How has global warming impacted the altimeter wet path delay over the altimetry record?

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Introduction and scope

- Wet path delay (WPD)
  - Motivation
  - Objective

30-year analysis of air temperature and water vapor (1993-2022)

Impact of global warming on radar altimeter WPD

Main conclusions and take-home message
Wet Path Delay (WPD)

- Thirty years of satellite radar altimetry allow the monitoring of sea level changes at global and regional scales.

- The accurate determination of these changes depends directly on the estimation of the wet path delay (WPD) in the altimeter measurements.
  
  ✓ **It is crucial to ensure the accuracy and long-term stability of the WPD estimation.**

- With a maximum instantaneous value of 50 cm, the WPD is mainly due to the presence of water vapor in the atmosphere.
  
  ✓ **WPD has a direct and strong dependence on the water vapor content in the atmosphere and possesses its characteristics, namely the spatial and temporal variability.**
Water vapor and WPD

*We are here.*

Water vapor (left) and WPD (right) for 19-21 Sep 2017 (Hurricane Maria over Puerto Rico)
Motivation and objective

- Water vapor in the atmosphere increases at a global average rate of 7% per 1°C increase in air temperature.

  ✓ Due to global warming, the Earth’s atmosphere is getting wetter.

- Since WPD is mainly dependent on atmospheric water vapor, which in turn depends on air temperature, **WPD has a direct dependence on air temperature**.

- **Objective**: to assess and quantify the impact of global warming on WPD over the satellite altimetry record (1993-2022).
Data

- ECMWF ERA5 monthly averaged data on single levels
  - Spatial resolution: $0.25^\circ \times 0.25^\circ$
  - Time span: 1993-2022 (30 years)
- Analyzed variables:
  - near surface air temperature (2m temperature, $T_{2m}$), in °C;
  - atmospheric water vapor (total column water vapor, $TCWV$), in mm or kg m$^{-2}$;
  - other variables (temperature and atmospheric humidity) for the computation of WPD at sea level.

Global analysis only over sea (ERA5 land-sea mask).
Temperature and water vapor: 30-year temporal analysis

Annual global mean anomalies of $T_{2m}$ and $TCWV$, relative to 1993-2022 averages
($16.68 \, ^\circ\text{C}$ and $26.52 \, \text{mm}$)

Linear trends: $0.18 \, ^\circ\text{C/decade}$ and $0.43 \, \text{mm/decade}$

Annual global means for the 30 years: $T_{2m}$ versus $TCWV$

Linear trend: $2.38 \, \text{mm}/^\circ\text{C}$
($9\%$ of the 30-year average)
Temperature and water vapor: 30-year spatial analysis

↓ Global map of $T_{2m}$ change, in °C, from 1993 to 2022

Global mean: **+0.53 °C**

$(0.18 \text{ °C/decade} \times 3)$

↓ Global map of $TCWV$ change, in mm, from 1993 to 2022

Global mean: **+1.28 mm**

$(0.43 \text{ mm/decade} \times 3)$
WPD: 30-year temporal analysis

↓ Annual global means and anomalies of WPD, relative to 1993-2022 average
(16.50 cm)

![Graph showing annual global means and anomalies of WPD.]

Linear trend: 0.26 cm/decade

↓ Annual global means for the 30 years:
T2m versus WPD

![Graph showing correlation between T2m and WPD.]

Linear trend: 1.44 cm/°C
(9% of the 30-year average)
WPD: 30-year spatial analysis

Global map of WPD change, in cm, from 1993 to 2022

Global mean: +0.79 cm
(0.26 cm/decade × 3)

- On average, WPD has increased 0.8 cm in the last 30 years.
- In some regions, this increase exceeds 2 cm.
Conclusions

Over ocean, for the satellite altimetry period (1993-2022):

✓ **T2m** has increased:
  
  0.18°C/decade
  
  0.53 °C in total

✓ **TCWV** has increased:
  
  0.43 mm/decade
  
  1.28 mm in total

✓ **WPD** has increased:
  
  0.26 cm/decade
  
  0.79 cm in total

✓ **Per 1°C of warming:**
  
  TCWV increases **2.38 mm (9%)**
  
  WPD increases **1.44 cm (9%)**
Take-home message

- Over 1993-2022, WPD has increased at an average rate of 0.26 mm/year over the global ocean, which represents:
  
  ✓ a total increase of 0.8 cm (5%);
  
  ✓ an average rate of 1.44 cm (9%) per 1°C of warming;
  
  ✓ about 8% of the total GMSL trend for about the same period (3.3 mm/year);
  
  ✓ the estimated GMSL trend error (± 0.3 mm/year).

- Due to the global warming over these 30 years, this is a physical signal that should not be misled with any kind of drift.
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