Climate Change and Astronomy: A Look at Long-term Trends on Maunakea

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Abstract

Maunakea is one of the world’s primary sites for astronomical observing, with multiple telescopes operating over submillimeter to optical wavelengths. With its summit higher than 4200 m above sea level, Maunakea is an ideal location for astronomy, with a historically dry, stable climate and minimal turbulence above the summit. Under a changing climate, however, we ask how the (above-)summit conditions may have evolved in recent decades since the site was first selected as an observatory location and how future-proof the site might be to continued change. We use data from a range of sources, including in situ meteorological observations, radiosonde profiles, and numerical reanalyses to construct a climatology at Maunakea over the previous 40 yr. We are interested in both the meteorological conditions (e.g., wind speed and humidity) and the image quality (e.g., seeing). We find that meteorological conditions were, in general, relatively stable over the period with few statistically significant trends and with quasi-cyclical interannual variability in astronomically significant parameters such as temperature and precipitable water vapor. We do, however, find that maximum wind speeds have increased over the past decades, with observed wind speeds above 15 m s\textsuperscript{-1} increasing in frequency by 1\%–2\%, which may have a significant impact on ground-layer turbulence. Further, we note that while the conditions themselves are not necessarily changing significantly, the combination of conditions that lead to dome closures (i.e., freezing conditions, increased summit wind speeds, and/or high humidities) are worsening to the point that the number of closure conditions have more than doubled in the last 20 yr. Importantly, we find that the Fried parameter has not changed in the last 40 yr, suggesting there has not been an increase in optical turbulence strength above the summit. Ultimately, more data and data sources—including profiling instruments—are needed at the site to ensure continued monitoring into the future and to detect changes in the summit climate.

Unified Astronomy Thesaurus concepts: Astronomical instrumentation (799); Observatories (1147); Earth atmosphere (437)

1. Introduction

With increasing global temperatures, weather around the world is changing (IPCC 2021). With more extreme weather events being attributed to climate change, research is focused on the impact of climate change on specific fields and industries. Astronomy may also be contributing to the crisis with the CO\textsubscript{2} emissions of an astronomer higher than the average adult (for example, 40\% higher in countries such as Australia) (Clery 2020; The climate issue 2020). The impact on climate of travel to conferences and meetings, operating observatories, and supercomputing could in turn be impacting the quality of our astronomical sites and in the future limit ground-based astronomy. Recently, Cantalloube et al. (2021) highlighted the need for in-depth study of the impact of climate change on astronomical observatories around the globe. Their recommendation was based on their investigation of parameters at the Paranal Observatory in Chile, where they found an increase in temperature and surface-layer turbulence. We investigate the climatology at Maunakea, one of the world’s primary sites for ground-based astronomy, in order to determine if, and how, conditions may have evolved over the previous decades.

We specifically focus on the impact weather has on performing astronomical observations in the optical and near-infrared/infrared wavelengths at night. We first focus on the summit weather itself. Conditions for opening the telescope dome require that there be no precipitation, that the wind speed be below a specific threshold, and that the temperature and relative humidity present no risk of condensation forming on the primary telescope mirror (e.g., Keck 2022). Should the nominal behavior of these parameters change, it could have a significant impact on the amount of time that observations can be made throughout a given year.
It is also possible that the conditions, while not severe enough to prevent operating of the telescope, degrade the image quality to such an extent that the ability to further improve current high-resolution imaging becomes limited. For example, atmospheric turbulence can lead to the distortion of images through the introduction of wave front aberrations caused by fluctuations in the index of refraction in air. Techniques—such as the use of adaptive optics (AO) and postprocessing algorithms—are able to mitigate some of the distortion; however, they are limited in what they can remove and not all instruments can benefit from such corrections (e.g., not all instruments are AO-fed). Should turbulence be increasing at the site, it means that future telescopes will need to be designed with more high-order AO systems (to correct for higher spatial frequencies) that can also correct for more turbulence (i.e., large stroke of the deformable mirror to correct for greater optical path differences due to changes in the index of refraction). This is particularly important when considering the building and operation of future extremely large telescopes such as the Thirty Meter Telescope (TMT); should the atmospheric turbulence be worsening, the performance requirements of future AO systems currently being designed might not be achieved. Recent work by Lee et al. (2019) shows that increasing wind shear above the North Atlantic will lead to significant increases in turbulence that could in turn impact air travel between North America and Europe. We investigate whether a similar increase in turbulence is also found above Maunakea (where a similar jet stream feature exists), and whether that in turn leads to an increasing optical wave front error. An important factor when considering turbulence is the “seeing” (related to the Fried parameter, \( r_0 \)), which is the full-width-half-maximum (FWHM) of the imaged point-spread function (PSF) without AO correction. We look specifically at the vertical structure function of the index of refraction, the \( C_n^2 \) profile, which is what ultimately determines \( r_0 \) and therefore the seeing. Larger values of \( r_0 \) at Maunakea have been shown to be correlated to higher wind speeds (Chun et al. 2009; Lyman et al. 2020). At the same time, slow wind speeds might increase the occurrence of the low-wind effect seen by the Subaru telescope on Maunakea (Vievard et al. 2019), which is due to slow-moving wind within the dome not allowing for proper cooling. We therefore consider both trends in \( r_0 \) and \( C_n^2 \) as well as the summit wind speed.

The rest of this paper is structured as follows. In Sections 2 and 3, we present an overview of the data and methods used in our analysis of the meteorological and turbulent characteristics of the summit, respectively. We then present the results of our analysis in Section 4, beginning with a general overview of the sites’ climatology over the previous decades, followed by an analysis of trends and impacts on observing/observable conditions. This is followed by a discussion of the results in Section 5 and a summary of the conclusions in Section 6.

2. Meteorological Data and Methods

2.1. Meteorological Data

We use three types of meteorological data in our analysis: in situ observations made at the summit, radiosonde profiles, and a numerical reanalysis. The left panel in Figure 1 presents a map of the area around the Island of Hawaii (also referred to as “The Big Island”), showing the location and extent of different data sources in relation to the summit of Maunakea, while the right panel includes the layout of the summit with major telescopes shown. Figure 2 further illustrates the vertical and temporal resolution of the various data sets. We deliberately sought data that are available for roughly 30 yr or more in order to be able to extract meaningful climatologies. The individual data sources are described in the following subsections.

2.1.1. In Situ Meteorological Data

In situ meteorological data is from the Canada–France–Hawaii Telescope (CFHT) meteorological tower located at the summit of Maunakea. These data—referred to as the METEO (meteorological) data—are available from 1991 to present day and can be downloaded from the Maunakea Weather Center.4 Included in the data set are 1 minute observations of wind speed (\( U \)), temperature (\( T \)), atmospheric pressure (\( p \)), and relative humidity (RH).

We use the METEO data in order to provide an indication of the weather on top of the mountain at the location of the telescopes, as well as a “ground truth” benchmark for assessing the quality of the other data. Unlike the other data sources, the METEO data do not provide any vertical resolution. In order to smooth noisy data, we average the 1 minute values over 10 minute periods.

2.1.2. Radiosonde

Radiosondes are instrument platforms—typically carried by balloons—that are used to profile the properties of the atmosphere from the surface through the stratosphere (WMO 2014). Observations are made as the balloon ascends, with values recorded at mandatory vertical levels (that change throughout the record), or at significant (thermo)dynamic locations in the profile (Schwartz & Govett 1992). A typical ascent lasts roughly 2 hr; because the balloons are not steered, this means they can potentially drift up to hundreds of kilometers from their release point (e.g., Siedel et al. 2011; Laroche & Sarrazin 2013). Yet, work by Bely (1987) demonstrates good agreement between in situ and radiosonde observations. In Section 2.1.4, we further compare the radiosonde measurements to summit observations in order to determine whether or not the results can be compared with confidence for Maunakea.

4 http://mkwc.ifa.hawaii.edu/archive/
Radiosonde observations have been made on Hawaii since the 1950s. With improvements to instruments, the number of levels at which an observation is made has increased from roughly 10 above-summit locations to greater than 100 in recent years (Figure 3). Released twice per day at the Hilo International Airport (Figure 1), the radiosonde data provide a useful secondary verification for the reanalysis data set we use (ERA5). They also provide quasi-in situ vertical information, which the METEO data is unable to provide. From the radiosonde, we have vertical profiles of the temperature, humidity, and wind speed. The radiosonde data were downloaded from the NOAA/ESRL Radiosonde Database.5 In the following, we refer to the radiosonde observations by the abbreviation, RDS.

2.1.3. ERA5 Reanalysis

Reanalysis data sets are constructed by running a posteriori simulations of numerical weather models and assimilating available in situ and remote-sensed data (e.g., radiosonde, weather station, surface temperature data) in order to provide a historical estimate of conditions over the globe. In essence, they provide time–space interpolations of sparse data. The European Centre for Medium-Range Weather Forecasts (ECMWF) produces its ERA5 reanalysis with 137 vertical levels (roughly 68 above Maunakea’s summit); the data are available for download as 3 hourly mean values from the Copernicus Climate Data Store6 on a horizontal grid of 0.25° x 0.25° and interpolated to 25 vertical levels above the summit (650–1 hPa). As with the in situ observations, the reanalysis includes values of temperature, wind speed, atmospheric pressure, and at least one metric of humidity from which other metrics can be determined. We downloaded the data at the closest model grid cell to the summit location of Maunakea, which is centered almost directly at the summit.

2.1.4. Validation with In Situ Observations

We present a very brief comparison of the statistics of the meteorological data used in our analysis in this section. We do this as a validation step to ensure that our data—particularly the reanalysis data—are reasonably representative of the observed conditions. While exact instantaneous values may differ, the statistics (e.g., mean and variance) of the different data sets should be similar in order to facilitate comparison between data sets. A series of histograms is presented in Figure 3 illustrating the distribution of summit-level temperature, humidity, and wind speed. Given that the radiosonde and ERA5 reanalysis data are reported on pressure levels, their measurements are not guaranteed to correspond precisely to the summit altitude of 4.2 km above sea level. As such, we select the observations taken at the level closest to the summit.

The METEO temperature distribution is broader than the others, with a slightly cooler peak. At the same time, while the ERA5 and in situ METEO data have nearly identical distributions in the range from roughly 10%–70%, the in situ METEO contains much higher relative humidity values, approaching saturation almost 5% of the time, while the other sources almost never reach saturation. This discrepancy could be related to local topographic effects (e.g., upslope advection of air leading to saturation) that are not resolved by the vertical profiling of the free atmosphere. The greatest deviation occurs in the wind speed, where the METEO reaches wind speeds greater than 10 m s⁻¹ far more often than in the radiosonde and reanalyses (which agree with each other). This may also be a local effect due to summit topography, as discussed by Bely (1987). While Bely corrects for deviations in wind between radiosonde and in situ observations, we are interested in the relative change on an instrument basis and so do not make any adjustments to the reported observations. Some of the differences in distributions may be due to the much higher rate of sampling of the METEO (here, 10 minute averaged versus ≥3 hr); however, resampling the METEO data (e.g., taking a 3 hr mean) does not bring the distributions closer (not shown). The fact that the vertical profiles are not sampling exactly at the summit may also lead to some of the differences seen.

Ultimately, as a result of this brief comparison, we conclude that the differences in the underlying summit distributions will potentially lead to significant differences when determining in situ conditions for observing. As such, we only use the in situ METEO data for analysis of summit conditions. The ERA5 reanalysis does, however, do a good job of reproducing the observed properties of the radiosonde (both near the summit as shown here, and vertically; not shown). We can therefore use the ERA5 profiles for the turbulent parameter estimation (see Section 3) for which summit values alone are insufficient. Using the ERA5 reanalysis rather than the radiosonde profiles allows for a much higher temporal resolution on a consistent vertical grid.

2.2. Meteorological Methods

In order to ensure that we are looking at nocturnal conditions, we use a strict window, limiting our analyses to the data taken at times between 2100 and 0600 local Hawaii Standard Time (HST; UTC+10). This means we have one radiosonde profile and four ERA5 values per night.

Meteorology influences observational astronomy in two primary ways. (1) The meteorological properties affect the quality of the observations through changes in the index of refraction and turbulent properties of the atmosphere, as well as (for longer wavelengths of observation) the background emissivity of the atmosphere. (2) Whether or not observations can even take place is also dependent on the weather. A simple

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5 https://uc.noaa.gov/raobs/
6 https://climate.copernicus.eu/ climate-reanalysis
example is risk of condensation; water condensing on the telescope not only reduces the transfer of light throughout the system but can also damage the surface of mirrors. Many telescopes have specific operating conditions where the dome cannot be opened (or must be closed) if conditions reach certain thresholds. In our investigations, we are therefore concerned with understanding the overall trend in the meteorological variables, as well as any changes in observable conditions.

We perform our meteorological analyses by binning the data into seasons classified according to three months as follows: spring (March, April, and May; MAM), summer (June, July, and August; JJA), fall (September, October, and November; SON), and winter (December, January, and February; DJF). We also look at annual values. In order to better ensure reliable results, we restrict ourselves to periods where at least 80% of the data are valid (i.e., no missing or invalid data).

We determine the long-term trends in meteorological conditions themselves based on the mean over the seasonal/annual period. We are interested in both the long-term trends at the summit, as well as in the column of atmosphere above the summit. We only consider the in situ meteorological data to determine summit trends, while the reanalyses and radiosondes are used to provide an indication of the above-summit conditions.

Determining a season’s (or year’s) potential for observation requires the further step of first comparing the in situ observations with the meteorological thresholds. At each observation time, we compare the available data to the threshold. If the data do not exceed the threshold, then the time step is considered “observable.” If, however, the threshold is exceeded, then it would be deemed “unobservable.” Our thresholds are based on those listed by the Keck Observatory (Keck 2022), which provides guidelines for Observing assistants on when to close the dome. The actual operation of the telescope will, of course, depend on the experienced decision-making of the Keck personnel at the summit and so these thresholds are not absolute. They do, however, suffice for the purposes of our analysis to give an indication of operational feasibility. Briefly, the primary thresholds for observable conditions that we consider here are \( U < 20 \text{ m s}^{-1}, \) \( \text{RH} < 95\% \), and \( T - T_{\text{dew}} > 2 \text{ K} \). A more detailed overview of the observing criteria can be found at Keck (2022).

### 2.2.1. Precipitable Water Vapor

The total precipitable water vapor (PWV) is the total amount of water within a column of the atmosphere:

\[
\text{PWV} = \frac{1}{\rho_w g} \int_{P_1}^{P_2} q(P) dP, \tag{1}
\]

where \( \rho_w \) is the density of water vapor, \( g \) the acceleration due to gravity, \( q \) specific humidity, and \( P \) the atmospheric pressure.
PWV is an important parameter for observing in the (near-) infrared (NIR/IR) and submillimeter wavelengths as water radiates at these wavelengths dominating background radiation. Water also introduces phase aberrations for longer wavelengths as it becomes a source of fluctuations in the index of refraction (the fluctuations are driven by temperature for optical/NIR wavelengths) (Colavita et al. 2004). With large amounts of water present in the atmosphere, it becomes difficult to observe in these wavelengths from the ground. PWV values around 5–10 mm can render it impossible to make scientifically impactful observations in the K band (central wavelength of 2.2 μm) for science cases such as the direct imaging of exoplanets. For the submillimeter, certain bands can only be observed when the PWV is less than 1 mm. We use the James Clerk Maxwell Telescope, JCMT, weather bands\(^7\) to bin the calculated PWV and study the long-term behavior of PWV for these wavelengths.

3. Turbulence Data and Methods

3.1. MASS-DIMM Data

The Canada–France–Hawaii Telescope (CFHT; Figure 1) provides nightly time series of the total seeing (i.e., \(r_0\)) and vertical profiles of the index of refraction structure function, \(C_n^2\), estimated by its Differential Image Motion Monitor (DIMM)
and Multi-Aperture Scintillation Sensor (MASS). The MASS C_n^2 profiles are estimated for fixed altitudes of 0.5, 1, 2, 4, 8, and 16 km above the telescope and are made approximately every 2 minutes. The data are available from 2009 to present. The MASS instrument has limited ability to measure the turbulence accurately for the first altitude of 0.5 km as it is blind to some of the turbulence in the layer and can only measure the seeing in the free atmosphere. The DIMM, however, measures the integrated turbulence for the entire column allowing r_0 to be estimated. By combining the DIMM/MASS, an estimation of the ground-layer turbulence can be made.

### 3.2. Estimating Turbulence Parameters

In ground-based optical and NIR astronomy, a few key parameters are used to describe atmospheric turbulence in a way that is meaningful for observing, including: the C_n^2 profile, the Fried parameter (r_0), and the atmospheric coherence time (τ_0). These parameters are either directly related to the image quality or have meaning for the performance of an AO system. C_n^2 is the structure function of the index of refraction as a function of altitude. At the observed wavelengths, fluctuations in the index of refraction cause the optical path differences (phase errors) that limit image quality and resolution of larger telescopes. The Fried parameter is related to the integrated C_n^2 and describes the total impact of the atmosphere. With units of length, r_0 can also be estimated as an angular separation in units of arcseconds, giving the more commonly used value of “seeing” that astronomers report as it relates to the FWHM of an aberrated PSF. Finally, τ_0 describes how quickly the turbulence is changing above the telescope. It is related to the wind speed and the turbulence strength profile. With these parameters, we can predict the quality of the observed data and the achievable image resolution. In this section we outline the calculation of these values.

#### 3.2.1. Determining the Structure Function of the Index of Refraction from Reanalysis Data

The ERA5 reanalysis data contain temperature and wind values at 25 pressure levels above the Maunakea summit (Figure 2). This corresponds to a value every few kilometers, which is relatively coarse, though much finer resolution than MASS data. We match synthetic C_n^2 profiles generated from ERA5 to the coarse profiles as measured at CFHT. Here we do not aim for exact instantaneous matches, rather we estimate the mean C_n^2 in order to calibrate out ERA5-derived profiles. This provides us with rough estimates of the local C_n^2 (although with such coarse resolution it cannot be a “local” estimate). Because the reanalysis has more layers than CFHT, we resample the C_n^2 data by summing the local C_n^2 dh. This provides us with the C_n^2 in m^-3, allowing us to compare to the CFHT measurements.

Below we outline our methodology for calculating the C_n^2 values from ERA5 data.

Using same methodology as Osborn & Sarazin (2018), we use the modified Gladstone relationship (Masciadri et al. 2016) to write C_n^2 as a function of the temperature structure function, C_T^2:

\[ C_n^2 = (80*10^{-6}P/\theta)^2 C_T^2, \]  

(2)

where \( \theta \) is the potential temperature,

\[ \theta = T P_0 \frac{\gamma}{P}, \]  

(3)

and \( P_0 = 1000 \text{ mbar} \) and \( \gamma = 0.289 \).

From Tatarskii (1971), C_T^2 as a function of altitude (z) is estimated using the potential temperature gradient and the scale of the largest energy scale of the turbulent flow, L:

\[ C_T^2 = kL(z)^2 \left( \frac{\delta \theta(z)}{\delta z} \right)^2, \]  

(4)

\[ L(z) = \sqrt{\frac{2E}{g \int \frac{\delta \theta(z)}{\theta(z)} \delta z}}. \]  

(5)

k is an unknown dimensionless constant that is calibrated against C_n^2 data; in reality, it encodes information about the stability of the atmosphere. In Osborn & Sarazin (2018), the authors found a k value of 6 for a global calibration. However, k can be determined for not only a specific site but also for altitude dependent. In this work we calibrate k using approximately 10 yr of MASS data starting from 2011 and find a value for each altitude: 6.3, 10.3, 25.6, 11.8, 18.2, and 12.0, going from the lower to higher altitudes, respectively. E, the turbulent kinetic energy, is given by the square of vertical wind shear as done in Osborn & Sarazin (2018):

\[ E = \left( \frac{\delta u}{\delta z} \right)^2 + \left( \frac{\delta v}{\delta z} \right)^2. \]  

(6)

#### 3.2.2. Determining the Fried Parameter and Atmospheric Coherence Time

From Hardy (1998), r_0 for light at 500 nm in the zenith direction can be calculated from the C_n^2 profile:

\[ r_0 = 0.423 \left( \frac{2\pi}{\lambda} \right)^2 \left( \int C_n^2(h) \, dh \right)^{-3/5}. \]  

(7)

From the Fried parameter, r_0, and the effective wind speed, V_eff, we can calculate the coherence time, τ_0, following Hardy (1998):

\[ \tau_0 = 0.314 \frac{r_0}{V_{\text{eff}}}. \]  

(8)
4. Results

4.1. Meteorology

4.1.1. Climate at Maunakea

We first present an overview of Maunakea’s climate based on the assembled data in order to provide a context for subsequent analysis. Figure 4 shows the seasonal-median summit values of temperature, wind speed, and relative humidity from the year 2000 to present as recorded at the CFHT weather station. All three parameters demonstrate a degree of seasonal variability though overall relatively stable characteristics. Temperature is within a few degrees of freezing throughout the year and summit wind speeds are typically around 5–7 m s\(^{-1}\). In general, the atmosphere is dry with relative humidity around 20%, but with significant variability

\[
V_{\text{eff}} = \left[ \frac{\int_0^\infty C_n^2(h) U(h)^{5/3} dh}{\int_0^\infty C_n^2(h) dh} \right]^{3/5}
\]

in the record (illustrated by the shading), including an increase in the standard deviation with time.

Of the standard meteorological variables, wind speed is the only parameter with any statistically significant increase in median value at the summit (Figure 5) with 5 yr averaged speeds increasing over 30 yr. For example, there is a rightward shift in the peak of the wind-speed distribution, with speeds above 15 m s\(^{-1}\) increasing by 1%–2%. Overall this does not have a significant impact on the mean summit wind speed, but it does indicate a greater likelihood for increased ground-layer turbulence and, by extension, wind buffeting as the wind interacts with the dome structures themselves (MacMynowski et al. 2006).

Figure 4. Median of the seasonally binned nocturnal METEO observations, with shading indicating the range spanned between the 25th and 75th percentiles. (a) Temperature, (b) wind speed, and (c) relative humidity.

Figure 5. 5 yr binned values of wind speed shown as the (a) probability density and (b) cumulative density functions.
The precipitable water vapor, related to specific humidity, shows considerable variability over the period from 1980 to present (Figure 7). PWV varies between 0.5–3 mm in both the radiosonde- (RDS) and ERA5-calculated values, with no significant long-term trend in the seasonal median. We also compare the PWV to the El Niño-Southern Oscillation (ENSO) in Figure 7. Minima in the signal appear to follow peaks in El Niño and subsequent transitions to La Niña conditions, providing a first-order predictor of conditions. Interestingly, there is a point before 1995 where the ERA5 and RDS values disagree, after which they are aligned, although the RDS does consistently lead to lower minima than the ERA5 estimates. The seemingly abrupt change in RDS values is likely due to an increase in the number of vertical levels sampled by the radiosonde between roughly 1995 (dashed line) and 1998, rather than any relevant climatological factor.

Figure 8 further highlights the seasonal distribution of total atmospheric PWV in different bins. The RDS observations indicate that, post-90’s, PWV is less than 0.83 mm almost 50% of the time, providing optimal conditions. The ERA5 reanalysis estimates a much lower fraction, though with PWV < 1.58 mm at least 50% of the time. The difference in estimates may be due to the different vertical resolution of the profiles. After the mid-90’s, the RDS data have a much higher vertical resolution than the ERA5 profiles. The consistent heights of the reanalysis data, however, allow for a long-term comparison of PWV to be made. While there are obvious variations over the previous 40 yr, they are of a cyclical nature with no obvious trend.

4.1.2. Weather-related Dome Closures

We next investigate the meteorological conditions that can lead to dome closures at the summit, using the Keck values as a guide. Figure 9 plots the fraction of all METEO observations that exceed the dome-closure criteria (i.e., the total number of times the criteria are exceeded, divided by the total number of observations made). This is analogous to the amount of time that the dome would need to be closed in a season, though not directly comparable due to operational considerations such as the waiting time needed before the dome can be reopened. We plot seasonal (different panels) and annual values (black dots in each panel). In all cases, there is a significant worsening trend in the fraction of observations that exceed the criteria, with an annual increase of 0.49% per year. The greatest increase is seen in spring (0.61% per year) and the lowest in summer (0.3% per year). These trends equate to a near-tripling in the fraction of conditions requiring dome closure over the 30 yr period. The trends are driven primarily by increasing summit winds in winter, spring, and fall, while increasing humidity drives the trend in the summer (not shown).

While the total fraction of observations is increasing, Figure 10 shows that this does not necessarily equate to the same change in unique nights impacted by weather (i.e., nights were at least one criterion is exceeded at least once in the night). Winter has the most nights affected by bad weather, but only spring and fall show significant trends, leading to an annually significant trend of around 0.65% of nights per year. Over the 30 yr, however, this does mean a rough doubling in the nights impacted by bad weather, going from approximately 15% to over 30% of unique nights by 2020.

4.2. Turbulence

Next we look at the behavior of turbulence above the telescope that drives the changes in optical path difference that causes image distortion and limits resolution. We split the
analysis of turbulence into two components: (1) the free atmosphere (starting from approx 0.5 km above summit) and (2) ground layer using $C_n^2$, $r_0$, and $\tau_0$.

4.2.1. Turbulence in the Free Atmosphere

From the equations outlined in Section 3.2, the mean $C_n^2$ profile for the free atmosphere was calculated using the ERA5 reanalysis, resampled to the MASS/DIMM altitudes, and then calibrated on the overlapping data from 2011 to early 2020 by calculating the ratio of the mean profiles in time. The calibration was then applied to all the ERA5 profiles. We plot the results in Figure 11, showing the median instead of the mean in order to highlight differences in the profiles. Note this means that while the mean profiles are the same due to the calibration, the extrema are different. As expected, we have good agreement with the overlapping data, while all of the ERA5 data have a slighter smaller mean value than the most recent data, suggesting that the mean profile has increased in strength though within the error bars of the most recent profile.

We calculate $r_0$ for the free atmosphere using the $C_n^2$ profiles, with 5 yr binned statistics of $r_0$ in Figure 12. From the probability density function (PDF) and cumulative density function (CDF), we see temporal variability in $r_0$ but no consistent trend toward better or worse values. These results suggest that the strength of turbulence has not changed in the last 40 yr.

While the strength of the turbulence has remained constant, we look to the free-atmosphere $\tau_0$ which can have a significant impact on the image quality for astronomical observations especially AO-assisted imaging. Taking the effective wind speed, we calculate $\tau_0$ with Figure 13 showing the statistics of $\tau_0$ over the same temporal bins. From 1980–2014, the peak of the PDF is decreasing with time and from the CDF we see that the curves shift to the right indicating that the $\tau_0$ has more larger values between 10 and 20. There is, however, an increase in the peak of the PDF for 2015–2020. Looking more closely at the temporal sampling of the data, we are unable to confirm whether the changes are significant as the amount of data...
available within each bin varies by tens of percentages as well as the distribution throughout the year. Qualitatively, we see no evidence of changes to the wind speed in the free atmosphere at the MASS altitudes that we use for the \( r_0 \) calculations.

The free-atmosphere behavior, however, does not provide the complete story; we must also look to what the ground-layer turbulence is doing. Given that the ERA5 wind speed does not agree well with the in situ observations (Section 2.1.4), we use the in situ MASS/DIMM observations rather than ERA5 as in the previous section.

From the MASS/DIMM measurements, we not only get the full \( r_0 \) value covering the entire atmosphere but also the \( r_0 \) value of the free atmosphere. From these values, we can calculate the ground-layer \( r_0 \) (Lyman et al. 2020). We compare the histograms of these different \( r_0 \) values for the complete data set in Figure 14. We see that the amount of turbulence in the ground and the free atmosphere are both log-normal distributions with slightly different mean values, as expected. We also see that the bulk of the turbulence (corresponding to smaller \( r_0 \) values) is found in the free atmosphere. The median value of the ground layer is 21 cm, which is in agreement with the 20 cm that was previously found through a dedicated SLODAR campaign by Chun et al. (2009). We also see from the figure that the ERA5 \( r_0 \) and free \( r_0 \) have good agreement with median \( r_0 \) values of 19 and 22 cm, respectively. These values agree with other studies that report a 21 cm \( r_0 \) using MASS data (Neyman 2004). The mean total \( r_0 \) of roughly 15 cm is also in agreement with the 4 yr mean of 15 cm found at Subaru (Neyman 2004). From Figure 14, we can further verify that our calculations of the \( C_n^2 \) profile and \( r_0 \) are in good agreement with the literature. Taking a closer look, we plot PDFs and CDFs for the fraction of turbulence in the free atmosphere and the ground in Figure 15 for every 2 yr. Over this short-term basis, there is little evidence of a trend to either

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**Figure 8.** Fraction of seasonal total atmospheric PWV in the JCMT’s weather bands (see footnote 4).
larger or smaller values with the peak of the PDF fluctuating. This suggests that the strength of the ground layer does vary with respect to the free atmosphere but the mean shows no trend in time from the current baseline available.

5. Discussion

In this section, we discuss some of the results above and their significance in relation to previous work and their implications for astronomy at the summit of Maunakea. We have chosen to highlight three key elements of our investigations, namely, (1) the trends in dome-closure criteria, (2) the impact of PWV, and (3) turbulence, while also looking toward future data needs.

5.1. Dome-closure Criteria

The general increase in summit winds (Figure 5), although modest, is sufficient to increase the number of times Keck’s dome-closure criteria would be exceeded in a given year (Figures 9 and 10). The overall increase in exceedances is significant, with a roughly doubling of unique nights (approximately 15% to over 30% of nights) reporting meteorological values that could lead to dome closure over
the course of a year (0.65% per year) and a corresponding significant trend in the fall of roughly 1% per year.

As mentioned above, it is important to note that this is not the actual dome-closure rate. The thresholds are guidelines that are used by the experienced observers and telescope operators on site who are responsible for making dome open/close decisions. It is also possible that many of the “bad nights” would already be lost to maintenance or other nonmeteorological closures that are upwards of 40 nights per year. Recent closure records indicate that the dome is closed—for any reason—roughly 40% of the year on average, with the lowest closure rate in May and June. Averaged historically, weather-related closures account for roughly 15% of all closures. Our analysis in Figure 9 agrees with these numbers provided by Keck, with lowest closure estimates in the spring and summer periods, and accounting for up to 20% of total nighttime hours. Ultimately, this agreement lends confidence to our analysis.

Overall, the trend is concerning. Should conditions continue to worsen, it is possible that weather-related closure could become a significant hindrance to future astronomy. We do not, however, have a long-enough time series to conclude whether this is a trend that has persisted for some time or simply a short-term increase as part of a larger cycle, and as such, the conditions will improve in coming decades. We also could not take into consideration other phenomena—such as changes in cloud cover or precipitation—that would also restrict observations. It could very well be that improvements in these variables offset the worsening conditions in the variables we could consider here. Continued monitoring of the site is therefore essential. This includes the need for wider—or at least more accessible—recording and reporting on seasonal and annual dome-closure statistics and their causes.

5.2. Precipitable Water Vapor

Taking a closer look at Figure 8, we look at the variability in the ERA5 PWV values, specifically comparing the minima and maxima. As mentioned in Section 4 following the analysis of Figure 7, minima in the PWV signal follow peaks in El Niño and transitions to La Niña conditions. Comparing the minima of Figure 8 in the years 1998, 2003, and then 2010, we see a large difference in the PWV value and how long the dry period spans. In 2010, we have a significantly longer period (twice as long) of PWV values falling within the smallest JCMT bin. Contrasting to more recently, the PWV values have been abnormally high providing poor conditions from 2019 until at least 2021. For astronomy such as NIR observations of exoplanets, the PWV can significantly impact the quality of the observation and ultimately be the difference between a detection or nondetection for a given night of observations. Specifically, the discovery of a fourth planet previously undetected around HR 8799 was made around 2009 and 2010 using W.M. Keck Observatory (Marois et al. 2010) on Maunakea when the PWV was abnormally low for a longer period; it is possible that these conditions favorably contributed to the detection. It would be interesting to compare the time of observations for impactful science in the NBR bandpass with values such as the PWV to determine how much the results depend on specific conditions in order to better understand the performance of our current and future instruments. This analysis, however, is outside the scope of this paper.

5.3. Turbulence

We discuss the results from Section 4.2 in more detail here. The Gladstone equation presented in Section 3 depends on the shear (derivative) of the wind as a function of altitude. From the wind profiles above Maunakea (i.e., Figure 6), we expect to have two peaks in the shear profile near 6 km and a second peak around 15 km (approximately where the change in wind is the greatest) on either side of the jet-stream layer. When studying the CFHT $C_n^2$ profiles, however, we only find one peak around 6 km lining up with the base of the jet stream but the second peak at the top of the jet stream is not present. When resampling the ERA5 data to match the CFHT resolution we also effectively miss this second peak higher up. Figure 16 shows the $C_n^2$ profile for the full-resolution ERA5 profile, which reveals both peaks as expected. We note that the lower peak in the full profile is considerably smaller than in the resampled profile. This suggests that some of the turbulence above the jet stream is being binned into the lower layer and that the amount

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8 Records provided by Jim Lyke for the period spanning 2018 July–2021 October.
9 Q&A at workshop in 2021 given by Keck personnel: https://www.keckobservatory.org/wp-content/uploads/2021/02/OMeara-QA.pdf?x32463.
of turbulence is not being missed but the distribution of
turbulence might be incorrect.

MASS/DIMM instruments depend on both the assumed
altitudes and the type of turbulence, providing an accuracy
of up to 10% when properly maintained (Tokovinin &
Kornilov 2007). Because the methods assume a thin layer of
turbulence at specific heights, turbulence at different heights
will be binned into a specific height. While the overall amount
of turbulence measured is correct, there is much uncertainty in
how it is distributed. The data suggest that the assumed layers

Figure 12. The PDF (left) and CDF (right) for 5 yr binned values of ERA5-derived values of $r_0$ of the free atmosphere. The lines go from lightest to darkest in chronological order with the legend indicating the start of the bin.

Figure 13. The same as Figure 12 but for $r_0$ for the free atmosphere.

on Maunakea for the MASS instrument could be changed to
better sample where the bulk of the turbulence is expected. This
might have implications for better understanding of turbulence
and instrument performance but also for AO methods such a
multiconjugate AO where wave front sensors are conjugate to
different altitudes to measure the turbulence at a given height.

With the ground-layer $r_0$ showing no trend over 10 yr, we
comment on the impact of the increase in ground-layer wind
speed that is seen in the in situ measurements presented in
Section 4.1.1. The increase in strong ground-layer winds not
only results in dome-closure criteria being met more often but will have an impact on how quickly the ground-layer turbulence is evolving as well as dome seeing (turbulence inside the dome itself). More quickly flowing air over the dome structure itself (and other structures including geophysical) could alter turbulence for one telescope and not for another (i.e., for one telescope it might increase vibrations along the support structure by a small, but still significant, amount). Due to the multifaceted impact that ground-layer wind can have, we do not calculate the coherence time of the ground layer (and only look at free-atmosphere coherence time in Section 4.2). The full impact of change in the ground-layer wind speed therefore must be evaluated for each telescope separately.

### 5.4. Future Data

As the astronomy community looks toward future telescopes such as the Thirty Meter Telescope (TMT) as well as continues to use current telescopes on Maunakea, it is desirable to expand
the work presented in this paper and increase the baseline to detect trends early. With such work, new instruments and new operation methods (i.e., queue observing) can have the necessary tools and data to produce the best science with these ground-based telescopes.

In this work we look for changes in meteorological data as well as various turbulent parameters. It is important to keep the current facilities up to date along with increasing their capabilities (e.g., improve MASS/DIMM resolution as well as number of operational nights). Specifically, with regard to the MASS, it will be important to understand why the distribution of turbulence is different compared to ERA5 as discussed above and make any necessary changes to what altitudes are chosen by the MASS. It would also be beneficial to have more data sources of similar data on the mountain so as to not be biased toward a specific geographical feature, answering questions such as: Are the winds measured at CFHT representative of winds at Keck Observatory or Subaru Telescope? Are these observatories really experiencing an increase in dome closure due to this? Finally, having observatories publish their current data on the percentage of nights with the dome open/closed would be good for understanding how the weather is affecting astronomy and if there are indeed any trends in dome opening.

Beyond observations, numerical simulations are also important to consider. In particular, climate projections will be important in order to relate current observed trends to potential future scenarios, although careful consideration of the potential mismatch between numerical estimates and highly local in situ observations (e.g., Section 2.1.4) will need to be undertaken. Waiting until we can observe a change is too late. While such an analysis is beyond the scope of this current manuscript, it is an important next step.

### 6. Conclusions

We present a study of long-term trends on Maunakea with the primary goal of determining whether climate change is already having an impact on astronomy at the site. Specifically, we look at weather (temperature, wind speed, and relative humidity) both at the summit using in situ data as well as above the summit using radiosonde and reanalysis data (ERA5). We use in situ $C_n^2$ profile measurements to calibrate the $C_n^2$ profile values extracted from ERA5 data, allowing us to look at the turbulence characteristics over the last 40 yr.

From the meteorological data, we find:

1. the wind speed is increasing at the summit (Figure 5) with 5 yr averaged speeds increasing over 30 yr,
2. there has been a doubling in nights impacted by bad weather over the last 30 yr based on the Keck dome-closure criteria (driven mainly by the wind speed), and
3. there is no long-term trend in PWV although there is significant interannual variability in PWV, possibly related to ENSO dynamics.

Studying the turbulence parameters, we show:

1. that the 5 yr means of $r_0$ and $\tau_0$ have not changed over the last 40 yr,
2. year to year, both $r_0$ and $\tau_0$ can change noticeably,
3. and that the fraction of turbulence in the ground and free atmosphere has no trend in the last 10 yr but note that it can vary greatly year to year.

To support further monitoring of climate-change impacts and to further understand the changes we are already seeing, we stress the need to maintain an up-to-data climatology on Maunakea. We would also encourage observatories to publish available data such as local temperature, wind speed, or dome-closure data, making it accessible to continue this work. An important follow-up to this work is to look toward climate projections in order to better understand how climate change could affect the site in the future and not just how it has affected Maunakea in the past (including whether any acceleration is possible). Finally, while it does not yet appear that significant deleterious changes have occurred on Maunakea, we urge the astronomy community to consider ways to reduce our carbon footprint, which will help to maintain the scientific quality of our global astronomical sites as well as the important ecological and social settings of our observatories.

We acknowledge that the land on which the University of California, Santa Cruz, is located is the unceded territory of the Awwaswas-speaking Uypi Tribe. The Amah Mutsun Tribal Band, composed of the descendants of indigenous people taken to missions Santa Cruz and San Juan Bautista during the Spanish colonization of the Central Coast, is today working...
hard to restore traditional stewardship practices on these lands and heal from historical trauma.

The authors also wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

We are grateful to all—known and unknown—who collected and provided the data used in these analyses. Unless otherwise noted, the individual data sets are all openly available and can be accessed as described in Section 2 and Section 3.

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