Impact of FORMOSAT-3/COSMIC Data on Typhoon and Mei-yu Prediction

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Abstract

The Formosa Satellite Mission #3/Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC), hereafter referred to as COSMIC, is a joint Taiwan-U.S. mission launched in April 2006. The COSMIC mission consists of six small satellites that employ the Global Positioning System (GPS) radio occultation (RO) technique to sound the neutral atmosphere and ionosphere with uniform global coverage. As of January 2008, COSMIC is providing approximately 2,000 RO soundings per day to support the research and operational communities. For East Asian countries, the COSMIC soundings are particularly valuable for the study of typhoons and Mei-yu convective systems, as they provide observations over the data-sparse Western Pacific Oceans and the South China Sea.

In this study, we assimilate COSMIC GPSRO soundings and examine their impact on the prediction of Typhoon Shanshan (2006). The assimilation is first carried out using the WRF-Var (3D-Var) system. We find that in order for COSMIC GPSRO soundings to have an impact, it is critical to perform continuous assimilation through cycling. With one-hour cycling over a one-day period, COSMIC GPSRO soundings significantly improve the track forecast. However, the assimilation of only seven COSMIC GPSRO soundings in a cold-start experiment produces virtually no impact. The continuous cycling assimilation is able to incorporate 110 GPSRO soundings, and has a profound impact. We also find that the assimilation of typhoon bogus soundings improves the typhoon intensity and track forecast, particularly during the first two days.

To assess the impact of data-assimilation systems, we compare the performance of the WRF 3D-Var system with the WRF/DART ensemble filter system for the
assimilation of COSMIC GPSRO soundings. The results show that 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 storm with more coherent typhoon structure after one day of continuous assimilation, while a much weaker and less coherent storm is produced by WRF 3D-Var.

In addition to Typhoon Shanshan (2006), we assimilate GPSRO soundings from COSMIC during the two-week period of 1 to 14 June 2007, associated with a Mei-yu system, using the WRF/DART ensemble filter data-assimilation system. We find that 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.
1. Introduction

The radio occultation (RO) technique, which makes use of radio signals transmitted by Global Position System (GPS) satellites, has emerged as a powerful and relatively inexpensive approach to sounding the global atmosphere with high precision, accuracy and vertical resolution in all weather and over both land and ocean. This was first demonstrated by the proof-of-concept GPS/MET (GPS Meteorology) experiment in 1995-1997 (Ware et al. 1996), and further substantiated by the CHAMP (CHAllenging Minisatellite Payload, Wickert et al. 2001) and the SAC-C (Satellite de Aplicaciones Cientificas-C, Hajj et al. 2004) missions. In April 2006, the Formosa Satellite Mission #3/Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC, hereafter referred to as COSMIC) was successfully launched into initial orbits of 512 km from the Vandenberg Air Force Base (Kuo et al. 1999; Rocken et al. 2000; Cheng et al. 2006). COSMIC started collecting GPSRO soundings eight days after launch, and three months later started providing data to the international science community. By the end of 2007, COSMIC satellites have already been deployed to their operational orbits at 800 km elevation, evenly spaced with 30-degree separation. This allows COSMIC soundings to be distributed uniformly around the globe. As of 5 March 2008, COSMIC Data Analysis and Archive Center (CDAAC) has processed 941,933 neutral atmospheric profiles and 1,227,682 ionospheric profiles, and delivered them to the operational and research community. Even though COSMIC was launched less than two years ago, COSMIC has already contributed significantly to global weather prediction, climate monitoring, and ionospheric research (Anthes et al. 2008).
In comparison with previous GPSRO missions, COSMIC offers three major advantages. First, COSMIC uses the advanced open-loop (OL) tracking technique (Sokolovskiy 2001). All previous GPSRO missions (with the exception of SAC-C, which was used to test the OL tracking) used the phase-lock-loop (PLL) tracking. With the use of PLL tracking, only a small fraction of GPSRO soundings penetrate to below 1 km. Those that do penetrate to the lower troposphere are often affected by tracking errors, especially over the tropical atmospheric boundary layer (ABL). With OL tracking, 70% of COSMIC soundings penetrate to the lower tropical troposphere, while that over the higher latitudes, more than 90% of COSMIC soundings, penetrate to below 1 km (Sokolovskiy et al. 2006a; Anthes et al. 2008). The deep penetration of GPSRO soundings allows us to monitor the variation of the height of ABL (Sokolovskiy et al. 2006b), and atmospheric river events over the Eastern Pacific Ocean (Neiman et al. 2008).

COSMIC represents the world’s first constellation designed to provide GPSRO soundings with uniform global distribution. The six satellites were launched with one single rocket. The differential precession technique is used to deploy the satellites to their final orbits at 800 km using the onboard propulsion system, with 30-degree separation (Yen et al. 2008). The evenly spaced orbital plans allow the COSMIC GPSRO soundings to be distributed uniformly around the globe in local solar time. This is very important for observing the diurnal cycle in the neutral atmosphere and ionosphere (where it is especially strong) and for preventing aliasing of the diurnal cycle in climate signals (Zeng et al. 2008). Moreover, with each of the six satellites capable of performing both rising
and setting occultation, COSMIC provides an order of magnitude more soundings compared to a single satellite mission, such as CHAMP.

The third advantage of COSMIC is the availability of GPSRO data in near real time to support operational application. With the support of two high-latitude ground stations, each COSMIC satellite can download its data once every orbit (100 min). After five min of data transfer and another 15 min of data processing, these data are available to support global operational numerical weather prediction through Global Telecommunication System (GTS; Rocken et al. 2000). After a few months of testing, ECMWF (European Centre for Medium Range Forecasts) began the operational assimilation of COSMIC GPSRO data on 12 December 2006, NCEP (National Centers for Environmental Prediction) on 1 May 2007, UKMO (United Kingdom Meteorological Office) on 15 May 2006, and Meteo France on 1 September 2007. All these operational centers have reported positive impact with the operational assimilation of COSMIC GPSRO data (Cucurull and Derber 2008; Healy 2008; Poli et al. 2008).

Taiwan is located at subtropical latitudes, and is affected by severe weather in every season. In particular, the heavy rainfall events during late spring and early summer, a period known as the Mei-yu (Kuo and Chen 1990), and the typhoons in the summer (Wu and Kuo 1999), are major weather-related disasters that can cause significant loss of lives and property. With the availability of the GPSRO observations from COSMIC, this provides an opportunity to improve the forecasting of these severe weather events, and to improve our understanding of the regional climate in the vicinity of Taiwan (Wu et al. 2000). In this paper, we examine the impact of COSMIC GPSRO soundings on the
prediction of Typhoon Shanshan (2006) and a Mei-yu heavy rainfall event that took place in June 2007.

In Section 2, we describe the Typhoon Shanshan (2006) case and the assimilation of COSMIC GPSRO soundings using the WRF-Var (3D-Var) system. We examine how the details of assimilation procedures could influence the impact of GPSRO soundings on typhoon prediction. In Section 3, we compare the performance of WRF-3D-Var and the WRF/DART (Data Assimilation Research Testbed) ensemble filter data-assimilation system in the assimilation of GPSRO soundings and their impact on Typhoon Shanshan prediction. In Section 4, we examine the impact of COSMIC GPSRO soundings on the prediction of a Mei-yu system, and its associated heavy rainfall over Taiwan. A summary and closing remarks are given in the final section.

2. WRF 3D-Var assimilation of COSMIC GPSRO data and its impact on the prediction of Typhoon Shanshan (2006)

2.1 Typhoon Shanshan case

Typhoon Shanshan formed on 9 September 2006 about 500 km north-northeast of Yap, near 14°N, 139°E (Fig. 1). The storm moved northwestward and went through rapid development, becoming a Category 4 storm by 12 September 2006. It then moved westward and northward, skirting to the east of Taiwan on 15 and 16 September. It reached its peak intensity near 0000 UTC 16 September, with a central pressure of 919 mb, and peak wind speed of about 60 m s⁻¹. Typhoon Shanshan made landfall on the island of Kyushu on 17 September. It was downgraded from a Category 4 storm to a Severe Tropical Storm by 0000 UTC 18 September, just before it crossed the island of
Hokkaido. Later, it was transformed into an extratropical cyclone after it interacted with a midlatitude system. Figure 1 shows the best track and storm central pressure as a function of time. For this study, we will focus on the period from 0000 UTC 13 September through 17 September. In particular, we will assimilate the COSMIC GPSRO soundings over a one-day period, from 0000 UTC 13 to 0000 UTUC 14 September, and assess their impact on the prediction of Typhoon Shanshan.

2.2 Assimilation of COSMIC data using WRF 3D-Var

Through collaboration between NCAR and the Central Weather Bureau (CWB), a WRF (Weather Research and Forecasting model) and WRF 3D-Var (three-dimensional variational data assimilation) system (Barker et al. 2004) has been established for operation, starting from July 2007. The operational WRF model consists of three nested domains, with grid sizes of 45, 15 and 5 km, respectively. In this study, we perform experiments only on the 45-km domain (without nesting). Additional information on the WRF-Var system can be found at: http://www.mmm.ucar.edu/wrf/WG4/wrfvar/wrfvar-tutorial.htm.

Figures 2a, 2b show the distribution of COSMIC GPSRO soundings, both in time and space, over the one-day period of 0000 UTC 13 to 0000 UTC 14 September 2006. During this 24-h period, there are very few GPSRO soundings in the vicinity of Typhoon Shanshan. Moreover, the temporal distribution of the soundings data is not homogeneous. It varies from zero at 0600 UTC 13 September to 13 soundings at 1600 UTC 13 September. A total of seven experiments are conducted (see Table 1).

The schematic diagram of all data-assimilation experiments is shown in Fig. 3, and the experimental domain is shown in Fig. 2a with the size of 222x128 in 45-km grid
distance. There are a total of 45 full vertical model levels with the η values of 1.0, 0.995, 0.988, 0.98, 0.97, 0.96, 0.945, 0.93, 0.91, 0.89, 0.87, 0.85, 0.82, 0.79, 0.76, 0.73, 0.69, 0.65, 0.61, 0.57, 0.53, 0.49, 0.45, 0.41, 0.37, 0.34, 0.31, 0.28, 0.26, 0.24, 0.22, 0.2, 0.18, 0.16, 0.14, 0.12, 0.10, 0.082, 0.066, 0.052, 0.04, 0.03, 0.02, 0.01, and 0.0. The model top is 30 hPa, and time step is 180 seconds. The moisture physics are the new Kain-Fritsch cumulus parameterization scheme and the WSM 5-class explicit scheme. The YSU PBL scheme and the Monin-Obukhov scheme are used as the boundary and surface layers’ physics, and the Noah land-surface model is selected for the low boundary condition over the land. The long-wave and short-wave radiation schemes, which are called every 30 minutes during the model integration, are the RRTM scheme, and the Goddard scheme, respectively. The first experiment (NODA) is a no data-assimilation experiment. The initial condition for this experiment is obtained from the NCEP AVN global analysis at 0000 UTC 13 September. The purpose of the NODA experiment is to serve as a benchmark to illustrate the impact of data assimilation.

In the data-assimilation experiments with WRF-Var (see the section on WRF-Var at link: http://www.mmm.ucar.edu/wrf/users/tutorial/tutorial_presentation.htm), the background error statistics (BES) are obtained by interpolation from a 41-level CV Option-5 BES file derived based on the three months’ (August, September, and October 2006) forecast data over the same domain with NMC method. The observations are obtained from CWB (referred to as “CWB-obs”), which include the upper-air soundings, PILOT, surface data (SYNOP, SHIPS, METAR, BUOY), aircraft data (AIREP), and the satellite-derived or -retrieved data (satellite wind, QuikScat wind, and SATEM, etc.). In addition to CWB-obs, the bogus data are also provided by CWB (Fig. 2c).
Two sets of data-assimilation experiments are conducted. The first set is cold-start experiments. For this set, data assimilation is performed at only one time, which is 0000 UTC 14 September. COLDNBNG is an experiment that does not assimilate bogus data or COSMIC GPSRO data. For CWB operation, two types of bogus data are used. The first is called “global bogus.” To minimize “systematic drifting” of regional analysis, CWB extracts a set of bogus soundings from their global analysis, and treats them as synthetic sounding data. These soundings are located at regular intervals. Based on past experiences, the assimilation of these global bogus soundings has been effective in maintaining consistence between regional and global analysis and in preventing regional analysis from drifting away from global analysis. When a typhoon is found within the analysis domain, CWB also creates a set of typhoon bogus soundings. These consist of wind soundings in the vicinity of the typhoon. For the Typhoon Shanshan case, a total of 134 global bogus soundings and 40 typhoon bogus soundings are available at 6-h intervals from 0000 UTC 13 to 0000 UTC 14 September 2006 (see Fig. 2c). For the COLDNBNG (meaning cold start, no bogus, no GPSRO soundings) experiment, only CWB-obs data are assimilated. Neither the bogus nor the GPSRO soundings are assimilated.

For COLDNB experiment, global and typhoon bogus data are not assimilated. However, a total of seven COSMIC GPSRO soundings (available within a one-hour interval centered at 0000 UTC 14 September) are assimilated, in addition to CWB-obs data. In COLDALL, the 134 global and 40 typhoon bogus soundings are assimilated, in addition to the seven COSMIC GPSRO soundings and CWB-obs data.
The second set of data-assimilation experiments is cycling data assimilation experiments. In these experiments, continuous assimilation is performed from 0000 UTC 13 to 0000 UTC 14 September at one-hour intervals. Basically, the one-hour forecast is used as the first guess for the next analysis cycle. Then data that fall within +/- 30 min of the particular hour are assimilated. This procedure is repeated over the 24-h period (see Fig. 3). Obviously, the cycling experiments will be able to assimilate a lot more data compared with the cold-start experiments. For CYCLNBNG, neither bogus nor COSMIC GPSRO soundings are assimilated. However, more CWB-obs data are assimilated, in comparison with COLDNBNG. For CYCLNB and CYCLALL, they are similar to COLDNB and COLDALL, with the exception of continuous cycling. CYCLNB assimilates a total of 110 COSMIC GPSRO soundings, and CYCLALL assimilates an additional 870 (174 x 5) bogus soundings (which are available at 6-h intervals) in addition to the GPSRO soundings. With the assimilation of a much larger numbers of soundings, we would expect the cycling data-assimilation experiments to have a larger impact on the forecast.

Figure 4 shows the track and central pressure of Typhoon Shanshan in no data assimilation, and cold-start series of WRF 3D-Var experiments. The best track and the observed central pressure are also shown in the figures. The no data-assimilation (NODA) experiment has the worst performance, as it is essentially a 24- to 96-h forecast using the NCEP AVN analysis at 0000 UTC 13 September 2006 as the initial condition. The averaged track forecast error over the period of 0300 UTC 14 to 0000 UTC 17 September is 273 km. With the assimilation of CWB-obs data, the COLDNBNG experiment had a noticeable improvement over the NODA experiment. The three-day
The averaged track forecast error is reduced from 273 km to 233 km. The assimilation of seven COSMIC GPSRO soundings at 0000 UTUC 14 September had only very minor impact on the track and intensity forecasts. The results of COLDNB are almost identical to those of COLDNBNG. However, the assimilation of 134 global bogus soundings and 40 typhoon bogus soundings at 0000 UTC 14 September in the COLDALL experiment has a major impact on the forecast. The three-day averaged track forecast error is reduced to 140 km, almost half of those in the COLDNB experiment. Figure 4 also clearly shows that the track in COLDALL is much closer to that of the best track and the intensity closer to the observation. These results suggest that for the cold-start experiment, the assimilation of bogus data (particularly the typhoon bogus data) has a positive and profound influence on typhoon track forecast.

The results of cycling data-assimilation experiments are shown in Fig. 5. In comparison with the cold-start experiments, the continuous assimilation improves the results considerably. For example, the three-day averaged track errors for CYCLNBNG and CYCLNB are 144 and 111 km, while they are 233 and 232 km for COLDNBNG and COLDNB experiments. Figure 5 also shows that the tracks of Typhoon Shanshan in CYCLNBNG and CYCLNB are much closer to the best track compared with their counterparts in the cold-start experiments. It is interesting to note that the assimilation of 110 COSMIC GPSRO soundings has produced a noticeable impact. The three-day average track error is reduced by 33 km (from 144 km to 111) with WRF 3D-Var. This is a 23% improvement. Also, the assimilation of COSMIC GPSRO soundings produces a storm with stronger intensity (by about 10 mb), which is closer to the observation. These
results suggest that in order for the COSMIC GPSRO soundings to have an impact, it is essential that a continuous assimilation approach should be used.

The incorporation of bogus data in the cycling experiments produces improvements for the first two days. However, for day three, CYCLALL experiment performs worse than without the assimilation of bogus data. Figure 5 shows that the storm track is biased westward after one day. The storm then moves much slower than the observation, ending with a larger track error on day three. The exact reasons for this poorer performance with the assimilation of the bogus data are not known. However, we suspect that this might be related to the details of the bogusing procedure and the background error statistics used in WRF 3D-Var, … etc. For the CWB typhoon bogusing procedure, 40 wind soundings are extracted from a symmetric Rankine vortex plus the large-scale environmental flow. These soundings are assimilated into the system without further data quality control. For a real typhoon, the storm would often develop asymmetric structures. The assimilation of the bogus soundings would destroy these real asymmetric structures, and the model storm must recreate them. A continuous assimilation of bogus data implies that these counter-acting procedures are repeated throughout the assimilation windows. One cannot make a general statement that the assimilation of a bogus vortex does not improve the forecast. However, it is clear that improvement in typhoon bogusing procedure is needed to improve WRF 3D-Var performance, particularly in cycling experiments.

2.3 Comparison of WRF 3D-Var and WRF/DART ensemble assimilation

Over the past several years, a Data Assimilation Research Testbed (DART), a community data-assimilation facility for geosciences, has been developed at NCAR. DART includes
a wide variety of ensemble filter assimilation algorithms (Anderson 2003) which can be applied to a wide range of geosciences problems, including those of atmosphere, oceans, atmospheric chemistry, and ionosphere. Details of the DART facility can be found at: http://www.image.ucar.edu/DARES. The DART facility makes it easy to implement deterministic ensemble filter data-assimilation approaches with various types of numerical models. A number of models have already been implemented with DART, including the WRF model and the CCSM-3 Atmospheric Model (CAM-3). Both CAM-3/DART and WRF/DART have been used for the assimilation of GPSRO data. For example, using the CAM-3/DART system, Liu et al. (2007) demonstrated the importance of forecast error multivariate correlations, between specific humidity, temperature, and surface pressure, on the assimilations of GPSRO data. Liu et al. (2008) used the WRF/DART system to compare the performance of a nonlocal observation operator (Sokolovskiy et al. 2005) and a local refractivity observation operator on the assimilation of GPSRO soundings. Since both WRF 3D-Var and WRF/DART ensemble filter data-assimilation systems are available for the assimilation of GPSRO soundings, it would be desirable to compare the performance of these two data-assimilation systems for the same Typhoon Shanshan case. For such a comparison, we try to make the two systems as compatible as possible. For example, they all use the same local refractivity observation operator, the same observational data sets, and the same model domain and grid configurations. For this paper, WRF/DART only assimilated the key observation types including the radiosonde, satellite wind, QuikScat wind from CWB, and GPSRO data from COSMIC/CDAAC. The WRF/DART system is also set up for continuous one-hour
cycling, in ways similar to that of WRF 3D-Var cycling experiments. For the WRF/DART system, we do not assimilate the global and typhoon bogus data.

Figure 6 compares the tracks and central pressures of Typhoon Shanshan in the WRF/DART and WRF 3D-Var experiments. The track map shows that the WRF/DART experiments (DARTNBNG and DARTNB) follow the best track closely. This is also reflected in Table 2. For a three-day average, DARTNBNG and DARTNB have track errors of 75 and 62 km, respectively. They represent almost a 50% improvement over the WRF 3D-Var experiments (e.g., CYCLNBNG and CYCLNB), which have 144 and 111 km, respectively. The central pressure time series also indicates that the WRF/DART experiments produce stronger typhoons, although they differ only by less than five mb initially (at 0000 UTC 14 September). By 36 h, they differ by more than 20 mb, with WRF/DART producing typhoons with more realistic intensity. It is interesting to note that in terms of track errors, WRF/DART without the assimilation of global and typhoon bogus data performs better than WRF 3D-Var which assimilates everything, including global and typhoon bogus data, after one day (as shown in Fig. 6c). Figure 6c also indicates that the assimilation of COSMIC GPSRO soundings with the WRF/DART system improves the track forecasts. The three-day averaged track error is reduced from 75 to 62 km (Table 2), a 17% improvement.

The more realistic simulation of Typhoon Shanshan by WRF/DART experiments is illustrated in Fig. 7. Here we show vertically integrated cloud water (which serves as surrogate cloud fields) for CYCLNB, CYCLALL and DARTNB experiments, together with the observed IR satellite images. Even with a horizontal resolution of 45 km, the DARTNB experiment clearly shows an eye for Typhoon Shanshan and the eyewall.
clouds. In contrast, the corresponding WRF 3D-Var data-assimilation experiment, CYCLNB, does not show an eye. The CYCLALL experiment gives the hint of an eye, with less cloud water in the center of the storm. However, its position is biased considerably westward when compared with that of the observed storm.

The more realistic structure of Typhoon Shanshan after one day of data assimilation with WRF/DART is illustrated in Fig. 8, which shows the potential temperature and tangential winds along a north-south cross section (along 125.8°E) that cuts across the center of the storm. The WRF/DART experiment without the assimilation of GPSRO produces a vortex, with a radius of maximum wind of about 250 km. The maximum tangential wind exceeds 15 m s\(^{-1}\). With the assimilation of GPSRO data from COSMIC, the tangential winds are increased, and the radius of maximum winds is also decreased slightly. In contrast, WRF 3D-Var produces a much weaker storm, with a radius of maximum wind of about 350 km and the maximum tangential wind just a little over 10 m s\(^{-1}\). The assimilation of GPSRO soundings does not seem to produce an appreciable improvement to the storm intensity and structure.

The corresponding plots of vorticity for DARTNB and CYCLNB are shown in Fig. 9. The vorticity plots verify our assessment. With the assimilation of GPSRO soundings, DARTNB produced a storm with a maximum vorticity of 22 x 10\(^{-5}\) s\(^{-1}\). The corresponding WRF 3D-Var experiment has a value of 9 x 10\(^{-5}\) s\(^{-1}\), less than 50% of the WRF/DART experiment. Moreover, the assimilation of COSMIC GPSRO soundings produces an increase of 3 x 10\(^{-5}\) s\(^{-1}\) in WRF/DART, that extends from 900 mb to 600 mb (Fig. 10). It is clear that the assimilation of COSMIC GPSRO soundings produces a stronger and more robust typhoon vortex. On the other hand, the impact of COSMIC
GPSRO assimilation with WRF 3D-Var is much weaker and only visible in the lowest 1 km.

Similar results are found for the moisture, temperature, and height fields. The WRF/DART system produces a stronger typhoon and a well-defined warm core. Also, the assimilation of GPSRO soundings from COSMIC increases the temperature at the center of typhoon by about 0.5°C with WRF/DART, while the impact is not apparent in WRF 3D-Var (not shown). The WRF/DART assimilation of GPSRO soundings produces profound changes of water vapor over the western Pacific, with amounts varying from 1.5 to 2 g kg\(^{-1}\) (Fig. 11a). The corresponding changes in WRF 3D-Var are much more modest, with amounts on the order of 0.5 g kg\(^{-1}\) or less (Fig. 11b).

The track of typhoons over the western Pacific is strongly affected by the subtropical high. Naturally, we would be interested in seeing how the analysis of the western Pacific subtropical high is influenced by the data-assimilation system. Figure 12 shows the 500-mb geopotential height for both the DARTNB experiment and the CYCLNB (WRF 3D-Var) experiment. We see a much stronger high-pressure system in the vicinity of the typhoon. For example, the height field to the northeast of Typhoon Shanshan has a geopotential height contour of 5920 m in the WRF/DART experiment (Fig. 12a), while that in the WRF 3D-Var experiment is only 5900 (Fig. 12b). Moreover, the assimilation of GPSRO soundings produces a 500-mb potential height difference of 30 m with WRF/DART (Fig. 12c), while the impact of COSMIC GPSRO data assimilation is barely visible with WRF 3D-Var (Fig. 12d).

One may ask, why should WRF/DART perform better than WRF 3D-Var? This is a very important question and will require considerably more analysis before we can fully
answer the question. However, we make the following observations. First of all, the ensemble data-assimilation system (i.e., WRF/DART) uses flow-dependent background error covariances, while the background-error covariances used in WRF 3D-Var are not flow dependent. Second, the WRF/DART system takes into account the forecast multivariate error correlations between specific humidity and temperature, as well as surface pressures, while they are not taken into consideration in WRF 3D-Var. Of course, one advantage of WRF 3D-Var is significantly reduced computational cost. For one-day assimilation with one-hour cycling, the WRF/DART system with 32 ensemble members takes 5.5 hours of wall-clock time on a machine with 32 IBM Power 5 processors. The corresponding cost for WRF 3D-Var is about 0.4 hours. So, the WRF/DART system is more than one order of magnitude more expensive than WRF 3D-Var. Therefore, the improved analysis comes with increased computational cost.

3. **Impact of COSMIC GPSRO soundings on Mei-yu prediction**

The Western Pacific Subtropical High (WPSH) has a profound influence on weather systems over East Asia, in particular, the East Asia monsoons and the tropical cyclones. In late spring and early summer, Taiwan and Southern China are significantly influenced by a quasi-stationary Mei-yu front. Mesoscale convective systems embedded within the Mei-yu front travel eastward along the front, and can produce heavy precipitation. The location and intensity of the Mei-yu front and the formation and development of mesoscale convective systems are strongly affected by the intensity and position of the WPSH, as well as the southwesterly monsoon flows that originate from the Indian oceans and the South China Sea. Because of the lack of observations over the Pacific Oceans,
South China Seas, and the Indian Ocean, and weather analysis particularly, the moisture analysis is often subject to significant uncertainty. Because of the lack of observations over the Pacific Ocean, intensity and location of the WPSH are often not accurately analyzed by global models. With the availability of GPSRO soundings, COSMIC provides an opportunity to improve the analysis of WPSH, the southwesterly monsoons, and the Mei-yu front.

In this study, we assimilate GPSRO soundings from COSMIC over a two-week period, from 1 to 14 June 2007, using the WRF/DART ensemble filter data-assimilation system. For this study, we use a WRF/DART system at a horizontal resolution of 36 km, with 35 vertical levels. The number of ensemble members is 32. Figure 13 shows the distribution of COSMIC GPS RO soundings during this period and the experimental domain. There are a total of 1,567 GPSRO soundings uniformly distributed over the model domain. In addition to GPSRO soundings, we assimilate upper-air soundings, surface reports, satellite winds, and the cloud-free AIRS retrieved temperature data. Two experiments are performed. The first is a NoGPS experiment, which assimilates the conventional operational data from NCEP that include radiosondes, satellite could motion winds, and QuikScat surface winds. The AIRS standard retrieved temperature profiles (at 50-km resolution) from NASA/JPL are also used. The other experiment is the GPS experiment, which assimilates COSMIC GPSRO soundings in addition to all the aforementioned data. The assimilation experiments are done with 3-hour cycling for the entire 2-week period.

Figure 14 shows the 850-mb wind fields averaged over the two-week period of 1 to 14 June 2007 for the NoGPS and GPS experiments. At first glance, they look almost
identical, aside from some subtle differences in the flow fields over the western Pacific to the east of Taiwan. The 850-mb wind fields show that the WPSH is extended to about 110°E over the South China Sea. During this period, Taiwan and southern China are under the influence of two confluent flows; one is the southwesterly monsoon flow originating from the Bay of Bengal, and the other is the southerly returning flow associated with the WPSH. The difference fields between NoGPS and GPS experiments show an anticyclonic gyre located at about 145°E and 25°N. This gyre is of a scale of about 2,500 km, and has a northeast and southwest orientation. The difference fields suggest that the assimilation of COSMIC GPSRO soundings has enhanced the WPSH over the western Pacific. Notice that there is little difference over the northern and eastern lateral boundaries of the model domain. This is because identical lateral boundary conditions, obtained from the NCEP AVN global analysis, are used for both GPS and NoGPS experiments. It is possible that if we use a much larger model domain that covers the entire Pacific Ocean, the COSMIC GPSRO soundings would have an even bigger impact on the entire Pacific subtropical high.

The intensity of the WPSH will have a profound influence on the moisture fluxes, which could have a significant impact on clouds and precipitation. Figure 15 shows the mean moisture fluxes at 850 mb averaged over the two-week period of 1 to 14 June 2007. The 850-mb moisture flux indicates that a significant amount of moisture originates from the Bay of Bengal, climbs over Indo-China peninsula, and converges with the returning moisture flow associated with the WPSH. Taiwan and Southern China are under the strong influence of the southwesterly moist flow, after these two air streams converge. The impact of COSMIC GPSRO simulation can be visualized by examining the
differences in moisture flux between the NoGPS and GPS experiments. Again, an anticyclonic gyre is clearly visible. Over the western part of this gyre, moisture is being transported toward Taiwan. This suggests that the assimilation of COSMIC GPSRO soundings produces an improved analysis, with more moisture being transported to the Taiwan area.

During the period of 6 to 9 June, Taiwan was under the influence of a Mei-yu front. Mesoscale convective systems propagated from west to east, and produced a significant amount of precipitation. Heavy precipitation took place at first on the west coast of Taiwan on 6 June 2007 (Fig. 16a). It then migrated over northwestern Taiwan, with 24-h accumulated rainfall exceeding 150 mm on 7 June (Fig. 16b). This continued into the day of 8 June (Fig. 16c), with significant precipitation over the Taichung area, as well as northern Taiwan and southern Taiwan immediately to the west of the Central Mountain Range. The maximum 24-h accumulated rainfall ending at 0000 UTC 9 June exceeded 300 mm over the Taichung area (Fig. 16c). By 0000 UTC 10 June, most of the precipitation, with weaker amounts, fell over the Central Mountain Range (Fig. 16d). An interesting question is: would the assimilation of COSMIC GPSRO soundings help improve rainfall forecasts?

To answer this question, we show in Fig. 17 the 850-mb moisture flux at 0000 UTC 8 June 2007 for the GPS run, and the differences between GPS and NoGPS experiments. The basic flow pattern and moisture flux pattern are essentially the same as those of the two-week averages. The difference field of the 850-mb moisture flux shows interesting structure. The anticyclonic gyre is already established at this time, although the center of the gyre is located further to the west from its two-week mean position.
Most interestingly, significant eastward moisture fluxes are found to the west of Taiwan and southern China. There is also enhanced moisture flux convergence over Southern China and the Taiwan Strait. This should contribute to increased precipitation over this region.

Figure 18 shows the 850-mb moisture analysis for the NoGPS and GPS experiments, and their differences (GPS – NoGPS) at 0000 UTC 8 June. The moisture content is much larger and robust in the GPS experiment. For example, the 16 g kg$^{-1}$ contour is found on the east coast of China near Fujian Province in the GPS experiment, while weaker amount is found in the NoGPS experiment at the same location. The difference in moisture over the southeastern China coast exceeds 1.0 g kg$^{-1}$ on the east coast of China that are directly related to the precipitation event (Fig. 18c). Figures 17 and 18 suggest that the assimilation of COSMIC GPSRO soundings over a one-week period (from 1 to 8 June 2007) has produced noticeable changes in moisture distribution and moisture fluxes associated with the Mei-yu system. One should expect that such changes would have an influence on precipitant forecasts.

Indeed, this is the case. Figure 19 shows the 24-h precipitation forecast from the WRF model at 12 km, which is initialized with the WRF/DART 36-km analysis at 0000 UTC 8 June from the NoGPS and GPS experiments. The location and intensity of precipitation over Southern China and the Taiwan Strait are very different. In particular, the WRF model initialized with the WRF/DART analysis that assimilates GPSRO soundings produces more intense precipitation over the Taiwan Strait. The difference field shows that more than 30 mm additional precipitation falls over western and southern Taiwan. In comparison with the available precipitation analysis over Taiwan (Fig. 16),
we find that the more intense precipitation as a result of COSMIC GPSRO data assimilation compares more favorably with the observed rainfall. The 24-h accumulated rainfall over Mainland China ending at 0000 UTC 9 June (Fig. 20) also compares more favorably with the GPS experiment, which gives precipitation further to the south than the NoGPS experiment.

4. Summary and conclusions

The successful launch of the FORMOSAT-3/COSMIC mission marked the beginning of a new era in GPS atmospheric remote sensing. By providing more than 2,000 GPS radio occultation soundings per day uniformly distributed around the globe in near real time, COSMIC provides the much-needed data over data-sparse regions of the world, including the tropical oceans and the polar regions. For weather forecasting over Taiwan and East Asia, COSMIC provides valuable data over the western Pacific and South China Sea. The assimilation of COSMIC GPSRO soundings can contribute to the improved forecast of typhoons and heavy precipitation associated with the Mei-yu front. In this paper, we examine the impact of COSMIC GPSRO soundings on the prediction of Typhoon Shanshan (2006) and the heavy precipitation event associated with a Mei-yu front in early June 2007. Our study has led to the following conclusions:

(i) It is essential to perform continuous assimilation through cycling in order for COSMIC GPSRO soundings to have a significant impact on typhoon track prediction. One needs to realize that even with 2,000 GPSRO soundings per day, the data density is still relatively low. Over the CWB 45-km domain, there are approximately 100 GPSRO soundings over a 24-h period, or 25
GPSRO soundings over a 6-h period. Continuous assimilation with a relatively narrow assimilation window (1 h) allows more COSMIC soundings to be assimilated at the time close to observations. A cold-start type data assimilation is usually not effective, as only a limited number of soundings are used.

(ii) The assimilation of COSMIC GPSRO soundings using the WRF/DART ensemble filter method is found to be more effective than the WRF 3D-Var assimilation method for the Typhoon Shanshan case. The WRF/DART system produces a much stronger typhoon than the WRF 3D-Var system with or without the assimilation of COSMIC GPSRO data. Moreover, the assimilation of COSMIC GPSRO data with the WRF/DART system produces much more profound changes than the WRF 3D-Var system. In other words, the WRF/DART ensemble system can extract more information from the same GPSRO data than the WRF 3D-Var system, and subsequently has a larger analysis increment. The superior performance of the WRF/DART ensemble system is attributed to the fact that WRF/DART uses flow-dependent background error covariances, and takes into consideration the forecast multivariate error correlations among moisture, temperature and surface pressure. On the other hand, WRF 3D-Var uses background error covariances derived from historical forecasts, which do not contain information directly related to the case at hand. Of course, we should also recognize that the improved performance of WRF/DART ensemble filter assimilation is obtained at the expense of increased computational cost. For the Typhoon
Shanshan case, the WRF/DART system requires more than an order of magnitude more computing resources than the WRF 3D-Var system.

(iii) The assimilation of typhoon bogus soundings is found to be quite important for improved typhoon track forecast, particularly for cold-start experiments. Because the NCEP AVN global analysis often underestimates the intensity of the storm, forecasts without the assimilation of typhoon bogus data usually give large track errors. However, for cycling experiments, we found that the assimilation of bogus soundings does not always give better results, particularly for longer-range forecasting. We conclude that improved typhoon bogusing procedures should be developed. Better yet, we should achieve improved forecasting by assimilating more real observations and avoiding the use of typhoon bogus soundings, which are the current practice at the ECMWF.

(iv) The assimilation of COSMIC GPSRO soundings with the WRF/DART system over a two-week period has produced a profound impact on the analysis of the Western Pacific Subtropical High. In particular, the COSMIC GPSRO assimilation strengthens the WPSH, increases the moisture content of the Mei-yu front, and increases moisture flux convergence along the Mei-yu front. These changes produce significant positive impact on short-range precipitation forecasts over both Taiwan and Southern China.

Although these results are very encouraging, they need to be verified with additional case studies. Moreover, the assimilation of GPSRO soundings should be tested
over an extended period before it can be used operationally. These efforts are currently being carried out at Taiwan’s Central Weather Bureau. Given the importance of the COSMIC GPSRO soundings for the typhoon and Mei-yu prediction, it is important that we continue the operation of the COSMIC mission through its life. We should also begin planning for a follow-on mission to replace COSMIC, which is expected to last through 2011 with a five-year mission life.

Acknowledgement

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References


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Table 1. List of WRF 3D-Var experiments

<table>
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<th>Name</th>
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Table 2. Track forecast errors averaged over different forecast periods for cold start and cycling WRF 3D-Var experiments, and cycling WRF/DART experiments.

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<th>27-48 h forecast</th>
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Fig. 1. (a) Best track and (b) central pressure time series of Typhoon Shanshan (courtesy of Japan Meteorological Agency). The color of the points represents the storm intensity: blue – tropical depression, green – tropical storm, yellow – severe tropical storm, red – typhoon, and magenta – extratropical cyclone.
Fig. 2. (a) The spatial and (b) temporal distribution of COSMIC GPSRO soundings and (c) the loci of CWB global and typhoon bogus soundings.
Fig. 3. Schematic diagram illustrating the design of data assimilation experiments
Fig. 4. (a) Track (the letters, “A”, “B”, “C”, and “D”, etc., indicate the 6-h storm positions, and the contours are SLP from NODA at 0000 UTC 14 September 2006) and (b) central pressure of cold start WRF 3D-Var experiments.
Fig. 5. Same as Fig. 4 but for 3DVAR cycling run experiments.
Fig. 6. (a) Track of cycling data assimilation experiments, including DARTNBNG, DARTNB, CYCLNBNG, CYCLNB, and the best track. The SLP field is obtained from the DARTNBNG at 0000 UTUC 14 September 2006; (b) The corresponding central pressure time series, and (c) Track forecast errors for the four cycling data assimilation experiments.
Fig. 7. The integrated cloud water forecasts from (a) CYCLNB, (b) CYCLALL, and (c) DATNB experiments valid at 0000 UTC 16 September 2006. The verifying observed IR Image at 0000 UTC 16 September 2006 is shown in (d).
Fig. 8. The zonal wind (solid line) and potential temperature (dashed line) analysis along 125.8°E from (a) DARTNB, (b) CYCLNB (3D-Var), (c) DARTNBNG, and (d) CYCLNBNG (3D-Var) at 0000 UTC 14 September 2006. Units: zonal wind (m/s), temperature (K). The location of the typhoon is marked with the typhoon symbol.
Fig. 9. The relative vorticity analysis along 125.8°E from: (a) DARTNB and (b) CYCLNB (3D-Var) at 0000 UTC 14 September 2006. Units: $1.0 \times 10^{-5} \text{ s}^{-1}$. The location of the typhoon is marked with the typhoon symbol.
Fig. 10. The relative vorticity difference analysis from (a) DARTNB-DARTNNG, and (b) CYCLNB-CYCLNNG (3D-Var) at 0000 UTC 14 September 2006. Units: $1.0 \times 10^{-5}$ s$^{-1}$. The location of the typhoon is marked with the typhoon symbol.
Fig. 11. The water vapor difference fields from (a) DARTNB-DARTNBNG, and (b) CYCLNB-CYCLNBNG (3D-Var) at 0000 UTC 14 September 2006. Units: $1.0 \times 10^{-3}$ g kg$^{-1}$. The location of the typhoon is marked with the typhoon symbol.
Fig. 12. The 500 hPa height analysis from (a) DARTNB, (b) CYCLNB at 0000 UTC 14 September 2006. The difference fields of (c) DARTNB - DATNBNG, and (d) CYCLNB - CYCLNBNG at the same time. Unit: meter. The location of the typhoon is marked with the typhoon symbol.
Fig. 13. Distribution of 1,567 COSMIC GPSRO soundings from 1 to 14 June 2007 over the experiment domain.
Fig. 14. The 850 mb wind fields for (a) NoGPS experiment and (b) GPS experiment, and (c) their differences.
Fig. 15. (a) The 850 mb moisture flux in the GPS experiment, and (b) differences in 850 mb moisture flux between GPS and NoGPS experiments averaged over the two-week period from 1 to 14 June 2007.
Fig. 16. 24-h accumulated precipitation over Taiwan ending at 0000 UTC on 7, 8, 9, and 10 June 2007.
Fig. 17. (a) The 850 mb moisture flux in the GPS experiment, and (b) differences in 850 mb moisture flux between GPS and NoGPS experiments, ending at 0000 UTC 8 June 2007.
Fig. 18. The 850 mb specific humidity for (a) NoGPS run, (b) GPS run, and (c) the difference between GPS and NoGPS run (in g kg$^{-1}$) at 0000 UTC 8 June 2007.
Fig. 19. The 24-h accumulated rainfall ending at 0000 UTC 9 June for (a) NoGPS experiment, (b) GPS experiment, and (c) their differences.
Fig. 20. Observed rainfall over China ending at 0000 UTC 9 June 2007.