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Exoplanet Climate Group

Exploring the Inner Edge of the Habitable Zone with Fully Coupled Oceans

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http://www.giss.nasa.gov/projects/astrobio

Abstract

The role of rotation in planetary atmospheres plays an important role in regulating atmospheric and oceanic heat flow, cloud formation and precipitation. Using the Goddard Institute for Space Studies (GISS) three dimension General Circulation Model (3D-GCM) we demonstrate how varying rotation rate and increasing the incident solar flux on a planet are related to each other and may allow the inner edge of the habitable zone to be much closer than many previous habitable zone studies have indicated. This is shown in particular for fully coupled ocean runs -- some of the first that have been utilized in this context. Results with a 100m mixed layer depth and our fully coupled ocean runs are compared with those of Yang et al. 2014, which demonstrates consistency across models. However, there are clear differences for rotations rates of 1-16x present earth day lengths between the mixed layer and fully couple ocean models, which points to the necessity of using fully coupled oceans whenever possible. The latter was recently demonstrated quite clearly by Hu & Yang 2014 in their aquaworld study with a fully coupled ocean when compared with similar mixed layer ocean studies and by Cullum et al. 2014. Atmospheric constituent amounts were also varied alongside adjustments to cloud parameterizations (results not shown here). While the latter have an effect on what a planet's global mean temperature is once the oceans reach equilibrium they do not qualitatively change the overall relationship between the globally averaged surface temperature and incident solar flux for rotation rates ranging from 1 to 256 times the present Earth day length. At the same time this study demonstrates that given the lack of knowledge about the atmospheric constituents and clouds on exoplanets there is still a large uncertainty as to where a planet will sit in a given star's habitable zone. *These results have serious implications for paleo-Venus in the Early history of the Solar System*.

- Cullum, J. Stevens, D. and Joshi, M. 2014, "The Importance of Planetary Rotation Period for Ocean Heat Transport," Astrobiology, vol 14, No. 8, pg 645
- Hu, Y. and Yang, J. 2014, "Role of ocean heat transport in climates of tidally locked exoplanets around M dwarf stars," PNAS, 111, 629
- Yang, J., Cowan, N.B. and Abbot, D.S. 2013, "Stabilizing Cloud Feedback Dramatically Expands the Habitable Zone of Tidally Locked Planets," ApJL, 771, 45
- Yang, J. et al. 2014, "Strong Dependence of the Inner Edge of the Habitable Zone on Planetary Rotation Rate," ApJL, 787, 2

Methodology & Model Inputs

Test simplified Earth model sensitivity with a limited number of parameterizations.

Ocean: Fully Coupled and 100 meter depth Q-flux ocean with fluxes set to zero..

Land Albedo: 0.2 At Model Start (AMS), No land ice (AMS), No vegetation

Obliquity & Eccentricity set to zero.

Resolution: 4 x 5 x 20 (Lat x Lon x H=height levels)

1.) Varying Atmospheric Constituents (Earth fractions or zero unless otherwise stated) and Cloud parameterizations.

N2, O3, H2O, CO2=400.0, CH4=1 ppmv

2.) Select a range of rotation periods as multiples of an Earth Sidereal Day

a.) Sidereal Days: 1x, 16x, 64x, 128, 256x, Tidally Locked.

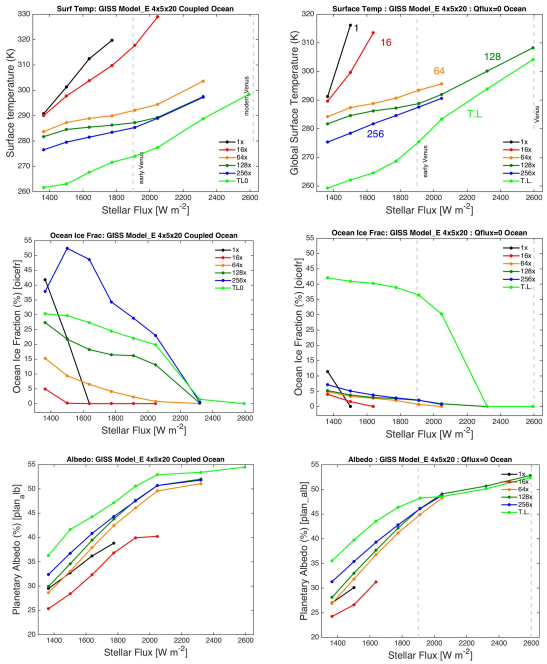
b.) Solar Days equivalent: 1x, 16.7, 76.6, 191, 848, T.L.

3.) Move to higher solar insolations (S0X) until one reaches the valid limits of the radiation code, or the limits of interest. We have attempted to reach the solar insolation incident upon present day Venus, but were not successful for all combinations.

Model Setup: N2, O3, H2O, CO2=400.0, CH4=1 ppmv, Cloud Parameterization (U00a=0.85, U00b=1, wmui_mult=5)

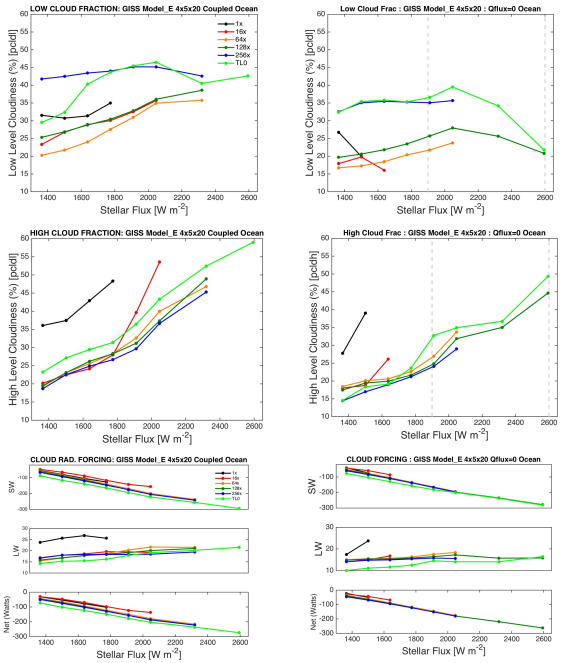
Model Output Case a: Fully Coupled Oceans

Model Output Case b: Qflux=0 Oceans



Case a: Fully Coupled Oceans

Case b: Qflux=0 Oceans



Conclusions

From the surface temperature plots above it is clear there is a split in the dynamics between 1-16x present day earth length and 64x and above regardless of the type of ocean used. For the lower solar insolations the ocean ice fraction and planetary albedos are quite different depending on the ocean used. This is because the ocean ice fraction in a Qflux=0 (mixed layer) ocean will almost always be less than a true fully coupled ocean since our model finds it harder to form ice in the former. Actually not only our model, but all 3-D models that use Qflux=0 oceans. We are still investigating why the fully coupled oceans have more high and low cloud fractions compared with the Qflux=0 oceans. However, the Cloud Radiative Forcings in the short wave are not so different regardless of the ocean used, while there are some modest differences in the long-wave. Other aspects of our study not shown here indicate that changes in Greenhouse gases (CO2=258 vs 400ppmv, and N2O=0 vs .27) contribute approximately +/- 4 Watts/m^2. This is a minor effect in comparison with the cloud parameterization experiments we have done. The cloud fraction and thickness of high and low levels in the troposphere may greatly influence the radiative balance of the planet and hence it's temperature. One can utilize these cloud effects to initialize the temperature and albedo of a given world over a fairly large range. The water vapor content in most of our cases is well below the classical water loss limit and hence with future high temperature extensions to our radiation code we expect to find that planets may be found at the inner edge of the habitable zone akin to a paleo Venus world with S0X=1.4 even with present day Earth rotation rates. With longer solar day periods it is clear that even present day Venus solar insolations may be tenable. We believe the large temperature transition at higher S0X between rotation periods of 16x and 64x earth days are likely due to circulation changes being dominated by the Hadley cells (1x-16x) to day-night transitions (64x and higher). We believe this is because the radiative relaxation timescale starts to be less than the rotation rate timescale at 64x and this fact causes a change in circulation patterns from x16->x64. This is also shown in how the different cloud parameterization schemes have their greatest effect in the Hadley regime (1-16x rotation) while in the day-night regime (64x and higher) the effect is less.