An Impact Assessment of GPS Radio Occultation Data on Prediction of a Rapidly Developing Cyclone over the Southern Ocean*

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ABSTRACT

The impact of global positioning system (GPS) radio occultation (RO) data on an intense synoptic-scale storm that occurred over the Southern Ocean in December 2007 is evaluated, and a synoptic explanation of the assessed impact is offered. The impact is assessed by using the three-dimensional variational data assimilation scheme (3DVAR) of the Weather Research and Forecasting (WRF) Model Data Assimilation system (WRFDA), and by comparing two experiments: one with and the other without assimilating the refractivity data from four different RO missions. Verifications indicate significant positive impacts of the RO data in various measures and parameters as well as in the track and intensity of the Antarctic cyclone. The analysis of the atmospheric processes underlying the impact shows that the assimilation of the RO data yields substantial improvements in the large-scale circulations that in turn control the development of the Antarctic storm. For instance, the RO data enhanced the strength of a 500-hPa trough over the Southern Ocean and prevented the katabatic flow near the coast of East Antarctica from an overintensification. This greatly influenced two low pressure systems of a comparable intensity, which later merged together and evolved into the major storm. The dominance of one low over the other in the merger dramatically changed the track, intensity, and structure of the merged storm. The assimilation of GPS RO data swapped the dominant low, leading to a remarkable improvement in the subsequent storm’s prediction.

1. Introduction

Recent observation-based studies reveal strong warming and rapid ice-mass loss from West Antarctica (Marshall et al. 2002; Vinnikov and Grody 2003; Turner et al. 2005; Shepherd et al. 2012; McMillan et al. 2014), which ultimately results in a sea level rise (Oppenheimer 1998; Pritchard et al. 2012; Bromwich et al. 2013, 2014). Synoptic-scale cyclones have the potential to deliver large amounts of precipitation, significant enough to counterbalance the loss of ice (Carleton and Fitch 1993; Nicolas and Bromwich 2011a). Thus, the improvement in storm forecasts over the Southern Ocean is desirable. Because the changes of storm tracks can affect the cloud cover (Pavolonis and Key 2003), which would subsequently impact the precipitation distribution, we focus on improvements of the cyclone track and intensity.

Many studies find it challenging to accurately predict synoptic-scale cyclones in the Antarctic region. For instance, operational global analyses from major numerical weather prediction (NWP) centers tend to show large differences over the Antarctic and Southern Ocean (Simmons and Hollingsworth 2002; Pendlebury et al. 2003). Global reanalyses also exhibit elevated uncertainties in the high southern latitudes (Lim and Simmonds 2007; Nicolas and Bromwich 2011b). The difference among the global analyses may be caused by the uncertainty in both the initial
and boundary conditions that stems from a scarcity of useful observations in this region (e.g., Adams 1997; Wee et al. 2008). Consequently, the structure and development mechanism of synoptic-scale cyclones over the area are poorly understood when compared to other parts of the globe (Bromwich and Parish 2002; Lazzara et al. 2012).

Numerical models tend to be better tested and tuned for data-rich areas. Thus, they do not perform equally well in the Antarctic region (Powers et al. 2012). Data assimilation systems also suffer a setback due to the lacking observations; they are limited in mitigating the model’s error by means of utilizing the observations. Although a large amount of satellite radiance data are available, strong emissions from the snow- and ice-covered surfaces (English 2008) and persistent cloudiness over the Southern Ocean (King and Turner 1997) pose practical difficulties in using these data effectively. It is also well known that satellite radiance data possess systematic errors, which could come from the observations, instruments, and/or forward models, and may be mitigated by assimilation of unbiased observations (Cucurull et al. 2014). A popular approach to deal with this problem is the so-called variational bias correction (Derber and Wu 1998; Dee and Uppala 2009), which deduces the observational bias by taking the model’s state as the reference. Once the model develops its own systematic errors, the process to correct the biases of the satellite data becomes suboptimal and renders the data less useful. While efforts to improve the usage of radiance data over the Antarctic area are continuing [e.g., improved modeling of surface emissivity (English 2008; Bouchard et al. 2010) and enhanced detection of clouds (McNally and Watts 2003)], new sources of observation are also receiving attention.

One promising data source is the global positioning system (GPS) radio occultation (RO) technique; this approach utilizes a GPS receiver on board a low Earth-orbiting (LEO) satellite that measures the GPS signal’s phase delay relative to that in the vacuum. The phase delay relates to the ray’s bending angle under the assumption of spherical symmetry and can be converted to an atmospheric refractive index via the inverse Abel transform. Many previous studies have demonstrated that GPS RO data possess some unique advantages, including high accuracy, high vertical resolution, and global coverage (e.g., Rocken et al. 1997; Anthes et al. 2000, 2008; Hajj et al. 2004; Wickert et al. 2004; Kuo et al. 2004, 2005). Thus, GPS RO data are used by all major NWP centers to support operational weather prediction, including the European Centre for Medium-Range Weather Forecasts (ECMWF; Healy and Thépaut 2006), the National Centers for Environmental Prediction (NCEP; Cucurull et al. 2007; Cucurull 2010), the Met Office (Rennie 2010), Environment Canada (Aparicio and Deblonde 2008), and Météo France (Poli et al. 2008). They all found that GPS RO data have positive impacts on the global weather forecasts, and some of the studies showed significant improvements in the Southern Hemisphere.

For instance, Healy and Thépaut (2006) assimilated GPS RO data with a one-dimensional bending angle operator using the ECMWF four-dimensional variational data assimilation (4DVAR) system, and showed that the GPS data improve the temperature forecast in the upper troposphere and lower stratosphere out to 5 days. Cucurull et al. (2007) compared the assimilations with the GPS refractivity versus the bending angle data and also obtained similar results with slight improvements in anomaly correlation for the temperature field; humidity biases were also greatly reduced at all latitudes. Rennie (2010) demonstrated that the GPS data provide the greatest improvements in temperature and geopotential height fields in the Southern Hemisphere extratropics by up to 10% at 250 hPa when verified against radiosondes.

Besides operational applications, a few researchers have assimilated GPS RO data into Antarctic regional models. Both Wee and Kuo (2004) and Cucurull et al. (2006) performed observing system simulation experiments (OSSEs) to assess the impact of GPS RO data on a cyclogenesis case over the Antarctic region. Wee et al. (2008) assimilated the GPS RO data from both the Challenging Minisatellite Payload (CHAMP) and the Satellite for Scientific Applications-C (SAC-C) missions into the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) 4DVAR system. They found that assimilating the GPS RO data leads to a better characterization of the tropopause and an improved prediction of the upper-level circulations. This is consistent with the conclusions referenced above that are based on operational global models.

The limited number of Antarctic regional assimilation studies used either synthetic data or only assimilated the limited number of GPS data available at that time (Wee and Kuo 2004; Cucurull et al. 2006; Wee et al. 2008). It is desirable to substantiate the earlier data studies now that considerably more GPS RO data are available. We assess the impact of GPS RO data on an intense synoptic-scale cyclone that occurred over the Southern Ocean in December 2007 by assimilating all GPS RO data available from four missions, including CHAMP, SAC-C, the Gravity Recovery and Climate Experiment (GRACE), and the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC). COSMIC, in particular, provides a significant amount of data (more than
2000 soundings per day globally) from a constellation of six microsatellites.

The outline of the paper is as follows. Section 2 provides a brief introduction of the storm of interest and the forward operator for the GPS RO data used in our study. The assimilation system, numerical model settings, and experimental design are also described. Section 3 presents the results and assesses the data impact. Discussions on the atmospheric processes underlying the GPS data impact are given in section 4. Finally, a summary is provided in section 5.

2. The storm overview and methodology

a. Case overview

An intense synoptic-scale storm started to develop over the Southern Ocean during 9–10 December 2007 (Fig. 1). It was initiated from two weak, low pressure systems downstream of a preexisting, large-amplitude, upper-level trough. One of the low pressure systems, with a central pressure of 990 hPa at 1800 UTC 9 December, was formed over the South Pacific Ocean between New Zealand and Australia; the other, with a central pressure of 975 hPa, formed at the coast of East Antarctica near Dumont d’Urville (Fig. 1b). The former moved southeastward, and the latter eastward along the Antarctic coast (Figs. 1b,c). The former cyclone developed slowly at first but rapidly deepened after it reached the sea ice zone (i.e., the green outline in Fig. 1a), where a large temperature gradient existed. After merging with the latter low over the Ross Sea, it grew into a major synoptic-scale storm, and the storm center at upper and lower levels became vertically aligned as shown in Fig. 1d (1200 UTC 11 December).

The low near the coast of East Antarctica shown in Fig. 1 frequently forms in conjunction with a large temperature gradient due to strong and cold katabatic outflow from the high topography in East Antarctica and the relatively warm sea level temperature (Bromwich et al. 2011). The cyclone track inferred from the NCEP Final (FNL) operational global analysis is shown in Fig. 1a. After attaining maximum intensity, the storm turned clockwise and stayed close to West Antarctica for an extended period. During the entire event, the storm underwent such a rapid development that the central sea level pressure dropped more than 70 hPa to reach about 923 hPa (the maximum intensity) at 1800 UTC 12 December.

b. The numerical model and model configurations

The numerical model used in this study is the Advanced Research version of the Weather Research and Forecasting (WRF-ARW) Model (Skamarock et al. 2008; hereafter referred to as the WRF Model). The WRF Model is fully compressible and nonhydrostatic, which is suitable for diverse applications across a wide range of spatial scales. The prognostic variables are the following: column mass of dry air, three-dimensional components of wind, potential temperature, and geopotential. Diagnostic variables (e.g., temperature, pressure, density) are derived from the prognostic variables. The WRF Data Assimilation system (WRFDA; Barker et al. 2012) is a data assimilation system developed for the WRF Model supporting variational (three- and four-dimensional frameworks, i.e., 3DVAR and 4DVAR) (Barker et al. 2004; Huang et al. 2009), ensemble Kalman filter (Anderson 2010), and hybrid (Wang et al. 2008a,b) approaches. Although the 4DVAR and ensemble-based data assimilation are more comprehensive than 3DVAR (e.g., with flow-dependent covariances), they are demanding. Hence, we use the 3DVAR as it serves adequately for the purpose of our study with a modest cost. Both of the WRF and WRFDA used in this study are version 3.3.1 (a detailed description of the WRF Model and WRFDA can be found online at http://wrf-model.org).

The Antarctic Mesoscale Prediction System (AMPS; Powers et al. 2012) is a real-time WRF forecasting system for Antarctica and the Southern Ocean, which has been running for more than a decade. The AMPS is empirically adapted to attain the optimal performance in that area, reflecting the research experience gained over this part of the world with the WRF Model. Thus, we largely follow the AMPS basic model settings. For instance, the physics options used in this study are adopted from the AMPS: the WRF single-moment 5-class scheme (WSM5; Hong et al. 2004; Hong and Lim 2006) for microphysics, the Rapid Radiative Transfer Model for GCMs (RRTMG; Mlawer et al. 1997) for longwave radiation, the Goddard shortwave radiation scheme (Chou and Suarez 1994) for shortwave radiation, the unified Noah land surface model (Chen and Dudhia 2001), the Mellor–Yamada–Janjic (Janjic 2002; Mellor and Yamada 1982) planetary boundary layer scheme, and the Kain–Fritsch (Kain and Fritsch 1990, 1993) convective parameterization.

Our model domain covers the entire Antarctic continent and Southern Ocean as shown in Fig. 1a. The model has a horizontal mesh of 401 × 401 with a grid spacing of 30 km, and 55 vertical levels with the model top at 10 hPa. The NCEP FNAL analysis (1° × 1° resolution) is used to provide the initial and lateral boundary conditions. For the lower boundary condition, the fractional sea ice representation from the National Snow and Ice Data Center (NSIDC) is used, in addition to the 0.5° real-time, global sea surface temperature from the NCEP.
c. The GPS RO refractivity

GPS RO offers a hierarchy of data products for data assimilation along the data processing chain, such as the ray’s bending angle, refractivity, and derived temperature, as well as both pressure and moisture (e.g., Kuo et al. 2000; Huang et al. 2005; Healy et al. 2007; Chen et al. 2009; Ma et al. 2009; Cucurull et al. 2013; Yang et al. 2014, etc.). In general, the data types produced at a later processing stage (e.g., the temperature) are easier to interpret as they closely pertain to ordinary geophysical parameters. However, their error characteristics are complicated due to continued layers of data processing. Although less processed data types are desirable in this regard, they require sophisticated observation operators to properly model them. Readers are

![Image of Figure 1: Storm track inferred from NCEP analysis, sea level pressure analysis, and the outline of sea ice coverage at time of maximum intensity, 1800 UTC 12 Dec 2007. The GPS RO soundings during 0600–1800 UTC 9 Dec 2007 are indicated by orange dots. Labels A to J point out 10 GPS RO soundings used in Figure 5, which are within 1000 km of the storm center and a ±1.5-h time window. (b) Sea level pressure and 500-hPa geopotential height from NCEP analysis at 1800 UTC 9 Dec. (c),(d) As in (b), but at 1800 UTC 10 Dec and 1200 UTC 11 Dec, respectively. A zoom-in area covers the upper-left quadrant of (a) for (b),(c), and another area over the Ross Sea for (d). The black line in (d) indicates the orientation of the cross section in Figure 13.](image-url)
referred to Kuo et al. (2000) and Wee et al. (2010) for in-depth discussions on this topic. It is also possible to employ different observation operators for a single data type. For instance, the refractivity can be modeled with or without taking the ray’s horizontal paths into account (Sokolovskiy et al. 2005a,b; Syndergaard et al. 2005). In view of the information content versus the practicability of the observation operator, the local refractivity has been a popular choice. Thus, we assimilate the local refractivity in this study, which relates to the atmospheric states (Smith and Weintraub 1953) as follows:

\[
N = 77.6 \frac{p}{T} + 3.73 \times 10^5 \frac{e}{T^2},
\]

where \( p \) is the pressure of the atmosphere (hPa), \( T \) is the air temperature (K), and \( e \) is the water vapor pressure (hPa). The GPS RO data used in this study are produced by the COSMIC Data Analysis and Archive Center (CDAAC) (the data are available online at http://cdaac-www.cosmic.ucar.edu/cdaac/products.html). There are approximately 2000 RO soundings available within our model domain during the storm’s lifetime: 0600 UTC 9 December–0000 UTC 15 December.

d. Data assimilation experiments

Two experiments, NG and WG, are carried out in this study. For the NG, conventional observations (e.g., radiosonde soundings, surface observations, and aircraft data, etc.) and a few satellite retrievals [i.e., Quick Scatterometer (QuikSCAT) surface winds and atmospheric motion vectors] are assimilated. The WG not only includes these data, but the GPS RO data are also assimilated. Therefore, NG and WG differ only in the use of the GPS RO data, where NG stands for “no” assimilation of the GPS RO data and WG indicates assimilation “with” the data. The impact of the GPS RO data on the analysis and forecast for our storm case is analyzed by comparing the differences between the two experiments.

Although previous studies have demonstrated the benefit of assimilating GPS RO data (e.g., Kuo et al. 2000; Healy 2008; Cucurull 2010; Huang et al. 2010), designing sensible experiments for a particular data assimilation system is not straightforward. For example, Kuo et al. (2000) stressed the importance of precise characterization of the observation error and a well-established strategy for data assimilation. Cucurull (2010) claimed that revisiting the quality control and observation error for the RO data in the NCEP operational 3DVAR results in a noticeable improvement in the Southern Hemisphere extratropics. During our preliminary tests, we encountered an issue with a significant fraction of the GPS RO data in the stratosphere being rejected by the background-based quality control procedure. The quality control discards the observations that deviate from the background by more than 5 times the assumed observation error. The specified observation error for the GPS refractivity in the WRFDA varies with height and latitude, and is similar to those proposed by Chen et al. (2009, 2011). For a GPS RO sounding located at the equator, the observation error is 2.5% from the surface to the height of 2.5 km, and then it linearly decreases to 1.3% at 5.5 km. It continues to decrease to 0.3% at 12 km. For a sounding located at the pole, it is 1.5% near the surface and linearly decreases to 0.3% at 12 km. All the observation errors above 12 km are the same constant value of 0.3%. The observational error of a RO sounding located between the equator and pole is obtained from linear interpolation.

It turns out that the data rejection in the upper part of our model domain is caused by a large systematic difference between the observation and the background. The remaining, unrejected observations manifest the same bias with respect to the background, leading to spotty and unrealistic analysis increments when assimilated. Previous studies report that the benefit of assimilating GPS RO data is more noticeable in the upper troposphere and lower stratosphere than at lower levels (e.g., Wee and Kuo 2004; Healy and Thépaut 2006; Rennie 2010). Therefore, the pronounced disagreement between the observation and its model counterpart in our tests might be due to the WRF Model; for example, deficiencies in the model formulation (Wee et al. 2012) or an imperfect upper boundary condition treatment resulting in the reflection of vertically propagating gravity waves (Wee and Kuo 2004). Because a remedy to this problem is beyond the scope of this study, we decided not to assimilate the data above 50 hPa. Since the height of the data cutoff is well above the Antarctic tropopause, the influence on the storm will be insignificant. We also thinned the GPS RO data down to a level comparable to the vertical resolution of the WRF Model. The errors of the GPS RO refractivity data for adjacent levels are correlated as a result of the inverse Abel transform used to produce the data. Thus, the thinning not only reduces data redundancy but also agrees well with the assumption of no vertical correlation for the observational error used in the WRFDA.

At the outset of the data assimilation, a 6-h WRF forecast (0006 UTC 9 December), made from the initial condition generated from the NCEP operational analysis at 0000 UTC 9 December, is provided as the first guess. This helps to reduce the initial dynamic imbalance that could impede the assessment of the data’s impact. We suppose that all the data used in this study have been assimilated into the NCEP system. If we used the NCEP analysis as the first guess, the same data will be used twice, leading to a possible overfitting of the observations. The 3DVAR data assimilations are carried out in
a cycling mode for a 12-h period for both the NG and WG experiments. Specifically, the data assimilations are conducted 3 times in total: once at 0600 UTC 9 December and repeated 6 and 12 h later (i.e., 1200 and 1800 UTC). The 6-h WRF forecasts initiated with the WRFDA analysis at each cycle are then used as the first guess for the next cycle. During the three cycles, data from the four GPS satellite missions are available (i.e., CHAMP, SAC-C, GRACE, and COSMIC). A total of 88, 81, and 71 GPS RO soundings are assimilated for each of the three cycles, respectively. After completion of the cycling analysis, longer-range forecasts (126 h ending at 0000 UTC 15 December) are made for both the NG and WG experiments.

e. Data for verification

To assess the impact of the GPS RO data assimilation, the global analyses from the ECMWF and NCEP are used for verification. The analyses from the ECMWF (nominal horizontal resolution of 25 km and 91 vertical levels) and the NCEP FNL (1° × 1° horizontal resolution and 27 vertical levels) are interpolated to our model grid for verification. Because there are not many observations of good quality available in the Southern Ocean area, the GPS RO data are also used to verify forecasts. Note that the GPS RO data used to verify the WG forecasts are not assimilated. The selected COSMIC GPS RO data are close to the storm, within a 1000-km radius of the center and a ±1.5-h time window, in order to compare the storm’s structure and intensity more closely.

3. Results

The free forecasts made after completing the cycling data assimilation are evaluated in a number of aspects. This includes the storm’s track and intensity, domain-wide statistics, and the statistics over a small area surrounding the storm and moving along the storm’s track.

a. Track and intensity

The track and intensity of predicted storms are compared with those of global analyses in Fig. 2. The comparison is made based on the sea level pressure minimum. Here, only the period of rapid cyclogenesis after the 30-h forecast time is shown; this period is of prime interest. Overall, both the NG and WG experiments give fairly realistic tracks in their respective forecasts. It is remarkable that the clockwise turning of the track is well reproduced in the forecasts of 4–5 days. The WRF-predicted tracks deviate somewhat from those of the global analyses around and after the time of turning, starting from 3.5 days into the forecasts. In comparing the WRF forecasts with corresponding global analyses, we assume that the WRF “long range” forecast error is much larger than the uncertainty in the global analyses. However, this is the period that the structure in the surface pressure becomes complicated making it difficult to pinpoint the storm’s location. During this period, the storm weakens and orography-induced, low pressure systems develop when the primary cyclone approaching the coastal mountains in West Antarctica. Therefore, the storm’s track after the turning is subject to greater uncertainty.

Although the NG and WG experiments do not show a significant difference in the track, the time-averaged track errors are 316 and 280 km for the NG and the WG, respectively. Also, the two experiments differ considerably in their intensity (Fig. 2b). Compared to the
global analyses and the WG, the NG shows a storm that deepens earlier and is a little stronger during the early development stage. It reaches the maximum intensity at 1200 UTC 12 December, which is about 5 hPa too weak and 6 h too early. Throughout the dissipation stage, the storm in the NG stays weaker. On the contrary, the WG agrees well with the global analyses in the intensity and timing of the development. As described in section 2a, the low pressure system moving southeastward merged with a coastal low over the Ross Sea at 0000 UTC 11 December. In the WRF forecasts, both the NG and the WG simulated the coastal low and the merging process, but with 12- and 6-h delays, respectively, relative to the global analyses. The track and intensity of the coastal lows are also compared in Fig. 2.

b. Domain-wide comparison

The comparisons between the WRF forecasts and the global analyses (hereafter referred to as ECMWF and NCEP, respectively) show improvements in the large-scale structures when GPS RO data are assimilated. For example, Fig. 3 compares the bias and standard deviation (SD) with respect to the ECMWF in the geopotential height, temperature, and water vapor mixing ratio at the time of the WRFDA analysis (1800 UTC 9 December). In the comparison made over the whole domain, the WG is significantly smaller than the NG in the bias error and SD of the geopotential height and temperature (Figs. 3a–d) when verified against the ECMWF. The errors are expected to be smaller when compared to the NCEP than to the ECMWF because the former provides the first guess, which makes the verification unsound (figure not shown). A larger difference between the NG and the WG appears at the midlevels (700–200 hPa) for the temperature and geopotential height. Even after 72 h into the forecast, the improvement of the WG over the NG persists and increases with time (Fig. 4). The initial difference in the moisture between the NG and the WG is not evident (Figs. 3e,f). This might be due to the limited amount of moisture in the high latitudes, particularly over the Antarctic continent. However, the forecast of the WG shows a notable error reduction in the SD (Fig. 4f). Although the GPS refractivity is related to the mass variables (i.e., atmospheric pressure, temperature, and water vapor pressure), the WG also shows an improvement in the wind field through the dynamical constraints in the WRF 3DVAR (figure not shown).

While Figs. 3 and 4 show the overall statistics for the whole model domain, Fig. 5 makes use of the individual GPS RO soundings. The 10 soundings nearest to the storm, in terms of the spatiotemporal distance along the predicted storm’s track, are chosen for the comparisons (as indicated in Fig. 1a). In most cases the WG agrees much better with the observed refractivity than the NG. The WG differs from the observed refractivity by no more than 2% except near the surface, whereas the NG can differ by up to 6% (Fig. 5b). It should be emphasized that the RO soundings are independent of the WG because they are available in the free forecast range and have not been assimilated into the WRFDA.

c. Comparisons within and around the cyclone

The fraction of the storm area in our model domain is very small as seen in Fig. 1a. Therefore, the domain-wide statistics do not reflect the difference around the storm very well. To highlight the area under direct influence of the storm, we extract the grid columns over a square box of 900 km by 900 km, centered on the storm for each of the four datasets (i.e., NCEP, ECMWF, NG, and WG), at 6-h intervals. The global analyses are interpolated in advance to the grid points of the WRF Model. The extracted square columns are then compared with each other by superposing one upon another. This focuses on the storm’s internal structure, such as the storm’s size and the orientation and strength of accompanying frontal structures.

Figure 6 compares the SD from the ECMWF in the temperature. As shown, the assimilation of GPS RO data significantly reduces the SD before 0000 UTC 14 December, which is from 3.3 K at 600 hPa in the NG (Fig. 6a) to 2.1 K in the WG (Fig. 6b). During this period, three areas of notably large SD appear in the NG below 500 hPa, whereas the WG yields much smaller SDs (Fig. 6c). Besides the temperature, the WG also shows better agreement with the ECMWF than the NG in the water vapor mixing ratio (Fig. 7) at 1200 UTC 11 December and 0000 UTC 13 December. The WG continues to have a smaller SD in the later forecasts when the cyclone is dissipating (e.g., 0000 UTC 14 December; Fig. 7c).

To give a close view of the storm’s structure, the relative vorticity fields at 500 hPa at the mature stage (1800 UTC 12 December) are shown in Fig. 8. Both the NG and the WG show more intense and narrower spirals in their forecasts than the NCEP (the data source for the initial condition). The WRF Model differs from global models in the formulation, the parameterized physical processes, and even the targeting aspects. Although the WRF forecasts are thus expected to be different from the global analyses, the lower resolution (1° × 1°) of the NCEP, available to us and used in this study, may have further flattened the storm’s structure in the data. Though the resolution of the ECMWF would not be a problem, the WRF
forecasts are, in general, more intense than the ECMWF in the relative vorticity. In addition to the difference in the model, the filtering effect of the background error covariance in the course of data assimilation might have smeared the spirals in the background field a bit more. Taking into account the difference in the absolute magnitude of the relative vorticity, the WG is closer to the ECMWF than the NG in the pattern and the
relative variation of intensity along the spirals. For instance, the intensity of relative vorticity at the vortex center and the hook-shaped structure in the ECMWF located within the area of 60°–70°S, 110°–120°W are both predicted in the WG. As shown in Fig. 2b, the WG differs by 1 hPa from the global analyses in the mean sea level pressure, whereas the NG is 7 hPa weaker than the WG. This demonstrates that the WRF Model is able to reproduce the detailed atmospheric circulation around the storm once the large-scale structures in the model’s initial condition are improved by the assimilation of GPS RO data.

Fig. 4. As in Fig. 3, but for the 72-h forecasts valid at 1800 UTC 12 Dec.
4. Atmospheric processes underlying the assessed data impact

The atmospheric processes associated with the data impact are analyzed with the experiments. Figure 9a shows the 500-hPa background temperature at 0600 UTC 9 December. It is noteworthy that a few of the temperature troughs of large amplitude and scale that originate from the cold Antarctic interior extend northward as far as South America and Australia. The large thermal gradients along the boundaries of the troughs tend to enhance baroclinic instability in the region and are thus favorable for storm developments. The additional assimilation of GPS RO data in the first cycle (0600 UTC 9 December) introduces small differences in the temperature (Fig. 9b). As expected, the influence of GPS RO data (i.e., the WG minus the NG) is confined in the vicinity of the observations. As the difference made in the previous cycle evolves with time in the forecast and new observations are introduced and assimilated in the continuing cycles, the change due to the GPS RO data becomes complicated in structure and extends across the whole model domain (Figs. 9c,d). After completion of three analysis cycles, the assimilation of GPS RO data results in an organized field of difference: warming over the Antarctic continent and cooling over the ocean. As-similation of RO data changes lower-level temperatures as well, where the change is similar in pattern but smaller in magnitude when compared to 500 hPa (figure not shown). The WG – NG compares well with the ECMWF – NG (Fig. 9e) in broad features, such as warming over the Antarctic continent and cooling over the surrounding ocean areas. This confirms that the assimilation of RO data greatly improves the temperature.

Global analyses and satellite images indicate that there are two low pressure systems involved in our storm case that later merged together and developed into the major storm. For instance, the ECMWF shows two lows of the same intensity (971 hPa) at 1800 UTC 10 December (Fig. 10a): one at the coast of East Antarctica near 155°E, and the other over the ocean near 170°E. The two merge 6 h later and deepen by 6 hPa (Fig. 10b). Earlier studies noticed that the coastal area of East Antarctica, where the former low is located, is one of the areas of most frequent cyclogenesis in the Southern Hemisphere (e.g., Simmonds et al. 2003; Hoskins and Hodges 2005; Uotila et al. 2011). In this region, the katabatic flow that carries cold, dry continental air to the coast (Parish and Bromwich 2007) is known to be an important factor in cyclone developments (Bromwich et al. 2011). Without the assimilation of RO data, the NG results in a stronger-than-actual temperature gradient normal to the coast due to prevailing cold bias over the continent and warm bias over the ocean. This, in turn, exaggerates the katabatic flow; overpredicts the convergence with the warm, moist air flowing from lower latitudes; and eventually leads to development of the premature, overintensified coastal low. This low later develops into the major storm, which is different from that which is observed (Figs. 10c,d). The assimilation of RO data allows the WG to correct the large-scale bias in temperature. Consequently, the WG is able to predict the development of the coastal low realistically (Figs. 10e,f). The assimilation of RO data also influences the development of the other low, which approaches the area
moving southeastward. As shown in Figs. 9b–d, the RO data produce a significant cooling over the South Pacific Ocean around 60°S, 140°-160°E. The cooling then intensifies the large-scale trough leading to an increase of baroclinic instability in the region. This again provides the ideal conditions for development of the southeastward-moving, low pressure system whose track is downstream of the trough. Consistent with that which is seen in the global analyses, this low dominates the coastal low and develops into the major storm (Figs. 10e,f). This contrasts with the NG, where the coastal low becomes the major storm engulfing the extratropical low. The false dominance of the coastal low in the merge causes a sizable error afterward in the process. The time evolution of the sea level pressure in the WG closely follows those of the global analyses, reaching a realistic minimum value (924 hPa) at the correct time (the 3-day forecast). The differences in the storm’s development and structure also bring a distinction in the precipitation, which is most noticeable at the storm’s maturity (Figs. 11e,d). The maximum precipitation in the vicinity of the storm accumulated for 24 h prior is 18.5 and 12.3 mm for the WG and the NG, respectively. Noticeable precipitation can be found over West Antarctica when the simulated cyclone is close to the continent (Figs. 11e,f). The 3-day accumulated precipitation in the WG is larger than that of the NG, especially near the coast. Unfortunately, it is impossible to discern which, the NG or the WG, is more accurate in the precipitation because of the lack of observations over the Antarctic region. However, seeing that the assimilation of RO data improves other parameters (i.e., pressure, temperature, moisture, and wind), an equivalent improvement in the precipitation is well expected provided that the WRF Model’s physics and dynamics are valid.

While the change in the temperature due to the assimilation of GPS RO data (Fig. 9) is by no means sizable...
when averaged over the entire model domain (as seen in Figs. 3 and 4), it is significant enough to alter the storm’s behavior by actively intervening in the physical and dynamic processes through which the two low pressure systems merge and evolve rapidly into a major storm. We track the origin of air parcels around the storm to provide a sketch of the temperature change (Fig. 12), that is, tracking back the airflow and checking if the changes come from regions that have GPS RO impact as shown in Fig. 9. The analysis of backward trajectories makes use of the WG’s forecasts; 33 parcels on each of the 850, 700, 500, and 300 hPa are released from the locations, which cover the whole storm and are shown in the inset of Fig. 12a. These parcels (132 in total) are released at 1800 UTC 12 December (the storm’s mature stage) and traced back for 72 h to 1800 UTC 9 December, where hourly model states are used to compute the Lagrangian trajectories. As shown in Fig. 12, the air parcels can travel long distances: more than 4000 km in some cases. This means that not only the local circulations around the storm but also those in the remote areas can affect the storm’s development. In other words, GPS RO data can positively impact the storm’s prediction by improving the large-scale circulations even if RO does not provide observations of high density in the immediate vicinity of the storm. In addition, Fig. 12 shows that the majority of parcels released on lower levels originate from the South Pacific Ocean and those released on high levels originate from the south Indian Ocean. As shown in Fig. 9, the assimilation of GPS RO data improves the temperature, moisture, and geopotential height over the regions, where the air parcels affecting the storm development originated. Consequently, the assimilation of GPS RO results in positive impacts on the prediction of the storm.
FIG. 9. (a) The 500-hPa temperature (color shaded with a 3-K interval) and mean sea level pressure (black contour with an interval of 4 hPa) in the 6-h WRF forecast valid at 0600 UTC 9 Dec. The difference between WG and NG (WG - NG) in 500-hPa temperature (color shaded with 0.3-K interval) at (b) 0600, (c) 1200, and (d) 1800 UTC 9 Dec. Black dots indicate the locations of the GPS RO soundings for each time. (e) As in (d), but a smoothed difference between ECMWF analysis and NG (ECMWF - NG).
FIG. 10. Sea level pressure from ECMWF analysis at (a) 1800 UTC 10 Dec and (b) 0000 UTC 11 Dec, and for NG at (c) 0000 UTC 11 Dec and (d) 0600 UTC 11 Dec. (e),(f) As in (c),(d), but for WG. The contour interval is 4 hPa.
FIG. 11. As in Fig. 10, but valid at 1800 UTC 11 Dec for (a) NG and (b) WG. (c),(d) As in (a),(b), but valid at 1800 UTC 12 Dec. The color shading represents the precipitation accumulated for 24 h prior. (e),(f) The three days accumulated precipitation (i.e., in past 72 h) at 1800 UTC 14 Dec for NG and WG, respectively.
Moreover, from a zonal cross section (as indicated in Fig. 1d) passing through the storm center, cold advection in the low- to midtroposphere and warm advection near the tropopause provide a favorable environment for cyclone development due to the large vertical variation of temperature advection (Fig. 13). The temperature advections are averaged in the 600-km distance into and out of the cross section. According to the geopotential tendency equation, a cold advection decreasing with height acts to produce height falls, thus amplifying a 500-hPa trough. Then, the 500-hPa trough deepening can help the surface low development. Before the merging of the two low pressure systems, the distributions of temperature advection are similar for both the NG and the WG as in Fig. 13a, but the horizontal distributions are slightly narrower (figures not shown). Note that the lows merged at 1200 UTC 11 December (42-h forecast time). The vertical variation of thermal advection in the NG is much weaker at the 60-h forecast, but it remains strong in the WG (Figs. 13b,c). This is possibly caused by the initial condition that is colder in the lower troposphere and warmer near the tropopause in the WG, which influences the thermal advection (Figs. 9, 12, and 13). The thermal structure in the WG is much more consistent with that in the ECMWF (Fig. 13d). The configuration helps to decrease the geopotential at 500 hPa and supports the surface cyclone development.

5. Summary

Because Southern Ocean cyclones are one of the major sources of water mass that can counterbalance the...
recent ice loss from the Antarctic region, accurate prediction of a storm’s track and intensity is important for the prediction of precipitation. Accurate prediction of Southern Ocean cyclones is also important to the logistic operation of Antarctic research facilities. The shortage of observations in the Southern Ocean makes GPS RO data more important in improving weather analysis and prediction in the region. We investigated the data impact of GPS RO on a rapidly developing synoptic-scale cyclone over the Southern Ocean, where the central pressure dropped nearly 70 hPa over a 3-day period in December 2007. The effects of GPS RO data assimilation on the cyclone development are examined by using the WRF 3DVAR.

The 5-day forecasts after three analysis cycles show that the predicted intensity of the cyclone in the WG is much closer to those in the global analyses (ECMWF and NCEP). For instance, without the assimilation of GPS RO data, the predicted storm is 7 hPa weaker at the mature stage (1800 UTC 12 December) than that in the WG for which the GPS RO data have been assimilated. In contrast, the WG is about the same as the global analyses in terms of the mean sea level pressure. The assimilation of GPS RO data results in a more accurate initial condition and improvements in the subsequent forecasts. All the statistical measures indicate the assimilation of GPS RO data reduces the forecast errors. The improvements are visible not only in the temperature and geopotential height, but also in the moisture field. This conclusion is also consistent with previous studies (e.g., Cucurull et al. 2006; Wee et al. 2008).

When GPS RO data are assimilated (WG), the southeastward-moving, low pressure system develops into the major storm after merging with another coastal low, which is backed by the ECMWF analysis, except for a 6-h delay in timing. On the contrary, the coastal low develops into the major storm in the NG, resulting in significant errors in the following forecasts. The assimilation of GPS data is essential in predicting the observed processes of cyclogenesis.

In general, the change in the temperature due to the assimilation of GPS RO data is a warming over the Antarctic continent and a cooling over the ocean. These temperature changes reduce the intensity of katabatic flow and the convergence with warm, moist airflow from lower latitudes along the coast of East Antarctica, and
eventually prevent the coastal low from overdeveloping. On the other hand, the cooling over the Pacific Ocean recovers the strength of the 500-hPa trough and encourages the development of the migrating extratropical low, which ultimately turns it into the major storm.

The development of a storm involves diverse physical and dynamical processes and the relative importance of individual processes varies significantly from one storm to another. Although this study provides some insights into the impact of GPS RO data on the development of the particular storm case, it would be desirable to extend our approach to many other storms. The results obtained from this study clearly indicate the positive impact of GPS RO data on the storm prediction in the Antarctic area. The impact is anticipated to be greater when more RO data are available from future missions (e.g., COSMIC-II, which has enhanced capabilities and a higher observation density).

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