Intercomparison of WRF 3/4-Dimensional Variational (3/4D-Var) Data Assimilation Methods for Antarctic Applications over the Month of October 2007

Qingnong Xiao[1]*, Kekuan Chu[1], Sha Feng[1], Bill Kuo[2], and David Bromwich[3]

1. College of Marine Science, University of South Florida, St. Petersburg, FL
2. National Center for Atmospheric Research, Boulder, CO
3. Byrd Polar Research Center and Atmospheric Sciences Program, Dept. of Geography, The Ohio State University, Columbus, OH

1. Introduction

Numerical models seeking to treat the environment of Antarctica and the surrounding Southern Ocean face unique challenges (Parish and Bromwich 2007). High southern latitudes are also home to important, yet nuanced climate variability and change, such as the rapid warming since 1950 in the western Antarctic Peninsula region and cooling over part of interior Antarctica (Monaghan and Bromwich 2008). Therefore, it is highly important to have accurate Antarctic meteorological analysis, so that we have a better understanding of the Antarctic environment and its variability as well as a more accurate analysis of the atmospheric state for numerical weather prediction (NWP) in Antarctica. Research on an improved data assimilation technique that can effectively and robustly incorporate observations for Antarctica and the Southern Ocean into a sound and comprehensive analysis, is one of the important goals of International Polar Year (IPY, *cf.* WMO 2007).

The Antarctic Mesoscale Prediction System (AMPS) was implemented in 2000 (Powers et al. 2003), and currently the Weather Research and Forecasting (WRF) 3-Dimensional Variational (3DVAR) data assimilation system (Barker et al. 2004; Skamaroch et al. 2008) was employed in the data assimilation. Although computationally more expensive than WRF 3DVAR, WRF 4-Dimensional Variational (4DVAR) data assimilation has added benefits in taking care of the details of the analysis (Huang et al. 2009). It employs a forecast model as a strong constraint in a least-squares fit problem. It has an implicit update of the flow-dependent background field and the capability to assimilate data at the exact observation time. The 4DVAR adjoint approach is one of the most attractive assimilation methods. In recent years, a considerable amount of work at the National Center for Atmospheric Research (NCAR) has been done for the development of WRF adjoint and WRF 4DVAR (Xiao et al. 2008; Huang et al. 2009). The WRF adjoint has been applied in Antarctic research to investigate the adjoint sensitivity of a severe windstorm in the Ross Sea and identified the sensitive regions for the improvement of the forecast of the storm (Xiao et al. 2008). The first version of WRF 4DVAR has been developed and employed in research of the mid-latitude weather systems (Huang et al. 2009). Application of WRF 4DVAR to improve the Antarctic analysis is beneficial to NWP in Antarctica, as well as for the diagnoses of the Antarctic environmental variability and climate change.

The objective of the inter-comparison between WRF 3/4DVAR data assimilation techniques is to evaluate the capabilities of WRF 4DVAR data assimilation in support of NWP in Antarctica. This is accomplished over the whole month of October 2007, which was one of the most active months of Antarctic cyclones. Because it was within the IPY, a relatively rich datasets including regionally intensive measurements were generated during the month. The up-to-date WRF 3/4DVAR system based on the WRF 3.2 is employed in this study.

2. Experimental Settings

Two series of data assimilation experiments over the month of October 2007 using WRF 3DVAR and 4DVAR are carried out. WRF V3.2 and WRFDA3.2 are employed for the study, with two-domains, two-way nested in the forecast, but data assimilation is performed in Domain 1 only (Figure 1). The first-guess fields for both WRF 3DVAR and 4DVAR are the 6-h forecast from NCEP/FNL interpolated initial conditions. Background error covariance matrix is generated using NMC-method (Parish and Derber 1992). Both 3DVAR and 4DVAR experiments are conducted two times a day at 0000 UTC and 1200 UTC from 1 till 31 October 2007.

Various types of meteorological observations are assimilated during the month of October 2007, namely winds, temperature and moisture from radionsondes, ships and surface stations (including the AWS data and the intensive surface observations from IPY); winds and temperature from aircrafts; QuikScat winds from satellite Scatterometers and MODIS winds from Terra and Aqua, GPS refractivity data. The

* Corresponding to qxiao@marine.usf.edu

observation pre-processing module (OBSPROC) of WRF-Var is implemented for data sorting, quality control and observational error assignment (Barker et al. 2004). WRF 3DVAR assimilated the observational data from -1.5h to +1.5h at each analysis time. The assimilation window of 4DVAR covers the period from -3 h to +3h of each analysis time, therefore all available observations distributed over such a 6-h window are assimilated. As an example, Figure 1 shows the surface observations at 1200 UTC 01 October 2007. Although radiosondes are just a few in Antarctica, there are a fair amount of surface observations there. The surface data inside the Antarctic Circle (shown in Fig. 1) are used for the forecast verifications in this study.

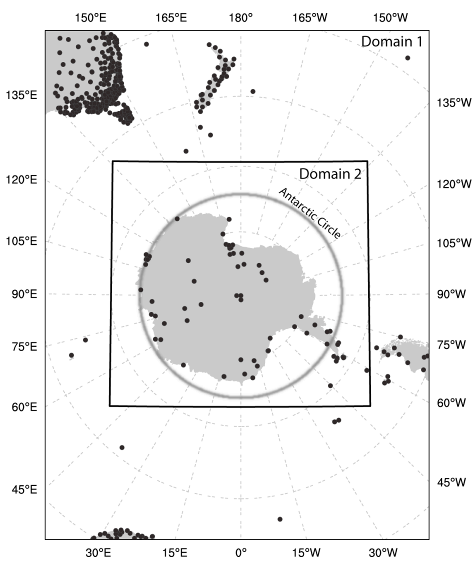

Figure 1. Configuration of the experimental domains and the surface observation locations (dots) in domain 1 (The circle inside domain 2 is the Antarctic Circle, and the 50 surface observations within the Antarctic Circle are used in forecast verifications.)

A 3-day forecast using WRF V3.2 follows each data assimilation analysis. The domain configuration is exactly the same as the Antarctica Mesoscale Prediction System (AMPS, Powers et al. 2003), which has a mother domain with a resolution of 45 km (220x290 grid mesh) and a 15-km nested domain (442x418 grid mesh) covering Antarctica and the parts of the Southern Ocean (Fig. 1). There are 44 layers in the vertical, with the model top at 10 hPa. The time step for the maximum doman is 180 s. The model physics include: WSM-5 class microphysics scheme (Hong et al. 2004), RRTM longwave radiation scheme (Mlawer et al. 1997), Goddard short-wave radiation scheme (Chou and Suarez 1994), unified Noah land-surface model, Kain-Fritsch cumulus parameterization (Kain and Fritsch 1993), Mellor-Yamada-Janjic TKE boundary layer parameterization scheme (Mellor and Yamada 1982).

3. Intercomparison of WRF 3DVAR and 4DVAR in Antarctica

First of all, we examined the performance of WRF 3DVAR and WRF 4DVAR analyses in the one-month period. The data assimilation was performed in Domain 1, all the surface observations were included in the verification of the analysis error. The root-mean-square error (RMSE), correlation (CORR) and Bias (BIAS) of horizontal winds (u, v), temperature (T) and the mixing ration of water vapor (q) are calculated between the WRF 3DVAR and 4DVAR analyses and the surface observations in Domain 1 over the whole month. There are a total of 62 analyses for both 3DVAR and 4DVAR experiments, initialized from 0000 and 1200 UTC each day in the month. Figure 2 shows the scattering distribution of the analyses vs. observations in 3DVAR and 4DVAR. In general, there is very good agreement between the analyses and observation in both 3DVAR and 4DVAR. However, the 4DVAR analyses display a little larger scattering than 3DVAR. Within the lower temperature range, both 3DVAR and 4DVAR analyses show obvious positive biases (Figs. 2a and b). In other fields (u, v, q), the scattering distribution looks normal, indicating that WRF data assimilation systems successfully incorporate the observation information into the analyses (Figs. 2c-h). Even though 3DVAR analyses fit the observation at the analysis times better, 4DVAR has its advantage that it tries to fit the observations in a 6-h window with model as a strong constraint. 4DVAR assimilates more observations in the 6-h window, and can achieve more balance with the model because model in directly involved in the variational minimization procedure. Previous research proved that model balance in the initial conditions is much more important than just fitting to the observations for the numerical weather prediction (Xiao et al. 2009). From Figure 2, all three verification indexes (RMSE, CORR, and BIAS) indicated that 3DVAR experiments obtained better fit to the observations than 4DVAR. However, how long this fit can last are our interests in this research.

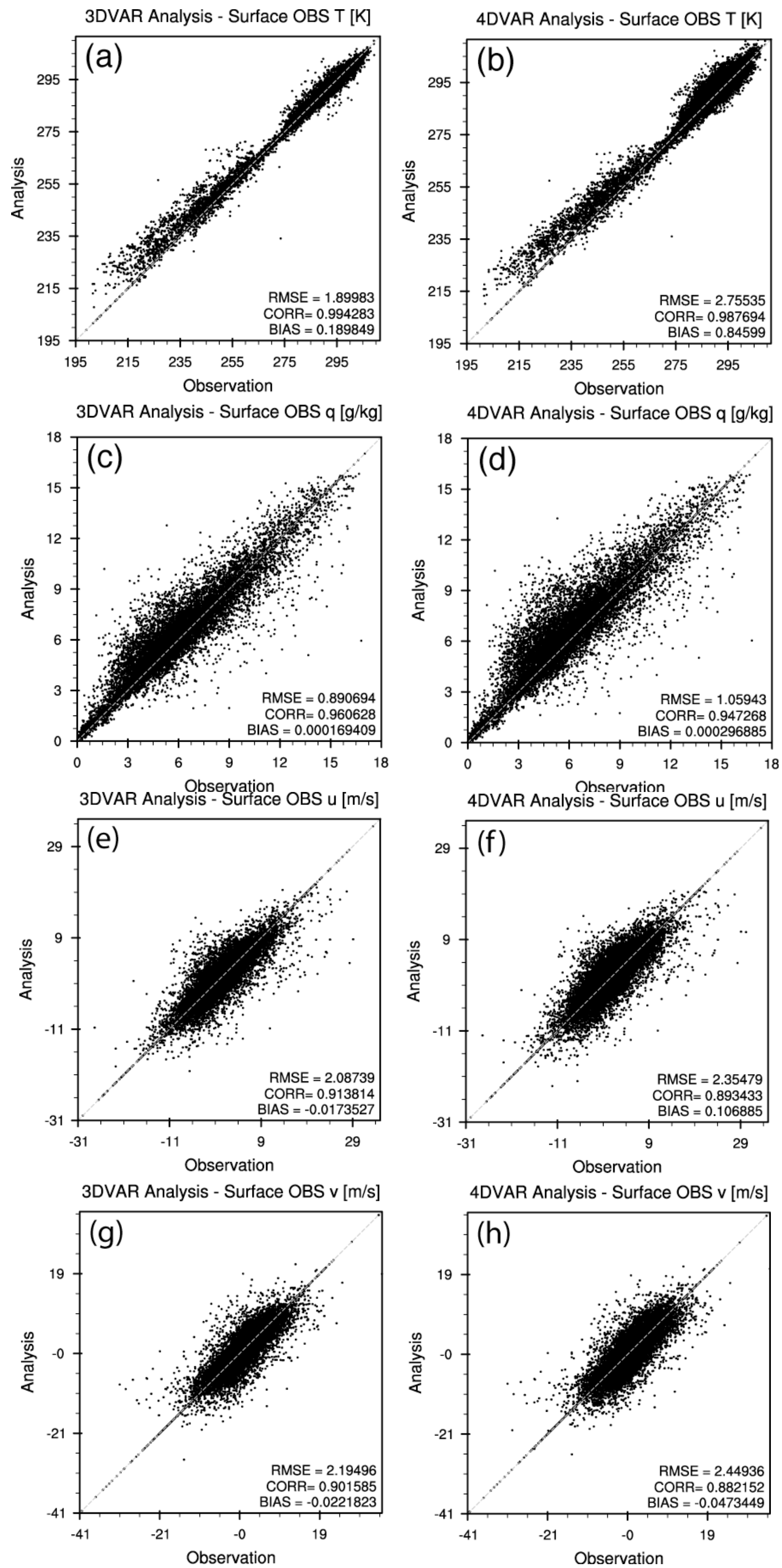

Figure 2. Scattering distributions of WRF 3DVAR and 4DVAR analyses vs. surface observations in the assimilation domain over the whole month of October 2007 at 0000 and 1200 UTC every day.

In order to avoid the complexity of the impact from lateral boundaries of the domains, we carried out the forecast verification inside the Antarctic Circle within Domain 2. There are 50 surface observations over the whole month of October 2007 which are selected for the verifications. Figure 3 presents the variations of the 12-h forecast RMSEs from WRF 3DVAR and 4DVAR experiments verified against the selected surface observations over the whole month of October. Each day there are two times forecasts initialized at 0000 and 1200 UTC. While apparent fluctuations in the verifications from initialization time are seen in both experiments, at least equal or better performances can be identified in 4DVAR compared with 3DVAR. Especially we note that the advantage of 4DVAR for temperature forecasts is fairly persistent throughout the month (Fig. 3a). For other forecast fields (q, u and v), 4DVAR and 3DVAR show comparable performances (Figs. 3 b-d), with the exception that in the mid period of the month the zonal wind (u) forecast in 4DVAR presents smaller RMSEs than in 3DVAR runs (Fig. 3c).

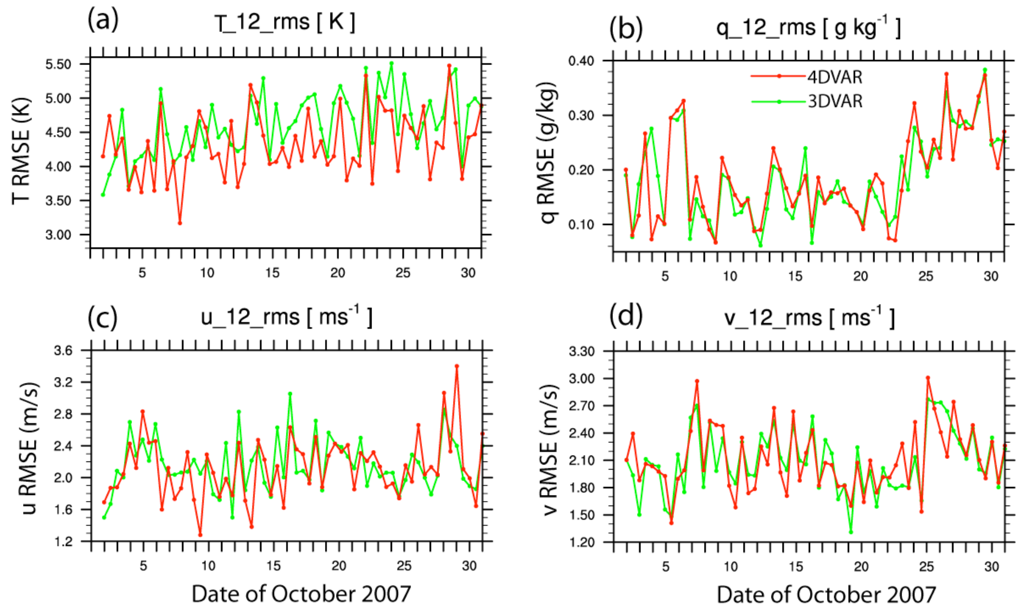

Figure 3. Variations of the 12-h forecast RMSEs from WRF 3DVAR (green) and 4DVAR (red) experiments verified against the selected surface observations inside the Antarctic Circle over the whole month of October 2007.

The better performances of 4DVAR compared with 3DVAR in Antarctic applications are more clearly shown with the increase of the forecast lead times. We notice that 4DVAR outperforms 3DVAR in the forecasts beyond 12 h, for all forecast variables nearly at all times. Similar to Figure 3, the verifications of the 72-h forecasts throughout the month are presented in Figure 4, which depicts the time evolution of the RMSEs from the forecasts in WRF 3DVAR and 4DVAR runs. It shows that 4DVAR has consistently smaller error than that of the 3DVAR in temperature forecasts throughout the whole month (Fig. 4a). The advantage of 4DVAR in comparison with 3DVAR can also be easily identified in other forecast variables (Fig. 4 b-d), that almost all 4DVAR runs have no larger RMSEs than 3DVAR. It implies that 4DVAR is superior to 3DVAR in the forecasts even though its fits to observations at analysis time are not as close as 3DVAR. Huang et al. (2009) have discussed that the flow-dependent nature of the analysis within the 4DVAR assimilation window results in a better forecast skill of tropical cyclones using WRF 4DVAR than using 3DVAR. The same conclusions are also drawn by Zhang and Pu (2011) from experiments of a convective case during the International H2O Project (IHOP_2002). Recently, Zhang et al. (2011) compared the performance of WRF 3DVAR and 4DVAR along with other data assimilation technique over the contiguous United States in a warm-season month of June 2003, and found that the 4DVAR has consistently smaller error than that of the 3DVAR on winds and temperature at all forecast lead times except at 60 and 72 h when the two forecast errors become comparable in amplitude, while the two schemes have similar performance in moisture at all lead times. Our study in this paper is the first investigation of the possible WRF 4DVAR application over the Antarctica. As Antarctica is a sensitive region to the global climate change and weather forecast in the continent is important to the Antarctic exploration, investigation of the newly developed WRF 4DVAR for Antarctic applications is of broad impact.

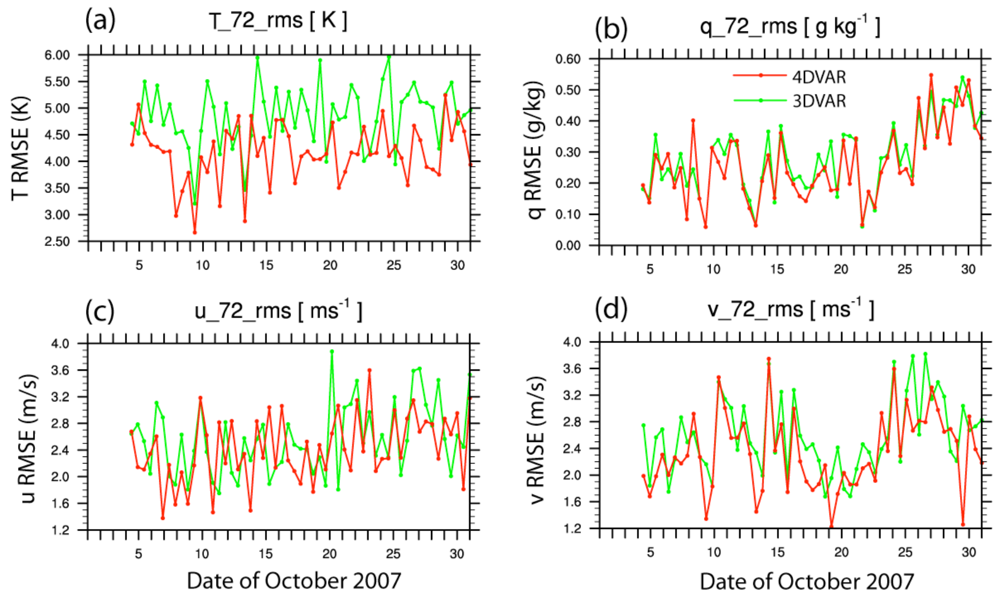

Figure 4. Variations of the 72-h forecast RMSEs from WRF 3DVAR (green) and 4DVAR (red) experiments verified against the selected surface observations inside the Antarctic Circle over the whole month of October 2007.

Averaged over the month of October 2007, Figure 5 displays the inter-comparisons between WRF 3DVAR and 4DVAR in the month-averaged RMSEs and BIASs of the forecasted temperature, mixing ratio of water vapor, and wind components within 72 hours at every 12 h interval. Note at 00 h (analysis time), 3DVAR always beat 4DVAR in all verification indexes. After 6 or 12 hours later, however, the verification scores of 4DVAR runs catch up and surpass 3DVAR runs. The RMSE of temperature after 6 h in 4DVAR is smaller than in 3DVAR (Fig. 5a). The RMSEs of moisture and winds after 12 h in 4DVAR is smaller than in 3DVAR (Figs. 5b-d). The BIASs of the forecasted wind components (u and v) are very small in both 3DVAR and 4DVAR runs. However, noticeable positive BIASs are shown in the forecasted temperature and moisture fields; but 4DVAR performs generally better than 3DVAR.

We notice that the temperature analyses (or at 00 h) of both 3DVAR and 4DVAR have large RMSE and BIAS in all experiments, which result in the subsequent larger RMSEs and BIASs of temperature forecasts after 12 h till 72 h. This indicates the DA setup in WRF-Var contains flaw for Antarctica. Because of the complex topography in Antarctica, the surface observation operators should be revised which should take consideration of the complex topography and landuse in Antarctica, and more accurate land surface process should be included in the DA setup. This is beyond the extent of this research, but we will explore it in the future. Nevertheless, WRF 4DVAR could greatly reduce the RMSE and BIAS in the temperature fields. The error reduction in 4DVAR from 3DVAR is the largest in temperature fields compared with other model variables. This demonstrates that 4DVAR possesses more powerful capability in reducing the errors in the analysis as well as in forecast. The clear advantage of 4DVAR over 3DVAR in the forecasts of all fields signifies the benefits of model constraint governing the analysis, since 3DVAR does not employ model in the analysis but 4DVAR does. In addition, 4DVAR includes more observational data compared with 3DVAR. In theory, 4DVAR can handle all observations at different times in the assimilation window, but 3DVAR can only use the observations at the analysis time. This definitely contributes to the better forecast skill of 4DVAR experiments as well.

Acknowledgement: This work is sponsored by NSF/OPP under grant ANT-#0839068.

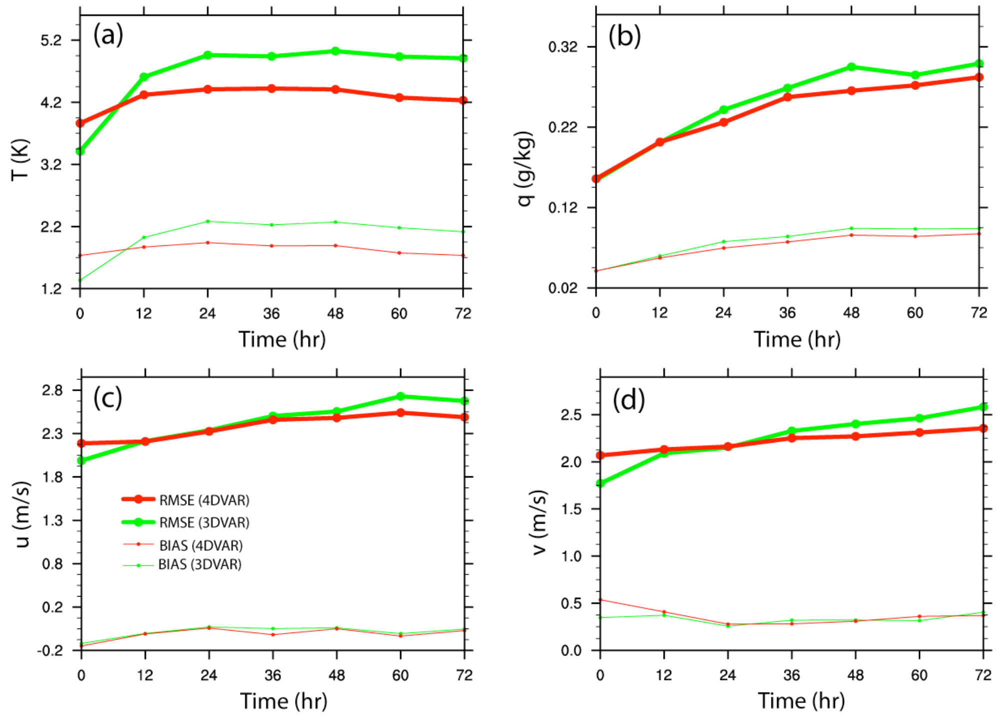

Figure 5. The RMSE (thick line) and BIAS (thin line) of (a) temperature T (K), (b) mixing ration of water vapor q (g/kg), (c) wind component u (m/s) and (d) v (m/s) at different forecast times for WRF 3DVAR (green lines) and 4DVAR (red lines) inside the Antarctic Circle over the whole month of October 2007.

References

Baker, D. M., and W. Huang, Y.-R. Guo, A. J. Bourgeois, and Q. Xiao, 2004: A three-dimensional variational data assimilation system for MM5: Implementation and initial results, *Mon. Wea. Rev.,* **132***,* 897-914.

Chou, M.-D., and M. J. Suarez, 1994: An efficient thermal infrared radiation parameterization for use in general circulation models. NASA Tech. Memo., 104606, 3, 85pp.

Hong, S.-Y., J. Dudhia, and S.-H. Chen, 2004: A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation, *Mon. Wea. Rev.,* **132***,* 103–120.

Huang, X.-Y., Q., Xiao, D. M. Barker, Xin Zhang, J. Michalakes, W. Huang, T. Henderson, J. Bray, Y. Chen, Z. Ma, J. Dudhia, Y.-Y. Guo, X. Zhang, D.-J. Won, H.-C. Lin, and Y.-H. Kuo, 2009: Four-dimensional variational data assimilation for WRF: Formulation and preliminary results. *Mon. Wea. Rev.*, **137**, 299-314.

Kain, J. S., and J. M. Fritsch, 1993: Convective parameterization for mesoscale models: The Kain–Fritsch scheme. The Representation of Cumulus Convection in Numerical Models, K. A. Emanuel and D. J. Raymond, Eds., *Amer. Meteor. Soc.,* 165–170.

Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems, *Rev. Geophys. Space Phys.,* **20***,* 851–875.

Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave, *J. Geophys. Res.*, **102(D14)**, 16,663–16,682, doi:10.1029/97JD00237.

Monaghan, A. J., and D. H. Bromwich, 2008: Advances in Describing Recent Antarctic Climate Variablity, *Bull. Amer. Meteor. Soc.*, **89**, 1295-1306.

Parish, T. R., and D. H. Bromwich, 2007: Re-examination of the near-surface air flow over the Antarctic continent and implications on atmospheric circulations at high southern latitudes. *Mon. Wea. Rev.*, **135**, 1961-1973.

Parrish, D. F., and J. Derber, 1992: The national meteorological center's spectral statistical-interpolation analysis system, *Mon. Wea. Rev.,* **120***,* 1747-1763.

Powers, J., A. J. Monaghan, C. A. Cayette, D. H. Bromwich, Y.-H. Kuo, and K. W. Manning, 2003: Real-time mesoscale modeling over Antarctica: The Antarctic Mesoscale

Prediction System (AMPS). *Bull. Amer. Meteor. Soc.,* **84,** 1533–1546.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X.-Y. Huang, W. Wang, and J. G. Powers, 2008: A description of the Advanced Research WRF Version 3, NCAR Tech. Note NCAR/TN-475+STR, 125 pp.

WMO, 2007: The scope of science for the International Polar Year 2007–2008, the ICSU/WMO Joint Committee for IPY 2007–2008, 84pp.

Xiao, Q., Y. Kuo, Z. Ma, W. Huang, X.-Y. Huang, X. Zhang, D. M. Barker, J. Michalakes, and J. Dudhia, 2008: Application of an adiabatic WRF adjoint to the investigation of the May 2004 McMurdo, Antarctica, severe wind event. *Mon. Wea. Rev.*, **136**, 3696-3713.

Zhang, Meng, Fuqing Zhang, Xiang-Yu Huang, and Xin Zhang, 2011: Intercomparison of an Ensemble Kalman Filter with Three- and Four-Dimensional Variational Data Assimilation Methods in a Limited-Area Model over the Month of June 2003. *Mon. Wea. Rev.*, **139**, 566-572.

Zhang, L. and Z.-X. Pu, 2011: Four-dimensional assimilation of multi-time wind profiles over a single station and numerical simulation of a mesoscale convective system observed during IHOP_2002. *Mon. Wea Rev.*, in press

.