The impact of climate change on astronomical observations

Climate change is affecting and will increasingly affect astronomical observations, particularly in terms of dome seeing, surface layer turbulence, atmospheric water vapour content and the wind-driven halo effect in exoplanet direct imaging.

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Astronomers are entering an era in which they will change the way they work, with the arrival of the 30–40 m class ground-based telescopes and large international observational projects sparking new ways of communicating and collaborating. These scientific challenges come together with societal ones, such as the role astronomers play in communicating and undertaking actions to significantly reduce the environmental footprint of astronomical research. More generally, it is urgent that astronomers, through their unique perspective on the Universe, communicate about and act on climate change consequences at any level. In this context, we have investigated the role some key weather parameters play in the quality of astronomical observations and analysed their long-term (longer than 30 years) trends in order to grasp the impact of climate change on future observations.

In what follows we give four examples of how climate change already affects or could potentially affect the operations of an astronomical observatory. This preliminary study is conducted with data from the Very Large Telescope (VLT), operated by the European Southern Observatory (ESO), located at Cerro Paranal in the Atacama Desert, Chile, which is one of the driest places on Earth. For the analyses presented below, we used the various sensors installed at Paranal Observatory but also, to show a longer time span (from 1980 to the present), we used the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate, ERA51, with a spatial resolution of 31 km, which we interpolated at the Paranal Observatory location. To investigate longer timescale evolution (from 1900 to 2010), at a cost of a coarser spatial resolution (130 km) that averages the actual orography and may blend the ocean–continent interfaces, we in some cases used the ERA20C reanalysis data2. In addition, we used the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate, ERA51, with a spatial resolution of 31 km, which we interpolated at the Paranal Observatory location. To investigate longer timescale evolution (from 1900 to 2010), at a cost of a coarser spatial resolution (130 km) that averages the actual orography and may blend the ocean–continent interfaces, we in some cases used the ERA20C reanalysis data2. In addition, we used the ERA20C reanalysis data (green) with its global median (green dotted line), and from the CMIP6 climate projection using the SSP5-8.5 scenario (Beijing Climate Centre, BCC-CSM2-MR model ensemble), adjusted to the ERA20C mean (orange).

**Fig. 1** | Temperature in the region around Paranal Observatory. a, Monthly averaged daily mean temperature over the Paranal Observatory as a function of time, retrieved from the ERA5 reanalysis data (blue) and as measured at the Paranal Observatory (red), with the corresponding yearly average (thick lines) and median (dashed lines). b, Occurrence of the real (green) and target (blue) temperature (limited to 16 °C, solid red line) of the UTs dome cooling system, from 2006 to 2020. c, Frequency of the sunset temperature measured at Paranal to be above the 16 °C limit of the current cooling system, as a function of time. d, Yearly median near surface air temperature as a function of time, from the ERA20C reanalysis data (green) with its global median (green dotted line), and from the CMIP6 climate projection using the SSP5-8.5 scenario (Beijing Climate Centre, BCC-CSM2-MR model ensemble), adjusted to the ERA20C mean (orange).
explored climate projections in this region, using the Coupled Model Intercomparison Project Phase 6 (CMIP6) multi-model ensemble, under the worst-case climate change Shared Socioeconomic Pathways (SSP5-8.5) scenario. Further investigation is needed to better understand the underlying mechanisms of change, as well as to assess the severity of the impact.

The first example is a consequence of the local increase in surface temperature at the Paranal Observatory, which affects any type of observation sensitive to atmospheric seeing; adverse seeing degrades the spatial resolution of the telescopes. During the day, the temperature inside the dome enclosure of the telescopes is cooled down to correspond to the outside temperature during the dome opening (at sunset). The thermal system used for the four unit telescopes (UTs) is an active control system aimed at minimizing the difference between the telescope temperature and the ambient temperature. At the end of each night, a prediction of the temperature for the following sunset is made and is set as the target temperature for the thermal system during the day. Currently, this system cannot reach a target temperature above 16 °C. However, with the increase in temperature at the location of the Paranal Observatory being 1.5 °C on average over the last 40 years (Fig. 1a), consistent with anthropogenic global warming, there are more and more occurrences of target temperatures exceeding the current cooling system limitations of 16 °C (Fig. 1b,c). In such cases, the outside temperature is warmer than the inner dome temperature during opening. The temperature difference between the telescope, particularly the primary mirror, and the ambient air enhances internal turbulence inside the dome, which is called dome seeing. The dome seeing degrades the image quality by causing blurring. In addition, we show the CMIP6 projection model of the surface temperature at the location of the Paranal Observatory, using the SSP5-8.5 scenario (Fig. 1d), which points towards an average increase of a further 4 °C at the end of the century. This transition should be taken into consideration for the ongoing construction of the Extremely Large Telescope (ELT) at the Cerro Armazones, situated 20 km eastward from the Cerro Paranal, and for the design of its instruments, which are currently under development.

The second example is the increase in surface layer turbulence, which has led to stronger seeing measured in recent years (Fig. 2). The surface layer is a thin, time-variable layer located in the first tens of metres above ground that contributes to a large fraction of the optical turbulence due to inefficient heat exchange between the ground and the airflow. The UTs are sensitive to the turbulence from 10 to 30 m onwards (depending on the wind conditions and pointing direction), but the image quality, as measured directly at the UTs, is not yet affected by the increase in surface layer turbulence, and is rather constant. At the Cerro Paranal, the seeing is measured by a differential image motion monitor (DIMM)⁶. In Fig. 2, we show a time series of seeing measurements from 1986 to 2020. The DIMM height above ground has changed through time: in 1986 it was installed on the mountaintop, 28 m higher that the current platform; in 1992 the mountaintop was levelled and it was installed on a 5 m tower; from 1994 to 2000 the four UTs were built; and in 2003 the VLT survey telescope (VST) was built. In 2016, a second DIMM was mounted on a 7 m tower, at a location where it is less impacted by disturbances due to the UTs or the VST. To match the two DIMM measurements, the measurements of the older DIMM were adjusted to the mean value of the new one. The measured increase in seeing (Fig. 2) is due to increased surface layer turbulence. The origin of this increase can be mainly explained by two hypotheses: either (1) the levelling of the mountain and the numerous changes of configuration of the DIMM altitude and remodelling of the air fluxes due to the erection of various buildings, or (2) the local changes due to global atmospheric circulation transition under ongoing climate change. The first hypothesis is supported by the fact that the new DIMM finds similar seeing values to the first DIMM before the levelling of the mountain. The second is supported by the

**Fig. 2 | Surface layer seeing.** Evolution of the seeing measured by the two DIMM instruments (blue and red lines) installed at Cerro Paranal from 1986 (before flattening the platform in 1991) to today. The blue line is normalized to match the red line.

**Fig. 3 | Horizontal speed of the jet stream.** a, Wind-driven halo observed in a coronagraphic image from the Spectro-Polarimetric High-contrast Exoplanet Research (VLT/SPHERE) instrument. The wind direction is indicated with the white arrow. b, Monthly averaged horizontal wind speed at the jet stream layer (200 mbars) as a function of time from the ERA5 reanalysis data. c, Niño 3.4 index showing El Niño (red) and La Niña (purple) events as a function of time. El Niño or La Niña events are defined when the Niño 3.4 sea surface temperatures anomaly, filtered with a five-month running mean, exceed ±0.4 °C for a period of six months or more.
clear increase in the surface temperature (Fig. 1a), potentially leading to higher temperature gradients and therefore higher radiative cooling or convection, which induces stronger turbulence close to the ground. Computational fluid dynamics simulations of the turbulence at the Paranal site or extensive understanding of the global to local scale mechanisms would allow us to address this question.

The third example is in the context of the demanding technique of exoplanet imaging, requiring both a very high angular resolution and a high contrast (about $10^{-6}$ at 500 milliarcseconds in the near-infrared). Adaptive optics correct for the atmospheric turbulence in near real time and provide an angular resolution close to the theoretical diffraction limit of the 8 m telescope. This enables the use of a coronagraph to reach a high-contrast regime. However, the time lag between the analysis of the atmospheric turbulence and its correction by a deformable mirror creates a wind-driven halo (Fig. 3a). The southern subtropical jet stream (located at about 12 km altitude, with wind speeds up to 60 m s$^{-1}$) is primarily responsible for the wind-driven halo$^{11,12}$. This structure arises 30 to 40% of the time and leads to a tenfold reduction in contrast$^{18}$. We therefore looked at the evolution of the horizontal wind speed at the jet stream layer (200 mbar) over time from the ERA5 reanalysis data (Fig. 3b).

On the monthly average, we can directly see the seasonal changes (being more prominent in winter) and on the yearly average we see longer trends linked with the El Niño–Southern Oscillation (ENSO, two to seven years variation) and the Pacific Decadal Oscillation (PDO, longer time scales), both linked to sea surface temperature anomalies. Over the 40 years of ERA5 data, we observe a slight increase in the average wind speed of about 3–4 m s$^{-1}$. When correlating with the Niño 3.4 index$^{12}$ (the best proxy for the strength of the ENSO), we observe a large fraction of wind-driven halo during strong El Niño events (the warm phase of the ENSO), such as the one in 2015. Recent modelling suggests that, due to greenhouse-effect-related warming, the ENSO variability will increase and El Niño will intensify$^{13,14}$. In a subsequent study, we will gather astronomical data sensitive to the wind-driven halo$^{15}$ and correlate it to the ERA5 data and mesoscale atmospheric models to further investigate the evolution of the jet stream over the Paranal Observatory.

Finally, three critical parameters affecting the scheduling and availability of astronomical instruments at large observatories are the integrated water vapour (I WV), the relative humidity, and the cloud coverage. Atacama is the driest place on Earth after Antarctica, but still experiences high-humidity events such as yearly altiplanic winters (also called South American summer monsoons$^{15}$), occurring in January/February and visible in Fig. 4a) and episodic atmospheric rivers (two to three days of high humidity$^{16}$). Strong I WV events are primarily related to high central equatorial sea surface temperatures during El Niño events. Recent climate studies give a hint that an increased CO$_2$ concentration in the atmosphere will give rise to a global increase in humidity$^{17}$ and to more violent El Niño events$^{18}$, which means more frequent severe flooding in the Atacama region, as witnessed in March 2015$^{19}$. Here, we extracted the I WV at the Paranal Observatory location from the ERA5 reanalysis, complemented by the ERA20C reanalysis that covers a full century (to probe the four-year ENSO cycle)$^{20}$, which we compared to on-site measurements using the Low Humidity and Atmospheric Temperature PROfiling (LHATPRO) radiometer installed at the Paranal Observatory$^{20}$ (Fig. 4a,b). We do not observe an obvious trend in the mean, extremes of I WV or in the frequency or duration of high-humidity events that might indicate a long-term effect due to climate change. The notable trend of increasing low I WV events revealed by the radiometer over the last five years (Fig. 4b) is not over a long enough timescale to be able to draw any statistical conclusions. By exploring different projection models, there are hints that the area will become drier, but this needs to be more thoroughly checked due to the coarse resolution of the current models, added to the very specific location of the Paranal Observatory, at the interface between the Andes and the Chilean coastal range. In the future, we will refine this analysis to better apprehend the potential variation of I WV in the context of large near-infrared, submillimetre and radio wavelength observatories.

The purpose of this work is to raise awareness among the astronomy community about the effect and immediate
consequences of climate change on astronomical data. Each telescope site is likely to have its own microclimate that calls for individual study, but we have highlighted three different areas — dome seeing, surface layer turbulence and the wind-driven halo effect — that will have an increasingly detrimental impact on astronomical observations at Paranal as climate change worsens. Increasing atmospheric water content in some areas may also degrade observations, but for Paranal at least, there are indications the region might get drier. Through this work we have intensified collaborations between astronomers, climatologists, atmospheric scientists and desert area specialists, and we encourage others to do the same. Measurements of weather quantities in the Southern Hemisphere are scarce, not only due to the economic status of the southern countries (for example, fewer airports means less data are collected), and satellite data are too recent for long-trend analyses. For more than 30 years, astronomical observatories have been collecting daily weather data that can be jointly used to study the effect of climate change and refine the link between synoptic and optical turbulence scales, in particular in Chile where interactions between the ocean, the coastal area and the Andes involve complex mechanisms.

As astronomers, we are privileged to work in such a fascinating field, studying objects beyond Earth for the sole purpose of increasing humanity’s knowledge. Our work consists of thinking outside of the box, solving problems and analysing data with critical thinking. On top of this, our subject of study goes beyond any political or financial stakes. As a consequence, we have the opportunity, the tools and the prospect to build and follow concrete and sustainable actions against climate crises such as (1) communicating inside and outside our community about the impact of climate change on our planet and our society, (2) optimizing the energy resources expended for our professional activity, and (3) revisiting and reshaping the whole scheme of research in astronomy to decrease our global footprint. To do so, a massive cultural shift is needed, and it is of prime importance that astronomy uses its unique perspective to claim this simple fact: there is no planet B.

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Competing interests

The authors declare no competing interests.