Planetary and Global WRF.

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Introduction.

PlanetWRF is a version of the WRF (Weather, Research and Forecasting) model that has been adapted for global and planetary research. We chose to adapt WRF (at that time a mesoscale model only) to be planetary and global, rather than adapting an existing global model, because of the benefits associated with WRF's one- and two-way nesting features, its modular structure, and its highly parallelized framework. The publicly released WRFv3 and later versions include the global modifications (see below) and these can be selected at compile time.

PlanetWRF is currently run for simplified Earth cases (such as with the standard Held-Suarez forcing used for testing of dynamical cores) but is primarily being used for simulating the climate and weather on Mars, Venus and Saturn's moon Titan. PlanetWRF is freely available from our website at www.planetwrf.com, with this publicly released version including basic Mars physics (described further below). Downloading planetWRF consists of first downloading WRFv3.0.1.1 from the NCAR website, then downloading a 'patch kit' of modified and new files from www.planetwrf.com. As the publicly released WRF model now includes the global modifications, the 'patch kit' includes only planetary changes, with the planet then chosen at configure time.

Global WRF.

To globalize WRF we needed to enable the 'mother' domain to cover the entire planet, stretching from pole to pole, which required a switch to a cylindrical (longitude-latitude) map projection. Previous map projections in WRF had been conformal, meaning that at all locations the 'map scale factors,' m (the ratio between the coordinate and physical spacing) were the same in the x and y directions. For a cylindrical map projection, however, the distance between equally spaced longitude points varies with latitude, whereas the distance between equally spaced latitude points does not. Hence m becomes m_x or m_y. Map scale factors appear frequently in the dynamical equations to convert between coordinate and physical space, so in all cases we needed to decide which was required – m_x or m_y – and in addition, we had to re-insert them where they previously cancelled out.

Another issue that arises in a global model (at least, one using cylindrical coordinates) is the polar boundary condition. We dealt with this initially by assuming zero velocities at the poles and no mass transport across the poles (though mass moves rapidly around the poles at high latitudes). The WRF development team has since improved this treatment, and the improved method is implemented in WRFv3.

The last major issue is the increasing proximity of points (smaller dx) equally spaced in longitude as we near the poles. This violates the CFL (Courant-Friedrichs-Lewy) criterion (for stability, dx/dt must be > the velocity of the fastest moving feature) and leads to instabilities unless dt is decreased also. However, this leads to the entire model being run with a small timestep for the sake of one or two longitude rows. One solution (and the one we implemented) is to introduce a polar filter to spatially smooth the u and v fields at high latitudes, increasing the *effective* value of dx there and allowing a larger dt to be used overall. There are several choices for how to do this, and we currently use as our default a filter that turns on at 45° and smooths progressively more and more towards the poles.

Planetary WRF.

A change common to all planetary runs involves the clocks and calendar routines and their link to solar forcing. We define planetary hours as 1/24 of a solar day, and planetary seconds as 1/(24x60x60) of a solar day, and use these to define timestep, run length etc. in the namelist file. Within planetWRF, however, we convert all times to SI units. We calculate the position of the sun by defining the orbital parameters (obliquity, eccentricity etc.) and then calculating the planetocentric solar longitude (L_s) for the number of seconds elapsed since perihelion (where L_s=0° is northern spring equinox, 90° is northern summer solstice, and so on).

For Mars, we have included full topography and surface variations in albedo and thermal inertia; a full radiative transfer scheme to deal with the passage of sunlight and thermal radiation through a thin, dusty, carbon dioxide atmosphere at temperatures from ~140 to 330 K; a boundary layer scheme to mix momentum, heat and tracers through the planetary boundary layer; a sub-surface scheme to deal with conduction of heat through the martian regolith; and a CO_2 sublimation/condensation scheme to deal with the annual transfer of CO_2 between the (primarily polar) surface and atmosphere.

Results from the MarsWRF model are shown in Richardson *et al.* [2007] and on the planetWRF website, where diagnostics and screenshots are provided both to enable users to verify their implementation of the planetWRF code, and to demonstrate that planetWRF produces a realistic martian climatology and captures the observed surface pressure cycle. We present selected results section below.

For Titan, we have included a full radiative transfer scheme to deal with the passage of sunlight and thermal radiation through a thick, hazy, nitrogen-methane atmosphere at temperatures from ~65 to 230 K; additional terms in the dynamical equations to model the effects of Saturn's gravity on Titan's atmosphere (producing 'tides'); a boundary layer and sub-surface scheme; and a methane cloud scheme to simulate the formation and rainout of methane ice, methane liquid and binary methane / nitrogen clouds in Titan's troposphere. Results from the TitanWRF model are shown in Richardson *et al.* [2007] but since then we have improved our representation of Titan's superrotating stratosphere, and we present these and other results below.

Results from MarsWRF.

Figure 1 shows horizontal wind speeds in the lowest level (~100m above the surface) for a high resolution (0.5 x 0.5°) global simulation of Mars during northern winter (L_s=270°). In this simulation the peak wind speeds are controlled by the position of the single solsticial Hadley cell (rising in the summer hemisphere, leading to cross-equatorial flow from north to south near the surface, with equatorial easterlies and strong westerlies at ~30° south), the strong baroclinic wave activity in the winter hemisphere, and the presence of major topographic gradients (including the Tharsis volcanoes around 120° west and the Hellas basin centered at 90° east, 45° south).

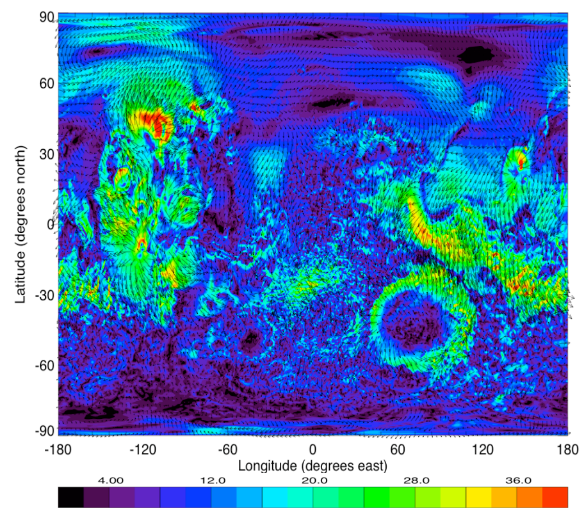

Figure 1: Horizontal wind speed (shaded) and vectors (arrows) in the lowest model level at the end of northern winter on Mars. For clarity, only every 6th wind vector is shown. Note the level of detail in this 0.5° resolution run; also note the peak wind speeds tied to major topographic features (see text for details) and the strong baroclinic wave activity in the winter hemisphere.

Figure 2 shows results from the same global simulation, but now zoomed into the Valles Marineris region (which is several km deep) to show how winds and surface temperatures are affected by the significant topography but also by the presence of strong thermal tides on Mars. The high temperatures to the east of the plot result from the sun being about to pass overhead. Similar results are obtained in a two-way nested MarsWRF run for a fraction of the computational cost.

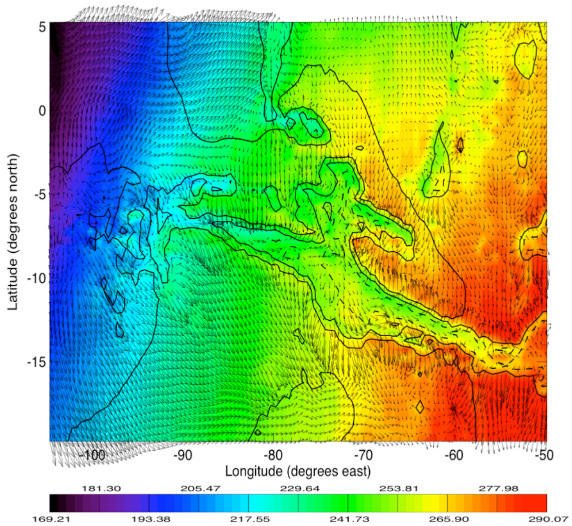

Figure 2: Surface temperature (shaded) and horizontal wind in the lowest model level (arrows), zooming in on Valles Marineris in the simulation shown in Figure 1. Topography is shown by the black contours.

Results from TitanWRF.

Initial simulations with TitanWRF were unsuccessful in reproducing the observed strong mid-latitude stratospheric jets or equatorial superrotation. However, as shown in Figure 3, we have recently made good progress in solving this problem. We discovered that the horizontal diffusion in TitanWRF – the same Smagorinsky scheme with the default value of the Smagorinsky parameter (c_s) as used for Earth and Mars – was too strong, and was mixing momentum too much and preventing the development of barotropic eddies that move from low to high latitudes and in doing so transfer momentum towards their source region (around the equator). The simulation shown in Figure 3 has zero horizontal diffusion, and eventually crashes due to polar instabilities, but we are currently tuning the model to determine the appropriate value of c_s for Titan.

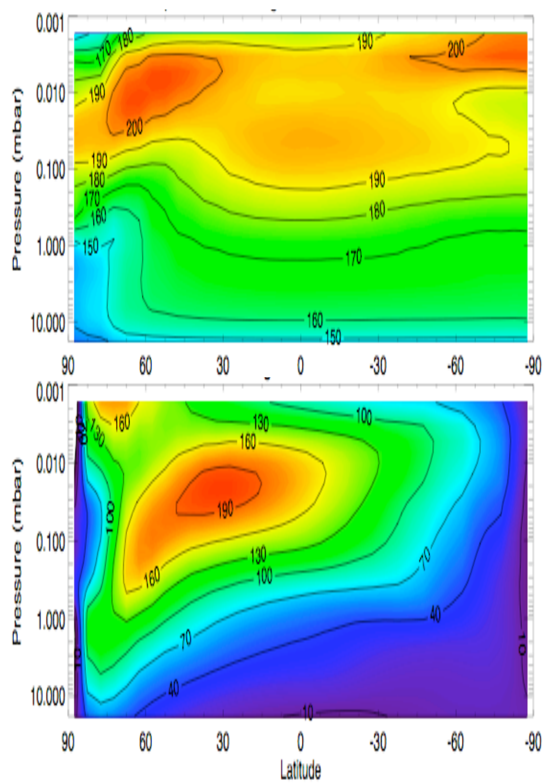

Figure 3: Stratospheric zonal mean temperature (top) and zonal wind (bottom) in northern winter for a global Titan simulation. These results compare reasonably well with thermal observations (and inferred zonal winds) made in the same season by the Cassini CIRS instrument (Achterberg *et al*., 2008). Note the strong winter hemisphere temperature gradients and jet, and the strong equatorial superrotation that requires up-gradient angular momentum transport, probably by barotropic eddies.

Figure 4 shows zonal-mean results as a function of latitude and time of year from a TitanWRF simulation running with a methane cycle. More methane evaporates during southern summer (L_s~270°) because perihelion occurs during this period (hence southern summer is warmer than northern summer) so the near-surface atmosphere is warmer and can hold more methane vapor. Methane is transported by advection, then precipitates out in spring (as methane accumulates at the cold poles) and where upwelling peaks (moving from pole to pole with season). The overall effect is a slight net transfer of surface methane from south to north, which is consistent with observations of methane-filled lakes in the northern polar regions but not the south.

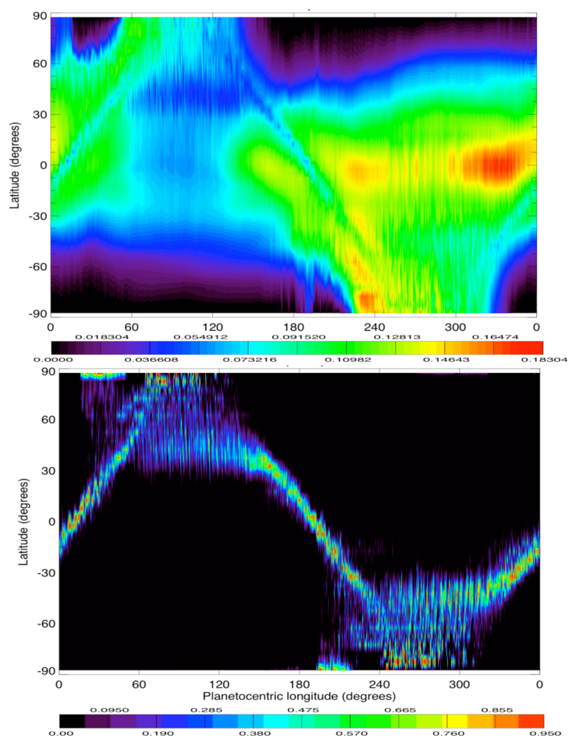

Figure 4: Factors in the re-distribution of liquid methane on Titan's surface: surface evaporation of methane (top) and surface precipitation of methane (bottom) in mm per Earth hour.

Ongoing work.

Although not funded to work further on the planetWRF public release, we do aim to improve the tools and assistance available to our users, and appreciate feedback and suggestions. You can download planetWRF and contact us via www.planetwrf.com.

Certain issues still prevent us making the most of planetWRF, the dominant one being problems with the existing tracer advection schemes. In a global model run for climate simulations (from decades to hundreds of Earth years) it becomes particularly important to ensure conservation of mass. *E.g.* for Mars a major research area is atmospheric dust. Dust is lifted from the surface – as a background effect or in a highly concentrated way during dust storms – and once aloft it strongly influences atmospheric radiative transfer and thus the entire circulation. Negative dust amounts introduced during advection become harder to deal with when a polar filter is involved. In addition, we want to keep track of sources and sinks of surface dust over several years, so we need a positive-definite advection scheme with excellent mass conservation.

For Titan the problem is more fundamental – methane condenses out of the atmosphere due to a 'cold trap' in the form of the tropopause (where the temperature drops to ~70 K) with very little penetrating into the stratosphere. However, the resulting sharp gradients in methane mixing ratio have proved difficult for the present advection scheme to maintain, leading to large amounts of methane crossing the barrier in artificial jumps and producing an unrealistic end state. We are currently working on a new positive definite, mass conserving advection scheme based on the Bott [1989] method, as adapted by Easter [1993] and implemented on the sphere by Li and Chang [1996], which we hope will prevent (or at least lessen) some of these problems.

References.

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