Local monitoring of atmospheric transparency from the NASA MERRA-2 global assimilation system

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ABSTRACT

Ground-based astronomy has to correct astronomical observations from the impact of the atmospheric transparency and its variability. The current objective of several observatories is to achieve a sub-percent level monitoring of atmospheric transmission. A promising approach has been to combine internal calibration of the observations with various external meteorological probes, upon availability and depending on quality. In this paper we investigate the use of the NASA Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) which is a global climate monitoring project that renders freely available for any given site, at any time, all the parameters constraining atmospheric transmission. This paper demonstrates the extraction of the relevant atmospheric parameters for optical astronomy at two sites: Mauna Kea in Hawaii and Cerro Tololo International Observatory in Chile. The temporal variability for the past eight years (annual, overnight and hourly), as well as the spatial gradients of ozone, precipitable water vapor, and aerosol optical depth is presented and their respective impacts on the atmospheric transparency is analyzed.

Introduction

The variability of atmospheric transparency above telescopes introduces a systematic uncertainty in their photometry. The traditional method to account for it is to normalize the observations against multi-epoch exposures of a set of stable stars (Regnault et al. 2009). The quality of the correction is a function of the type and number of reference stars within a given field of view, as well as the number of reference frames. The limits of this empirical method are twofold: the information is limited by the coarse resolution of the passbands, and by the evolution of the telescope throughput. The most successful methods (Burke et al. 2018) mitigate these factors by adding external priors on several atmospheric parameters and demonstrate a stable broadband calibration at the level 5-6 permil.

Global assimilation systems developed by earth science experiments now routinely record the level of atmospheric constituents that translate into sub-percent variability of the atmospheric throughput. The avalanche of data has been organized in a comprehensive manner by the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2)¹. This is the assimilation of satellites data from space agencies (NASA, ESA, Taiwan) as well as other external probes, such as AERONET, aircrafts and cruise ships onboard instrumentation (Gelaro et al. 2017). Since the project is central for climate research, it has been under strong scrutiny and benefits from extensive analysis of consistency of the observations and the performance of assimilation methods (Randles et al. 2017 and references therein).

This paper demonstrates the assimilation of NASA MERRA-2 data for two astronomical sites: Mauna Kea in Hawaii, and Cerro Tololo International Observatory (CTIO) in Chile. Section 1 presents the results of the local vertical integration of longitudinally and latitudinally interpolated precipitable water vapor (PWV), aerosol optical depth (AOD) and ozone column depth. Along with barometric pressure, the set of parameters allows to fully constrain radiative transfer simulations which deliver atmospheric transparency curves as a function of time and pointing: In section 2, the LibRadTran simulator (Mayer & Kylling 2005, Obregón et al. 2015, Smette et al. 2015) is used to translate the variabilities of the atmospheric parameters into the variability of the atmospheric optical transmission.

1. MERRA-2 atmospheric parameters extraction

Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) is a climate monitoring project undertaken by NASA’s Global Modeling and Assimilation Office (GMAO). It follows two primary objectives: (i) Place observations from NASA’s Earth Observing System (EOS) satellites into a climate context, (ii) Update MERRA system to include the most recent satellite data (McCarty 2016). It is produced using the GEOS-5 atmospheric model and data assimilation system (Molod et al. 2015), a global mesoscale numerical simulations at 10 km resolution through 1.5 km resolution, and the three-dimensional variational data analysis (3DVAR) and Gridpoint Statistical Interpolation (GSI) meteorological analysis scheme (Wu et al. 2002). The earth’s

¹ https://disc.sci.gsfc.nasa.gov/datasets?page=1&keywords=MERRA-2
atmosphere is resolved on a cubed-sphere grid with 0.5° latitude times 0.625° longitude and 72 layers from the surface to 0.01 hPa, on which an incremental analysis update procedure is performed every 6 h.

1.1. Ozone

The total ozone column observations are extracted from the Ozone Monitoring Instrument (OMI), onboard NASA’s EOS Aura satellite (Wargan et al. 2015), while the stratospheric profiles are extracted from the Microwave Limb Sounder instrument. The meteorological analysis in GEOS-5 is performed daily at four synoptic time, using 6 h model forecasts and observations within a ±3 h window of the analysis time. McPeters et al. (2008) discuss validation of the OMI daily total ozone against ground station measurements: On large space (continental) and time (months) scales, an offset of +0.4% is found with OMI total ozone (OMI being higher), while aircraft measurements indicated -0.2% offset with an RMS difference of 3%. Assuming average OMI total ozone of 300 Dobson Unit (1 DU = 0.01 mm of trace gas when the total column is compressed down to sea level at standard temperature and pressure), these numbers indicate a small offset of ≈1 DU and RMS difference of 9 DU, varying between 2 and 12, depending on the latitudes. For instance, 12 years of sonde-minus-analysis differences at Hohenpeissenberg show a mean residual of 1.43 DU and standard deviations of 8.1 DU (Ziemke et al. 2014).

Most of the ozone content lies in the upper tropopause, between 20-30 km (profiles are shown in appendix A.5). This is well above the ground, so the variability is driven rather by jet stream winds than by local meteorological events. The integrated value at a given time and location can be obtained from latitude, longitude and time interpolation of the MERRA-2 Single-Level Diagnostics table M2INXASM (Bosilovich 2016). Figure 1 presents the recorded values between 2011 and 2018 at the Mauna Kea (Hawaii) and CTIO (Chile) sites. The median value for the CTIO and Mauna Kea sites are respectively 268 and 270 DU with variability 46 and 45 DU (10 to 90 percentile). The modulation peaks in March-April at Hawaii and October-November in Chile. During spring seasons of both hemispheres, the hourly variability (central panels) can be as high as 5 DU. The bottom panels report on the West-East (in red) and South-North (in blue) gradients on a 10 km scale: Above Mauna Kea, over the period, the mean South-North gradient is 0.4±0.3 DU/10km and 0.05±0.14 DU/10km along West-East direction. The figures are -0.1±0.3 DU/10km (South-North) and -0.6±0.2 DU/10km (East-West) above CTIO. The combination of z-profile (figure A.5) and gradients (figure 1 bottom panels) allows to turn the apriori axis-symmetric hypothesis that is often made in astronomy into numbers: Observations which lines of sights are 45° apart will result in 1 DU (S-N, Mauna Kea) and 3 DU (E-W, CTIO) variations. It translates into a 0.4% and 1.2% modulation of the atmospheric absorption at 600 nm.

1.2. Precipitable Water Vapor

MERRA-2 monitoring of Precipitable Water Vapor (PWV) is obtained from assimilating a large amount of in situ and remote sensing observations into an atmospheric general circulation model (Reichle et al. 2017a). An evaluation of the performance of the reanalysis is presented in Reichle et al. 2017b which reports an averaged precipitation offset against external probes of -0.15 ±0.9
mm/day over global land, during the years 1980–2015. PWV above a given telescope site can be obtained from the Assimilated Meteorological Fields M2I3NVASM (Bosilovich 2016) by vertically integrating the longitudinally and latitudinally interpolated specific humidity (weight of water vapor in the air per unit weight of air, in \( \text{kg/} \text{kg} \)). The PWV is the largest at the ground level. This is illustrated by figure 2 which shows the specific humidity vertical profiles above the CTIO and Mauna Kea telescope sites during the month of January 2017: The amount of water and its variability is larger at the altitude of the CTIO (2.3 km, left panel) than at the Mauna Kea summit (4.2 km, right panel). It become negligible above 10 km.

The integrated specific humidity (in \( \text{kg/m}^2 \) or \( \text{mm} \)) from top of the atmosphere down to the telescope altitude level, as a function of time, is shown for both sites on the top two panels of figure 3. The ctio site PWV median value for the period 2011-2018 is 3.60 mm with variability 6.54 mm (10 to 90 percentile). The Mauna Kea site median value is 2.26 mm with variability 5.33 mm (10 to 90 percentile). An annual modulation is also visible, but less pronounced than for the ozone: episodic large excursions events are spread throughout the year at both site. The hourly variability (middle panels) is ±0.15 mm above Mauna Kea and ±0.23 mm above CTIO (figure A.2, central panels). The erratic variation of PWV timeseries indicate that smooth overnight variation assumptions are not usually valid. The mean South-North gradient above the Mauna Kea over the period is -0.01±0.08 mm/10km, and a West-East gradient at -0.006±0.06 mm/10km. The mean spatial asymmetries above CTIO are -0.01±0.10 mm/10km (S-N), and 0.05±0.12 mm/10km (W-E). A noticeable seasonal modulation of the West-East gradient above the CTIO is found (figure 3, left bottom panel).
1.3. Aerosols

The MERRA-2 aerosol optical depth (AOD) is determined from observations by MODIS (Terra and Aqua satellites), NOAA Polar Operational Environmental Satellites (POES), NASA Earth Observing System (EOS) platforms, NASA ground-based observations, and AERONET. Aerosols are assimilated concurrently to the meteorological parameters using a radiatively coupled version of the GOddard Chemistry, Aerosol, Radiation, and Transport model (GOCART) which treats the sources, sinks, and chemistry of 15 externally mixed aerosol mass mixing ratio tracers:

- Dust (5 non-interacting size bins with dry effective radii 0.64, 1.34, 2.32, 4.20 and 7.75 μm),
- Sea salt (5 non-interacting size bins with dry effective radii 0.08, 0.27, 1.05, 2.50 and 7.48 μm),
- Hydrophobic and hydophobic black carbon (2 tracers, effective radius 0.04 μm),
- Hydrophobic and hydophobic organic carbon (2 tracers, effective radius 0.09 μm),
- Sulfate (SO₄, effective radius 0.16 μm).

The model includes loss processes, including dry deposition, wet removal, convective scavenging and sedimentation (Buchard et al. 2017). The dust and sea-salt particle size distribution is resolved across five non-interacting size bins each, with surface wind speed dependent emissions. The other components are prescribed from emissions inventories as well as chemical reactions. Sulfate (SO₄) and carbonaceous aerosol species have emissions principally from fossil fuel combustion, biomass burning, and biofuel consumption, with additional biogenic sources of particulate organic matter. The aerosols assimilation into GEOS-5 native 72 coordinate levels is performed at 8 synoptic times a day (0, 3, 6, 9, 12, 15, 18, and 21). The outputs are 15 three-dimensional fields of aerosol mass mixing ratio that can be integrated to deliver the Aerosol Optical Depth at 550 nm, following:

$$AOD_{550\text{nm}} = \sum_{z} \left( \sum_{i} (AMR(z) \times \beta_{550\text{nm}}(z) \times AP(z)/g) \right)$$

Where $AMR(z)$ is the Aerosol Mixing Ratio (kg kg⁻¹) of the 15 species, as a function of altitude $z$, tabulated in MERRA-2 tables. $\beta_{550\text{nm}}$ is the optical extinction coefficient derived from Mie theory and which depends both on the species and the relative humidity (see Supplementary Tables and Figures, Randles et al. 2017). The relative humidity profile differs from the specific humidity profiles that are shown figure 2: This is a function of the equilibrium vapor pressure, which evolves with temperature. As such, relative humidity is larger in the tropopause, where temperature reach a local minimum, than on the ground (profiles above both telescope’s sites are shown in appendix A.4). As a result, the optical depth of species with a large $\beta_{550\text{nm}}$ coefficient is driven by high altitude contents. The independent validation of the MERRA-2 aerosol products is rendered difficult because most of the global, readily available, space-borne and ground-based observations, are already included in the assimilation. However several tests are being reported in Randles et al. (2016) from which it is concluded that the bias between analyzed and observed AOD is generally within the ±0.02 instrumental uncertainty.

The MERRA-2 monitoring of the total AOD and its decomposition into species is presented figure 4. The AOD median value at CTIO for the period 2011-2018 is 0.023 with variability 0.038 (10 to 90 percentile) and about 20% smaller at Mauna Kea, with gradients over Mauna Kea are negligible, at 7.0e-05 variability, a noticeable steady West-East gradient at 0.002 that is more pronounced above Mauna Kea, thus indicating the predominance of higher altitude components. Regarding spatial variability, a noticeable steady West-East gradient at 0.002±0.002/10km is visible above CTIO, also following an annual modulation. The gradients over Mauna Kea are negligible, at 7.0e-05±0.0003/10km (South-North) and -2e-05±0.0002/10km (West-East).

2. Atmospheric transparency variability above CTIO and Mauna Kea sites

The MERRA-2 atmospheric parameters can be translated into atmospheric transparency curves using radiative transfer simulation. The ability of radiative transfer simulation to produce atmospheric transmission as a function of wavelength has been extensively tested (Mayer & Kylling 2005, Obregón et al. 2015, Smette et al. 2015). In this work, the calculations of the atmospheric transmission is performed using the Libradtran software package.

The nominal transmission above both sites for the period 2011-2017 is shown figure 5. The variability of the transparency (blue area) corresponds to the 10 to 80 percentiles of the recorded $O_3$, PWV, and AOD parameters. It is observed that the overall transmission are of the same magnitude at both sites, but that the variability is about twice larger at CTIO (left panel). Part of the variability is induced by seasonal modulation (mainly from ozone and some aerosol species). An interesting information for astronomy is the analysis of the typical overnight variability: Figure 6 indicates the relative overnight modulation above both sites.
as a function of wavelength and depending on the parameter (darker blue for PWV, darker green for O$_3$, darker red for AOD). At Mauna Kea, the typical overnight modulations ($\Delta_{\text{overnight}}$ 80 percentile) are 1.13 mm for PWV, 5.9 DU for O$_3$ and 0.004 for AOD. The figures for CTIO are 1.84 mm for PWV, 7.9 DU for O$_3$ and 0.012 for AOD. These numbers are to be put in the perspective of the nominal relative modulations over the entire period (light colors), as well as the propagation of the estimated MERRA-2 uncertainties (dashed green corresponds to 8 DU for O$_3$, dashed blue corresponds to 1 mm for PWV and dashed red corresponds to 0.02 for AOD).

Each parameter has a specific signature on atmospheric transmission. The ozone column depth impacts atmospheric transparency curve in two distinct regions: the Huggins band, below 350 nm, and the Chappuis band, between 500 nm and 700 nm. The PWV imprints several features on the redder end of the optical spectrum, and the AOD modulates a continuous attenuation. The ozone modulation has a subpercent impact on both the nominal and overnight atmospheric transmission variability, the PWV absorption features vary in the 1 to 10% range on a nightly basis, while the AOD attenuation changes by ~1% overnight. In all cases, the MERRA-2 dataset is found to be reliable at reporting annual variations. Its level of precision reaches the range of the typical overnight modulation for the ozone and the PWV signals, while it is in between the nominal and overnight AOD attenuation variability, at ~2%.

3. Discussion

Ubiquitous monitoring of atmospheric parameters from earth science observatories has now been made freely available to everyone. This work is a first step in assessing how this could benefit ground based astronomy in its need to correct observations of astrophysical scenes from the atmospheric transmission. The MERRA-2 data product offers the possibility to extract an atmospheric transmission curve for any optical observation, anytime, anywhere. This paper describes the interpolation above two world class astronomical sites, the Mauna Kea summit in Hawaii, and the CTIO site in Chilean Andes, of the atmospheric parameters recorded between 2011 and 2018 by MERRA-2. A first result of the continuous (hourly), long term, time-series is to provide a picture of both seasonal and circadian modulations of atmospheric transparency above the observatories. Using and propagating the estimations from the literature of MERRA-2 uncertainties sets the precision of the calibration in the 2-4%, range, depending on the wavelength. The error budget is different for the various atmospheric constituents: The impact of ozone on the optical atmospheric transmission is probably well captured to a few permil level, while the impact of aerosols is probably well estimated at the 2% level.

The relevance of using MERRA-2 at a given astronomical site is both a function of its location and the scientific use of the observations: Because the nominal atmospheric variability of a site strongly correlates with the altitude, the lower the observatory, the most significant the MERRA-2 monitoring. With respect to the most stable sites (few % level modulations) and the most stringent monitoring requirements (sub-percent calibration), MERRA-2 is still able to provide robust priors on the nominal value and seasonal variation of the atmospheric parameters.

A second interesting outcome of MERRA-2 data applied to ground based astronomy is that the combination of z-profiles and latitudinal and longitudinal gradients delivers quantitative counterparts to the two common assumptions of axis symmetry and...
smooth variation of the atmospheric transmission. The variability is smoother for high altitude parameters (such as ozone and some aerosols) than components that are larger nearer to the ground layer (such as PWV and other aerosols) and that are influenced by meteorological events at all scales.

The next step to assess and optimize the integration of MERRA-2 into ground based astronomy atmospheric correction scheme is to compare current calibration procedures with MERRA-2 data product. Punctual experiments at CTIO have reported local observations that are consistent with the MERRA-2 interpolation: Li et al. (2014) measured a 1 mm PWV overnight variability, in agreement with the value reported in the present work. With respect to aerosols, Coughlin et al. (2018) are reporting an \( \sim 0.025 \) AOD, also in agreement with the value recorded by MERRA-2 for this night. However, these comparisons are at the sensibility limit and more extensive comparison could be obtained by direct comparison with the many past and ongoing surveys at these two sites. The reliability of local interpolation of 3-D variables from global data in the context of abrupt orography could also be further assessed by combining local probes with a mesoscale weather forecast algorithm to control the assimilated profiles. Such forecast

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Fig. 5. Nominal transmission above CTIO site (left) and Mauna Kea (right) for the period 2011-2017. The variability of the transparency, corresponding to the 10-80 percentiles of the recorded \( \text{O}_3 \), PWV, and AOD parameters, is indicated by the blue area.

Fig. 6. Atmospheric attenuation variability above CTIO (left) and Mauna Kea (right) as a function of PWV (blue), \( \text{O}_3 \) (green) and AOD (red) parameters. Plain colors indicate the nominal modulation for the period 2011-2017 while light colors inform on the typical overnight variabilities \(|\Delta_{\text{overnight}}| 80\text{ percentile})

The propagation of the estimated MERRA-2 uncertainties are indicated by the dashed lines.
algorithms have already been used successfully by Pérez-Jordán et al. (2018) at La Palma Roque de los Muchachos Observatory to predict PWV content at millimeter level precision and sub-millimeter accuracy.

In the future, the Large Synoptic Survey Telescope (LSST), a next generation optical survey that will be targeting a permil level photometric calibration\(^4\) and that will be located on the CTIO site, could benefit from MERRA-2: The project will supplement the main broadband survey telescope with a second telescope equipped with a slitless spectrograph. The instrument, that will be dedicated to real time monitoring of the atmospheric transmission along the survey line of sight, could combine its observations with priors on the seasonal modulation of the atmosphere from MERRA-2.

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Appendices

Appendix A: MERRA-2 parameters distributions and profiles

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4 The requirement is driven by the objective to improve the precision of the current measurement of dark energy by a factor of 5, to reach a percent level (LSST Dark Energy Science Collaboration 2012).
**Fig. A.2.** Precipitable water vapor distribution (left), hourly variation distribution (center) and maximum overnight variation distribution (right) above Mauna Kea (upper panels) and CTIO (lower panels).

**Fig. A.3.** Aerosol optical depth distribution (left), hourly variation distribution (center) and maximum overnight variation distribution (right) above Mauna Kea (upper panels) and CTIO (lower panels).
Fig. A.4. Top panels: Tri-hourly relative humidity profiles above CTIO (left) and Mauna Kea sites (right) during January 2017. Relative humidity is the ratio of the partial pressure of water vapor to the equilibrium vapor pressure, which changes with temperature (bottom panels): as a result, a given water vapor amount results in higher relative humidity in cool air than warm air.

Fig. A.5. Hourly ozone profiles above CTIO (left) and Mauna Kea sites (right) during January 2017.
Fig. A.6. Top panels: Aerosol total angstrom exponent between 2011 and 2018 at CTIO (left) and Mauna Kea (right) latitude-longitude coordinates obtained from MERRA-2 2-D tables. The angstrom exponent median value at the CTIO is 1.38 with variability 0.31 (10 to 90 percentile). The overnight modulation is 0.11 (|Δ_{overnight}| 80 percentile). The mean South-North gradient over the period is -0.004 ± 0.01/10km, and a West-East gradient at 0.02 ± 0.01/10km (bottom left panel). The angstrom exponent median value at the Mauna Kea summit is 0.78 with variability 0.59 (10 to 90 percentile). The overnight modulation is 0.24 (|Δ_{overnight}| 80 percentile). The mean South-North gradient over the period is -0.02 ± 0.02/10km, and a West-East gradient at -0.002 ± 0.016/10km (bottom right panel). The interpolation above both sites is probably unreliable given the context of abrupt orography that surrounds both the Mauna Kea volcano and the Andes pacific coast.