DEVELOPMENT OF A NEW GLOBAL, SCALABLE AND GENERIC GENERAL CIRCULATION MODEL FOR STUDIES OF THE MARTIAN ATMOSPHERE

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Introduction: We present here results from a new atmospheric model—'Planet-WRF'—that is based upon the terrestrial mesoscale Weather Research and Forecasting (WRF) model developed primarily at NCAR (http://www.wrf-model.org). The WRF model was originally intended as a regional-scale research and forecasting tool, thus we have applied a series of core modifications to permit its use as both a global and 1-D model. Changes to timing routines and model constants were also made to allow Planet-WRF to be as generic as possible, and usable on virtually any planet. Here we introduce the Planet-WRF model, discuss in detail some specifics of the new modeling system, and present some initial results to validate the Planet-WRF model as a GCM, a large eddy simulation (LES) and a 1-D single-column model (SCM) of the martian atmosphere.

The Weather Research and Forecasting Model: The WRF model is a flexible, state-of-the-art, portable code originally designed for computationally intensive, non-hydrostatic mesoscale simulations, written in Fortran 90/95 and efficient in massively parallel computing environments. The code is highly modular, with an array of physics parameterizations available to represent a wide range of physical processes, including cloud microphysics, convection, boundary layer interactions, surface and subsurface behavior and atmospheric radiation. The choice of which modules to use can be made by the user at runtime through a namelist file, which minimizes compiling and execution time.

The dynamical core of the model solves the fully compressible primitive equations in either hydrostatic or non-hydrostatic mode, also selectable at runtime, and is both highly accurate and conservative. (During our validation runs, we have found that, for example, mass is conserved to better than 1 part in 10^6 over a time period of 1000 days.) WRF also allows two-way grid nesting for the study of local regions of the planet at higher resolution. Within each time step, a higher model domain may pass boundary conditions 'down' to smaller sub-domains and assimilate this higher resolution data back into the next model time step. Multiple levels of nesting are permitted, and multiple independent sub-domains can be nested within a domain

Converting WRF to a Global Planetary Model: In its original form as a mesoscale model, WRF provides the user with a variety of map projection options, but anticipates a small spatial area, so these conformal projections assume equal scaling in both the *x* and *y* directions. This assumption simplifies the dynamical equations, however for our purposes, such an assumption will not work. In a global model, mapping to a non-conformal projection dictates that we have independent scaling in both the N-S and E-W directions, hence the dynamical equations have been re-derived with independent map scaling factors in the *x* and *y* directions, allowing for any conformal/non-conformal projection to be used, including a standard simple cylindrical GCM map projection, "rotated pole" (see below) and stretched or zoomed grids. Grid choice is made when constructing the model initial condition files—the executable is inherently non-specific with regard to the grid mapping.

To fully convert WRF from a mesoscale into a global model, we need to address the polar boundary condition, and incorporate polar filtering within the model. Polar boundary conditions have been added following the standard convention for an Arakawa C-grid model, with the pole defined as a *v*-point having zero value. Spatial operators near the pole are modified to prevent the flow of information directly over the pole. Instead, information is passed around the pole at the ½ offset *u* locations. The requisite Fourier filtering is applied in the polar regions to remove high frequency information and damp instabilities that will otherwise arise. This permits us to use a reasonable model timestep despite the small longitudinal grid spacing in the high latitudes.

To better study the polar regions without the issue of filtering, Planet-WRF provides the capability of rotating the numerical "pole" to any arbitrary orientation off the spin axis. For polar investigations, this is particularly useful as the numerical singularity at the pole is removed completely from the domain of interest.

Lastly, converting WRF to a generic planetary model requires modification to the system of "time" to account for the different definition of the day and year on other planets. An alternate calendar system has been introduced, based upon planetocentric solar longitude, to allow for arbitrary planetary orbits. In addition, a central module was designed to hold all relevant physical constants for any planet, which are used to define the planetary calendar, and also basic physical properties such as orbital position, gravity, *etc.* Selection of the proper planetary constants is made at compile time through the designation of an appropriate flag.

Converting WRF to a 1-D Model: WRF can be used as a one-dimensional model by appropriate setup of the WRF initial condition and namelist files, without modification to the model code or executable itself. This has significant advantages, since new physical process schemes can be developed without need of a separate 1-D version of Planet-WRF. In this one-dimensional mode, a runtime option to use "perturbation Coriolis" allows for the specification of a large-scale geostrophic wind system which permits the full wind to generate appropriate frictional drag while the ageostrophic component is allowed to experience local Coriolis deflection—this is standard for 1-D PBL models. The 1-D model can be used as a boundary-layer model using detailed PBL parameterizations (several options are available within the standard WRF release), or as a global-mean model.

The Planet-WRF SCM uses a modified version of the GCM initialization routine, allowing user specification of surface thermal and physical properties, the model vertical structure (currently 25 or 40 layers), the geostrophic "background" and initial winds, temperature and other tracer fields. For our Mars experiments, we incorporate values from Haberle *et al.* (1993) as our initial conditions.

Converting WRF to a Large Eddy Model: WRF has been further modified to allow its use as an LES model. A simple surface heat flux system is implemented, and the subgrid scale diffusion of heat, momentum and tracers in the atmosphere is treated using the standard Smagorinsky scheme. In LES mode, WRF is typically run in a doubly periodic configuration. To date, we have used meshes of roughly 100x100x100 grid boxes.

Validation: A prescription for thermal forcing and frictional drag was proposed by Held and Suarez (1994) to test and intercompare dynamical cores of climate models. This "Held-Suarez" forcing has since become a *de facto* benchmark for dynamical cores, and was used to validate the Planet-WRF global model dynamical core in comparison with published results of other models.

The Planet-WRF GCM was run for 1200 days as an Earth model using the Held-Suarez forcing. The final 1000 days were averaged to yield the '*WRF GCM*' panels in Fig. 1. Both zonal-mean temperature and zonal-mean zonal wind are shown as a function of the σ-vertical coordinate. The results compare favorably with those presented by Held and Suarez. Eddy diagnostics were also generated, compared and found to agree well with the benchmark Held-Suarez result.

Results from Planet-WRF: Following are some preliminary results from the Planet-WRF architecture for Mars, in SCM, LES and GCM mode:

1-D SCM Results: WRF has several options for representation of diffusive mixing in the planetary boundary layer. Results of a Mars simulation with the MRF scheme are shown in Fig. 2 for a 1-D Planet-WRF run designed to emulate Fig. 2 of Forget *et al.* (1999). The Planet-WRF PBL is a little deeper than simulated by LMD, but the two models agree very well on wind speed and structure.

Global, 3-D Results: To this point, the results we have obtained during our diagnostic and debugging phase have been excellent. An example of the output of this model for a Mars simulation is found in Fig. 3. We see temperature, wind speed and mass streamfunction at three times of year, and the output has been compared to both the GFDL and Oxford Mars GCMs (not shown) with positive results. Temperature and wind fields have also been compared with MGS zonal-mean TES results with an encouraging similarity.

LES Results: Large eddy simulations are notoriously computer-intensive calculations to perform, although they are extremely valuable as tools to understand basic boundary layer behavior, including convection and boundary layer mixing. Because of the parallel nature of the WRF code, we can take advantage of high-end computing clusters to split the problem across several computational nodes, proportionally speeding up execution time. In Fig. 4, we see an example of an LES during the early morning hours at 45°N latitude, showing the onset of convection in map view (Fig. 4a) and in vertical cross-section (Fig. 4b).

Future Work: We are currently incorporating improved radiation and microphysics schemes into the model in order to consider a wider range of atmospheric conditions throughout martian history. We have introduced a new radiation scheme based upon the Hadley Centre two-stream model, but incorporating the correlated-*k* method. While somewhat slower than the wideband models typically used in Mars GCMs, it provides the added benefit of accommodating multiple absorbing gases in the atmosphere—a feature especially beneficial when studying putative warm, wet early Mars conditions, or alternate atmospheric compositions.

We are also adding a microphysics scheme based on Toon *et al.* (1988). The nucleation rate of water ice particles is calculated based on the ice nuclei radius (dependent upon the observed particle size distribution in the atmosphere), with the saturation ratio and growth rate due to water vapor diffusion. This provides the size distribution of created water ice particles, which is important for the sedimentation rate of cloud particles and radiation field.

References: Haberle *et al., J. Atmos. Sci.*, **50**, 1544-1559, (1993); Held and Suarez, *Bull. Am. Met. Soc.*, **75**, 1825-1830, (1994); Forget *et al.*, *J. Geophys. Res.*, **104**, 24,155-24,175, (1999); Mellor and Yamada, *Rev. of Geophys.*, **20**, 851-875, (1982); Toon *et al., J. Atmos. Sci.*, ,**45**, 2123-2143, (1988).

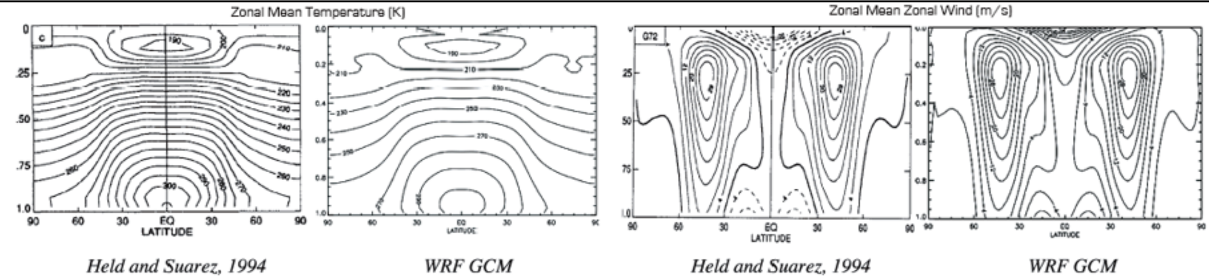

Figure 1: Comparison of the Held-Suarez results for zonal mean temperature and zonal mean zonal wind with Planet-WRF output under the same conditions. Comparatively, the Planet-WRF results are quite good.

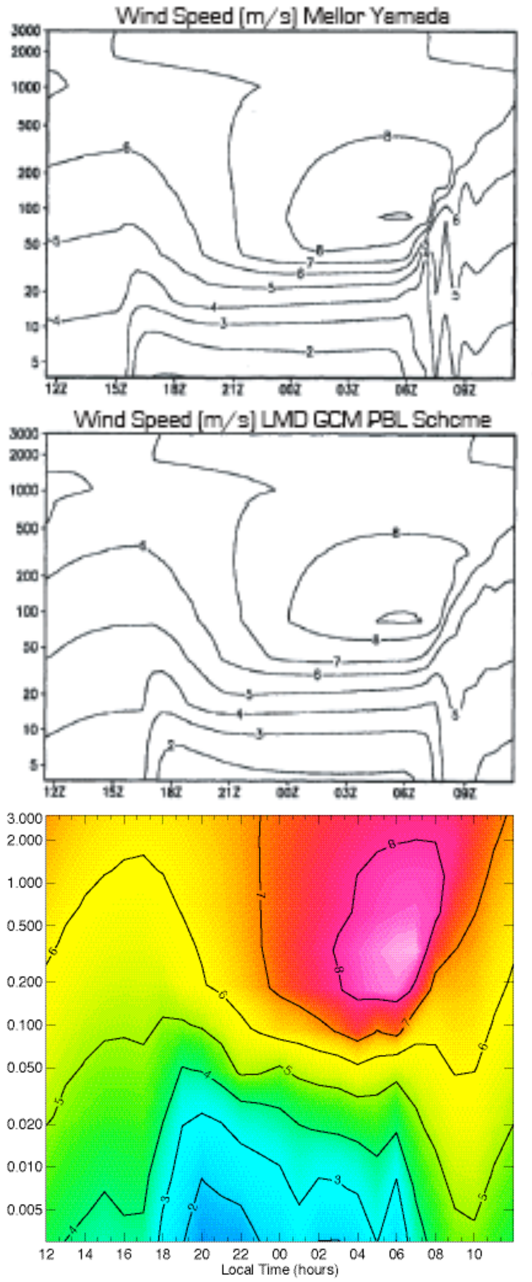

Figure 2: Results from the Planet-WRF SCM (bottom panel) measuring horizontal wind speed (magnitude only) compared with similar results from Mellor and Yamada (1982) (top panel) and Forget *et al.* (1999) (middle panel).

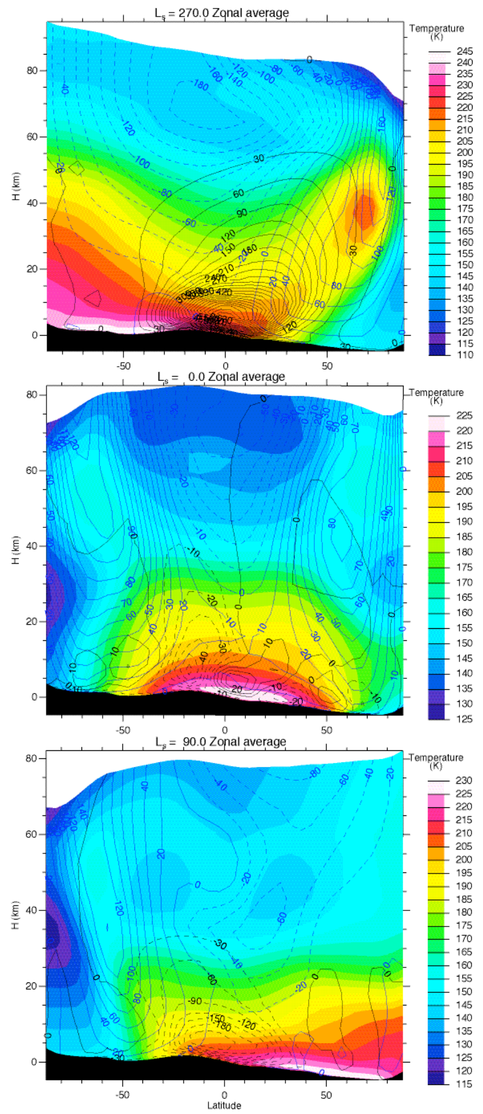

Figure 3: Three snapshots in time from Planet-WRF GCM output showing mass streamfunction (solid contours), windspeed (dashed contours) and atmospheric temperature (shading) at northern winter solstice (top), spring equinox (middle) and summer solstice (bottom) on Mars. Reproduction of the Hadley circulation is quite good, and temperature profiles match those from TES during the same time period.

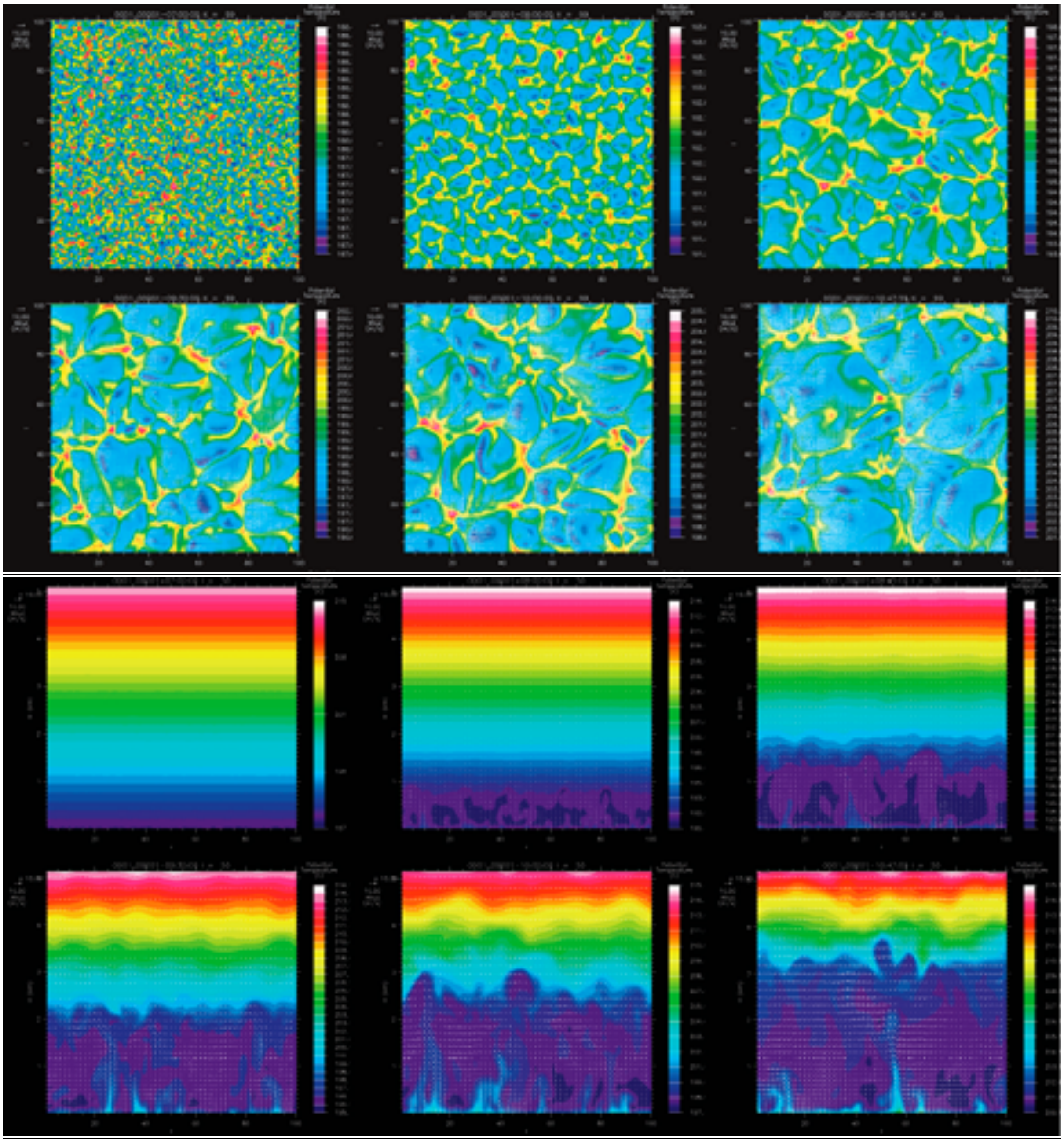

Figure 4: Output from the Planet-WRF in LES configuration showing the onset of convection during the early morning hours at 45°N latitude. Map view is illustrated in top two rows, and a vertical cross-section through the domain in the bottom two rows. Shading indicates potential temperature, with warmer colors indicating higher temperatures. The initial condition (top left) has been seeded with random perturbations to remove symmetry in the domain. The presence of low-level thermal plumes is quite evident in the lower three panels.