Extraterrestrial CAM

MarsCAM

This model was developed from CAM Version 3.1 by Prof. Brian Toon's research group at the University of Colorado (http://lasp.colorado.edu/home/aerosol/?doing_wp_cron=1439076916.8070240020751953125000). CAM's radiation transport algorithm is replaced by one suitable for a carbon dioxide atmosphere, and cycling of carbon dioxide between the surface and atmosphere is allowed. With time-invariant dust aerosols prescribed to be consistent with observations, the model achieves reasonable agreement with observed variations of temperature and surface pressure. It also can achieve agreement with the observed hydrologic cycle by "tuning" the polar cap albedo. Simulated early Mars climates are highly sensitive to assumed water-ice cloud properties. See the two 2013 papers in Icarus by R. A. Urata and O. B. Toon:

"A New General Circulation Model for Mars Based on the NCAR Community Atmosphere Model" (http://adsabs.harvard.edu/abs/2013Icar..226..336U)

"Simulations of the Martian Hydrologic Cycle with a General Circulation Model: Implications for the Ancient Martian Climate" (http://adsabs.harvard.edu/abs/2013Icar..226..229)

Subsequent work has added interactive aerosols to the model, using the Community Aerosol and Radiation Model for Atmospheres (CARMA). See the 2014 Mars Conference abstract by V. L. Hartwick and O. B. Toon:

"A Mars Dust Model with Interactive Dynamics, Radiation, and Microphysics" (http://www.hou.usra.edu/meetings/8thmars2014/pdf/1152.pdf)

VenusCAM

Published versions of this model use an idealized thermal forcing that "pushes" temperatures toward observed values (Held and Suarez, BAMS 1994). In VenusCAM the resulting time-averaged circulation is dominated by high altitude super-rotation, as observed, but the super-rotation's magnitude and its vertical extent are both weaker than observed. These problems are typical of Venus GCM simulations (see Lebonnois et al. in *Towards Understanding the Climate of Venus: Applications of Terrestrial Models to Our Sister Planet*, ISSI Scientific Report Series; Lennart Bengtsson, Roger-Maurice Bonnet, David Grinspoon and Symeon Koumoutsaris, eds., 2013). Oscillations of the wind with a period of about 10 Earth-years are also prominent. See H. F. Parish, G. Schubert, C. Covey, R. L. Walterscheid and A. Grossman, 2011: "Decadal Variations in a Venus General Circulation Model," Icarus 212: 42-65 (http://www.sciencedirect.com/science/article/pii/S0019103510004343). Documentation on running this version of VenusCAM is available at https://e-reports-ext.llnl.gov/pdf/802655.pdf.

Subsequent work has involved collaboration with Sebastien Lebonnois, creator of the LMD Venus GCM. Relaxation of VenusCAM's simplifying assumptions and reduction of parameterized sub-grid scale momentum diffusion produce noticeably different circulations, in some cases agreeing better with observations, but decadal oscillations are still present. Also, the atmospheric angular momentum budgets of both the LMD model and CAM contain surprisingly large inaccuracies for not only Venus but also for Titan and Earth. These results suggest that a more careful examination of angular momentum in terrestrial GCMs is warranted. See S. Lebonnois, C. C. Covey, A. S. Grossman, H. F. Parish, G. Schubert, R. L. Walterscheid, P. H. Lauritzen and C. Jablonowski, 2012: "Angular Momentum Budget in General Circulation Models of Superrotating Atmospheres: A Critical Diagnostic," JGR Planets, 117, E12004, doi:10.1029/2012JE004223 (http://onlinelibrary.wiley.com/doi/10.1029/2012JE004223/abstract).

Follow-up work with the Earth version of CAM shows that substituting the default finite element (FV) dynamical core with a newer spectral element (SE) dynamical core greatly improves the model's conservation of angular momentum: "the spurious sources/sinks of AAM in CAM-SE are 3 orders of magnitude smaller than the parameterized (physical) sources/sinks." See P. H. Lauritzen, J. T. Bacmeister, T. Dubos, S. Lebonnois and M. V. Taylor, 2014: "Held-Suarez Simulations with the Community Atmosphere Model Spectral Element (CAM-SE) Dynamical Core: A Global Axial Angular Momentum Analysis Using Eulerian and Floating Lagrangian Vertical Coordinates, *JAMES* 2014 (http://onlinelibrary.wiley.com/doi/10.1002/2013MS000268/abstract).

TitanCAM

The original version of this model was published by A. J. Friedson, R. A. West, E. H. Wilson, F. Oyafuso and G. S. Orton in 2009 ("A Global Climate Model of Titan's Atmosphere and Surface," Planetary and Space Science 57: 1931-1949; http://www.sciencedirect.com/science/article/pii/S0032063309001500). It has been updated to include the microphysical aerosol package CARMA (see above) which treats the aerosol particles as fractal aggregates. The aerosols are coupled to the dynamics as well as the radiation package. TitanCAM has been used to determine microphysical properties of Titan's aerosol particles, such as size, shape, electrical charge, and production rate. It reproduces the detached haze layer observed on Titan and its seasonal variation in altitude. An ad hoc acceleration term that forces the zonal winds toward observed values has been added. This artificial acceleration allows 20 K meridional temperature gradients to form, similar to observations. There is evidence from our simulations that topography on Titan may play a role in determining the direction of the dune forming surface winds as well. See the 2014 and 2015 papers in Icarus by E. J. L. Larson, O. B. Toon, R. A. West and A. J. Friedson:

Simulating Titan's aerosols in a three- dimensional global circulation model (http://www.sciencedirect.com/science/article/pii/S0019103514004655)

Microphysical modeling of Titan's detached haze layer in a 3D GCM (http://www.sciencedirect.com/science/article/pii/S0019103515001104)

TitanCAM is not yet able to reproduce the strong super-rotation observed in Titan's atmosphere without artificial acceleration. This is a common problem with Titan atmosphere GCMs. One possible avenue of improvement for TitanCAM is to use CAM's new spectral element dynamical core, which conserves angular momentum much better than the default dynamical core (cf. above remarks on VenusCAM). See Larson's presentation at the joint Atmosphere / Whole Atmosphere Working Group meeting, NCAR, February 2014 (http://www.cesm.ucar.edu/working_groups/WACCM/Presentations/2014/larson.pdf).

SaturnCAM

See A. J. Friedson and J. I. Moses, 2012: "General Circulation and Transport in Saturn's Upper Troposphere and Stratosphere," Icarus 218: 861-875 (http://www.sciencedirect.com/science/article/pii/S0019103512000437).

Deep Paleo / Exoplanet CAM

CAM has also been used to simulate Earth-like atmospheres important for deep paleoclimate and exoplanetary studies. The common theme amongst these studies is planetary habitability. What atmospheric conditions are suitable for maintaining abundant liquid surface water and thus life? Studies have focus on varying the solar forcing, atmospheric CO_2, and rotation rate.

In 2013, the radiative transfer code was replaced entirely, in favor of a correlated-*k* scheme. We use HITRAN 2004 derived absorption coefficients for high-CO_2, high-CH_4 anoxic atmospheres that occurred during the Archean period of Earth's history (3.8 to 2.5 Ga) (Wolf & Toon, 2013; Wolf & Toon, 2014b).

In 2015, the numerical solver for the entropy calculation within the Zhang-MacFarlane deep convection scheme was improved (courtesy C.A. Shields, *NCAR*), and the temperature space for the correlated-*k* absorption coefficients were expanded to higher temperatures. These changes facilitated successful simulations of moist greenhouse atmospheres, with mean surface temperatures up to ~365 K, and water vapor partial pressures up to ~0.2 bar (Wolf & Toon 2015)

In 2016, we included H_2O absorption coefficients using HITRAN 2012, and also incorporated new water-vapor continuum coefficients. Furthermore, numerical stability was improved by “dribbling” of *U, V,* and *T* physics tendencies through the dynamics substeps (courtesy of C. Bardeen, *NCAR*).

Concurrently, several studies have used standard configurations of CAM to study tidally locked aquaplanets (Yang et al. 2013; Yang et al. 2014; Kopparapu et al. 2016).

Here, we have included a set of simple instructions, along with the relevant SourceMods files, and initial conditions files to run Exoplanet CAM starting from CESM version 1.2.1.

NOTE: *ExoCAM_cesm1.2.1.tar* file included here will no longer be updated as of 5/19/2018. For all future updates, see the Github distributions, and email me eric.wolf@colorado.edu

https://github.com/storyofthewolf/ExoCAM https://github.com/storyofthewolf/ExoRT

Deep paleoclimate papers

E.T. Wolf and O.B. Toon, 2013: "Hospitable Archean Climates Simulated by a General Circulation Model." *Astrobiology* 13(7) 1-18, http://online.liebertpub.com/doi/pdf/10.1089/ast.2012.0936

E.T. Wolf and O.B. Toon, 2014a: "Controls on the Archean climate system investigated with a global climate model." *Astrobiology* 14(3) 241-252, http://online.liebertpub.com/doi/pdf/10.1089/ast.2013.1112

Moist greenhouse/future Earth papers

E.T. Wolf and O.B. Toon, 2014b: "Delayed onset of runaway and moist greenhouse climates for Earth." *Geophys. Res. Lett.* 41, http://onlinelibrary.wiley.com/doi/10.1002/2013GL058376/full

E.T. Wolf and O.B. Toon, 2015: "The evolution of habitable climates under the brightening Sun." *JGR-Atmospheres* 120(12) 5775-5794, http://onlinelibrary.wiley.com/doi/10.1002/2015JD023302/full

Tidally locked planets around M dwarf stars papers

J. Yang, N.B. Cowan, and D.S. Abbot, 2013: "Stabilizing cloud feedback dramatically expands the habitable zone of tidally locked planets." *The Astrophysical Journal Letters*, 771, L45, http://iopscience.iop.org/article/10.1088/2041-8205/771/2/L45/pdf

J. Yang, G. Boue, D. C. Frabrycky, and D. S. Abbot, 2014: "Strong Dependence of the Inner Edge of the Habitable Zone on Planetary Rotation Rate." *The Astrophysical Journal Letters*, 787, L2, http://arxiv.org/pdf/1404.4992v1.pdf

R.k. Kopparapu, E.T. Wolf, J. Haqq-Misra, J. Yang, J.F. Kasting, V. Meadows, R. Terrien, & S. Mahadevan, 2016: "The Inner Edge of The Habitable Zone For Synchronously Rotating Planets Around Low-Mass Stars Using General Circulation Models." *Astrophysical Journal Letters* 819:84 (14pp), http://iopscience.iop.org/article/10.3847/0004-637X/819/1/84/pdf

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