

## RESEARCH LETTER

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## Key Points:

- OCO-2 can measure total column water vapor with high precision, accuracy, and spatial resolution over land and ocean surfaces
- OCO-2 is the first space-based sensor to accurately measure the two most important greenhouse gases, H<sub>2</sub>O and CO<sub>2</sub>, at high spatial resolution
- OCO-2 water vapor measurements may be useful in improving numerical weather predictions and acting as a validation source for other sensors

## Supporting Information:

- Supporting Information S1

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## High-accuracy measurements of total column water vapor from the Orbiting Carbon Observatory-2

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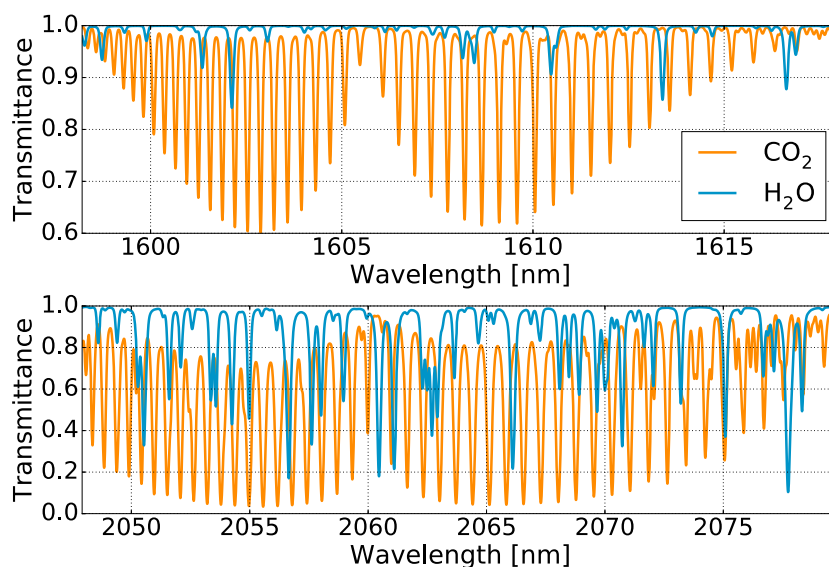
**Abstract** Accurate knowledge of the distribution of water vapor in Earth's atmosphere is of critical importance to both weather and climate studies. Here we report on measurements of total column water vapor (TCWV) from hyperspectral observations of near-infrared reflected sunlight over land and ocean surfaces from the Orbiting Carbon Observatory-2 (OCO-2). These measurements are an ancillary product of the retrieval algorithm used to measure atmospheric carbon dioxide concentrations, with information coming from three highly resolved spectral bands. Comparisons to high-accuracy validation data, including ground-based GPS and microwave radiometer data, demonstrate that OCO-2 TCWV measurements have maximum root-mean-square deviations of 0.9–1.3 mm. Our results indicate that OCO-2 is the first space-based sensor to accurately and precisely measure the two most important greenhouse gases, water vapor and carbon dioxide, at high spatial resolution (1.3 × 2.3 km<sup>2</sup>) and that OCO-2 TCWV measurements may be useful in improving numerical weather predictions and reanalysis products.

### 1. Introduction

The Orbiting Carbon Observatory-2 (OCO-2) [Crisp *et al.*, 2008] was launched on 2 July 2014 with the goal of using hyperspectral observations of near-infrared reflected sunlight to measure the column-averaged dry-air mole fraction of carbon dioxide ( $X_{\text{CO}_2}$ ) with the accuracy and precision needed to constrain net carbon dioxide (CO<sub>2</sub>) fluxes on regional scales. While CO<sub>2</sub> sources and sinks currently represent a large scientific uncertainty, knowledge of water (H<sub>2</sub>O) is also critical in understanding our planet. Water vapor, specifically, is important in how it influences the radiation budget, hydrologic cycle, weather patterns, and climate change. Improved knowledge of water vapor could lead to an enhanced understanding in all of these fields.

Currently, global space-based information on water vapor comes from a number of satellite instruments. First, there are sensors that operate at microwave wavelengths such as the Special Sensor Microwave Imager [Wentz and Spencer, 1998], the Advanced Microwave Scanning Radiometer Earth Observing System, the Advanced Microwave Scanning Radiometer 2 (AMSR2), the Tropical Rainfall Measuring Mission Microwave Imager, and the Global Precipitation Measurement Microwave Imager. Second, there are sensors that operate at thermal infrared wavelengths such as the Atmospheric Infrared Sounder (AIRS) [Susskind *et al.*, 2003], the Infrared Atmospheric Sounding Interferometer (IASI) [Pouget *et al.*, 2009], the Cross-track Infrared Sounder [Bloom, 2001], and the High-resolution Infrared Radiation Sounder [Bates and Jackson, 2001]. Third, there are sensors that operate at near-infrared wavelengths such as the Moderate Resolution Imaging Spectroradiometer (MODIS) [Gao and Kaufman, 2003; Albert *et al.*, 2005] and the MEdium Resolution Imaging Spectrometer (MERIS) [Bennartz and Fischer, 2001; Lindstrot *et al.*, 2012]. Finally, there are sensors that operate at visible wavelengths such as the Global Ozone Monitoring Experiment-2 [Grossi *et al.*, 2015]. Over ocean, microwave and infrared sensors are typically used, as the surface temperature and emissivity are relatively well known. Over land, emissivity constraints result in a preference toward near-infrared sensors.

OCO-2 measures reflected sunlight in clear-sky scenes over both land and ocean and is at the front of NASA's Afternoon Constellation [L'Ecuyer and Jiang, 2010]. It is a clear-sky instrument because of the large errors typically induced by severe light path modification effects caused by scenes containing an appreciable amount of clouds or aerosols. It makes eight measurements simultaneously across a narrow (<10 km) swath every 2.3 km and has a repeat cycle of 16 days. Despite the restricted spatial coverage, OCO-2's orbital path and subsequent collocation with other satellites makes it well suited to provide robust and well-calibrated products over



**Figure 1.** Simulated OCO-2 (top) 1.61  $\mu\text{m}$  band and (bottom) 2.06  $\mu\text{m}$  band transmittance spectra in a typical downward looking observation, demonstrating the prevalence of water vapor absorption features (blue) within the  $\text{CO}_2$  absorption bands (orange).

much of the globe. OCO-2 uses high-resolution grating spectrometers with a resolving power greater than 18,000 to measure light in three spectral bands centered at approximately 0.76, 1.61, and 2.06  $\mu\text{m}$ . The primary OCO-2  $X_{\text{CO}_2}$  retrieval algorithm is referred to as the ACOS (Atmospheric Carbon Observations from Space) [O'Dell *et al.*, 2012] algorithm and uses optimal estimation [Rodgers, 2000] to estimate  $X_{\text{CO}_2}$  and a number of other quantities that impact the  $X_{\text{CO}_2}$  retrieval. These additional quantities include aerosol optical depth and height, surface pressure, and surface albedo. At the near-infrared wavelengths that OCO-2 observes, there are many  $\text{H}_2\text{O}$  lines present. If these absorption features and  $\text{H}_2\text{O}$ 's foreign broadening impact on the  $\text{CO}_2$  lines are not accounted for, biases are introduced into the  $X_{\text{CO}_2}$  retrieval. Thus, one of the retrieved variables in the ACOS algorithm is total column water vapor (TCWV), which is defined as the total gaseous water contained in a vertical column of atmosphere. The unit of TCWV throughout this work is the millimeter (mm), where 1 mm is equal to  $1\text{kg}/\text{m}^2$ . Absorption coefficient tables (ABSCO v4.2) were created using  $\text{H}_2\text{O}$  lines from a custom list, similar to the line list used in the High-resolution TRANsmission molecular absorption database compilation (HITRAN2012) [Rothman *et al.*, 2013; I. Gordon, personal communication, 2012]. The  $\text{H}_2\text{O}$  continuum model used is a custom version of the Mlawer-Tobin-Clough-Kneizys-Davies model [Mlawer *et al.*, 2012]. These ABSCO tables are used to supply absorption cross-section values for the retrieved gases and are critically important in retrieving nearly bias-free measurements. The inclusion of TCWV in the ACOS retrieval leads to the following question: how well can OCO-2 retrieve  $\text{H}_2\text{O}$  information?

In this work, we evaluate the precision and accuracy of OCO-2 TCWV measurements via simulations and comparisons to multiple independent validation sources. We then discuss improvements that could be made to the retrieval algorithm as well as potential applications of the water vapor product.

## 2. Theoretical Basis

As water is a nonlinear molecule with a net dipole moment, many rotational and vibrational absorption features exist throughout the electromagnetic spectrum. OCO-2 resolves a number of strong  $\text{H}_2\text{O}$  absorption features in both its 1.61 and 2.06  $\mu\text{m}$  bands. Figure 1 shows an example of absorption features in these bands, as seen through the OCO-2 spectral response function. While the majority of the lines are due to carbon dioxide, many water vapor lines are also evident. In an atmosphere devoid of clouds and aerosols, the relative line depth is directly related to TCWV. The lines are well resolved, and because of OCO-2's high signal-to-noise ratio of several hundred to greater than 1000 [Frankenberg *et al.*, 2015], even small changes in the relative line depth can be detected.

The ACOS algorithm uses the European Centre for Medium-Range Weather Forecasts Integrated Forecast System (ECMWF IFS) [ECMWF, 2015] for meteorological a priori information on temperature, water vapor, and

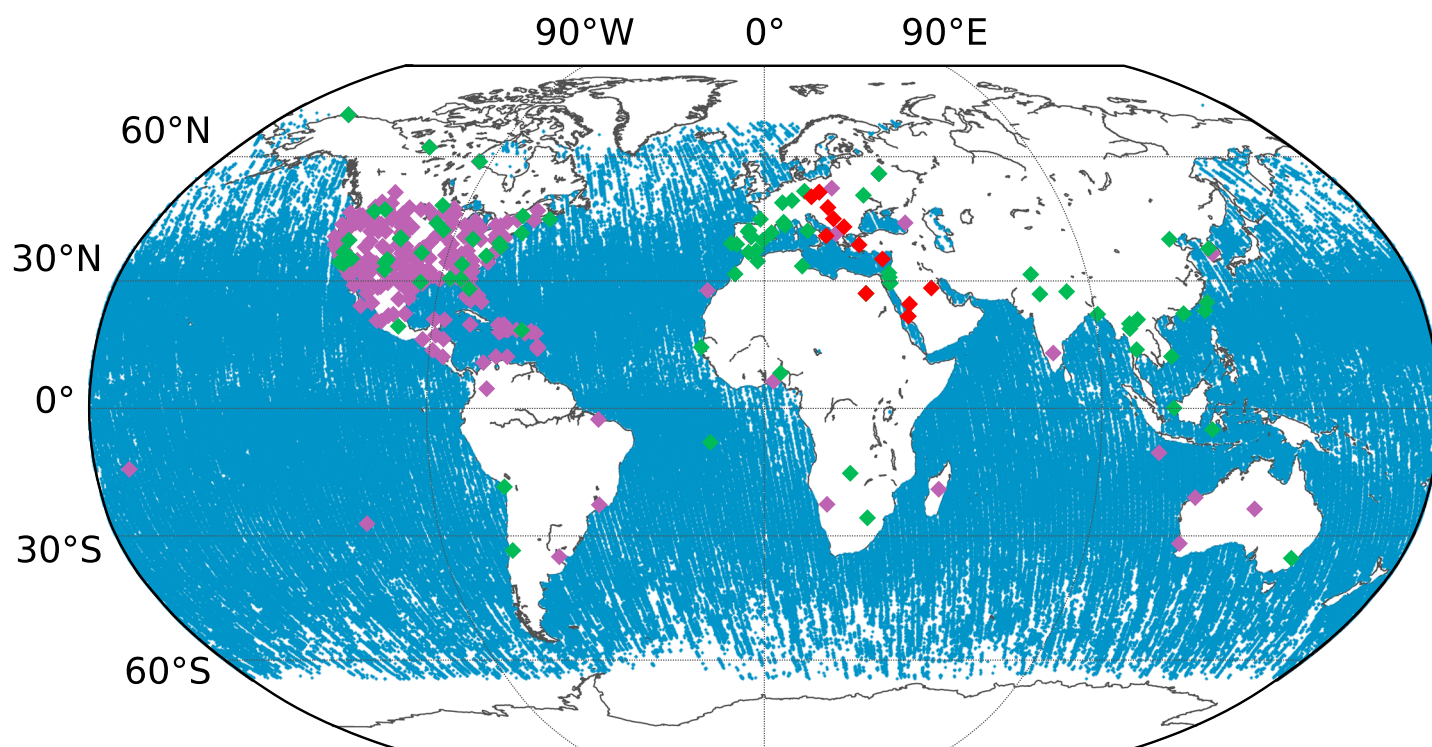
surface pressure and retrieves a single scaling factor applied to the ECMWF water vapor profile. This is done to reduce possible correlations between the retrieved  $X_{\text{CO}_2}$  and water vapor. Because the ACOS algorithm is given the precise spectral response function and SNR of the instrument, the optimal estimation approach produces an estimate of the uncertainty in its retrieved TCWV. This estimate is typically only 0.1–0.2mm and includes errors due to both instrument noise as well as cross-talk errors due to other retrieved variables such as aerosols and carbon dioxide. However, the estimate does not include errors in the prescribed ECMWF vertical profile of water vapor and may not fully account for errors due to clouds and aerosols, so it may be an underestimate. This theoretical uncertainty therefore serves as a useful lower limit of the actual TCWV retrieval error.

We next improve on this estimate by performing retrievals on simulated spectra in realistic atmospheres created using the Colorado State University (CSU) Orbit Simulator (see *O'Brien et al.* [2009] for details). These simulations include realistic representations of the viewing geometry and surface reflectance, profiles of clouds and aerosols from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) [*Winker et al.*, 2009], and meteorology from ECMWF. Gaussian instrument noise is also added to the spectra. For more details on the methodology, see *O'Dell et al.* [2012]. Scenes contaminated by clouds and aerosols are rejected via a spectral-based cloud-screening technique [*Taylor et al.*, 2012, 2016], as OCO-2 is only able to make accurate retrievals in scenes nearly free of cloud and aerosol contamination. However, scenes passing this prefilter may still contain some clouds and aerosols, typically with an optical depth less than 0.3.

ACOS retrievals were then performed on scenes passing the cloud and aerosol prefilter. To challenge our retrieval, we set the prior meteorological data to be from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis-1 [*Kalnay et al.*, 1996], rather than from ECMWF, as a proxy for realistic errors in water vapor amount and vertical distribution, as well as errors in the temperature profile and surface pressure. Despite these error sources, we were able to retrieve TCWV values with an almost perfect correlation with the true water vapor ( $R = 0.999$ ) and effectively no bias ( $-0.08\text{mm}$ ) compared to the true TCWV used to create the synthetic measurements (see Figure S1 in the supporting information). The root-mean-square deviation (RMSD) between the retrieved TCWV and true TCWV was reduced from about 4mm (7mm) in the prior to 0.39mm (0.75mm) in the retrieval over land (ocean) (see Tables S1 and S2 in the supporting information). This mean error of about 0.6mm is higher than the simple theoretical estimate of approximately 0.1–0.2mm likely because of additional cloud and aerosol light path modification effects but also potentially because of errors in the prior temperature profile, surface pressure, and water vapor profile shape.

### 3. Data Description

We now extend our analysis to real OCO-2 data by comparing OCO-2 TCWV measurements to four TCWV validation sources: SuomiNet [*Ware et al.*, 2000], the AEROSOL ROBOTIC NETWORK (AERONET) [*Holben et al.*, 1998], the Integrated Global Radiosonde Archive (IGRA) [*Durre et al.*, 2006], and the Advanced Microwave Scanning Radiometer 2 (AMSR2) [*Imaoka et al.*, 2010]. SuomiNet is a ground-based Global Positioning System (GPS) network that measures TCWV concentrations using the time delay in the 1.6 and 1.2GHz GPS signals. As a GPS satellite passes overhead, the transmitted signal is slowed by Earth's atmosphere and the time it takes to reach a given SuomiNet instrument on the ground is recorded. The delay in this time is a function of how much water vapor is in the column of air, the temperature profile, etc. Using a simple equation, TCWV can then be retrieved with an estimated accuracy of 1–2mm [*Ware et al.*, 2000]. AERONET is a ground-based Sun photometer network primarily designed to measure aerosol properties. Each AERONET instrument tracks the Sun as it travels across the sky and uses measured radiances to infer column values of several quantities, including water vapor (using a band around 0.94  $\mu\text{m}$  via the Direct Sun Algorithm version 2) [*Reagan et al.*, 1987; *Schmid et al.*, 1996] with a reported accuracy of better than 2mm [*Michalsky et al.*, 1995]. IGRA is a collection of radiosonde and pilot balloon observations from over 1500 globally distributed stations. While primarily used for operational weather forecasting, radiosonde observations have also been used for other applications including the verification of satellite measurements. *Yu et al.* [2015] found mean differences in TCWV between radiosondes and a ground-based microwave radiometer of 0.9mm. An exponential fit to each IGRA profile was used to account for any water vapor present above the altitude at which the radiosonde stopped taking data. Only Vaisala RS92s were used in this study, as they have been extensively validated [e.g., *Yu et al.*, 2015; *Wang et al.*, 2013]. We also required each profile to contain at least 30 vertical measurements. The primary limitation

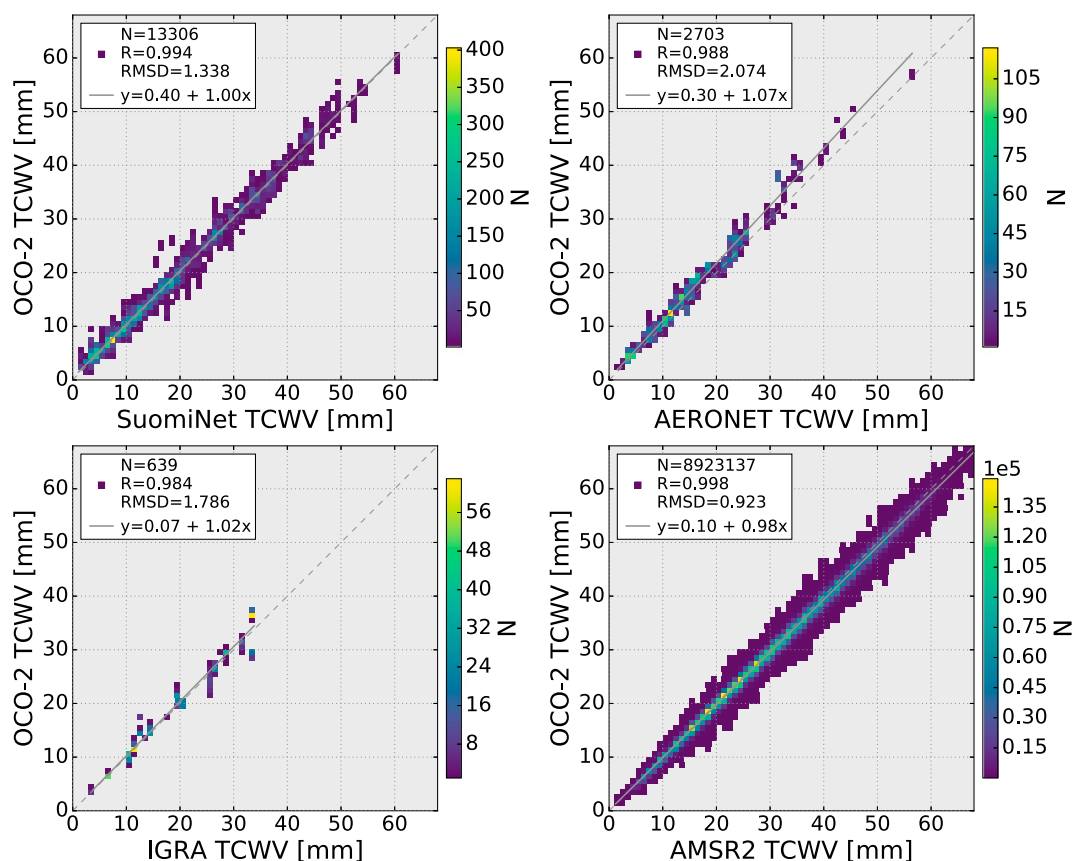


**Figure 2.** Location of SuomiNet sites (purple), AERONET sites (green), IGRA sites (red), and AMSR2 grid cells (blue) that have a valid OCO-2 measurement collocated in time and space from 6 September 2014 to 10 February 2016.

of these three ground-based networks is their lack of coverage over ocean and sparse coverage over land, which restricted the number of collocations as OCO-2's orbit track is less than 10km wide and has a repeat cycle of approximately 16 days. Additionally, the infrequent launch times of radiosondes (typically only 0Z and 12Z) further restrict the number of available collocations of IGRA with OCO-2. The fourth validation source, AMSR2, is a radiometer that measures water vapor at microwave wavelengths over ocean using horizontally and vertically polarized channels at 18.7, 23.8, and 36.5GHz. It flies in the Afternoon Constellation a few minutes behind OCO-2 and thus provides a substantial number of collocated measurements. *Duncan and Kummerow [2016]* found a RMSD between AMSR2 and a radiosonde data set of 2.6mm. For this work, the Remote Sensing Systems 0.25° gridded TCWV product was used (version 7.2; *Wentz et al. [2014]*). The MODIS instrument on NASA's Aqua satellite, despite being in the Afternoon Constellation with OCO-2, was not selected as a validation source, as its water vapor errors are likely larger than those from OCO-2 [e.g., *Gao and Kaufman, 2003; Li et al., 2003*]. While a custom retrieval has been shown to have smaller errors than the operational algorithm [*Diedrich et al., 2015*], our previously described validation sources over land were considered sufficient.

To compare OCO-2 TCWV measurements to SuomiNet and AERONET, collocation criteria of 30min in time and 0.1° latitude (about 11km) in space were chosen. We examined the potential of expanding the collocation thresholds in order to increase the number of matched measurements but found that the differences between the OCO-2 and validation TCWV values increased substantially for larger thresholds, indicating that the spatial and temporal variability of water vapor imposes limits on the chosen collocation thresholds. Supporting information Figure S2 shows a minimum in RMSD between OCO-2 and SuomiNet TCWV using a collocation distance threshold of about 0.1° latitude. Smaller spatial collocation thresholds than about 0.1° have a larger RMSD because there are too few remaining SuomiNet measurements. In an attempt to increase the number of IGRA collocations, we allowed radiosondes within 0.1° to have been launched up to an hour before the corresponding OCO-2 measurement, as radiosonde balloons typically take 1–2h to ascend through the atmosphere. We also applied a station surface pressure or station altitude difference threshold to ensure that OCO-2 was not measuring substantially shorter or longer path lengths (and thus retrieving less or more water vapor, which is concentrated near the surface). Against SuomiNet and IGRA, a surface pressure difference threshold of less than 10hPa was used, while against AERONET an altitude difference threshold of less than 100m was used. The chosen thresholds removed expected biases that were appearing when OCO-2 measurements were



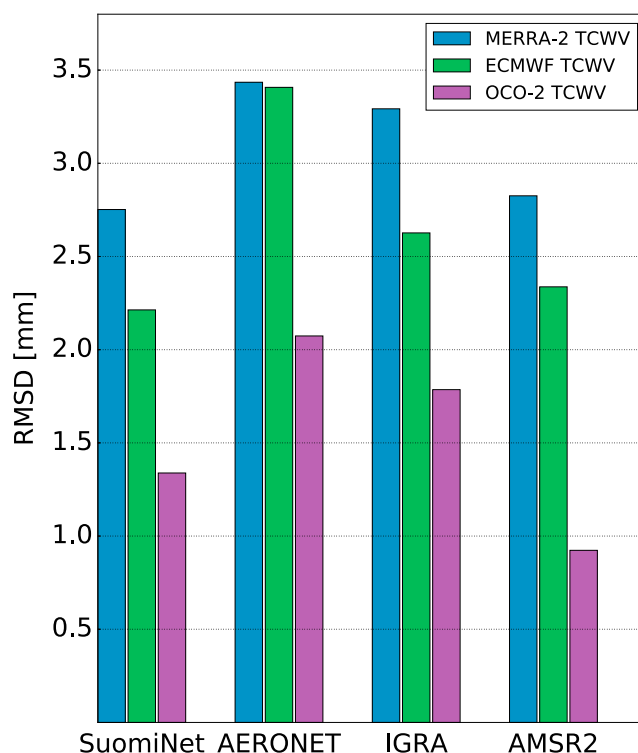


**Figure 3.** Heatmap comparison of the retrieved OCO-2 TCWV to SuomiNet, AERONET, IGRA, and AMSR2 TCWV measurements.

sampling columns of air much higher or lower in elevation than the nearby SuomiNet, AERONET, or IGRA station. We chose to reject data instead of trying to apply a custom water vapor correction because water vapor is highly concentrated near the surface and thus any errors or uncertainty in the correction could represent a disproportionately large fraction of the total TCWV.

OCO-2 measurements (ACOS B7 lite files) [Mandrake *et al.*, 2015] from 6 September 2014 to 10 February 2016 were used for this study. This represents a majority of the currently available OCO-2 measurements, as the satellite was launched in the summer of 2014. As was done for the simulated measurements, the prefilter of Taylor *et al.* [2012, 2016] was used to eliminate scenes contaminated by clouds and aerosols. Despite this, some poor retrievals remain in the data set, typically due to uncorrected cloud and aerosol effects. The ACOS B7 “lite” files used at the time of this writing only include data passing an additional “warn level”-based filter (warn level less than 17, see Mandrake *et al.* [2013, 2015] for details).

OCO-2 nadir and glint measurements over land and glint measurements over ocean were used for this study. Glint geometry, where the satellite views a surface footprint near the Sun glint spot on the Earth’s surface, is primarily used over oceans but, due to satellite maneuvering restrictions, is also used over land. Land has a sufficiently strong surface reflectance in glint geometry and thus enables the use of glint measurements along with nadir (downward looking) measurements. Target mode measurements, where OCO-2 dithers across a specific target and gathers thousands of measurements, were excluded from the main analysis. This was to avoid having the statistics overly influenced by a large number of measurements collocated with a small number of validation measurements. The target mode measurements, however, agreed with our overall conclusions (see Table S3 in supporting information). Figure 2 shows the location of the 282 SuomiNet stations, 83 AERONET stations, 12 IGRA stations, and 229,390  $0.25^\circ \times 0.25^\circ$  AMSR2 grid cells that had at least one collocated OCO-2 measurement for this study.



**Figure 4.** RMSD between MERRA-2, ECMWF, and OCO-2 TCWV and all four validation sources: SuomiNet, AERONET, IGRA, and AMSR2.

As previously stated, OCO-2 uses ECMWF model output as its meteorological prior. This gave us an opportunity to see if the OCO-2 retrieval is able to improve upon model output, which would indicate that OCO-2 TCWV measurements may be useful in improving numerical prediction models. Additionally, we collocated OCO-2 TCWV measurements with the Modern-Era Retrospective analysis for Research and Applications (Version 2 of MERRA-2) [Bosilovich *et al.*, 2015], to provide a model comparison independent of the OCO-2 retrieval framework. MERRA-2 is a 3-hourly,  $0.625^\circ \times 0.5^\circ$  atmospheric reanalysis produced by the NASA Global Modeling and Assimilation Office.

#### 4. Validation

Comparing OCO-2 TCWV measurements to our four validation sources, Figure 3 demonstrates that ACOS is able to retrieve TCWV with relatively high accuracy and small biases. The ECMWF TCWV values, used as the prior, have RMSDs of about 2.2mm, 3.4mm, 2.6mm, and 2.3mm relative to SuomiNet, AERONET, IGRA, and AMSR2, respectively (see Figure S3 and Table S4 in the supporting information). The OCO-2 retrievals (Figure 3) are able to reduce these RMSDs down to about 1.3mm, 2.1mm, 1.8mm, and 0.9mm. The correlation coefficients relative to the prior are improved against all four validation sources and represent a reduction in error variance of 66%, 69%, 55%, and 87% for SuomiNet, AERONET, IGRA, and AMSR2, respectively. The mean bias relative to SuomiNet, IGRA, and AMSR2 are 0.3, 0.4mm, and  $-0.4$ mm, respectively, while the AERONET TCWV measurements appear to be low biased by approximately 1.4mm (see Table S3 in the supporting information). The slope of the best fit line for AERONET is about 1.07 which equates to a low bias of 7% relative to the retrieved OCO-2 TCWV values. In addition to ECMWF, MERRA-2 was also found to have worse error statistics than OCO-2, relative to the validation sources. We found RMSDs of 2.8mm, 3.4mm, 3.3mm, and 2.8mm relative to SuomiNet, AERONET, IGRA, and AMSR2, respectively (see Figure S4 and Table S5 in the supporting information). A summary of the RMSDs between MERRA-2, ECMWF, and OCO-2 and the four validation sources is shown in Figure 4.

Regional biases were difficult to examine for SuomiNet, AERONET, and IGRA due to their limited global coverage. The comparison of OCO-2 to AMSR2, however, showed small latitudinal biases ( $<5\%$ ) in TCWV,

with AMSR2 having larger TCWV values, especially in the tropics and far southern latitudes (see supporting information Figure S5). Additional study is needed to identify the source of these differences.

Finally, our results were not significantly dependent on the observation mode (nadir, glint, or target) of OCO-2, nor were they dependent on the quality flag (a binary flag derived from several metrics, which indicates the overall quality of the final  $X_{\text{CO}_2}$  product) or warn level. For example, the RMSD between OCO-2 and SuomiNet TCWV for all quality flags is 1.38mm, compared to 1.34mm for only “good” quality flags. This indicates that potentially many more OCO-2 measurements with “low-quality”  $X_{\text{CO}_2}$  values may still have a TCWV measurement with comparably small errors. This is partly because the precision requirements for TCWV are less stringent than  $X_{\text{CO}_2}$ , i.e., about 1 part in 10–60 (1mm precision for a typical range of TCWV values) versus 1 part in 200 for  $X_{\text{CO}_2}$  (2 ppm precision for typical  $X_{\text{CO}_2}$  values).

## 5. Discussion

Our initial analysis of retrievals performed on synthetic measurements demonstrated that ACOS can accurately retrieve TCWV in simulated conditions and that improvement over the prior in real retrievals is to be expected. The comparison of OCO-2 TCWV measurements to four independent validation sources revealed that OCO-2 is able to accurately and precisely measure TCWV. Small biases and standard deviations were found when OCO-2 TCWV was compared to SuomiNet, IGRA, and AMSR2, while it was found that AERONET may have a mean low bias of approximately 1.4mm (7%). This is approximately in agreement with the 5–6% low bias in AERONET found by *Pérez-Ramírez et al.* [2014]. The small biases between OCO-2 and SuomiNet (+0.34mm), IGRA (+0.41mm), and AMSR2 (−0.44mm) may partly be a result of biases in SuomiNet, IGRA, and AMSR2 themselves, as absolute water vapor calibration is difficult to achieve. However, these bias and scatter estimates, composed of errors in OCO-2, errors in the validation sources, and spatial and temporal collocation errors, still provide a useful upper limit on the true OCO-2 TCWV errors. Using the most accurate validation source over land (SuomiNet) and our sole validation source over ocean (AMSR2) leads to a TCWV RMSD upper limit of 0.9–1.3mm. This range is larger than that predicted by our simulated tests. Potential reasons for the larger TCWV RMSDs between OCO-2 and the validation sources include imperfect spectroscopy, aerosol and cloud contamination, other forward model errors, and collocation errors. The comparison of OCO-2 to the four validation sources suggests that the error statistics of the OCO-2 TCWV product are not substantially different over land and ocean. This is in contrast to other operational instruments that perform poorly over certain surface types. MERIS, for example, is sensitive to aerosols and their distribution over ocean surfaces, which can result in large errors ( $\geq 5\text{mm}$ , *Lindstrot et al.* [2012]). OCO-2, however, is able to continuously view Sun glint during its orbits over ocean, resulting in high signal-to-noise ratios and thus less sensitivity to aerosol layers.

As this study was done with the operational ACOS algorithm, which was designed for  $\text{CO}_2$  and only contained  $\text{H}_2\text{O}$  as an ancillary product, improvements specifically related to water vapor might enable even more accurate  $\text{H}_2\text{O}$  retrievals from OCO-2. Upgrades to the water vapor spectroscopy, improved aerosol parameterizations, and more elaborate water vapor retrieval schemes could all result in more information about water vapor being extracted from the measured radiances. For example, above-cloud retrievals of water vapor are likely possible with OCO-2, which would vastly increase the number of valid measurements (as cloudy scenes are currently screened out). This analysis, however, is beyond the scope of this study.

Our results give evidence that OCO-2 may be accurate enough to be used as a validation source for reanalysis products as well as other methods of measuring TCWV (e.g., MODIS, MERIS, the Suomi National Polar-orbiting Partnership (NPP), AIRS, and IASI). Additionally, OCO-2 coverage, while limited by its narrow yet dense ground track, covers both land and ocean over much of the low and middle latitudes. This means that these TCWV measurements may be useful in improving numerical weather prediction models, which are dependent on the assimilation of accurate water vapor measurements. However, further work must be done to determine if measurements from OCO-2 can provide water vapor information not already measured by other instruments. Besides showing how OCO-2 is able to improve upon the ECMWF prior, we also briefly compared the MERRA-2 reanalysis product to our validation sources and found that OCO-2 would be able to improve upon MERRA-2 as well. These model RMSDs, visualized in Figure 4, are considerably larger than the RMSDs between OCO-2 and the validation sources, which provides additional evidence that OCO-2 TCWV measurements may be useful for numerical weather prediction and data assimilation applications over land and ocean.

## 6. Conclusions

In this work we validate measurements of total column water vapor from hyperspectral, near-infrared measurements of reflected sunlight made by OCO-2 over both land and ocean. We find that theoretical single-sounding TCWV errors are approximately 0.6mm, while comparisons to validation sources reveals that OCO-2 TCWV measurements are highly accurate, with RMSDs of 0.9–1.3mm and mean biases typically of less than 0.5mm. The results of this study show that OCO-2 is the first space-based instrument to accurately measure the most important natural greenhouse gas (water vapor) simultaneously with the most important anthropogenic greenhouse gas (carbon dioxide) [Crisp, 2015], at high spatial resolution ( $1.3 \times 2.3\text{km}^2$ ). These OCO-2 TCWV measurements may be useful regarding the improvement of numerical weather prediction models and reanalysis products along with acting as a validation source for other instruments. Additionally, future satellites with OCO-2-like capabilities, such as OCO-3, MicroCarb, GOSAT-2, and CarbonSat, may be able to measure water vapor with the same or better accuracy than OCO-2.

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