Calculating the Moist Static Energy Budget around the ITCZ using Idealized WRF Simulations

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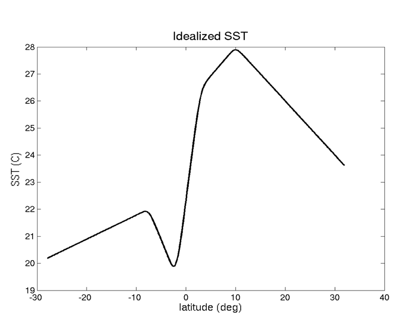
1. Introduction

Prior studies have indicated the presence of a meridional shallow return flow out of the intertropical convergence zone (ITCZ) over open ocean (Nolan, et al., 2007, Zhang, et al., 2004). Contrary to the conventional Hadley cell model consisting of a boundary layer inflow and an upper level tropospheric return flow from the ITCZ to middle latitudes, a shallow return flow exists between 2 and 4km above the surface, accompanied by a dry air inflow between 6km and 8km. As such, water vapor transport within the vertical structure of the ITCZ should be significantly affected by these weaker shallow meridional circulations (SMC), and advection of moist static energy differs than that in the conventional Hadley cell model. In order to illustrate the importance of considering these SMCs in this more general large-scale circulation, budgets of moist static energies were calculated. Using the Weather Research and Forecasting Model (WRF) 2.1.2, simulations of these circulations were created using various sea surface temperature (SST) profiles. Simulations were performed using an SST profile with a temperature maximum at the geographic equator (henceforth called the equatorial simulation), and using a more realistic profile including the East Pacific (EPAC) cold tongue, and a temperature maximum at about 10°N (the "Idealized EPAC" simulation). Components of the moist static energy, including energy fluxes from incoming and outgoing radiation and sensible and latent heating fluxes from the ocean, are computed in each simulation.

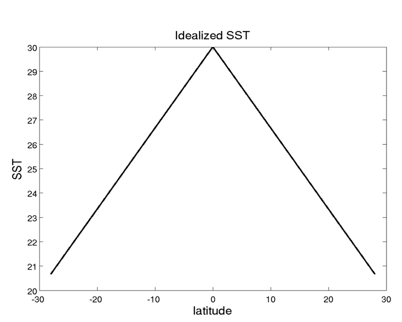
2. Model

WRF 2.1.2 was used for this study, with domain spacing of 20.87km in the latitudinal and longitudinal directions, and 40 vertical levels divided evenly by pressure—resulting in a greater number of vertical levels closer to the surface where the SMC is found. Standard boundary layer, microphysics, and radiation parameterizations were used (Nolan, et al., 2007). Simulations were run until a steady-state was reached such that the features of the large scale circulation became stable. The two temperature profiles used are shown below.

a. "Idealized EPAC" Simulation



b. Equatorial Simulation

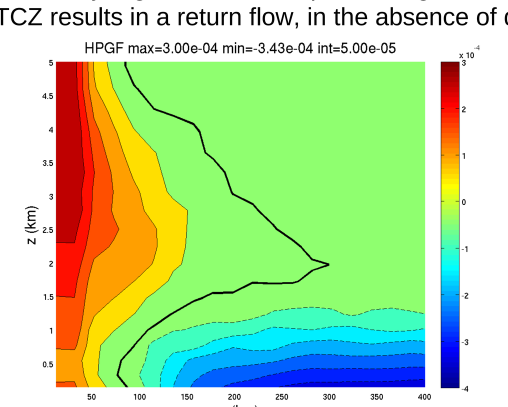


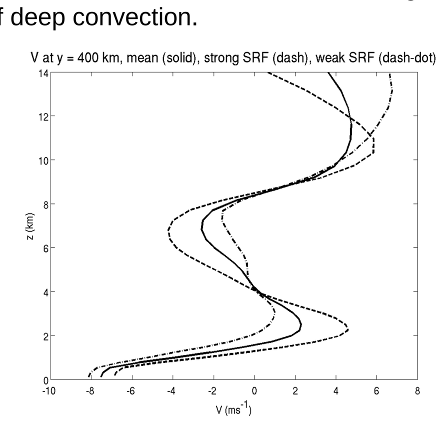
3. Shallow Meridional Circulation

• The shallow circulation may be thought of essentially as a large-scale "sea-breeze" driven by surface temperature and pressure gradients as suggested by Nolan, et al. (2007).

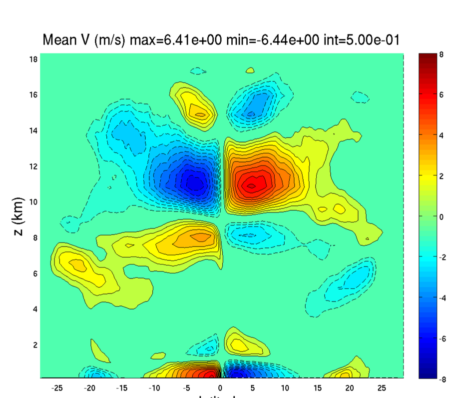
• The top images illustrate the horizontal pressure gradient force near the surface in a simulation including a domain on one side of the equator only, and a variation of the strength of this shallow return flow and dry air inflow.

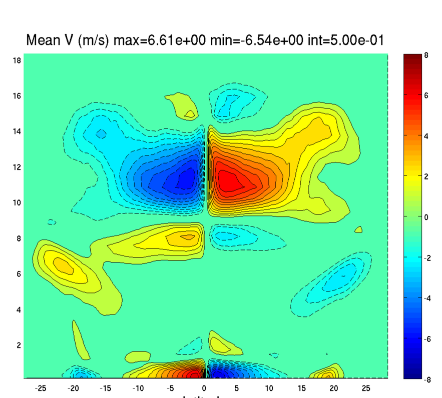
• A locally higher horizontal pressure gradient force between 2km and 4km along the ITCZ results in a return flow, in the absence of deep convection.





• The next images show the relationship between diabatic heating and meridional winds. The left image shows a composite mean of meridional winds when diabatic heating within 5 grid points (104km) of the equator is less than one standard deviation of the mean. The right image gives a composite mean of meridional winds when this diabatic heating is greater than one standard deviation over the mean. Stronger diabatic heating—resulting in more deep convection, weakens the SMC.





•Note that with strong diabatic heating, the upper level flow is stronger, and the components of the SMC are noticeably weaker.

4. The Shallow Circulation and Advection of Moist Static Energy

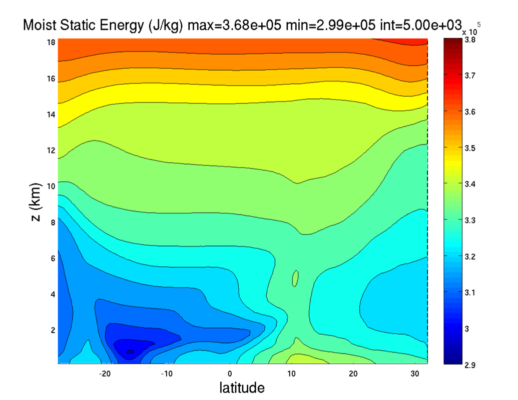
Moist static energy is defined as the dry static energy plus the product of the latent heat of vaporization and water vapor mixing ratio:

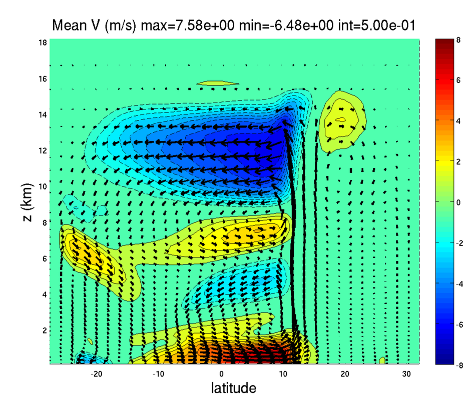
$$s = C_pT + gz + L_vr,$$

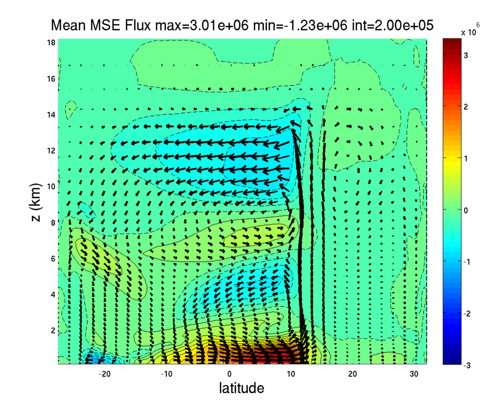
where C_p is the specific heat of air at constant pressure, T is absolute temperature, the product of g and height z is the geopotential, L_v is the latent heat of vaporization, and r is the mixing ratio.

We choose to calculate a budget for moist static energy since MSE should be approximately conserved vertically. As water vapor is transported vertically and meridionally, it will also be transported into and out of the ITCZ through the large scale Hadley circulation and the SMC. The following illustrations show the presence of moist static energy, a vertical cross section of the longitudinal mean meridional winds, and resulting MSE flux due to advection along the same cross section.

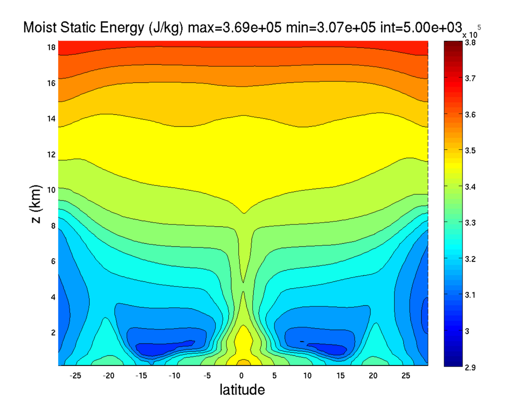
a. "Idealized EPAC" Simulation

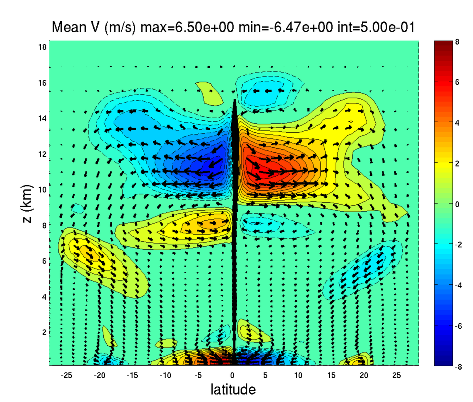


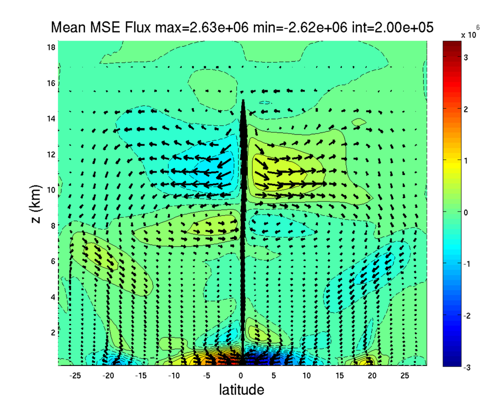




b. Equatorial Simulation







• Moist static energy is greatest near the surface within the ITCZ, where water vapor content is highest. At higher altitudes, cooler air cannot hold as much water vapor; however, the geopotential increases, thus increasing the static energy of a column.

• MSE transported by advection clearly contributes to the overall budget. MSE advected by the shallow return flow and dry air inflow are apparent in the above images.

• The return flow is much weaker in the equatorial simulation and is confined to about 2km above the surface; however, the ideal simulation shows a much more rigorous circulation, extending from 4 to 6km, with a strong dry air inflow extending to 8km.

Note that wind vectors overlaid on meridional wind and MSE flux images use meridional and vertical wind components, with vertical winds multiplied by 100 in order to clearly illustrate the presence of the circulation.

5. Calculating the moist static energy budget

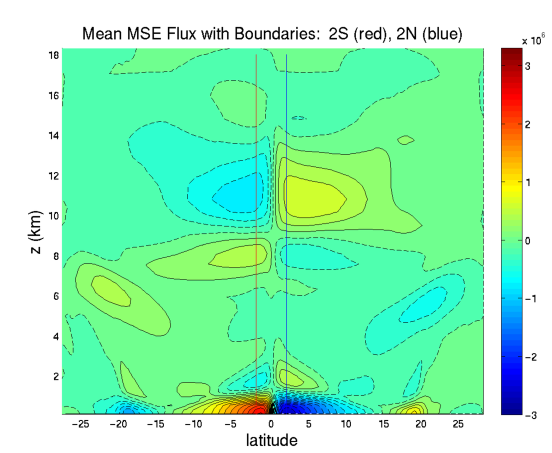
• In order to budget MSE, each component must be calculated:
  • Incoming and outgoing radiation
  • Sensible and latent heating fluxes
  • Advected MSE

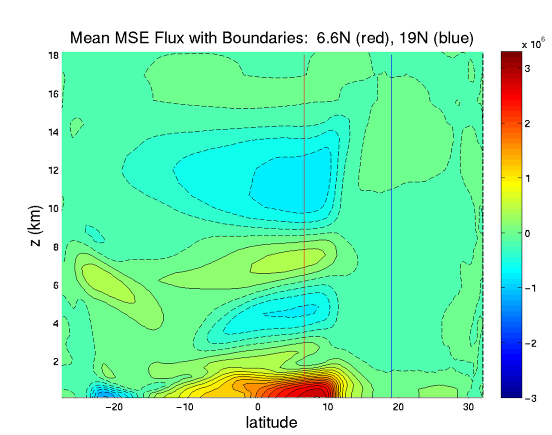
• Vertical "walls" were established north and south of the ITCZ in each simulation, resulting in a "box" where MSE should be approximately balanced over time. A 30-day time mean was calculated for MSE flux, latent and sensible heating resulting from the ocean, and MSE fluxes due to longwave and shortwave radiation.

• In the "Idealized EPAC" simulation, the circulation is much more rigorous to the south of the ITCZ, and the equatorial simulation gives a mostly symmetric result on either side of the ITCZ.

•Boundaries for the boxes are equally set at 2S to 2N for the equatorial simulation and at 6.6N and 19.0N for the "Idealized EPAC" simulation. 6.6N represents an arbitrary area of active advection into and out of the ITCZ, and 19.0N corresponds with the weak upper level tropospheric return flow to the north of the ITCZ.

•Top image shows boundary for equatorial simulation; bottom shows "Idealized EPAC" simulation.





6. Calculations of the moist static energy budget: Advection

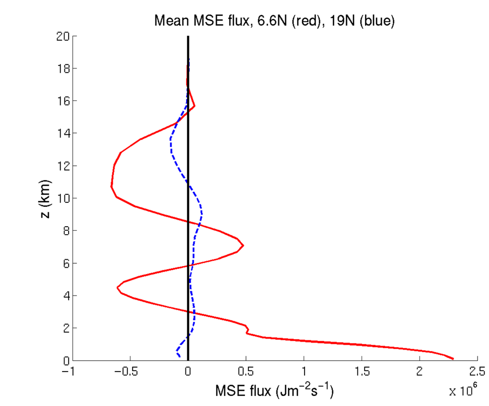
Flux of moist static energy at a single grid point due to advection is calculated simply by:

$$\Phi_{MSE,\ point} = \rho*v*s,$$

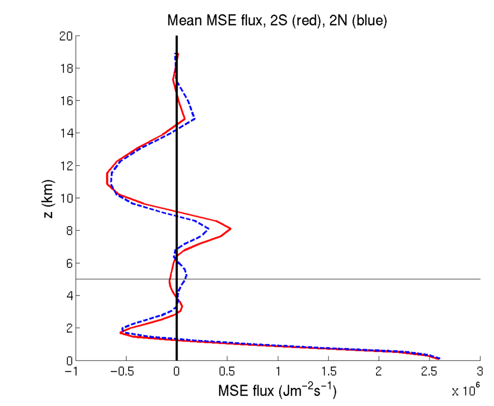
where ρ = air density, v = meridional wind, s = moist static energy, and all values are taken from each individual grid point. In these calculations, the values represent longitudinal means of each variable across all points on the domain.

The following images plot MSE flux due to advection with height. The red curve plots MSE flux on the southern boundary of each simulation's "box", and the blue curve represents the northern boundary. Since return flow in the northern hemisphere has a positive sign, MSE flux on the northern boundary is multiplied by -1, so that a negative MSE flux represents a flux out of the ITCZ region.

a. "Idealized EPAC" Simulation



b. Equatorial Simulation



• In the "Idealized EPAC" simulation, the height separating the shallow return flow and mid-level inflow is defined by a switch in sign of meridional winds around 5km on the southern boundary. In the equatorial simulation, small variations in wind direction near the equator results in an unclear separation between shallow return flow and mid-level inflow. The horizontal black line is placed at 5km to set this height. The vertical black lines in both plots represent an MSE flux of zero. Since the equatorial simulation is symmetrical, a circulation is formed in the simulation on both sides of the ITCZ. No such circulation was observed on the north side of the ITCZ in the "Idealized EPAC" simulation.

• Additionally, advected MSE flux must be summed over all altitude points of the domain. This may be most accurately described as the product of moist static energy, meridional winds, and the integral of the pressure level divided by g, where dP = ρ*g*dz from the hydrostatic balance equation. This results in a product essentially equivalent to the MSE flux at a single point multiplied by dz; however, here, dP is calculated directly from model output so the product ρ*dz is more accurate than the product calculated when each individual variable is calculated from model output. As such, total MSE flux is described by

$$\Phi_{MSE,\ total} = s*v*dP/g,$$

where dP = integral of pressure level, and g = acceleration due to gravity.

• The following tables quantify moist static energy budget to each component of the SMC. Again, note that no such SMC exists north of the ITCZ in the equatorial simulation. Fluxes have units of $J*m^{-1}*s^{-1}$.

a. "Idealized EPAC" Simulation

SMC Level	MSE Flux: 6.6N
Upper level return flow	-3.26E+9
Mid-level inflow	7.76E+8
Shallow return flow	-1.17E+9
Boundary Layer inflow	3.57E+9
Total	-8.40E+7

b. Equatorial Simulation

SMC Level	MSE Flux: 2S	MSE Flux: 2N
Upper level return flow	-2.26E+9	-2.05E+9
Mid-level inflow	7.50E+8	4.42E+8
Shallow return flow	-5.04E+8	-5.21E+8
Boundary Layer inflow	1.98E+9	2.10E+9
Total	-3.10E+7	-1.67E+7

7. Calculating the Moist Static Energy Budget: Radiation and Heating Fluxes

• Also contributing the moist static energy budget are heating fluxes from the ocean and energy fluxes from radiation. The following tables quantify each component of the moist static energy budget in each "box" previously defined.

a. "Idealized EPAC" Simulation

Component	Advection: 6.6N	Advection: 19N	Outgoing Longwave Radiation	Incoming Shortwave Radiation	Latent Heat Flux	Sensible Heat Flux	Total
MSE Flux ($J*m^{-1}*s^{-1}$)	-8.40E+7	-4.18E+7	-2.45E+8	1.13E+8	2.26E+8	2.97E+7	-2.66E+6

b. Equatorial Simulation

Component	Advection: 2S	Advection: 2N	Outgoing Longwave Radiation	Incoming Shortwave Radiation	Latent Heat Flux	Sensible Heat Flux	Total
MSE Flux ($J*m^{-1}*s^{-1}$)	-3.10E+7	-1.67E+7	-7.26E+7	3.90E+7	7.21E+7	9.88E+6	7.66E+5

8. Summary

• The total MSE fluxes through the boundaries of the "box" for each simulation is only a small fraction of the smallest component of the MSE budget, meaning that the budget is reasonably balanced.

• The MSE budget is largely dominated by advection. Each component of the MSE results in a flux on the order of 10^8 to 10^9 $J*m^{-1}*s^{-1}$.

• MSE fluxes due to radiation are on the order of 10^7, and MSE fluxes due to surface fluxes are between 10^7 and 10^8 $J*m^{-1}*s^{-1}$ for a domain from 6.6N to 19N, and from 10^6 to 10^7 on a domain from 2S to 2N. Note that MSE flux due to radiation and heating fluxes vary based on the size of the "box" defined.

• Results indicate that each component of the SMC is vital to include in the overall budget. Fluxes due to shallow return flow and mid-level inflow are at least 20 percent that of MSE flux due to the upper level outflow or boundary layer inflow and contribute to at least 8 percent of the total flux due to advection.

• When a more realistic temperature profile is applied, no significant circulation is shown on the northern side of the ITCZ, however, the plot of meridional winds in Section 4A indicate that the upper level return flow contributes most to MSE flux in this location.

• The shallow return flow and mid-level inflow are strong enough to be important in describing the larger Hadley circulation and in calculating other budgets around the ITCZ where these circulations are active.

9. Acknowledgments

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10. References

Nolan, D. S., C. Zhang, and S. Chen, 2007: Dynamics of the Shallow Meridional Circulation around Intertropical Convergence Zones. *J. Atmos. Sci.*, ***64***, 2262-2285

Zhang C., M. McGauley, and N. A. Bond, 2004: Shallow Meridional Circulation in the Eastern Pacific. *J. Climate*, **17**, 133-139.

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