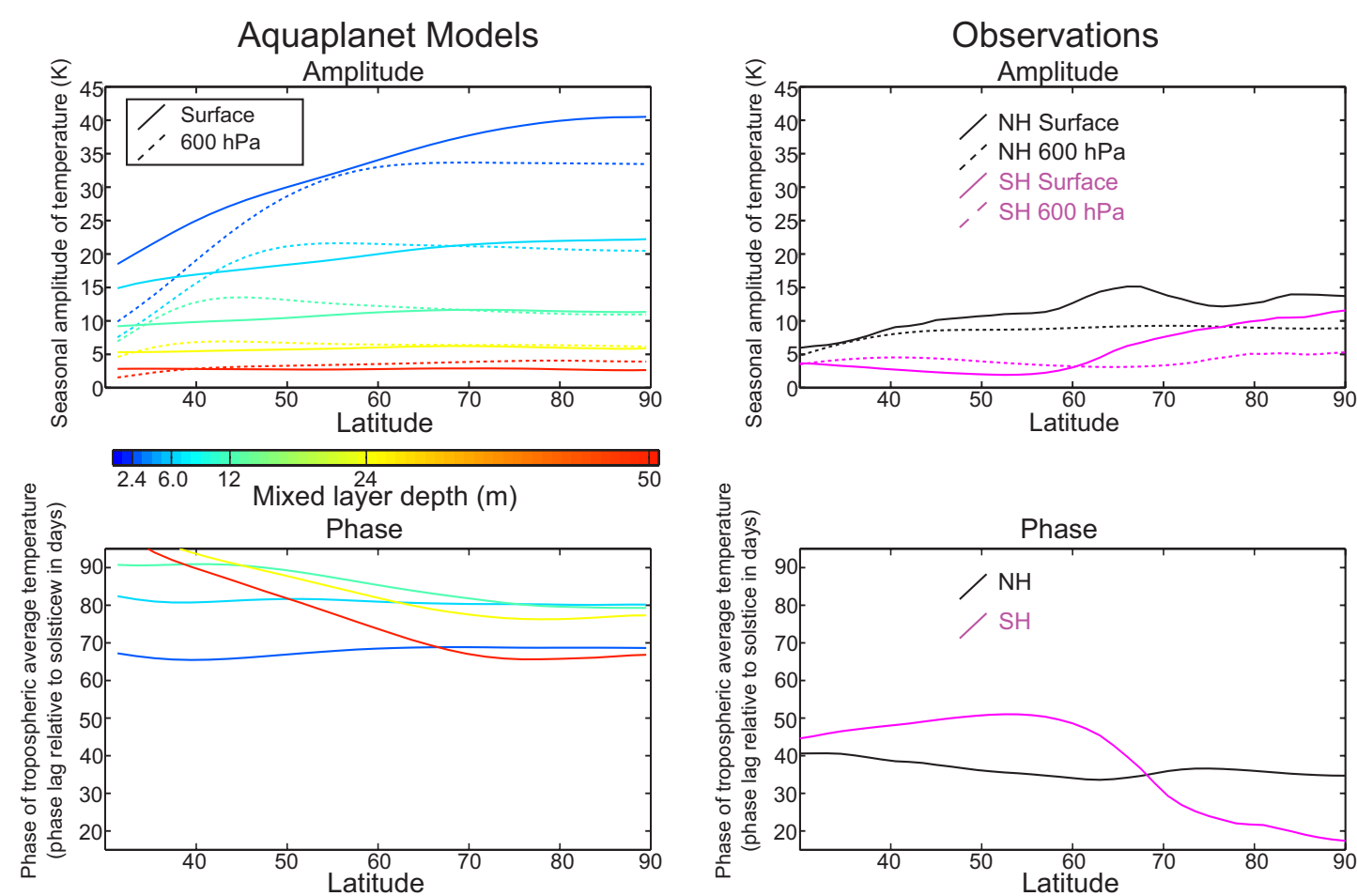


## Introduction

We explore the effect of slab ocean depth on climate in an ensemble of GFDL2.1 simulations with an atmosphere coupled to a slab ocean of varying depth ranging from 2.4 meters to 50 meters. In addition to the anticipated decrease in the amplitude of the seasonal cycle of temperature with increasing mixed layer depth we find several unexpected results :

- The phase lag of the seasonal cycle with respect to insolation is a non-monotonic function of ocean depth, maximizing at 10 meter depth
- The ocean depth has a non-trivial impact on annual mean climate due to the rectification of the seasonal cycle on the global and equator-to-pole energetics  
→The shallow ocean run is 7K colder in the global mean, the mid-latitude energy transport is half the magnitude and the mid-latitude jet is shifted poleward by 10 degrees

## Amplitude and phase of the seasonal cycle of temperature.



**Figure 1.** (Top) The seasonal amplitude of atmospheric temperature at the surface (solid lines) and at 600 hPa (dashed lines) in the slab-ocean aquaplanet simulations (Left Panel) and observations (Right Panel). The different ocean mixed layer depths are indicated by the colorbar below the plot. (Bottom) Phase lag of seasonal cycle of tropospheric averaged (below 250 hPa) temperature with respect to insolation in the slab-ocean aquaplanet simulations (Left) and observations (Right). The phase lag is expressed in days past the summer solstice.

## Seasonal Amplitude

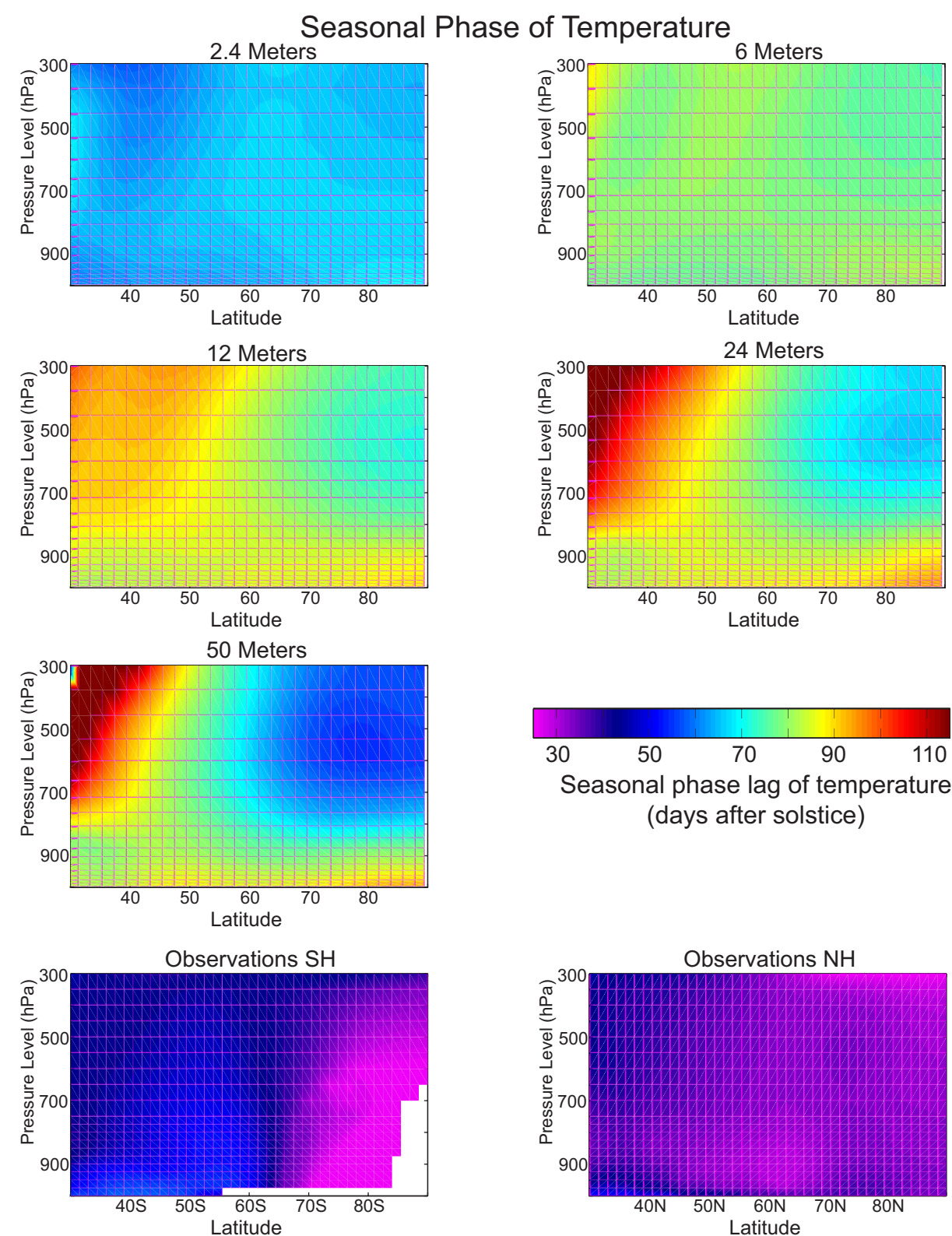
- As expected, the seasonal amplitude of atmospheric temperature decreases with increasing ocean depth
- The observed seasonal amplitude of temperature is achieved with an ocean depth of 12m for NH and 24m for SH

## Phase of seasonal cycle

- Phase lag of seasonal cycle relative to insolation increases as expected from slab depths of 2.4 to 12 meters but then the phase advances as the slab depth is further increased from 12-50m
- The observed phase is closer to in phase with the insolation than all aquaplanet simulations (even with a 2m deep ocean)

## Vertical structure of Amplitude and phase

- The seasonal cycle is surface amplified for shallow ocean depths and amplified aloft for the deeper ocean runs
- Observations are surface amplified over land and nearly vertically invariant over ocean
- The seasonal phase is vertically invariant for shallow ocean depth and surface delayed for deeper ocean depths
- Observed phase is nearly altitude independent to the tropopause

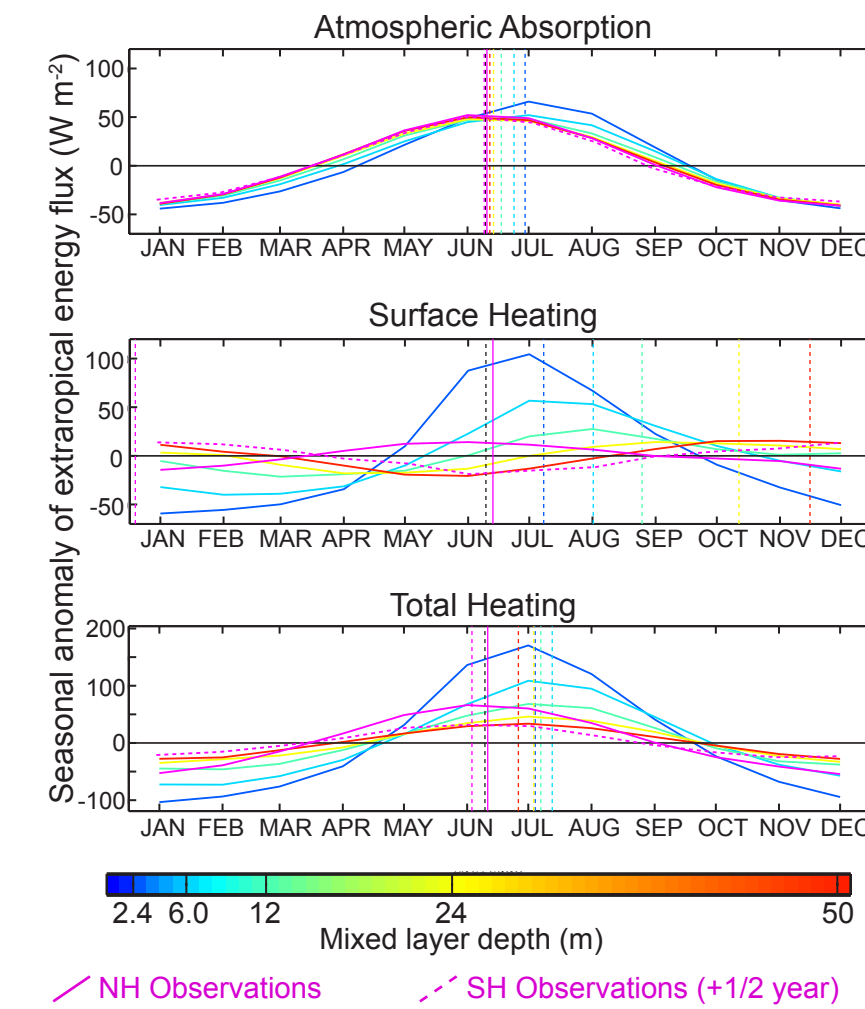


**Figure 2.** Meridional-height cross sections of the phase of the seasonal cycle of atmospheric temperature in each of the slab-ocean aquaplanet simulations (upper panels) and the observations (lower panels). Values are expressed as the phase lag relative to the insolation in days.

## Source of atmospheric heating

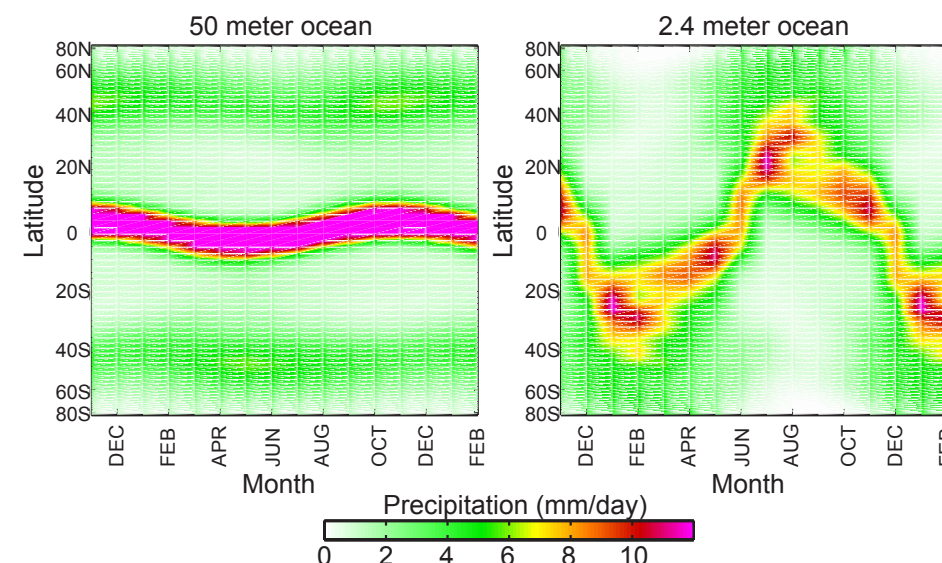
The seasonal heating of the atmosphere is decomposed into contributions from: 1. The (non-solar) surface energy fluxes and 2. shortwave absorption within the atmospheric column

- The atmosphere absorbs approximately 20% of the seasonal variations in insolation directly. This result is independent of mixed layer depth
- The surface energy fluxes to atmosphere decrease with increasing ocean depth as more of the solar heating of the surface goes into energy storage
- Shallow ocean → atmosphere is heated from below
- Deep ocean → atmosphere heated directly from sun
- This change in the dominant source of seasonal atmospheric heating explains the non-monotonic dependence of seasonal phase on ocean depth
- Observed seasonal cycle driven by direct solar absorption in the atmosphere



**Figure 3.** Time series of atmospheric heating averaged over the Northern Extratropics defined as poleward of 40N. The total atmospheric heating (bottom panel) is decomposed into contributions from solar absorption in the atmospheric column (SWABS--top) and surface energy fluxes (SHF--middle panel). The annual mean value of each contribution has been subtracted from the time series. The different ocean mixed layer depths are indicated in the colorbar at the bottom and the observations in the Northern and Southern hemisphere are shown by the solid and dashed purple lines respectively. The SH curve has been shifted by half a year. The dashed solid lines represent the phase of the seasonal cycle and the solid black line is the summer solstice.

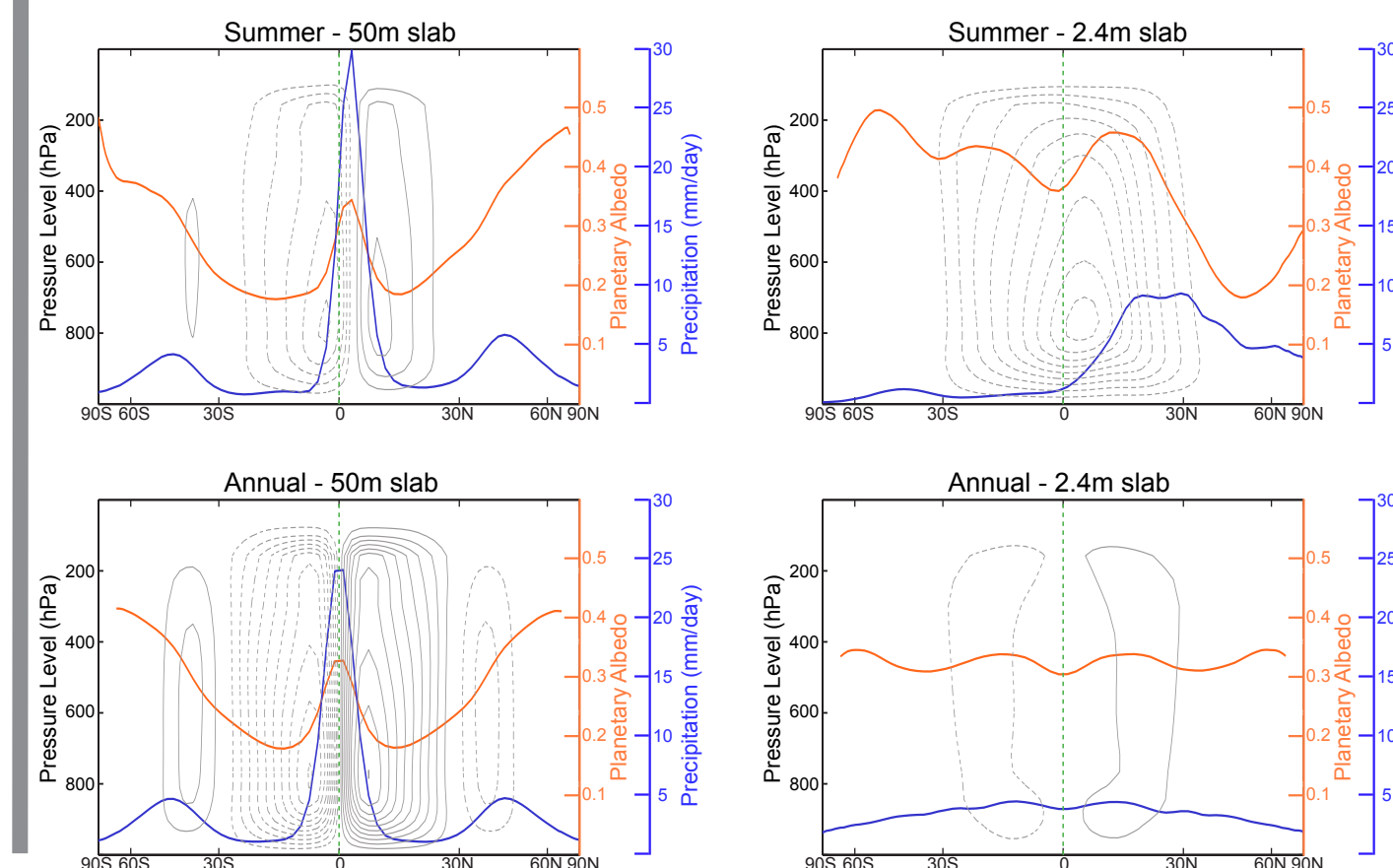
## Seasonal Migration Tropical Precipitation (ITCZ)



**Figure 4.** Seasonal cycle of zonal mean precipitation in the (left) 50 meter ocean depth simulation and (right) 2.4 meter ocean simulations

The intertropical convergence zone (ITCZ) is fixed to within 5° of the equator during all seasons in the 50 meter simulation. In contrast, the ITCZ moves to 20° during the warm season in the 2.4 meter simulation

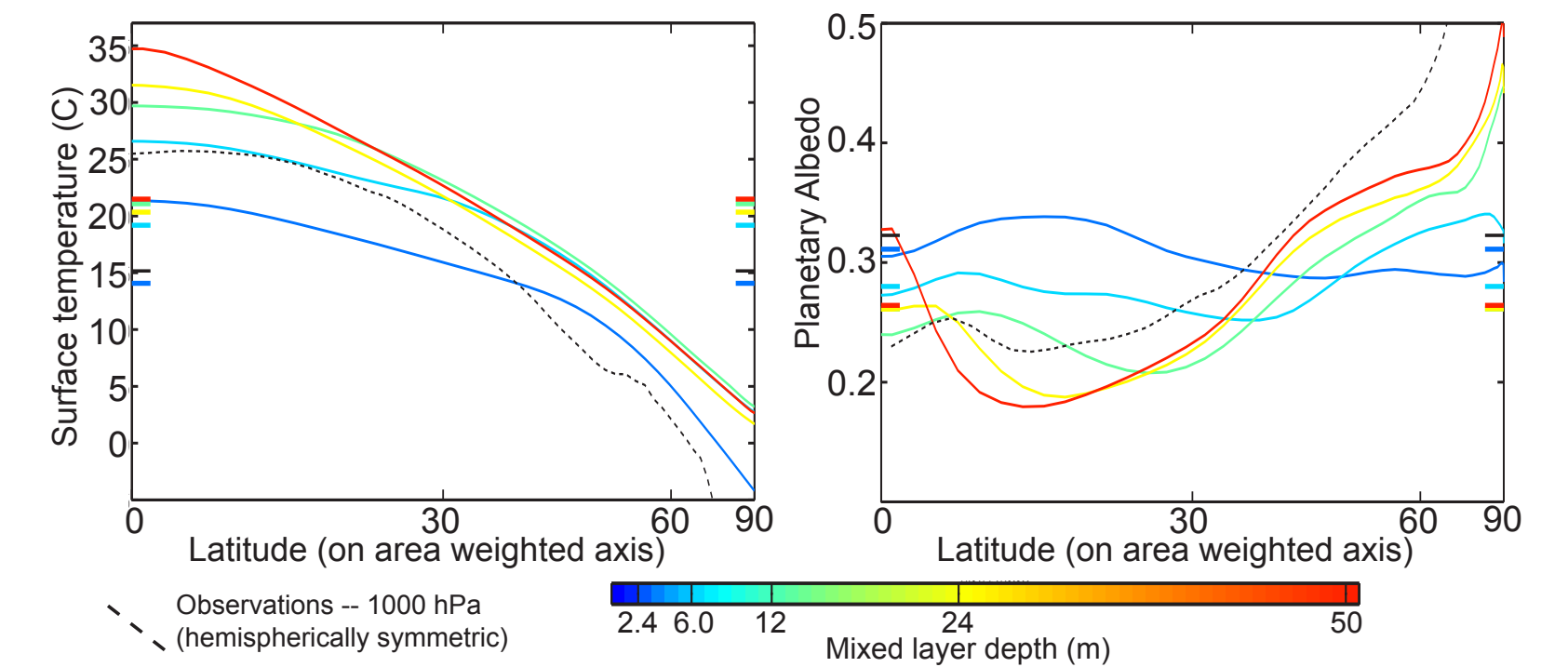
- The ITCZ follows the sea surface temperature maximum which remains on the equator (where the annual mean insolation maximum is) in the deep ocean runs since seasonal variations in insolation are primarily stored in the ocean.
- In contrast, the SST maximum more closely follow the seasonal insolation maximum in the shallow ocean runs since ocean energy storage is limited
- Alternatively, the ITCZ migration can be understood in terms of the hemispheric contrast in energy input to the atmosphere and the cross equatorial atmospheric energy transport demanded by the Hadley cell
- As the ITCZ migrates off the equator in the shallow ocean runs, the winter Hadley cell intensifies and the summer Hadley cell nearly disappears (Figure 5, top right)
- The annual mean Hadley cell in the shallow ocean runs is the small residual of large seasonal variations → Weak amplitude overturning circulation → Meridionally expanded tropics with convective clouds extending to 15° and meridionally expansive subtropical region of weak subsidence
- In contrast, in deep ocean runs the tropical region of deep convective clouds is meridionally confined to within 5° of equator
- **The width of the tropics is set by the seasonal migration of the ITCZ with a more expansive tropical region for shallow ocean depth**



**Figure 5.** (Top panels) Boreal summer and (bottom panels) annual mean mass overturning streamfunction, precipitation, and planetary albedo for the (left panels) 50 meter and (right panels) 2.4 meter slab ocean simulations. The mass overturning streamfunction is shown in gray contours with solid lines denoting clockwise rotation and dashed line denoting counter-clockwise rotation. The contour interval is 50 Sv ( $10^7 \text{ kg s}^{-1}$  for the top panels and 20 Sv for the bottom panels). The zonal mean planetary albedo is the orange line and the precipitation is the blue line (with scales given by the orange and blues axes to the right respectively).

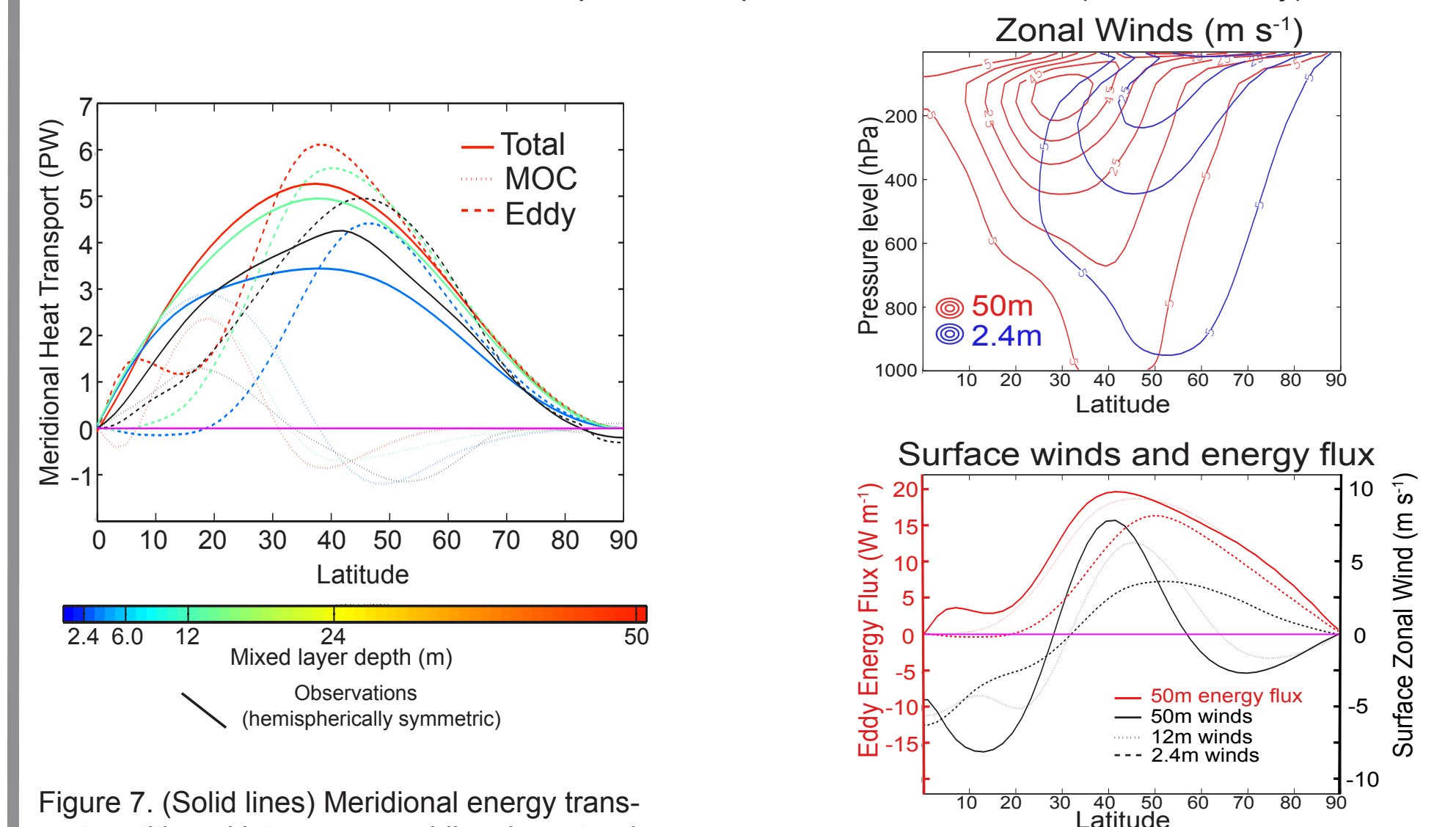
## Effect on global temperature and atmospheric circulation

- The global mean temperature is 7K colder in the shallow ocean runs  
→This result runs contrary to theory since the heat capacity should have no effect on the annual mean energy balance and temperature
- Result of seasonal rectification of the ITCZ migration on the planetary albedo
- More expansive tropics in the shallow simulations result in a meridionally broad area of high planetary albedo (Figure 6, right) which causes a colder planet globally, even in the extra-tropics where the planetary albedo is reduced



**Figure 6.** (Left panel) Zonal and annual mean surface temperature and (right panel) planetary albedo. Each of the colors is a different aquaplanet slab ocean simulation with slab depth given by the color bar on the bottom. The dashed black line is the observations averaged over both hemispheres. The thick horizontal lines on the left and right hand side of plot is the global mean value for each run.

- Differences in the meridional contrast of planetary albedo between the shallow and deep simulations is profound  
→Deep ocean, meridionally confined tropics, lower planetary albedo in low latitudes  
→Shallow ocean, expansive tropics, high albedo in low latitudes, nearly spatially invariant planetary albedo
- The reduced equator-to-pole contrast in planetary albedo in the shallow ocean runs results in 50% less meridional energy transport in the atmosphere  
→Transient eddies (storms) are reduced in amplitude in shallow ocean runs and shifted poleward (Figure 7)
- The jets and surface winds follow the eddy energy and momentum fluxes which are constrained to weaken in magnitude and shift poleward due to the large scale radiative constraint and the more expansive tropics in the shallow run (EP flux theory)



**Figure 7.** (Solid lines) Meridional energy transport partitioned into mean meridional overturning circulation (MOC -- vertically dashed line) and eddy contribution (horizontal dashed lines). The 50m, 12m, and 2.4m slab ocean depth simulations are shown, with colors given by the legend at the bottom of the figure.

**Figure 8.** (Top Panel) The annual and zonal mean zonal wind cross section for the 50m deep slab ocean simulation (red contours) and the 2.4m run (blue contours). The contour interval is 10 m s<sup>-1</sup> and only positive contours are shown. The contour (Bottom Panel) Zonally averaged eddy energy flux (red lines in 10<sup>7</sup> W m<sup>-1</sup> with scale to the left) and surface zonal wind (black lines in m s<sup>-1</sup> with scale to the right) in the slab ocean aquaplanet simulations. The 50m run is shown with the solid line. The 12m run is shown with the vertical dashed line and the 2.4m run is shown with the horizontal dashed line.

## Reference:

Donohoe, A., D.M.W. Frierson and D.S. Battisti (2013). The effect of ocean mixed layer depth on climate in slab ocean aquaplanet experiments. Climate Dynamics. DOI 10.1007/s00382-013-1843-4. 15 pages.