# Climate of an Earth-like Aquaplanet: the high-obliquity case and the tidally-locked case

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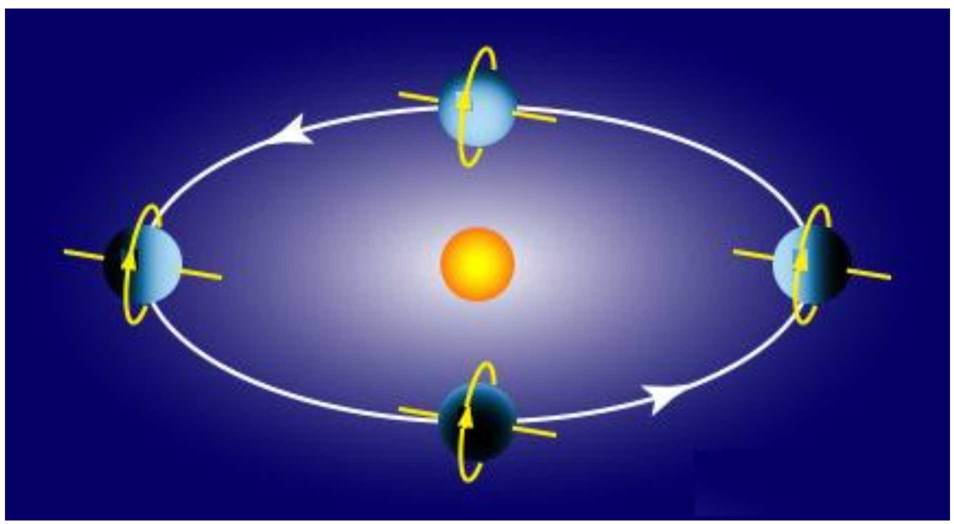
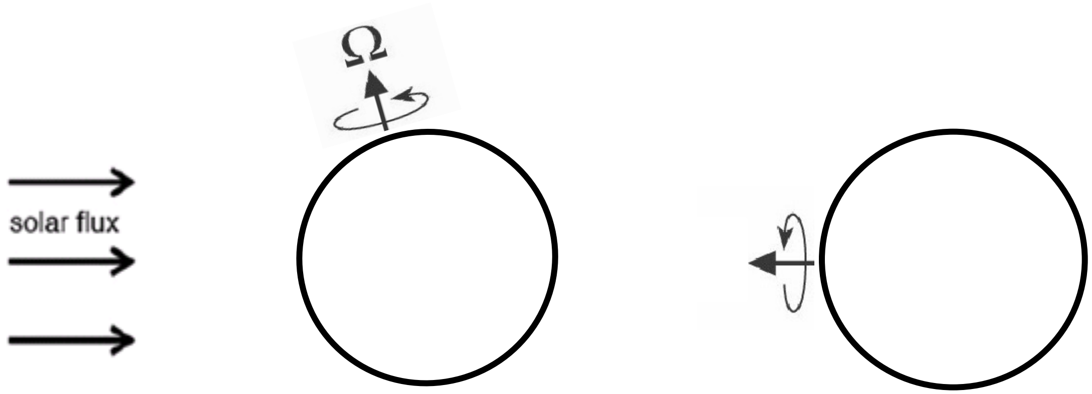


# Outline




1 Why is the problem interesting from a climate dynamics perspective?

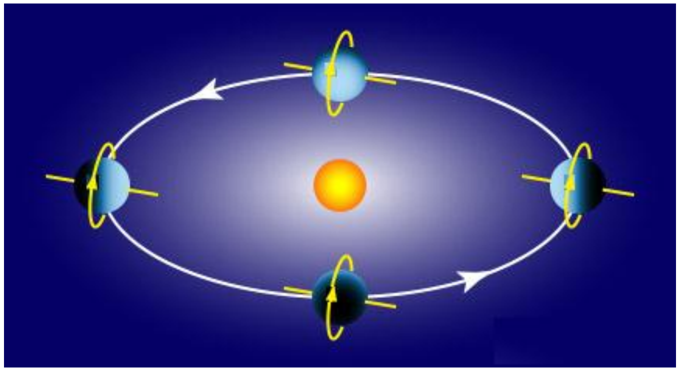
2 Our approach: Earth-like planet with an atmosphere, an ocean and possibility of ice, ................but no land! + Coupled GCM

3 Climate of an aquaplanet at high obliquity

4 Tidally-locked aquaplanets

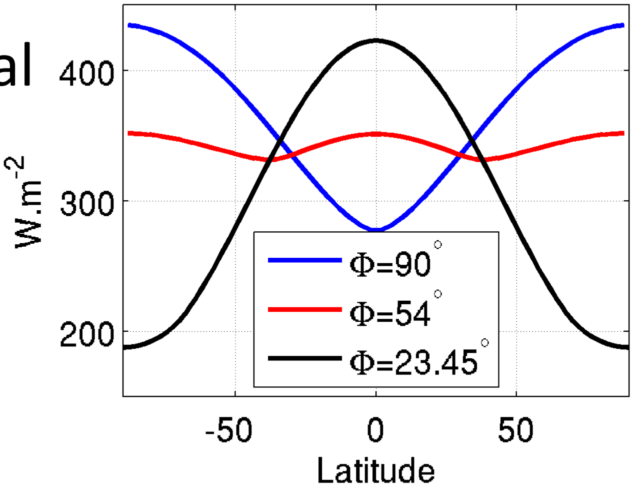
Conclusions

1 Why is the problem interesting from a climate dynamics perspective?



Incoming solar radiation

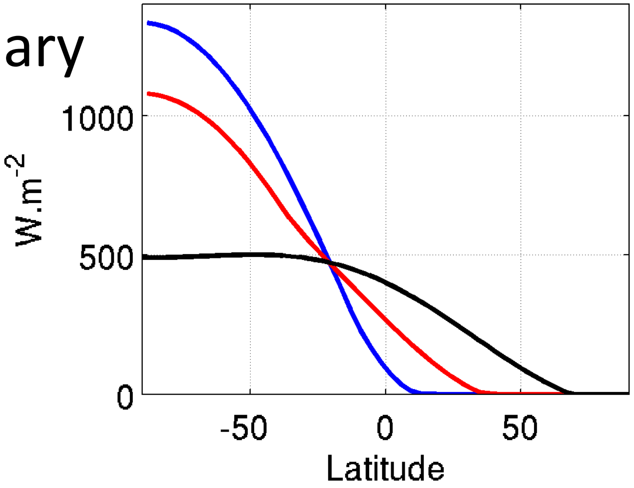
Annual mean




At high obliquity the poles are warmed more than the equator

Expect a reversal of pole-equator temperature gradient !!

January

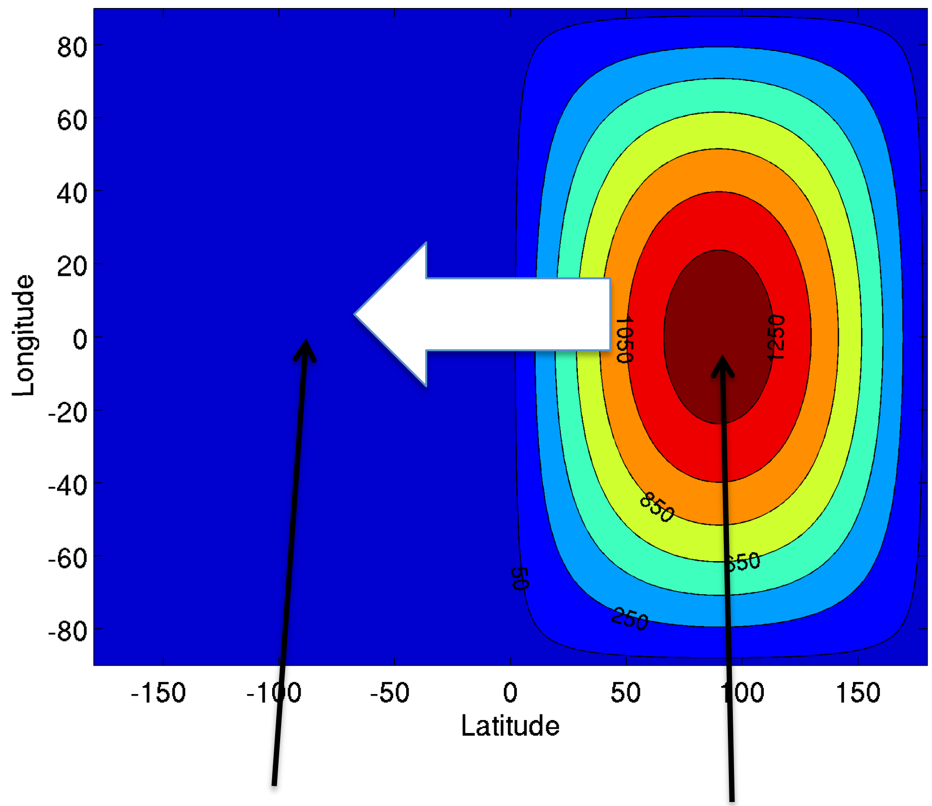



Extreme seasonal cycle

If polar temperatures are not to wildly fluctuate, heat must be stored or carried there.

Likely key role for the ocean

## Insolation for a tidally-locked Earth-like planet




0 W/m^2 1300 W/m^2

- Large and steady insolation contrast,
- Outgoing long wave on night side.

➔requires a transport from day side to night side: Atmosphere and Ocean

➔no role for storage in ocean

# Key climate questions

- What is the role of the ocean in modulating extremes of temperature (through storage and transport)?

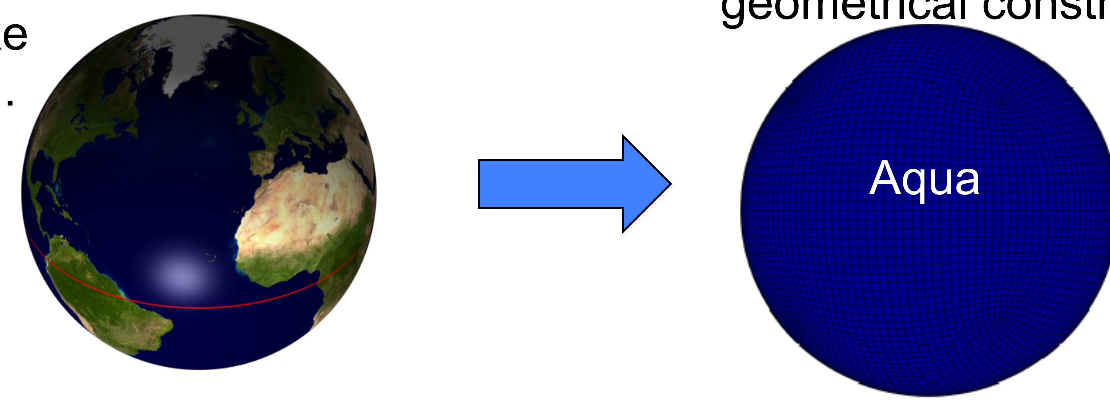
- What determines the pattern of surface winds?

  (i.e. atmos angular mtm transport) - critical to ocean circulation

- What determines the meridional energy transport and its partition between the atmosphere and ocean?

… but without geometrical constraints

Earth-like planet …

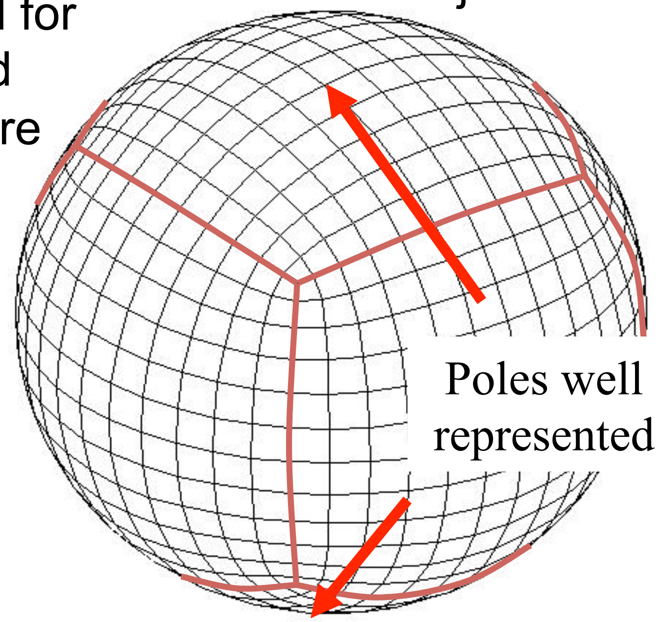


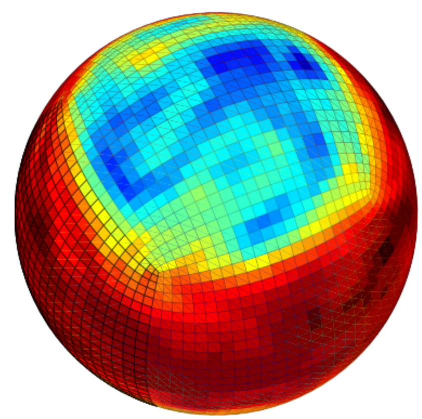

Coupled GCM

**Atmosphere-only work:** Joshi et al., 97; Joshi, 03; Williams and Kasting, 97; Williams and Pollard, 03; Merlis and Schneider, 2010; Showman et al. 2009; Heng and Vogt, 2011.

# 2 MIT GCM: Coupled Ocean-Atmosphere-Sea ice:

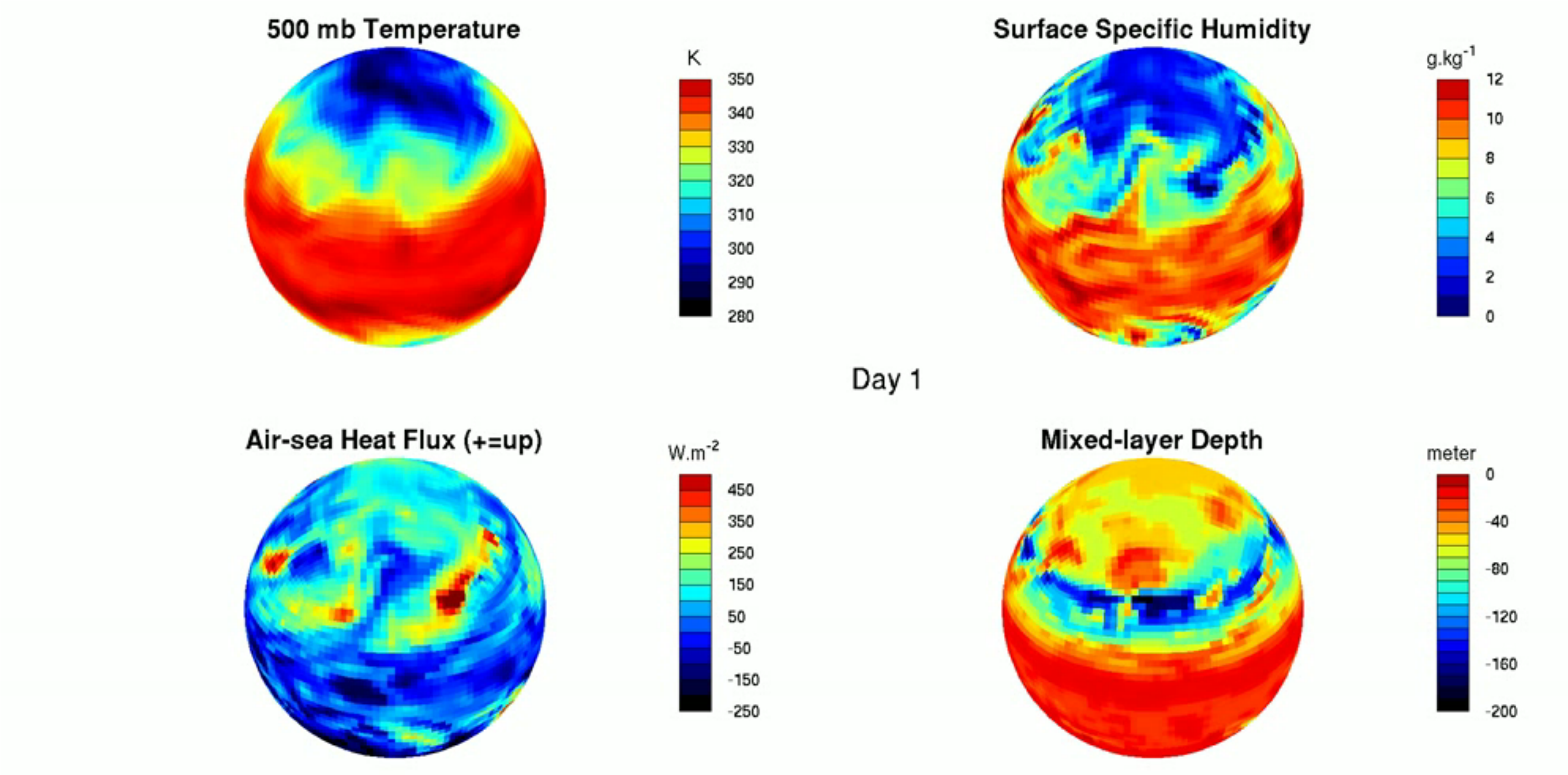
- Primitive equation models,
- Cube-sphere grid: ~3.75º,
- Synoptic scale eddies in the atmosphere,
- Gent and McWilliams eddy parameterization in the ocean,
- Simplified atmospheric physics (SPEEDY, Molteni 2003),
- Conservation to numerical precision (Campin et al. 2008)



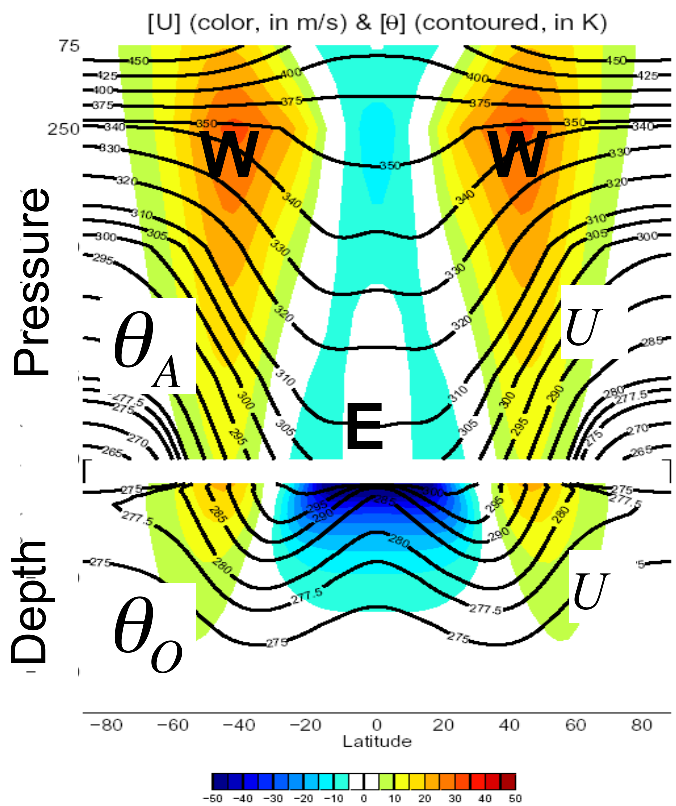



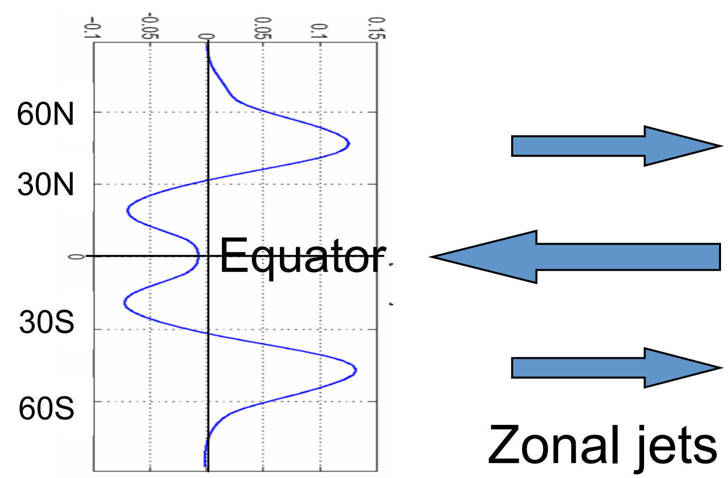
Temperature snap-shot at 500 mb.

# Aquaplanet at 23.5 obliquity



# Climate of Aquaplanet at obliquity of 23°

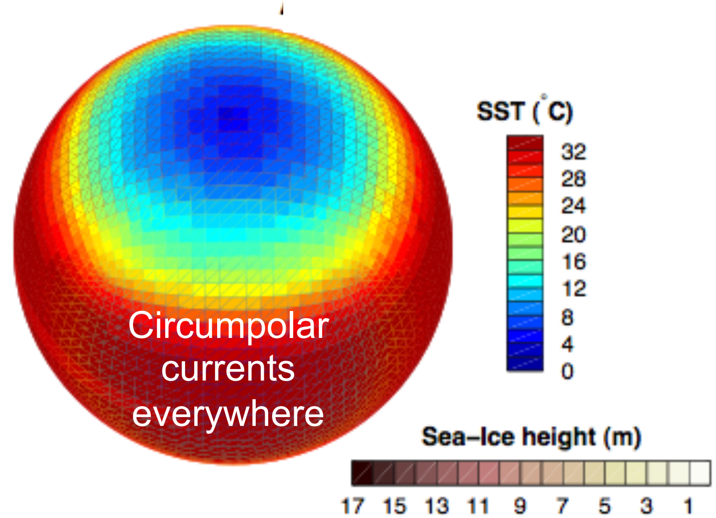



Pattern of surface winds

Zonal jets in ocean

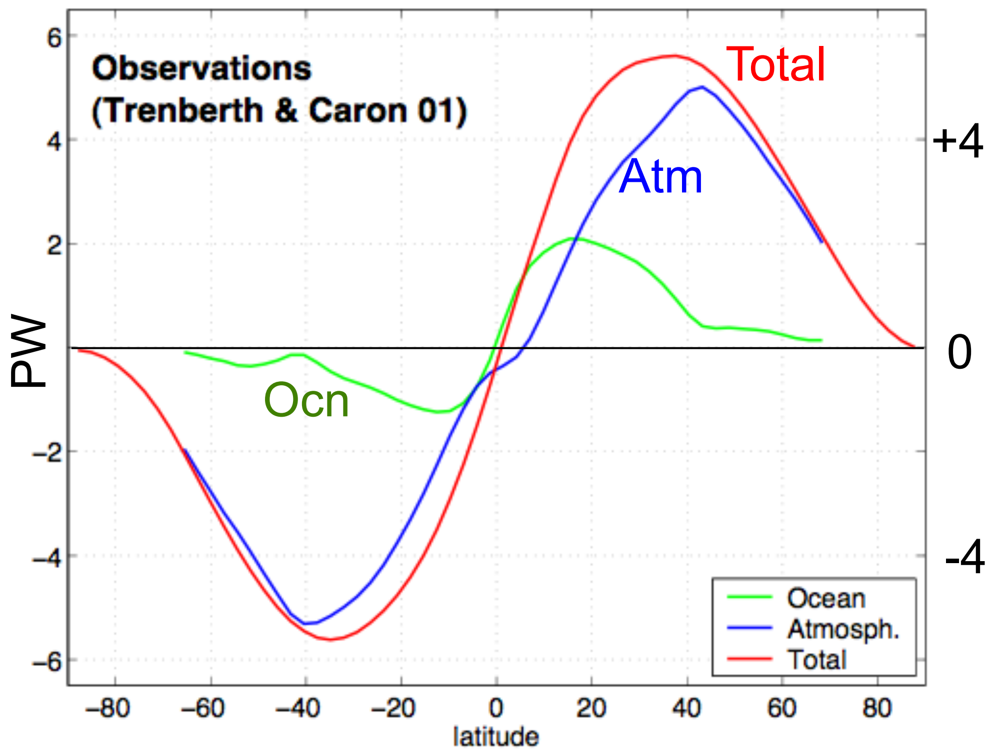
SST & sea ice



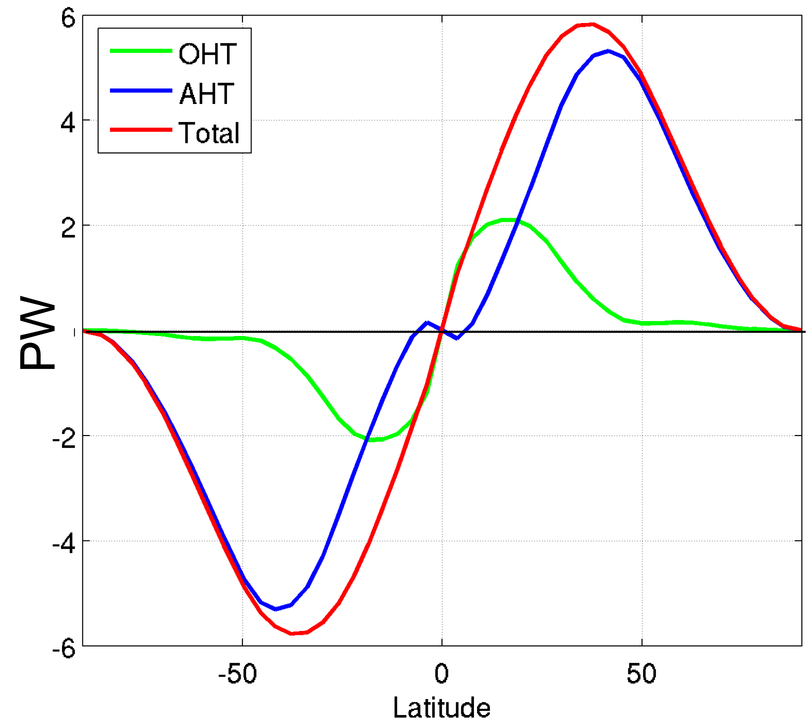

Aquaplanet solution discussed in Marshall, Ferreira et al. (2007, J. Atmos. Sci.)

# Energy transports in an Aquaplanet

Today's Earth climate




Aquaplanet at 23.5° obliquity

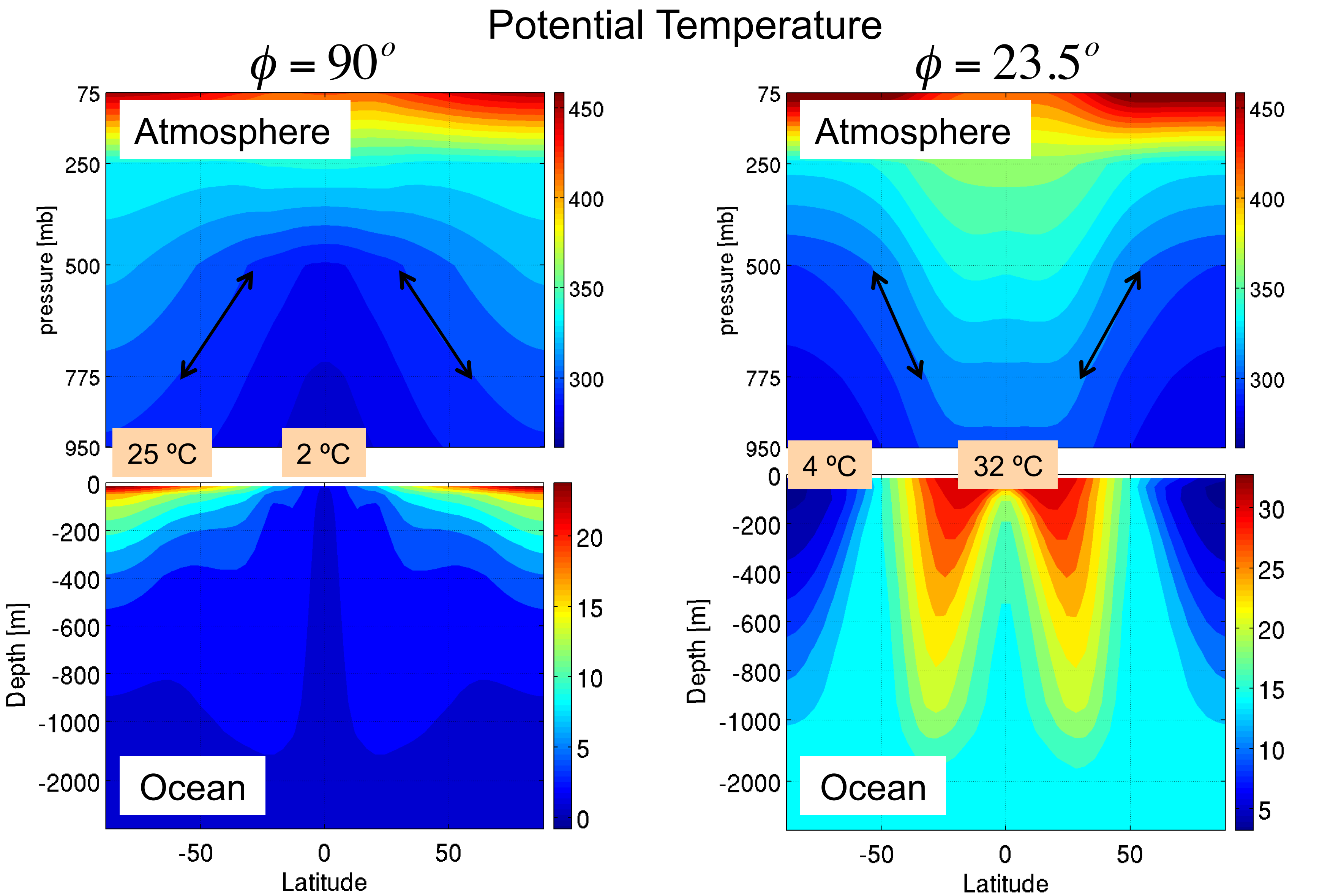



- Patterns and magnitudes of transports are well captured in an Aquaplanet

➔ to first order, continents are not necessary to explore the climate of an Earth-like planet

# 3 Climate at high obliquity

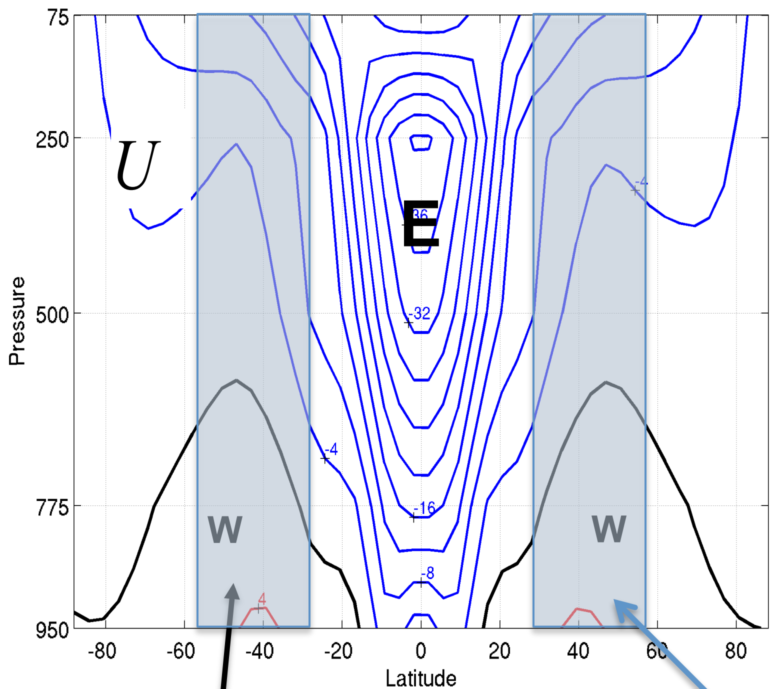
Annual means



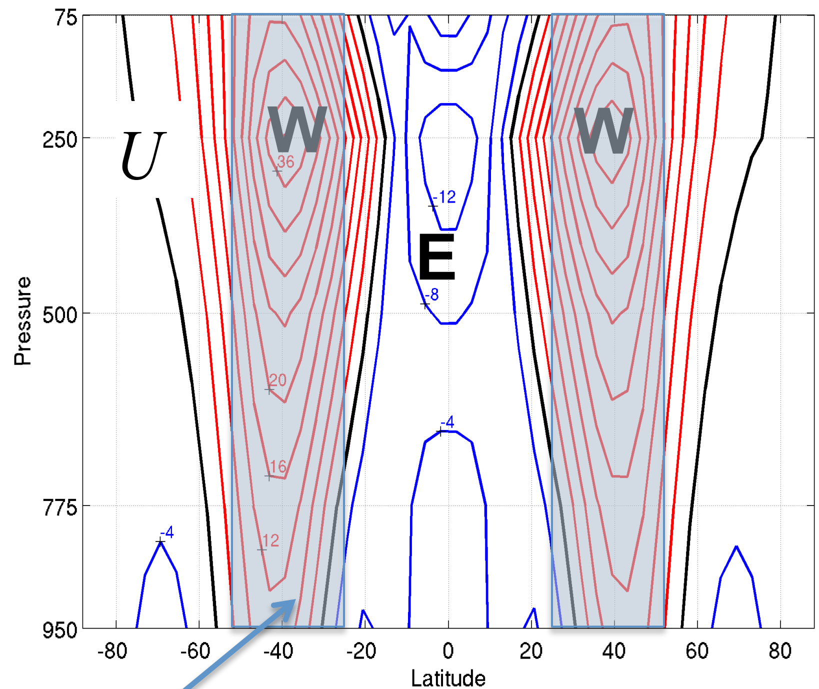
# Winds

Annual means

$\phi = 90^o$




$\phi = 23.5^o$




Surface westerlies in middle latitudes, easterlies in tropics

**Baroclinic zones**

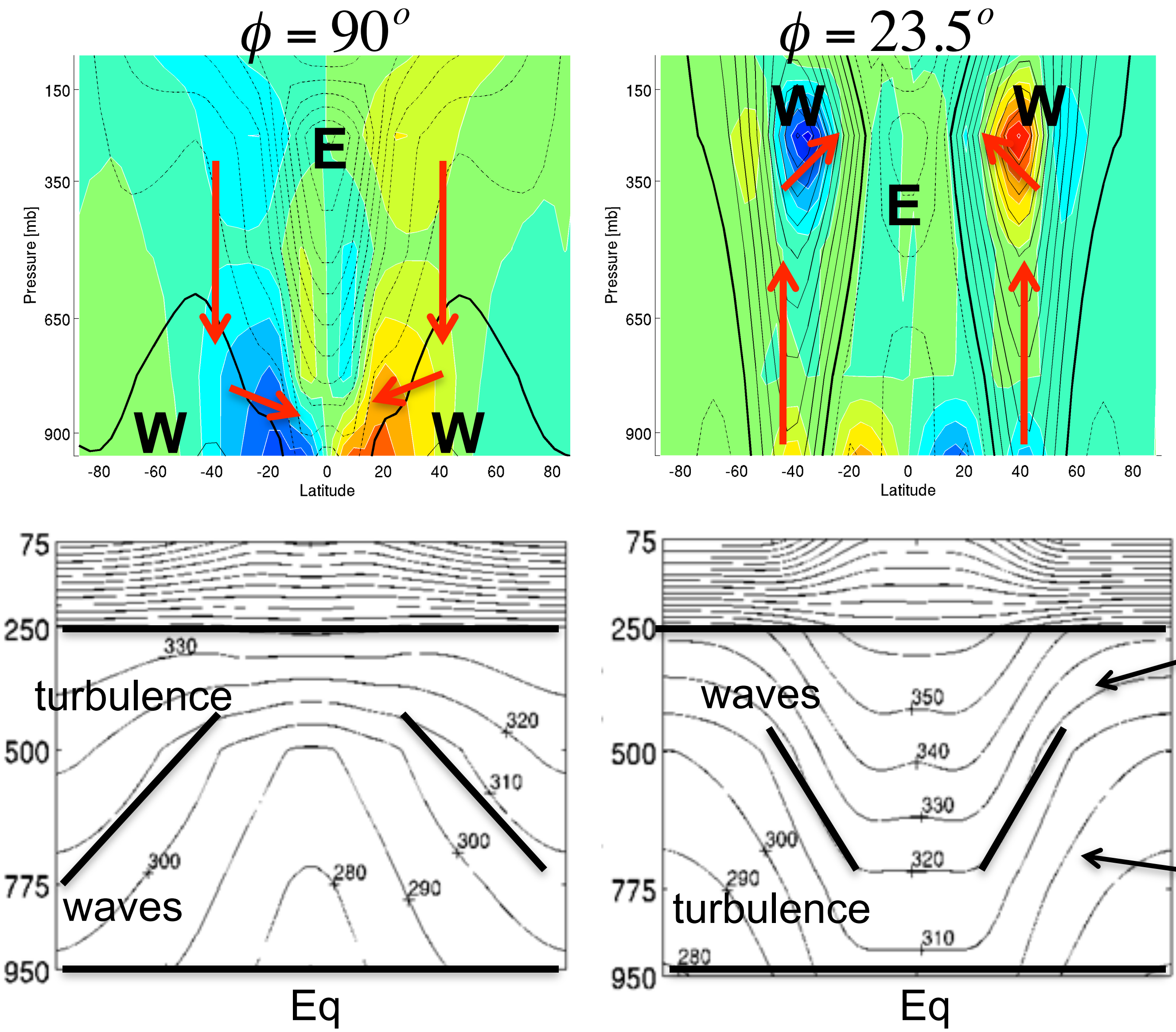
$$\tau_S = -\int_{bottom}^{top} \partial_y [u'v'] dz$$

Surface wind stress = Convergence of eddy momentum fluxes

# Asymmetries between easterly and westerly sheared flows

$\overline{u'v'}$ (colors)

$\overline{U}$ (contours)



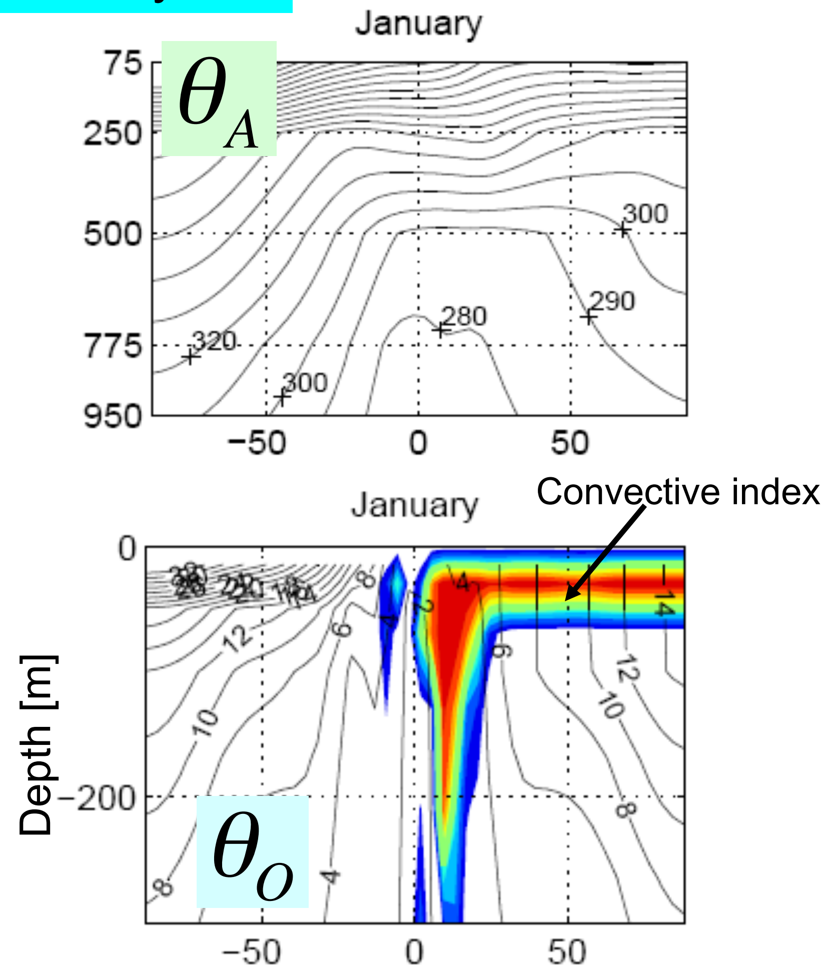

Eliassen-Palm fluxes:

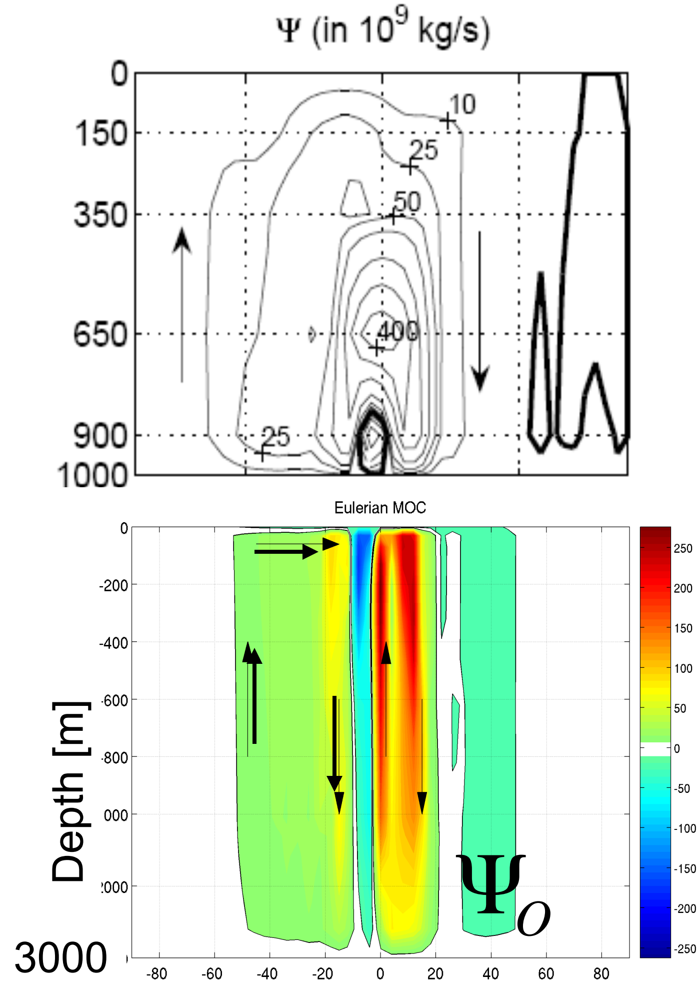
$$EP = \left( \overline{-u'v'}, f\,\frac{\overline{v'\theta'}}{\overline{\theta}_z} \right)$$

$$\frac{\overline{q}_y}{\beta} >> 1$$

$$\frac{\overline{q}_y}{\beta} \approx 1$$

# Seasonal Cycle

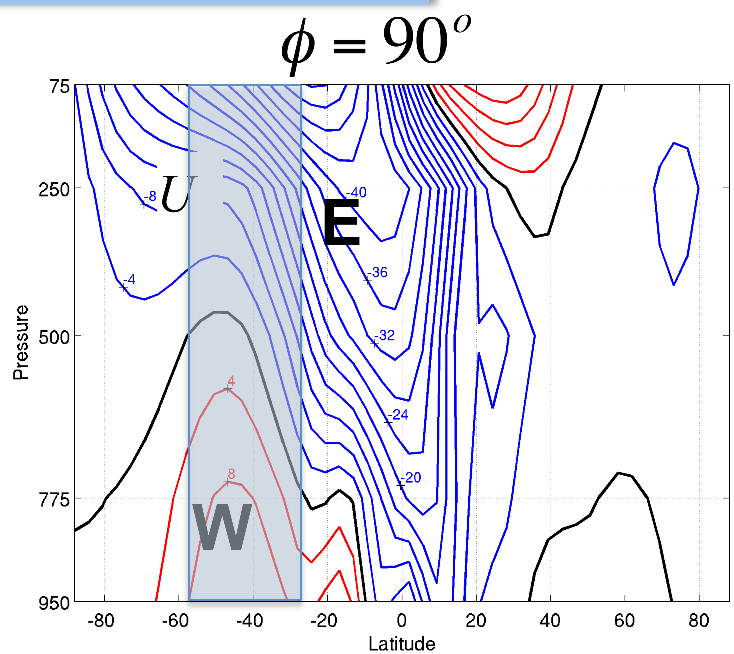


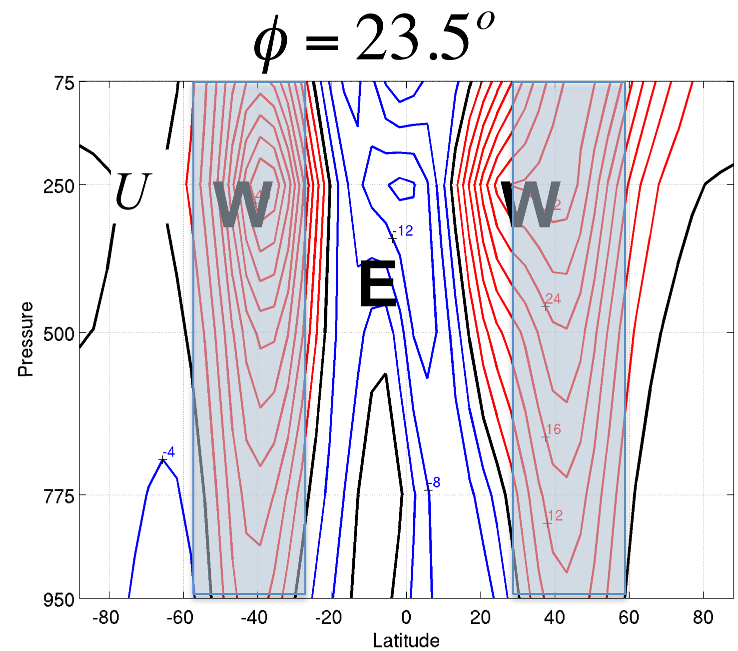



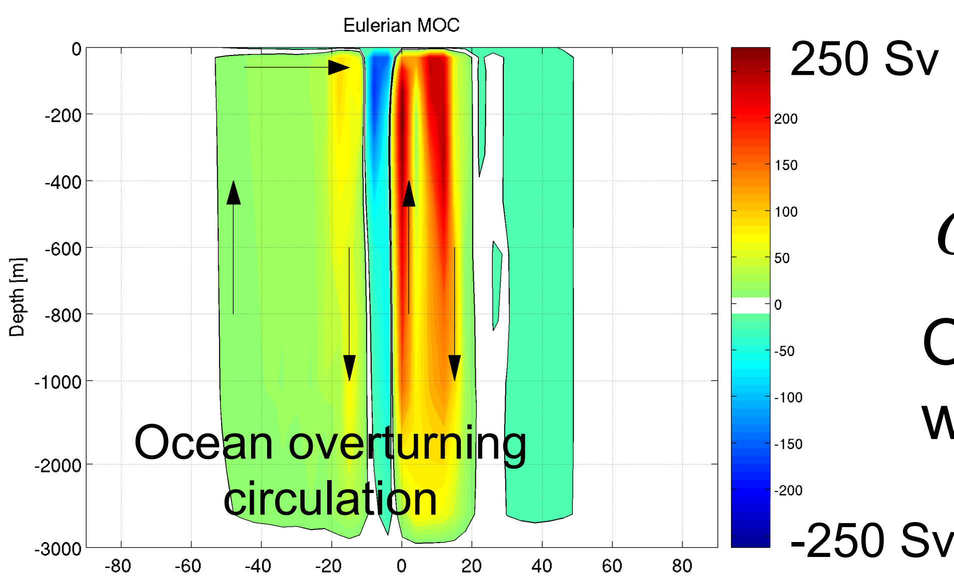

**Atmosphere** | Strong surface temperature gradient in summer hemisphere (~40K) and weak gradient in winter hemisphere (~10K)

**Ocean** | Seasonal variations restricted to top 200m
- --- amplitude of ~12K at pole
- --- almost steady and ~2K at equator

# January winds



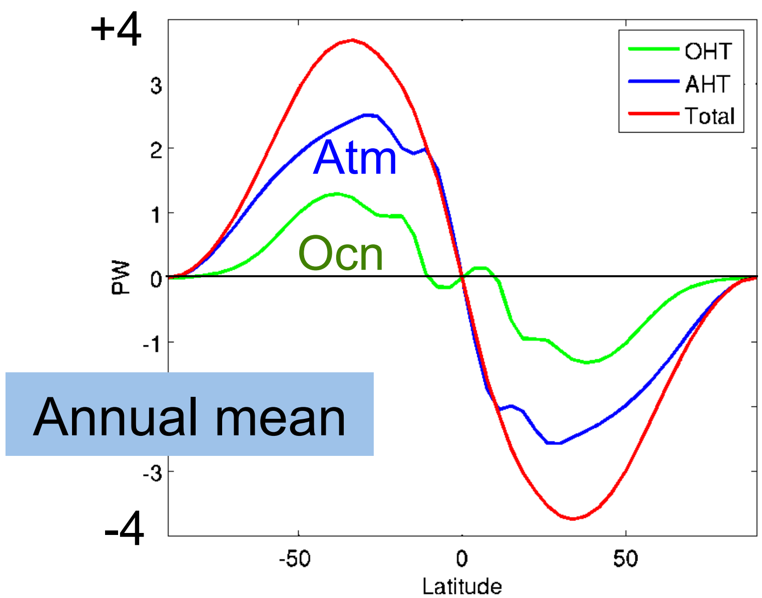



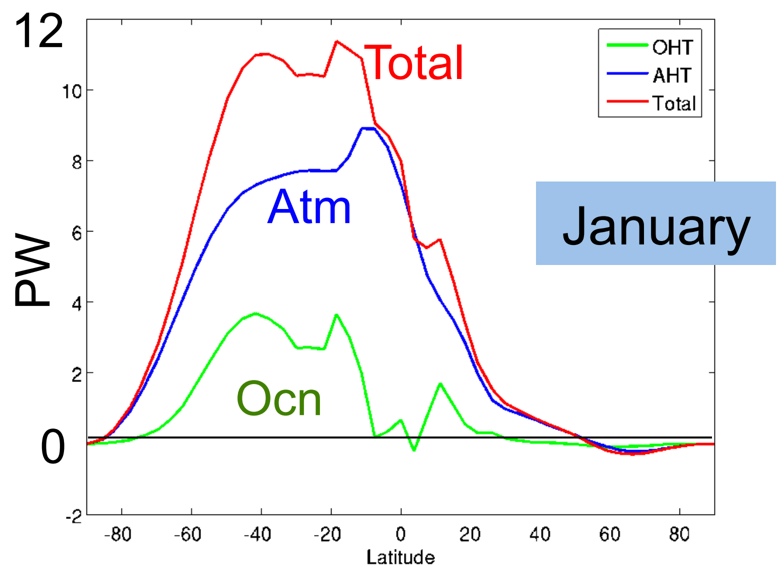



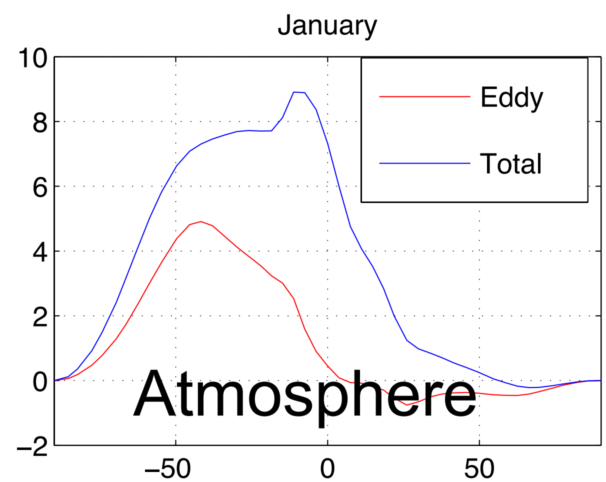

$$OHT \approx \rho_O C_P \Psi_O \times \Delta T$$

OHT dominated by Eulerian wind-driven circulation

# Atmos and Ocean energy transport at high obliquity



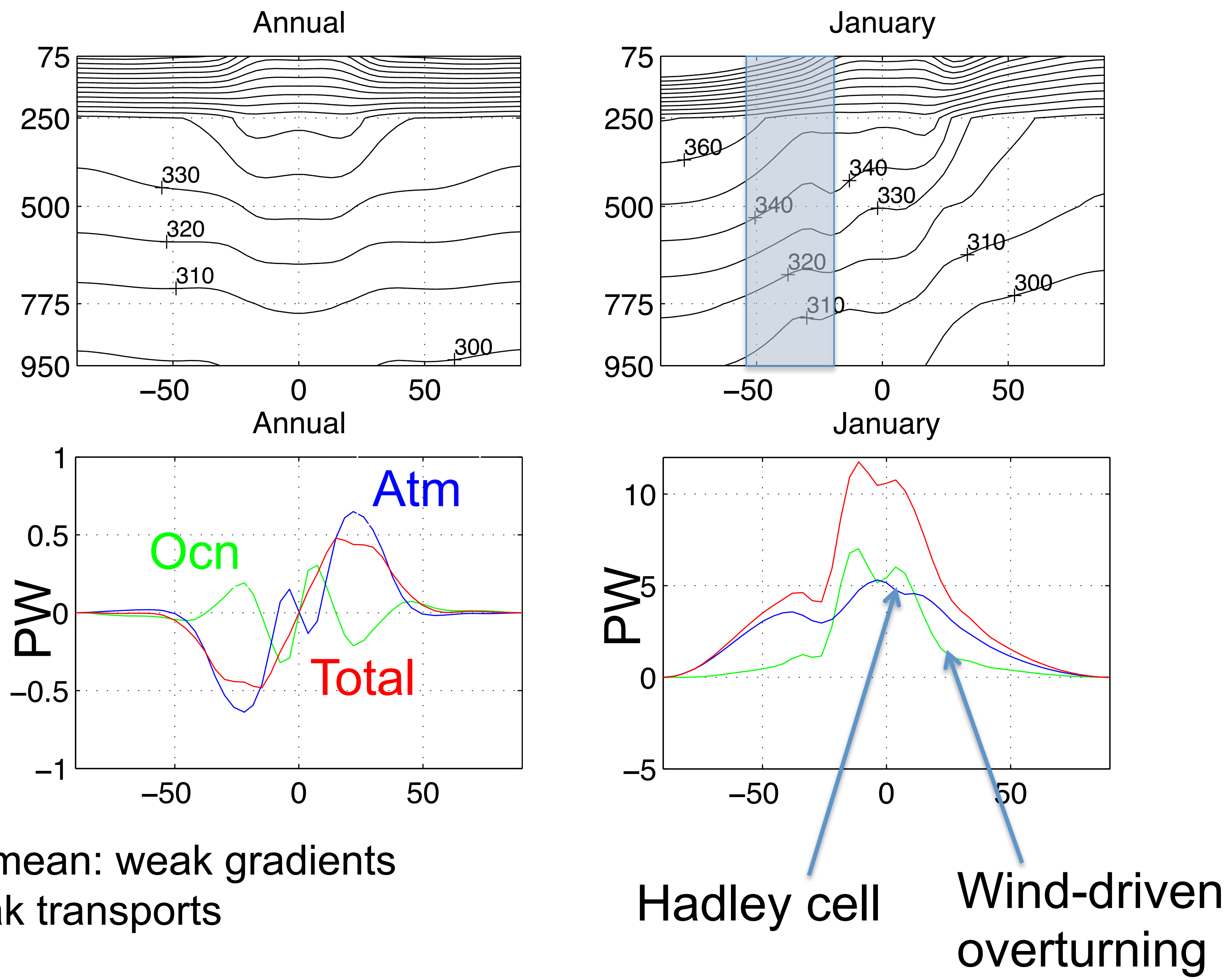




Atmosphere and Ocean heat transports are achieved seasonally:
----- large in the summer hemisphere
----- nearly vanish in the winter hemisphere

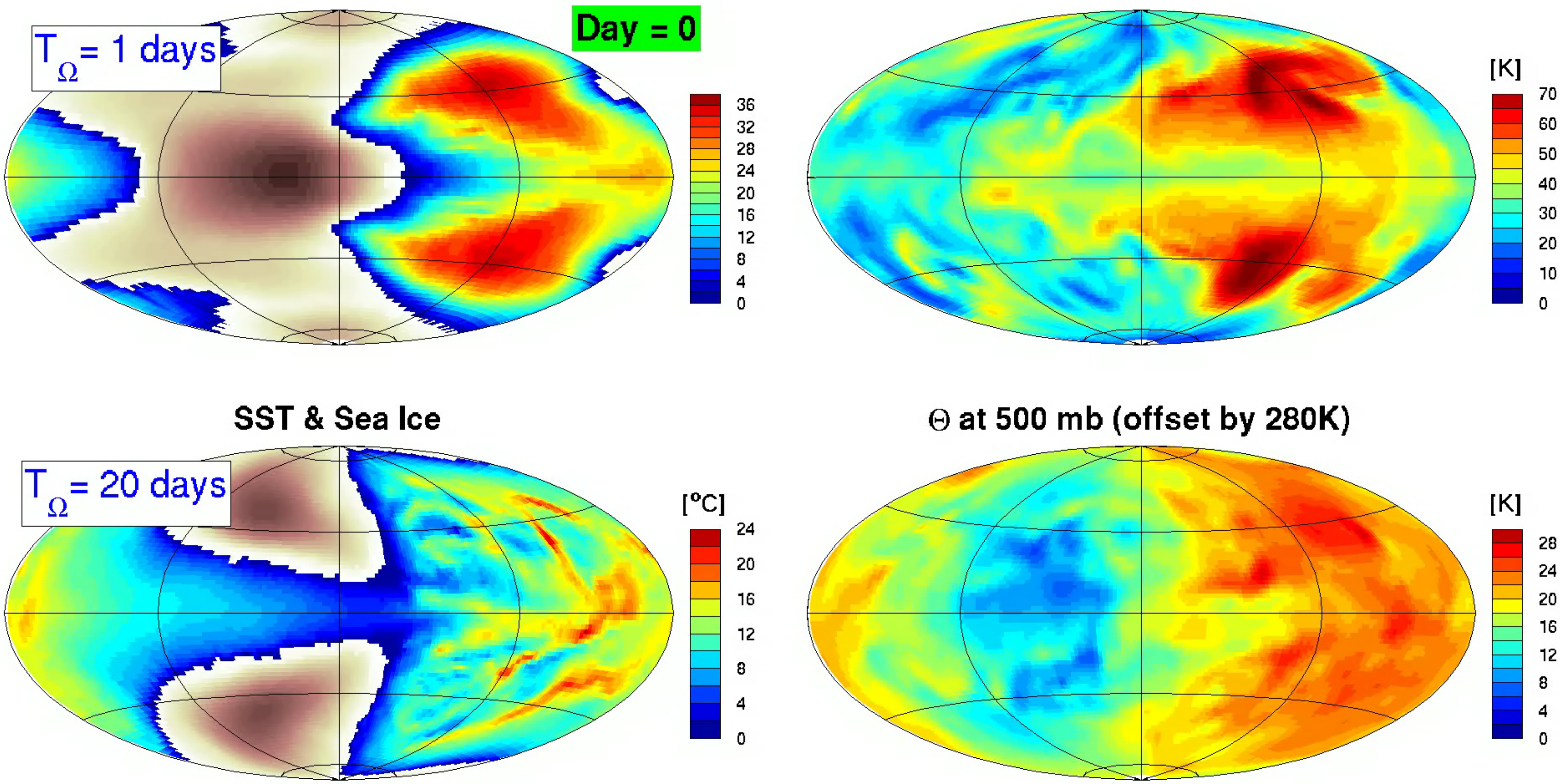
Equatorward transport everywhere
----- down large-scale temperature gradient

# Climate at 54 degree obliquity



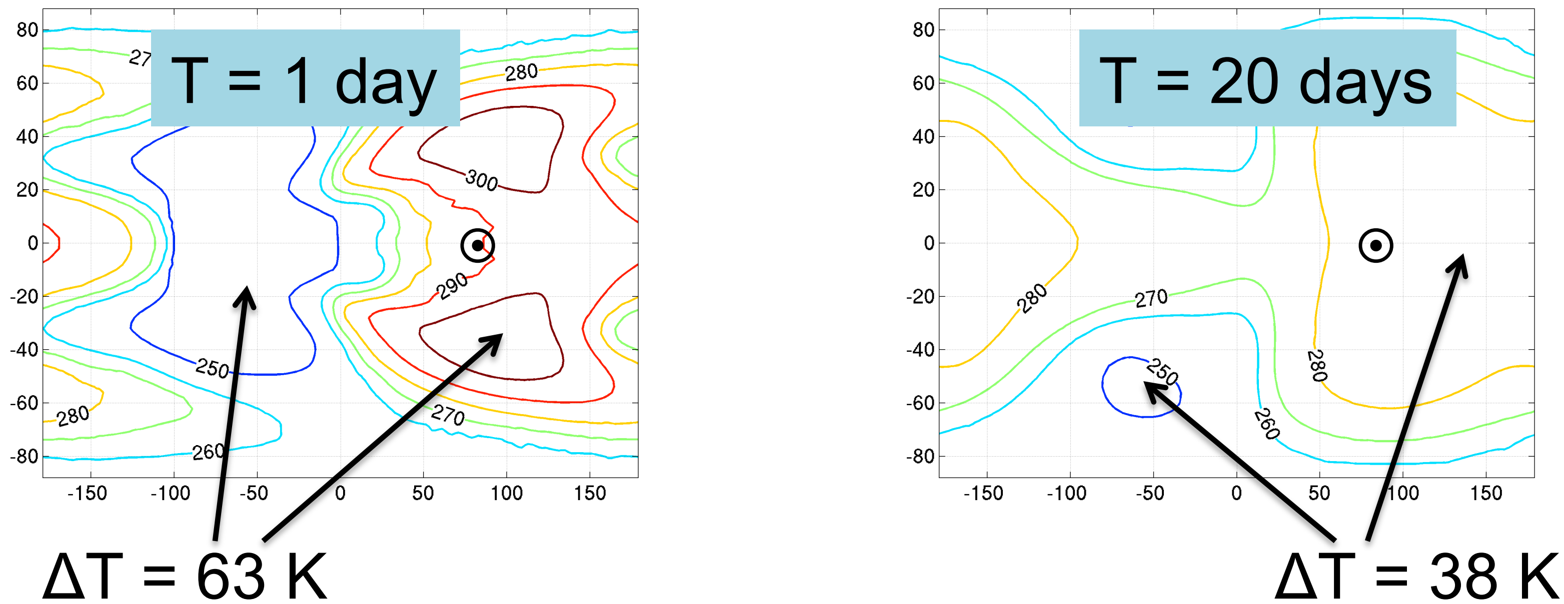

Annual mean: weak gradients and weak transports

# 4 Tidally-locked Aquaplanet

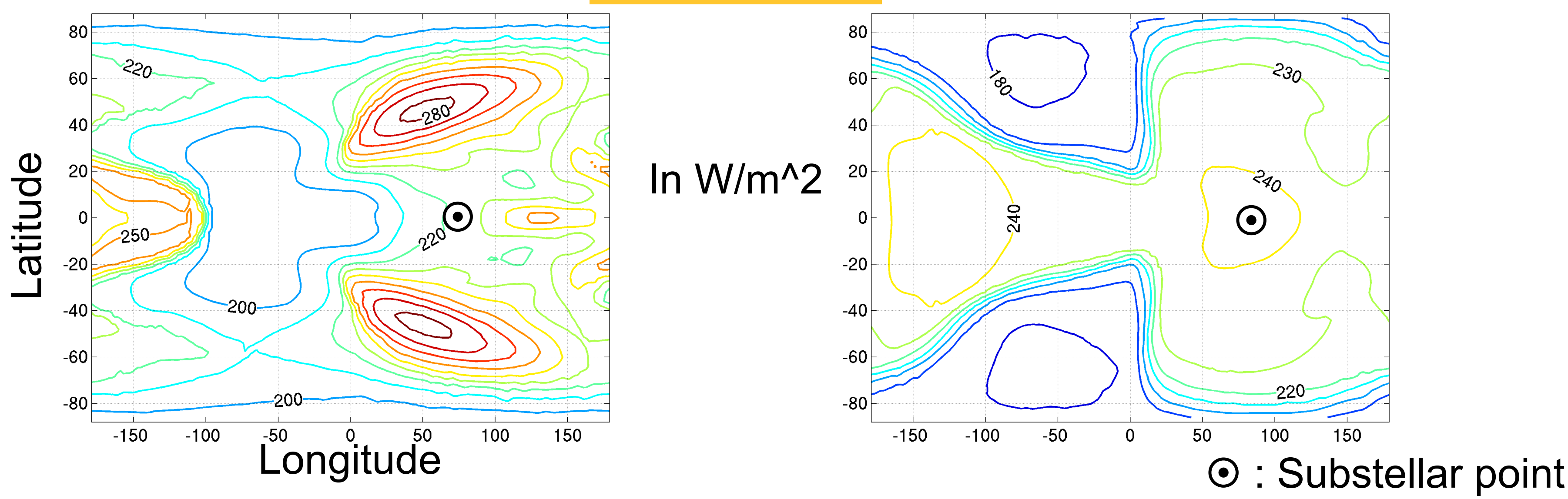



Rossby radius $= \dfrac{NH}{f} = \begin{cases} \text{800 km (Atm)} \\ \text{50 km (Ocean)} \end{cases}$ at T=1 day → 16000 km, 1000 km at T=20 days

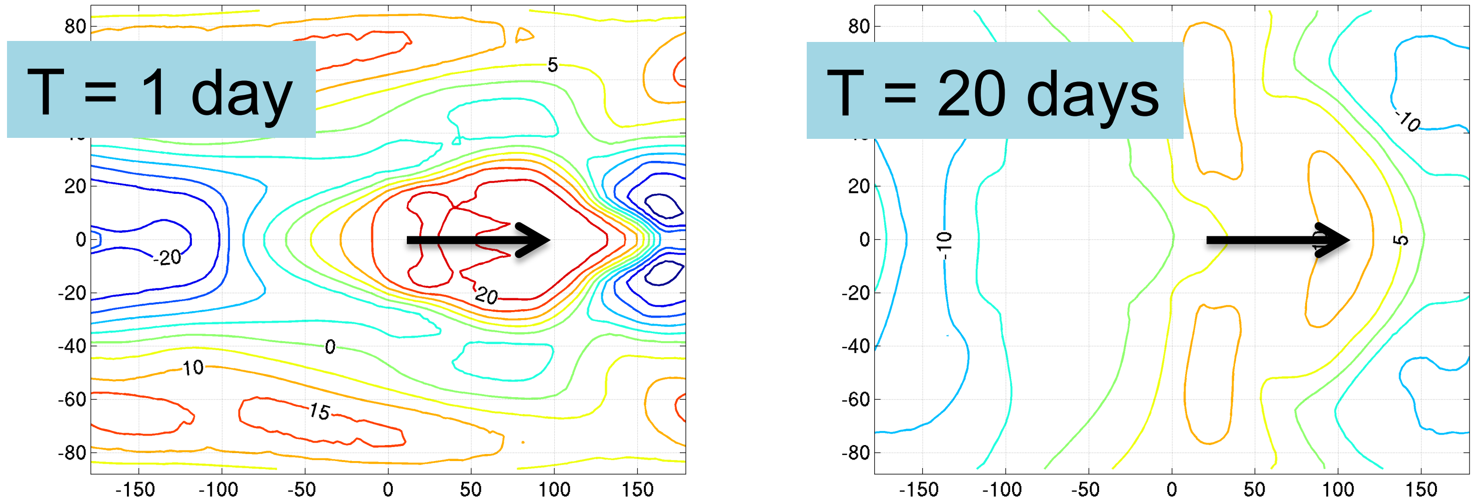
# Surface air temperature:



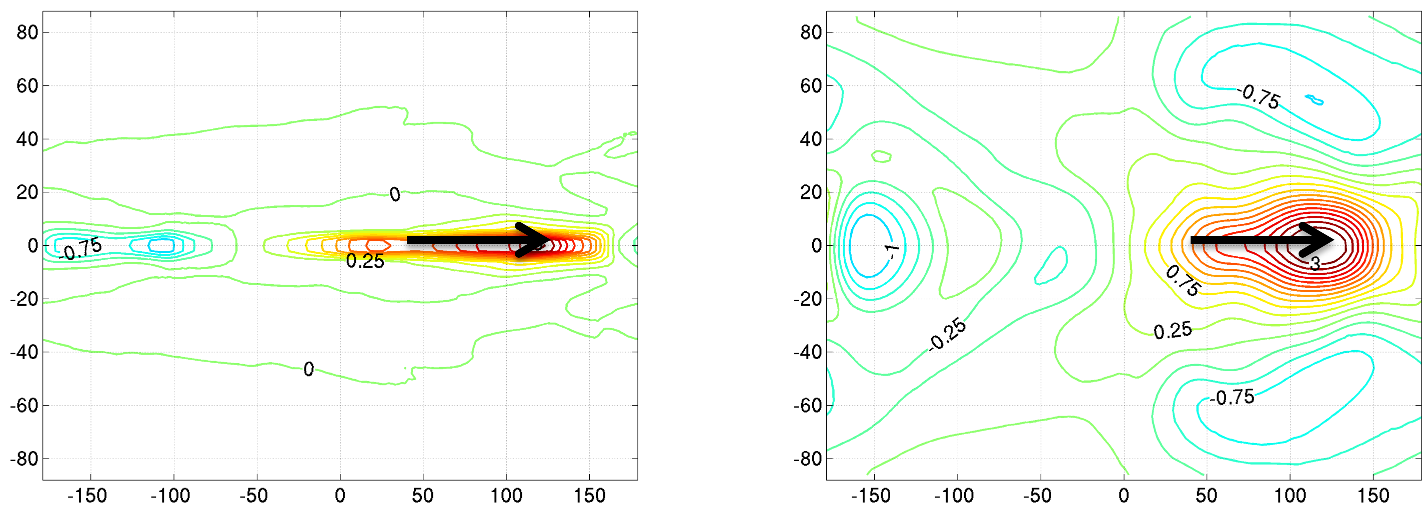

# TOA OLR:



# Surface winds




# Surface ocean currents

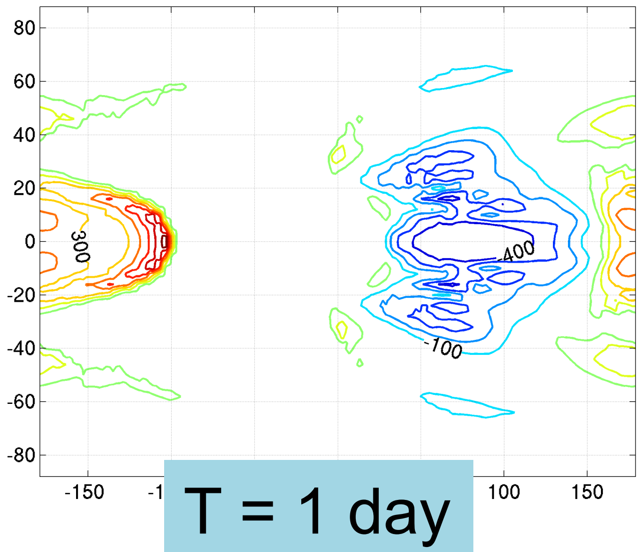


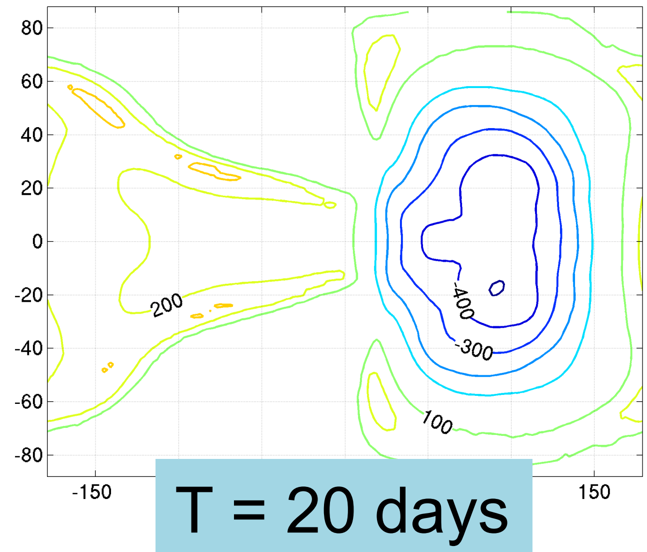

Merlis and Schneider, 2010; Showman and Polvani 2011, Heng and Vogt, 2011

# Ocean Surface heat flux

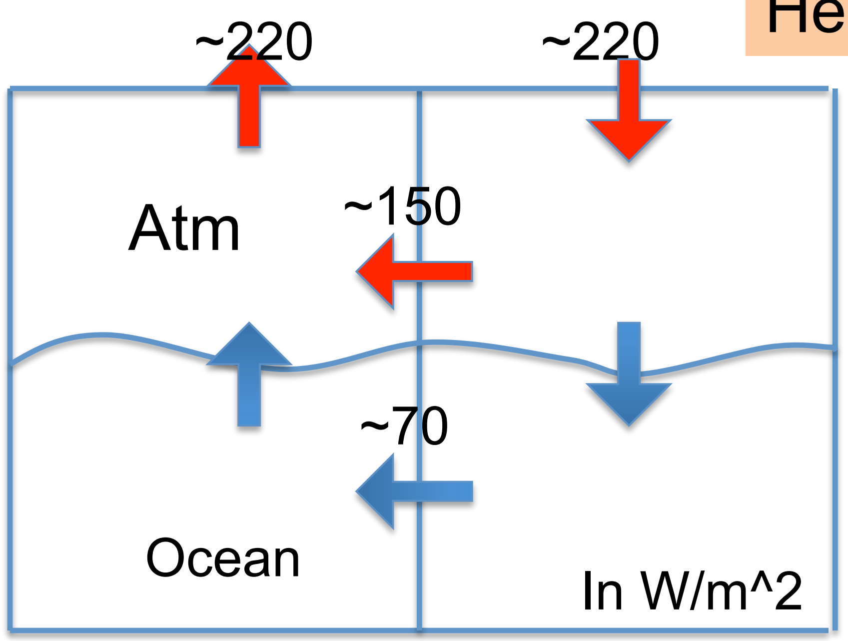
(W/m^2)

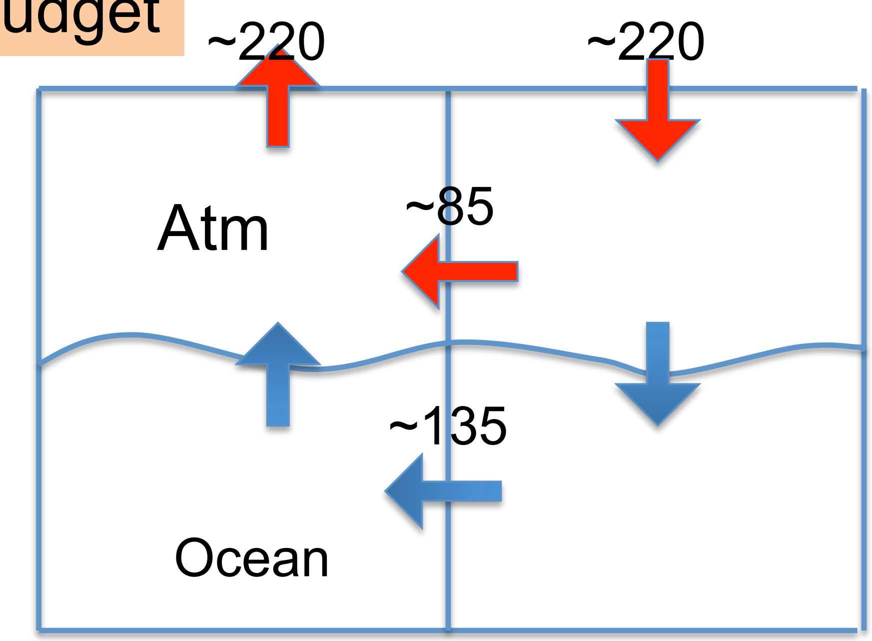
Positive = into the atmosphere



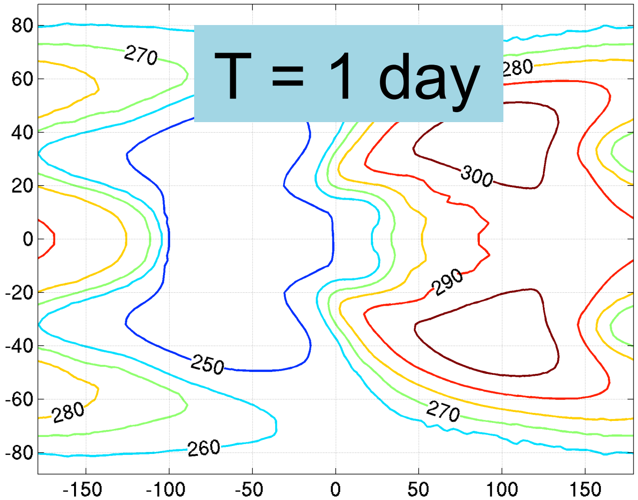



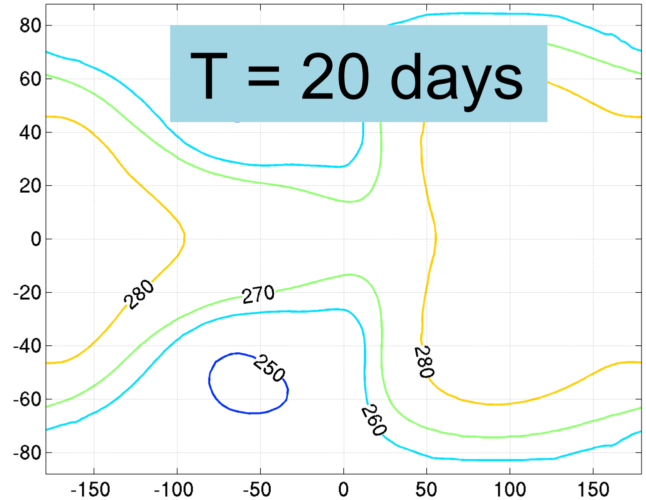

## Heat budget



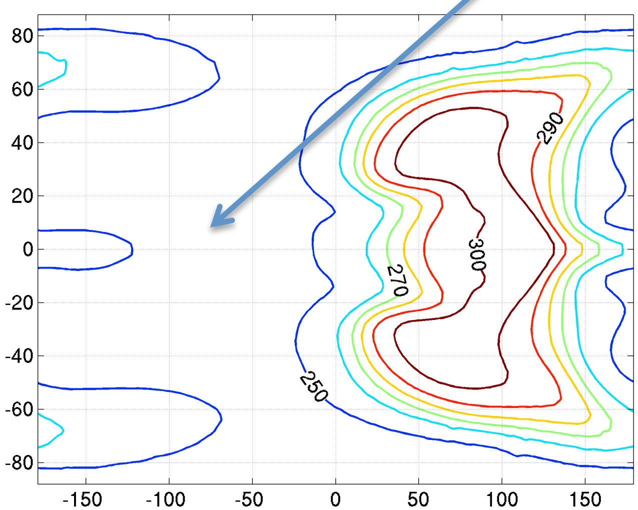
# Surface air temperature:

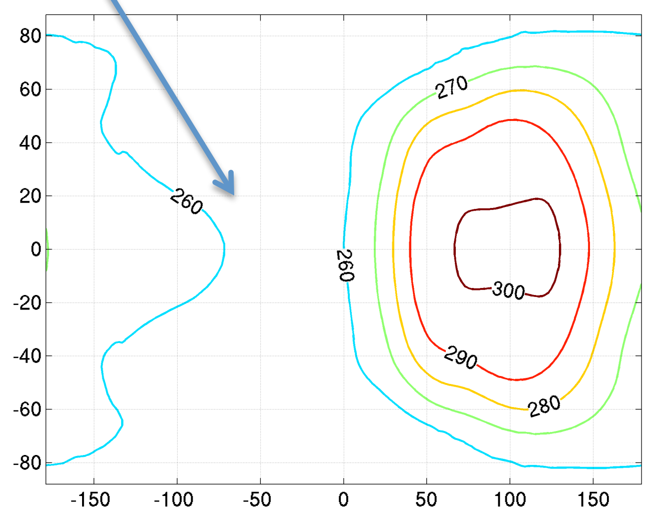



Coupled GCM

Ice covered night side




Atm GCM
+
Slab ocean

# Conclusions

## At high obliquity:

- Surface climates are rather mild despite extreme summer insolation and long polar nights – seasonal cycle between 10 and 35K.
- Baroclinic eddies are the primary heat transport mechanism – Hadley cell plays lesser role,

- Ocean plays an important role in heat transport, carrying about 1/3 of the total
- Wind-driven middle-latitude Ekman cells are the primary mechanism subtropical/equatorial cells play a lesser role
- Heat is stored in the ocean in the summer and delivered to the atmosphere in the winter, keeping it warm and somewhat moist.

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## Tidally locked case:

- Surface climates are rather mild despite extreme,
- Both ocean and atmosphere transport energy from the day to the night side,
- as the rotation rate decreases, nigth-day heat transport moves to the ocean,
- the ocean is more “efficient” at smoothing out the night-day temperature constrast.