The effect of rotation rate and seasonal forcing on the migration of the ITCZ in a moist GCM

Sean Faulk[1], Jonathan Mitchell[1], Simona Bordoni[2]

1. University of California Los Angeles, Los Angeles, CA, USA
2. California Institute of Technology, Pasadena, CA, USA

contact: spfaulk@ucla.edu

Monsoon Workshop Caltech:
May 18 – 22, 2015

UCLA

Introduction

We use an idealized aquaplanet GCM to examine the structure of the Intertropical Convergence Zone (ITCZ), the seasonally migrating tropical precipitation zone on Earth, over a wide range of rotation rates, keeping everything else Earth-like.

Our primary focus is the extent of the ITCZ, specifically its poleward boundary in the summer hemisphere associated with the seasonally moving ascending branch of the Hadley circulation. On Earth, the precipitation of the ITCZ is concentrated in a relatively narrow latitudinal band in the tropics. However, on planetary settings such as Titan, it has been argued that the equivalent precipitation zone can migrate significantly off the equator into the summer hemisphere, perhaps even to the summer pole. This is in agreement with Titan being an "all-tropics" planet with a far-reaching Hadley cell (Mitchell et al., 2011).

Thus, it is not surprising that we find the extent of the ITCZ moving significantly away from the equator as the rotation rate decreases, **even reaching the summer pole for small enough rotation rates** (see Fig. 3).

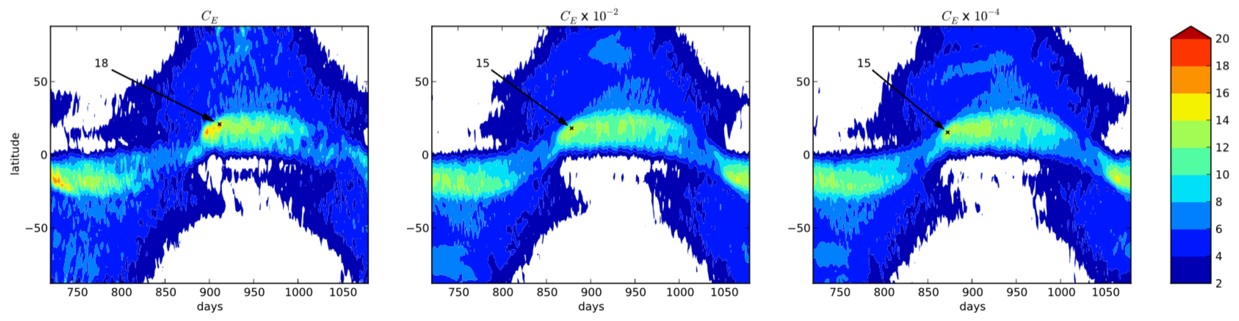


Figure 1: Zonal-mean precipitation (color contours, mm/day) from our simulations of Earth for decreasing surface heat capacities, from the control heat capacity $C_E = 10^7$ J K^{-1} m^{-2} , which is equivalent to ~2m slab ocean depth (left) to 1/100 of that depth (middle) to 1/10,000 of that depth (right).

Decreasing the thermal inertia of the slab ocean by making the mixed layer shallower, however, has little effect in moving the ITCZ off the equator, as seen from Fig. 1. This suggests that, after a certain limit, the heat capacity's role in determining the extent of the ITCZ is less important than previously thought; and that the momentum budget must be taken into account in addition to the surface energy budget.

Experiment Design

- Moist aquaplanet GCM (Frierson et al., 2006; Frierson, 2007)
- 64 x 128 horizontal resolution; 25 vertical levels
- **$\Omega = \alpha\Omega_E$ for α = 1, 1/2 , 1/4 , 1/8 , 1/16 , 1/32**
  - 3-year seasonal runs
  - 10-year eternal runs, end-members only (α=1, 1/32)

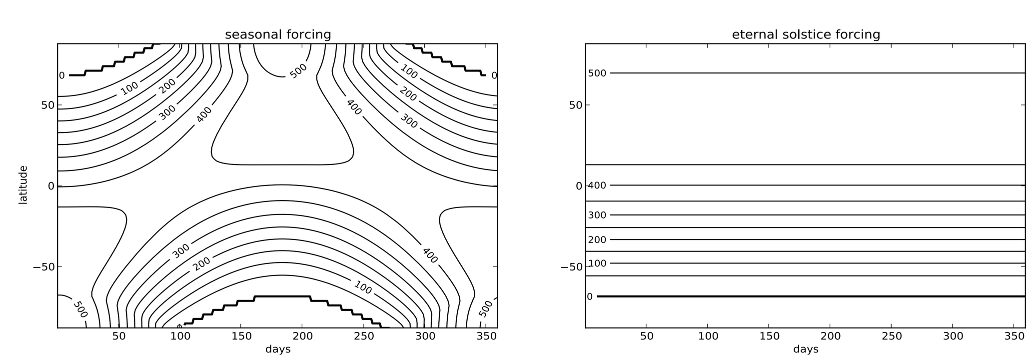


Figure 2: Insolation forcing (W/m^2) for seasonal cycle (left), as formulated by Hartmann (1994), and eternal solstice (right).

Results

We focus on three features that represent the extent of the ITCZ: 1) precipitation, 2) Hadley cell extent, and 3) near-surface temperature.

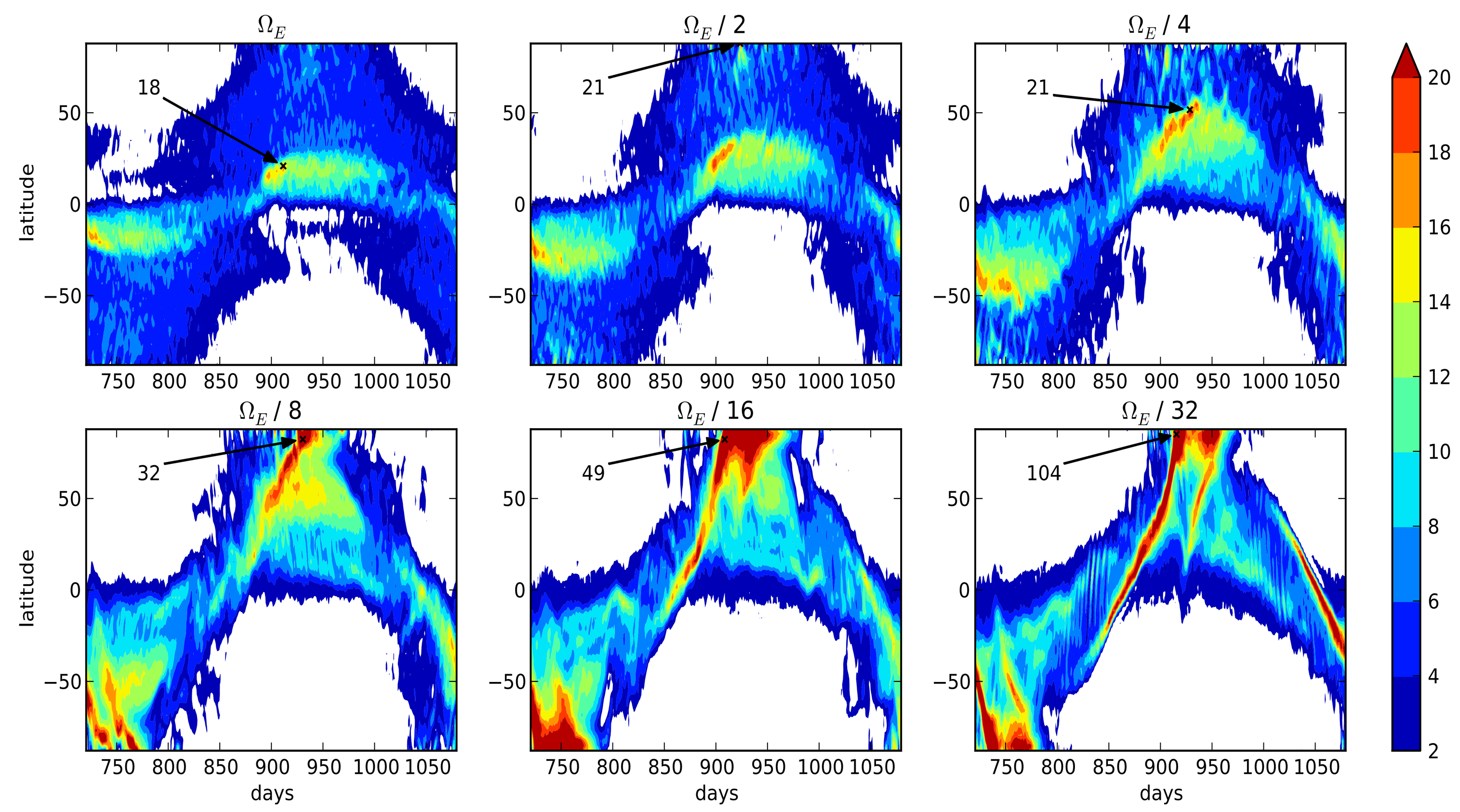


Figure 3: Seasonal cycle of zonal-mean precipitation (color contours, mm/day) for changing rotation with ocean mixed layer thickness of 2 m. Value of α is given at top of each subplot. Vertical black lines indicate 20-day periods over which solstitial averages were taken in Figs. 4 and 5.

ITCZ reaches the pole for Ω/Ω_E = 1/8, 1/16, 1/32

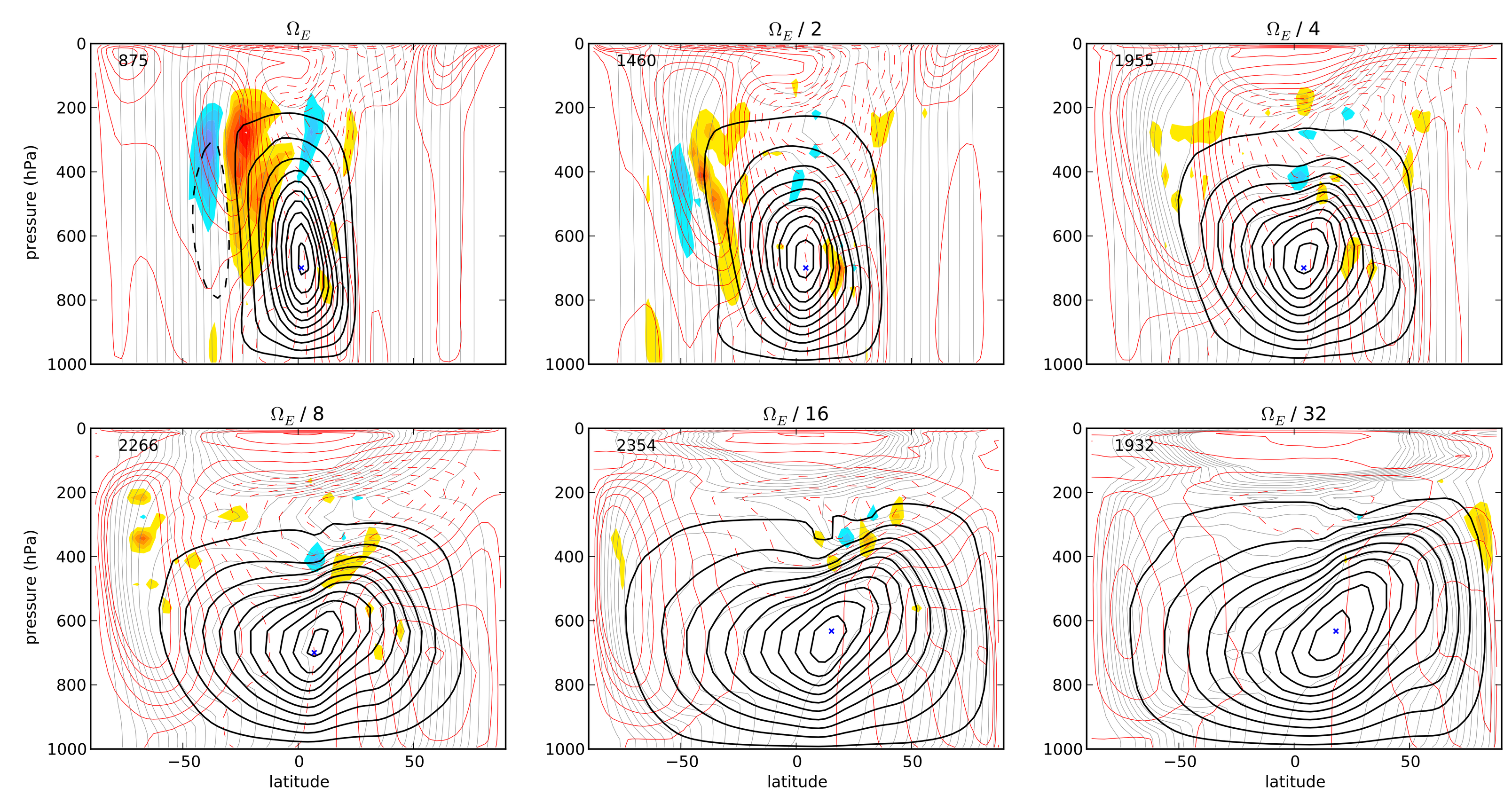


Figure 4: Solstitial streamfunction contours (black, solid lines counter-clockwise) are 10% of max, printed in top left corner in kg/s. Wind contours (red) are 6 m/s, with the dotted contours being negative (indicating easterlies). Color contours indicate eddy momentum flux divergence, where warm colors are divergence and cool colors are convergence (8 x 10^{-6} m/s^2 interval). Grey contours are angular momentum contours ($\Omega a^2/17$ interval).

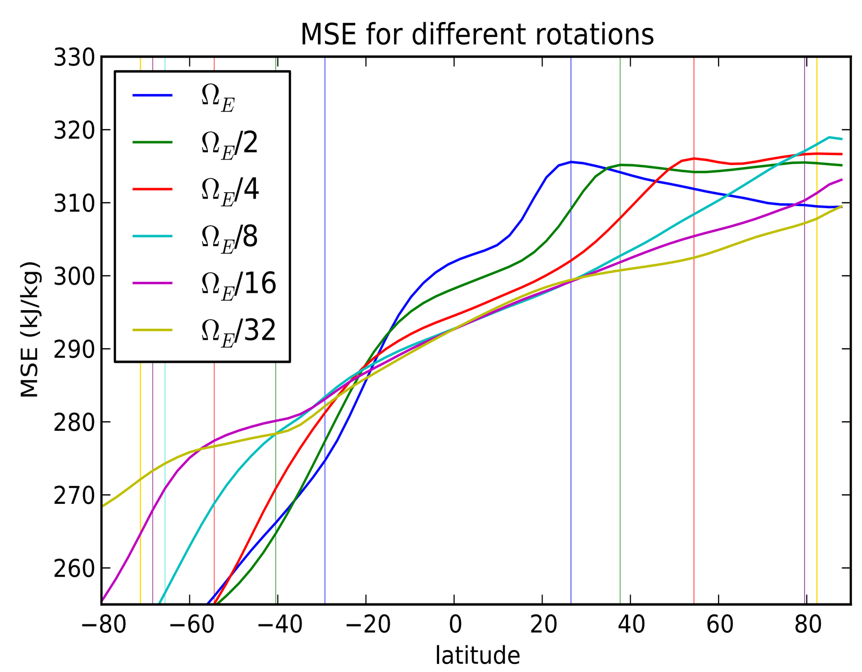
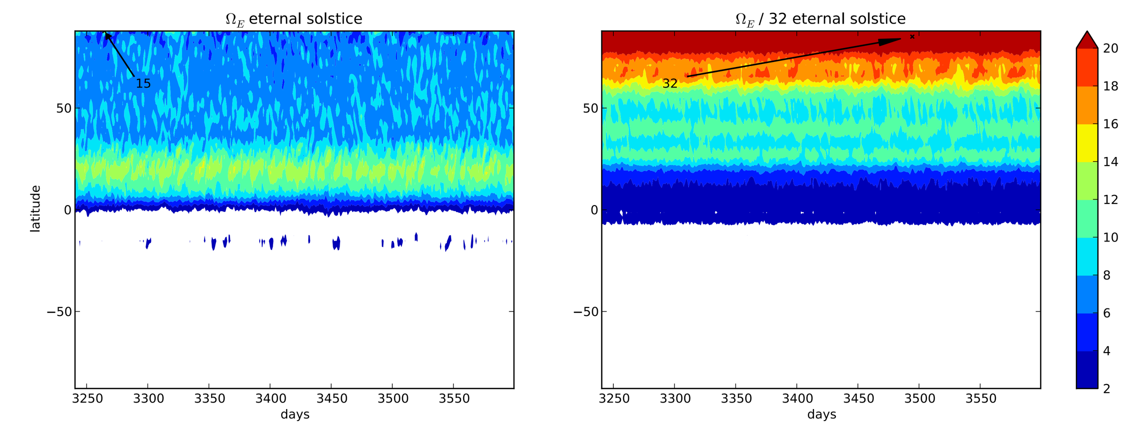


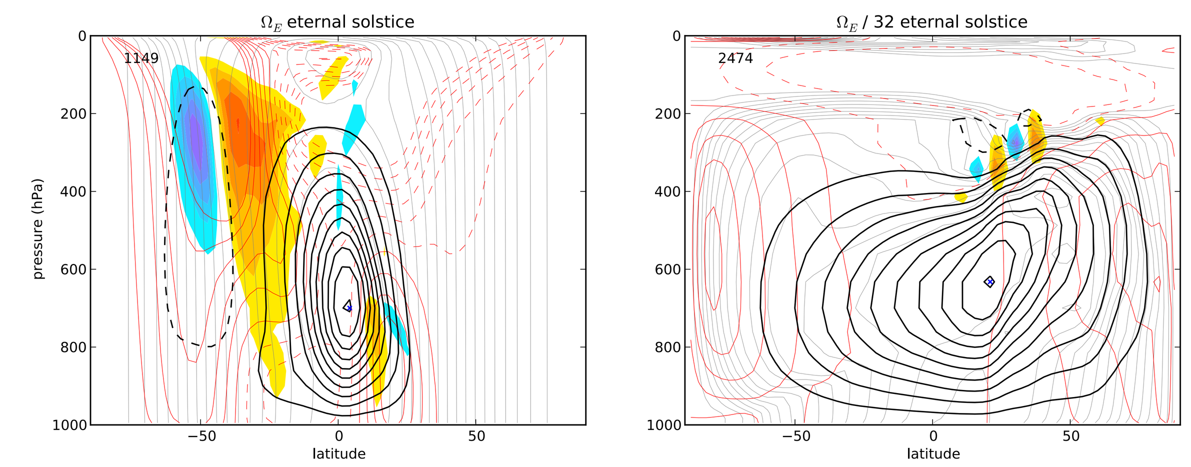
Figure 5: Zonal-mean near-surface (850 hPa) temperature averaged over northern summer solstice for rotation cases. Corresponding vertical lines represent the extents of the winter Hadley cell, defined as the latitudes at which the streamfunction of meridional overturning circulation is 2% of the cell's max value. Note that the northern extents for Ω/Ω_E = 1/8 and Ω/Ω_E = 1/16 are the same.

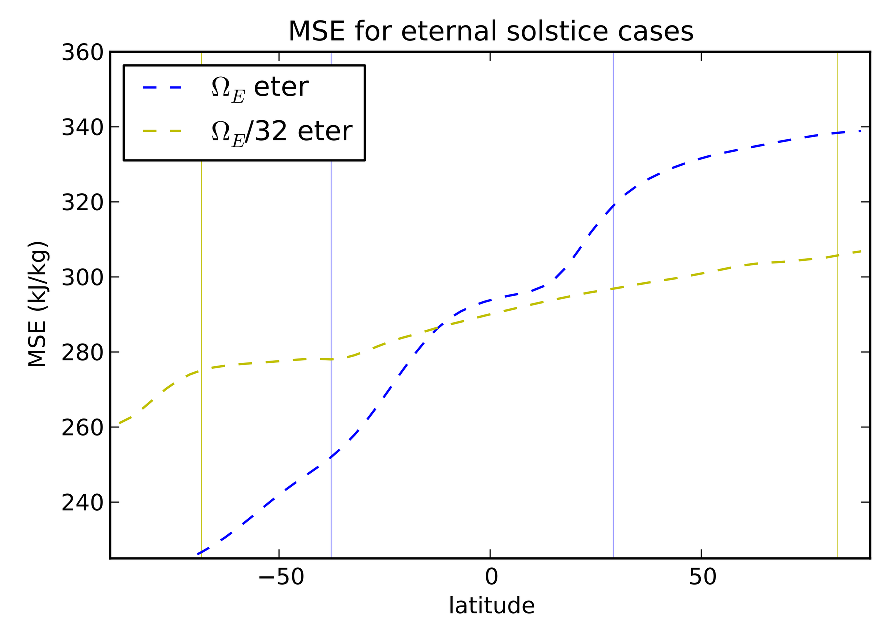
- The main ascent region of the Hadley cell is near the local MSE (as in Bordoni and Schneider, 2008)
- Smaller temperature gradients at lower rotation suggest a lack of baroclinic eddies in the high latitudes of the summer hemisphere

So it would seem that baroclinic activity in the summer hemisphere limits the extent of the ITCZ. However…

Eternal Solstice Runs







Figures 6,7,8: Same plots as Figs. 3,4, and 5 but with the eternal solstice cases, averaged over the full tenth year. (Also with mixed layer thickness of 2 m.)

The MSE max argument does NOT apply to the Earth-like eternal solstice case! Minimal baroclinic activity and still the ITCZ remains at low latitudes.

Next Directions

We've shown that the extent of the ITCZ in an aquaplanet simulation with moist convection can reach the summer pole with a rotation rate as large as 1/8 of Earth's. This is evidenced by several diagnostics, including precipitation, Hadley cell extent, and maximum near-surface temperature, all reaching the pole for small rotation cases. We've also shown the MSE maximum condition fails to predict the location of the ITCZ in eternal solstice runs.

Future work to obtain general scaling laws for latitude of ITCZ:

- Hadley cell width theory (Held and Hou, 1980; Caballero, 2008)
  - Energy balance within circulation
  - Angular momentum conservation
- Momentum force balances in the boundary layer at the convergence zone

References

Bordoni, S., and T. Schneider, 2008: Monsoons as eddy-mediated regime transitions of the tropical overturning circulation. *Nature Geoscience*, 1, doi: 10.1038/ngeo248.

Caballero, R., R. T. Pierrehumbert, and J. L. Mitchell, 2008: Axisymmetric, nearly inviscid circulations in non-condensing radiative-convective atmospheres. *Quat. J. Roy. Meteor. Soc.*, 134, 1269-1285.

Frierson, D. M. W., I. M. Held, and P. Zurita-Gotor, 2006: A gray-radiation aquaplanet moist GCM. Part I: Static stability and eddy scale. *J. Atmos. Sci.*, 63, 2548-2566.

Frierson, D. M. W., 2007: The dynamics of idealized convection schemes and their effect on the zonally averaged tropical circulation. *J. Atmos. Sci.*, 64, 1959-1976.

Hartmann, D.L.: *Global Physical Climatology*, Academic Press, San Diego, 1994.

Held, I. M., and A. Y. Hou, 1980: Nonlinear axially symmetric circulations in a nearly inviscid atmosphere. *J. Atmos. Sci.*, 37, 515-533.

Mitchell, J.L., M. Ádámkovics, R. Caballero, and E. Turtle, 2011: Locally enhanced precipitation organized by planetary-scale waves on Titan. *Nature Geosciences*, 4, 589-592.