The MM5 and Plate Tectonics: the atmosphere's role in solid earth science

S. Mark Leidner[†,*] **Arthur E. Niell**[‡] **and John M. Henderson**[†]
[†]Atmospheric and Environmental Research Inc., Lexington, Massachusetts
[‡]Haystack Observatory, Massachusetts Institute of Technology, Westford, Massachusetts

1. Introduction

Space geodesy provides valuable information about Earth's reference frame, including Earth rotation, the motion of the pole, and the movement of plates on the Earth's surface. One of the principal space geodetic techniques is called Very Long Baseline Interferometry (VLBI). Given two radio telescopes that measure incoming signals from the same radio source in the sky at the same time, the arrival of these signals at one station will be delayed relative to the other due to the differing distances along the ray emanating from the radio source, and hence the phase of the signal at the radio telescope stations. Correlation of the group delay measured over a day from different radio sources can be used to infer the separation (or baseline length) between the two telescopes.

The accuracy of space geodetic techniques has increased approximately two orders of magnitude in the last 30 years from ∼1 m to ∼1 cm. And further refinements are on the horizon to bring the accuracy to the millimeter level. The distance between two such points on Earth can now be determined reliably to within 1-2 cm (e.g., Westford, Massachusetts and Johannesburg, South Africa). Of the remaining uncertainties in such precise analyses, however, the effect of refraction by the atmosphere of the incoming radio signals can be as much as 40% of the error budget. This is because the distribution of mass along slant paths through the atmosphere around the radio telescope sites is generally unknown and is currently highly parameterized.

The goal of this study is to improve the characterization of the distribution of atmospheric mass, particularly water vapor, along the line of sight of radio telescope measurements.

We present results of a study to use high-resolution MM5 forecasts to characterize the distribution of mass (dry air and water vapor) in the troposphere around selected VLBI radio telescope sites. § 2 presents current and future methods for determining atmospheric delay, § 3 introduces the MM5 and its use in this study, § 4 discusses MM5 verification against radiosondes, and § 5 concludes with a summary of the present findings.

Corresponding author address: S. Mark Leidner, Atmospheric and Environmental Research, Inc., 131 Hartwell Avenue, Lexington, Massachusetts 02421; email leidner@aer.com

2. Atmospheric Delay

Current methods that account for atmospheric refraction in space geodesy are called mapping functions. Refraction lengthens the ray path through the atmosphere compared to a straight path (*i.e.*, no refraction, as in a vacuum). A longer path length results in a delay in the arrival of a signal at the radio telescope (distinct from the radio signal's group delay between two stations mentioned previously).

Mapping functions parameterize the change in atmospheric delay as a function of elevation angle. At zenith (elevation angle = $90°$), a mapping function is unity, by definition, and at lower elevations angles ($< 10°$), the functions can be as large as 10 to 15. Several authors have developed mapping functions of varying complexity (Niell 1996, 2000, 2001). Mapping functions typically treat delays from the atmosphere's "dry" and "wet" constituents separately. The "dry" or hydrostatic delays are well-characterized by the height of the 200 hPa surface over the station plus a simple gradient term, since the evolution of this surface is relatively slow (order 6-12 hours). But the "wet" delay (owing to water vapor gradients) can vary much more rapidly and does not vary smoothly. Most of the current mapping functions assume the atmosphere is horizontally homogeneous. Yet refractivity may vary dramatically with azimuth and elevation in some meteorological situations.

As an example, Figure 1c and d show cross sections of water vapor mixing ratio from the 3-km resolution MM5 grid around Hartebeesthoek Radio Astronomical Observatory (HartRAO), South Africa for 0 hour and 6 hour forecasts, valid 0000 UTC 20 October 2002. Cross sections locations are shown in Fig. a and b. In contrast, Figure 1e shows the same cross section, but assuming a horizontally homogeneous atmosphere. Notice that the $5°$ elevation and zenith sight lines are overlaid. Clearly, there are horizontal variations in water vapor in Figure 1c and d that will effect atmospheric refraction.

3. Mesoscale Modelling

We use the MM5 to generate short-term forecasts in the vicinity of selected radio telescopes to help characterize the distribution of water vapor. During sixteen days in October 2002, a continuous (*i.e.*, 24 hours/day) intensive observing campaign was conducted among eight radio telescopes around the world, named CONT02.

We used GFS "final" analyses (*i.e.*, long data cutoff time) to initialize the MM5 every 6 hours during CONT02 at three radio telescope sites: Westford, Massachusetts, Kokee, Hawaii and HartRAO, South Africa. Nested grids are set up around each site using 81, 27, 9 and 3 km resolution domains, centered exactly on the radio telescope site. As an example, Figure 1e shows the nested grid configuration around the HartRAO telescope.

4. Verification Results

Figure 2 shows a summary the verification of 0, 6 and 12 hour forecasts at 81, 27, 9 and 3 km resolutions at three radio telescope locations (Westford, Massachusetts; Kauai, Hawaii; and HartRAO, South Africa) during CONT02. Our verification compares MM5 forecasts to local radiosondes (forecast - radiosondes) on mandatory pressure levels for temperature (Fig. 2, left column) and water vapor mixing ratio (Fig. 2, right column). The comparisons were made using the MM5 3d-VAR software.

Westford uses four local radiosonde sites for verification (Albany, NY; Gray, ME; Chatham, MA and Brookhaven, NY). Kokee has two nearby radiosondes for the 81 km domain (Hilo, HI and Lihue, HI), but the nested grids can only be verified by the Lihue, HI radiosonde site. The HartRAO site has only two radiosonde sites for verification of the 9 and 3 km grids (Pretoria, South Africa; Seretse Khama, Botswana). Other radiosonde sites are available for verifying the 81 and 27 km grids, but the root mean squared error of temperature suggest that either the observations or the model forecasts are of poor quality. We are still investigating the cause.

Figures 2a and b present and interesting comparison of GFS initial conditions and a short-term mesoscale forecast. In this case, convection has broken out over the high plains of South Africa during austral springtime. The short-term forecast produced by the MM5 matches the gross features of the GFS analysis, but many fine details are realized.

Overall, mean error and root mean squared error (RMSE) of temperature and water vapor increase marginally with forecast time. Notable exceptions include the mean temperature error at Westford and the mean water vapor error at Kokee, which are both reduced with increasing forecast time. Also, mean error and RMSE do not seem to be systematically larger or smaller at for lower or higher grid resolutions.

5. Summary

We have used the MM5 to generate mesoscale forecasts at three radio telescope sites during the CONT02 period (October 16-31, 2002). Initial verification of these forecasts against radiosondes suggest that errors in 6 and 12 hour forecasts are comparable to GFS initial conditions. This opens the possibility of using mesoscale forecasts to estimate atmospheric delays along radio telescope sight lines, directly from mesoscale forecasts. This is effectively using the MM5 as a down scaling tool. Further plans will include the use of these mesoscale forecasts in geodetic analyses during the CONT02 period.

6. Acknowledgments

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7. References

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Fig. 1:

Plan views at 1 km AGL (upper panels) and two corresponding cross sections (middle panels), showing water vapor mixing ratio from 0 hour (left column) and 6 hour (right column) MM5 forecasts on a 3-km grid around Hartebeesthoek Radio Astronomical Observatory (HartRAO), South Africa, valid 0000 UTC 20 October 2002. Bottom left panel shows the MM5 grid configuration and bottom right panel shows a cross section assuming azimuthal symmetry.

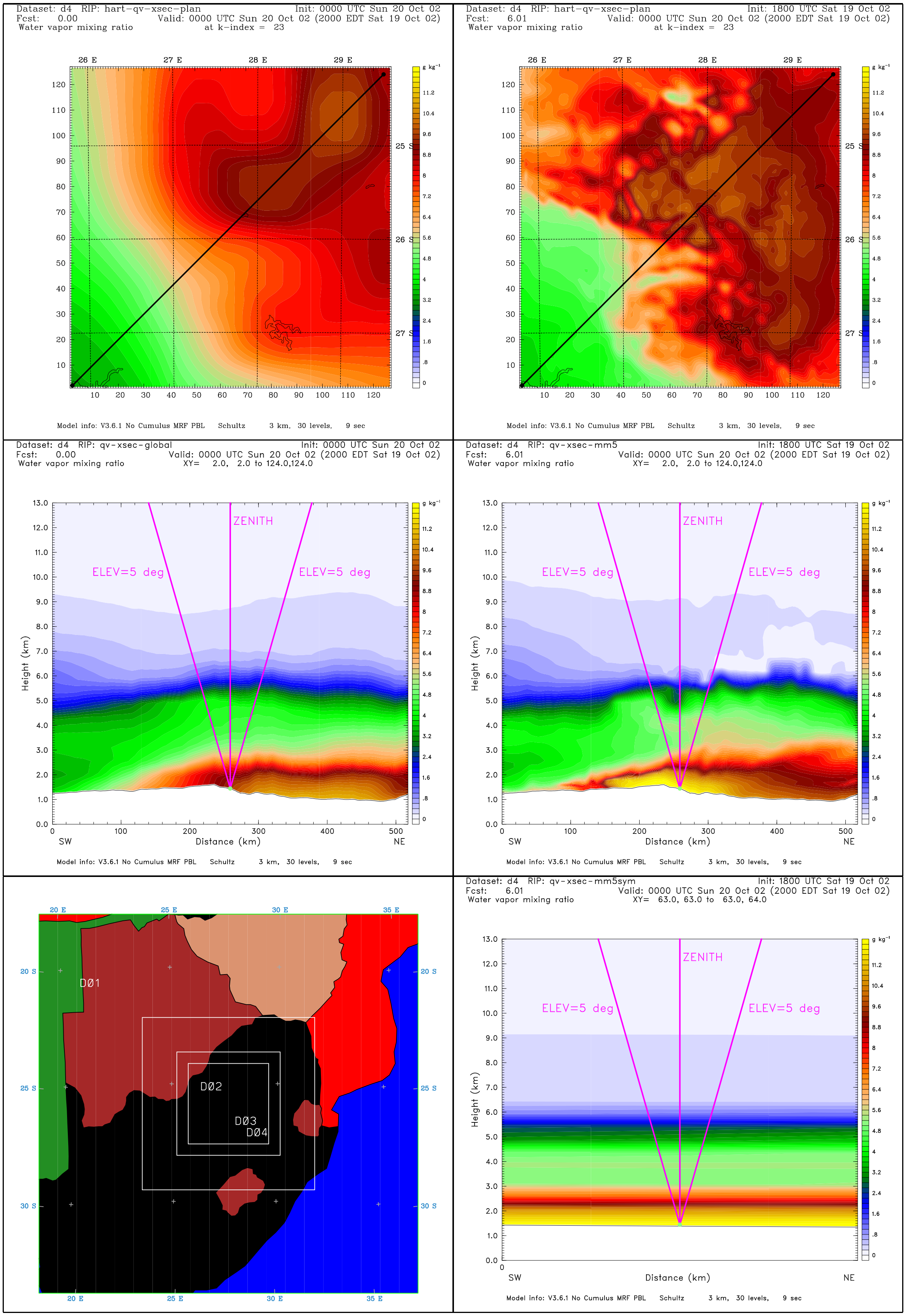

Fig. 2:

Verification statistics (forecast - radiosonde) for Westford, Massachusetts (upper panel), Kokee, Hawaii (middle panels) and HartRAO, South Africa (lower panels) of temperature (right column) and water vapor mixing ratio (left column).