Impact of GPS RO Data on the Prediction of Tropical Cyclones

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Five Necessary Conditions for Tropical Cyclogenesis

1. Sea surface temperature above 26.5 – 27°C
2. A deep surface-based layer of conditional instability
3. Enhanced values of cyclonic low-level absolute vorticity
4. Organized deep convection in an area with large-scale mean ascent and high midlevel humidity; and
5. Weak to moderate vertical wind shear

Tory and Frank (2010), based on a revision of Gray’s (1968) first global TC genesis climatology
Precipitable Water Errors and Missed TCs: Day 7

0-h GFS Forecasts (2014)

168-h GFS Forecasts (2014)

PWTR (mm)(average 0-15N)

8-Aug
18-Aug
28-Aug
7-Sep
17-Sep
27-Sep
7-Oct
17-Oct
27-Oct
0 60E 120E 180 120W 60W

0 60E 120E 180 120W 60W

O = Missed TC

Courtesy of Davis and Galarneau
NCEP GFS Initial Condition

Ten day forecasts initialized at 2017-09-28-00

Precipitable Water + 850 hPa Wind vector + 200 hPa Height and wind speed
NCEP 120 and 240 h FCST

Analysis

Forecast

120 h FCST

240 h FCST
Skill of Tropical Cyclogenesis (2004-2014)
Prediction by Global Models

Challenges for model prediction:
- Lack of observations over the ocean
- Modeling of physical processes

False Alarm = 1 – success ratio

From Halperin et al 2016
Typhoon Nuri (2008)

- Formed at 1800 UTC 16 August 2008 over Western Pacific Ocean.
- WRF Forecasts from 1800 UTC 14 August 2008 with either ECMWF or NCEP global analysis fail to predict the genesis of Nuri.
- Perform 3-Day data assimilation with and without the use of GPS RO data, starting at 1800 UTC 11 to 1800 UTC 14 August 2008.
- 4.5 Day WRF forecasts begin at 1800 UTC 14 August 2008.
WRF (15 km) Forecast initialized at 1800 UTC 14 August 2008

GFS I.C. – No Genesis

ECMWF I.C. – 30 h delay

48h FCST
Valid at 1800 UTC 16 August

102h FCST
Valid at 0000 UTC 19 August

SLP + 10m wind speed
# Experimental Design

<table>
<thead>
<tr>
<th>Model</th>
<th>WRF and WRFDA v3.3.1</th>
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</thead>
<tbody>
<tr>
<td>Model grids</td>
<td>600x400x45</td>
</tr>
<tr>
<td>H-resolution</td>
<td>15 km</td>
</tr>
<tr>
<td>Model top</td>
<td>30 hPa</td>
</tr>
<tr>
<td>I.C. &amp; B.C.</td>
<td>NCEP 0.5°x0.5°</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Physical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphysics</td>
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<tr>
<td>Longwave Radiation</td>
</tr>
<tr>
<td>Shortwave Radiation</td>
</tr>
<tr>
<td>Surface Layer</td>
</tr>
<tr>
<td>Land Surface</td>
</tr>
<tr>
<td>Planetary Boundary layer</td>
</tr>
<tr>
<td>Cumulus Parameterization</td>
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</tbody>
</table>

### DA starts

- Forecast Time
- 3 days cycling

### Forecast

- Forecast starts 2 day prior to genesis time

**NO GPS (GTS):** assimilate operational available data at Taiwan’s CWB (no radiance)

**GPS (EPH):** assimilation operational available data + GPS RO data by using the local operator
WRF Model Forecast Starting at 18UTC 14 August 2008, Following 3-day of Data Assimilation

No GPS RO Data

With GPS RO Data

Integrated Cloud Hyrdometeors
WRF Model Forecast After 3-day of Data Assimilation
Starting at 1800 UTC 14 August 2008

No GPS RO Data

With GPS RO Data

Sea Level Pressure (contour) and PW (color)
Time-Height section of differences in water vapor (contour) and vertical motion (color) between experiments with and without GPS RO assimilation

DA begins at $t = -72\text{h}$

DA ends at $t = 0\text{h}$

Averaged over a $6^\circ \times 6^\circ$ box following the 500 mb vorticity center

Units:
- Vertical motion: m/s
- Water Vapor: Kg/kg
Time-Height section of differences in relative vorticity (contour) and vertical motion (color) between experiments with and without GPS RO assimilation

DA begins at $t = -72h$

DA ends at $t = 0h$

Averaged over a $6^\circ \times 6^\circ$ box following the storm

Units:
- Vertical motion: m/s
- Vorticity: $10^{-5}\, s^{-1}$
How did GPS RO data impact the genesis of Typhoon Nuri (2008)?

• Assimilation of GPS RO results in significant moistening of tropical lower troposphere
• Enhanced convective instability triggers deep convection, and produces sustained strong vertical motion.
• Significant mid-level vorticity is created through stretching, resulting in a robust mid-level vortex with high humidity.
• The moist mid-level vortex plays a critical role in fostering the formation of Typhoon Nuri (2008)
What would happen if we remove 16 soundings in the vicinity of the storm?

<table>
<thead>
<tr>
<th>DA day</th>
<th>Data amounts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>60+49+53+63 = 225</td>
</tr>
<tr>
<td>Day 2</td>
<td>59+40+44+78 = 221</td>
</tr>
<tr>
<td>Day 3</td>
<td>58+56+53+65+52 = 284</td>
</tr>
<tr>
<td>Total</td>
<td>730</td>
</tr>
</tbody>
</table>

pre-depression area
Remove 16 RO soundings near the storm kill the genesis

Units:
Vertical motion: m/s
Water Vapor: Kg/kg

Averaged over a 6° x 6° box following the 500 mb vorticity center
Use of Local vs Non-Local Operators

Averaged over a 6° x 6° box following the 500 mb vorticity center

DA begins at t = -72h

DA ends at t = 0h

Typhoon center

W & Q

EPH-LOC

PW

T & Dia.H
Summary of Sensitivity Experiments

• Without GPS RO assimilation
  – Lower troposphere was too dry
  – No convection, no strong mid-level vorticity center with high humidity
  – No genesis

• With GPS RO assimilation, but no latent heating
  – Low-level moisture was increased
  – No large-scale ascent, no mid-level vorticity generation
  – No genesis

• With 16 GPS RO soundings near storm removed
  – Results similar to no GPS RO assimilation
  – No genesis

• With local observation operator
  – Less moisture in the lower tropical troposphere
  – Genesis delayed by 30 hour
Statistics for 10 Typhoons over the NW Pacific, 2008 - 2010

• Repeat the same set of experiments on ten typhoons over the North Western Pacific
  – 2008: Kalmaegi, Fung-wong, Nuri, Sinlaku, Hagupit, Jangmi
  – 2009: Morakot, Parma
  – 2010: Fanapi, Megi

• Probability of detection is increased from 30% (without GPS RO DA) to 60% (with GPS RO DA).

<table>
<thead>
<tr>
<th>GPS (EPH)</th>
<th>NO GPS (GTS)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With genesis</td>
<td>With genesis</td>
<td>No genesis</td>
</tr>
<tr>
<td>With genesis</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>No genesis</td>
<td>0</td>
<td>4</td>
<td></td>
</tr>
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</table>

Hit is counted when model produced genesis within ±24h of the observation.
The use of local observation operator reduces the probability detection from 60% to 40%. Two out of six cases failed (Nuri and Megi)

<table>
<thead>
<tr>
<th></th>
<th>GPS (EPH)</th>
<th>Local Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through genesis</td>
<td>With genesis</td>
<td>4</td>
</tr>
<tr>
<td>Through no genesis</td>
<td>No genesis</td>
<td>0</td>
</tr>
</tbody>
</table>
Heights where GPS-RO is reducing the 24hr errors

7-35 km height interval is sometimes called the GPS-RO “core region”.

Global model sees little value of GNSS RO in lower troposphere. Yet for Tropical Cyclone the lower tropical troposphere observation is most CRITICAL.
How do we better use the RO data in the lower tropical troposphere?

Improved specification of observation error:

Each sounding has its own observation error based on actual measurement uncertainty
Local Spectral Width of Bending Angle Spectrum
(when transformed to impact parameter representation)

Spectrograms of two bending angle profiles

- **polar** (low BA uncertainty at all heights)
- **tropics** (high BA uncertainty below a certain height)

Local spectral width (LSW) = BA2 - BA1

High LSW corresponds to high uncertainty in RO bending angle
Data assimilation system and Experiments

• Forecast model – the Global Forecast System – **GFS**
  • T574 horizontally
  • 64 vertical levels with model top ~0.27hPa

• Data assimilation system – **GSI**
  • 3DVar analysis done at T574
  • 6h continuously cycles for 6 weeks (August 1 – September 12 2008) covering TCs Ike and Sinlaku

• Observations (see next slide)
  • Conventional data, satellite radiance, and cloud-motion vectors.
  • **COSMIC bending angles (not other missions): Only COSMIC has LSW data**

• Experiments
  • **CTRL:** use the operational setup and the bending angle observation errors (BAOE)
  • **NORO:** same as CTRL, but GPS RO data denial
  • **DYNE:** same as CTRL, except that use dynamic **BAOE** based on the LSW/2
  • **DYNEL:** use DYNE/1.5, a low-bound BAOE experiment

ECMWF 5-day ensemble forecast
From 00 UTC Sep 10 2008

WRF 5-day forecast
From 00 UTC Sep 10 2008

Komaromi et al. 2011 MWR
• Wu et al. (2011) reported that the Pacific subtropical high (H) to the east is the primary factor that advects Sinlaku northwestward motion, and the monsoon trough (L) plays a secondary role.

• Specifically, the Pacific subtropical high weakens at 1200 UTC 11 September leading to the northward motion of Sinlaku.

• The subtropical high expands westward on 12 September, leading Sinlaku’s northwest movement.
Results - RO space statistics

Example of RO distributions on September 11 (00Z-18Z) CTRL vs. DYNEL

The distributions of rejected ROs are quite different between CTRL and the dynamic BAOE experiments.
Results-data impact

500hPa geopotential height forecast (contours; 10gpm) & DYNE-CTRL (shaded) initialized at 00Z Sep. 10. Thick lines highlight 5860 and 5880 gpm

- Stronger monsoon trough in DYNEL
- CTRL shows weak Pacific subtropical high expands westward quickly in DYNE.
• CTRL shows weak Pacific subtropical high.

• The Pacific subtropical high expands westward quickly in DYNE.
- **CTRL**: Sinlaku tends to merge with the trough to its north while the Pacific subtropical high is weak.
- **DYNE**: Sinlalu is still moving northwestward.
DYNE: the subtropical high weakens and Sinlaku starts to move northeastward.
Results-track forecast

All track forecast for Sinlaku

5 day track forecasts between 2008090912-2008091212

Aggregated track errors
Forecast numbers labelled on the top

It shows the dynamic experiments can reduce the track error in the 4–5 days forecast.
Results - Precipitation forecast

Observed 3 day accumulated rainfall Sep. 12-15

(a) OBS (CWB)

The rainfall intensity is relatively weak due to the low-resolution global model.

The dynamic experiments’ accurate track forecasts also help improve precipitation forecasts.

Black-best track; blue-experimental track forecast, big circles – storm position at 00 Z Sep. 15.
Results - Precipitation forecast

Observed 3 day accumulated rainfall Sep. 12-15

3 day accumulated rainfall forecasts initialized from different analyses

CTRL

DYNEL

00Z Sep 11

12Z Sep 11
Case study with a hybrid data assimilation system: Typhoon Haiyan (2013)

WRF-DART: 36 members
72-h (11/03-06) DA (12 cycling)
Case study with a hybrid data assimilation system: Typhoon Megi (2010)

WRF-DART: 36 members
48-h (10/17-19) DA (8 cycling)
Summary

• Prediction of tropical cyclone remains a significant challenge:
  – Track: Improvement becoming marginal
  – Genesis: Low probability of detection, high false alarm
  – Intensity: Not better than statistical methods, need high res.
  → Future: High-resolution nonhydrostatic global modeling, requiring better and more observation for initialization

• Research over the past 10 years have demonstrated the value of GPS RO data on tropical cyclone prediction on:
  – Track, intensity, rainfall and genesis

• Moisture information derived from RO sounding in the lower tropical troposphere, in the vicinity of the storm is most valuable
• Tropical lower troposphere is a challenging for RO:
  – Large moisture variability in time and space
  – Large uncertainties in RO measurement and retrieval
  – Small impact on global NWP
  – Yet, tropical lower troposphere observation is critical for tropical cyclone prediction

• To optimally use RO data for tropical cyclone prediction, efforts are needed on improving:
  – Observation operator
  – Data QC, obs errors specification
  – Data assimilation system (hybrid is better than 3DVAR)
RO Soundings from FORMOSAT-7/COSMIC-2 First Launch in 24 h

A factor of 10 more RO soundings over the tropics!
FORMOSAT-7/COSMIC-2

• FORMOSAT-7/COSMIC-2 to be launched in Q4 of 2018 will provide GNSS RO data with:
  – Higher quality
  – Higher data density (a factor of 5)

• We can expect significant impact on tropical cyclone prediction
  – We need to continue to optimize the assimilation

• THANK YOU to NSPO, NOAA, and Air Force!!!