Impact of GPS Radio Occultation Measurements on Severe Weather Prediction in Asia: What is Taiwan looking for from COSMIC

Ching-Yuang Huang 黃清勇
Department of Atmospheric Sciences, National Central University, Jhong-Li, Taiwan

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Collaborators

CHING-YUANG HUANG¹, YING-HWA KUO²,³, SHU-YA CHEN¹, MIEN-TZE KUEH¹, MING-JEN YANG¹, PAI-LIAM LIN¹, CHUEN-TSYR TERNG⁴, FANG-CHING CHIEN⁵, SONG-CHIN LIN¹, KUO-YING WANG¹, SHU-HUA CHEN⁶, CHIÉN-JU WANG¹, and ANISETTY S. K. A. V. PRASAD RAO¹

¹Department of Atmospheric Sciences, National Central University, Jhongli, Taiwan
²University Corporation for Atmospheric Research, Boulder, Colorado, USA
³National Center for Atmospheric Research, Boulder, Colorado, USA
⁴Central Weather Bureau, Taipei, Taiwan
⁵Department of Earth Sciences, National Taiwan Normal University, Taipei, Taiwan
⁶Department of Land, Air & Water Resources, University of California, Davis, California, USA
Outline

- Introduction
  - Group infrastructure
  - Focuses and missions
- Recent achievements in Taiwan
- The impact of FORMOSAT-3/COSMIC data from international community
- Prospective works in Taiwan
Taiwan’s Missions of F-3/C Meteorological Research

The main goals of meteorological research in Taiwan are to develop and improve skills of data assimilation on both basic research and application, and to expose the maximum values of FORMOSAT-3/COSMIC GPS radio occultation data on global and regional weather and climate prediction. Through data assimilation of different GPS data formats and different retrieval methods; their impact on global and regional predictions can be assessed.

This achievement will be anticipated to improve Taiwan’s weather prediction by 20%!
Integrated Meteorological Research in GPS Application and Research Center (GPS-ARC)

The main objectives of meteorological research in GPS-ARC are to

- establish/improve current skills of data assimilation on both basic research and application through 3DVAR and 4DVAR with GPS radio occultation and ground-based data;
- demonstrate the maximum values of FORMOSAT-3 RO and GPS ground-based data for weather and climate prediction on real-time mode and research mode;
- assess data impact on weather simulation and prediction through assimilation of different GPS data formats and different retrieval methods for severe disastrous weathers in vicinity of Taiwan (e.g., Meiyu fronts, typhoons, etc.);
- validate/improve retrieval methods/algorithms of atmospheric variables for FORMOSAT-3 data set (in collaboration);
- investigate GPS RO data impact on meteorological and hydrological analysis in application to global/regional climate;
- investigate GPS RO data impact on global/regional environment modeling (WRF-Chem and others).
GPS Radio Occultation

GPS/MET data

- L1 and L2 phase excess data: $\phi_1(t), \phi_2(t)$
- Doppler-shifted frequencies: $f_d = \frac{f_T \Delta \phi}{c_0 \Delta t}$

Bending angles and impact parameters
Satellites' geometry (GPS and LEO):

$$f_d = \frac{f_T}{c_0} (-u_g \cos \theta_g + u_i \cos \theta_i + v_g \sin \theta_g - v_i \sin \theta_i)$$

Local spherical symmetry assumption:

$$a = r_i \sin \theta_i = r_g \sin \theta_g \rightarrow \theta_i, \theta_g \rightarrow \alpha_1, a_1, a_2, a_2$$

$$\alpha = \theta_i - \theta_g + \psi$$

Ionospheric correction

$$\alpha(a) = \frac{f_{T1}^2 \alpha_1(a) - f_{T2}^2 \alpha_2(a)}{f_{T1}^2 - f_{T2}^2}$$

Index of refraction
Under local spherical symmetry assumption:

$$\ln \mu(x) = \frac{1}{\pi} \int_{s}^{x} \frac{\alpha(a)}{(a^2 - x^2) v_2} \, da, \quad x = \mu r$$

Refractivity

$$N = (\mu - 1) \times 10^6$$

Temperature and pressure
Under dry-atmosphere assumption: $N = 77.6 \frac{p}{T}$

The equation of state:
$$\rho R = \frac{p}{T}$$

Hydrostatic equation:
$$dp = -\frac{gN}{77.6R} \, dz, \quad T = \frac{77.6p}{N}$$
- 6 LEO satellites provide 2000~2500 measurements daily.
- It will offer up to about 50 soundings in a regional model domain for a 6-h assimilation time window.
Current Assimilation Tasks in Taiwan

- Assimilation by WRF 3DVAR for local refractivity, nonlocal refractivity
- Assimilation by MM5 4DVAR for local refractivity
- Assimilation by CWB GFS 3DVAR (SSI) for local refractivity, nonlocal refractivity and 2-D bending angle
Assimilation Tasks to Be Implemented in Taiwan

- Assimilation by WRF 3DVAR for local bending angle (2008)
- Assimilation by WRF 4DVAR for local refractivity, nonlocal refractivity
- Assimilation by WRF DART (using ensemble Kalman filter) for local refractivity and nonlocal refractivity
The simulated severe weather cases in 2006, 2007 and 2008 with FORMOSAT-3 RO data.

<table>
<thead>
<tr>
<th>Initial Time</th>
<th>Event</th>
<th>GPS RO</th>
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<tbody>
<tr>
<td>2006-07-1200</td>
<td>Typhoon Bilis</td>
<td>2</td>
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<tr>
<td>2006-07-2300</td>
<td>Typhoon Kaemi</td>
<td>7</td>
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<td>2006-09-1312</td>
<td>Typhoon Shanshan</td>
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<tr>
<td>2007-06-0212</td>
<td>Meiyu Front</td>
<td>31</td>
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<td>2007-06-0300</td>
<td>Cyclone Gonu</td>
<td>56</td>
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<tr>
<td>2007-07-1100</td>
<td>Typhoon Manyi</td>
<td>15</td>
</tr>
<tr>
<td>2007-07-2900</td>
<td>Typhoon Usagi</td>
<td>39</td>
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<tr>
<td>2007-08-1600</td>
<td>Typhoon Sepat</td>
<td>21</td>
</tr>
<tr>
<td>2007-10-0412 (0500)*</td>
<td>Typhoon Krosa</td>
<td>31 (17)</td>
</tr>
<tr>
<td>2008-04-2900 (2906)*</td>
<td>Cyclone Nargis</td>
<td>21 (24)</td>
</tr>
</tbody>
</table>
WRF (with AVN) for Typhoon Krosa

2007/10/04 0000UTC

2007/10/04 1200UTC

Forecast 84h

Forecast 72h

Compared with best tracks (red dotted-line) from http://agora.ex.nii.ac.jp/digital-typhoon/
Typhoon Krosa (2007/10/04 12UTC)

Increments of N

Simulated tracks

Assimilation for 3 domains

31 GPS RO Soundings
Daily Rainfall

DAY 2 10/05 12:00 ~ 10/06 12:00

Obs. Max. value 531 mm

DAY 3 10/06 12:00 ~ 10/07 12:00

Obs. Max. value 590 mm
TS : Typhoon Krosa (Initial time: 2007-10-04-12:00)

Sea level pressure
Typhoon Krosa

Experiments | Assimilated data | Assimilated domain
--- | --- | ---
NONE | None | None
EPHrt | GPS refractivity (COSMIC real time) | 3 domains
GTS | GTS data | 3 domains
GTS+EPHrt | GTS data and GPS real time data | 3 domains
EPHqc | GPS refractivity (COSMIC quality check) | 3 domains

EPHrt_d1 | GPS refractivity (COSMIC real time) | 1 domain
EPHrt_r2 | GPS refractivity (COSMIC real time) | 2 domains
EPHrt_r3 | GPS refractivity (COSMIC real time) | 3 domains
EPHrt_r5 | GPS refractivity (COSMIC real time) | 1 domains

EPHqc_cyc | GPS refractivity (COSMIC quality check) | 3 domains
EPHrt_cyc | GPS refractivity (COSMIC real time) | 3 domains
EPHrt_r5_cyc | GPS refractivity (COSMIC real time) | 3 domains
GTS+EPHrt_cyc | GTS data and GPS real time data | 3 domains

Experiments | Initial conditions | Different IC
--- | --- | ---
AVN | NCEP Aviation Model (AVN) global analysis ([http://www.dss.ucar.edu/](http://www.dss.ucar.edu/))
NCEP | NCEP / GFS forecast
NOMAD3 | NCEP / GFS forecast ([http://nomad3.ncep.noaa.gov/pub/gfs](http://nomad3.ncep.noaa.gov/pub/gfs))
CWB.analysis | CWB / GFS analysis (Central Weather Bureau)
CWB.forecast | CWB / GFS forecast (Central Weather Bureau)

The typhoon track prediction is sensitive to many model and physical factors!
The large impact case Bilis (2006)
The large impact case

WRF D1,D2

TYPHOON SEPAT
2007/08/14/12Z ~ 2007/08/17/12Z

unit: km

(P.-L. Lin)

Blue: GPS
Red: CTRL

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<tr>
<th></th>
<th>12</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>60</th>
<th>72</th>
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<tr>
<td>CTRL</td>
<td>120</td>
<td>52</td>
<td>95</td>
<td>122</td>
<td>160</td>
<td>152</td>
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<tr>
<td>GPS</td>
<td>148</td>
<td>118</td>
<td>45</td>
<td>23</td>
<td>35</td>
<td>30</td>
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Typhoon Sepat (2007)

The best track (black line) and simulated tracks for experiment NONE (green line) and EPH (blue line).

The 24-h mean track errors for experiments NONE and EPH.
24h accumulated rainfall

Day 2

Obs. Max. value 531 mm

Day 3

Obs. Max. value 875 mm

TS : Typhoon Sepat (Initial time: 2007-08-16-00:00)
Forecast track error for Typhoon Krosa (initial time : 12Z 4th Oct. 2007) using CWB WRF

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<thead>
<tr>
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<tr>
<td>CS_NGPS / CS_NGPS</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>CS-WGPS / CS_NGPS</td>
<td>0.98</td>
<td>1.03</td>
<td>0.67</td>
<td>1.61</td>
<td>1.42</td>
<td>1.47</td>
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<tr>
<td>FU-NGPS / CS_NGPS</td>
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<td>1.17</td>
<td>0.63</td>
<td>2.37</td>
<td>2.28</td>
<td>2.12</td>
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<tr>
<td>FU-WGPS / CS_NGPS</td>
<td>5.34</td>
<td>1.29</td>
<td>0.81</td>
<td>2.19</td>
<td>2.29</td>
<td>2.78</td>
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<tr>
<td>NODATA / CS_NGPS</td>
<td>2.34</td>
<td>1.41</td>
<td>0.97</td>
<td>2.36</td>
<td>1.51</td>
<td>1.92</td>
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Forecast track error for typhoon Krosa (initial time : 00Z 5th Oct. 2007)

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<td>1</td>
<td>1</td>
<td>1</td>
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<td>1</td>
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<tr>
<td>CS-WGPS / CS_NGPS</td>
<td>1.01</td>
<td>1.25</td>
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<td>FU-NGPS / CS_NGPS</td>
<td>1.31</td>
<td>1.90</td>
<td>2.34</td>
<td>3.93</td>
<td>1.66</td>
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<tr>
<td>FU-WGPS / CS_NGPS</td>
<td>1.42</td>
<td>1.90</td>
<td>4.16</td>
<td>4.06</td>
<td>1.85</td>
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<tr>
<td>NODATA / CS_NGPS</td>
<td>0.84</td>
<td>0.57</td>
<td>1.02</td>
<td>3.61</td>
<td>1.36</td>
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Forecast track error for typhoon Krosa (initial time : 12Z 5th Oct. 2007)

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<td>1</td>
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<tr>
<td>CS-WGPS / CS_NGPS</td>
<td>0.93</td>
<td>1.06</td>
<td>0.73</td>
<td>1.24</td>
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<tr>
<td>FU-NGPS / CS_NGPS</td>
<td>0.27</td>
<td>1.54</td>
<td>0.61</td>
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<tr>
<td>FU-WGPS / CS_NGPS</td>
<td>0.42</td>
<td>1.71</td>
<td>0.59</td>
<td>0.60</td>
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<tr>
<td>NODATA / CS_NGPS</td>
<td>2.64</td>
<td>0.80</td>
<td>0.85</td>
<td>0.60</td>
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</table>

Forecast track error for typhoon Krosa (initial time : 00Z 6th Oct. 2007)

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<tr>
<td>CS_NGPS / CS_NGPS</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CS-WGPS / CS_NGPS</td>
<td>0.91</td>
<td>1.23</td>
<td>0.95</td>
</tr>
<tr>
<td>FU-NGPS / CS_NGPS</td>
<td>0.78</td>
<td>0.49</td>
<td>1.15</td>
</tr>
<tr>
<td>FU-WGPS / CS_NGPS</td>
<td>1.41</td>
<td>0.53</td>
<td>1.25</td>
</tr>
<tr>
<td>NODATA / CS_NGPS</td>
<td>1.43</td>
<td>0.71</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Krosa track predictions are improved with GPS RO data assimilation, for a large portion of the forecasts, in general, giving positive impact.
The typhoon track error ratio is defined as (track error for GPS) / (track error for CONTROL). CONTROL is the experiment assimilating all the GTS observations, and GPS is the experiment assimilating GTS and FORMOSAT-3/COSMIC GPS RO data.

<table>
<thead>
<tr>
<th></th>
<th>12 H</th>
<th>24 H</th>
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<th>48 H</th>
<th>60 H</th>
<th>72 H</th>
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<td>1312</td>
<td>0.88</td>
<td>1.11</td>
<td>1.67</td>
<td>1.69</td>
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<td>1400</td>
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<td>2.98</td>
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<td>1412</td>
<td>0.58</td>
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<td>0.21</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>1500</td>
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<td>1.90</td>
<td>2.64</td>
<td>1.80</td>
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<tr>
<td>1512</td>
<td>0.29</td>
<td>0.36</td>
<td>0.36</td>
<td>0.29</td>
<td>0.31</td>
<td>0.71</td>
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<tr>
<td>1600</td>
<td>0.48</td>
<td>0.14</td>
<td>0.18</td>
<td>0.31</td>
<td>0.5</td>
<td>0.66</td>
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<td>1612</td>
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<td>1712</td>
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<td>1800</td>
<td>0.46</td>
<td>0.16</td>
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</tbody>
</table>
Real-time validation (May-Sept.) in 2007

WRF D1, D2

72 hours forecast

H vertical profile

T vertical profile

RMS

S_D

M-error

Abs_m
Real-time validation (May-Sept.) in 2007
The forecast experiment was run 4 times a day in cold-start mode with the first guess from CWB GFS analysis.
The GPS RO assimilation run shows the typhoon in 72-hr forecast, while the denial run misses the forecast.
In the next initial time 12-h, the control run captures the more realistic typhoon structure at 72-h as compared with satellite image.
The dropsonde data were over the ocean near the southwest of Taiwan. Each experiment contains 22 runs of 72-h simulation, initialized twice daily from 0000 UTC 5 June 2007 to 1200 UTC 15 June 2007 by NCEP GFS. The initial data of the other 21 runs were obtained from the 12-h update cycle of the previous WRF run.
GPS RO soundings show stronger ridge extended from the western Pacific subtropical high.
GPS RO soundings show significant cloud-top cooling over north Philippine where deep convective activities exist.

Mei-yu case (June 2006)  S.-C. Lin
Observation of accumulated rainfall (mm) for the 2007 June 02 Mei-yu front case, the predicted rainfalls (mm) with no GPS data, and with 31 GPS RO data in the second day and the third day.

The GPS RO data give a remote impact on the Taiwan Mei-yu rainfall.
24h accumulated rainfall

Threat Score: Meiyu Front (Initial time: 2007-06-02-12:00)

Day1

Day2

Obs. Max. value 117.2 mm
Obs. Max. value 262.2 mm
Global Assimilation Methodology

- ECMWF assimilates the COSMIC GPSRO local bending angle data into the modeling system. Test result shown below is for the experiment period of 15 Dec 2006 to 28 Feb 2007.

- CWB assimilates the COSMIC GPSRO local refractivity data in the modeling system. Test result shown below is for the experiment period of 1 April to 30 April 2007.

\[ \alpha(a) = -2a \int_{a}^{\infty} \frac{d \ln n}{d x} \left( x^2 - a^2 \right)^{1/2} dx \]
Anomaly Correlation Difference of H (GPS - NoGPS) over North Hemisphere  

CWB result (2007/04)

ECMWF result (2006/12~2007/02)

1000 hPa

500 hPa

200 hPa

The fractional improvement in RMS errors \( \frac{\text{RMSCTL} - \text{RMSCOS1}}{\text{RMSCTL}} \)
Anomaly Correlation Difference of H (GPS - NoGPS) over South Hemisphere

CWB result (2007/04)

- 850 hPa
- 500 hPa
- 200 hPa

M.-J. Yang

ECMWF result (2006/12~2007/02)

- 1000 hPa
- 500 hPa
- 200 hPa

Healy (2008)
Global assimilation of GPS/RO local refractivity

2006/10 500-hPa H over South Hemisphere

**mean ach score**

![Graph showing mean ach score for GPS and noGPS conditions over 7 days.](image)

**CWB (local refractivity)**

**NCEP result** (Cucurull et al. 2007)

**Fig. 17.** Anomaly correlation scores for the 500-hPa geopotential heights in the Southern Hemisphere for CTL, REF, and BND, 0000 UTC 10 Jul–31 Aug 2005.
Global assimilation of GPS RO non-local refractivity

2006/07 500-hPa H over North Hemisphere

200607 500mb H AC - NA

CWB (nonlocal refractivity)
Geopotential height in N. Hemisphere (20-80N) from CWB global model

2007 MAR 500hPa mean ach score area--NA
(gpsw1d-nogps)/nogps & 95% confidence interval

2007 MAR 500hPa mean frh score area--NA
(nogps-gpsw1d)/nogps & 95% confidence interval

Red: 95%

Fractional anomaly correlation

2007 MAR 100hPa mean ach score area--NA
(gpsw1d-nogps)/nogps & 95% confidence interval

2007 MAR 100hPa mean frh score area--NA
(nogps-gpsw1d)/nogps & 95% confidence interval

Fractional RMS error
Geopotential height in the Tropics (20S-20N) from CWB global model

2007 MAR 500hPa mean ach score area--TP
(gpsw1d-nogps)/nogps & 95% confidence interval

2007 MAR 500hPa mean frh score area--TP
(nogps-gpsw1d)/nogps & 95% confidence interval

2007 MAR 100hPa mean ach score area--TP
(gpsw1d-nogps)/nogps & 95% confidence interval

2007 MAR 100hPa mean frh score area--TP
(nogps-gpsw1d)/nogps & 95% confidence interval
500 hPa height in S. Hemisphere (20-80S) from CWB global model

Fractional anomaly correlation

Fractional RMS error

100 hPa height in S. Hemisphere scores give a big jump on 7th day!

The degradation of ensuing forecasts appears to be lessened due to continuous GPS RO data assimilation.
Conclusions from the Centers

- ECMWF shows good improvement in the height scores in both the Northern and Southern Hemispheres, as well as good improvement in stratospheric temperature scores, for a longer performance time.

- CWB shows significantly better forecasting of the height field in the Southern Hemisphere, and slightly better forecasting of height field in the Northern Hemisphere for a limited time.
The impact of FORMOSAT-3/COSMIC data on other recent cyclone predictions
Gonu Cyclone: 03 June 2007. (56 GPS RO)
Myanmar Cyclone Nargis (2008)

Rainfall accumulations along Cyclone Nargis by Tropical Rainfall Measuring Mission (TRMM) satellite (http://earthobservatory.nasa.gov)

Flood area caused by Cyclone Nargis Analyzed form MODIS data by UNOSAT (http://services.google.com/earth/kmz/nargis_n.kmz)

A perfect cyclone!
Myanmar Cyclone Nargis

FORMOSAT-2 Image
3/18/2008: Yangon farm before flood
5/7/2008: severe flood
5/8/2008: subsiding flood

(From: CSRSR, NCU, Taiwan)
TRMM-based, near-real time Multi-satellite Precipitation Analysis (MPA) rainfall totals from April 27 to May 4, 2008. (From NOAA)
Typhoon Nargis (Initial time: 2008-04-29-00:00)

NONE (pressure perturbation and wind vector)

Init: none d2  RIP: narg
Valid: 0000 UTC Tue 29 Apr 08
Pressure perturbation from MM5 std. atm.
Horizontal wind vectors at k-index = 34

EPH (pressure perturbation and wind vector)

Init: 0000 UTC Tue 29 Apr 08
Valid: 0000 UTC Tue 29 Apr 08 (0800 LST Tue 29 Apr 08)
Pressure perturbation from MM5 std. atm.
Horizontal wind vectors at k-index = 34
Initial increments of temperature and moisture and wind vector at 2km (BG)

Temperature, contour interval=0.2 °C

Moisture, contour interval=0.3 g kg⁻¹

BG: assimilating a bogus Rankine vortex (P_min = 975 mb) at 0000 UTC 29 April 2008
Typhoon Nargis (Initial time: 2008-04-29-00:00)

Bogus-vortex run (BG)

Dataset: bg d2   RF: narg
Init: 0000 UTC Tue 29 Apr 08
Valid: 0600 UTC Tue 29 Apr 08
Pressure pert. (from M05 std atm.) at k-index = 34
Horizontal wind vectors at k-index = 34

[picture of a map showing Typhoon Nargis]
GPS RO points (Initial time: 2008-04-29-06)
Initial increments of temperature and moisture and wind vector at 2km (CYCLING)—24 GPS RO

Temperature, contour interval=0.2 °C.

Moisture, contour interval=0.3 g kg⁻¹.

CYCLING : as EPH but with cycling GPS data at 2008/04/29/06UTC.
Typhoon Nargis  (Initial time: 2008-04-29-06:00)

CYCLING (pressure perturbation and wind vector)

Dataset: ds  RP: margin
Forecast: 0.00 h  Valid: 0600 UTC Tue 29 Apr 08 (1400 LST Tue 29 Apr 08)
Pressure pert. (from MM5 std. atm.) at x-index = 34
Horizontal wind vectors at k-index = 34
An OSSE Study for Typhoon Krosa

- Perform 96-h MM5 simulation (400x400, 15 km resolution) with an initial Rankine vortex at 0400 Oct. 2007, served as the nature run.
- Retrieve RO soundings by running a ray-tracing model with the input of the nature run to obtain bending angles (assuming uniform 45° azimuthal angle) and the converted RO refractivity in the region of the typhoon vortex circulation at 0412 Oct. 2007.
- Perform a linear filter to smooth the nature run at 0412 Oct. 2007 to provide the control run (as the first guess at coarser resolution).
- Perform WRF 3DVAR to assimilate the RO refractivity soundings using the nonlocal operator and local operators at 041200 Oct. 2007.
- Compare the assimilation runs and non-assimilation run with the nature run.
Krosa OSSE runs

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTL</td>
<td>MM5 initialization with AVN analysis at 2007100400UTC at 15-km resolution Nature with a Rankine vortex at $R_{\text{max}}$ of 200 km and $V_{\text{max}}$ of 46 m s$^{-1}$.</td>
</tr>
<tr>
<td>CTL</td>
<td>Degraded NTL by smoothing 100 times the model prediction at 2007100412UTC using a 1-2-1 linear filter.</td>
</tr>
<tr>
<td>REF</td>
<td>As CTL but assimilating nonlocal REF (as retrieved*) in the vortex (30-km resolution) using the localized nonlocal operator</td>
</tr>
<tr>
<td>EPH</td>
<td>As CTL but assimilating EPH (path nonlocal REF) in the typhoon vortex (30-km resolution) using the nonlocal operator</td>
</tr>
<tr>
<td>LOC</td>
<td>As CTL but assimilating local REF in the vortex (30-km resolution) using the localized nonlocal operator</td>
</tr>
</tbody>
</table>

*The retrieved soundings are located within the typhoon vortex circulation at 30-km horizontal resolution, with a total of 1252 points assimilated.*
Nature run at 0400

Nature run at 0412
GPS RO refractivity soundings at 30-km resolution
127 GPS RO soundings assimilated by nonlocal operator

Krosa Typhoon (2007)
Temperature increment near the surface at 100412
CNTL (no GPS)  

REF with 1252 GPS
Wind difference at k= 26

Wind difference at k= 30
Temp. difference at k= 26

Temp. difference at k= 30
The impact of FORMOSAT-3/COSMIC data from international community

**Data:** FORMOSAT-3/COSMIC  
**Variables:** local refractivity  
**Model:** WRF 3DVAR and WRF/DART EnKF

**Mei-yu case**

850 mb wind fields

➢ The assimilation of COSMIC data significantly strengthens the Western Pacific Subtropical High, and consequently improves the prediction of Mei-yu precipitation over southern China and Taiwan.
Typhoon case (Shanshan 2006)

The WRF/DART ensemble filter system can assimilate the GPSRO data more effectively than the WRF 3D-Var method. In particular, the WRF/DART ensemble filter system is able to produce a more coherent storm after one day of continuous assimilation, while a much weaker and less coherent storm is produced by WRF 3D-Var.

Track forecast errors averaged over different forecast periods

<table>
<thead>
<tr>
<th>Experiment</th>
<th>3-24 h forecast</th>
<th>27-48 h forecast</th>
<th>51-72 h forecast</th>
<th>3-72 h forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>NODA</td>
<td>276</td>
<td>294</td>
<td>248</td>
<td>273</td>
</tr>
<tr>
<td>COLDNBNG</td>
<td>197</td>
<td>237</td>
<td>264</td>
<td>233</td>
</tr>
<tr>
<td>COLDNB</td>
<td>199</td>
<td>233</td>
<td>265</td>
<td>232</td>
</tr>
<tr>
<td>COLDALL</td>
<td>111</td>
<td>150</td>
<td>160</td>
<td>140</td>
</tr>
<tr>
<td>CYCLNBNG</td>
<td>166</td>
<td>147</td>
<td>119</td>
<td>144</td>
</tr>
<tr>
<td>CYCLNB</td>
<td>117</td>
<td>132</td>
<td>82</td>
<td>111</td>
</tr>
<tr>
<td>CYCLALL</td>
<td>61</td>
<td>124</td>
<td>211</td>
<td>132</td>
</tr>
<tr>
<td>DARTNBNG</td>
<td>75</td>
<td>57</td>
<td>94</td>
<td>75</td>
</tr>
<tr>
<td>DARTNB</td>
<td>69</td>
<td>38</td>
<td>80</td>
<td>62</td>
</tr>
</tbody>
</table>

Relative vorticity analysis

- The WRF/DART ensemble filter system can assimilate the GPSRO data more effectively than the WRF 3D-Var method.
- In particular, the WRF/DART ensemble filter system is able to produce a more coherent storm after one day of continuous assimilation, while a much weaker and less coherent storm is produced by WRF 3D-Var.

Units: 1.0 x10-5 s⁻¹

**Data:** CHAMP, and FORMOSAT-3/COSMIC (Dec. 2005 and Jun. 2006)

**Variables:** local refractivity

**Model:** WRF 3DVAR

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**A significant impact on the temperature analysis when the GPS RO data is assimilated.**

**Assimilated with GPS RO data can reduce the temperature overestimation from the global analysis in the upper model level.**

**Data:** CHAMP  
**Variables:** 1-D bending angle  
**Model:** ECMWF Global 4DVAR (run for 60 days)

The statistical significance (%) of the chance in r.m.s. fit to radiosonde temperature values at four pressure levels (hPa) due to assimilation of GPSRO data.

<table>
<thead>
<tr>
<th>Forecast day</th>
<th>Northern hemisphere</th>
<th>Tropics</th>
<th>Southern hemisphere</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>–</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>10.0</td>
<td>–</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>–</td>
<td>10.0</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

A negative value indicates that the r.m.s. fit is degraded at this level. Only values ≤10% are considered significant. Values >10% are shown as ‘–’.

- **Southern Hemisphere:** A clear, statistically significant improvement in the r.m.s. forecast fit to radiosonde measurements over the day 1 to day 5 forecast range at 300, 200, 100 and 50 hPa.
- **Tropics:** An improved r.m.s. fit to radiosondes is also evident at 100 hPa.
Operational implementation of GPSRO at ECMWF

Neutral in the troposphere, but some improvement in the stratospheric temperature scores. Obvious improvement in time series for operations.

Operational implementation represented a quite conservative use of data. No data below 4 km, no rising occultations.

Next set of experiments to investigate increased use of the data.
(O-B)/σ₀ bending angle statistics for rising and setting occultations (eg, SH, COSMIC-3)

CONTROL

BLACK = setting

GREY = rising

 hectometers (km)


The only significant differences are near 10 km. This is a transition height in the processing.

Above 10 km = Phase-lock-loop.
Below 10 km = Open-loop.
Conclusions from ECMWF

- GPSRO becomes operational from December 12, 2006. Good improvement in stratospheric temperature scores.
- Good improvement in the height scores in both Northern Hemisphere and Southern Hemisphere.
- Future missions: where does GPSRO fit into the global observing system – remember GPSRO can improve the bias correction of satellite radiances.
Data: FORMOSAT-3/COSMIC
Variables: local bending angle
Model: Météo-France’s operational global 4DVAR data assimilation system

After assimilation, the standard deviations of the departures are reduced between 5-15 km altitudes. The limited reduction is an effect of the conservative observation error estimate.
Indicate a very clear positive impact of the assimilation of F3C bending angle data in the Southern Hemisphere for the prediction of geopotential heights and winds. Also observe an improvement in wind forecast skill in the Northern hemisphere, albeit smaller than in the Southern Hemisphere.

**Data:** CHAMP  
**Variables:** local bending angle, local refractivity  
**Model:** Grid-point Statistical Interpolation (GSI) developed by NCEP/EMC

Anomaly correlation scores for the temperature field at 200 hPa (0000 UTC 10 Jul–31 Aug 2005)

- The use of GPS RO observations slightly improves anomaly correlation scores for temperature (by 0.01–0.03) in the Southern Hemisphere and Tropics throughout the depth of the atmosphere while a slight degradation is found in the upper troposphere and stratosphere in the Northern Hemisphere.
The benefits from assimilating GPS RO data also extend to other fields, such as 500-hPa geopotential heights and tropical winds (not shown).

Significant reduction of the temperature and humidity biases (not shown) is found for all latitudes.
Cucurull, L. and J. C. Derber 2008: Operational implementation of COSMIC observations into the NCEP’s global data assimilation system. *Wea. Forecasting*, accepted.

**Data:** FORMOSAT-3/COSMIC  
**Variables:** local refractivity  
**Model:** Grid-point Statistical Interpolation (GSI) developed by NCEP/EMC

A significant improvement of the anomaly correlation skill and a global reduction of the NCEP model bias and root-mean-squared errors when COSMIC observations are assimilated into the system.  
The improvement is found for the temperature, geopotential heights and moisture variables.
Anomaly correlation scores for the 1000 hPa geopotential height

Larger benefits are found in the Southern Hemisphere Extratropics, although a significant positive impact is also found in the Northern Hemisphere Extratropics and Tropics.

A slight benefit is found in the wind components.
Prospective works

- Use FORMOSAT-3/COSMIC and CHAMP data for severe weather cases, e.g. typhoon, meiyu, cold front and heavy rainfall, etc. in WRF 3DVAR, WRF 4DVAR, and WRF DART.
- Develop a local bending angle operator and insert it into WRF 3DVAR, and then compare it with the local refractivity.
- Assimilate GPS RO data by using WRF 4DVAR and/or MM5 4DVAR with local bending angle operator.
- Conduct OSSE studies to fully understand the impacts of the GPS RO data on regional weather prediction with more verifications and better quantify the performances of different GPS assimilation operators.
Help to insert the nonlocal operator into CWB WRFVAR version (operational system) and compare it with the local operator.

Test for different data assimilation schemes in the operational system (ex. WRFVAR V3.0 and EnKF), different background errors, and investigate different data quality control.

Quantify and clarify the impact of GPS RO data on the CWB GFS through statistically systematic yearly evaluation.

Determine the statistical confidence level of the improvement of CWB/GFS performance introduced as assimilating the GPS RO data.