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ORIGINAL ARTICLE

Impact of GPS radio occultation data assimilation on regional weather predictions

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Abstract The impact of GPS radio occultation (RO) data assimilation on severe weather predictions in East Asia is introduced and reviewed. Both the local observation operator that assimilates the retrieved refractivity as local point measurement, and the nonlocal observation operator that assimilates the integrated retrieved refractivity along a straight raypath have been utilized in WRF 3DVAR to improve the initial analysis of the model. A general evaluation of the impact of these approaches on Asian regional analysis and daily prediction is provided in this paper. In general, the GPS RO data assimilation may improve 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. Based on a number of experiments, regional model predictions at 5 km resolution were not significantly influenced by different observation operators, although the nonlocal observation operator sometimes results in slightly better track forecast. 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 also appealing when compared to other tracks assimilated with different observations. From a successive evaluation of skill scores for real-time forecasts on Mei-yu frontal systems operationally conducted over a longer period and predictions of six typhoons in 2008, assimilation of GPS RO data appears to have some positive impact on regional weather predictions, on top of existent assimilation with all other observations.

Keywords GPS · Radio occultation · WRF · Data assimilation · FORMOSAT-3 · COSMIC

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Introduction

With the global coverage of global positioning system (GPS) satellites, radio occultation (RO) technique for sounding earth's atmosphere by limb links was demonstrated by the proof-of-concept GPS Meteorology (GPS/MET) experiment in 1995–1997 (Ware et al. 1996). This successful mission of GPS/MET then was followed by two similar missions, the Challenging Minisatellite Payload (CHAMP) and the Satellite de Aplicaciones

Cientificas-C (SAC-C). According to the RO principle and retrieval, these global measurements as procured are actually commensurable with radiosonde soundings in accuracy (Kursinski et al. 2000). The newly operational FORMOSAT-3/COSMIC consisting of six satellites to provide up to 1800–2200 global soundings daily (Anthes et al. 2008) has drawn attention to the great value of GPS RO measurements in many global climate and weather applications. Assimilations of the RO retrieved data (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. 2009). For global models, assimilation of bending angle has the advantage of providing better accuracy, but at the cost of computational expense (Zou et al. 1999; Kuo et al. 2000). For regional models, assimilation of refractivity has usually been undertaken using a local observation operator or a nonlocal observation operator (Huang et al. 2005; Chen et al. 2009).

GPS RO data have been proven to give a positive impact on some typhoon track and rainfall predications (Huang et al. 2005) and the prediction of monsoon-induced rainfall over western Indian coast with Gatt mountain (Huang et al. 2007), based on the control experiment with assimilation of the GPS RO data and the denial experiment without the GPS RO data available from two earlier satellites. 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 introduce and review the impact of the GPS RO soundings from COSMIC on prediction of recent severe weathers (typhoons and Mei-yu systems) in Asia, in addition to assessing their general impact on continuous forecasts over selected periods. This paper highlights the current status of GPS RO data assimilation in regional weather prediction and their potential impact based on a number of numerical experiments. In "The methodologies and the operators", the methodologies and the observation operators are introduced. The results for selected cases are presented and described in "The results". Finally, our conclusions are given in "Conclusions".

The methodologies and the operators

The methodologies used in this study include the meteorological prediction model WRF and its preprocessor using three-dimensional variational (3DVAR) method to provide model initial conditions with different observational data assimilated by their operators.

The prediction model and preprocessor

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

The observation operators 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 neutral atmospheric refractivity N is given by

$$N = 77.6\frac{P}{T} + 3.73 \times 10^{5}\frac{P_w}{T^2} \quad (1)$$

where P_w is water vapor pressure in hPa, T air temperature in K, and P the pressure of the atmosphere in hPa. In order 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 (as observed). Thus, in the S representation, the error induced by horizontal gradients can be substantially reduced to give a more accurate analysis (Ma et al. 2009). The nonlocal operator for assimilating excess phase has been implemented into WRF 3DVAR (Chen et al. 2009), 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.

The results

Severe weathers such as typhoons and Mei-yu systems were simulated when COSMIC data were available. General assessments of continuous forecasts were conducted by CWB (Central Weather Bureau) and NCU (National Cental University), respectively, for some monthly periods in 2007 and 2008. Impacts on typhoon/cyclone prediction in 2006 and 2007 and on Mei-yu frontal cases in 2007 and 2008 are explored. Impact on typhoon predictions in 2008 are illustrated, in particular, since the COSMIC data in 2008 have reached maturity in quantity and quality.

Simulated severe weather cases in 2006, 2007, and 2008

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 (5 km) with focus on the regional area. A list of the simulated events in 2006, 2007, and 2008 is given in Table 1 which includes typhoons/tropical cyclones as well as Mei-yu frontal systems. 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 or describe some results of these simulated events with the available GPS soundings assimilated into the model.

General assessment of continuous forecasts

Central Weather Bureau in Taiwan has been using the regional WRF model to conduct daily semi-operational experiments. Before formally assimilating the GPS RO data into the operational version, the model performance with assimilation of the GPS RO data was extensively verified. The verifications are made for the model predictions (with and without assimilation of the GPS RO refractivity soundings) against sounding observations in the outer model domain. Note that the experiments are for operational tests and thus include all other routinely available observations (conventional radiosonde sounding, thickness and oceanic wind and cloud motion wind from satellites, etc.). Figure 1 shows the model verification for predicted temperature against soundings in August 2007 by CWB using WRF model for the denial run without GPS RO data and the control run with GPS RO data. As can be clearly seen, both the bias and the standard deviation have been reduced by assimilation of the GPS RO data,

Table 1 The simulated severe weather cases in 2006, 2007, and 2008 with the FORMOSAT-3/COSMIC RO data assimilated into the regional model within an assimilation time window of 6 h (centered on the model initial time)

Initial time	Event	GPS RO
2006–2007-1200	Typhoon Bilis	2
2006–2007-2300	Typhoon Kaemi	7
2006–2009-1312	Typhoon Shanshan	27
2007–2006-0212	Mei-yu Front	31
2007–2006-0300	Cyclone Gonu	56
2007–2007-1100	Typhoon Manyi	15
2007–2007-2900	Typhoon Usagi	39
2007-08-1600	Typhoon Sepat	21
2007–2010-0412 (0500)[a]	Typhoon Krosa	31 (17)
2008–2004-2900 (2906)[a]	Cyclone Nargis	21 (24)
2008–2006-2500	Mei-yu Front	26
2008–2007-1600	Typhoon Kamaegi	15
2008–2007-2600	Typhoon Fung-Wong	43
2008–2009-1200	Typhoon Sinlaku	12
2008–2009-2700	Typhoon Jangmi	27

[a] Cycling

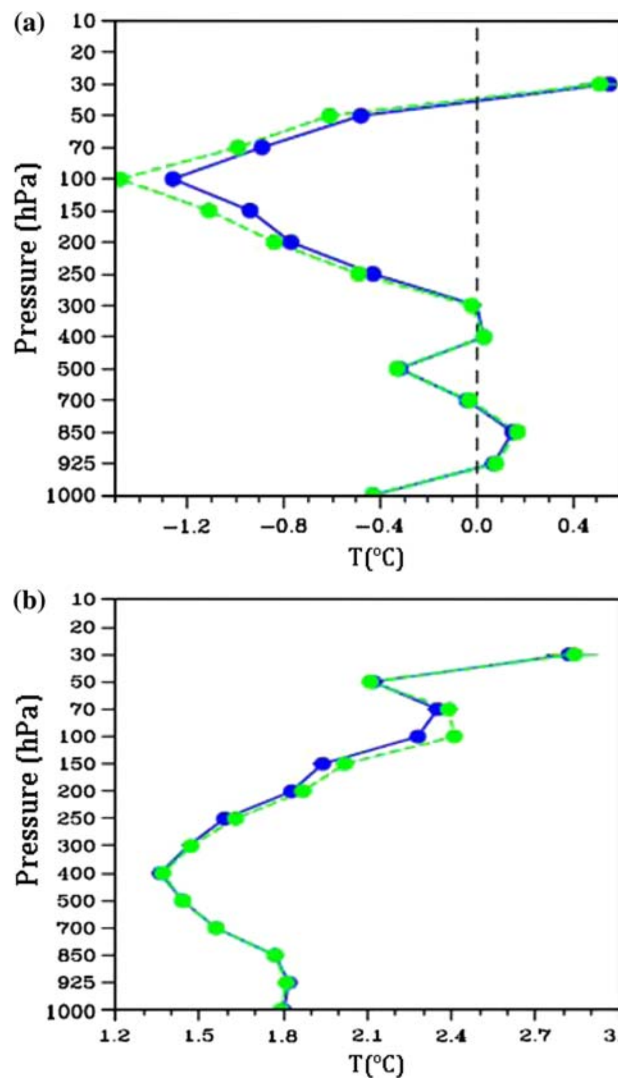

Fig. 1 Temperature verification of the model performance against radiosonde soundings in August 2007 by CWB using WRF model for the denial run without GPS RO data (*dashed green line*) and the control run with GPS RO data (*solid blue line*). **a** Bias in °C, and **b** standard deviation in °C

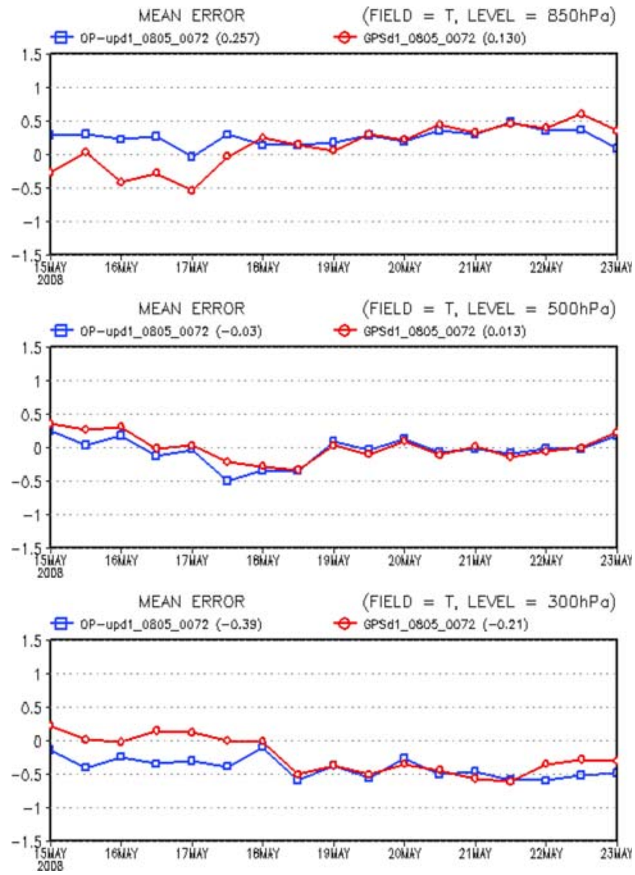

Fig. 2 Mean errors for 72 h forecasted temperatures during an 8-day period from 15 to 23 May 2008. The CONTROL experiment (assimilating FORMOSAT-3/COSMIC GPS RO data and all the GTS observations, *red lines*) against the DENIAL experiment (assimilating all the GTS observations only, *blue lines*) at 850, 500, and 300 hPa are shown from *top* to *bottom*. These forecasts are conducted using the WRF model with two nested domains (at horizontal resolutions of 45 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

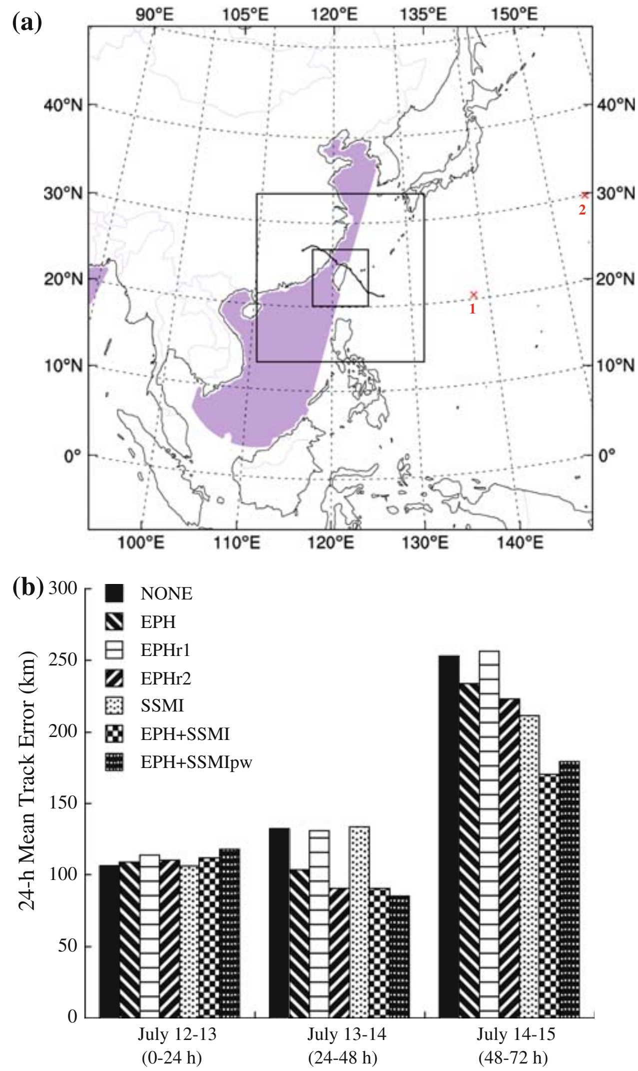

Fig. 3 **a** Three model simulation domains for Typhoon Bilis (2006), with horizontal resolutions of 45, 15, and 5 km, respectively. The best track from CWB during the simulation period (*black line*), and the locations of two GPS RO soundings (cross sign) and the coverage of SSM/I data swaths (*shaded*) are superimposed. **b** Average track errors (km) during 0–24, 24–48 and 48–72 h in sequence 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)

especially from above 300 mb to the model top. Through dynamic linkage, other improvements also exist for predicted wind (not shown). The greater positive impact on prediction of upper temperature in Asia appears to be in consistence with the global model performance with the GPS RO data at ECMWF (Healy 2008).

Real-time prediction has also been continuously conducted for experiments including a GPS control run (with GPS RO data) and a denial run (without GPS RO data) at National Central University, Taiwan. Figure 2 gives an example of the two comparative runs for an 8-day period (15–23 May 2008) when a Mei-yu system was situated near Taiwan. The WRF model with moderate resolution (45 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 slightly smaller mean errors in the temperature forecast (red lines) than the denial run (blue lines) at the three vertical levels (850, 500 and 300 hPa) for 72 h forecasts with a 6 h update cycle. However, at 850 hPa, the GPS run shows significant degradation (worse performance) early in the forecast period. We should continue to explore why there is such poor performance at this lower level when the GPS RO data have been ingested.

Another demonstration of the GPS RO data impact is the semi-operational CWB WRF performance for an extended period (1–20 August 2007) with no severe weather. Both 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.

Impact on typhoon/cyclone prediction in 2006 and 2007

In this subsection, we briefly present some results for the GPS RO data impact on the prediction of typhoons/cyclones in 2006 and 2007 using higher model resolutions (45 km, 15 km and 5 km). The first case is Typhoon Bilis (2006). The GPS RO data impact for this case was discussed in more detail by Kueh et al. (2009). In the earlier stage of COSMIC measurement, only two GPS RO soundings (points 1 and 2) were located within the outer model domain (Fig. 3a). 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. 3b. 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 RO 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. 3a). This indicates the beneficial impact of some favorable 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) was not very helpful for this case. However, when the GPS RO data were also assimilated, the track prediction became improved (Fig. 3b). 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 of the typhoon.

For 2006, we have also investigated Typhoon Kaemi in July with seven GPS RO points (Chen et al. 2009). The nonlocal operator reduced the track error by 50% in the first day compared to that using the local operator (figures not shown). However, no major improvement was found in the second and third days. For another 2006 typhoon, Shanshan from 13 to 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 combination with conventional

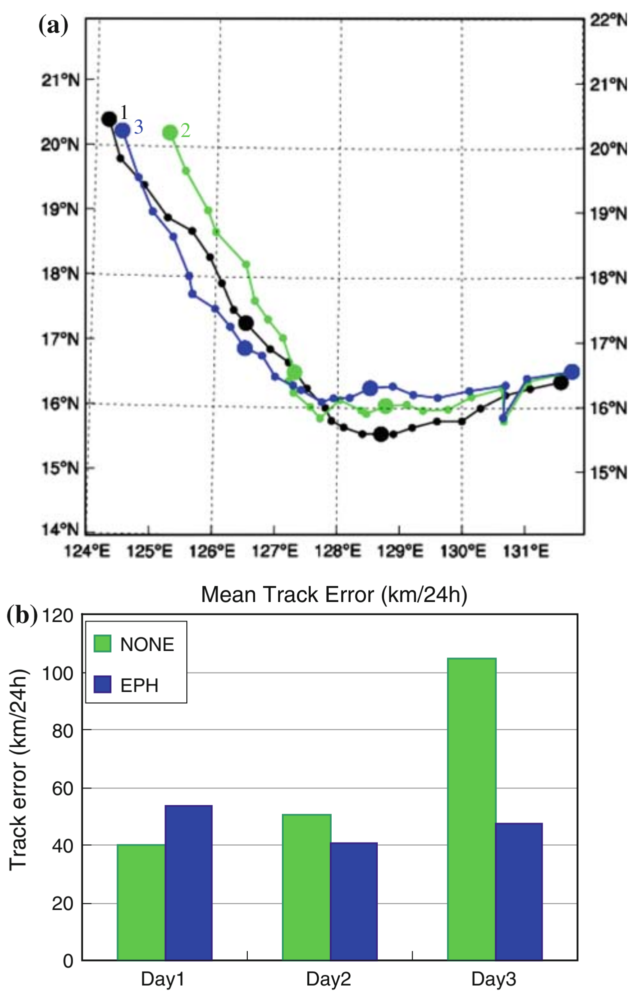

Fig. 4 **a** The best track (*black line 1*) for Typhoon Sepat (2007) and simulated tracks for experiment NONE (*green line 2*) and EPH (*blue line 3*). **b** The 24 h mean track errors (unit: km) for experiments NONE and EPH. NONE does not assimilate GPS RO refractivity and EPH assimilates excess phase

Table 2 Simulated track error ratio for Typhoon Sepat during the period from 13 to 18 August 2007

	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				

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 some available satellite observations, and the GPS is the same experiment as CONTROL but also assimilating FORMOSAT-3/COSMIC GPS RO data

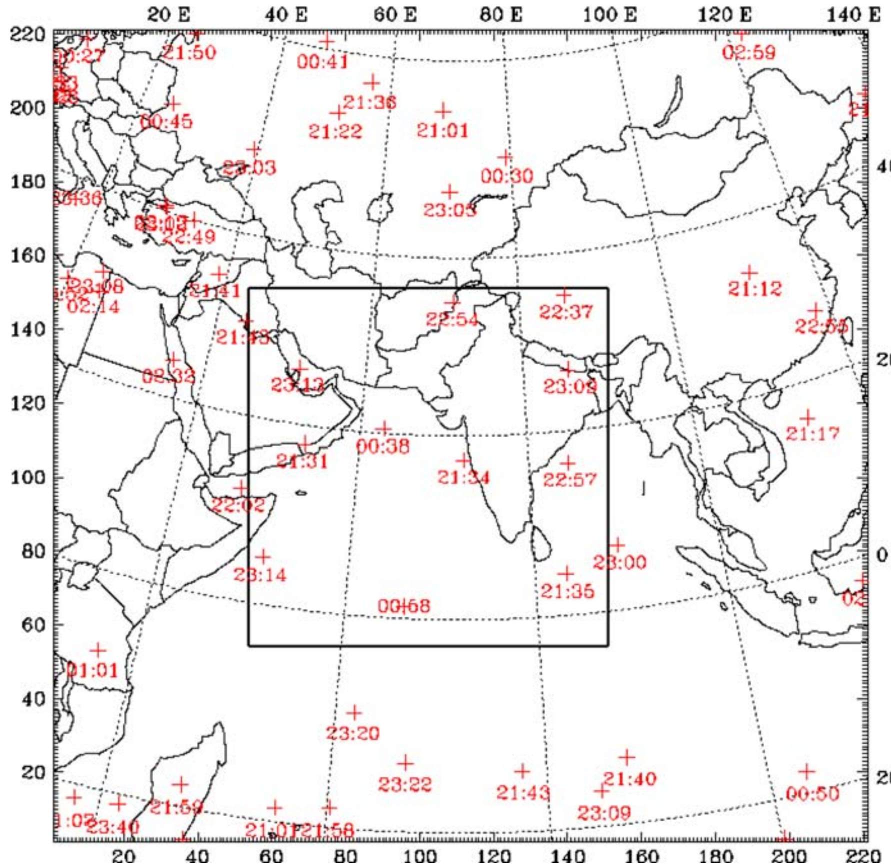

Fig. 5 Fifty-six COSMIC radio occultation points in the outermost domain available in a 6 h window assimilation initialized at 0000 UTC 3 June 2007. The *plus signs* and numbers indicate the occultation positions and their corresponding UTC times, respectively

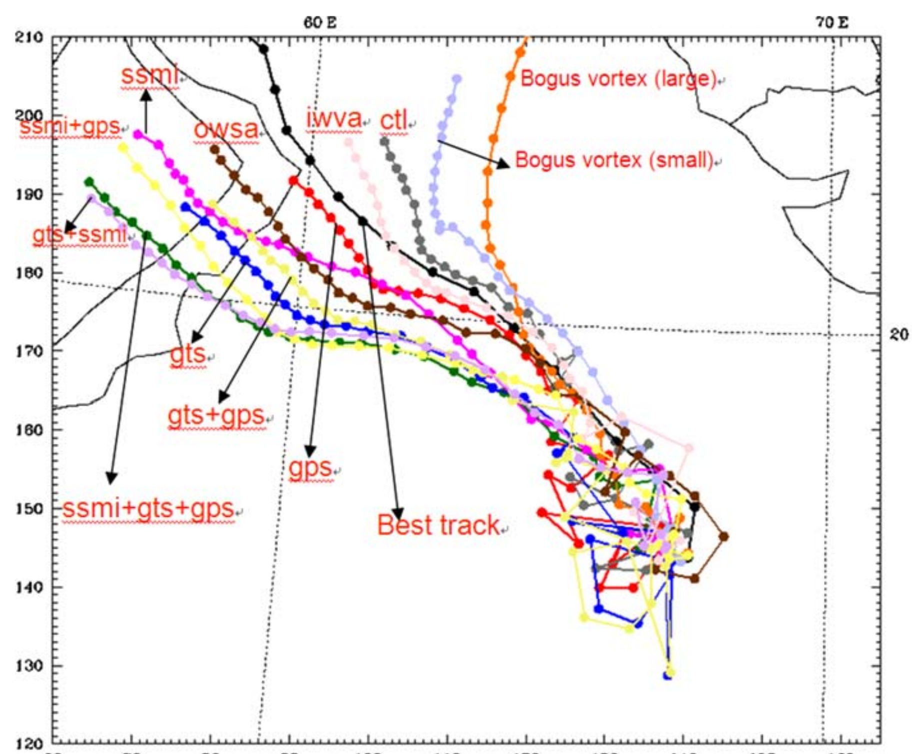

Fig. 6 The best track from JTWC (*black line*) for Cyclone Gonu (2007) and simulated tracks for experiments CTL and GPS without and with the RO data assimilated, respectively, and other experiments with different data, GTS (radiosondes), SSMI (SSM/I retrieved oceanic near-surface wind speed OWS and integrated precipitable water PW, denoted as OWSA an IWVA, respectively), bogus vortex 1 (*large vortex*) and bogus vortex 2 (*small vortex*)

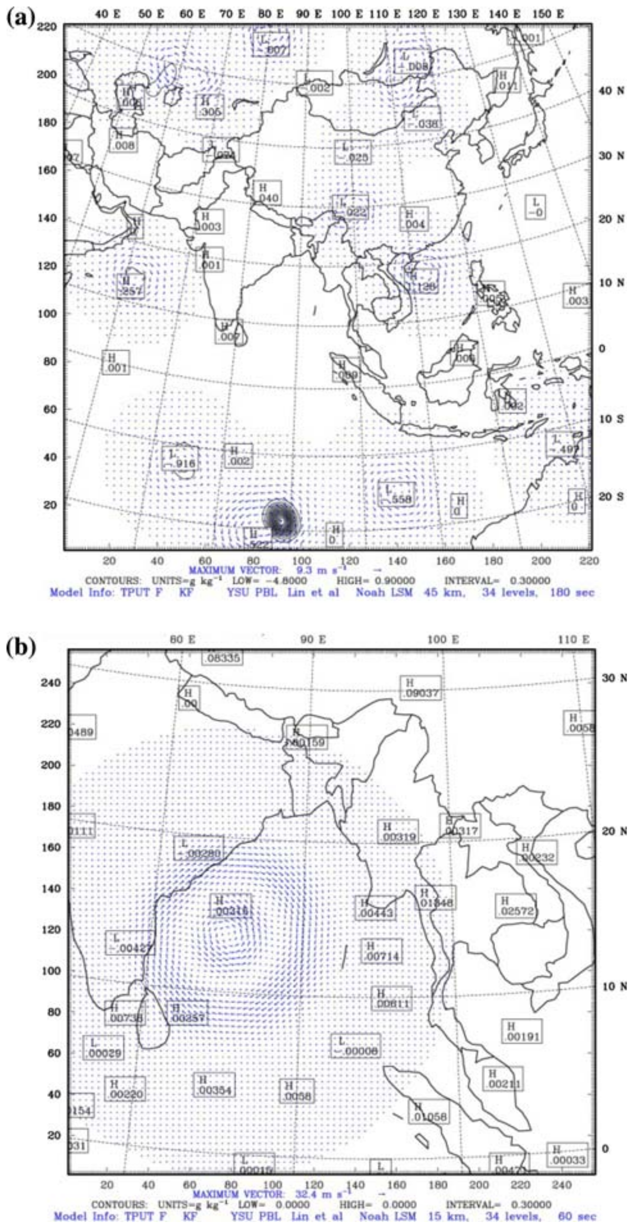

Fig. 7 **a** The initial increments of moisture and wind vector at 2 km at 0000 UTC 29 April 2008, produced by the nonlocal operator at the WRF outer domain (45 and 15 km resolution) containing 21 GPS RO points, (**b**) as in (**a**) but for the run with a bogus vortex at the inner domain (15 km resolution)

soundings (GTS) or use of a bogus vortex usually dominated the track prediction (e.g., Zou and Xiao 2000), which made assessing the impact of GPS RO data difficult for such cases. Nevertheless, we found that the best performance resulted 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 reasonably well in terms of their locations and intensities (figures not shown).

In 2007, the clear impact of available GPS RO data was better demonstrated by the prediction of intense Typhoon Sepat in August. Figure 4 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 RO data assimilation (using excess phase). This unquestionable improvement is also found in the track errors of the WRF prediction at CWB, as summarized in Table 2. For most of the evaluation times, the reduction in track errors is quite obvious; sometimes, they can be reduced by half or more. Again, the improvement on the 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 5 shows the simulated model domains and the available GPS RO data points within the assimilation window. In this case, there were 56 RO 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 of GPS RO data on track prediction is clearly seen in Fig. 6. It is surprisingly found that assimilations with all other data (including SSM/I, GTS and their combinations) do not outperform the run with GTS + GPS or even the run with GPS RO data only. As will be seen later, such a GPS run is not a lucky case simulation for typhoon or cyclone track.

Another severe cyclone over south Asia was the Myanmar Nargis in April 2008, prior to the typhoon season in East Asia. For this case, there were only 29 RO points available in the model domain (Fig. 7a), and none of them were close to the genesis area of the cyclone where a bogus vortex was inserted (Fig. 7b). Even though this cyclone was not very intense (190 km per h for maximum wind speed) and the accumulated maximum rainfall of about 600 mm during the event was not particularly large when compared to most Taiwan cases, there were more than 100,000 victims due to severe flooding. Assimilation with such RO data appears to have minor impact on track prediction (Fig. 8). Both noncycling and cycling (6 h update) runs showed similar tracks, which appear to be driven too far northward compared to the observed. Note that this cyclone was not well resolved by the initial global analysis, and that the cyclone emerging later was generated by the WRF model. When a Rankine vortex was inserted (as seen in Fig. 7b) to enhance the initial cyclone intensity, the model cyclone disappeared after some time but emerged again south of the observed track at a later time. Interestingly, this bogus vortex luckily makes a more consistent landfall at the riverside of Burma. The GPS RO data

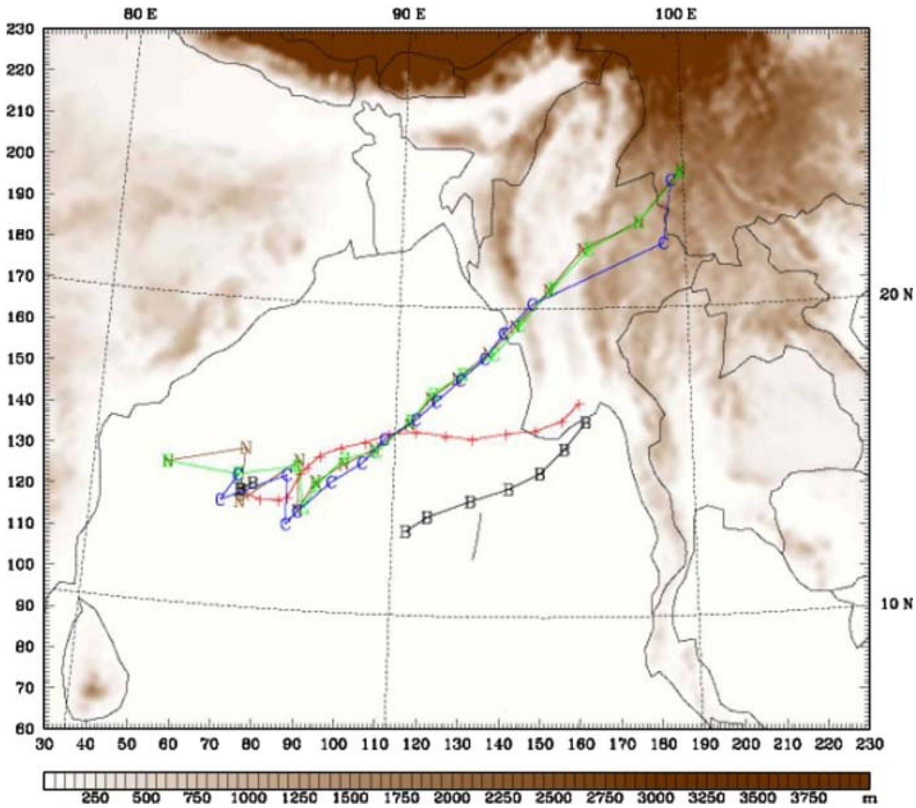

Fig. 8 The best track of Cyclone Nargis in 2008 (denoted by *plus sign*) and the WRF simulated tracks for different runs with no GPS RO data (marked by *N*), 21 GPS RO points (by *E*), with additional bogus vortex (by *B*) and the cycling run (by *C*) (assimilating an additional 24 GPS RO points within 3 h of 0600 UTC 29 April 2008)

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 worthy of further investigation.

Impact on Mei-yu system prediction in 2007 and 2008

Another severe weather phenomenon in East Asia is the Mei-yu frontal 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 of more than 1 week. Large rainfalls are often produced as the prefrontal intense flow confronts the deflected flow due to mountain blocking effects. The predictability is usually quite low for Mei-yu systems when compared to that of impinging typhoons. We simulated a severe Mei-yu event in early June 2007. 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. 9) with a 12 h update cycle. For most of the forecast times, the control run (with GPS RO 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. 3. 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 often than negative values.

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 10 shows the initial increments generated by assimilation of these RO points. There are no significant modifications on wind and moisture in the vicinity of the front along the southeast China at the initial time, due to no GPS RO data nearby. However, it was found that assimilation of the environmental GPS RO data resulted in more consistent patterns of intense daily rainfall over Taiwan. For example, in the third day, the overprediction on rainfall in south Taiwan for the control run (with no GPS data) has been considerably suppressed in the GPS assimilation run, as shown in Fig. 11. The results indicate that the remote GPS RO soundings might have an influential impact on the prediction of the Mei-yu frontal system and the associated rainfall over Taiwan. Such improvement on rainfall prediction was also found for some of Mei-yu frontal systems in 2008, e.g. the period from 25 June (Huang et al. 2009). Note that we herein have emphasized the positive impact, if ever existing, on Mei-yu

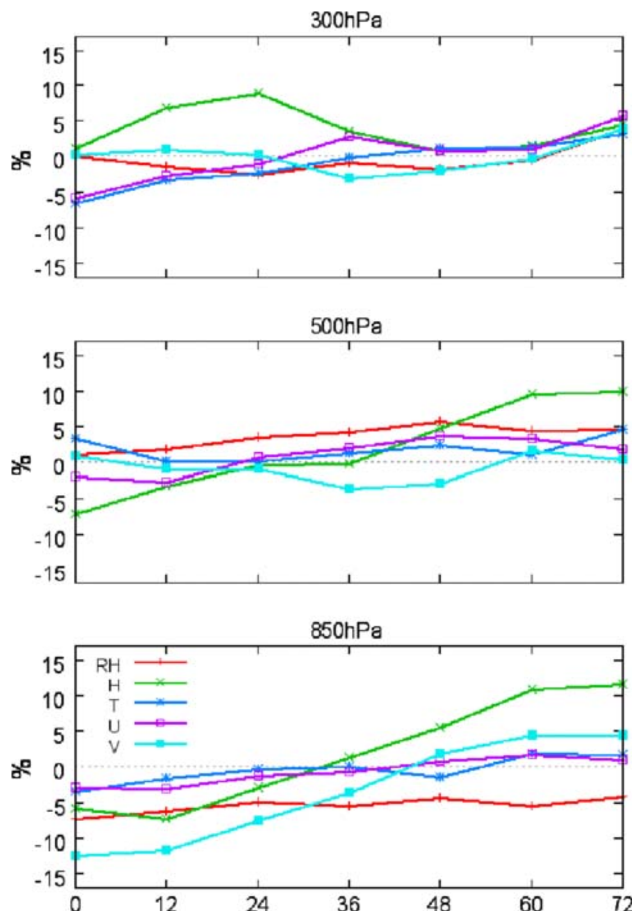

Fig. 9 Skill scores for the evaluation of the forecast of Mei-yu events in Taiwan during an 11-day period from 5 to 15 June 2007. These forecasts using the WRF model were initialized twice daily from 0000 UTC 5 to 1200 UTC 15 June 2007. Each experiment contains 22 runs of 72 h simulation. The model includes two domains with 45 and 15 km resolution. The GPS experiment (assimilating FORMOSAT-3/COSMIC GPS RO data) compared against the CONTROL experiment (no GPS RO data assimilated) at 300, 500, and 850 hPa. Color curves in *red*, *green*, *blue*, *magenta*, and *cyan* represent results of RH (relative humidity- *plus sign*), H (geopotential height- *cross sign*), T (temperature- *asterisk*), U (east–west wind- *open square*), and V (north–south wind- *solid square*), respectively. Positive (negative) values (percentages) are the positive (negative) impacts relative to the CONTROL experiment

frontal rainfall prediction over Taiwan. We did find that frontal predictability of the island rainfall was quite low in many cases and was not sensitive to the GPS RO data assimilation. Nevertheless, assimilation of GPS RO data occasionally appears to have some positive impact for such frontal systems that are difficult to predict accurately.

Impact on typhoon predictions in 2008

With a stable amount of GPS RO retrievals, the typhoon prediction with assimilation of the GPS RO data in 2008 would be particularly presented. As listed in Table 1, the maximum number of RO points in the outer model domain within the assimilation time window (6 h) is still less than 50 in 2008. This indicates the saturation of the data procurement for the COSMIC mission. Figure 12 shows the tracks of WRF high-resolution simulations for Typhoon Kamaegi from 0000 UTC 16 July 2008 for 72 h and for Typhoon Fung-Wong from 0000 UTC 26 July 2008 for 72 h, including the denial run (NONE) and runs with assimilation of GPS RO (using excess phase), dropsonde, GTS, and SSM/I data. Each run only assimilates one kind of observations. For Typhoon Kamaegi, the WRF simulations cannot capture the best track fairly well, producing similar tracks all too much eastward. However, the GPS run (with 15 RO data assimilated) seems to exhibit a less eastward track at the final stage of simulation when compared to the other tracks with assimilation of different observation data. Assimilation of dropsonde soundings (six soundings available) results in the furthermost eastward biased track. Assimilation of areal data from SSM/I is competitive, but showing no advantage over the GPS run at all the simulation stages. For the other typhoon Fung-Wong, all the simulated tracks follow the best track quite well. However, only the GPS run (with 43 GPS RO data assimilated) can remedy the landfall position, which otherwise is located somewhat to the north to the observed. The dropsonde run (with seven soundings assimilated) shows the most northward landfall position for this case. As we have to recognize, no GPS RO actually occurs within the two typhoons. The positive impact is thus remarkable in terms of the cost-effective data inventory.

There are more typhoons in 2008, and some are not presented herein without loss to general understanding of the GPS RO data impact. We found that for typhoons Sinlaku and Jangmi, a proper bogus vortex may be needed and combined with the GPS RO observations in order to improve the track prediction (figures not shown). As seen earlier for cyclones Gonu and Nargis, inclusion of additional bogus vortex, however, may sometimes result in even larger track errors, compared to that with assimilation of GPS RO data alone. This is a complicated issue for typhoon track prediction, and we avoid presenting the optimal solution if even existent. We should herein emphasize that assimilation of the GPS RO data will not smear the track prediction with insensitivity to the data information for most of the time, but can remarkably improve the track prediction with sensitivity to the retrieved data information.

Figure 13 concludes this scenario of the GPS RO data impact on typhoon track prediction from the experiments with six typhoons in 2008 by CWB using WRF at 45 km resolution. Not surprisingly, the GPS RO data impact

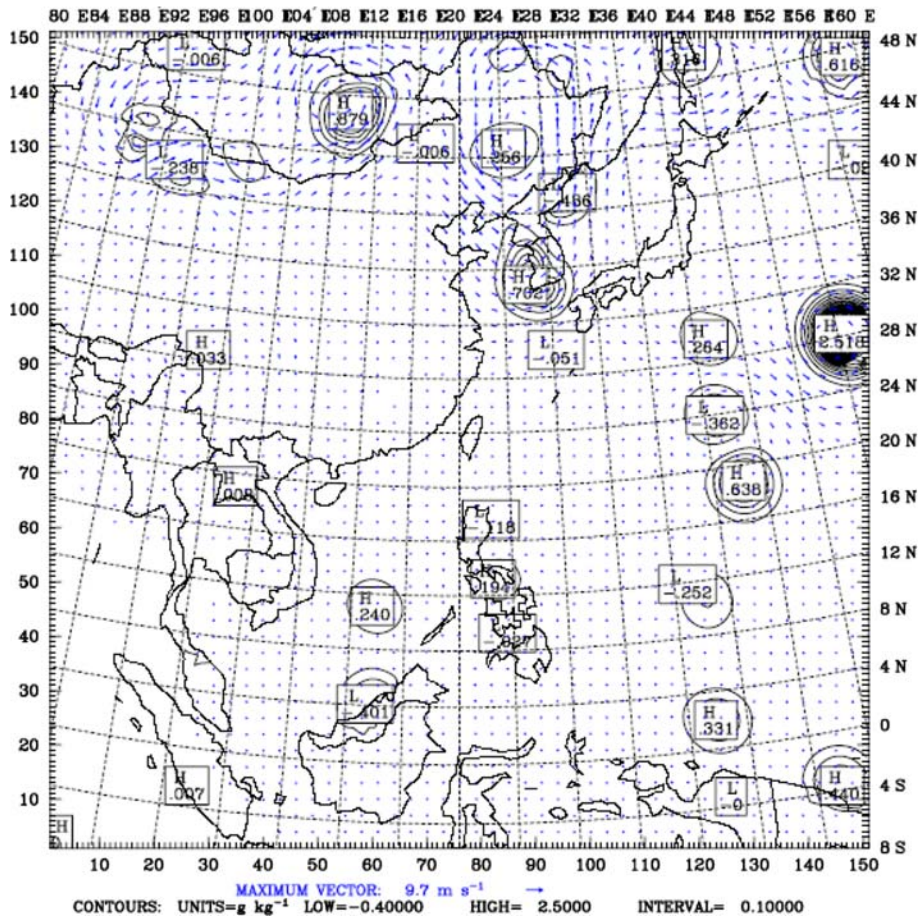

Fig. 10 The initial moisture increments (at an interval of 0.1 g/kg) and wind increments (m/s) at 1200 UTC 02 June 2007, produced by the nonlocal observation operator assimilating 31 GPS RO refractivity soundings in the domain

appears to be neutral or slightly negative to the track prediction at earlier stages, e.g., 12 h (F12) and 24 h (F24). However, improvement is confidently evident for later track prediction at 48 and 60 h, although only 4 km less error on average. This result is quite consistent with previous typhoon simulations at 5 km resolution, e.g. Figs. 3 and 4. The reason may be attributed to the fact that the tiny increments produced by GPS RO data assimilation take time to develop into sizable changes that lead to an impact on track prediction. Note that in CWB semi-operational experiments, track predictions have included all the other available observations and an initial bogus vortex. Thus, such an impact of GPS RO data assimilation is on top of the current efforts and best available observations apart from FORMOSAT-3.

Conclusions

We have presented or described some model results to summarize the impact of FORMOSAT-3/COSMIC RO data assimilation on the prediction of severe weathers in Asia, ranging from western Pacific typhoons to southern Indian cyclones and the Mei-yu frontal systems. Some of the cases showed a large impact even when only one GPS RO sounding was assimilated. But, several of them with much more RO soundings did not exhibit a statistically significant impact. This was especially true for typhoon predictions involving more complicated factors (e.g. vortex bogussing) 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 a number of high-resolution hindcasts of selected cases, we found that assimilation of GPS RO data appears to be beneficial for most of the weather predictions/simulations. Most of the high-resolution simulations of typhoons/cyclones tend to indicate that the model performances are less dependent on the local observation operator (assimilating the retrieved refractivity) or nonlocal observation operator (assimilating the raypath-integrated refractivity), although the latter sometimes does result in slightly better track prediction.

On operational demand, the impact of the GPS RO data should be clearly demonstrated. There was a remarkable

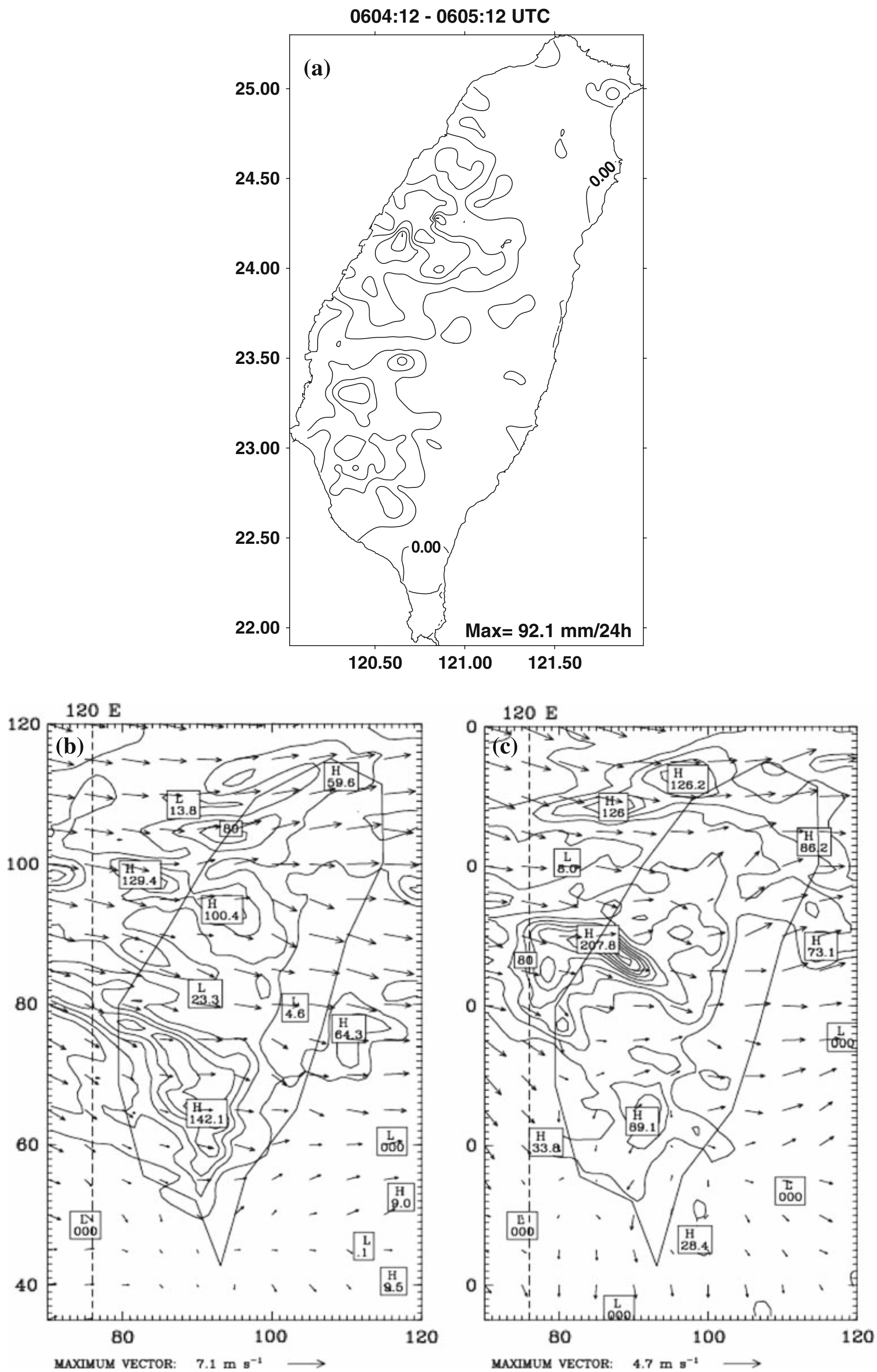

Fig. 11 **a**, **b,** and **c** are the observed accumulated rainfall (mm), the predicted rainfalls (mm) for the runs with no GPS data assimilated and with 31 GPS RO data on the third day for the 2007 Mei-yu front case, respectively. Contour intervals are 20 mm

reduction in bias and standard deviation of errors in analyzed and predicted upper temperatures against sounding observations in the model domain of WRF forecasts conducted semi-operationally for 1 month at CWB, and such improvement on regional modeling is consistent with the operational global model performances at ECMWF (Healy 2008). From prediction of six typhoons in 2008 by the CWB semi-operational WRF at 45 km resolution, the results indicate that the GPS RO data impact is neutral to the track prediction at earlier forecast times, but appears to

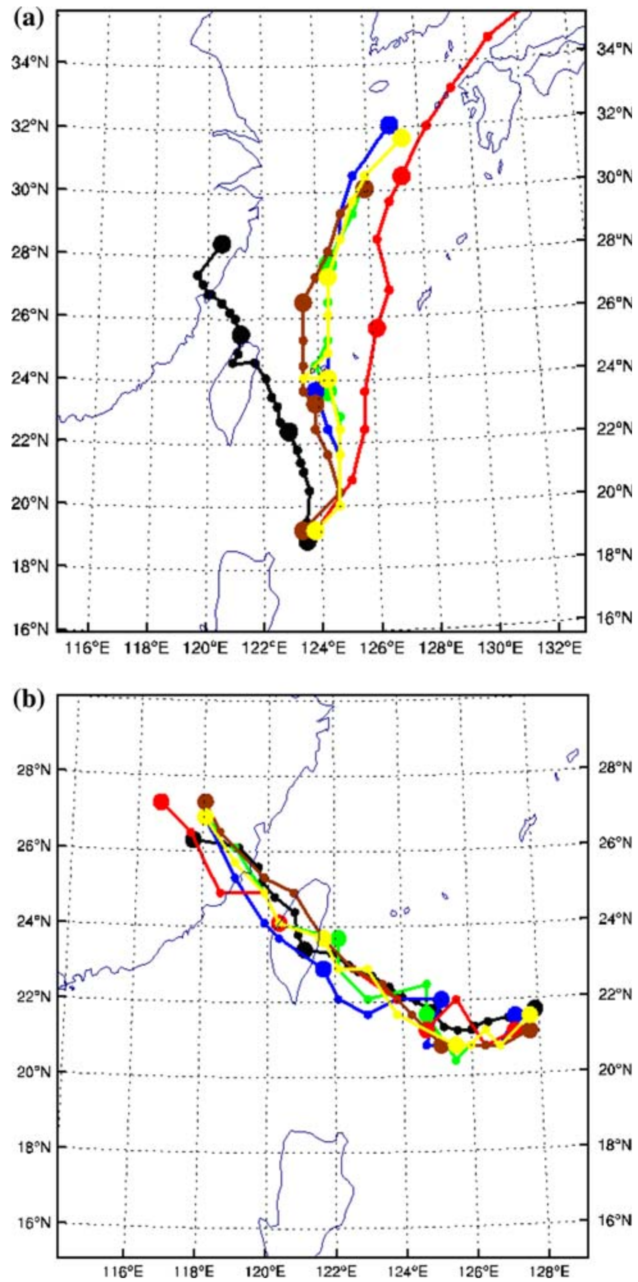

Fig. 12 **a** The best track (*black line*) for Typhoon Kamaegi (2008) from 0000 UTC 16 July 2008 for 72 h and simulated tracks for experiment NONE (*green*), GPS using excess phase (*blue*), GTS (*brown*), dropsonde (*red*) and SSM/I (*yellow*). **b** as in (**a**) but for Typhoon Fung-Wong from 0000 UTC 26 July 2008 for 72 h. Each run assimilates only one kind of observations. There are 6 (15) and 7 (43) GPS soundings (dropsonde soundings) in (**a**) and (**b**), respectively

be confidently positive at later forecast times. This improvement is on top of existent assimilation with all other available observations (including a bogus vortex) and thus sheds light on a prospective future for greater impacts

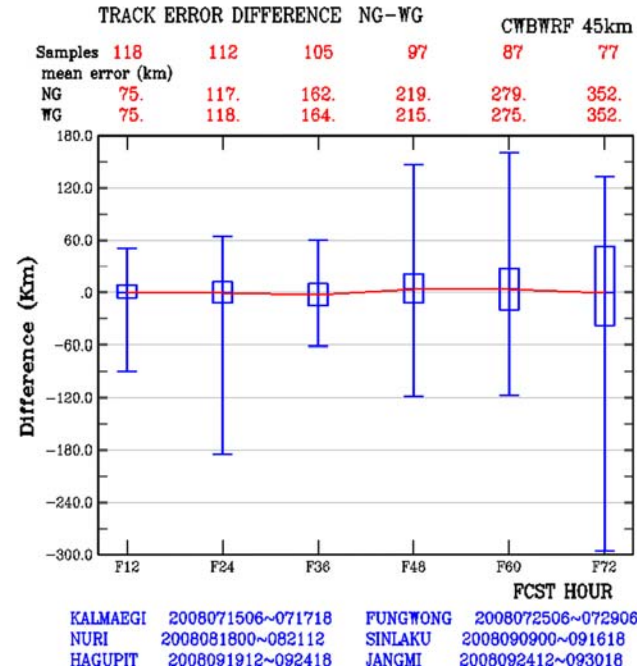

Fig. 13 Track verification for prediction of six typhoons (Kalmaegi, Fung-Wong, Nuri, Sinlaku, Hagupit, and Jangmi) in 2008 by CWB using WRF model at 45 km horizontal resolution with 3 h cycle in a window of 12 h to assimilate FORMOSAT-3 GPS RO refractivity soundings. The difference (in km) in red is between the track errors for the denial run (with no GPS RO data) and the control run (with GPS RO data), thus indicating a positive (negative) impact with a positive (negative) value. The blue box and horizontal line indicate the 50% and 25% confidences, respectively, and the blue vertical line shows the maximum range

of GPS RO data assimilation on regional weather and typhoon predictions.

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