DEMONSTRATION OF A GCM FOR MARS, GJ 1214B, PLUTO, AND TRITON Angela M. Zalucha[1],
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Introduction: General circulation models (GCMs) are global models of the atmosphere that are particularly useful in planetary science where measurements, especially of wind, may be sparse in space and time. The Massachusetts Institute of Technology (MIT) GCM dynamical core, in conjunction with the appropriate radiative transfer (RT) schemes, has been adapted to simulate the atmospheres of many planetary bodies to date, including: Mars, super-Earth GJ 1214b, Pluto, and Triton. Current applications of these versions of the GCM will be demonstrated here.

GCM Configuration: The dynamical core of the MIT GCM solves the fundamental equations of geophysical fluid dynamics in 3D using a finite volume method on an Arakawa C-grid [1] on a sphere. The model atmosphere is hydrostatic and compressible, and may exchange mass with the surface via a source/sink term in the continuity equation. Convective adjustment is performed on the temperature profiles to prevent superadiabatic temperature profiles. The default configuration has neither viscosity nor vertical diffusion, but uses an eighth-order Shapiro filter to remove purely numerical noise. In the horizontal a cubed-sphere grid [2] with 32 × 32 points per cube face is used, equivalent to a grid spacing of 2.8° at the equator.

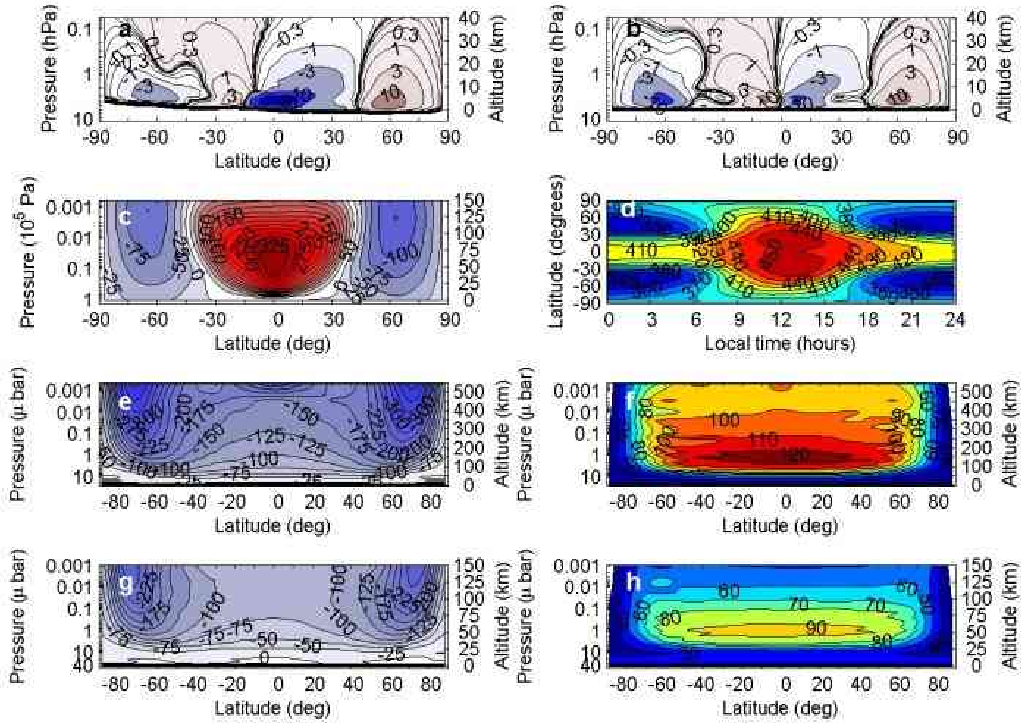
The vertical grid is an η coordinate [3] based in atmospheric pressure and is scaled according to the prescribed global mean surface pressure. It is assumed that the gravitational acceleration is constant with height. Surface boundary layer friction is represented by a drag law (linearly dependent on the horizontal velocity) that decreases with height, reaches zero at the top of the boundary layer, and is zero at all levels above. Rayleigh friction is present at the top of the atmosphere to damp interactions with the model top boundary (except in the Pluto/Triton case, where nonzero Rayleigh friction produced a poorer match with stellar occultation data). Measured surface topography is used when known (Mars only). Surface albedo and surface thermal inertia are constant globally.

Application:

Mars. The Martian topography is 5 km higher in the Southern Hemisphere than in the Northern hemisphere[4], which produces equatorial and seasonal asymmetries in the Hadley cell strength and locations[5, 6]. To investigate this behavior (Fig. 1a,b), Zalucha et al. (2010)[7] adapted the MIT GCM to Mars. In that work the model was used to determine a radiative-convective equilibrium state using Newtonian relaxation of the thermal field and a relatively simple RT parameterization (gray at long wavelengths and diurnally-averaged insolation). Whenever the temperature dropped below the freezing point of CO_2, the temperature was immediately set to the CO_2 ice saturation temperature (emulating the release of latent heat due to CO_2 condensation), but no mass was removed from the atmosphere. The surface temperature was assumed to be in radiative equilibrium. This Mars GCM has since undergone further improvements. First, the surface and atmosphere may now exchange mass. Secondly, the thermal heating rates are specified directly (instead of the Newtonian relaxation method) using a semi-gray RT scheme[8] and the diurnally varying insolation is now included. Finally, the surface is modeled as a single slab of finite thickness with a nonzero thermal inertia. Currently, a dust heating/cooling rate is being added to the RT scheme.

GJ 1214b. GJ 1214b is a tidally-locked, super-Earth (mass 6.556±0.98$M_\oplus$, radius 2.6786±0.13$R_\oplus$[9]) exoplanet that orbits closely to its parent star. Observations suggest that the atmosphere is consistent with a H_2O vapor atmosphere[10]. Zalucha et al. (2012)[11] used the MIT GCM to simulate the circulation of GJ 1214b assuming a solid (rocky) surface, H_2O vapor atmosphere, and zero obliquity. The RT scheme is gray at long wavelengths with optical depth linearly dependent on pressure. A variety of global mean surface pressures (10^4 – 10^7 Pa) and surface albedos (0.1–0.7) were tested. Figure 1 (c,d) shows that a westerly jet is present aloft at the equator and that the longitude of maximum temperature on the equator is shifted eastward of the substellar point (consistent with simple theoretical calculations[12]).

Pluto and Triton. Pluto's enigmatic atmosphere has undergone numerous studies focusing on temperature and pressure, but only recently are GCMs being developed to simulate Pluto's circulation in addition to these variables. Zalucha and Gulbis (2012)[13] have begun development of a Pluto GCM in 2D mode (latitude, pressure, and time). A simple RT scheme is used[14] that calculates non-local thermodynamic equilibrium heating and cooling by CH_4 at 3.3 μm and 7.6 μm, respectively. The temperature was fixed at the N_2 freezing temperature; at present, surface-atmosphere mass exchange is not allowed. Figure 1(e,f) shows high-speed, prograde jets that encircle the poles, and a temperature inversion persists at low altitudes (expected from radiative-conductive equilibrium calculations). The development of the Pluto GCM is multifold. 3D simulations are already being carried



out, which show a significant day-night component to the flow. Next, the surface-atmosphere mass exchange will be turned on, and an extensive analysis of the effect of various surface ice parameters on the atmospheric circulation will be assessed. The RT scheme has been augmented with a troposphere, making it appropriate for Triton[15]. Figure 1 (g,h) show the results of temperature and zonal wind from a 2D version of the Triton model. The Pluto model will be useful for interpreting observations of Pluto by the *New Horizons* spacecraft in 2015, and could also be applied to KBOs with similar atmospheres if discovered in the future.

References: [1] J. Marshall, et al. (1997) *J Geophys Res* 102:5753. [2] A. Adcroft, et al. (2004) *Mon Wea Rev* 132:2845. [3] A. Adcroft, et al. (2004) *Ocean Modelling* 7:269. [4] D. E. Smith, et al. (1999) *Science* 284(5419):1495. [5] M. I. Richardson, et al. (2002) *Nature* 416:298. [6] Y. O. Takahashi, et al. (2003) *J Geophys Res* 108(E3) [7] A. M. Zalucha, et al. (2010) *J Atmos Sci* 67:673. [8] R. Caballero, et al. (2008) *Quart J Roy Meteor Soc* 134:1269. [9] D. Charbonneau, et al. (2009) *Nature* 462:891. [10] Z. K. Berta, et al. (2012) *Astrophys J* 747:35. [11] A. M. Zalucha, et al. (2012) *Icarus* submitted. [12] A. P. Showman, et al. (2011) *Astrophys J* 738:71. [13] A. M. Zalucha, et al. (2012) *J Geophs Res - Planets* in press. [14] R. V. Yelle, et al. (1989) *Nature* 339:288. [15] E. C. Stone, et al. (1989) *Science 246:1417.*

Figure 1: Demonstration of GCM capabilities. (a) Zonal and time averaged mass stream function (10^8 kg s^{-1}; positive is counterclockwise flow) from 3D Mars GCM at L_s = 0 and with MOLA topography[4]. The Southern Hemisphere cell is stronger than the Northern and the latitude of the dividing streamline (i.e., 0 value) is located at −15º latitude. (b) Same as (a) but with flat topography. The strengths are now equal and the latitude of the dividing streamline is located at the equator. (c) Zonal and time averaged zonal wind (m s^{-1}) from GJ 1214b 3D GCM assuming a global mean surface pressure of 10^5 Pa and a surface albedo of 0.4. The winds are westerly at the equator and easterly in the midlatitudes. (d) Time averaged temperature on GJ 1214b on the 680 Pa level (about 62 km altitude) assuming a global mean surface pressure of 10^5 Pa and a surface albedo of 0.4. The equatorial temperature maximum is shifted eastward of the substellar point (located at 12 hours local time). (e) Time averaged zonal wind (m s^{-1}) from 2D Pluto GCM on 12 June 2006 assuming 24 μbar global mean surface pressure and 1% CH_4 mixing ratio. The winds are everywhere easterly (i.e. prograde with Pluto's rotation) and in cyclostrophic balance. (f) Temperature field corresponding to panel (e). Pluto has a near-surface temperature inversion. (g) Time averaged zonal wind (m s^{-1}) from 2D Triton GCM on 4 November 1997 assuming 40 μbar global mean surface pressure, 0.0245% CH_4 mixing ratio, 52 K surface temperature, and a critical troposphere depth of 25 km. The winds have the same structure as Pluto but are weaker. (h) Temperature field corresponding to panel (g). The atmosphere of Triton is colder than Pluto because of the lower CH4 mixing ratio.