Two decades of km-resolution satellite- and ground-based measurements of the precipitable water vapor in the Atacama Desert

A comparison of climate measurements for submillimeter astronomy

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ABSTRACT

Context. The Atacama Desert has long been established as an excellent site for submillimeter observations. Yet identifying potentially optimal locations for a new facility within this region can be costly, traditionally requiring long field campaigns in multiple locations that rely on the construction of weather stations and radiometer facilities to take data over sufficiently long timescales, often years. Meanwhile, high-level remote sensing data products from satellites have generally only been available at ≳25 km resolution, limiting their utility for astronomical site selection.

Aims. We aim to improve and expedite the process of site characterization and selection through the use of kilometer resolution satellite data.

Methods. We analyze the daytime precipitable water vapor (PWV) values inferred using near-infrared measurements from the Moderate Resolution Imaging Spectrometer (MODIS) Aqua and Terra satellites, comparing the level-2 satellite products to those from existing ground-based measurements from the radiometer at the Atacama Pathfinder Experiment (APEX) site. Since the APEX radiometer data has been extensively tested and compared to atmospheric transmission models, particularly in low-PWV conditions of interest for astronomy, we use these data to re-calibrate the MODIS data for the entire region, reducing systematic errors to a level of < 3%.

Results. After re-calibration, the satellite data allow mapping of the PWV across the region, and we identify several promising sites. Our findings confirm previous results, but provide a more complete and higher resolution picture, filling in key spatial and temporal information often missing from dedicated field campaigns. We also examine the seasonal trends in the ground-based data from APEX and in the satellite for a large region encompassing the Atacama Astronomical Park (Parque Astronómico de Atacama) in Chile, finding that both data sets provide indications that PWV has increased moderately over the past two decades.

Conclusions. We demonstrate a potentially powerful method for siting new facilities such as the Atacama Large Aperture Submillimeter Telescope and extensions to global very long baseline interferometry networks like the Event Horizon Telescope. Over time, the ability to determine long term trends will improve as further satellite observations are accumulated and new instruments are deployed.

Key words. Precipitable water vapor – Atmospheric opacity – Microwave radiometers – Atmospheric measurements – Radiometry – Atmospheric modeling - Climate Science

1. Introduction

The Atacama Desert has long been established as an excellent site for millimeter and submillimeter observations (e.g. Radford et al. 2008; Radford & Peterson 2016; Otarola et al. 2019; Cortés et al. 2020), owing to its reputation for low precipitable water vapor (PWV) as one of the driest deserts on Earth. It therefore serves as host to many of the preeminent millimeter and submillimeter astronomical observatories and experiments built in the last several decades, such as the Atacama Submillimeter Telescope Experiment (ASTE; Ezawa et al. 2004), Atacama Cosmology Telescope (ACT; Fowler et al. 2007), Atacama Pathfinder Experiment (APEX; Güsten et al. 2006), Atacama Large Millimeter/Submillimeter Array (ALMA; Wootten & Thompson 2009), CCAT-prime (CCAT, also known as the Fred Young Submillimeter Telescope, or FYST; Parshley et al. 2018), and Simons Observatory (SO; Ade et al. 2019).

Submillimeter atmospheric transmission can be characterized mainly by two components: a dry component dominated by telluric lines such as oxygen, and a wet component dominated by (liquid) water vapor in the atmosphere. In large part, the dry component is a function of altitude, while contributions from the wet component can be reduced by choosing sites that minimize the PWV. This leads astronomers to site their observatories at high and dry locations, though we note of course that considerations such as accessibility (road access, infrastructure, and legal
restrictions\(^1\)), wind conditions, and temperature play a crucial role.

Long-term trends and interannual variability for these sites are difficult to establish due to the absence of weather stations in this sparsely inhabited region. The most detailed measurement campaigns, especially at high elevations, are generally those done as part of site testing (e.g. Otarola et al. 2019).

Recently, the work presented in Cantalloube et al. (2020) examined, at relatively low (≤31 km) resolution, the impact of climate change and El Niño on our ability to perform high resolution astronomical imaging using ground based observatories sited in locations traditionally exhibiting superb atmospheric transmission and seeing. They used onsite observations of temperature for the period covering 2000-2020, and integrated water vapor (IWV) for 2015-2020, at Paranal Observatory, which is south of our region of interest, and at a much lower elevation of ~2600 meters above sea level (a.s.l.). They also relied on modelled reanalyses of approximately four decades of satellite data and climate projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to study long-term changes. They note that climate change will soon change the conditions for operations and observations especially as temperature increases, although each observatory location can be dominated by its microclimate variability. Changes in El Niño, which has been shown to contribute to variability in the whole region, could also have an impact in the near future. In terms of findings directly relevant to submillimeter astronomy, they also identify a potential trend for worsening atmospheric turbulence, which would affect phase coherence, and they report an increase in the number of days with low water vapor in recent years for the region surrounding Paranal, although they note that time series is too short to determine the statistical significance.

At the same time, Böhm et al. (2020) studied the variability of the integrated water vapor column over the Atacama region, mainly using reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA5; Hersbach et al. 2020) to determine trends over the entire 20th Century. They also compare these data to satellite data from MODIS spanning 2000-2010, and find that in years dominated by La Niña, the variability increases, producing more extreme PWV values.

In this study, we are concerned with conditions that affect astronomical observations at submillimeter (submm) and mm wavelengths (e.g. 30-1000 GHz), though we note that such conditions also affect visible wavelength observations.

We focus on studies of the temporal and geographic trends, with applicability in particular to the Atacama Large Aperture Submillimeter Telescope Project (AtLAST; Klaassen et al. 2019, 2020).\(^2\) We also report our findings when comparing sites with the Atacama Astronomical Park\(^3\) (AAP, a.k.a. Parque Astronómico de Atacama; see Bustos et al. 2014, for further site details), the ALMA concession, and surrounding regions nearby, such as the Large Latin American Millimeter Array (LLAMA; Romero 2020). We note that the AAP surrounds the ALMA concession, and only show the outer border of the former in each map figure (see e.g. the shape region in Figure 1).

\(^1\) For example, as noted in e.g. De Breuck (2018) and Otarola et al. (2019), both the hardships of working at high altitude and Chilean labor law make it challenging to build and operate a facility at more than 5500 meters above sea level.

\(^2\) https://atlast-telescope.org/

\(^3\) https://www.conicyt.cl/astronomia/sobre-el-parque/

\(^4\) https://www.gebco.net/data_and_products/gridded_bathymetry_data/
These level-2 measurements are used to infer the integrated column of water vapor using absorption, aerosol scattering, and surface reflection of solar radiation at a resulting resolution of 1 km for daytime data. Hereafter, we equate the integrated column of water vapor with precipitable water vapor. The PWV is inferred using the ratios of clear NIR windows at 0.865 and 1.24 μm, and lines due to absorption by atmospheric water at 0.905, 0.936, and 0.94 μm (see Gao & Kaufman 1998, 2015a,b).5

As cloud cover can affect the ability to compute the NIR transmission through the atmosphere and therefore affect completeness of the dataset, we exclude data flagged for cloud cover. In Figure 2, it can be seen that the cloud coverage fraction is typically ≈15-25%, and is typically higher to for locations farther to the east. We note that some data flagged for cloud cover at a given location may be due to solar glint, rather than poor atmospheric transmission. Therefore, the flagging does not necessarily imply that a given flagged measurement has high PWV.

MODIS Terra and Aqua also provide mid-IR data at a more limited resolution of 5 km. These data include nighttime measurements. However, initial tests indicated large systematic offsets between the NIR and mid-IR measurements, confirming the results of Wang et al. (2017). Since the topology of the region varies quickly (see Section 2.1), we exclude the mid-IR data from our analysis, noting that the PWV generally drops at night. Thus, the daytime PWV we report on here can serve as a generally good indicator of the worst-case conditions. A future work will address the diurnal variability in PWV in more detail.

### 2.3. Ground-based water vapor radiometer data

We use PWV data collected since May 2006 by the Atacama Pathfinder Experiment using their ground-based water vapor radiometer mounted inside the Cassegrain cabin of the telescope6. In short, the radiometer measures the irradiance in the 183 GHz water line of the atmosphere, which is sampled in three (up to 2012) or six (from 2012) bands. This is combined with a model of the atmosphere using local measurements of temperature, atmospheric pressure and humidity as additional input parameters.

The PWV is then derived using the ATM model (Pardo 2019) which is then used to infer the atmospheric transmission. Since water dominates the transmission at this frequency, the signal provides information on the wet component of the atmosphere. The results in Cortés et al. (2020) indicate that the systematic uncertainty in the calibration of the APEX radiometer data should be < 3% (i.e. more than 97% accurate), due to atmospheric modelling uncertainties. Since we are mainly interested in using the APEX radiometer values to correct the values inferred from MODIS Terra and Aqua during conditions of low PWV, we only use values of PWV < 3 mm to re-calibrate (or correct) the MODIS Terra and Aqua data.

### 2.4. Wind data

The wind data are part of the ERA5 land reanalysis project (Balismo et al. 2012) and provide 9 km resolution.7 We use their results from over the period 1981-2019. Figure 3 and additional plots in Appendix B show the average (mean) and maximum yearly and monthly values for the wind, confirming that westerly winds generally prevail with the AAP+ALMA region (red outline in Fig. 3), and that values for the 2° x 2° region analyzed in this work peak to the southeast of the AAP+ALMA region. We do not compare the wind data to any ground based weather station measurements, and instead leave that a future study.

### 3. Methodology

An overview of our methodology is provided in Figure 4. We obtained the MODIS NIR data from the Level-2 and Atmosphere Archive & Distribution System (LAADS) website hosted by, and part of, the National Aeronautics and Space Administration (NASA).8 The MOD05_L2 and MYD05_L2 data correspond to Terra and Aqua, respectively.

We select the 2° x 2° region spanning longitudes of 66.3° to 68.3° West, and latitudes of 22.5° to 24.5° South (i.e. the region -68.3°,-22.5°,-66.3°,-24.5°), which includes the entire area

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5 [https://modis.gsfc.nasa.gov/data/atbd/atbd_mod093.pdf](https://modis.gsfc.nasa.gov/data/atbd/atbd_mod093.pdf)

6 See [http://archive.eso.org/eso/meteo_apex.html](http://archive.eso.org/eso/meteo_apex.html)

7 [https://doi.org/10.24381/cds.e2161baco](https://doi.org/10.24381/cds.e2161baco)

8 [https://ladsweb.modaps.eosdis.nasa.gov/search/](https://ladsweb.modaps.eosdis.nasa.gov/search/)
around the Parque Astronómico de Atacama (Atacama Astronomy Park, see region indicated in red in Figure 1) in Chile, which surround APEX, ALMA, and several other observatories. The $2^\circ \times 2^\circ$ region was selected to include the future site of LLAMA nearby in Argentina.

While the level-2 data are gridded at a resolution of 1 km, the grid itself is at an arbitrary orientation dependent upon the scan direction of the satellite during that pass. We therefore regridded it onto a new grid with pixels that are $1^\circ / 110$ degree ($\approx 1.01$ km) in extent. We note that this operation forced some measurements into the same pixel bin, while others have no data. Hence, for each scan, we first averaged the available data for each pixel and then performed a simple bilinear interpolation to fill in the gaps of those empty ones. To avoid having misleading data on those days when recorded data was scarce, we decided to apply this interpolation only to those pixels with at least 4 out of the 8 surrounding pixels with original data.

Having nearly 20 years of MODIS data stored within a readily-accessible numpy array, we compare the MODIS PWV values for the bin containing the APEX site to the in-situ APEX radiometer measurements. For this, we separately analyze the Terra and Aqua satellite data. After determining the scaling between the PWV measurements and any temporal evolution versus the APEX data, we apply these corrections to the original MODIS data. Since the measurement values from MODIS should not suffer systematics that depend on position above the Earth, we can in principle apply our inferred corrections for the Aqua and Terra 1 km resolution data to that from any dry location across the globe, as long as the conditions are generally PWV < 6 mm. APEX does not generally operate when the PWV exceeds 6 mm.

Using only the data flagged as useful, reliable and without clouds (see the MODIS atmosphere QA plan for Collection 061, page 18 from https://modis-images.gsfc.nasa.gov/_docs/QA_Plan_C61_Master_2017_03_15.pdf), we find a tight scaling relation between MODIS NIR measurements and the ground-based APEX radiometer measurements. The MODIS data are shown compared to the APEX radiometer in the upper left panel of Figure 5, with data flagged as useful shown in blue. As can be seen in the figure, the slope is not 1:1; rather the space-based MODIS NIR measurements of PWV are systematically higher than the ground-based radiometer ones. While it is clear the majority of the data points we excluded fall on the same scaling relation as those included (e.g. the cluster of points at MODIS PWV < 3 mm and APEX PWV < 2.5 mm in the leftmost panel of Fig. 5), the data that were potentially affected by clouds or were otherwise ‘unreliable’ exhibit systematically higher scatter.

Since the ground-based measurements have been shown to be accurate to within an uncertainty of $< 3\%$, we derive and apply a simple slope-intercept scaling relation to correct this:

$$\text{PWV}_c(t) = \frac{\text{PWV}_m(t) - b(t)}{m(t)}$$

Here $\text{PWV}_c(t)$ is the corrected value for the PWV, $\text{PWV}_m(t)$ is the measured value, $b(t)$ is the (possibly time-dependent) value for the intercept, and $m(t)$ is the (possibly time-dependent) value for the slope.

We find a significant time dependence whenever comparing the uncorrected Aqua and Terra PWV data, regardless of location. We then compare both MODIS data sets to the fiducial APEX radiometer data. The right four panels of Fig. 5 report the fit, time-dependent values for $m(t)$ and $b(t)$ used for recalibration of the MODIS PWV data, assuming a linear form. The error bars represent the 95% confidence interval for each value. As the data reported only include up to the beginning of August 2020, and since APEX was largely shut from mid-March through late August, we exclude 2020 from our analysis. The data point for the first seven months of 2020, shown in blue, is only plotted for completeness.

In the case of Aqua, a significant time dependence versus the APEX radiometer data is seen in the values for the slope $m(t)$ (upper left panel of the right four in Fig. 5). This is supported by the higher value we find for the linear regression coefficient of determination $R^2$. This value quantifies the improvement in fit versus a time-independent model, and is closest to $R^2 = 1$ when the variance after fit model subtraction is much smaller than the variance after subtraction of the mean data value. We also note that the intercept (upper right panel of the right four, Fig. 5) has slightly decreased, implying that Aqua now reports systematically higher PWV values than it did in its first several years. To correct for this, we re-calibrate the Aqua data by applying Equation 1 with $m(t) = 0.0237 \cdot t - 46.1863$, $b(t) = -0.0169 \cdot t + 34.3632$, where $t$ is measured in years.

In the case of Terra, we do not see any significant variation versus time in the slope we inferred ($m(t)$, lower left panel of the right four in Fig. 5). The apparent evolution in the $b(t)$ values is likely due to the relative sparsity of Terra measurements between 2014 and 2018 (note the larger error bars; the number of measurements drops to below 80 per year for the APEX site, compared to more than 250 for Aqua in each of these years). We exclude data from 2018 in particular as only 7 valid values of PWV were available for the bin including APEX. After finding no significant time evolution in the Terra data (vs that from APEX), we exclude any time dependence and fit the entire data set (see Figure 6).

After applying these re-calibration corrections, we find the values for PWV versus time for the three instruments are in good agreement (see Figure 7), apparently justifying our approach to re-calibration. We note that the lowest values reported by the APEX radiometer and shown in Fig. 7 are likely nighttime measurements. The resulting re-calibrated data are then used for the maps and time series analyses presented in the following sections.
4. Results
4.1. Yearly and seasonal Averages

After re-calibration, we map the yearly median and mean values, averaged over all years, in Fig. 8, while in Appendix A, we show in Figures A.1 & A.2 the seasonal median and mean values, respectively, for the entire region. For consistency with other studies (e.g. Paine 2017), we define the four seasons as the three integral months beginning with the one in which the season commences (i.e. ‘Austral summer’ is treated as December-January-February, ‘autumn’ is March-April-May, ‘winter’ is June-July-August, and ‘spring’ is September-October-November). The median values in each map are consistently lower due to the skewed nature of the PWV distribution. As is clear in the upper left panel of Fig. 5, the distribution in measured PWV values is non-Gaussian and exhibits a long tail of high PWV values. Such val-

Fig. 5. Upper left: Scatter in the values of PWV as measured by MODIS versus those from the APEX site radiometer. MODIS data flagged by NASA as both ‘reliable’ and ‘no clouds’ are reported in blue, while the rest of the data are shown in red, and are excluded from the fitted relations to the right. A unity slope line with zero intercept is shown in black as a visual guide. Right four panels: The fit slopes and intercepts used for re-calibration of the MODIS PWV data. The error bars denote the 95% confidence interval for each value and the red lines denote the best fit and ± 2 – σ deviations from this. As the data reported include up to the beginning of August 2020, we exclude 2020 from the analysis but show the data point in faint blue for completeness. The upper panels show the case of Aqua, for which a significant time dependence in the slope is clear and confirmed by the higher value for the linear regression coefficient of determination $R^2$. The lower panels show the case of Terra, for which we do not see any significant time variation.

Fig. 6. Regression analysis between the Terra and APEX measurements of PWV. Here we only use values for the driest conditions, PWV < 3 mm. We find that the slope $m = 1.48$ and intercept $b = 0.61$ can be treated as a constant versus time.

Fig. 7. Using the re-calibration relation we inferred, the mean PWV vs time of Terra (blue) and Aqua (orange) are shown in comparison to the APEX radiometer data (green).
Austral winter (i.e. July–September), while it is worst (highest) during the Austral summer, which coincides with the altiplanic winter (particularly January–March). We also confirm that the highest peaks in the region tend to show the lowest PWV. This can be seen more clearly in Figure 9, where we identify the locations having the best (driest) 5% of PWV for each decile (percentiles of the distribution in steps of 10%) of PWV conditions. To compute the values in this map, we calculate for each location the 10 deciles (10, 20, ...90, 100 percentiles) from the full distribution of daily values. Then, for each decile, we rank the corresponding decile value among all the locations in the whole region. The driest 5% locations get a value of 1 in the map. We do that for each decile, and keep adding. Locations with a map value equal to 10 belong to the driest 5% in all the deciles and hence, are best in all conditions.

4.2. Seasonality and temporal trends near APEX

We report here on the variations over the last two decades, focusing on the APEX site and then generalizing to other locations. The results for APEX are displayed in Figures 10, 11 and 12. Our results agree in general with those found by Cortés et al. (2020). Here we define a quantile as the lowest value in that quarter of the data (e.g. the second quartile corresponds to the median). Figure 10 shows the seasonal variability at APEX, and it confirms that January and February are generally the worst months to observe while July and August are the best.

In Figure 11, we show our trend analysis in the monthly deseasonalised PWV mean and yearly mean (upper panel) of the APEX radiometer data (2007-2019), where we have used the statsmodel package in Python (Seabold & Perktold 2010). In order to deseasonalize the monthly time series data, we subtract the average seasonal cycle from each year of data, e.g. we subtract the average January value from each individual January value, he average February value from each individual Febru-

![Image](image_url)
As noted in e.g. Böhm et al. (2020) and Cortés et al. (2020), the variability in PWV over time may depend on phenomena such as El Niño. Periods of higher Oceanic Niño Index (ONI), which is one way to trace the strength of El Niño, are known to correlate with more rain at both lower and higher latitudes along the western coast of South America (Glantz & Ramirez 2020). We do not see a clear correlation between the ONI and the deseasonalized PWV or the 1-year boxcar smoothed time series. The cause of interannual variability likely depends on the season, as confirmed in the middle panel of Figure 12, which hints at differing levels of variability over time for each season. During austral summer, variability depends on factors such as the altiplanic winter, the period around February when wet air from the Amazon region traverses the Andes and precipitates predominantly in Northern Chile (Gan et al. 2005; Canedo-Rosso et al. 2019, e.g.). Moreover, variability in the Andes precipitation also depend on variability in the Antarctic Ozone and in the Southern Annular Mode, which is strengthening with climate change (Feron et al. 2020). In a future study, we will more fully explore the relation between PWV in the Atacama Desert and the South American Monsoon (SAM), El Niño–Southern Oscillation (ENSO), and variations in the ozone layer.

As the temperature increases with climate change and heat waves become more and more frequent (Feron et al. 2019), the total amount of water vapor in the atmosphere is predicted to increase. The severity of rains will also increase (Asadieh & Krakauer 2015), but the change in the patterns of water vapor and rain fall will vary with location. According to the 2013 Report of the Intergovernmental Panel on Climate Change (see Annex I Stocker 2014), the median annual precipitation is predicted to decrease everywhere in the Atacama desert in the 39 multimodel trend. When looking seasonally, most models agree that the austral summer will become drier over time (i.e. the altiplanic winter will be less intense) but the winter season, which is best for observations, could become wetter in the northern Atacama. These seasonal predictions are corroborated by Cabré.
et al. (2016), who use the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5) specifically to look at precipitation and temperature trends in South America, and also by private communication with the authors of Feron et al. (2020).

4.3. Comparison to other sites

One of the primary motivations of this study is to determine which are the best sites for future submillimeter observatories such as AtLAST (Klaassen et al. 2019, 2020). Figure 14 shows the average seasonal cycle for several existing and planned facilities that are sited in locations featuring low PWV, including the entire AAP region and ALMA concession. Overall, it appears that Cerros Toco and Honar enjoy similarly low PWV values as those available at Cerro Chajnantor.

Given the trend seen for the APEX site in Figures 12 and 11, we are interested in whether and how the conditions for the region have shifted over the last 20 years. The change in the mean PWV, in units of mm year$^{-1}$, is shown in Figure 13. Generally speaking, there has been a slight increase in the PWV recorded values for the entire region, following the same overall trend as that of APEX location. The trend for the median values is similar, and is therefore not shown here. We note that this represents a maximum increase in the mean PWV of about +0.5 mm over the past 20 years, but the trend, which is common across all

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Table 1. Fit slopes and $R^2$ values for the fit relations shown in Figures 11 and 12.

| Conditions | Data set | Change [mm/year] | $R^2$ |
|------------|----------|------------------|-------|
| Deseasonalized | APEX | 0.04 ± 0.03 | 0.049 |
| Yearly | APEX | 0.03 ± 0.03 | 0.271 |
| Summer | APEX | 0.01 ± 0.10 | 0.01 |
| Autumn | APEX | 0.03 ± 0.05 | 0.09 |
| Winter | APEX | 0.02 ± 0.02 | 0.21 |
| Spring | APEX | 0.04 ± 0.05 | 0.21 |
| Deseas. | MODIS | 0.02 ± 0.01 | 0.044 |
| Yearly | MODIS | 0.02 ± 0.01 | 0.523 |
| Summer | MODIS | 0.01 ± 0.03 | 0.01 |
| Autumn | MODIS | 0.01 ± 0.02 | 0.05 |
| Winter | MODIS | 0.01 ± 0.01 | 0.08 |
| Spring | MODIS | 0.02 ± 0.01 | 0.44 |
| 1st Quartile | MODIS | 0.02 ± 0.01 | 0.074 |
| 2nd Quartile | MODIS | 0.02 ± 0.01 | 0.055 |
| 3rd Quartile | MODIS | 0.01 ± 0.01 | 0.013 |

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Fig. 12. Upper: Trend analysis in the deseasonalized monthly time series (blue dots) and the yearly mean time series (red crosses) in PWV using the re-calibrated MODIS data for the 1 km x 1 km cell containing the APEX site. Middle: Seasonal trend analysis in seasons at the same location using the re-calibrated MODIS data. As in Fig. 11, the curves going rom highest to lowest average PWV are summer (red), autumn (black), spring (blue), and winter (green). Lower: Trend analysis for the first, second, and third quartiles (i.e. the lowest value of the best quarter, median, and best value in worst quarter of the overall distribution). The values of the fit slopes and the $R^2$ values for the fits are reported in Table 1.

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Fig. 13. 20-year long term in the mean, in units of mm year$^{-1}$, calculated from the deseasonalized time series. The borders, AAP+ALMA boundary, markers, and elevation contours are the same as in Figure 1.
220 × 220 pixels, is statistically more significant than that for the APEX site alone. We also note that, had we excluded the time variability for the MODIS Aqua data, the trend inferred without re-calibration would have been systematically stronger.

The observed increase in PWV over time may be attributed to either inter-decadal variability or climate change, and a longer baseline of time will be required before we understand the nature of the time dependence. If this trend continues unmitigated and can be attributed to climate change globally, this could negatively impact ground-based submillimeter-wave astronomy. The significance and root cause of any trend for our region of study, in particular for ground-based astronomy, will be explored in a future work.

Our findings that the mean and median precipitable water vapor has increased over the past two decades (Figures 11 and 12) appear to be in contrast to those of Cantalloube et al. (2020), who report that the number of days with low water vapor has increased in recent years for the region surrounding Paranal. As noted in Cantalloube et al. (2020), however, their study is generally limited to ≥31 km resolution, and their radiometer-based measurements only cover the last 5 years, which is too short to draw strong statistical conclusions. Most importantly, the trends in precipitation might in fact be opposite with the region surrounding Paranal becoming drier over time, especially during the winter season, while the northern Atacama becomes wetter. Ultimately, our findings, while indicating the trend is significant at ≈ 95% confidence (i.e. ≈ 2 – σ), also require more robust confirmation.

5. Discussion and Conclusions

In this work, we report on relatively high (1/110°, ≈ 1 km) resolution satellite studies of the precipitable water vapor above the Atacama Astronomy Park and surrounding regions for a period spanning nearly two decades. In comparison, previous studies such as Cantalloube et al. (2020) relied on much lower resolution data, such as ERA5, which yields 0.25° resolution for atmospheric data, or on ground-based measurements made from specific sites stationed in the field (Otárola et al. 2019). As noted above, the work presented relies on data taken in the near infrared that can only probe the daytime PWV values.

From the maps in Figures 8 and Appendix A, one can identify several promising locations in terms of having exceptionally low PWV. We note this is a single parameter, of course, and does not account for active or dormant volcanoes or the accessibility of the site (e.g. existing roads, power, data transport). Comparison with the wind data in Fig. 3 and Appendix B additionally shows that the AAP region and ALMA concession enjoy on average less severe wind conditions that many of the similarly high elevation regions in the immediate surroundings. We note that while the LLAMA site has lower yearly average and maximum windspeeds, the monthly average and maximum windspeeds in the drier months (winter) are higher than those within the AAP (see Figures B.1 and B.2).

A full in-situ characterization will be required before a site for AILAST (or any other future facility) can be selected. However, our results confirm that out of the prospective submillimeter astronomical sites considered, those exhibiting the driest conditions are generally located at the some of highest accessible altitudes. These include Cerro Chajnantor (CCAT site, 5640 m a.s.l.), Cerro Toco (5604 m a.s.l.), Cerros de Honar (a broad series of peaks ~5400 m a.s.l.), and the LLAMA site (4800 m a.s.l.), and are shown in Figure 14. We also note that several exceptionally dry regions at elevations < 5500 m a.s.l. and not currently used for astronomy can be identified in Figure 9.

Finally, we hypothesize that our re-calibration approach should be extensible to any site worldwide that low values of PWV (≤ 5 mm) on average. This condition typically describes any site of interest to the ground-based millimeter, submillimeter, and optical astronomical communities. In addition to potentially saving substantial time, effort, and costs in the field by allowing one to pre-select prospective locations for further in-situ characterization, our approach may allow for further studies of the variability to establish seasonal variations and trends associated with climate change, particularly in areas where water and precipitation are scarce. Future studies will address climate and interannual variability, will expand to other locations, and will include yet higher spatial resolution through interferometric satellite measurements (e.g. Mateus et al. 2017).

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Appendix A: Seasonal, monthly, and year variability in the precipitable water vapor

In Figures A.3 and A.4 we show the monthly maps of the median and mean PWV.

Appendix B: Monthly variability in the average wind speed and direction

In Figures B.1 and B.2 we show the maps of the monthly mean and monthly average maximum wind speed and direction.
Fig. A.1. Seasonal median PWV values. The panels show summer, autumn, winter, and spring, where we have defined the seasons for consistency with Paine (2017) as the three integral months beginning with the one in which the season commences (e.g. ‘Austral summer’ is treated as December-January-February, ‘autumn’ is March-April-May, ‘winter’ is June-July-August, and ‘spring’ is September-October-November). The borders, AAP+ALMA boundary, site markers, and elevation contours are the same as in Figure 8.
Fig. A.2. Same as Figure A.1, but this time showing the mean PWV values for the seasons.
Fig. A.3. Median monthly daytime PWV values across all years. The borders, AAP+ALMA boundary, site location markers, and elevation contours are the same as in Figure 8.
Fig. A.4. Mean monthly daytime PWV values across all years. The borders, AAP+ALMA boundary, site location markers, and elevation contours are the same as in Figure 8.
Fig. A.5. Median yearly daytime PWV values across years 2000-2011. The borders, AAP+ALMA boundary, site location markers, and elevation contours are the same as in Figure 8.
Fig. A.6. Median yearly daytime PWV values across years 2012-2020. The borders, AAP+ALMA boundary, site location markers, and elevation contours are the same as in Figure 8.
Fig. B.1. Average monthly wind speed and direction inferred from ERA5 data at 9 km resolution. The upper left is the average wind speed in January from 1981-2019, and the plots proceed through the months from there. The borders, AAP+ALMA boundary, site location markers, and elevation contours are the same as in Figure 1.
Fig. B.2. Maximum values for the monthly wind speed and direction inferred from ERA5 data at 9 km resolution. The upper left is the average wind speed in January from 1981–2019, and the plots proceed through the months from there. The borders, AAP+ALMA boundary, site location markers, and elevation contours are the same as in Figure 1.