Global and Regional Water Vapor Trends from 2006 to 2023 using Climatology Constructed from STAR Multi-Radio Occultation Mission Data

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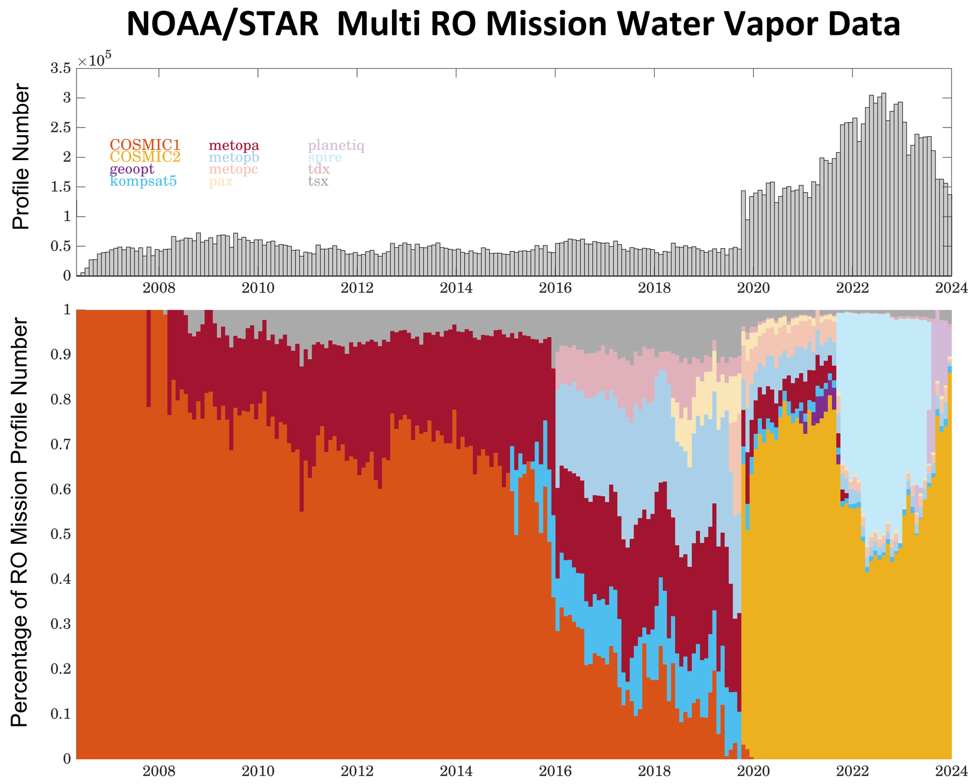
Introduction

- Atmospheric water vapor is a crucial component of the Earth's climate system and is critical in regulating the global energy balance and hydrological cycle. Accurate estimates of atmospheric water vapor profiles in the troposphere are crucial for understanding the mechanisms contorting Earth's climate system.
- Current long-term global water vapor climate data records (CDRs) were mainly constructed from infrared satellite sensors over lands and oceans or microwave radiometers over the oceans. While the infrared measurements cannot penetrate the clouds, microwave radiometer measurements have more significant uncertainty under precipitation conditions.
- The global GNSS radio occultation (RO) temperature and water vapor data are invaluable for climate studies due to their accurate all-sky observations over lands and oceans. The consistency of multi-RO mission water vapor data is crucial for long-term global climate studies, which require reliable and consistent data to identify trends, patterns, and changes in atmospheric water vapor.
- In this study, the water vapor data from multiple RO missions (e.g., COSMIC-1, COSMIC-2, MetOp A/B/C, KOMPSAT-5, GeoOptics, PlanetiQ, and Spire) consistently retrieved with the same NOAA Center for Satellite Applications and Research (STAR) 1DVAR retrieval model are used to establish long-term CDRs and to study the water vapor trends.
- The time series of water vapor data from multi-RO missions are processed to derive total-column water vapor (TCWV) and partial-column water vapor (PCWV) . Sampling error removal and de-seasonalization to filter out the annual oscillation are performed to prepare the data for estimating global, ocean, land, and regional WV trends.
- The difference between RO TCWV and PCWV data in detecting trends are evaluated through comparison with the ERA5 global reanalysis data, to understand the consistency and difference (over cloudy regions) between RO and reanalysis models. Results show that RO and reanalysis data have similar global and regional water vapor trends.
- We also examined their water vapor variations under the El Niño or La Niña conditions and examined the close relationship between temperature and water vapor growth under climate change governed by the Clausius-Clapeyron equation.

NOAA/STAR Multi RO Mission Water Vapor Data



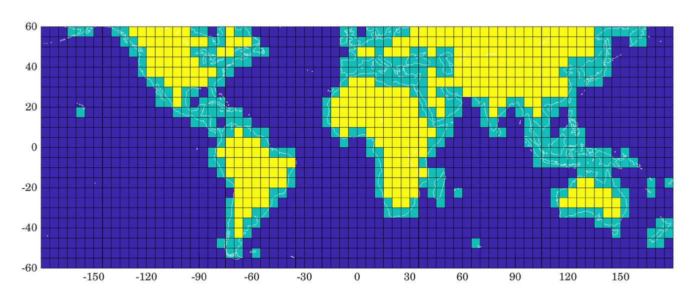
- NOAA/STAR multi-RO mission 1Dvar WetPrf (neutral atmospheric temperature and water vapor) data are available at https://gpsmet.umd.edu/star_gnssro/download.html
- NOAA/STAR 1Dvar WerPrf Algorithm Theoretical Basis Documents (ATBD): https://gpsmet.umd.edu/star_gnssro/img/STAR_GNSS_RO_1DVAR_1.0_ATBD.pdf
- Validation of the accuracy and uncertainty of the STAR 1D-Var temperature and water vapor profiles for COSMIC-2 were validated through comparisons with RS41 radiosonde measurements, ERA5 global reanalysis data, UCAR 1D-Var products (wetPrf2), and NOAA Advanced Technology Microwave Sounder (ATMS) and Cross-track Infrared Sounder (CrIS) observations using radiative transfer modeling.
- See Ho, S.-p.; Kireev, S.; Shao, X.; Zhou, X.; Jing, X. Processing and Validation of the STAR COSMIC-2 Temperature and Water Vapor Profiles in the Neutral Atmosphere. *Remote Sens.* **2022**, *14*, 5588.
- 2006-2023 STAR multi-RO mission WetPrf data used
  - COSMIC-1, COSMIC-2, GeoOptics, Kampsat-5, MetOp- A/B/C, PlanetiQ, PAZ, Spire, TerraSAR-X. and TanDEM-X

TCWV/PCWV Calculation and Sampling Error Removal

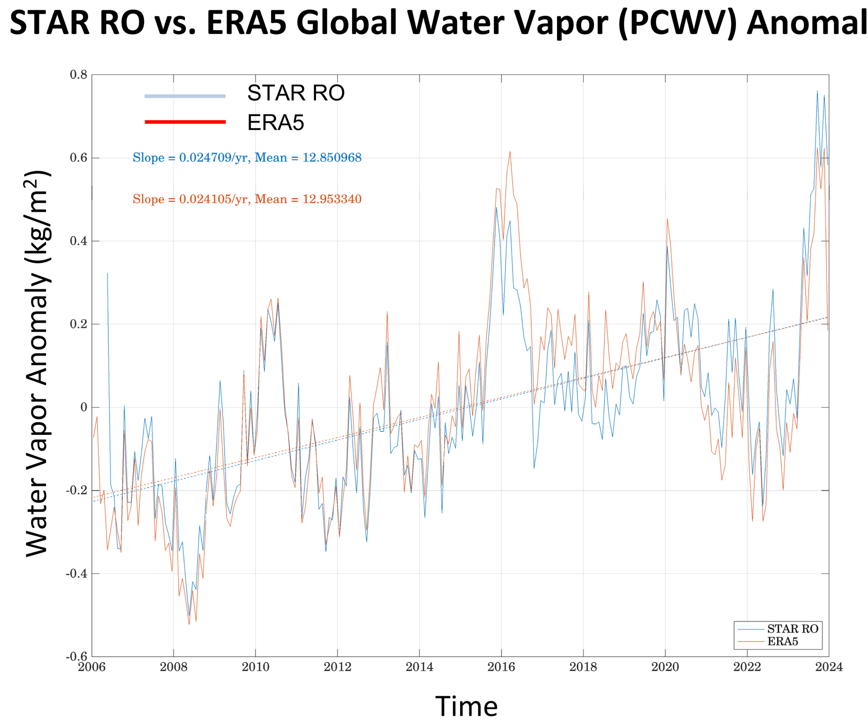
- Total Column Water Vapor (TCWV): integrate WV above surface
  - For RO data, padding of water vapor below the RO penetration depth is needed over both land and ocean.
    - The penetration depth for different RO missions varies over time and among RO missions.
    - RO WV usually has negative biases relative to ERA5; The padding can introduce additional bias variation over time
- Partial Column Water Vapor (PCWV): integrate WV above 850 hPa for both RO and ERA5 WV profiles with no padding for RO WV
- Water vapor time series analysis and trending

1. Monthly collocated RO and ERA5 water vapor time series
2. Sampling error removal
   - Account for the difference between the orbital-specific distribution of RO measurements and uniformly-distributed global ERA5 data
   - Account for variation of RO profile number
3. De-seasonalize water vapor time series data to filter out the annual oscillation
4. Linear regression to estimate long term water vapor trends at different spatial scales: Global, Land, Ocean, and 10º x 10º global grids.

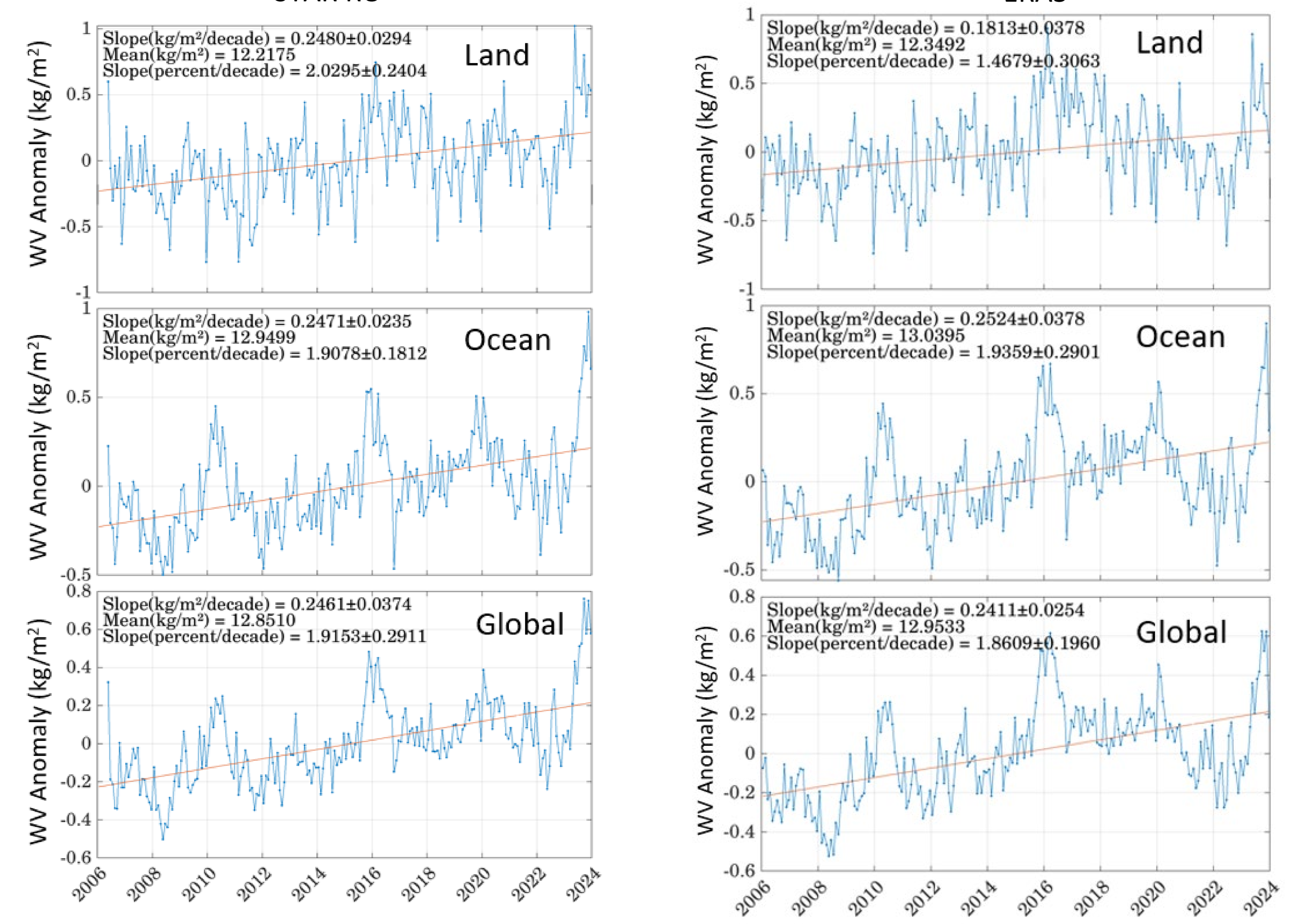
Land-Ocean Mask



STAR RO vs. ERA5 Global Water Vapor (PCWV) Anomaly



Global/Ocean/Land Water Vapor (PCWV) Trend Comparison

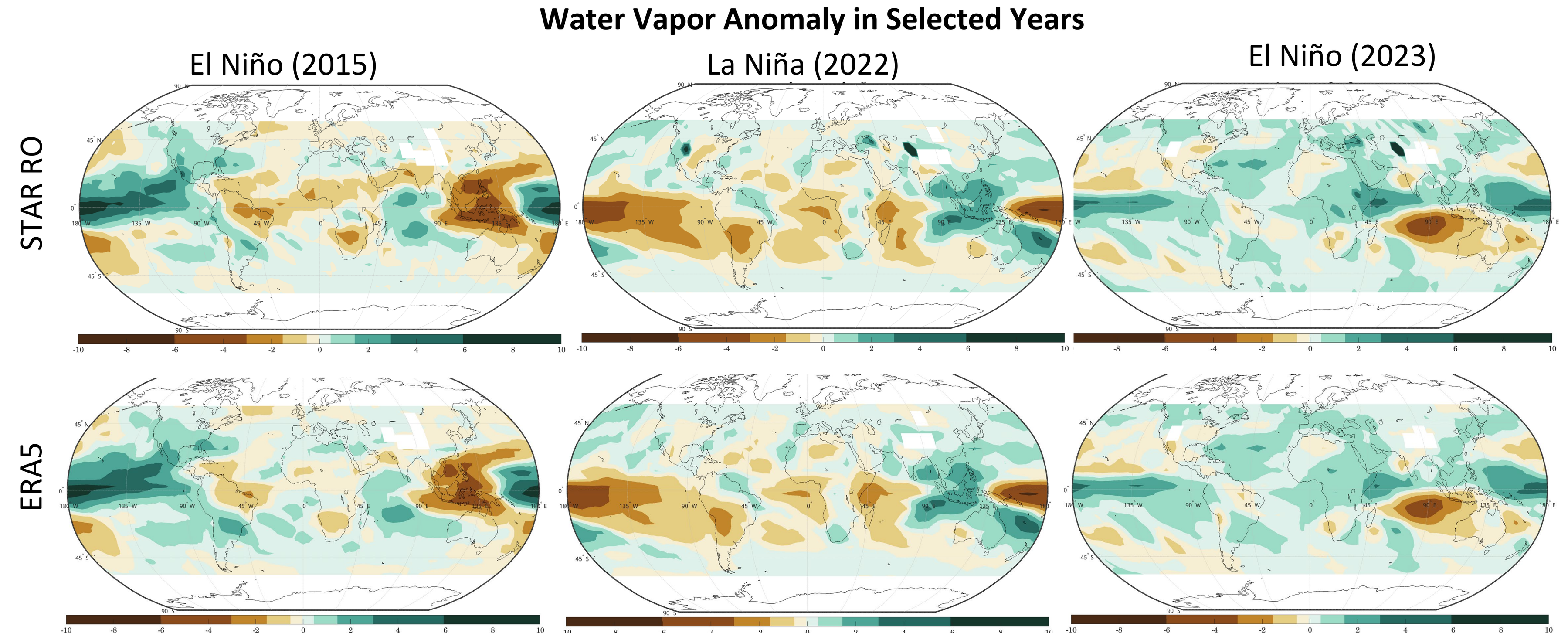


Water Vapor Tend (%/Decade) Comparison

	STAR RO PCWV (%/decade)	ERA5 PCWV (%/decade)	STAR RO TCWV (with padding) (%/decade)	ERA5 TCWV
Ocean	1.91±0.18	1.94±0.29	1.57±0.16	1.82±0.21
Land	2.03±0.24	1.47±0.31	1.25±0.18	1.45±0.20
Global	1.92±0.29	1.86±0.20	1.98±0.21	1.74±0.15

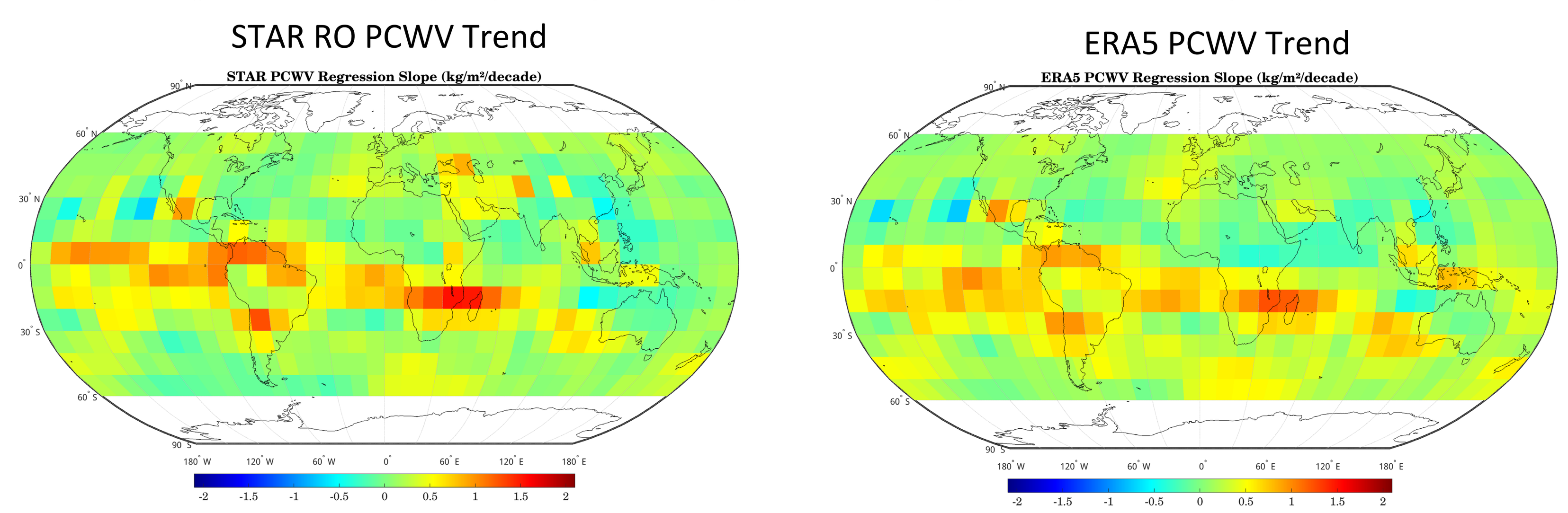
- STAR RO and ERA5 PCWV trends are consistent over ocean and global (dominated by WV over ocean)
- The WV trend over land has larger uncertainty due to WV transportation from ocean and terrain-related cut-off in RO WV
- Difference between ERA5 TCWV and PCWV is about 0.1%/decade.

Water Vapor Anomaly in Selected Years

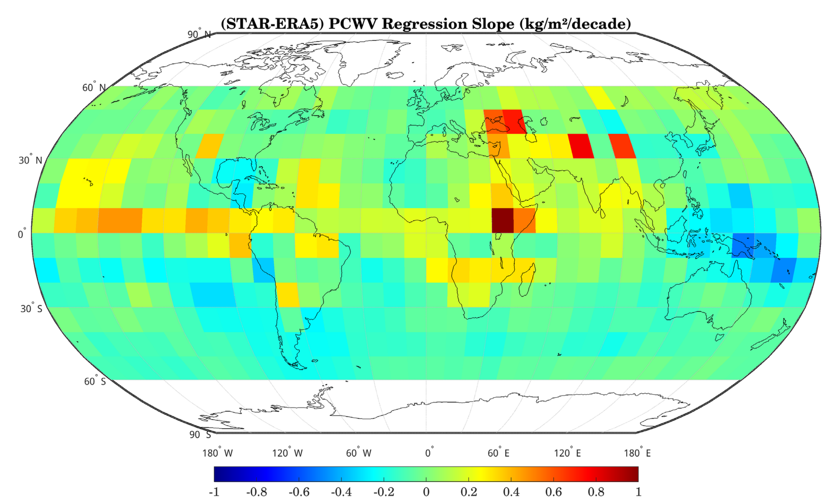


- PCWV anomalies from STAR RO and ERA-5 are highly consistent with regards to spatial distributions and amplitudes during the El Nino/La Nina events. Both products manifest similar, intense water vapor increase and decrease occurring in the tropical central-eastern Pacific during two El Nino years (2015 and 2023) and one La Nina year (2022), respectively.

Regional Water Vapor (PCWV) Trend (kg/m²/Decade) (STAR RO vs. ERA5) Comparison

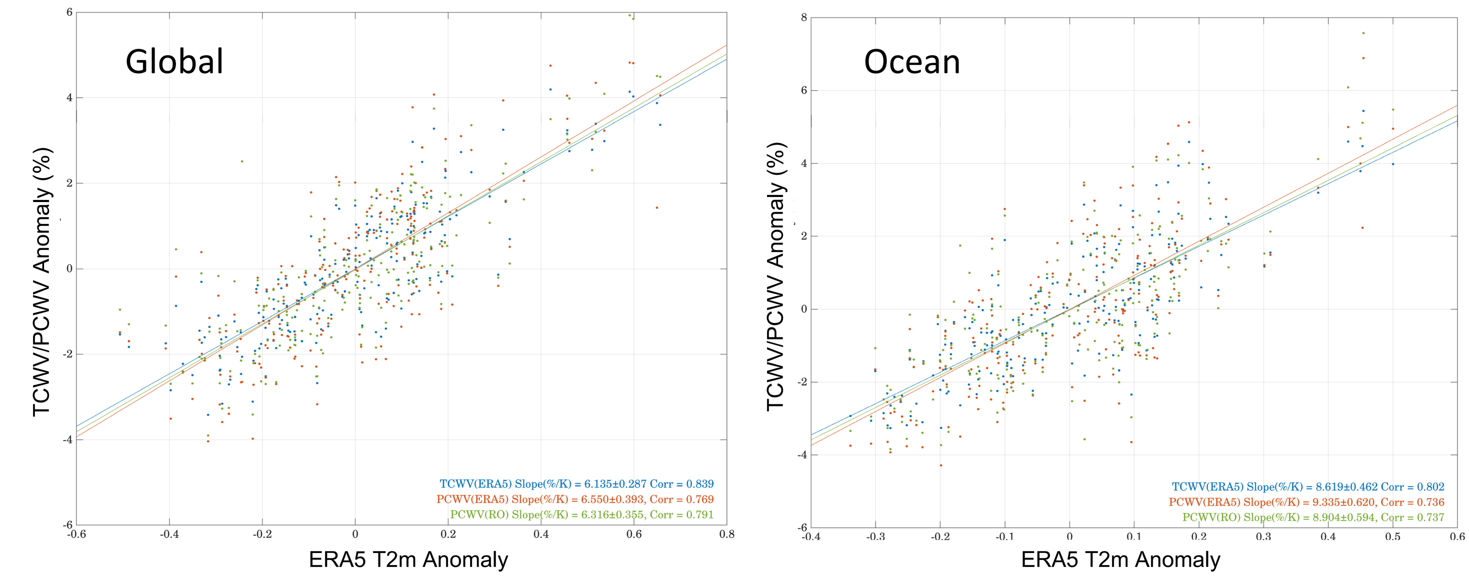


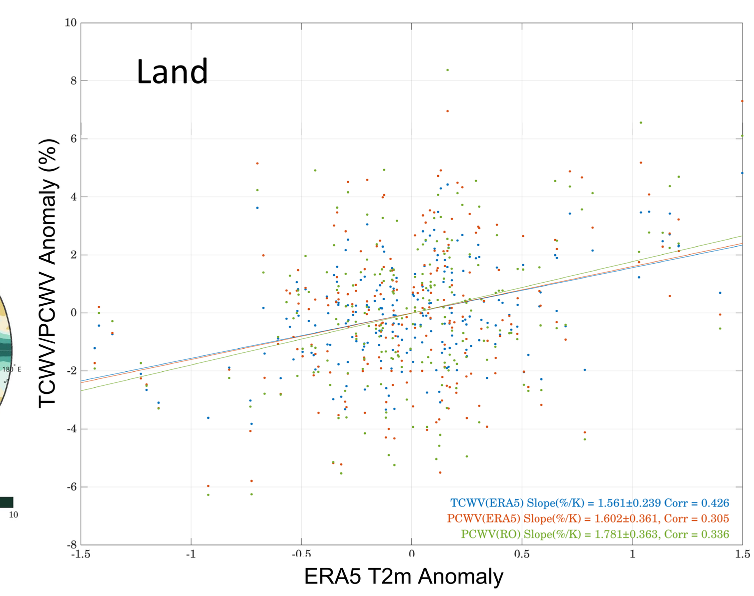
STAR RO – ERA5 Water Vapor Trend Difference



- Regional (10ºx10º grid) water vapor trends from STAR RO and ERA5 generally agree
- Regional water vapor trend variabilities with strong increasing and decreasing slopes are observed in the tropics and sub-tropics regions.
  - Increasing WV trends over tropical Pacific, Atlantic and Indian ocean region and small decreasing trend over the west side of Indo-Pacific Warm Pool (IPWP) region.
- Differences between STAR RO and ERA5 water vapor trends are primarily in the Intertropical Convergence Zone (ITCZ) area with frequent occurrences of convection (deep clouds).
  - Larger WV trends over equatorial Pacific Ocean and weaker WV trends around IPWP region from RO in comparison with ERA5; Possibly due to the RO's capability of cloud penetration over the ITCZ region.

RO and ERA5 Water Vapor Growth vs. ERA5 Surface Temperature (t2m) Growth





- The increase of global water vapor can be attributed to the increase global surface temperature
- Close relationship between temperature and saturation water vapor pressure is governed by the Clausius-Clapeyron equation:
  - Approximately 7% increase in atmospheric water vapor per 1 K global temperature rise
- Our analysis of RO and ERA5 WV anomaly vs. ERA5 surface temperature anomaly show that such a relationship in general holds over ocean and global.
- Over land, the relationship is quite weak. This can be due to the water vapor transportation from ocean to land.

Water Vapor vs. ERA5 Surface Temperature (t2m) Growth (%/K)

	Ocean	Land	Global
STAR RO PCWV vs. ERA5 T2m (%/K)	8.90±0.59	1.56±0.24	6.32±0.36
ERA5 PCWV vs. ERA5 T2m (%/K)	9.34±0.62	1.60±0.36	6.55±0.39
ERA5 TCWV vs. ERA5 T2m (%/K)	8.62±0.46	1.78±0.36	6.14±0.29

Summary

- In this study, long-term (2006-2023) water vapor data from multiple RO missions consistently retrieved with the same NOAA STAR 1DVAR retrieval model are used to establish long-term CDRs, derive time series of sampling error removed PCWV from RO data, and to study the water vapor trends.
- The trends in PCWV from STAR RO and ERA5 are consistent both over the ocean and globally (largely influenced by water vapor over the ocean), showing a growth rate of approximately 1.9% per decade. The difference between TCWV and PCWV in ERA5 is around 0.1% per decade.
- The anomalies in PCWV observed by STAR RO and ERA5 display strong consistency in both spatial distribution and amplitude during El Niño and La Niña events.
- Regional water vapor trends from STAR RO and ERA5 generally align, showing significant variability with both strong increasing and decreasing slopes in tropical and subtropical regions.
- The main differences between STAR RO and ERA5 water vapor trends are observed in the ITCZ, potentially due to the unique capability of RO to penetrate the clouds in this region.
- The analysis of water vapor anomalies from RO and ERA5, compared to ERA5 surface temperature anomalies, demonstrates that the relationship between temperature and water vapor growth, as described by the Clausius-Clapeyron equation, generally holds true over both oceanic and global scales in the context of climate change.

Acknowledgements

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect those of NOAA or the Department of Commerce.