Introduction: The North Pole Residual Ice Cap (NPRC) is probably the most important source of atmospheric water vapor on Mars. Shortly after summer solstice the NPRC is fully exposed to the atmosphere; and, during the seasonal period between Ls~105° and Ls~120°, the largest global and annual water column abundances are seen in the polar atmosphere. This is also the season during which the NPRC temperatures reach their maximum; ice temperature is the single most important factor in determining water ice sublimation rates.

A prominent feature of the water cycle during the present epoch is the atmospheric transport of a significant amount of this water to the south. General Circulation Models (GCMs) have been used in recent years to better understand the dynamics of the water cycle, e.g., [1], [2] and [3]. Results from these studies have agreed quite well with observations (specifically how the zonal mean distribution of water vapor varies with latitude and solar longitude), strong evidence that the large scale dynamics in these models are realistically representing that of the Martian atmosphere itself.

New observations [4], along with a re-analysis of the TES water data, have revealed that the water cycle is actually much drier than was believed (only 2/3 as wet). Also, the role of the polar regolith in the water cycle is difficult to constrain, and it may be significant, e.g., [1], [2], [4] and [5]. The NASA Phoenix Scout mission is very timely in this regard, as “ground-truth” observations of water ice in the polar regolith and the humidity of the Martian air are being collected.

The NPRC is a rather complex structure, both in topography and due to the sharp gradients in albedo and thermal inertia. It is also relatively small, and when considered in the context of typical GCM model domains (and their typical spatial resolutions) it is poorly resolved. Because of this, GCMs tend to overestimate the size of the NPRC [6], allowing more water to be released into the polar atmosphere, yielding a wetter water cycle than might otherwise be simulated. Moreover, the “pole problem” inherent with traditional GCM grids (globally uniform grid spacing in latitude and longitude), and the filtering that is required to maintain computational stability, raise questions regarding the reliability of the very high-latitude dynamics in these models. Such problems can only be fully addressed when using a model domain (map projection) that is appropriate for the simulation of atmospheric circulations in polar regions.

When a mesoscale model is used, and the mother domain is polar stereographic (with the NPRC at the center of the modeling grid), the GCM “pole problem” and dynamical filtering issues are entirely avoided. Additionally, mesoscale models can typically utilize two way nesting such that very high resolutions are possible over the NPRC and the surrounding region, where the relatively small and complex aspects of the circulation, and its vigor in relation to that typically seen in GCMs, are fully resolved, e.g., [7] and [8].

Our earlier work, and the methods described therein to represent the polar thermal environment as realistically as possible, can be built upon to enable water transport studies where the problems inherent in a GCM are avoided. Mesoscale modeling, however, has its own unique set of problems. These are mostly defined in relation to the amount of simulation time required for the model to “spin-up” from an initial state (as typically provided by a GCM) and the length of simulation required to effectively characterize the mean circulation. Careful mesoscale modeling during the time that the NPRC is providing water to the atmosphere (using a sufficiently realistic physics package), will certainly improve our understanding of the water cycle, and would be expected to help constrain the role and importance of regolith water ice by allowing tighter constraints to be placed on the sublimation of ice and atmospheric transport of water vapor. As this new work matures, and grid spacings reach below ~5 km, it should also become possible to provide some insight into the long term stability and evolution of the present day spiral troughs.

Model Modifications: In this work we use the OSU MMM5 [9], specifically a new version of the model that is presently undergoing development. Prior to this work our simulations were performed with a dry atmosphere; thus, the first phase of this work involved 1) defining the active source for water in the model, 2) allowing this source to sublimate into the atmosphere according to a vapor pressure relationship appropriate for Mars, and 3) demonstrating that the transport of atmospheric water vapor occurs realistically according to model dynamics. An important final aspect of this first phase was to demonstrate that all of this was
working to our satisfaction when nesting had been enabled.

The simulations described below were performed with a polar stereographic semi-global mother domain (having a nominal resolution of 108 km) and one nest (having a nominal resolution of 36 km). A map showing the albedo for the nest is provided in Fig. 1.

At present we have adopted the saturation vapor pressure relationship of [1]. The result, given in mbar, defines the saturation vapor pressure with respect to ice at the ground and in the atmosphere. The relationship is as follows:

$$P_{\text{sat}} = 6.11 \times \exp \left( 22.5 \times \left( 1 - \frac{273.16}{T} \right) \right).$$

To determine the rate that water sublimates into the atmosphere, we have simply adopted the present relationship in the MRF PBL scheme (used in the OSU MMM5) to the purposes of this work. The basic formulation is simple, a mixing coefficient multiplies the difference between the saturation mass mixing ratio at ground temperature and surface pressure and the actual mass mixing ratio of the lowest atmospheric layer, as follows:

$$Q_{\text{flux}} = K_v \times (Q_{\text{sat}}^\text{ground} - Q_{\text{atmos}}).$$

Our formulation for the mixing coefficient $K_v$ is similar to that used by [3], the product of air density, friction velocity and a drag coefficient, where one more term is used in our $K_v$ to identify the availability of moisture, MAVAIL.

During model initialization the value of MAVAIL is set according to thermal inertia. For the largest thermal inertias, presumably almost pure ice locations in the NPRC or residual outliers (the albedo is brighter than 0.27), MAVAIL=1.0. If the location is a transition thermal inertia (albedo brighter than 0.25) then a somewhat smaller availability of water is assumed, and we set MAVAIL=0.75. All other model locations have MAVAIL=0.0 since thermal inertias are much smaller.

The drop term of our mixing coefficient formulation is somewhat non-standard, and some literature hunting was required to determine its origin [10]. However, when actual values of $K_v$ are examined from our simulations, they are certainly within the range of expectations, a good starting point.

Concerning the transport scheme for water vapor (other tracers soon), typical mixing ratios for water vapor in the Mars case are not that many orders of magnitude different than we would expect for the terrestrial atmosphere; thus, truncation errors are of little concern and diffusion should not be excessively mixing out vapor gradients (the scheme should work as implemented). And, as expected, mixing ratio profiles compare very well between the mother domain and the nest (for the same location), with no strange behavior seen at the nest boundaries in the mother domain. Simply activate new model functionality and it works, a surprisingly pleasant experience!

In our modeling at present the effects of latent heat are being neglected. The ability to include this forcing is, however, a simple switch at compile time and may become something we choose to activate for sensitivity studies in the future.

Primarily as a matter of convenience, our initial simulations were configured to a seasonal date of $L_s=120^\circ$. We do have some familiarity with the atmospheric dynamics during this season [7]. Since that earlier work was performed, we have greatly improved upon the method used in our modeling to prescribe atmospheric dust, facilitating some useful $L_s=120^\circ$ comparisons as a consequence.

Three changes were made to provide a more realistic dust prescription: 1) the visible opacity at reference pressure is now a function of latitude; 2) the Conrath-Nu Parameter is now a function of latitude; and, 3) the reference pressure itself (the pressure at which the prescribed visible opacity is reached) is a function of latitude. A linear approximation to the zonal mean surface pressure, as taken from the GCM, is used to pre-
scribe the reference pressure. Visible opacities are thus prescribed in relation to zonal mean total atmospheric column values (not 6.1 mbar surface values). Thus, the altitude at which dust mass mixing ratios begin to fall rapidly towards zero (as determined by the Conrath-Nu parameter) is more related to geometric height above the ground. This approach has grown from ongoing work being performed for MSL, and has been a key part of efforts to produce zonal mean atmospheric temperatures in good agreement with TES. Clearly, a realistic representation of the thermal environment leads to greater confidence in model dynamics.

A version of the NASA Ames Mars GCM [11], that we maintain at OSU, is used to generate initial and hourly boundary conditions for the OSU MMM5. The GCM is run on a 3° by 6° lat/lon grid and uses this same new prescription for atmospheric dust, as was described immediately above.

**Figure 2.** TES zonal mean atmospheric water vapor abundances are shown for two different Mars years. Amounts are given in precipitable microns.

**TES Water Vapor Data:** By \( L_s = 120 \), atmospheric water vapor abundances over the most poleward latitudes are in rapid decline. Due to the nature of the polar circulation, there will certainly be some variability in this trend; the appearance of strong high latitude transients is unpredictable. The occurrence of these transients is evidenced by the “hot spots” in the data and in the differences between the two years of zonal mean recalibrated TES water vapor data, as shown in Fig. 2.

Although it does not provide an instantaneous synoptic “snapshot,” we can examine the same TES data mapped in latitude and longitude for a specific short seasonal period (good spatial coverage when a 5° solar longitude bin is used). From one year (the \( L_s = 120^\circ \) to \( L_s = 125^\circ \) period) these data are shown in Fig. 3. If alternative years are examined, the locations of “hot spots” are quite different, evidence that transient circulations are active and important in the sublimation and transport of water vapor. We have also constructed animations of these data, quite useful.

**Figure 3.** TES atmospheric water vapor abundances are shown for a bin period between \( L_s = 120^\circ \) and \( L_s = 125^\circ \). The maximum value is 65 pr μm.

**Simulation Results:** The OSU MMM5 is run for a period of 29 sols, where the atmosphere is initially dry. Sublimation and vapor transport are active from the beginning of the simulation; the 36 km nest is activated after two sols. Two cases were performed, where there was only one difference between them. In the first case, all water ice that is sublimated into vapor is allowed to stay in the atmosphere. In the second case, any water vapor in excess of local atmospheric saturation condenses and immediately falls out of the atmosphere to the ground (permanently removed). Both cases are examined at the end of the run.

In the first case, the wettest regions have water equivalent column depths of 80 pr μm (not shown). In the second case the wettest regions are only 50 pr μm; these data are shown in Fig. 4 for the final time of the model simulation (\( L_s = 125^\circ \)). These two simulations can be seen as bounding cases (none or all of the su-
persaturation is removed from the atmosphere) for the more realistic simulations to come. Soon our model will include clouds and other processes that will lessen the amount of atmospheric supersaturation. It is at least a good sign (for these first results) that the wettest location of the TES data of Fig. 3 is the mean of the wettest values in these two bounding cases.

One clear issue with the present OSU MMM5 simulations is that much of the atmosphere remains far too dry, even after a full 29 sols. The distribution of water vapor in Fig. 4 does help us to understand the timescales involved in the transport of vapor over larger distances, even clearly showing preference for specific longitude corridors (something that requires much closer examination in comparison with the TES data as in Fig. 3 and the related animations). Clearly, however, providing some initial water vapor distribution for the model, as we strive to constrain the role of atmospheric transport, will be an important step as this work progresses.

![Water Vapor in OSU MMM5 (Ls=125)](image)

**Figure 4.** Atmospheric water vapor abundances in the 36 km nest are shown for the OSU MMM5 “fallout” case. Values are given in pr μm and contours of topography are shown in gray (same region as in Fig. 1).

It is encouraging that the spatial variability and sharply decreasing abundances of water vapor toward the equator are in reasonable qualitative agreement with the TES data of Fig. 3. A similar qualitative structure is also seen in the “no fallout” case that has much larger column abundances. As the physics in our model is improved, a continual agreement in the overall structure of water vapor column abundances will be strong evidence that the transient circulations in the model circulation are quite representative of that in the real Martian atmosphere. It will also be very instructive to examine cloud water ice opacities in relation to the TES data.

**Ongoing Development:** As can be noticed in Figs. 2, 3 and 4, the maximum water vapor abundances do not occur directly over the pole. There may be many reasons for this, with the simple fact of the elevated NPRC topography being one cause. However, we have already observed that the largest water vapor mass mixing ratios occur along the periphery of the NPRC (not over the center of the NPRC itself). These steep southward facing slopes have the warmest temperatures of the NPRC complex. It may be that the bulk of the atmospheric water vapor comes from the sublimation of ices along the NPRC periphery. Clearly, due in great part to the existence of strong transient circulations, the NPRC periphery experiences the most consistent wind; and, friction velocity has an important role in the relationship determining the amount of sublimated water ice. Periphery NPRC ices are the warmest and see the most wind.

Our work is already suggesting that a significant amount of atmospheric water, when it is transported over the colder interior of the NPRC (after being released from the warmer NPRC periphery), is quickly deposited back onto the colder central NPRC ices. The sharp meridional gradient of NPRC temperature is certainly related to the sharp gradient in NPRC albedo. This is a field that will get a great deal of attention, so that this work can eventually move into the higher resolution studies we are intending to perform.

Finally, we have decided to implement the cloud scheme described by [3]. At the time of this writing this is where our efforts are being directed. We anticipate having many more results by the time of the Williamsburg conference and look forward to sharing thoughts with others that have already been down some of these roads...