Impact of GPS Radio Occultation Measurements on Severe Weather Prediction in Asia

Ching-Yuang Huang[1], Ying-Hwa Kuo[2,3], Shu-Ya Chen[1], Mien-Tze Kueh[1], Pai-Liam Lin[1], Chuen-Tsy[r] Terng[4], Fang-Ching Chien[5], Ming-Jen Yang[1], Song-Chin Lin[1], Kuo-Ying Wang[1], Shu-Hua Chen[6], Chien-Ju Wang[1] and Anisetty S.K.A.V. Prasad Rao[1]

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

Abstract

The impact of GPS radio occultation (RO) refractivity measurements on severe weather prediction in Asia was reviewed. Both the local operator that assimilates the retrieved refractivity as local point measurements and the nonlocal operator that assimilates the integrated retrieved refractivity along a straight raypath have been employed in WRF 3DVAR to improve the model initial analysis. We provide a general evaluation of the impact of these approaches on Asian regional analysis and daily prediction. GPS RO data assimilation was found beneficial for some periods of the predictions. In particular, such data improved prediction of severe weather such as typhoons and Mei-yu systems when COSMIC data were available, ranging from several points in 2006 to a maximum of about 60 in 2007 and 2008 in this region. These positive impacts are seen not only in typhoon track prediction but also in prediction of local heavy rainfall associated with severe weather over Taiwan. The impact of 56 GPS RO soundings on track prediction of Cyclone Gonu (2007) over the Indian Ocean is appealing. When extended to the other cyclones such as the disastrous Myanmar Cyclone Nargis (2008), the initial cyclone was not well recovered by assimilation of limited GPS RO soundings away from the cyclone, which had a lesser impact on prediction despite including an initial bogus vortex or cycling assimilation.

To highlight the potential impact of GPS RO data, we conducted Observing System Sensitivity Experiments (OSSEs) for Typhoon Krosa (2007), which made landfall over northern Taiwan. The OSSEs with assimilation of either dense RO refractivity soundings (1252 points) or diluted soundings (45 points) surrounding the typhoon center exhibited a remarkable improvement in the track, which demonstrates the unequivocal impact of GPS RO data.

1. Introduction

The newly operational six satellites of FORMOSAT-3/COSMIC, which provides up to 2500 global soundings daily (Anthes et al. 2008), has drawn attention to the great value of GPS radio occultation (RO) measurements in many global climate and weather applications. According to the RO principle, these global measurements are obtained with good accuracy, comparable with that of radiosonde soundings (e.g., Kursinski et al. 2000). Among many studies using GPS RO soundings, assimilations of refractivity and bending angle have exhibited promising impact on regional as well as global weather predictions (Kuo et al. 1997; Zou et al. 1999; Liu and Zou 2003; Huang et al. 2005; Healy et al. 2005; Healy and Thepaut 2006; Cucurull et al. 2006, 2007; Poli et al. 2008; Healy 2008; Chen et al. 2008). For global models, assimilation of bending angle has the advantage of providing better accuracy, but at the cost of computational expense (e.g., Zou et al. 1999; Kuo et al. 2000). For regional models, assimilation of refractivity has usually been undertaken using local and nonlocal operators (e.g., Huang et al. 2005; Chen et al. 2008).

The FORMOSAT-3/COSMIC satellites are providing plentiful reliable soundings for assimilation into regional models like WRF (Weather Research and Forecasting). In this paper, we review the impact of the GPS RO soundings from COSMIC on prediction of recent severe weather (typhoons and Mei-yu systems) in Asia, in addition to assessing their general impact on continuous forecasts over selected periods. A brief introduction to the methodologies (including the observation operators and the weather model) will be given in section 2. The results of selected cases will be presented in section 3. Observing System Sensitivity Experiments (OSSEs) that assimilate the GPS RO soundings generated by the model simulation may help to understand whether these data have impact on weather prediction. Thus, we also conducted OSSEs for Typhoon Krosa (2007) to demonstrate the impact of various GPS RO data density around the typhoon in particular. Finally, we will give our conclusions in section 4.

2. The methodologies and the operators

2.1. The prediction models and preprocessor

For most of the impact studies, the WRF Model (version 2) has been used for weather prediction. The details of the WRF model can be found on the web site (http://wrf-model.org). For the OSSE study, we also employed MM5 (version 3.7) for prediction. The WRF 3DVAR, the preprocessor of the WRF model, was utilized here to ingest the RO observations with the observation operator to map model variables onto the observables at the observation time and location.

2.2. The observation operator in WRF 3DVAR

The observables as retrieved or derived from GPS RO are the Abel-retrieved atmospheric refractivity as a path average refractivity and the excess phase (the integrated amount of the refractivity along a raypath). The atmospheric refractivity N is given by

$$N = 77.6\frac{P}{T} + 3.73\times10^{5}\frac{P_w}{T^2} \quad (1)$$

where P_w is water vapor pressure in hPa, T air temperature in K, and P the pressure of the atmosphere in hPa. To account for nonlocal effects, model local refractivity may be integrated along a raypath that may be approximated by a straight line (Sokolovskiy et al. 2005). This line integral is treated as a new observable (excess phase) defined as

$$S = \int N dl \quad (2)$$

where l is the raypath, and S can be calculated for model local refractivity as well as retrieved refractivity (observed). Thus, in the S-representation, the error induced by horizontal gradients can be substantially reduced to give a more accurate analysis (e.g., Ma et al. 2008). The nonlocal operator for assimilating excess phase has been implemented into WRF 3DVAR (Chen et al. 2008), which may also assimilate point refractivity simply by deactivating the ray's integration. Also, horizontal smear of tangent point trajectories has been taken into account in the nonlocal operator of the WRF 3DVAR.

3. The results

3.1. Simulated severe weather

Since the launch of the FORMOSAT-3/COSMIC satellites, there have been a number of interesting and important severe weather events in Asia. We have conducted numerical simulations/forecasts for many of them using higher model resolutions with focus on the Taiwan area. A list of the simulated events, which include typhoons/tropical cyclones as well as Mei-yu frontal systems, is given in Table 1. The GPS RO soundings available for one assimilation time window and the outer model domain (covering most of East Asia) range from 2 to 56, depending on the cases. We will briefly present some results of these simulated events with the available GPS soundings assimilated.

Table 1: The simulated severe weather cases in 2006, 2007 and 2008 with FORMOSAT-3/COSMIC RO data.

Initial Time	Event	GPS RO
2006-07-1200	Typhoon Bilis	2
2006-07-2300	Typhoon Kaemi	7
2006-09-1312	Typhoon Shanshan	27
2007-06-0212	Mei-yu Front	31
2007-06-0300	Cyclone Gonu	56
2007-07-1100	Typhoon Manyi	15
2007-07-2900	Typhoon Usagi	39
2007-08-1600	Typhoon Sepat	21
2007-10-0412 (0500)*	Typhoon Krosa	31 (17)
2008-04-2900 (2906)*	Cyclone Nargis	21 (24)

*cycling

3.2. General assessment of continuous forecasts

The real-time prediction experiment project at National Central University (NCU), Taiwan, has been continuously digesting the real-time GPS RO refractivity and conducting a GPS run (with GPS RO data) and a denial run (without GPS RO data). Figure 1 gives an example of the two comparative runs for an 8-day period (15 to 23 May 2008) when a Mei-yu system was situated near Taiwan. The WRF model with moderate resolution (45-km and 15-km) was used for prediction and WRF 3DVAR with the local operator for assimilation of GPS RO refractivity. In general, the GPS run shows lower mean errors in temperature forecast (red lines) than the denial run (blue lines) at the three vertical levels (850, 500 and 300 hPa) for 24-h and 72-h forecasts with a 6-h update cycle. However, at 850 hPa the GPS run shows significant degradation (worse performance) early in the 72-h forecast. We should continue to explore why there is such poor performance at this level when the GPS data have been ingested.

Another demonstration of the GPS RO data impact is the operational CWB WRF performance for an extended period (1 to 20 August 2007) with no severe weather. The GPS run and denial run were conducted operationally but in hindcast mode with a 6-h update cycling. We found that there was a general reduction in refractivity analysis errors at most of the vertical levels in terms of standard deviation and bias (figures not shown) when assimilating GPS RO data. More time periods need to be evaluated for a consolidated demonstration of the data impact on operational regional model analysis.

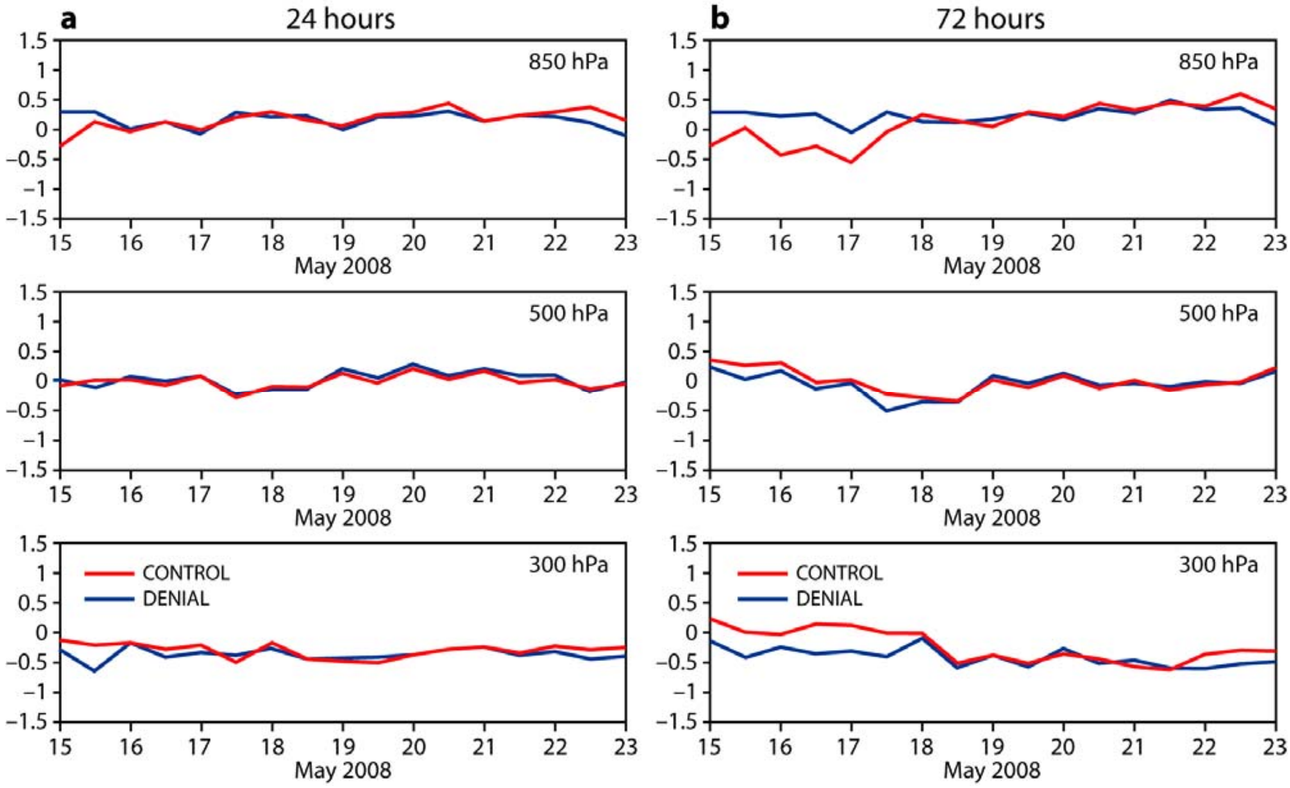


Figure 1 Mean errors for the (a) 24-h forecast and (b) 72-h forecast temperature during an 8-day period from 15 to 23 May 2008. The CONTROL experiment (assimilating FORMOSAT-3/COSMIC GPS RO data and all the GTS observations, red lines) against the DENIAL experiment (assimilating all the GTS observations only, blue lines) at 850 hPa, 500 hPa, and 300 hPa are shown from top to bottom for each panel. These forecasts are conducted using the WRF model with two nested domains (at horizontal resolutions of 45 km and 15 km) and 45 vertical levels. The experiments were run four times a day, each integrated for 72-h with a 6-h update cycle.

3.3. Impact on typhoon/cyclone prediction

In this subsection, we briefly present some results for the GPS data impact on typhoon/cyclone prediction using higher model resolutions. The first case is Typhoon Bilis (2006). The GPS data impact for this case was discussed in more detail by Kueh et al. (2008). In the earlier stage of COSMIC measurement, only two GPS RO soundings (points 1 and 2) were located within the model domain (Fig. 2a). Assimilation of the two GPS RO soundings using the nonlocal operator (EPH) led to a big improvement in later track prediction (days 2 and 3), as seen in Fig. 2b. Removal of RO sounding 1 (EPHr1) resulted in a large increase in track error at later times, but removing point 2 (EPHr2) was much less influential. Without GPS data assimilation, the track (not shown) deviated southward and crossed northern Taiwan (the best track is just touching the northern tip of Taiwan, as shown in Fig. 2a). This indicates the beneficial impact of some soundings. Assimilation of SSM/I data (denoted as SSMI with precipitable water PW and 2D near-surface wind speed) or PW data only (denoted as SSMIpw) were not very helpful for this case. However, when the GPS RO data were also assimilated, the track prediction was improved (Fig. 2b). In this case, the impact of the GPS RO soundings at remote places was not smeared out by the much denser SSM/I data to the west.

For 2006, we have also investigated Typhoon Kaemi in July with 7 GPS RO points (Chen et al. 2008). The nonlocal operator reduced the track error by 50% in the first day compared to that using the local operator (not shown). However, no major improvement was produced in the second and third days. For another 2006 typhoon, Shanshan from 13-18 September, 27 GPS RO soundings helped to reduce the track error in the first day but also had much less impact on later forecasts (not shown). In particular, we found that the combined GTS data or use of a bogus vortex usually dominated the track prediction, which made assessing the impact of GPS data difficult. Nevertheless, we found that the best performance came from the combination of the three different kinds of data (observational and bogus), especially for later prediction times when the typhoon was closer to Taiwan. Consequently, severe rainfalls over Taiwan could be predicted very well in terms of their locations and intensities.

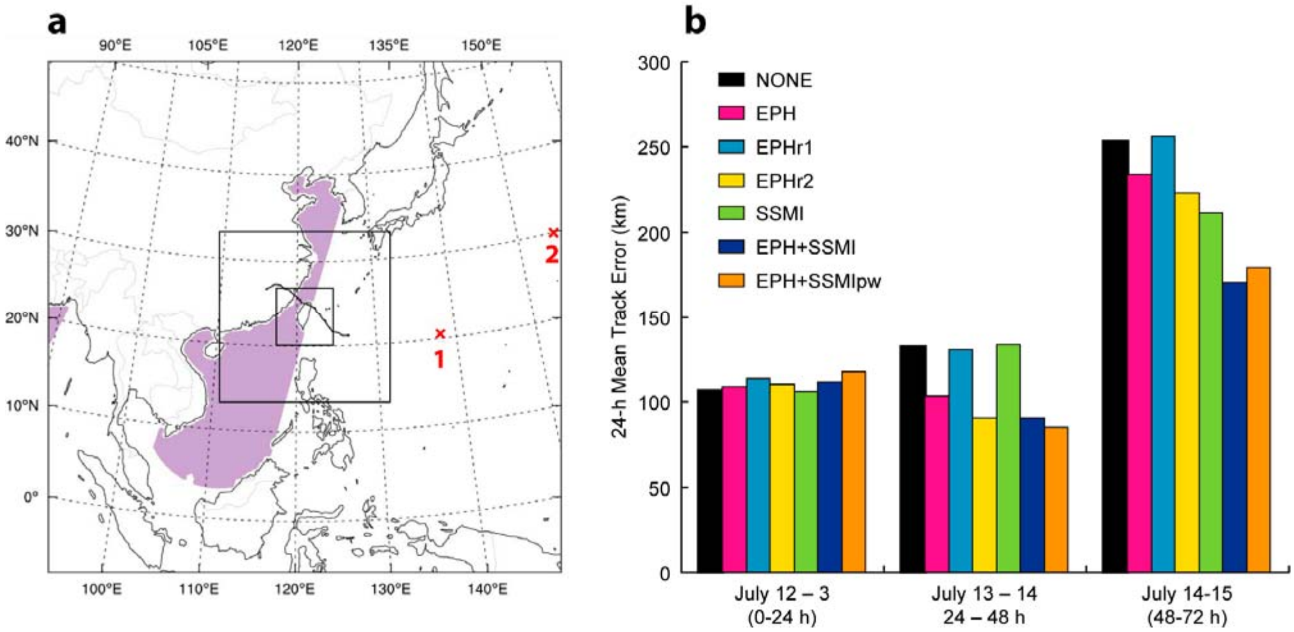


Figure 2: (a) Three model simulation domains for Typhoon Bilis (2006), with horizontal resolutions of 45 km, 15 km and 5 km, respectively. The best track from CWB during the simulation period (black line), and the locations of two GPS RO soundings (cross sign) and the coverage of SSM/I data swaths (shaded) are superimposed. (b) Average track errors (km) during 0-24 h, 24-48 h and 48-72 h for all experiments, NONE (no data assimilated), EPH (assimilation with excess phase), EPHr1 (as EPH but removing sounding 1), EPHr2 (as EPH but removing sounding 2), SSMI and SSMIpw (see the text).

Table 2: Simulated track error ratio for Typhoon Sepat during the period from 13 to 18 August 2007. The track error ratio is defined as (track error for GPS) / (track error for CONTROL). The leftmost column is the initial time for each experiment, and the uppermost row presents the forecast lengths for each experiment. The CONTROL is the experiment assimilating all the GTS observations, and the GPS is the experiment assimilating FORMOSAT-3/COSMIC GPS RO data and all the GTS observations. These experiments are the same as in Figure 2.

	12 H	**24 H**	**36 H**	**48 H**	**60 H**	**72 H**
1312	0.88	1.11	1.67	1.69	1.92	2.08
1400	5.42	1.43	2.98	4.84	7.65	4.98
1412	0.58	0.20	0.21	0.04	0.04	0.27
1500	2.59	1.55	1.90	2.64	1.80	2.16
1512	0.29	0.36	0.36	0.29	0.31	0.71
1600	0.48	0.14	0.18	0.31	0.5	0.66
1612	0.30	0.70	0.79	0.90	1.01	
1700	0.90	1.65	1.09	0.81		
1712	1.57	1.22	1.46			
1800	0.46	0.16				

In 2007, the clear impact of available GPS data was better demonstrated by the prediction of intense Typhoon Sepat in August. Figure 3 shows the simulated tracks for Sepat and the daily track errors. The assimilation of 23 GPS RO soundings (EPH) resulted in a significant reduction of the northward bias in track for NONE (without assimilation) at later times. On the third day, this improvement was substantial and solely due to the GPS data assimilation (using excess phase). This unquestionable improvement is also found in the track errors of the CWB WRF prediction in Table 2. For most of the evaluation times, the reduction in track errors is quite obvious; sometimes, they can be reduced by half. Again, the improvement for prediction was not that prominent if starting at earlier times.

Our impact study was also extended to Tropical Cyclone Gonu (2007) over the western Indian Ocean. This cyclone was one of the most intense in regional history and had severe impact. Figure 4 shows the simulated model domains and the available GPS RO data points. In this case, there were 56 soundings in the outer model domain and several of them were near the environment of the active cyclone. As in the other cases, the positive impact on track prediction is clear.

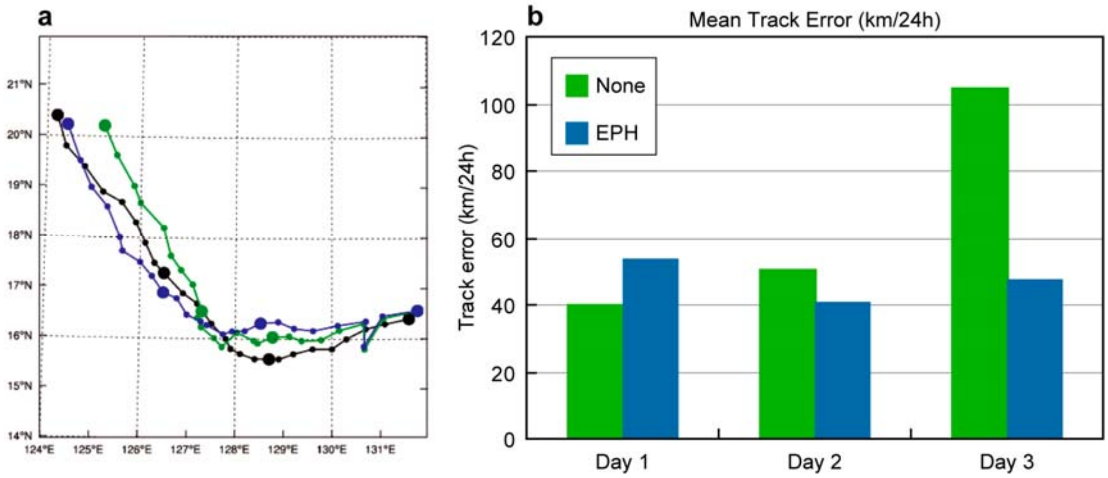


Figure 3 (a) The best track (black line 1) for Typhoon Sepat (2007) and simulated tracks for experiment NONE (green line 2) and EPH (blue line 3). (b) The 24-h mean track errors (unit: km) for experiments NONE and EPH. NONE contains no assimilated GPS data and EPH assimilates excess phase.

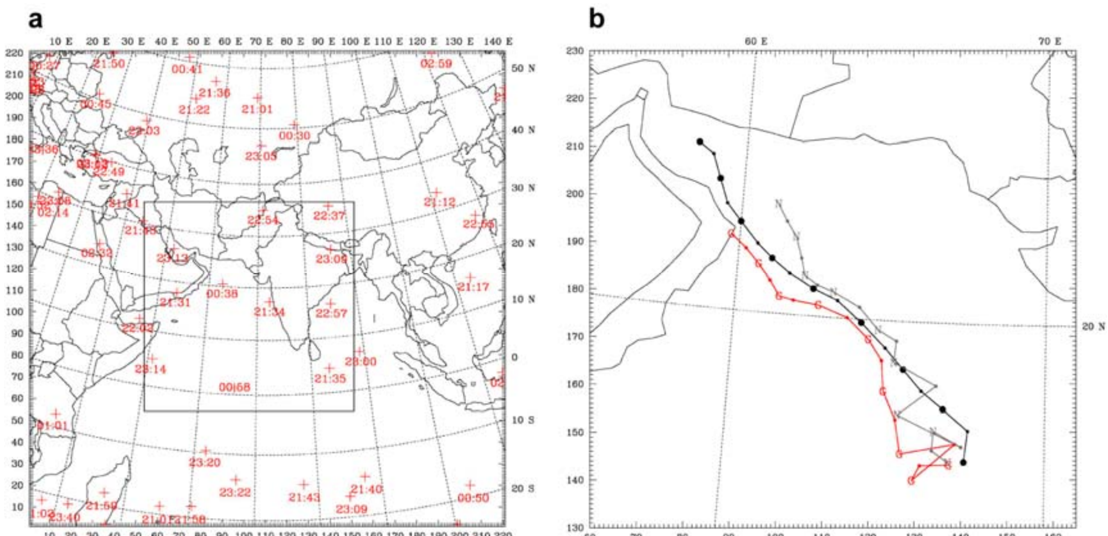


Figure 4: (a) Fifty six COSMIC radio occultation points in the outermost domain available in a 6-h window assimilation initialized at 0000 UTC 3 June 2007. The plus signs and numbers indicate the occultation positions and their corresponding UTC times, respectively. (b) The best track from JTWC (black dotted line) for Cyclone Gonu (2007) and simulated tracks for experiments NONE (gray line with sign 'N') and GPS (red line with sign 'G'), without and with the RO data assimilated, respectively.

Another severe cyclone over south Asia was the Myanmar Nargis in April 2008, prior to the typhoon season in East Asia. Even though this cyclone was not very intense (190 km per hour for maximum wind speed) and the accumulated rainfall during the event (Fig. 5c) was not particularly high as compared to most Taiwan cases, there were more than 100,000 victims due to severe flooding. For this case, there were only 29 points available in the model domain and none of them were close to the genesis area of the cyclone (Fig. 5a). Assimilation with such RO data appears to have minor impact on track. Both non-cycling and cycling (6-h update) runs showed similar tracks, which appear to be driven too far northward compared to the observed (Fig. 5d). Note that this cyclone was not well resolved by the initial global analysis but that the cyclone emerging later was generated by the WRF model. When a Rankine vortex was inserted (Fig. 5b), the model cyclone disappeared after some time but emerged again south of the observed track at a later time.

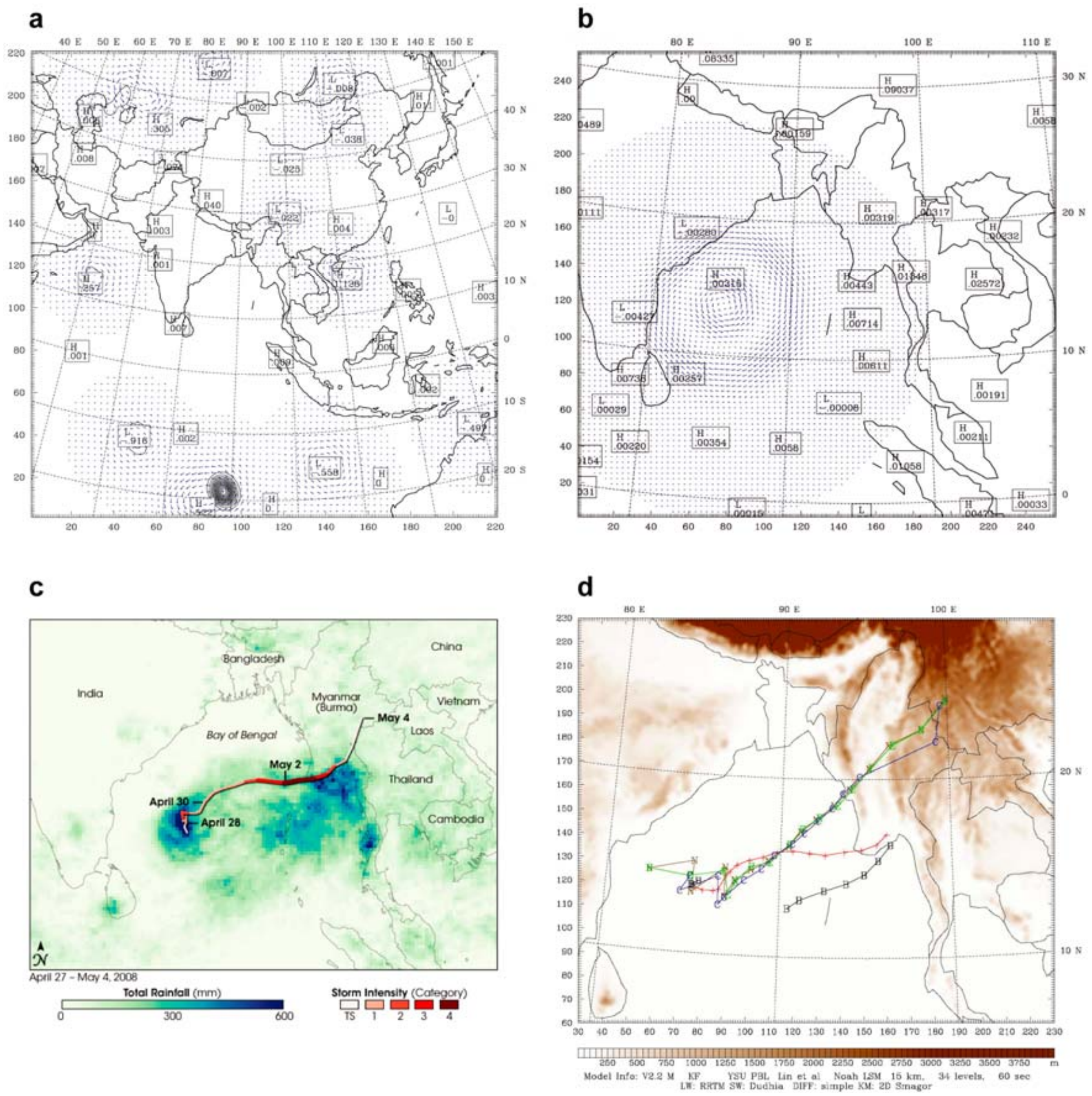


Figure 5: (a) The initial increments of moisture and wind vector at 2 km at 0000 UTC 29 April 2008 produced by the nonlocal operator at the WRF outer domain (45-km and 15-km resolution) containing 21 GPS RO points, (b) as in (a) but for the run with a bogus vortex at the inner domain (15-km resolution). (c) The estimated best track and accumulated rainfalls from April 27 to May 4, 2008 along the path of Cyclone Nargis by Tropical Rainfall Measuring Mission (TRMM) satellite (available from http://earthobservatory.nasa.gov). (d) The best track (denoted by plus) and the WRF simulated tracks for different runs with no GPS data (marked by N), 21 GPS RO points (by E), with an additional bogus vortex (by B) and the cycling run (by C) (assimilating an additional 24 GPS RO points within 3 h of 0600 UTC 29 April 2008).

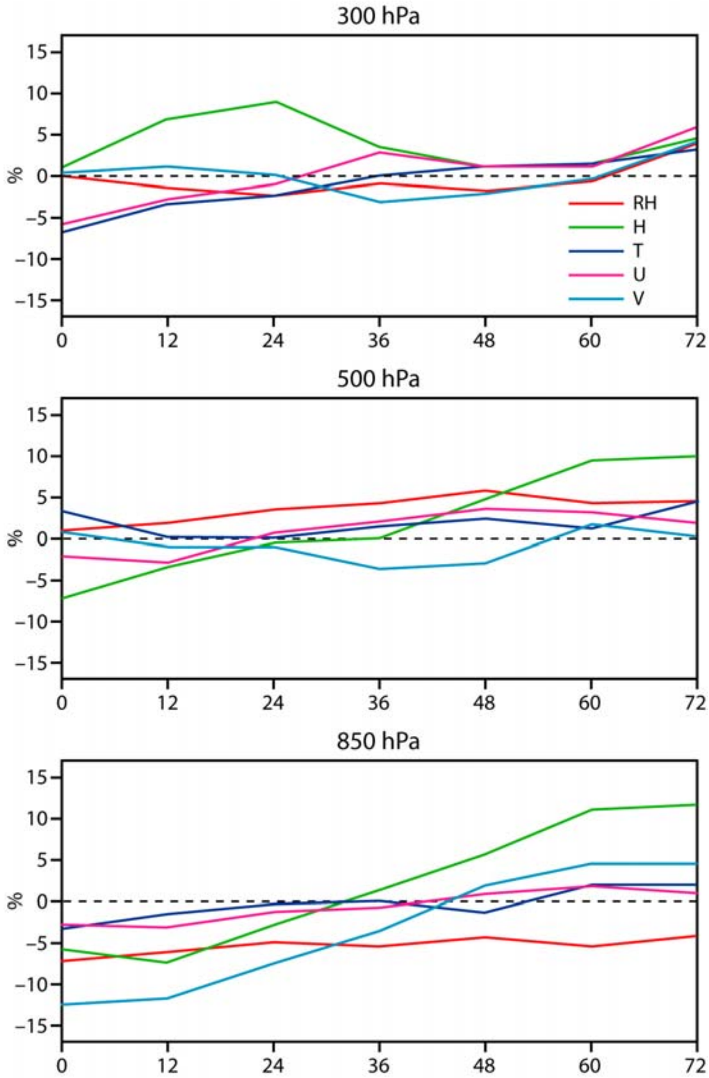
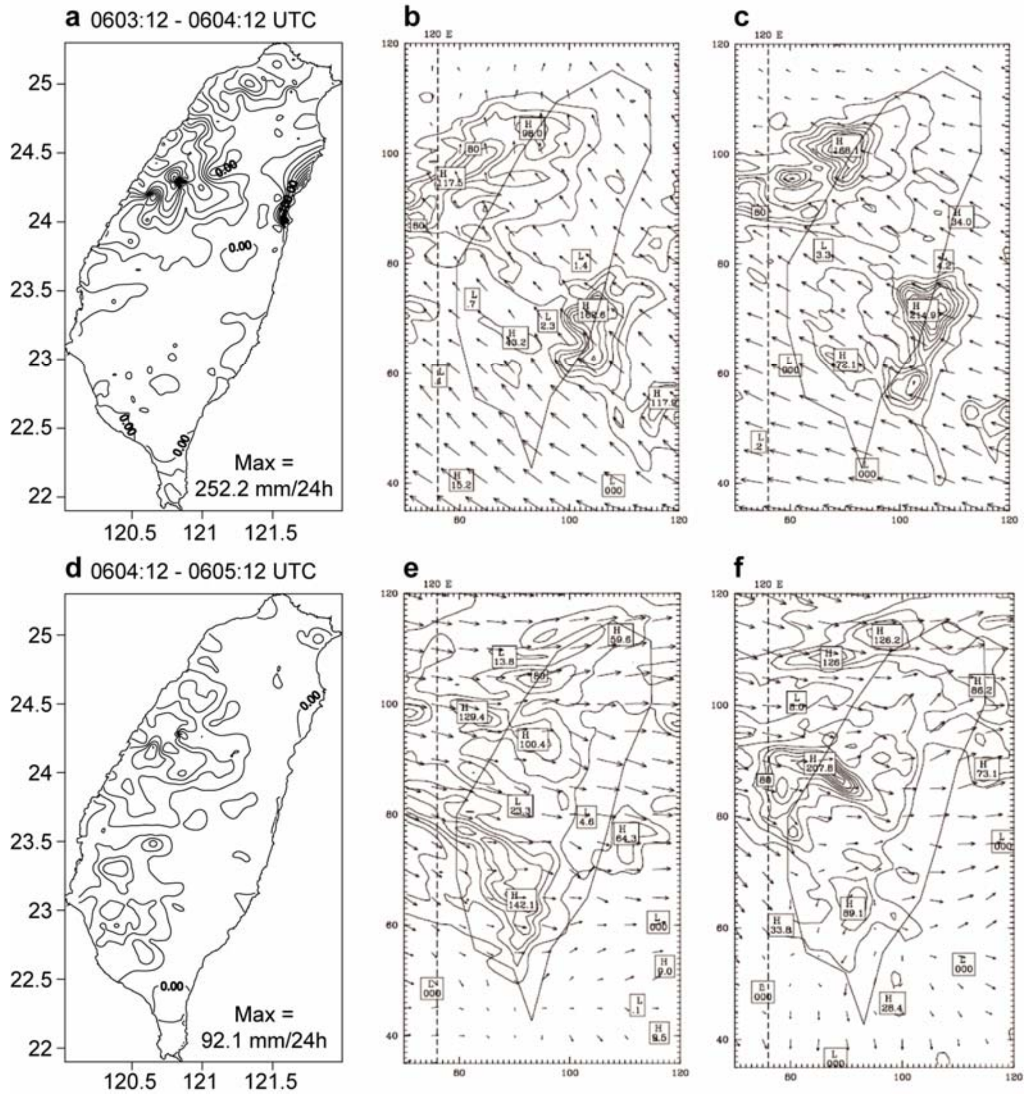


Figure 6: Skill scores for the evaluation of the forecast of Mei-yu events in Taiwan during an 11-day period from 5 to 15 June 2007. These forecasts using the WRF model were initialized twice daily from 0000 UTC 5 to 1200 UTC 15 June 2007. Each experiment contains 22 runs of 72-h simulation. The model includes two domains with 45-km and 15-km resolution. The GPS experiment (assimilating FORMOSAT-3/COSMIC GPS RO data) compared against the CONTROL experiment (no GPS data assimilated) at 300, 500 and 850 hPa. Color curves in red, green, blue, magenta, and cyan represent results of RH, H, T, U, and V, respectively. Positive (negative) values (percentages) are the positive (negative) impacts relative to the performances of the CONTROL experiment.

Interestingly, this bogus vortex makes a more consistent landfall at the riverside of Burma. The GPS data impact for this case is marginal; only a slight decrease in the large track error was found for the cycling run. This Indian cyclone is a challenging case for further investigation.

3.4. Impact on Mei-yu system prediction

Another severe weather phenomenon in East Asia is the Mei-yu system, which usually originates from southeast China and then migrates offshore to pass over Taiwan. When this frontal system approaches, Taiwan often experiences a lengthy rainy period that may last for more than one week. Large rainfalls are often produced as the prefrontal intense flow confronts the deflected mountain flow due to blocking effects. We simulated a severe Mei-yu event in early June 2007. The predictability is usually low for Mei-yu systems as compared to that of impinging typhoons. To explore the impact of the GPS RO soundings for such a case, the skill scores were evaluated for an 11-day period from 5 to 15 June 2007, based on forecasts up to 72-h (Fig. 6) with a 12-h update cycle. For most of the forecast times, the control run (with GPS data assimilation) gave better scores (positive percentages) at all three vertical levels than the denial run, except for moisture at 850 hPa. The verification of the forecasts is on a simulation domain similar to the innermost domain in Fig. 2. Improvements appear to be more evident for longer forecasts, except for the north-south wind component (V). In general, such improvements are more confident at higher levels where positive percentages are observed more than negative values.



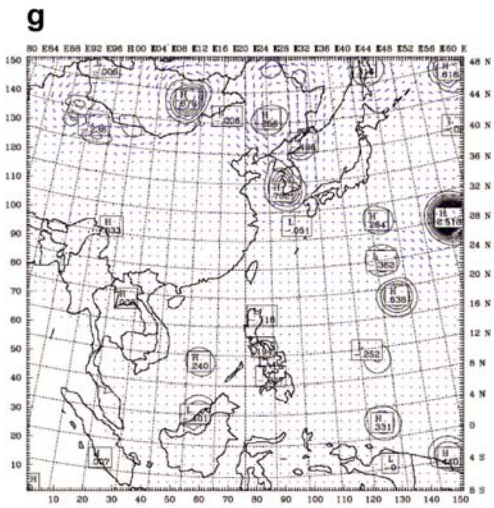


Figure 7: (a), (b) and (c) are the observed accumulated rainfall (mm) for the 2007 Mei-yu front case, the predicted rainfalls (mm) for the runs with no GPS data assimilated and with 31 GPS RO data for the second day; (d), (e) and (f) as (a), (b) and (c), respectively, but for the third day. The initial moisture increments (at an interval of 0.1 g kg^{-1}) and wind increments (m s^{-1}) produced by the nonlocal operator at 1200 UTC 02 June 2007 are shown in (g).

We also simulated this Mei-yu front case in the earlier period (from 1200 UTC 02 June to 1200 UTC 05 June) using three nested domains with 31 GPS RO points available for assimilation. Figure 7 shows the initial increments generated by assimilation of these RO points and the daily accumulated rainfall over Taiwan. We found that assimilation of the GPS RO data resulted in more consistent patterns of intense rainfall. Moreover, in the third day, the large rainfall in south Taiwan in the control run has been considerably suppressed in the GPS assimilation run. The results indicate that the remote GPS soundings might have an influential impact on the prediction of the Mei-yu frontal system and the associated rainfall over Taiwan.

3.5. An OSSE study for Typhoon Krosa (2007)

Is typhoon track prediction notably improved by assimilation of GPS RO data? To answer this question, we conducted an OSSE study for Typhoon Krosa (2007), which made landfall in northern Taiwan. First we conducted a 96-h MM5 simulation at 15-km resolution with an initial Rankine vortex inserted at 0400 October 2007; this run served as the nature run. Then, we retrieved RO soundings by running a 2-D ray-tracing model with the analysis of the nature run at 0412 October 2007 (12 h later) to obtain bending angles (assuming a uniform azimuthal angle of 45°) and the converted RO refractivity in the target region of the typhoon vortex. The RO soundings extended from 300 m to 16 km height, at a vertical resolution of ~300 m. We applied a linear filter to smooth the prediction of the nature run at 0412 October 2007 in order to generate the initial analysis of the control run (as the first guess from coarser global analysis), and then employed WRF 3DVAR to assimilate the retrieved RO refractivity soundings using the nonlocal operator and local operator. Finally, we compared the results of the runs with and without assimilation of these GPS data with a benchmark reference from the nature run.

Figure 8 shows the real best track, the simulated tracks of the nature run, the control run and the GPS assimilation runs with the total RO soundings (1252 points at 30-km resolution) and the diluted soundings (45 points at 120-km resolution) surrounding the typhoon center. At the initial time (0412), the nature (control) run has a maximum near-surface wind speed of 26.9 m s^{-1} (22.2 m s^{-1}). After assimilating these soundings, the control vortex was intensified to 24.7 m s^{-1} with an anticyclonic (cyclonic) vortex generated in

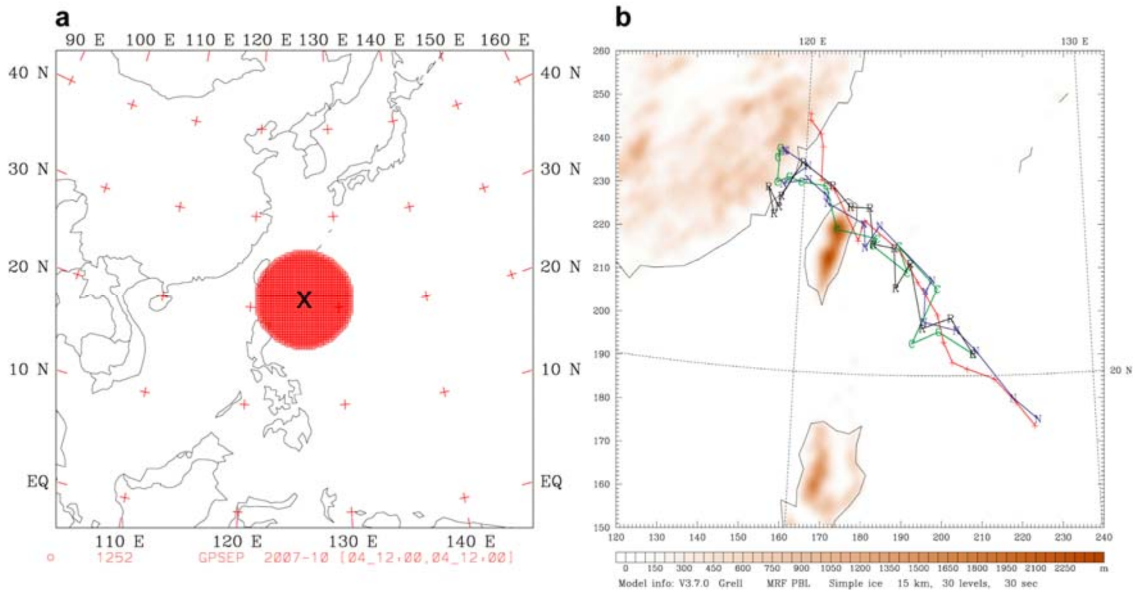


Figure 8 (a) Distribution of 1252 GPS RO soundings surrounding the typhoon center (marked by 'x') of Krosa (2007). (b) The real best track (+), the simulated tracks of the nature run (N), the control run (C), and the GPS runs with assimilation of the dense soundings (1252 points) using the local operator (R) or the nonlocal operator (E) and the diluted soundings (45 points) using the nonlocal operator (F).

the south (north) region of the soundings embedded in a cold dome (negative temperature increments up to 2° C). Thus, the GPS data assimilation helped recover the cyclone intensity and may explain why the track that made a more southward landfall was successfully remedied. Note that both the control run and GPS runs have identical environments; their initial differences are located just within the typhoon target zone. Therefore, we believe that the improved track is primarily due to the initial good recovery of a stronger vortex by assimilation of the 1252 GPS RO soundings, regardless of use of the local operator or nonlocal operator. This number of RO soundings is rather hypothetical and may not be realistic in the near future. However, assimilation of the diluted soundings (45 points) also gave a similar improvement in track prediction. Indeed, further reduction of the RO data density (e.g., down to 20 points or so) may still allow a commensurate improvement (not shown). The critical density of GPS RO data in the typhoon target zone as well as the environment needs to be investigated more thoroughly. We will proceed along this line for other intense typhoons, likely Shanshan (2007) with a recurved track.

4. Conclusions

In this study, we have presented some model results to summarize the impact of COSMIC RO data on prediction of severe weather in Asia, ranging from East Pacific typhoons to South Indian cyclones and the Mei-yu frontal system. Some of the cases showed a large impact even when only one GPS RO sounding was assimilated. But several of them with many more soundings did not display a statistically significant impact. This was especially the case for typhoon predictions involving more complex factors contributing to model performance. In general, from a continuous evaluation of skill scores for real-time forecasts in this region over a longer period or high-resolution weather simulations, we found that assimilation of GPS RO data appears to be beneficial for most of our model predictions. Based on an OSSE study for Typhoon Krosa (2007), this positive impact on typhoon track prediction has been shown to be unequivocal even for hypothetical dense (1252 points) or diluted (45 points) GPS RO data..

Acknowledgments

This study was supported by the National Science Council (NSC) and the National Space Program Organization (NSPO) in Taiwan.

References

Anthes and Coauthors, 2008: The COSMIC/FORMOSAT-3 Mission: Early results. *Bull. Amer. Meteor. Soc.*, in press.

Chen, S.-Y., C.-Y. Huang, Y.-H. Kuo, Y.-R. Guo and S. Sokolovskiy, 2008: Typhoon predictions with GPS radio occultation data assimilations by WRF-VAR using local and nonlocal operators. *Terr. Atmos. Oceanic Sci.*, in press.

Cucurull, L., Y.-H. Kuo, D. Barker, and S. R. H. Rizvi, 2006: Assessing the impact of simulated COSMIC GPS radio occultation data on weather analysis over the Antarctic: A case study. *Mon. Wea. Rev.*, **134**, 3283-3296.

Cucurull, L., J.C. Derber, R. Treadon and R.J. Purser, 2007: Assimilation of Global Positioning System radio occultation observations into NCEP's Global Data Assimilation System. *Mon Wea. Rev.*, **135**, 3174-3193.

Healy, S., 2008: Forecast impact experiment with a constellation of GPS radio occultation receivers. *Geophys. Res. Letter*, in press.

Healy, S. B., A. M. Jupp, and C. Marquardt, 2005: Forecast impact experiment with GPS radio occultation measurements. *Geophys. Res. Lett*., **32**, L03804, doi:10.1029/2004GL020806.

Healy, S. B., and J.-N. Thepaut, 2006: Assimilation experiments with CHAMP GPS radio occultation measurements. *Quart. J. Roy. Meteor. Soc*., **132**, 605-623.

Huang, C.-Y., Y.-H. Kuo, S.-H. Chen and F. Vandenberghe, 2005: Improvements on typhoon forecast with assimilated GPS occultation refractivity. *Wea. Forecasting*, **20**, 931–953.

Kueh, M.-T., C.-Y. Huang, S.-Y. Chen, S.-H. Chen and C.-J. Wang, 2008: Impact of GPS radio occultation soundings on prediction of Typhoon Bilis (2006) landfalling Taiwan. *Terr. Atmos. Oceanic Sci*., in press.

Kuo, Y.-H., X. Zou, and W. Huang, 1997: The impact of GPS data on the prediction of an extratropical cyclone: An observing system simulation experiment. *J. Dyn. Atmos. Ocean*, **27**, 413-439.

Kuo, Y.-H., S. V. Sokolovskiy, R. A. Anthes, and F. Vandenberghe, 2000: Assimilation of GPS radio occultation data for numerical weather prediction. *Terr. Atmos. Oceanic Sci*., **11**, 157-186.

Kursinski, E. R., G. A. Hajj, S. S. Leroy, and B. Herman, 2000: The GPS radio occultation technique. *Terr. Atmos. Oceanic Sci*., **11**, 53-114.

Liu, H., and X. Zou, 2003: Improvements to GPS radio occultation ray-tracing model and their impacts on assimilation of bending angle. *J. Geophys. Res*., **108** (D17), 4548, doi: 10.1029/2002JD003160.

Ma, Z., Y.-H. Kuo, B. Wang, W.-S. Wu, and S. Sokolovskiy, 2008: Comparison of local and non-local observation operators for the assimilation of GPS radio occultation refractivity data in the NCEP GSI system: an observing system simulation experiment. Submitted to *Mon Wea. Rev.*

Poli, P., P. Moll, D. Puech, F. Rabier, and S. B. Healy, 2008: Quality control, error analysis, and impact assessment of FORMOSAT-3/COSMIC in numerical weather prediction. *Terr. Atmos. Oceanic Sci*., in press.

Sokolovskiy, S., Y.-H. Kuo, and W. Wang, 2005: Assessing the accuracy of linearized observation operator for assimilation of the Abel-retrieved refractivity: Case simulation with high-resolution weather model. *Mon. Wea. Rev.*, **133**, 2200-2212.

Zou, X., F. Vandenberghe, B. Wang, M. E. Gorbunov, Y.-H. Kuo, S. Sokolovskiy, J. C. Chang, J. G. Sela, and R. Anthes, 1999: A raytracing operator and its adjoint for the use of GPS/MET refraction angle measurements. *J. Geophys. Res*., **104**, 22301-22318.