Characteristics of Global Precipitable Water Revealed by COSMIC Measurements

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ICGPSRO, 12-14 May, 2013, Tuoyang, Taiwan
Introduction

- In light of the helpful complementary information provided by GPS RO observations for climate variability, we are looking into the gross features of Precipitable Water (PW) on the globe for its important role in radiation, latent energy and cloud convection.

- PW from FORMOSAT-3/COSMIC GPS RO measurements was analyzed and compared with those derived from Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Scanning Radiometer for Earth Observation System (AMSR-E) during the El Niño-Southern Oscillation (ENSO) events from 2007 to 2011.

- The COSMIC PW over land is also compared with GPS ground-based PW and NCEP global reanalysis for six years (2007-2012).

- We then explore the six-year evolution of the monthly
The Data and Methodology

- Data from 2007 to 2011 (binned into $72 \times 36$ global grids):
  GPS RO retrieved specific humidity
  SSM/I and AMSR-E estimated PWs (taken from Remote Sensing System)

- We only use the available RO retrievals with perigee heights below 1 km. To calculate COSMIC PW, we compensate the layer of void data from the perigee height to the surface by filling the same water vapor value obtained at the perigee height.

<table>
<thead>
<tr>
<th>Year</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amounts</td>
<td>639033</td>
<td>649588</td>
<td>646551</td>
<td>493204</td>
<td>412811</td>
</tr>
<tr>
<td>Perigee height &lt; 3 km</td>
<td>614916</td>
<td>634212</td>
<td>632811</td>
<td>481987</td>
<td>403251</td>
</tr>
<tr>
<td></td>
<td>(96.2%)</td>
<td>(97.6%)</td>
<td>(97.9%)</td>
<td>(97.7%)</td>
<td>(97.7%)</td>
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<tr>
<td>Perigee height &lt; 2 km</td>
<td>582443</td>
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<td>603341</td>
<td>457774</td>
<td>383368</td>
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<tr>
<td></td>
<td>(91.1%)</td>
<td>(93.0%)</td>
<td>(93.3%)</td>
<td>(92.8%)</td>
<td>(92.9%)</td>
</tr>
<tr>
<td>Perigee height &lt; 1 km</td>
<td>465941</td>
<td>486337</td>
<td>485766</td>
<td>367146</td>
<td>307833</td>
</tr>
<tr>
<td></td>
<td>(72.9%)</td>
<td>(74.9%)</td>
<td>(75.1%)</td>
<td>(74.4%)</td>
<td>(74.6%)</td>
</tr>
</tbody>
</table>
The Data and Methodology

- **SSM/I** (onboard the DMSP F15 satellite)
  seven microwave frequency channels (19.35, 37.0, 85.5 GHz with dual-polarization; 22.235 GHz with V-polarization only) with a scanned swath of about 1400 km in width.

- **AMSR-E** (onboard the NASA Aqua satellite)
  twelve microwave frequency channels (6.9 GHz to 89.0 GHz with dual-polarization) with a scanned swath of about 1445 km in width.

  SSM/I and AMSR-E PWs obtained from RSS are available in $0.25^\circ \times 0.25^\circ$ grids.

- **Other data:**
  NCEP global reanalysis, the gridded global precipitation rate from GPCP, outgoing longwave radiation (OLR), and SST.

<table>
<thead>
<tr>
<th>Year</th>
<th>DJF</th>
<th>JFM</th>
<th>FMA</th>
<th>MAM</th>
<th>AMJ</th>
<th>MJJ</th>
<th>JJA</th>
<th>JAS</th>
<th>ASO</th>
<th>SON</th>
<th>OND</th>
<th>NDJ</th>
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<tr>
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<td>-0.9</td>
<td>-0.7</td>
<td>-0.5</td>
<td>-0.3</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
<td>0.8</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2007</td>
<td>0.7</td>
<td>0.3</td>
<td>-0.1</td>
<td>-0.2</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.6</td>
<td>-0.9</td>
<td>-1.1</td>
<td>-1.2</td>
<td>-1.4</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.2</td>
<td>-0.9</td>
<td>-0.7</td>
<td>-0.5</td>
<td>-0.3</td>
<td>-0.2</td>
<td>-0.1</td>
<td>-0.2</td>
<td>-0.4</td>
<td>-0.7</td>
</tr>
<tr>
<td>2009</td>
<td>-0.9</td>
<td>-0.8</td>
<td>-0.6</td>
<td>-0.2</td>
<td>0.1</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>1.0</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>2010</td>
<td>1.6</td>
<td>1.4</td>
<td>1.1</td>
<td>0.7</td>
<td>0.2</td>
<td>-0.3</td>
<td>-0.8</td>
<td>-1.2</td>
<td>-1.4</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>2011</td>
<td>-1.4</td>
<td>-1.3</td>
<td>-1.0</td>
<td>-0.7</td>
<td>-0.4</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.3</td>
<td>-0.6</td>
<td>-0.8</td>
<td>-1.0</td>
<td>-1.0</td>
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<tr>
<td>2012</td>
<td>-0.9</td>
<td>-0.7</td>
<td>-0.5</td>
<td>-0.3</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.3</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Oceanic Nino Index (ONI) for 2006-2012. The ONI is defined as the anomaly of three-month averaged SST over the Niño 3.4 ($5^\circ$N-$5^\circ$S, 120$^\circ$-170$^\circ$W) with respect to the climate average (1971-2000).
Seasonal average of the winter months from December 2007 to February 2008 (the cold ENSO event) for (a) sea surface temperature (°C), (b) precipitation rate (mm d⁻¹), (c) NCEP PW (mm), and (d) the horizontal divergence of water vapor flux (g kg⁻¹ s⁻¹) (color shape) and horizontal wind (m s⁻¹) at 850 hPa.
2009 El Niño (warm event)

Seasonal average of the winter months from December 2009 to February 2010 (the warm ENSO event).
Seasonal average of PW (mm) at bins in the winter months for (a) the cold event (December 2007 to February 2008) for COSMIC, (b) as in (a) but for AMSR-E, and (c) for the differences in PW between COSMIC and AMSR-E; (d), (e) and (f) as in (a), (b) and (c), respectively, but for the warm event (December 2009 to February 2010).
(a) Scatter plot of COSMIC PW and AMSR-E PW at collocated bins in 2007-2008 DJF monthly mean, (b) same as (a) but for 2009-2010 DJF monthly mean, (c) same as (a) but for COSMIC and SSM/I F15, and (d) same as (c) but for 2009-2010 DJF monthly mean. The root-mean-square differences, correlations, mean differences and their standard deviations are given.
Time variations of monthly mean PW (mm) in 2007-2011 for COSMIC (blue) SSM/I (green), and AMSR-E (red). The upper and lower three curves are the PW averages in the equatorial western Pacific (EWP) (0°-10°S, 150°E-170°E) and the equatorial eastern Pacific (EEP) (0°-10°S, 120°W-140°W), respectively.
Zonal seasonal mean differences of PW between constant fit of COSMIC and AMSR-E, SSM/I, quadratic fit and least-square fit of COSMIC, respectively, in the two periods of (a) December 2007 to February 2008 (the cold ENSO event) and (b) December 2009 to February 2010 (the warm ENSO event).
Latitudinal variations of monthly mean PW (mm) in 2007-2011 for (a) NCEP global reanalysis, (b) COSMIC, (c) SSM/I, and (d) AMSR-E. Note that the data for AMSR-E are available only before September 2011 as seen in (d).
Anomaly of seasonal average PW (mm) in the winter months from COSMIC for (a) 2007 cold event, (b) 2009 warm event, (c) 2010 cold event; (d), (e) and (f) as in (a), (b), (c), respectively, but from AMSR-E.
Scatter plots of anomaly of seasonal average PW (mm) at collocated bins in the winter months in the 2007 cold event for (a) COSMIC and SSM/I F15, (b) COSMIC and AMSR-E, and (c) SSM/I F15 and AMSR-E. (d), (e) and (f) as in (a), (b) and (c), respectively, but for the 2009 warm event. (g), (h) and (i) as in (a), (b) and (c), respectively, but for the 2010 cold event. Red line in each panel indicates the linear regression.
Amazon Basin, Central Africa, Tibetan Plateau, Central Australia
Time variations of monthly sample average PW (mm) in 2007-2012 for co-located COSMIC RO (blue) and ground-based GPS (red). (a), (b) and (c) are stations in high latitude area; (d), (e) and (f) same as (a), (b) and (c) but in middle latitude area; (g), (h) and (i) same as (a), (b) and (c) but in low latitude area.
(a) Scatter plot of COSMIC PW and Ground-based GPS PW collocated samples in 2007-2012 for high latitude area (60° S - 90° S; 60° N - 90° N), (b) same as (a) but for middle latitude area (30° S - 60° S; 30° N - 60° N), (c) same as (a) but for low latitude area (30° S - 30° N).

Collocation: in 150 km, in 1.5 h, Difference of both heights less than 0.5 km.
Latitudinal average of monthly mean (a) COSMIC PW, (b) Ground-based GPS PW collocated in 2007-2012.
Time variations of monthly mean PW (mm) (not collocated) in 2007-2012 for COSMIC (blue) and NCEP global reanalysis (black). (a) PW averages in the Central Africa (10S-10N, 15E-35E) (b) Amazon basin (0N-10S, 50W-70W), (c) Tibetan Plateau (27.5-37.5N, 80E-100E) and (d) Central Australia (20S-30S, 120E-140E), respectively.
Conclusions

- For the three ENSO events in 2007-2011, monthly mean binned COSMIC PW results are in a very high correlation (up to 0.98) with those of SSM/I and AMSR-E over the ocean, generally with root-mean-square differences less than 4 mm. PW retrievals from the three satellites are also of similar latitudinal variations.

- The PW is slightly underestimated by GPS RO, in particular, in the tropical regions. This underestimate may be caused partially by the fact that not all RO measurements can reach the surface.

- Inter-satellite PW anomaly comparisons for the winter months in the ENSO events, with respect to those during the neutral (non-ENSO) months, show consistent ENSO signals with major PW anomaly near the central Pacific in the warm event and near the Indonesian region and east of Australia in the two cold events.

- However, the 2007/2008 La Niña is somewhat less correlated for COSMIC with AMSR-E and SSM/I. For the stronger 2010/2011 La Niña, their PW anomalies are in higher correlations of about 0.8.
The COSMIC PW over land is also compared with GPS ground-based PW for six years (2007-2012). On collocated comparisons at specific sites, COSMIC PW is generally within very small deviation from GPS ground-based PW.

On global collocated comparisons, both GPS RO and ground-based PWs exhibit very high correlations (above 0.95) at low, mid-, and high latitudes. The mean bias (-0.68 mm) and standard deviation (4.26 mm) of PW are largest in low latitudes (30°S to 30°N).

COSMIC PWs are used to display the six-year (2007-2012) evolution of the monthly mean PW on several specific regions, as an illustration of robustness and effectiveness of the RO data compared to NCEP global reanalysis (and ground-based PW):

- **Amazon Basin-Plateau**: Type annual, stronger inter-annual
- **Central Africa-Central Africa**: Less annual, stronger semi-annual
- **Tibetan Plateau-Gaussian**: Type annual, stronger inter-annual
- **Central Australia-Gaussian**: Type annual, stronger inter-annual (2010/2011 flood)

We are looking forward to having FORMOSAT-7/COSMIC-2 data.
THANKS.
Global Variation of Mean Latitudinal COSMIC PW

Zonal mean distributions of COSMIC PW (mm) in different latitudinal zones for monthly mean at March (red), June (blue), September (green) and December (pink) in (a) 2007, (b) 2008, (c) 2009, (d) 2010, and (e) 2011. (f) Anomaly of zonal mean PW in December from 2007 to 2011 averages.
Zonal seasonal mean PW of COSMIC, AMSR-E and SSM/I in the two periods (a) December 2007 to February 2008 (the cold ENSO event) and (b) December 2009 to February 2010 (the warm ENSO event). (c) and (d) as in (a) and (b), respectively, but for their differences.
Vertical profiles of specific humidity from COSMIC in the equatorial western Pacific (0°-10°S, 150°E-170°E) at (a) (2.27 °S, 163.67 °E), (b) (2.22 °S, 169.76 °E) and (c) (8.24 °S, 163.87 °E), and in the equatorial eastern Pacific (0°-10°S, 120°W-140°W) at (d) (6.92 °S, 130.77 °W), (e) (9.66°S, 125.70 °W) and (f) (6.87°S, 127.54 °W) in February 2010. The green (pink) line indicates the extrapolated profile from the perigee height of the RO by a quadratic fit (a least-square fit). The red asterisks represent the coincident specific humidity from NCEP global reanalysis at the RO point.