Comparing integrated water vapor sun photometer observations over the Arctic with ERA5 and MERRA-2 reanalyses.

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Key Points:

- Arctic IWV from reanalysis is moister than data from sun photometers. Daily means correlate more accurate but less precise than hourly
- IWV differences between reanalyses and sun photometers are independent of sun photometer IWV vapor magnitudes and solar zenith angles
- Sun photometer IWV observations may be used as a secondary standard for validating IWV from reanalyses in the Arctic

Abstract

Atmospheric water vapor, a greenhouse gas, is increasing in the Arctic. It is a scientific challenge to understand the causes for this increase and determine adaptation and mitigation actions to confront its climatic effects. During the last decades, spatial and temporal coverage of water vapor satellite observations increased notably, and reanalysis water vapor estimates have steadily improved. However, the scarce spatial and temporal coverage in the Arctic of integrated water vapor (IWV) surface-based observations, limits the representativeness of satellite observations and reanalysis estimate validations. Recently we validated sun photometer IWV (IWVsp) observations with IWV from radiosondes in the Arctic with good results. Here we compare the hourly and daily means of IWVsp from thirteen Arctic AERONET stations and the IWV from ERA-5 and MERRA-2 reanalyses. The comparison is conducted at hourly and daily time scales for individual stations, for two Arctic regions and for the whole Arctic. The comparison showed a moist bias of IWV from reanalyses with respect to IWVsp. For the individual stations the daily mean IWV from reanalyses increases in accuracy and correlation but decreases in the precision with respect to the hourly values. The individual station wise pattern shows slightly better accuracy and precision for ERA5 than for MERRA-2, also evident at the selected sub-regional scale. The differences of IWV from ERA5 and MERRA-2 and IWVsp show no dependence on IWVsp nor the solar zenith angle. This study corroborates that IWVsp may be used for validations of satellite IWV observations and IWV reanalyses products.

Plain Language Summary

Water vapor is increasing in the Arctic. Being a greenhouse gas, it is necessary to understand the causes for that increase. It will allow adaptation and mitigation actions for its climate effects. Progress in integrated water vapor (IWV) satellite observations and reanalyses estimates still do not match uncertainty levels from surface-based Arctic observations. However, the amount and geographical and temporal distributions of Arctic surface IWV observations is limited, limiting validation of spatial and temporal representativeness of IWV from satellite and reanalysis. We recently validated sun photometer IWV with radiosonde IWV, showing good agreement between those instruments. Here we report validating IWV_{ERA5} and $IWV_{MERRA\text{-}2}$ reanalyses with sun photometer IWV. Hourly and daily mean IWV values from reanalyses were compared with sun photometer IWV for individual stations, two Arctic subregions, and the entire Arctic. The results showed that the IWV reanalyses overestimates sun photometer IWV, so called "moist bias". IWV_{ERA5} agrees better with sun photometer IWV than $IWV_{MERRA\text{-}2}$ at all spatial scales. The differences between sun photometer IWV and IWV from reanalyses do not depend on the IWV amount, neither they have a diurnal cycle. The sun photometer IWV observations can serve as a secondary standard to validate the IWV reanalysis.

1 Introduction

Water vapor is associated with several important hydrological cycle processes in the Arctic. It is the source for the formation of clouds and fog but also has notable effects in the energy budget resulting from condensation-evaporation and radiative transfer processes (Vihma et al., 2016). Also, it plays an important role in the amplification of climate warming, caused by the Arctic hydrological cycle intensification resulting in the surface temperature increase (Box et al., 2019). However, it is particularly difficult to assess Arctic water vapor magnitude, geographical distribution and seasonal patterns because of two reasons. The First, its high spatial and temporal variability, exemplified by the changes in atmospheric water vapor reaching 100% within a few hours under atmospheric river events (Crewell et al., 2021). Second, the lack of reliable water vapor observations due to the limited number of surface stations (Vihma et al., 2016). To cope with the last issue, some networks like AERONET (Aerosol RObotic NETwork; Holben et al., 1998) provide IWV than can be used as an independent source for validation. The lack of IWV observations spread widely throughout the Arctic means that current research on the Arctic's global hydrological budget heavily relies on atmospheric reanalyses data (e.g., Dufour et al. 2016; Vihma et al. 2016). Reanalysis consists of the assimilation of ground based and remote sensing observations in a consistent manner with model physics, resulting in long-term gridded datasets with physical interpolation into data-missing regions (Thorne and Vose 2010; Parker, 2016). The products from reanalysis must be compared with real observations to establish their uncertainty and applicability. In this sense, an appreciable number of comparisons of reanalysis IWV products with ground based and satellite observations have been already reported extensively for the earlier generations of reanalyses (Schröder et al., 2016; 2018; 2019), although few cover the Arctic region (ex. Negusini et al., 2021). Among those comparisons, the Global Energy and Water cycle Exchanges (GEWEX) Water Vapor Assessment reported a general disagreement in IWV trend estimates for the global ice-free ocean within 60° N/S, from eleven global IWV datasets, including six reanalyses, with MERRA-2 among them, and five IWV satellite products. The trends in IWV are in the range from -1.51 ± 0.17 kg m^{-2} decade^{-1} to 1.22 ± 0.16 kg m^{-2} decade^{-1}. Break points on global and regional scales are also present (Schröder et al., 2017).

Comparisons of the IWV from the last generation of reanalyses, in particular European Centre for Medium-Range Weather Forecasts (ECMWF) 5th Re-Analysis (ERA5) and the NASA Global Modeling and Assimilation Office (GMAO) Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) with IWV from ground-based instruments have been recently reported for several regions and worldwide (Schröder et al., 2016; 2018; 2019). However, those reports do not include comparisons of IWV from ERA5 and/or MERRA-2 with AERONET IWV product focusing on the Arctic.

We recently reported the comparison of IWV observations from radiosondes and IWV from AERONET sun photometers (IWVsp) at ten sites located across the Arctic (Antuña-Marrero et al., 2022). At those sites, it was identified the predominant dry bias of AERONET IWV observations with respect to radiosondes, already reported at midlatitudes and tropical sites. At eight out of ten stations, using onsite sounding systems with state of the art humidity sensors and retrieval algorithms, precision and accuracy obtained were below 8% and 2%, respectively (Antuña-Marrero et al., 2022). One of the main conclusions of the study was the capability of AERONET water vapor observations in the Arctic for research, considering the robust quantification of its dry bias established in the cited study. Based on the former conclusion, and the fact that AERONET uses standard instruments and a centralized-standard processing algorithm, we also concluded that the AERONET water vapor observations in the Arctic could be used as a secondary standard to re-calibrate or homogenize other integrated water vapor datasets in the Arctic (Antuña-Marrero et al., 2022). The present study, based on the two above-mentioned conclusions, and taking advantage of the geographical regular grid and high resolution of the ERA5 and MERRA-2 reanalyses, is aimed at comparing the water vapor from both reanalyses with the available AERONET water vapor observations.

We report the validation of IWV from ERA5 and MERRA-2 with the IWVsp product from 13 AERONET sites in the Arctic. In section 2, we describe IWVsp datasets from AERONET sun photometers and the reanalyses ERA5 and MERA-2, as well as the spatio-temporal coincidence criteria applied. We also show and discuss in that section the correction of the reanalyses IWV values by the differences in elevation between each AERONET site and the elevation of the 4 surrounding grid points for each reanalysis. The statistics used for the comparison are also described. Section 3 shows the results and discussion. Finally, the conclusions are provided in section 4.

2 Materials and Methods

2.1 Sun photometer IWV observations

The main dataset of this work consists of IWVsp observations from AERONET version 3 level 2.0 daytime products (Giles et al., 2019; AERONET, 2023), recorded by sun photometers located within the Arctic circle. A detailed explanation of the AERONET version 2 basic processing algorithm of the IWVsp observations is available in Pérez-Ramírez et al., (2014). Improvements introduced in version 3 include: temperature correction for all spectral channels in all AERONET instruments using the sensor head temperature; and the use of solar aureole radiance for cirrus cloud-screening (Giles et al., 2019).

The lack of sunlight during the polar night limits the availability of IWVsp AERONET data in winter. However, the scarcity of spatially and temporally distributed IWV observations in the Arctic makes the IWVsp AERONET dataset a unique source of information to complement and validate other available IWV datasets in the region. The uncertainty on this AERONET IWVsp product is typically less than 12% (Holben et al., 1998).

The AERONET IWVsp values have been hourly averaged in the interval of ± 30 minutes around each hour using all the available instantaneous observations in each interval. Then, daily IWVsp averages have been calculated averaging these hourly IWVsp data for each available day.

Table 1 lists the 20 AERONET stations that are available in the Arctic, providing information about its geographical location, number of available instantaneous observations, hourly and daily calculated IWVsp values and the observation period. The representativeness of the 20 datasets was evaluated considering its spatial and temporal coverage and the station mean quantity of hourly observations.
The first step was to exclude the stations with less than 2 years of data. The excluded stations were Matorova FMI, Abisko, Ny Ålesund, and North_Pole. Then we identified the stations located less than 0.25º apart both in latitude and longitude and with altitude differences lower than 100 m. Barrow and NEON BARR were found to satisfy these criteria and the shorter duration dataset NEON BARR was discarded. Finally, we decided to exclude the stations of NEON TOOL and Longyearbyen because they have less than 20% of the average number of hourly observations. The reason to exclude the stations with less than 2 years of data or less than 20% of the station average number of hourly observations (i.e., 1500 observations) was a reasonable size of the observation samples at each of the stations to warrant robust statistics. In

the case of the stations located less than 0.25° apart and a difference in altitude lower than 100 m, the goal was to eliminate duplicated observations at the same geographical location. The 7 discarded stations are highlighted on Table 1 by a grayish background.

A number and an ID have been assigned to the 13 selected stations on Table 1. The total number of available sun photometer IWV data is also shown in Table 1 for instantaneous observations (601,029), hourly mean values (98,185), and daily mean values (12,158) for the 13 selected stations. Figure 1 shows the geographical distribution, identified by the red stars, of the 13 selected stations in the Arctic. Blue stars and names identify Greenland and European Arctic (GEA) stations while Russia, Alaska, and Canadian Arctic (RACA) stations are identified by brown diamonds and names. The encircled red star represents the very close OPAL and PEARL stations in North Canada.

2.2 Hourly coincident IWV values from ERA5 and MERRA-2 Reanalyses

Regarding reanalysis data, we have used the IWV hourly data from ERA5 and MERRA-2 described by Hersbach et al. (2020) and Gelaro et al. (2017), respectively. IWV data from ERA5 (IWV_{ERA5}) and MERRA-2 ($IWV_{MERRA\text{-}2}$) are available for each hour. ERA5 is a new ECMWF global atmospheric reanalysis model replacing ERA-Interim (stopped being produced on August 2019). It provides hourly estimates of atmospheric variables at a spatial resolution of 0.25° x 0.25° (Hersbach et al., 2020). Similarly, MERRA-2 is a new GMAO atmospheric reanalysis model replacing the original MERRA, discontinued in February 2016. The hourly atmospheric variable products have a coarser spatial resolution of 0.5° x 0.625° (Gelaro et al., 2017). Most of the global temperature and moisture products in ERA5 and MERRA-2 are determined from the direct assimilation of satellite radiances. Those radiances are currently the main source of information to produce the water vapor profiles and the integrated water vapor in ERA5 (ECMWF, 2016; Hersbach et al. 2020) and in MERRA-2 (McCarty et al., 2016; Gelaro et al., 2017).

A preliminary spatial and temporal coincidence criterion to select the IWV values from ERA5 and MERRA-2 consisted in selecting the four grid points around the location of each AERONET station with the same dates of the IWVsp, producing a first reanalysis dataset. Then, a subset of the former dataset was generated retaining only the four grid points coincident only with the hours in which at least one IWVsp observation is available. Both datasets were subject to bilinear interpolation and correction procedures described below.

2.3 Correcting reanalysis IWV values

For the AERONET-reanalysis comparison, the hourly IWV values from ERA5 and MERRA-2 have been corrected by the difference in altitudes of the surrounding reanalysis grid points and the altitude of the corresponding AERONET station. For each of the reanalysis, both the IWV magnitude and the altitudes at the 4 grid points around the AERONET station location were bi-linearly interpolated to the AERONET station geographical coordinates. The bilinear interpolated altitudes (H_{Rean}) were used to calculate $\Delta \boldsymbol{H} = \boldsymbol{H}_{\boldsymbol{Rean}} - \boldsymbol{H}_{\boldsymbol{SP}}$ at each site, where the term $\boldsymbol{H}_{\boldsymbol{SP}}$ is the altitude of the AERONET station and $\boldsymbol{H}_{\boldsymbol{Rean}}$ is the mean of the altitudes of the four surrounding Reanalysis points. The bi-linearly interpolated IWV_{Rean} and the corresponding $\Delta \boldsymbol{H}$ were then used to calculate the corrected IWV values from ERA5 (IWV_{ERA5}) and MERRA-2

($IWV_{MERRA\text{-}2}$) using the next equation (1) for both reanalyses (Leckner, 1978; Wang, Y. et al., 2017; Wang, S. et al, 2020; Zhu et al., 2021):

$$\boldsymbol{IWV_{Rean} = IWV_{Rean} exp\left(\frac{C_2 \Delta H}{1{,}000}\right)} \qquad (1)$$

where the value C_2 is equal to 0.439 m^{-1} (Leckner, 1978), the exponential term is the altitude correction coefficient, and the subscript *Rean* refers to both reanalyses.

The altitudes of the AERONET sites and the coincident bilinearly interpolated altitudes $\boldsymbol{H_{ERA}}$ and $\boldsymbol{H_{MERR}}$ are shown on the top panel of Figure 2, where the station numbers are the ones listed on Table 1. The IWV correction coefficients, in the bottom panel of Figure 2, show that the maximum values of the altitude correction factors (1.105 and 1.144) for both ERA5 and MERRA-2 are found at Ny Ålesund AWI, and the minimum at PEARL station (0.802 and 0.828). These are the sites with higher positive and negative altitude differences respectively.

2.4 Processing

The comparison has been conducted for individual stations, for two regions and for the whole Arctic. The hourly time scale was selected because it is the reanalysis temporal resolution. The daily time scale was included because it is an intermediate scale between the hourly reanalysis' resolution and the typical residence time (~1 week) for the water vapor in the Artic (Vihma et al., 2016). Daily means were calculated using the spatial and temporal coincident values of IWVsp, IWV_{ERA5} and $IWV_{MERRA\text{-}2}$ for each individual station. Two already defined geographical regions have been considered also in this study. They were defined for the comparison of the IWV from sun photometers and radiosondes. The sun photometer only diurnal observations were required to match the respective maximum amounts of the available diurnal radio sounding observations 12:00 Local Time (LT) at meridians 0° and 180°. As mentioned, the regions are Greenland and European Arctic (GEA), ± 90º around the meridian 0º; and Russia, Alaska, and Canadian Arctic (RACA), ± 90º around the meridian 180º. (Antuña-Marrero et al., 2022). These two geographical regions also match the regions of the Atlantic and Pacific Artic, associated to the respective sub-Arctic oceans (Mauritzen et al., 2013). A total of four stations are in the RACA region: ARM Oliktok AK, Barrow, Tiksi and Resolute Bay, while the other nine stations fall inside the GEA.

2.4.1 Selected Statistics

Two main statistical indicators were selected for comparing IWV from reanalysis and photometer: 1) the Mean Bias Error (MBE), which defines the mean of $\boldsymbol{\Delta IWV}$ ($\boldsymbol{IWV_{Rean}} -$ **IWVsp**) and quantifies the accuracy on $\boldsymbol{IWV_{Rean}}$, and 2) the standard deviation (STD) of the differences between $\boldsymbol{IWV_{Rean}}$ and IWVsp, representing the precision of $\boldsymbol{IWV_{Rean}}$. Both statistics are defined in equations (2) and (3), respectively:

$$\boldsymbol{MBE = \frac{1}{N}\sum_{j=1}^{N}\left[\Delta IWV_j\right]} \qquad (2)$$

$$\boldsymbol{STD = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left[\Delta IWV_j - MBE\right]^2}} \qquad (3)$$

where $\boldsymbol{\Delta IWV_j}$ is the difference between $\boldsymbol{IWV_{Rean}}$ and $\boldsymbol{IWVsp}$ values, and N is the number of pairs of coincident AERONET and reanalysis data. The relative magnitude (in %) of STD (rSTD) and MBE (rMBE) have been determined dividing each term by the mean value of the N observations of IWVsp. In addition, the Pearson linear correlation coefficient (R) and the slope of the linear regression fit between IWVsp and $\boldsymbol{IWV_{Rean}}$have been calculated.

3 Results and discussion

3.1 Comparison for the individual stations

3.1.1 Hourly means

Table 2 shows the statistics and linear fits from the comparisons between hourly IWV_{ERA} vs IWVsp (hereinafter ERA5) and hourly $IWV_{MERRA-2}$ vs IWVsp (hereinafter MERRA-2) for each one of the 13 stations. For all the stations, the magnitudes of STD (rSTD), show slightly higher values, in the order of 0.01 cm (1 to 7 %), for MERRA-2 than for ERA5. It reveals slightly better precision for IWV_{ERA5} than for $IWV_{MERRA-2}$ values. In the case of MBE (rMBE), it is in general slightly higher for $IWV_{MERRA-2}$ than for IWV_{ERA5}, showing values between 0.1cm and 0.01 cm (3 and 14 %); 'this points to better accuracy for IWV_{ERA5} compared to $IWV_{MERRA-2}$ dataset. In the case of Hornsund, MBE (rMBE) shows slightly higher accuracy from $IWV_{MERRA-2}$ than for IWV_{ERA5}.

The statistics associated to the linear fit show that the slopes for ERA5 are slightly lower (with differences in the order of 0.1 to 0.01) than for MERRA-2 at 11 of the stations. In the other 2 stations, Ny Ålesund AWI and Hornsund, the slopes for ERA5 are slightly higher (differences in the order of 0.01) than for MERRA-2. The values of R at 9 stations are slightly higher (in the order of 10^{-2}) for ERA5 than for MERRA-2 with no change in the rest. In general, the results reveal better accuracy and precision for hourly IWV values from ERA5 than from MERRA-2.

For ERA5 (Table 2) the STD values range between 0.25 cm (Barrow) and 0.08 cm (Thule) while rSTD ranges between 11.0% (Ittoqqortoormiit) and 29.7% (PEARL). The absolute MBE values range between 0.34 and 0.01 cm at Barrow and Kangerlussuaq, respectively, and for rMBE the absolute values range between 50.9 and 0.06 % at PEARL and Kangerlussuaq. For MERRA-2 the range of STD values is between 0.28 and 0.09 cm at Barrow and Thule respectively while for rSTD it ranges from 37.4 at PEARL down to 12.9 % at Ittoqqortoormiit. Absolute MBE values range from 0.36 to 0.02 cm at Barrow and Ittoqqortoormiit, respectively, and for rMBE absolute values it is 60.3 to 2.7 % at PEARL and Ittoqqortoormiit. Regarding the linear fits for ERA5 the slopes are in the range 1.43 and 0.87 at PEARL and Thule with 12 of the stations having slopes between 0.8 and 1.2. For MERRA-2 the range is between 1.55 at PEARL and 0.89 at Thule, broader than the former. For ERA5, 7 stations have slopes in the range of 1.0 ± 0.1, while for MERRA-2 only 4 are in the cited range.

The results described above show a clear pattern for both ERA5 and MERRA-2: Barrow has the lower absolute precision and accuracy while PEARL shows the lower relative precision and accuracy. Conversely, for the higher accuracies and precisions the only common pattern for ERA5 and MERRA-2 is that Thule has the higher absolute precision for both of them. Then, for ERA5, Kangerlussuaq shows the higher absolute and relative accuracies and Ittoqqortoormiit the higher relative precision. Meanwhile, for MERRA-2, Ittoqqortoormiit has higher relative precision and the higher absolute and relative accuracies.

When R is compared among stations, for ERA5 its values are in the range 0.99 to 0.95 at Ny Ålesund AWI and Tiksi respectively. For MERRA-2 the range is 0.98 (Ny Ålesund AWI and Sodankyla) to 0.94 (Resolute Bay). The former results support the previous characterization, showing that, in general at station level, the IWV_{ERA5} values match slightly better the observed IWVsp than the $IWV_{MERRA\text{-}2}$.

3.1.2 Daily means

Table 3 is analogous to Table 2, but for the daily means of IWVsp, IWV_{ERA5} and $IWV_{MERRA\text{-}2}$. For all the stations the comparison of the magnitudes of STD, rSTD, absolute MBE and absolute rMBE values between daily means of ERA5 and MERRA-2 show the same pattern than for hourly values in Table 2: slightly higher precision in IWV_{ERA5} than in $IWV_{MERRA\text{-}2}$ for all the stations and slightly higher accuracy also in 11 stations for IWV_{ERA5} than in $IWV_{MERRA\text{-}2}$, but higher for $IWV_{MERRA\text{-}2}$ at Thule and Hornsund. Only 5 slopes from the linear fits for both ERA5 and MERRA-2 are in the range of 1.0 ± 0.1. In the case of R, as found for the hourly IWV_{ERA5} and $IWV_{MERRA\text{-}2}$, its magnitudes slightly decrease at 7 stations in the fits of MERRA-2 with respect to the fits of ERA5, with the other 6 showing no change.

The comparison of the hourly and daily statistics on Tables 2 and 3 reveals a slight decrease in the magnitudes of STD and rSTD between hourly and daily means of ERA5 and also between hourly and daily means of MERRA-2, implying also a slight increase of the precision. For the absolute values of MBE (rMBE) the stations show a slight increase at 6 stations in the order of 0.01cm (1 %) and lower than those at the remaining 7 stations.

For the linear fit results, when the hourly and daily statistics reported in Tables 2 and 3 are compared, the number of stations with slopes for ERA5 in the range of 1.0 ± 0.1 decreases from 7 for hourly values to 5 for the daily means. For MERRA-2, up to 5 stations remain in that range both for hourly and daily values. In the case of R, both for ERA5 and MERRA-2 the daily mean R values at all the stations are higher in the order of 0.01 than the corresponding hourly values. Overall, there is almost no difference between hourly and daily statistics.

3.2 Comparison for GEA and RACA regions and for all the stations

The statistics of the comparison considering the data in the GEA and RACA regions and all the stations together, are provided in Table 4 for hourly and daily means. This table shows, for all regions and for both ERA5 and MERRA-2, a slight increase in the absolute and relative precision (decrease in STD and rSTD in the orders of 10^{-2} cm and 2 to 3 % respectively) in the daily means of ERA5 and MERRA-2 with respect to the hourly values. For MBE and rMBE a similar pattern is present between hourly and daily mean values. Both the slopes and R also have a similar pattern.

When comparing ERA5 with MERRA-2, it could be noted an increase of 0.05 cm or lower (6% or lower) for STD (rSTD), and about 0.06 cm or lower (7% or lower) for MBE (rMBE). The slopes increase also by 0.1 or lower and R decreases 0.02 or less. There are no significant differences between GEA and RACA regions.

We have also compared the accuracy for all stations of the hourly IWV_{ERA} and $IWV_{MERRA\text{-}2}$ with the accuracy reported for the comparison between the IWVsp and IWV from radiosondes (Antuña-Marrero et al. 2022). The accuracies (MBE) for all the stations of the hourly IWV_{ERA5} and $IWV_{MERRA\text{-}2}$ (All Hr) in Table 4 are 0.10 and 0.15 cm respectively. Those values are about three times higher than the accuracy of -0.02 cm reported for the IWVsp for the set of 10 stations (All sites [(1)]) in comparison with radiosondes (see Table 3 of Antuña-Marrero et al., 2022). In addition to the lower accuracy in the case of the reanalyses, they demonstrate a moist/dry bias with respect to the IWVsp in the order of 10^{-1} cm. Moreover, the IWVsp demonstrate a moist/dry bias with respect to the IWV from radiosondes in the order of 10^{-2} cm, an order of magnitude lower than the moist bias of the reanalyses with respect to the IWVsp. As a conclusion, IWV_{ERA5} and $IWV_{MERRA\text{-}2}$ have also a moist bias with respect to the IWV from radiosondes.

Considering now the precision for the same two sets of stations, the comparison with IWV_{ERA} and IWV_{MERRA} shows (Table 4) the relative precisions of 24.9 and 29.5 % respectively. In the case of the comparison with the IWV from radiosondes (Table 3 of Antuña-Marrero et al., 2022) the precision was 8 %. Then the precision of reanalysis data with respect to the IWV from radiosondes could be estimated as 15 % and 20 % for IWV_{ERA5} and $IWV_{MERRA\text{-}2}$, respectively. A more conservative estimate, considering the 12 % estimated precision for AERONET IWV observations (Holben et al., 1998), the uncertainty in both reanalyses is, respectively, about 13 % and 18 %.

Figure 3 provides a visual perspective of the former results, evidencing the very slight differences between the linear fits for IWV_{ERA5} and $IWV_{MERRA\text{-}2}$ with IWVsp for all the stations together. The differences in the slopes and R between ERA5 hourly and daily means (left two panels) are 0.03 and 0.02 while for MERRA-2 (right two panels) are 0.03 and 0.01, showing no major differences. If we compare hourly ERA5 and MERRA-2 (top two panels) the slope increased for MERRA-2 by 0.08 but R is unchanged. In the case of daily means ERA5 and MERRA-2 (bottom two panels) the slope increased for MERRA-2 also 0.08 but R decreased 0.01.

3.3 Hourly ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$ dependence on the IWVsp and the solar zenith angle

The possible dependence of the hourly ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$ on the IWVsp observations and the solar zenith angle (SZA) was evaluated. To that end, the linear fits between hourly ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$ with the IWVsp values and with the SZA of the observations were calculated. Table 5 reports the values of R from the linear fits of the hourly

ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$ with IWVsp and SZA for each of the stations. The magnitudes of R show higher values for MERRA-2 than for ERA5, but the higher R values for both are lower than 0.8 showing low correlation. R values for the linear fits with IWVsp higher than 0.5 (shadowed in gray) occurs at 4 stations (Sodankyla, Andenes, Barrow and PEARL) both for ERA5 and MERRA-2, and at OPAL for MERRA-2. In the rest of the cases, for R lower than 0.5 we also find 3 negative values of R for ERA5 and 2 for MERRA-2. It is relevant the fact that the highest values of R occur at PEARL (0.76 for ERA5 and 0.77 for MERRA-2), the same location that reported the highest values of rSTD and rMBE in tables 2 and 3, i.e. the lowest relative precision and accuracy among all the stations. In a similar way Barrow, having (Table 5) the second highest R value for ERA5 and the third higher for MERRA-2, has the highest STD and MBE values in tables 2 and 3, associated with the lowest precision and accuracy for all the stations. The former results support the hypothesis that, at both stations, the magnitude of the errors increase as the IWVsp increases.

Figure 4 shows the scatter plots of ΔIWV_{ERA5} vs. IWVsp (top left) panel and $\Delta IWV_{MERRA\text{-}2}$ vs. IWVsp (top right panel) for all the stations together. Both for ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$ the trend shows that their magnitudes increase as IWVsp increases. R values are low for both reanalyses, with higher values for MERRA-2, similar as it was found for the individual stations. R is approximately in the range 0.3 to 0.4. Both scatter plots illustrate that ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$ range from 0 to 1.5 cm, displaying an extensive cloud of data. The data scatter is lowest for the extreme values of IWVsp (0 cm and 3 cm).

The R values of the linear fits between the hourly ΔIWV from both reanalyses and SZA are also shown in Table 5. In this case the maximum R value is 0.2, representative of no correlation between the variables at the station level. In the bottom panel of Figure 4 the scatter plots of the hourly ΔIWV from both reanalyses and SZA, shows a similar data scatter range (0 cm to 1.5 cm) than for the dependence on IWVsp; however, the data show no dependence at all of ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$ with respect to SZA. Moreover, the R of the fits with SZA, for all the stations, is in the order of 10^{-2} (Figure 4), i.e negligible compared to the R for the fits vs. IWVsp. The main results discussed in this section show that the main sources of the ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$ are associated to the respective reanalyses.

3.4. Discussion

The results of the comparisons, shown on Tables 2, 3 and 4, of hourly and daily IWV_{ERA5} and $IWV_{MERRA\text{-}2}$ vs IWVsp at the stations, the GEA and RACA regions and for all the stations together show, in general, that IWV values from ERA5 perform better than MERRA-2 both in precision and accuracy. The main reason has already been identified to be the ERA5 higher spatial resolution (Huang et al., 2021; Yuan et al., 2023). Because the AERONET stations do not exactly match the reanalyses grid points, the spatial adjustment is applied using the nearby grid points. An additional adjustment considering the topography is applied, both described in section 2.3. The larger spatial separation of the reanalysis at the nearby grid points increases the uncertainty in the spatial adjustments used for IWV match-up. In addition, the coarser topography mask of the reanalyses increases the uncertainties of the topographic adjustment, more enhanced at highly variable topography.

The comparison also shows a moist bias of the IWV from both reanalyses with respect to the IWVsp. This feature has already been documented and explained. In the Arctic, reanalyses (including ERA5 and MERRA-2) have a poor representation of the vertical profiles of temperature and specific humidity inversions at 875 hPa, causing warm and dry biases at this level. There are also collocated specific and relative humidity inversions at 750 and 600 hPa. ERA5 and MERRA-2 simulated the inversion at 750 hPa. However, the one at 600 hPa is missing in the reanalyses. Then the reanalyses are too moist above 800 hPa, with MERRA-2 moister than ERA5 (Graham et al., 2019).

The comparison of the hourly ERA5 and MERRA-2 vs IWVsp for all the 13 stations (Table 4), show STD (rSTD) of 0.21 cm (25 %) for ERA5 and 0.24 cm (30 %) for MERRA-2. However, for the 10 Arctic stations used in the comparison between IWVsp and IWV from radiosondes reported in Table 3 from Antuña-Marrero et al. (2022), the same statistic indicators had a value of 0.09 cm (10.4 %). This means that the IWV values from both reanalyses in the Arctic are less precise by an order of magnitude in the absolute IWV. Their precisions are also between 2 and 3 times lower for the relative values with respect to the IWV from radiosondes. The absolute magnitudes of MBE (rMBE) for all the stations in the current study are 0.10 cm (12 %) and 0.15 cm (18 %) for ERA5 and MERRA-2, respectively. In contrast with the cited study, they are 0.01 cm (1 %) for the comparison of IWVsp and the IWV from radiosondes, thus also and order of magnitude higher in the current study. It means that the accuracy (absolute and relative) is lower for both reanalyses by an order of magnitude with respect to the IWV from radiosondes. Regarding the linear fit, the magnitude of the R value in the present study is 0.95 and in the cited comparison of IWVsp with IWV from radiosondes, it was 0.99. The analysis above and the cited scarcity and inhomogeneity of IWV observations suggest that AERONET sun photometer IWV observations could be used as a secondary standard in the Arctic (WMO, 2021). AERONET is characterized by its standardized instrumentation, centralized processing, quality control, and calibration services. These are unique features among instruments performing IWV observations in the Arctic. We found no reports of comparison between IWVsp and IWV from ERA5 and MERRA-2 reanalyses focused on the Arctic. However, there are some comparisons between IWV observations from Global Positioning System (GPS) and ERA5 and MERRA-2 reanalyses using broad geographical regions and including few Arctic sites. The GPS technique has proven to be a reliable method for retrieving atmospheric water vapor (e.g., Vaquero-Martinez and Antón, 2021). A recent study has compared IWV time series from several reanalyses vs. GPS-derived IWV (IWV_{GPS}) from 108 GPS stations for more than two decades (1994-2018) over Europe (Yuan et al., 2021). It includes 4 stations from the Arctic but does not provide quantitative information on them. For the entire region, it revealed IWV from ERA5 was the best in matching the diurnal variability in IWV_{GPS} observations, followed by MERRA-2 as the second best. In addition, the comparison of both ERA5 and MERRA-2 with GPS IWV daily means for the entire region, STD values of 0.05cm to 0.16cm and 0.07cm to 0.23cm, respectively, are reported. For the linear fits, mean R values of 0.996 and 0.991 are found. Comparing with the present study of daily mean values (Table 3), the STD range from 0.07cm to 0.22cm for ERA5 and from 0.08cm to 0.25cm for MERRA-2, quite similar except in the upper values for ERA5, which are higher in the present study. In the case of the reported mean R values in the cited study, we may compare it to the R values in Table 4 for all stations together at daily time scale, that shows R vales of 0.95 and 0.94 for ERA5 and MERRA-2 respectively, much lower than the ones reported in the cited research. The cited and present study agree reporting a moist bias for IWV from ERA5 and MERRA-2 respect to IWV_{GPS} and IWVsp.

The dependence of the hourly ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$ values on IWVsp and SZA is very low for IWVsp and negligible for SZA considering the magnitudes of R shown in figure 4. In the case of the dependence on SZA, this result agrees with the reported negligible effect of the SZA on the ΔIWVsp - Sonde in Antuña-Marrero et al., (2022).

4 Conclusions

The present study reports the first comparison specific to the Arctic thus far between IWVsp and IWV from ERA5 and MERRA-2 reanalyses. The IWV from both reanalyses show a predominant moist bias with respect to IWVsp. At the individual stations the daily mean IWV from reanalyses increases in accuracy and correlation but decreases in the precision with respect to the hourly values. Also, at station level and both at hourly and daily scales, the IWV_{ERA5} values match better the observed IWVsp than the $IWV_{MERRA\text{-}2}$. That pattern is also present at the sub-regional scale. The correlations between the hourly reanalyses' differences with IWVsp show a very low dependence on IWVsp values and no dependence at all on SZA, which points at both reanalyses as the main sources of the ΔIWV_{ERA5} and $\Delta IWV_{MERRA\text{-}2}$. The set of IWVsp for AERONET in the Arctic could be used as a secondary standard in the Arctic, with the potential to conduct validations of other sources of IWV information with a primary standard dataset like the IWV from radiosonde observations.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The MERRA-2 reanalysis data are obtained from National Aeronautics and Space Administration, Global Modeling and Assimilation Office (GMAO, 2023), available at https://disc.gsfc.nasa.gov/datasets/M2I1NXINT_5.12.4/summary. The ERA5 reanalysis data are obtained from European Centre for Medium-Range Weather Forecasts (ECMWF, 2023), available at https://doi.org/10.24381/cds.adbb2d47. AERONET sun photometer data are obtained from AErosol RObotic NETwork (AERONET, 2023) available at https://aeronet.gsfc.nasa.gov/new_web/data.html.

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Figures:

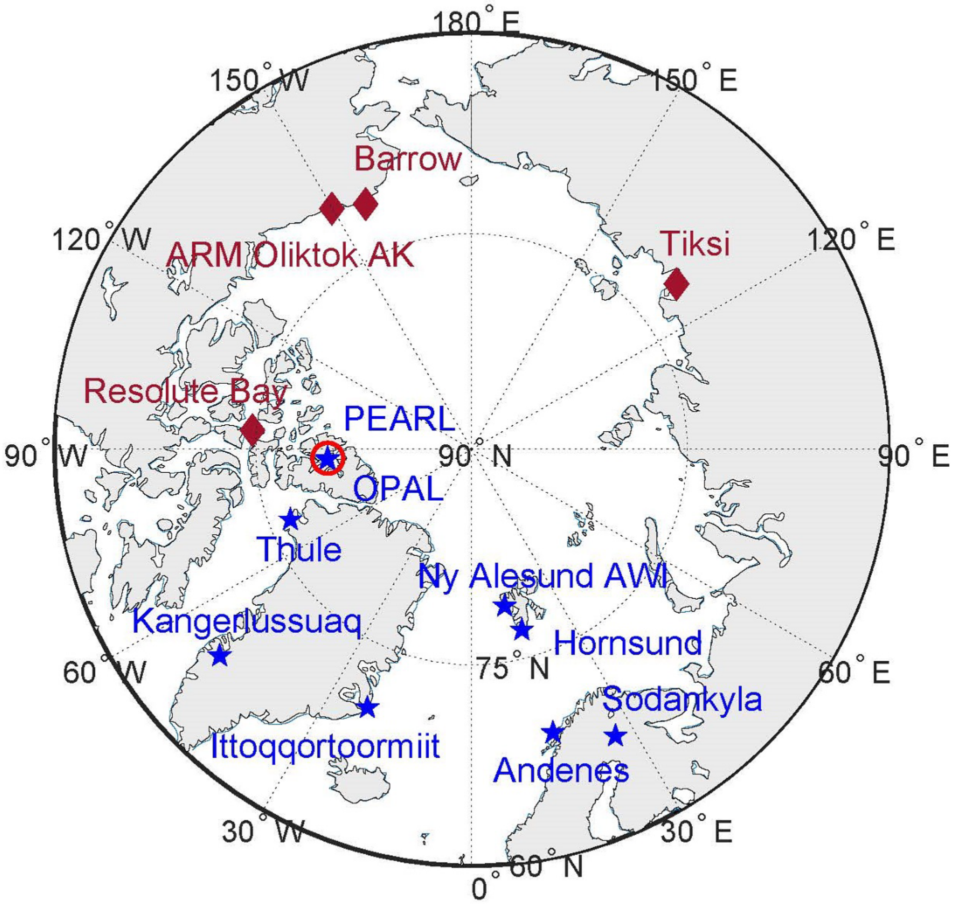

Figure 1: Map of the 13 Arctic AERONET stations used in the present study. Stations belonging to the GEA region are identified by blue stars and the ones in RACA region by brown diamonds, with their names following the same colors pattern. The blue star surrounded by a red circle represents the very close OPAL and PEARL stations in North Canada.

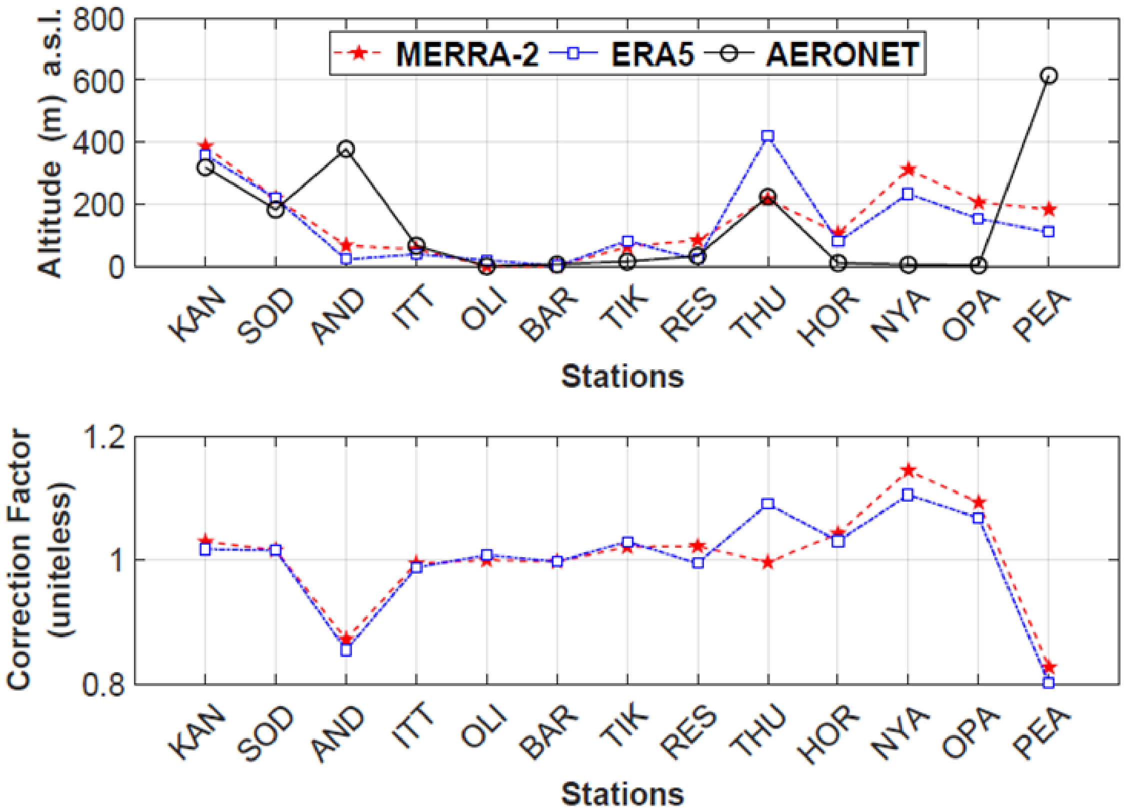

Figure 2: Top panel: altitudes of the 13 AERONET stations and the reanalyses respective altitudes. Altitudes were bilinearly interpolated from the 4 grid points around the station. Bottom panel: IWV correction factors applied to the IWV from ERA5 and MERRA-2 reanalyses. The stations abbreviations and names are: KAN (Kangerlussuaq), SOD (Sodankyla), AND (Andenes), ITT (Ittoqqortoormiit), OLI (ARM Oliktok AK), BAR (Barrow), TIK (Tiksi), RES (Resolute Bay), THU (Thule), HOR (Hornsund), NYA (Ny Ålesund AWI), OPA (OPAL) and PEA (PEARL). For more information about the station see Table 1.

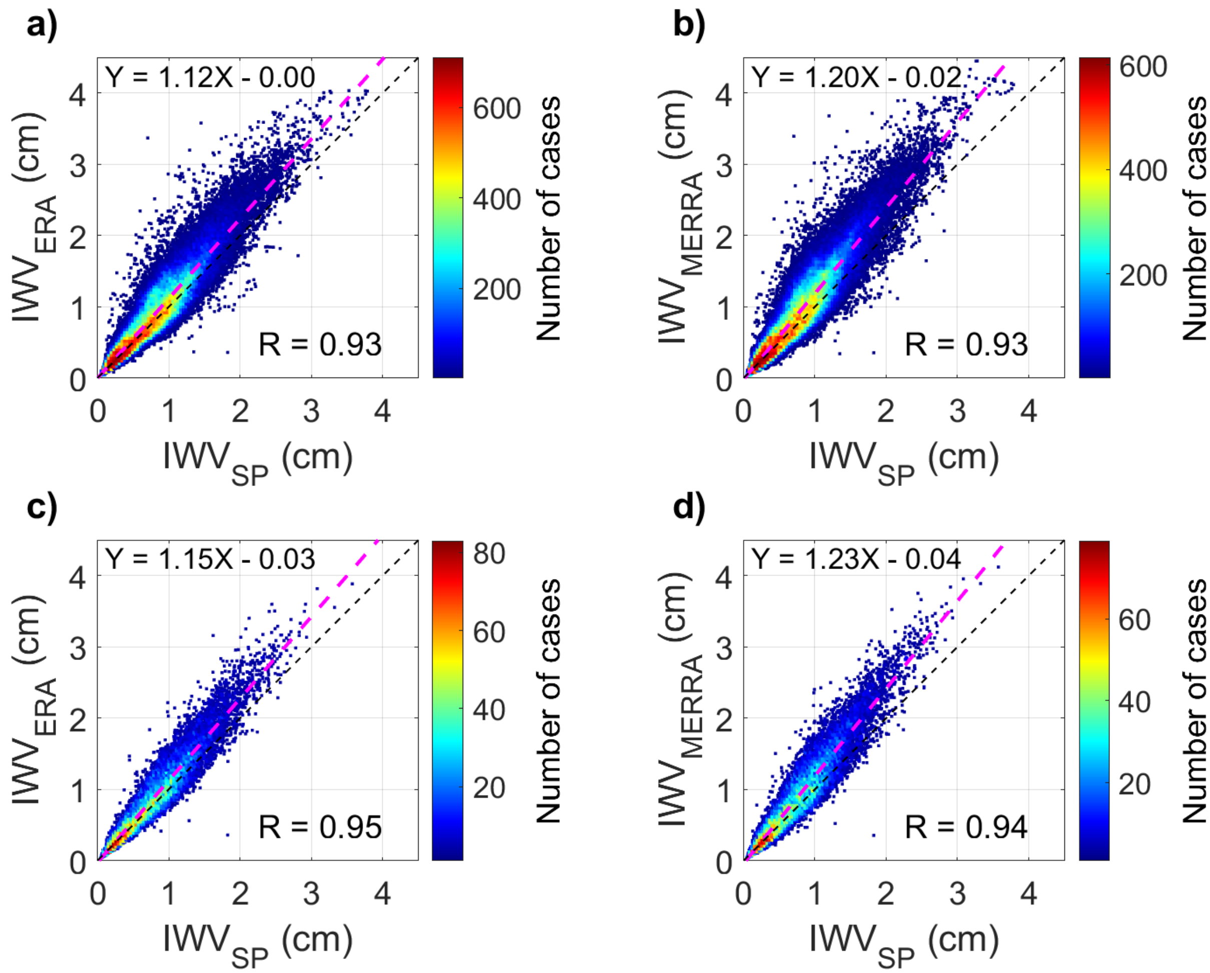

Figure 3: Density scatter plots of hourly and daily means for all the stations together for IWV_{ERA5} & $IWV_{MERRA-2}$. Hourly values on top (panels a and b) and daily means in the bottom (panel c and d). ERA5 in the left panels and MERRA-2 in the right panels. The magenta dashed lines denote the respective linear fits, and the black dashed line denotes the 1:1 line.

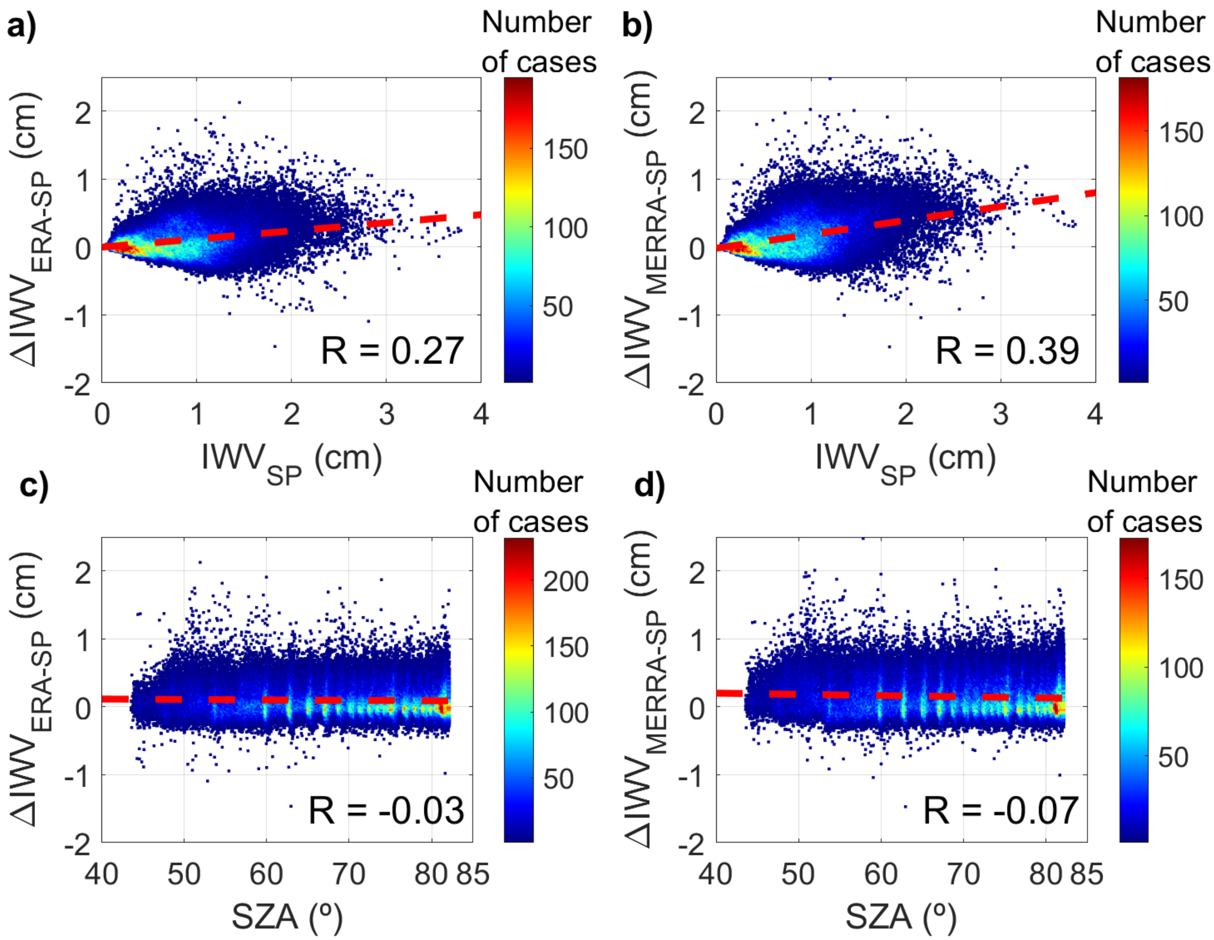

Figure 4: In top panels, the scatter plots of the hourly for ΔIWV_{ERA5} & $\Delta IWV_{MERRA\text{-}2}$. with respect to IWVsp (panels a and b respectively) for all the stations together. The red dashed lines denote the respective linear fits. Bottom panel also ΔIWV_{ERA5} & $\Delta IWV_{MERRA\text{-}2}$ scatter plots (panels c and d respectively) but with respect to the SZA.

Tables:

Table 1: Information about all the available AERONET sun photometer stations in the Arctic, listed in increasing latitude order. Geographical location and number of available instantaneous observations, hourly and daily calculated values are given. Also, the beginning and ending dates of the observations at each site. Stations having less than 1,500 hourly IWVsp values, shadowed in gray, were discarded. The 13 numbered stations were used in the present study. The total number of observations (last row), pertain only to the 13 stations used.

		AERONET station's location & altitude				Time coverage		# IWV available data		
No.	ID	Station	Lat	Long	H (m)	Begin	End	Obs.	Hourly	Daily
1	KAN	Kangerlussuaq	67.00	-50.62	320	01/04/2008	17/07/2020	55,636	11,056	1,386
2	SOD	Sodankyla	67.37	26.63	184	10/02/2007	19/06/2020	18,074	5,595	899
		Matorova FMI	68.00	24.24	340	10/09/2020	27/09/2021	7,535	482	77
		Abisko	68.35	18.82	390	27/04/2007	21/08/2007	1,091	373	61
		NEON TOOL	68.66	-149.37	843	12/02/2017	25/09/2021	7,094	1,136	280
3	AND	Andenes	69.28	16.01	379	04/06/2002	03/08/2020	39,681	8,609	1,244
4	ITT	Ittoqqortoormiit	70.48	-21.95	68	10/05/2010	27/09/2019	25,991	7,728	885
5	OLI	ARM Oliktok AK	70.50	-149.88	2	23/09/2013	19/06/2021	20,171	3,219	587
		NEON BARR	71.28	-156.62	6	19/04/2017	09/10/2021	1,523	472	107
6	BAR	Barrow	71.31	-156.66	8	30/07/1997	11/08/2020	30,553	7,946	1,261
7	TIK	Tiksi	71.59	128.92	17	08/06/2010	07/09/2015	4,634	1,786	335
8	RES	Resolute Bay	74.71	-94.97	35	04/07/2004	25/09/2019	73,529	7,064	866
9	THU	Thule	76.52	-68.77	225	15/03/2007	03/10/2021	65,615	13,864	1,582
10	HOR	Hornsund	77.00	15.54	12.4	07/05/2004	04/10/2020	18,951	6,562	1,024
		Longyearbyen	78.22	15.65	30	25/04/2003	13/08/2018	1,841	707	112
11	NYA	Ny Ålesund AWI	78.92	11.92	7	01/06/2017	19/05/2021	15,917	2,134	305
		Ny Ålesund	78.93	11.86	46	22/03/2006	01/04/2006	711	59	9
12	OPA	OPAL	79.99	-85.94	5	02/04/2007	13/06/2021	94,498	10,067	1,031
13	PEA	PEARL	80.05	-86.42	615	21/03/2007	06/09/2019	137,779	12,555	1,103
		North_Pole	88.80	24.25	1	18/04/2002	09/06/2002	309	97	17
		Totals						**601,029**	**98,185**	**12,158**

Table 2: Statistics of the comparison of hourly ERA & MERRA for each site for all the available observations. The highest values of STD, rSTD, R and the absolute values of MBE and rMBE among the 13 stations are highlighted in bold, and the lowest values in grayish background.

	IWV_{ERA} vs IWVsp							$IWV_{MERRA-2}$ vs IWVsp						
Station	**STD cm**	**rSTD/ %**	**MBE/ cm**	**rMBE /%**	**Slope**	**Interc/ cm**	**R**	**STD /cm**	**rSTD /%**	**MBE/ cm**	**rMBE/ %**	**Slope**	**Interc/ cm**	**R**
Kangerlussuaq	0.12	14.9	0.01	0.6	0.95	0.04	0.96	0.14	16.7	0.06	6.90	1.02	0.04	0.95
Sodankyla	0.15	12.9	0.14	12.7	1.12	0.01	0.98	0.21	18.9	0.30	26.90	1.24	0.04	**0.98**
Andenes	0.16	16.3	0.25	25.3	1.18	0.08	0.98	0.19	19.7	0.35	35.90	1.25	0.11	0.97
Ittoqqortoormiit	0.09	11.0	-0.10	-11.7	0.89	-0.01	0.97	0.11	12.9	-0.02	-2.70	1.03	-0.05	0.96
ARM_Oliktok_AK	0.18	16.2	0.12	11.3	1.08	0.03	0.96	0.21	19.8	0.21	19.50	1.17	0.02	0.96
Barrow	**0.25**	24.6	**0.34**	33.6	1.29	0.05	0.96	**0.28**	28.1	**0.36**	36.50	1.33	0.03	0.96
Tiksi	0.19	15.4	0.09	7.3	1.09	-0.02	0.95	0.24	19.4	0.22	17.80	1.18	-0.01	0.95
Resolute_Bay	0.13	15.5	0.10	12.2	1.08	0.04	0.96	0.16	19.3	0.14	16.10	1.13	0.03	0.94
Thule	0.08	13.6	-0.09	-14.7	0.87	-0.01	0.97	0.09	14.1	-0.09	-15.40	0.89	-0.03	0.97
Hornsund	0.09	11.5	-0.02	-2.4	1.01	-0.03	0.98	0.10	13.0	-0.05	-6.90	0.95	-0.02	0.97
Ny_Ålesund_AWI	0.10	13.1	0.06	8.0	1.10	-0.02	**0.99**	0.12	15.9	0.06	8.00	1.07	0.01	**0.98**
OPAL	0.11	12.7	0.07	7.5	1.09	-0.02	0.97	0.16	18.3	0.17	19.40	1.23	-0.03	0.96
PEARL	0.18	**29.7**	0.30	**50.9**	1.43	0.04	0.97	0.22	**37.4**	0.35	**60.30**	1.55	0.03	0.96

Table 3: Statistics of the comparison of daily mean ERA & MERRA for each site. Daily mean values of IWV_{ERA} & IWV_{MERRA} calculated using only the hourly coincident observations with IWVsp. The highest values of STD, rSTD, R and the absolute values of MBE and rMBE among the 13 stations are highlighted in bold, and the lowest values in grayish background.

	IWV_{ERA} vs IWVsp							IWV_{MERRA} vs IWVsp						
Station	**STD /cm**	**rSTD/ %**	**MBE /cm**	**rMBE/ %**	**Slope**	**Interc/ cm**	**R**	**STD/ cm**	**rSTD / %**	**MBE/ cm**	**rMBE/ %**	**Slop e**	**Interc /cm**	**R**
Kangerlussuaq	0.10	12.1	0.00	0.4	0.97	0.03	0.98	0.12	14.5	0.05	5.8	1.02	0.03	0.97
Sodankyla	0.13	11.7	0.16	14.2	1.15	0.00	**0.99**	0.20	17.6	0.30	26.9	1.25	0.02	**0.99**
Andenes	0.15	15.3	0.25	26.2	1.21	0.05	0.98	0.18	18.4	0.35	36.0	1.27	0.08	0.98
Ittoqqortoormiit	0.08	9.5	-0.09	-10.6	0.91	-0.02	0.98	0.10	12.0	-0.01	-1.8	1.05	-0.06	0.97
ARM_Oliktok_AK	0.14	12.8	0.12	11.0	1.09	0.02	0.98	0.18	16.7	0.21	19.4	1.18	0.02	0.97
Barrow	**0.22**	22.1	**0.34**	33.4	1.31	0.02	0.98	**0.25**	25.2	**0.37**	36.6	1.36	0.01	0.97
Tiksi	0.14	11.9	0.09	7.3	1.11	-0.04	0.98	0.20	16.6	0.20	16.8	1.20	-0.04	0.97
Resolute_Bay	0.11	12.8	0.10	11.6	1.09	0.02	0.97	0.14	16.5	0.13	15.5	1.14	0.01	0.96
Thule	0.07	12.1	-0.09	-14.5	0.89	-0.02	0.98	0.08	12.6	-0.09	-15.0	0.91	-0.03	0.97
Hornsund	0.08	10.7	-0.01	-1.8	1.04	-0.04	0.98	0.09	11.0	-0.05	-6.6	0.97	-0.03	0.98
Ny_Ålesund_AWI	0.09	10.6	0.07	8.8	1.11	-0.02	0.99	0.12	14.6	0.08	9.6	1.10	-0.01	0.98
OPAL	0.10	11.3	0.07	8.4	1.11	-0.02	0.98	0.15	16.9	0.17	19.7	1.24	-0.04	0.97
PEARL	0.18	**29.7**	0.30	**51.0**	1.49	0.02	0.98	0.22	**36.8**	0.35	**59.5**	1.60	0.00	0.98

Table 4: Statistics of the comparison of hourly and daily mean ERA and MERRA for GEA and RACA regions and for all the stations. Daily mean values of ERA and MERRA were calculated using only the hourly observations coincident with IWVsp.

Region/ Scale	IWV_{ERA} vs IWVsp							IWV_{MERRA} vs IWVsp							N. Observ.
	STD/ cm	rSTD/ %	MBE/ cm	rMBE/ %	Slope	Interc/ cm	R	STD/ cm	rSTD/ %	MBE/ cm	rMBE/ %	Slope	Interc/ cm	R	
GEA Hr	0.19	24.4	0.07	8.9	1.08	0.01	0.93	0.24	30.0	0.13	16.0	1.18	-0.01	0.92	78,170
GEA Dy	0.18	22.3	0.07	8.8	1.11	-0.02	0.95	0.23	27.9	0.12	15.2	1.20	-0.04	0.93	9,207
RACA Hr	0.23	23.0	0.20	20.1	1.18	0.03	0.95	0.25	25.6	0.25	25.2	1.24	0.01	0.95	20,015
RACA Dy	0.21	20.9	0.20	20.1	1.19	0.01	0.96	0.23	23.2	0.25	25.4	1.26	-0.01	0.96	2,951
ALL Hr	0.21	24.9	0.10	11.6	1.12	0.00	0.93	0.24	29.5	0.15	18.2	1.20	-0.02	0.93	98,185
ALL Dy	0.20	22.9	0.10	12.0	1.15	-0.03	0.95	0.23	27.3	0.15	18.1	1.23	-0.04	0.94	12,158

Table 5: Correlation coefficients (R) from the linear fits of the hourly ΔIWV_{ERA} and ΔIWV_{MERRA} with IWVsp and SZA for each of the stations. R values higher than 0.50 are shadowed in gray. The scale identifiers are: Hr (Hourly) and Dy (Daily).

Station	IWVsp		SZA		Number Cases
	ERA	MERRA	ERA	MERRA	
Kangerlussuaq	-0.16	0.06	-0.02	-0.07	11056
Sodankyla	0.51	0.68	-0.12	-0.19	5595
Andenes	0.55	0.64	0.00	-0.08	8609
Ittoqqortoormiit	-0.43	0.10	0.17	0.11	7728
ARM_Oliktok_AK	0.26	0.45	-0.03	-0.08	3219
Barrow	0.63	0.64	-0.11	-0.14	7946
Tiksi	0.25	0.42	-0.03	-0.10	1786
Resolute_Bay	0.23	0.30	0.02	0.02	7064
Thule	-0.49	-0.42	0.17	0.20	13864
Hornsund	0.05	-0.19	0.12	0.11	6562
Ny_Alesund_AWI	0.49	0.28	0.01	0.05	2134
OPAL	0.32	0.54	-0.06	-0.08	10067
PEARL	0.76	0.77	-0.17	-0.16	12,555