing was not improved from day to night. Besides the diurnal trend, the rapid variations of seeing were also accompanied by rapid temperature inversion variations, possibly owing to the fast variation of wind direction. This example implies that the seeing is strongly correlated with the intensity of temperature inversion.

Seeing-weather correlation

An example of seeing and weather data from 4 to 5 March 2019 is presented in Extended Data Fig. 2. The seeing shows a strong diurnal variation, ranging from around 0.3 arcsec at local midnight and around 1 arcsec at noon. Sporadic bursts of seeing variations are also apparent on timescales as short as 1 h. On these days, the air temperature at the snow surface, T_air, also varied diurnally. It was about $-55^\circ$C at night, rising quickly to about $-45^\circ$C after sunrise, then falling again to $-55^\circ$C after sunset. Smaller variations are seen in the temperatures T_8 and T_12 at 8 m and 12 m heights, which were typically close to $-40^\circ$C and showed little diurnal trend. These two heights are adopted because 8 m is the height of the KL-DIMM and 12 m is the highest height for which we have a valid temperature measurement (the sensor at 14 m was faulty). A strong temperature inversion developed rapidly at night, with the temperature difference between 8 m and the snow surface (T_8 − T_air) often exceeding 15°C. The temperature gradient generally decreased rapidly with height. The inversion decreased or even disappeared during the day, owing to solar heating. Yet the temperature inversion was not always strong at night. For instance, on the night of 5 March when T_air decreased rapidly, T_8 and T_12 also decreased, owing to the strong wind and wind speed gradient. At that time, the seeing was not improved from day to night. Besides the diurnal trend, the rapid variations of seeing were also accompanied by rapid temperature inversion variations, possibly owing to the fast variation of wind direction. This example implies that the seeing is strongly correlated with the intensity of temperature inversion.

Data availability

The seeing and weather data at Dome A in 2019 that support the findings of this study are available in the China-VO Paper Data Repository, http://paperdata.china-vo.org/BinMa/DomeA-seeing2019.zip. The weather data in 2015 have been published34 and are available in http://aag.bao.ac.cn/klaws/downloads/. The data are also displayed on a public website, http://aag.bao.ac.cn/klaws2g.php.
**Extended Data Fig. 1 | Map of Antarctica.** The red dots indicate locations of Dome A (Chinese Kunlun Station), Dome C (French–Italian Concordia Station), Dome F (Japanese Dome Fuji Station) and the South Pole (United States Amundsen–Scott Station), respectively. Map drawn using CorelDRAW and used with permission from Xiaoping Pang and Shiyun Wang (2020).
Extended Data Fig. 2 | An example of seeing and meteorological data from 4 and 5 March 2019. a, Seeing (black) and Sun elevation (red). b, Air temperature \( T \) at heights of 12 m, 8 m and 0 m. c, Wind speed \( U \) at heights of 12 m, 8 m and 2 m. d, Wind direction at a height of 8 m. Dotted vertical lines mark times when seeing either increased or decreased rapidly.