Introduction to Tropical Climate

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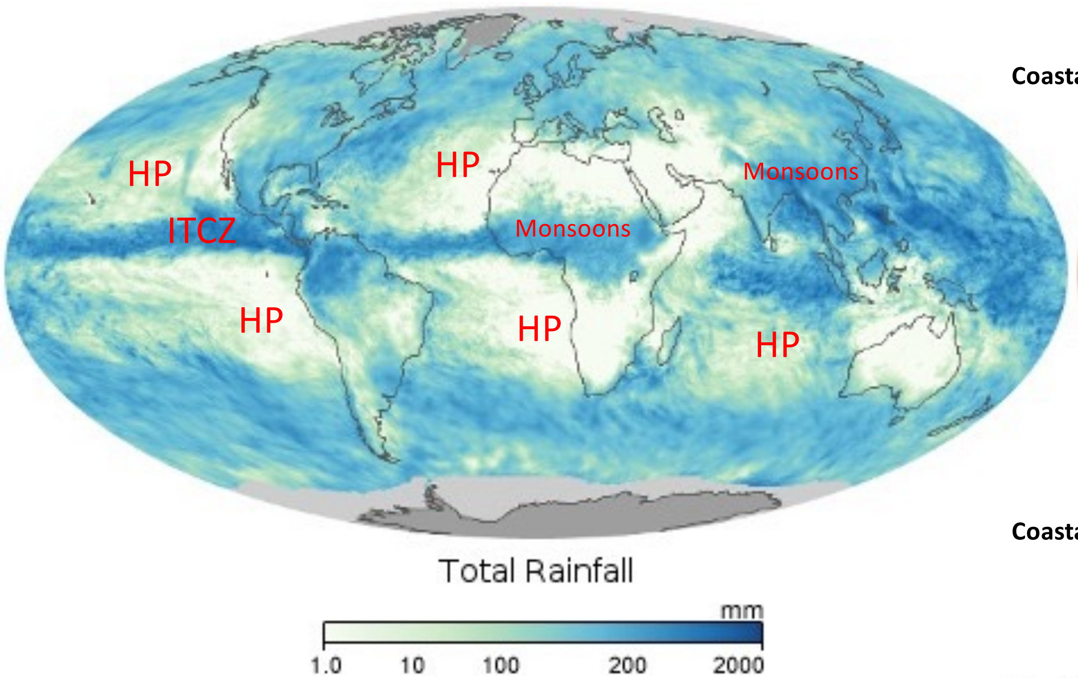
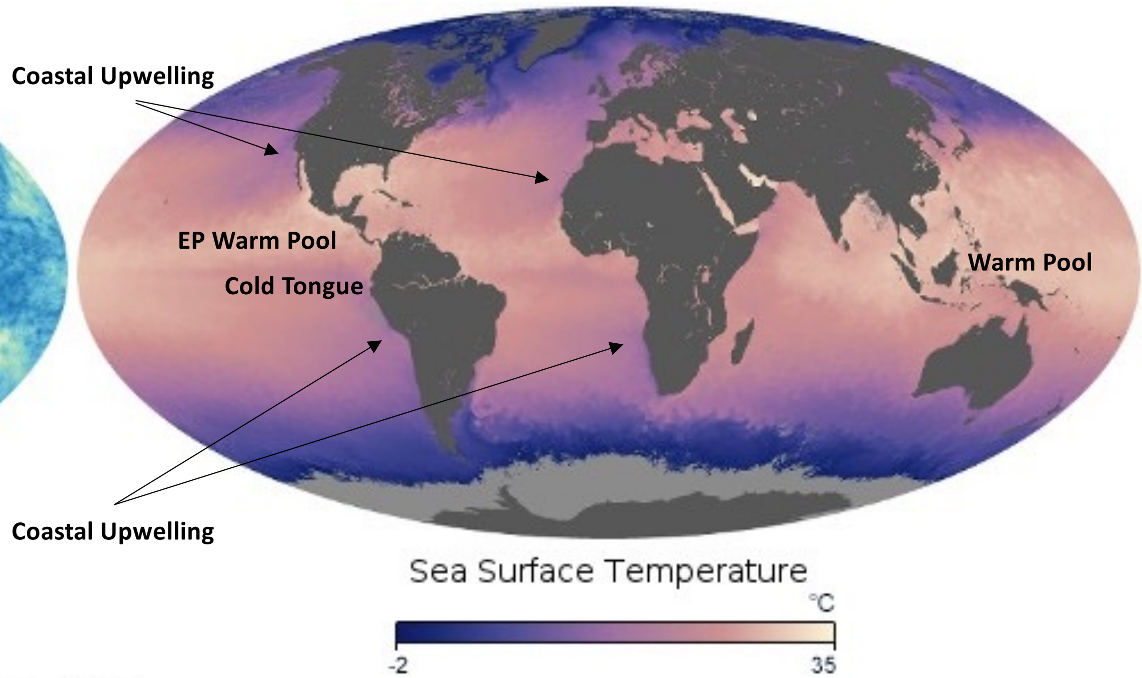
ICTP Summer School on Atlantic Variability and Tropical Basin Interactions at Interannual to Multi-Decadal Time Scales

Salient Features of Tropical Climate





July 2002

Based on observations by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite

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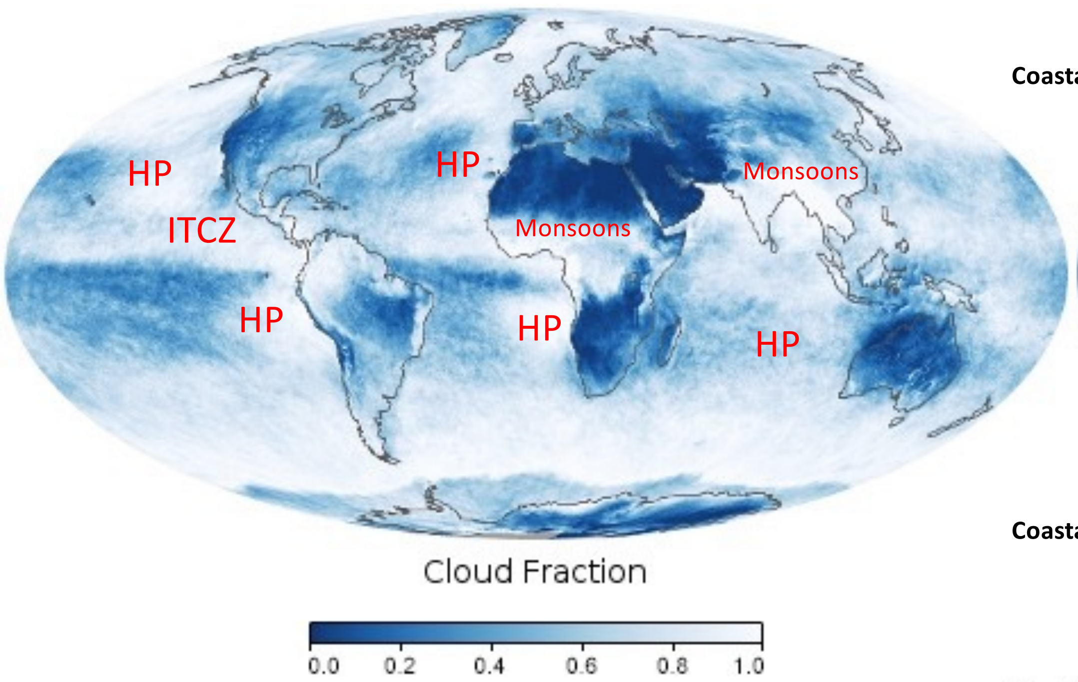
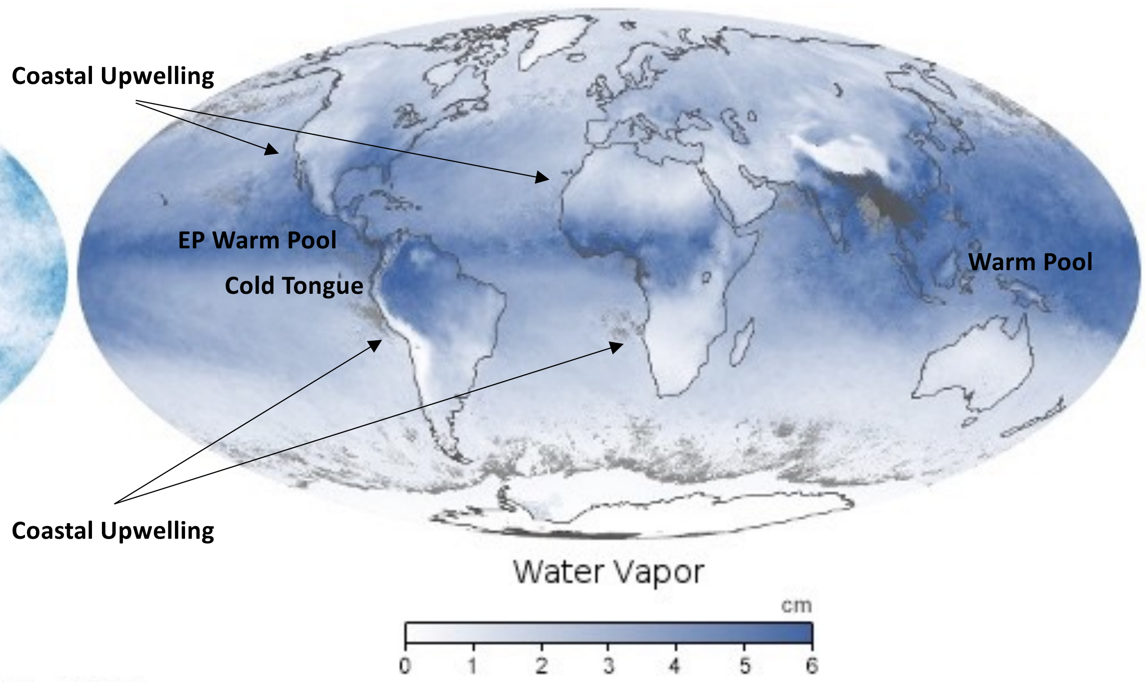
https://earthobservatory.nasa.gov/

Salient Features of Tropical Climate





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Based on observations by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite

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What processes are responsible for these salient features of tropical climate?

Outline

The Tropical Atmosphere

- Radiative Equilibrium
- Radiative Convective Equilibrium
- Add Dynamics – Large-scale thermally direct circulations

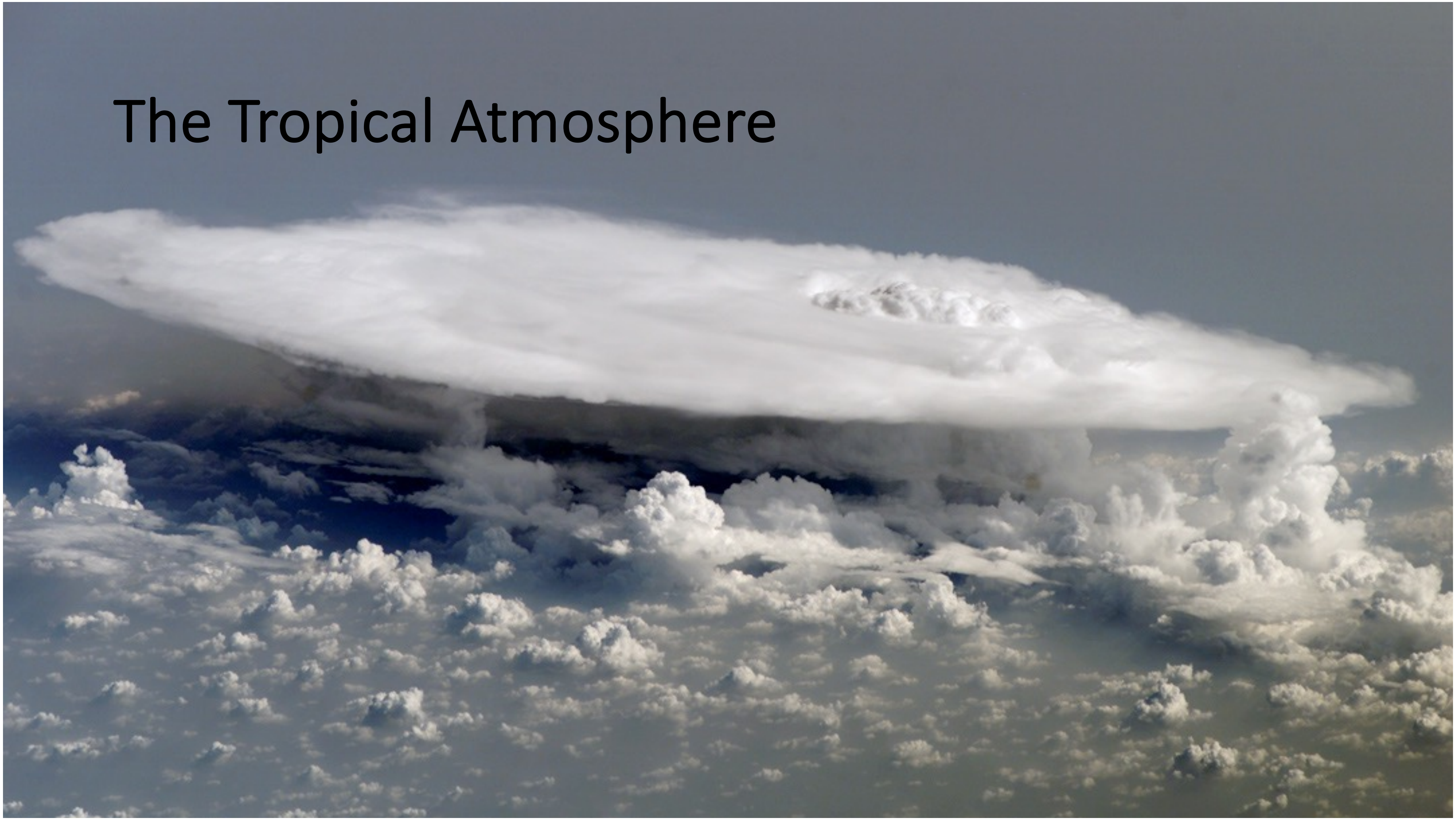
The Tropical Ocean

- Forced from above – surface buoyancy and momentum fluxes
- Wind Driven Circulation
- Thermal structure of the Tropical Ocean

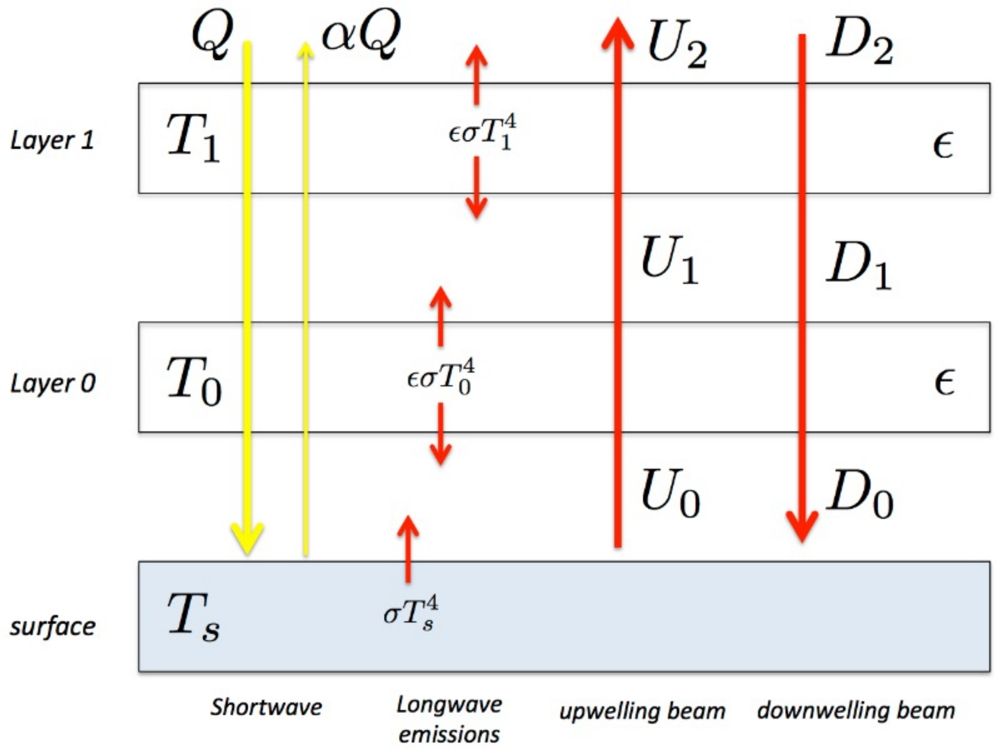
Tropical Ocean-Atmosphere Interactions

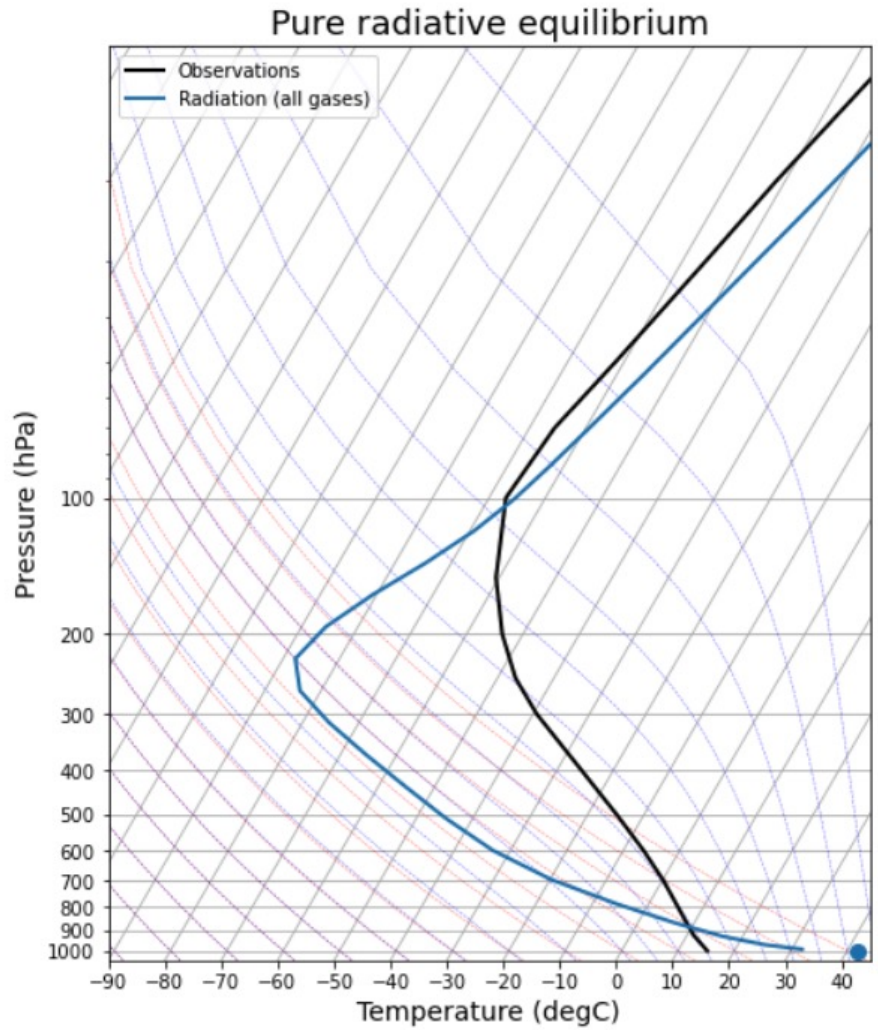
- Coupled Theory
- Diagnosing coupled processes
- The role of coupling in the season cycle

The Tropical Atmosphere



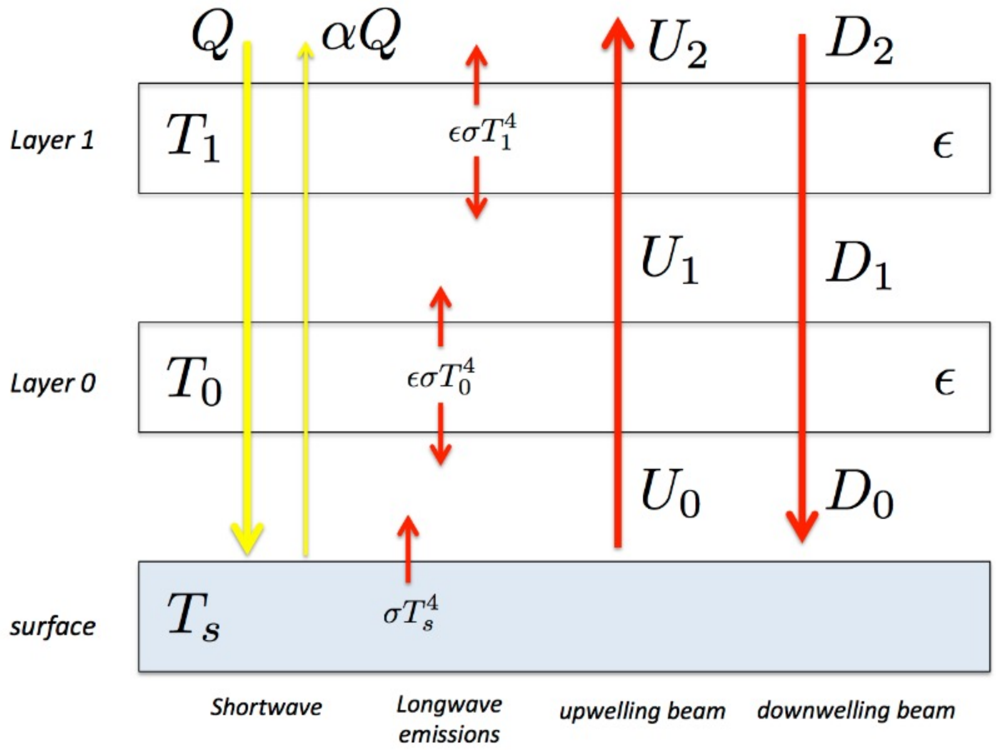
Radiative Equilibrium

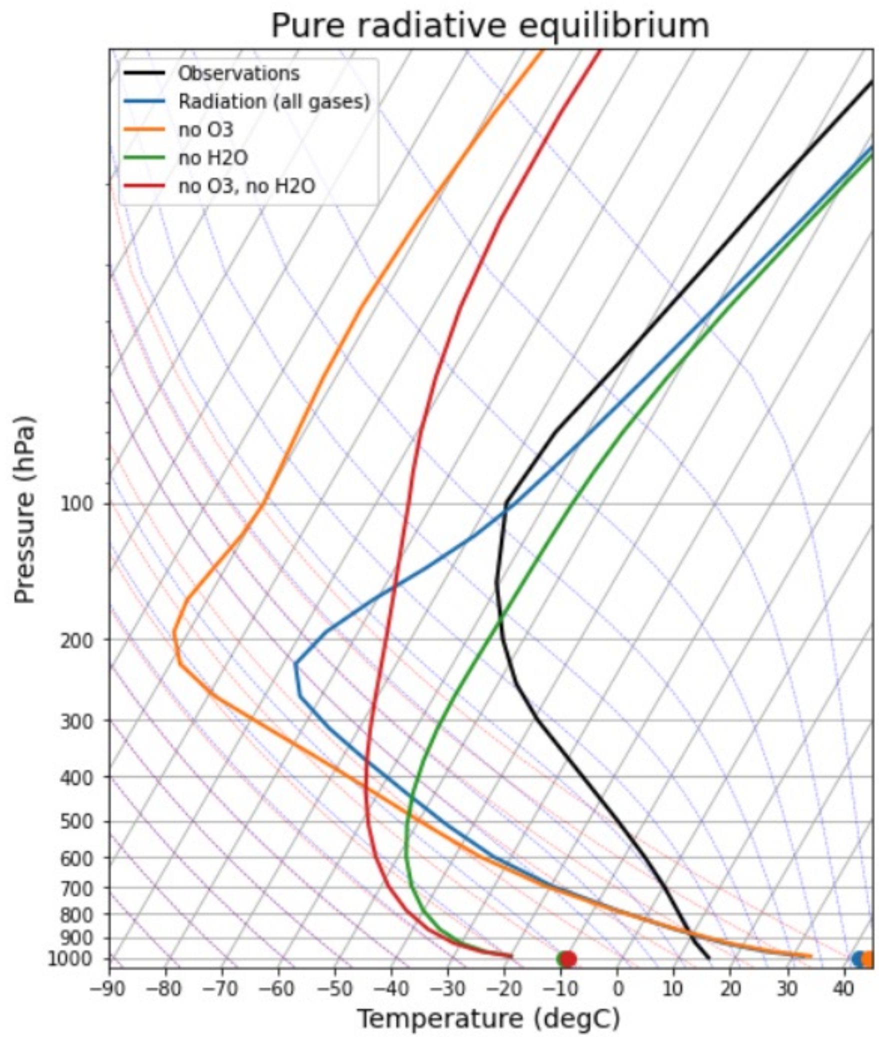




https://brian-rose.github.io/ClimateLaboratoryBook/courseware/radeq.html, Rose 2018

Radiative Equilibrium





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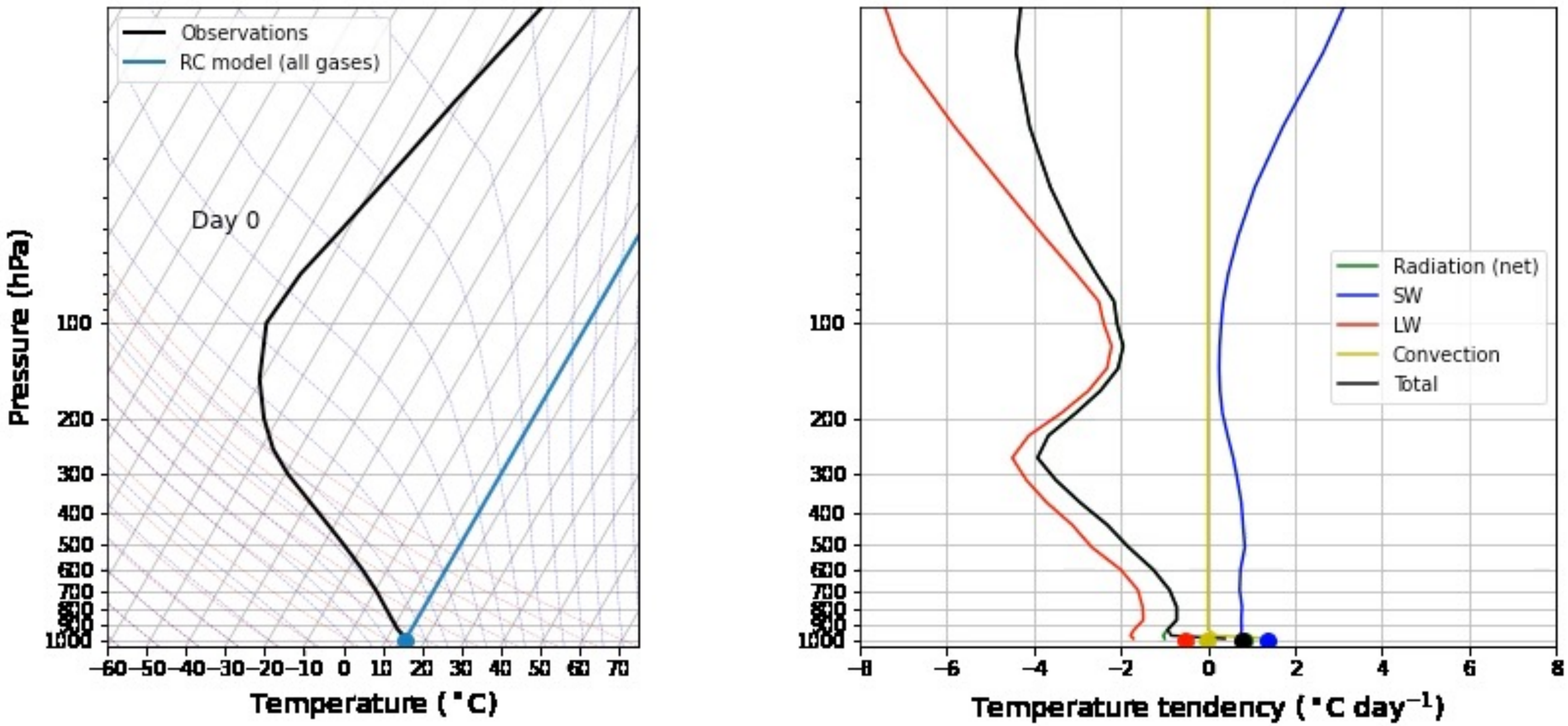
Radiative Convective Equilibrium



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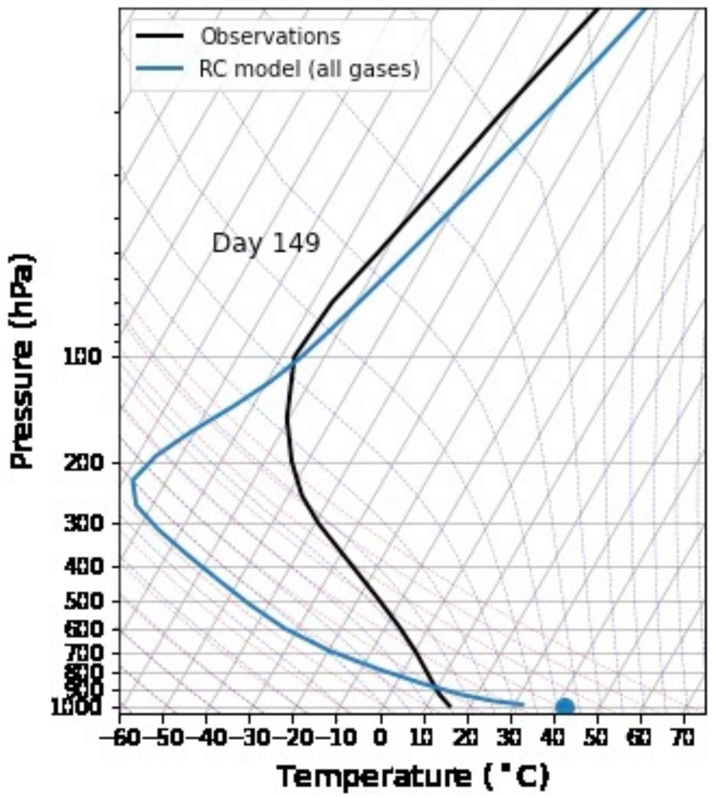
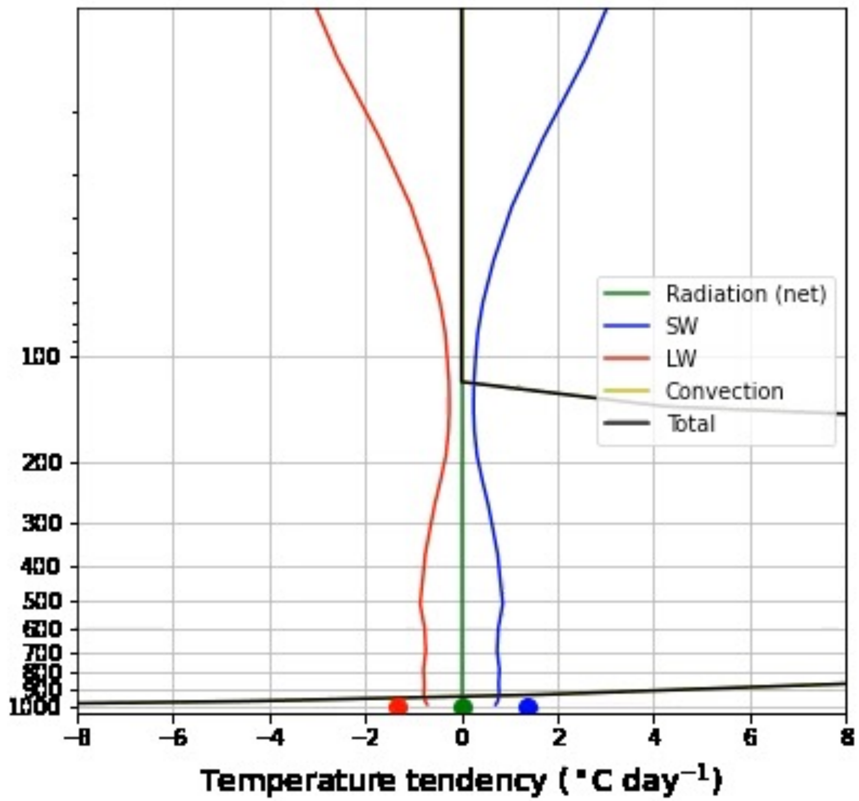
Radiative Convective Equilibrium





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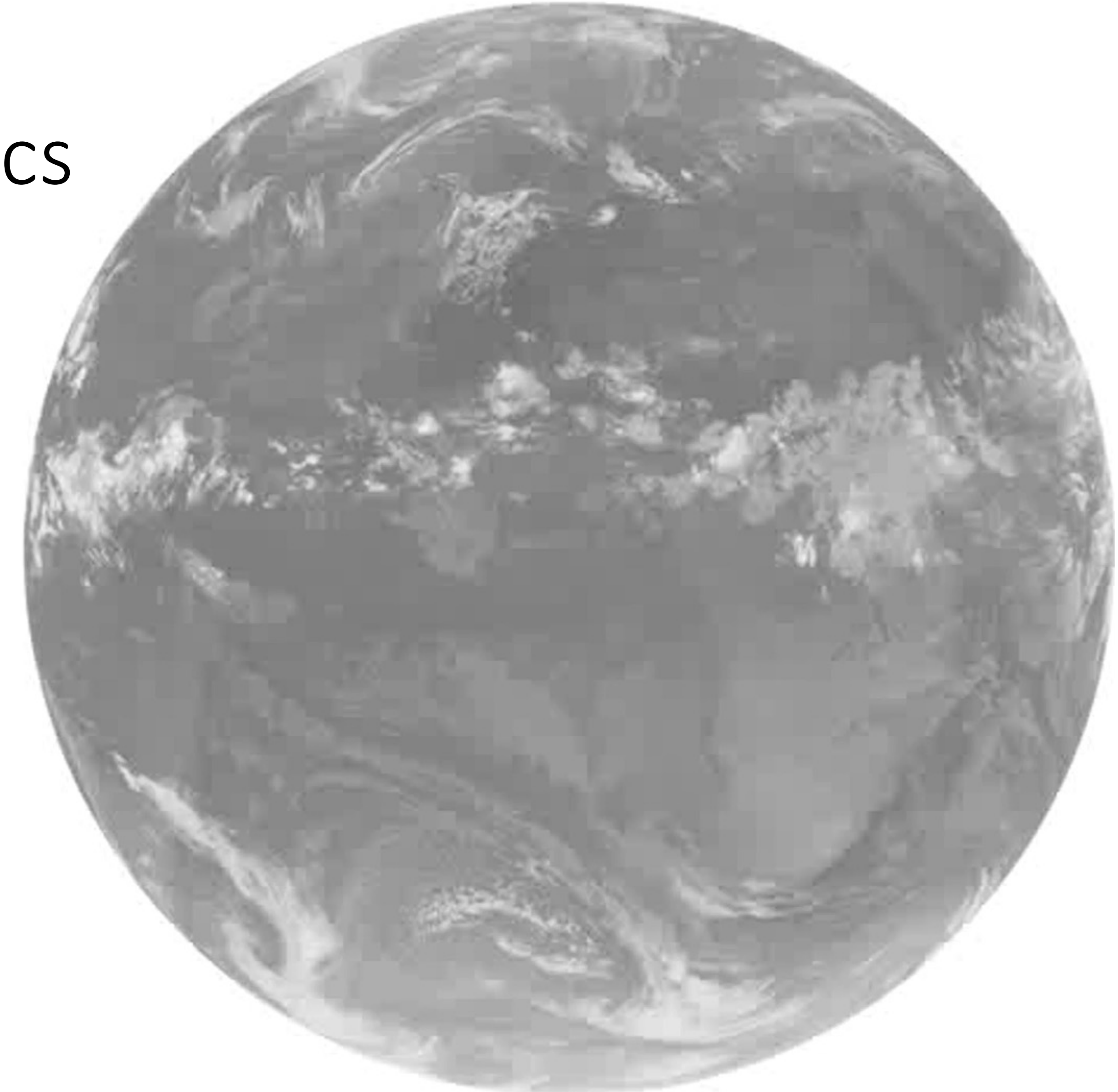
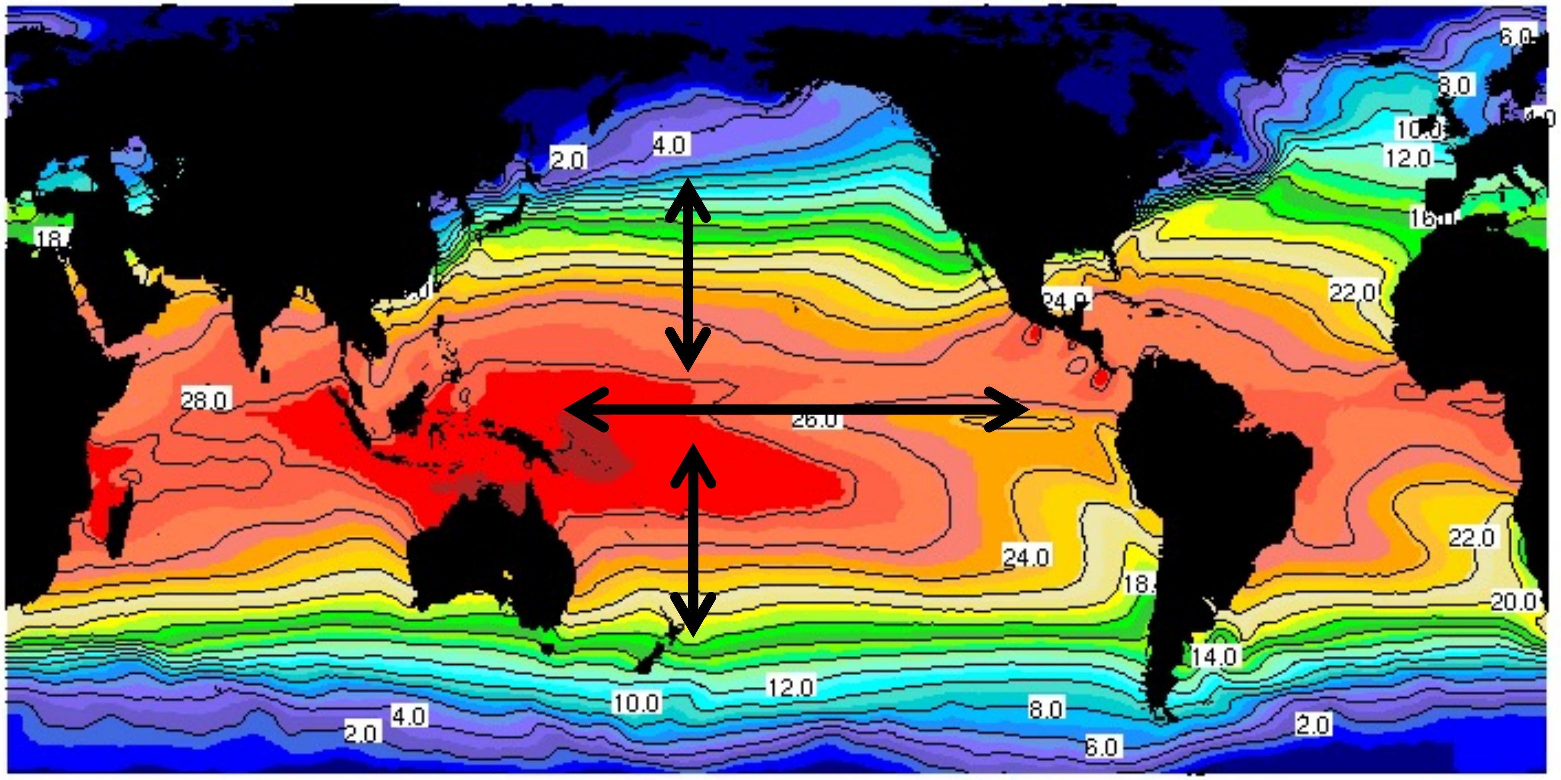
Dynamics



Surface Temperature Gradients



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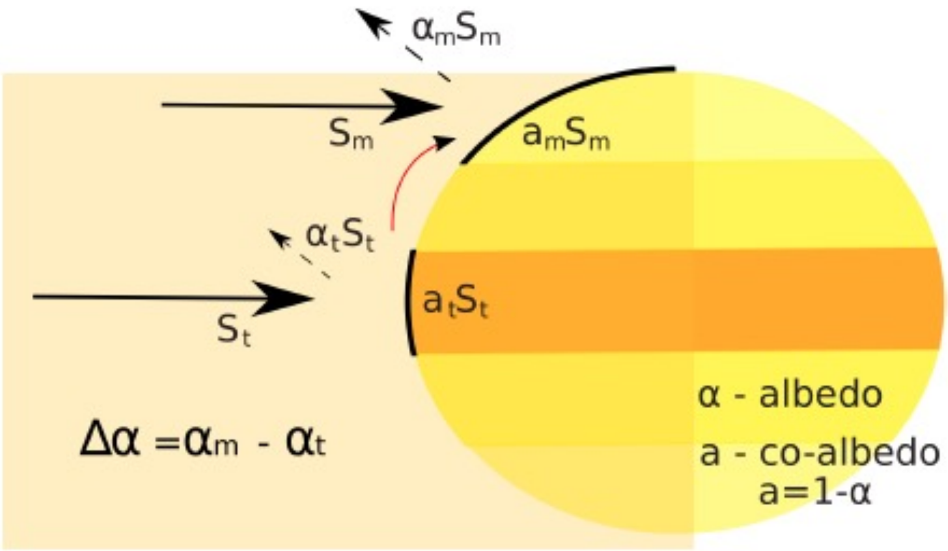
What set horizontal temperature gradients

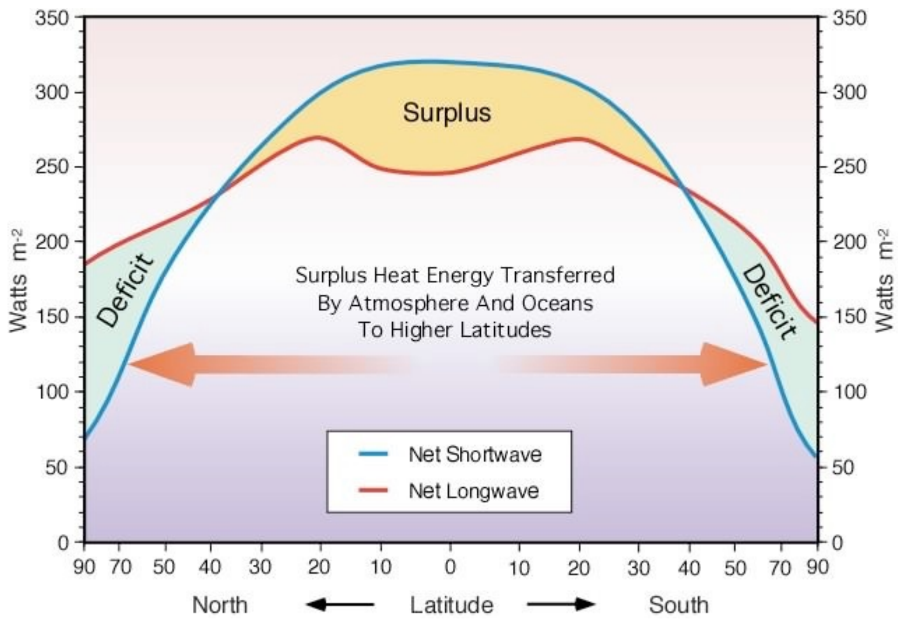


Factors controlling the meridional temperature gradient

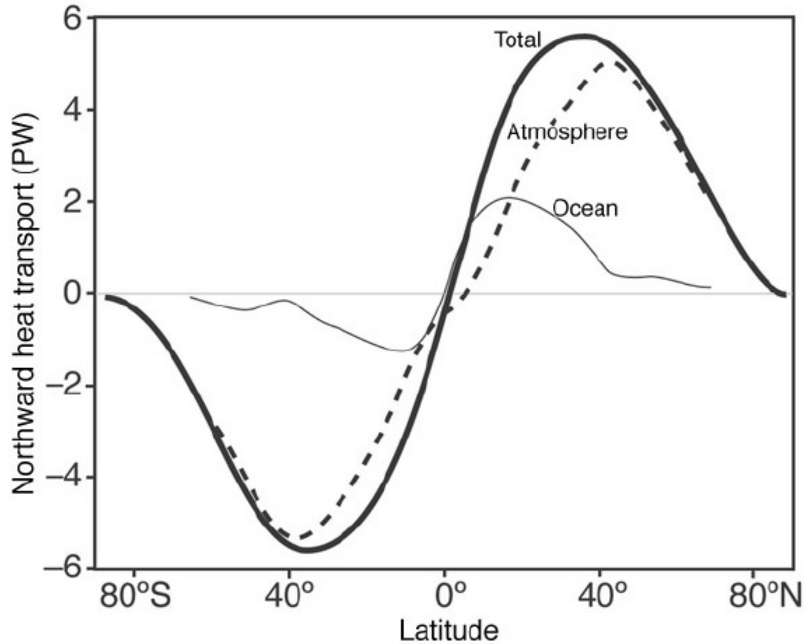
* Gradient in solar heating due to curvature of the Earth.
* Meridional albedo gradient.
* Efficiency of the atmosphere and ocean in transporting heat.

Poleward Energy Transport

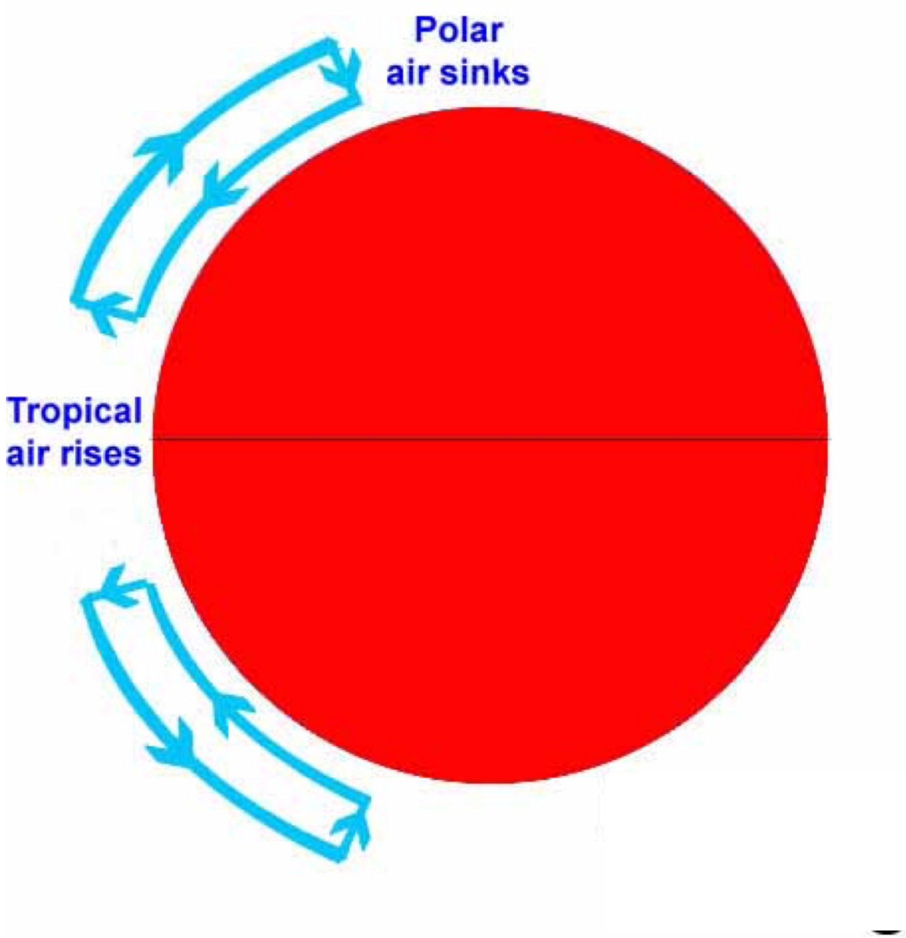
Top of the Atmosphere Energy Flux



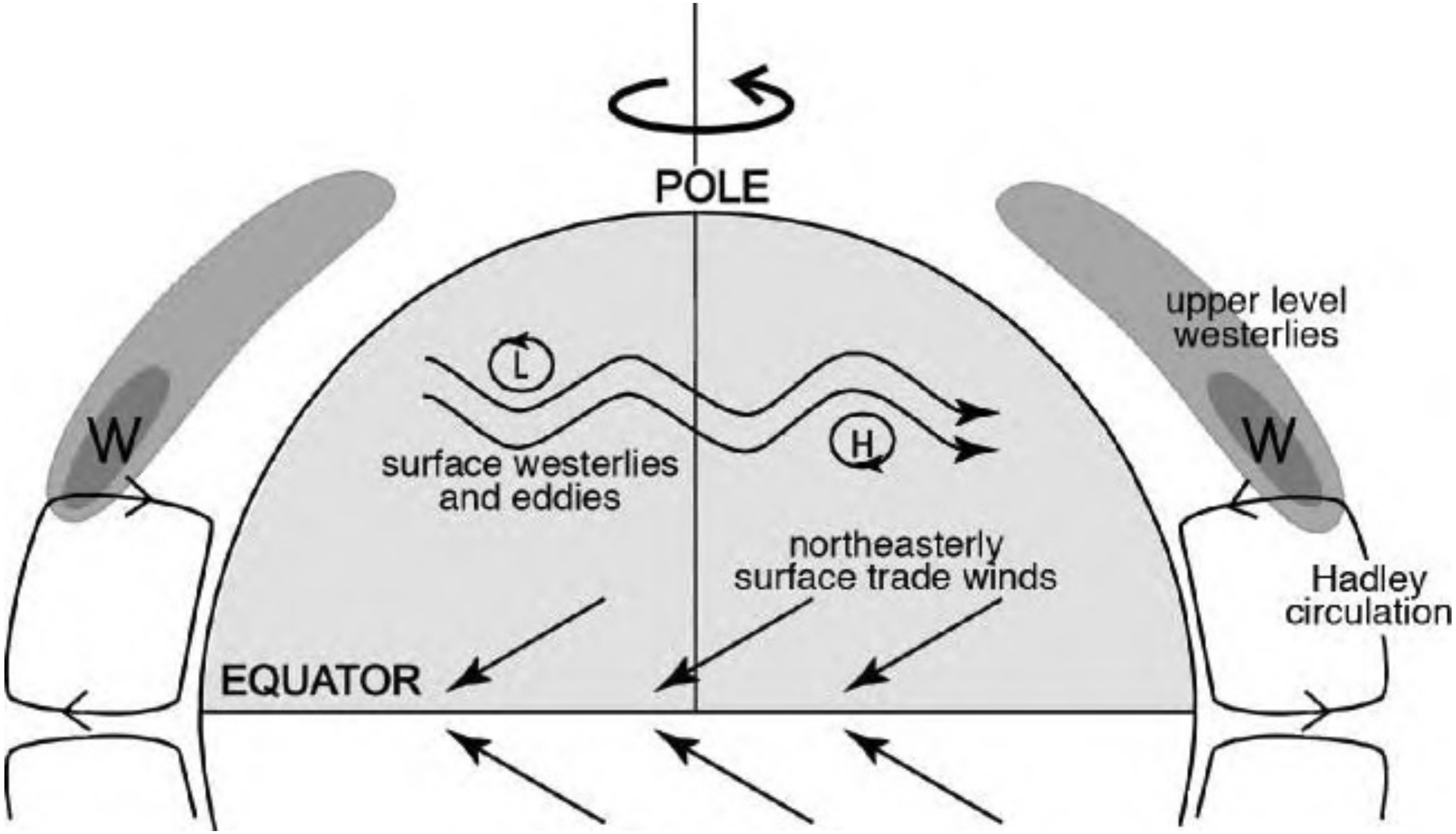
Poleward energy transport



Non Rotating Planet

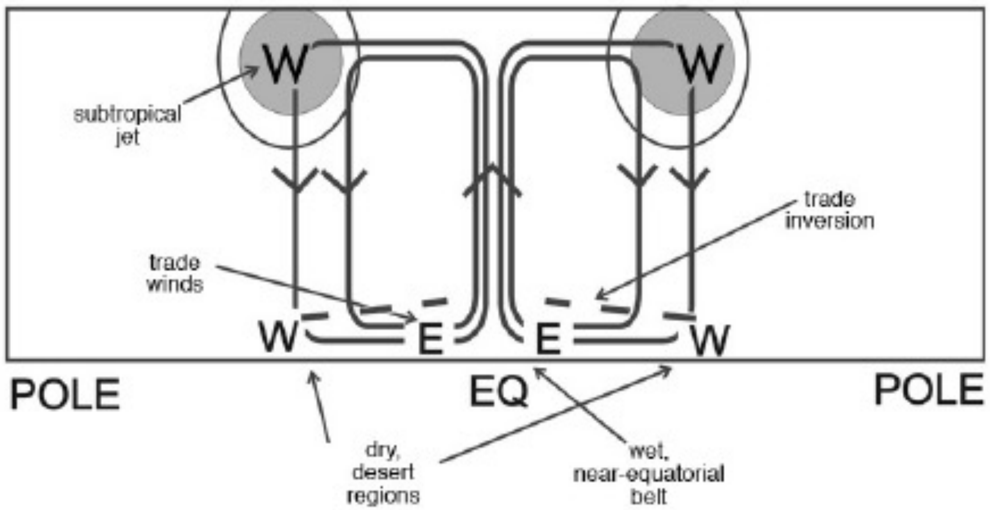


The general circulation of the Atmosphere



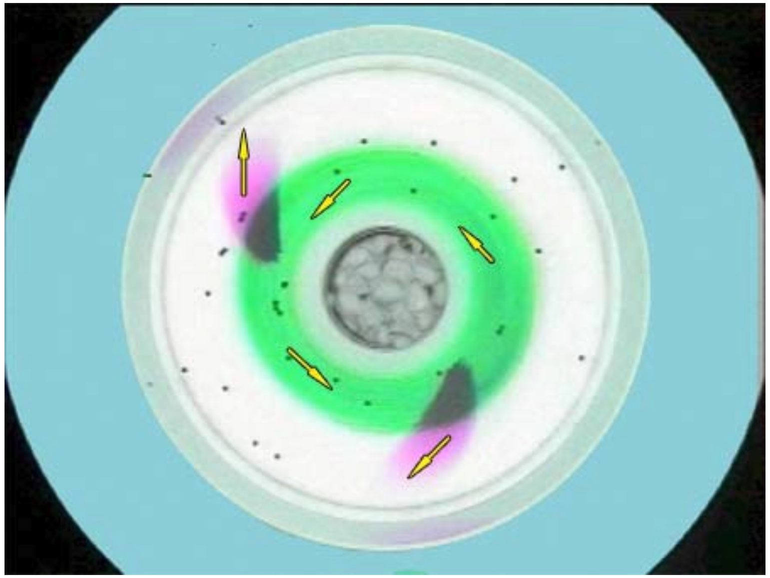
Source: Marshall and Plumb

Hadley Circulation



Source: Marshall and Plumb

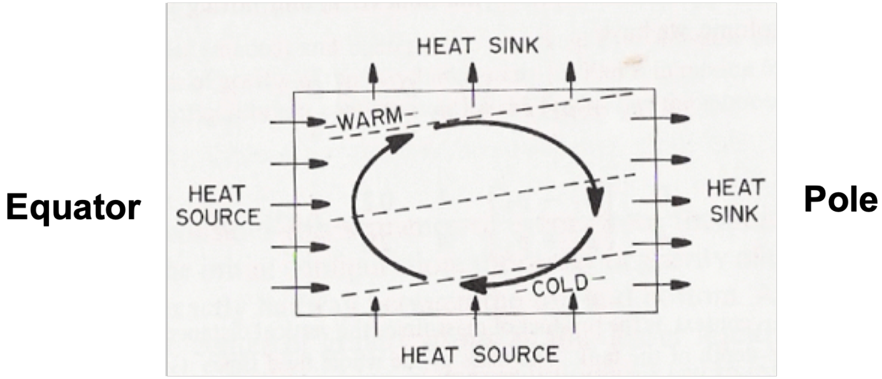
Hadley Circulation – slow rotation



Source: MIT Weather in a Tank, http://weathertank.mit.edu/

Gradient of heating drives a slow circulation cell

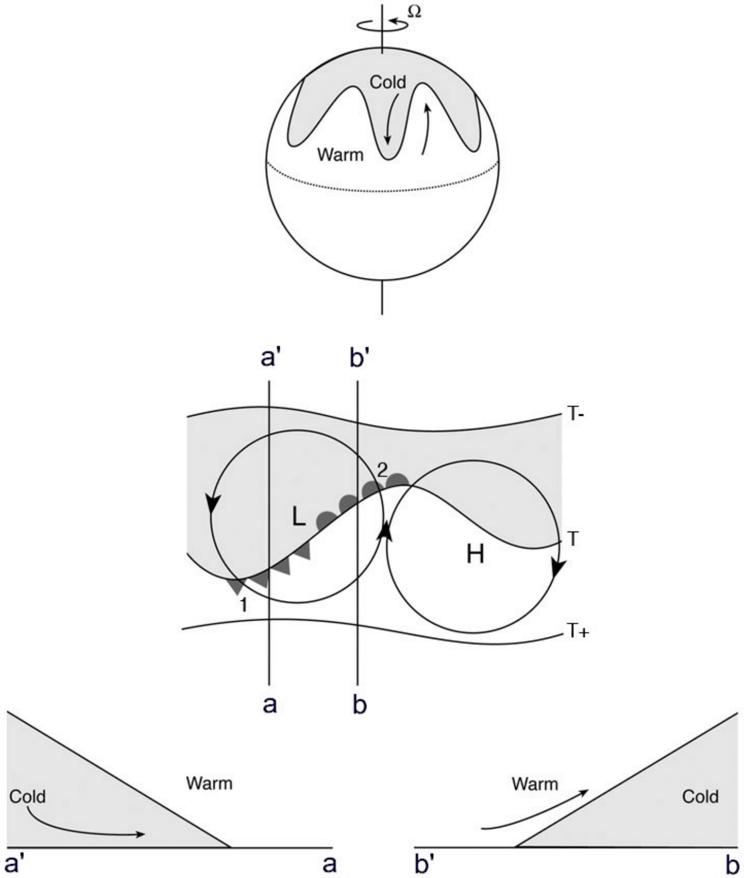
Emission of infra-red **radiation to space** (strongest in the upper atmosphere)



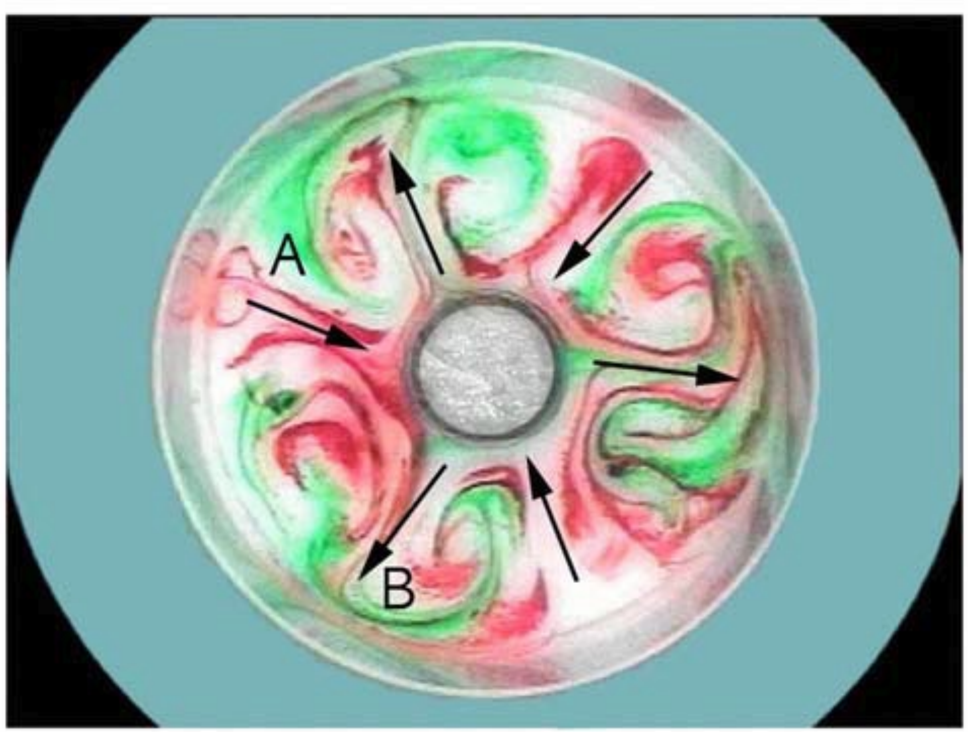
Shortwave, longwave, latent and sensible **input of energy** in the lower atmosphere.

Convection cools the surface of the Earth, redistributing heat upwards and polewards.

Mid-latitude Weather systems – fast rotation

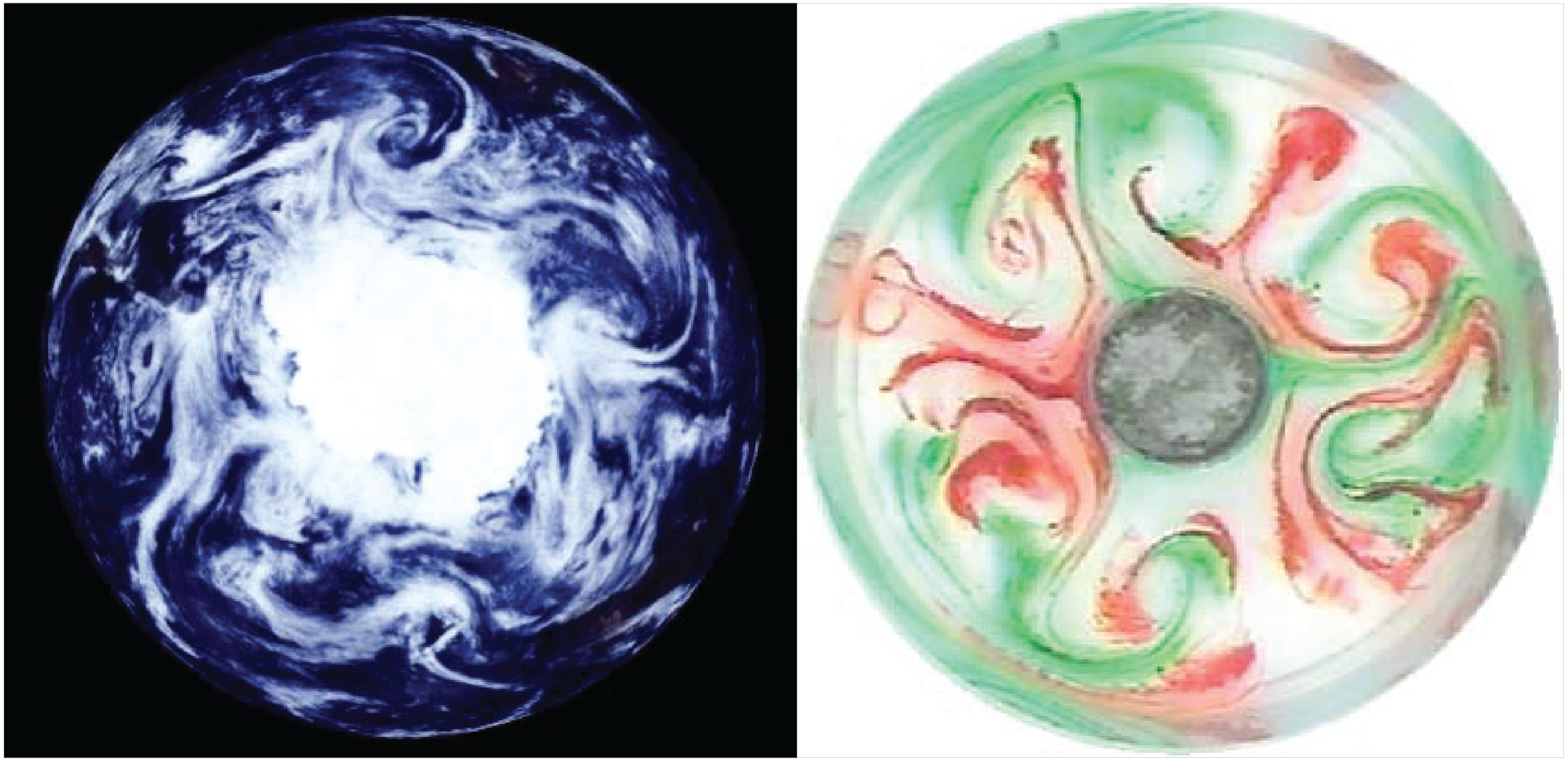


Marshall and Plumb



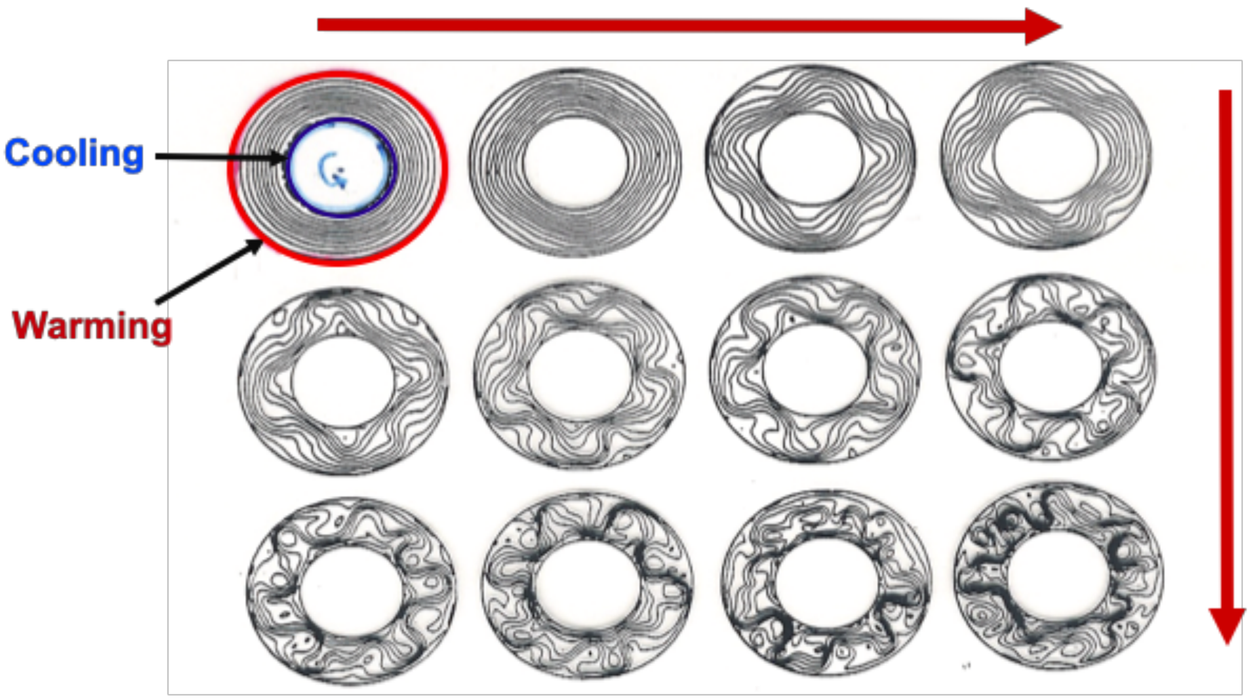
Unstable to baroclinic instability

Source: MIT Weather in a Tank, http://weathertank.mit.edu/



Annulus Experiment
(view from above)

Increase in temp gradient and the rate of rotation



FYI see animation @ http://paoc.mit.edu/labweb/lab11/eddies.mpg and http://paoc.mit.edu/labweb/lab11/gfd_11.htm

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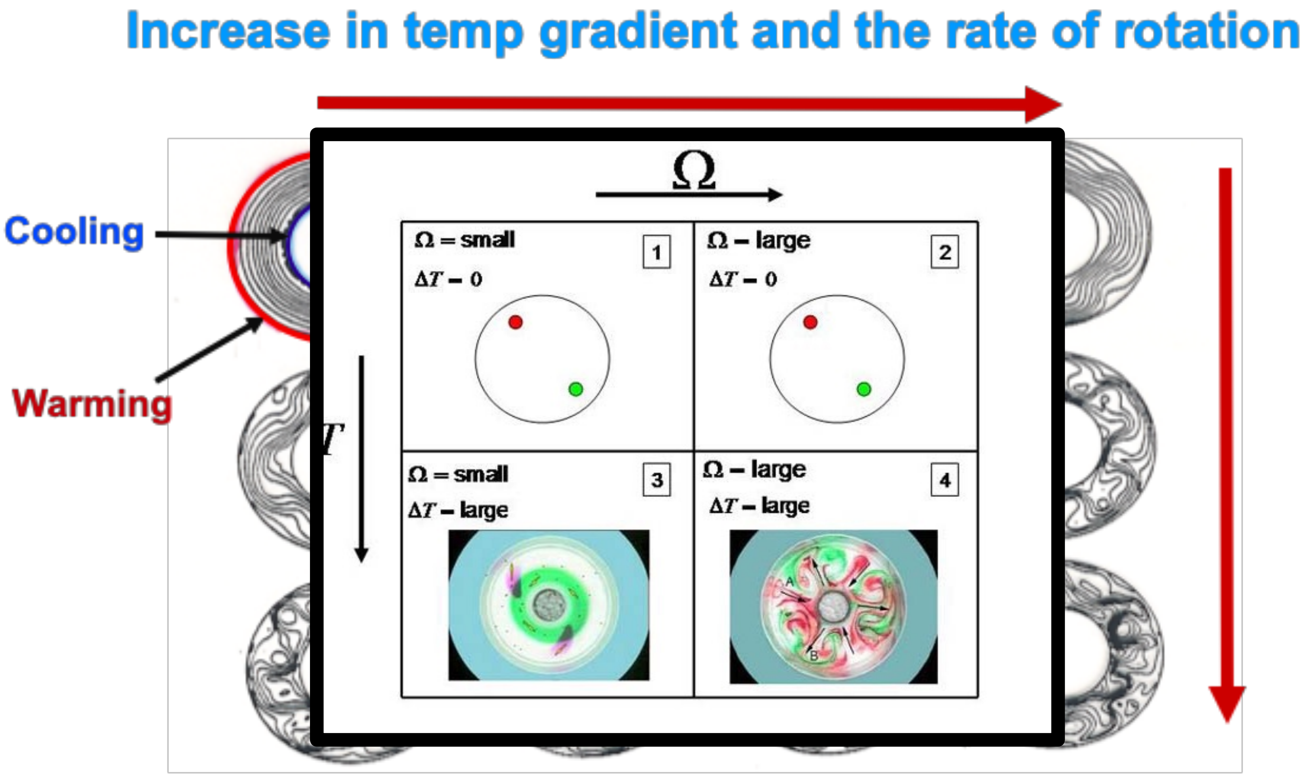

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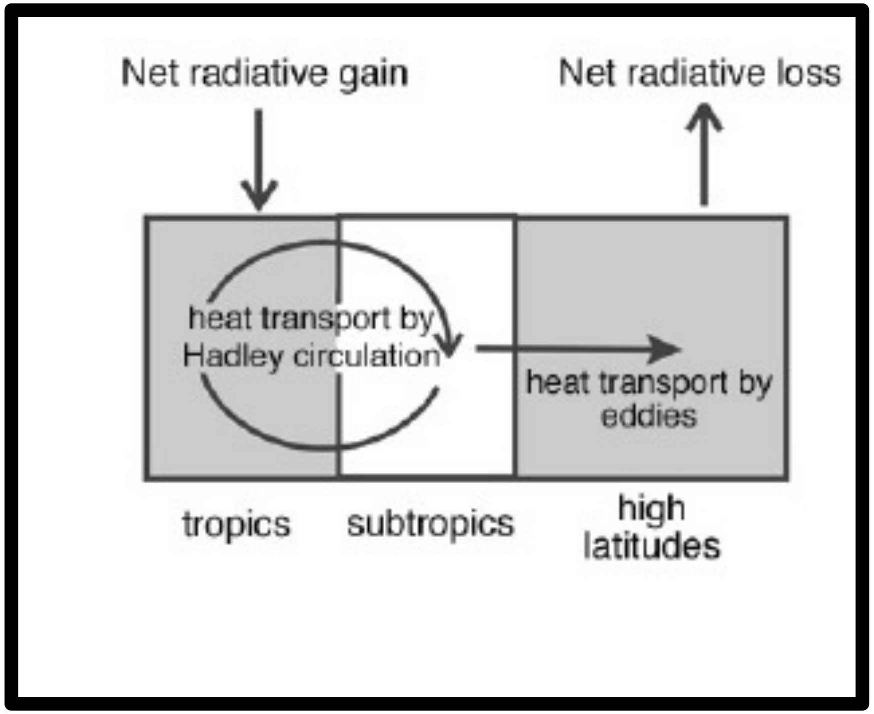
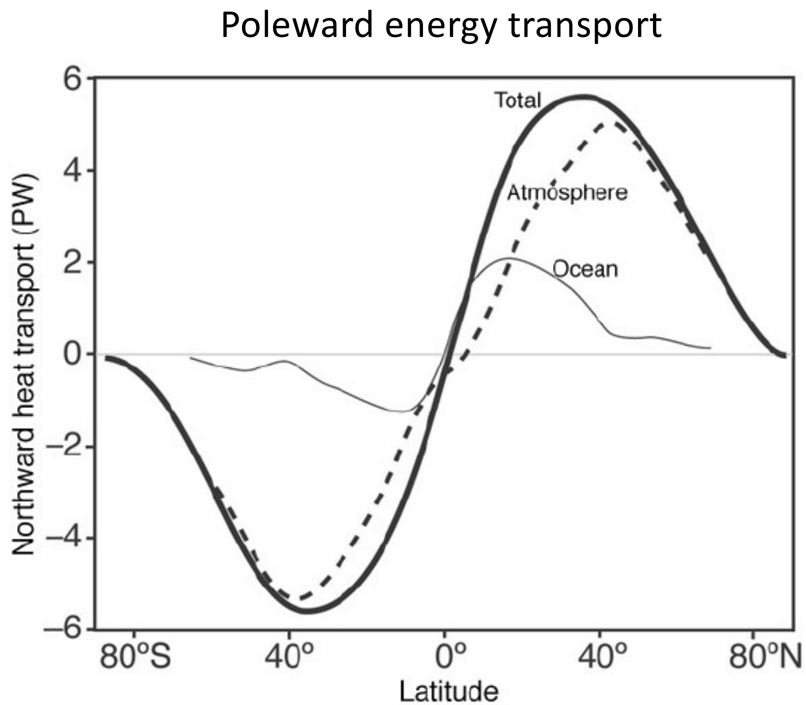
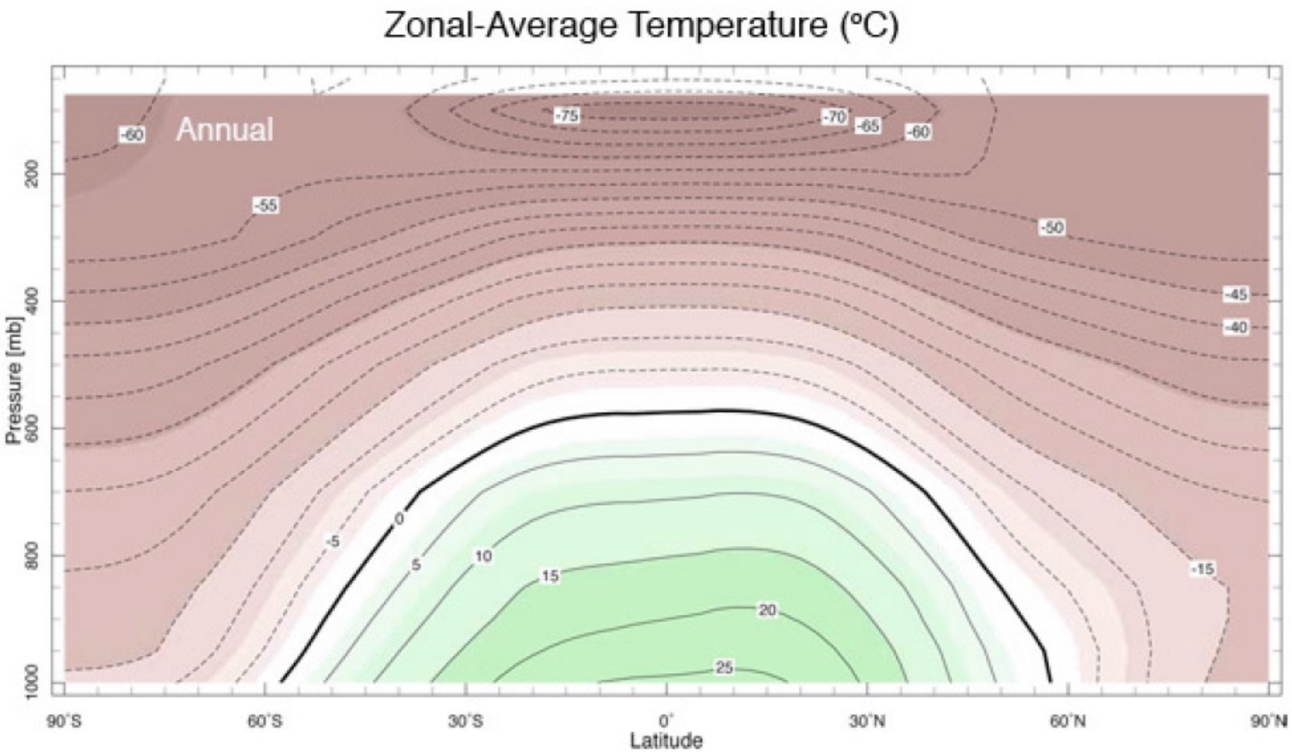
Poleward Energy Transport





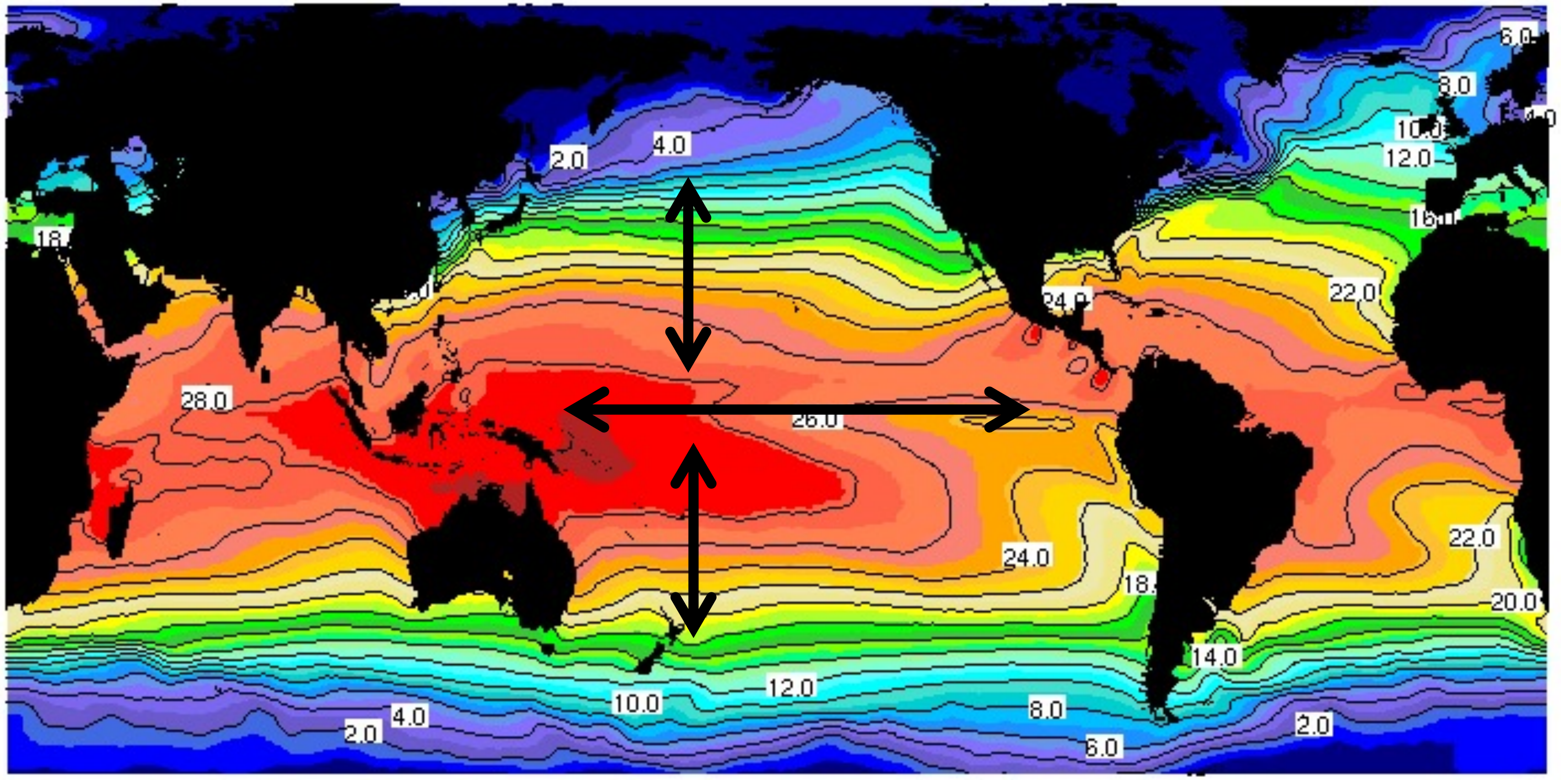
Marshall and Plumb

Weak Temperature Gradient Approximation



Marshall and Plumb

Surface Temperature Gradients



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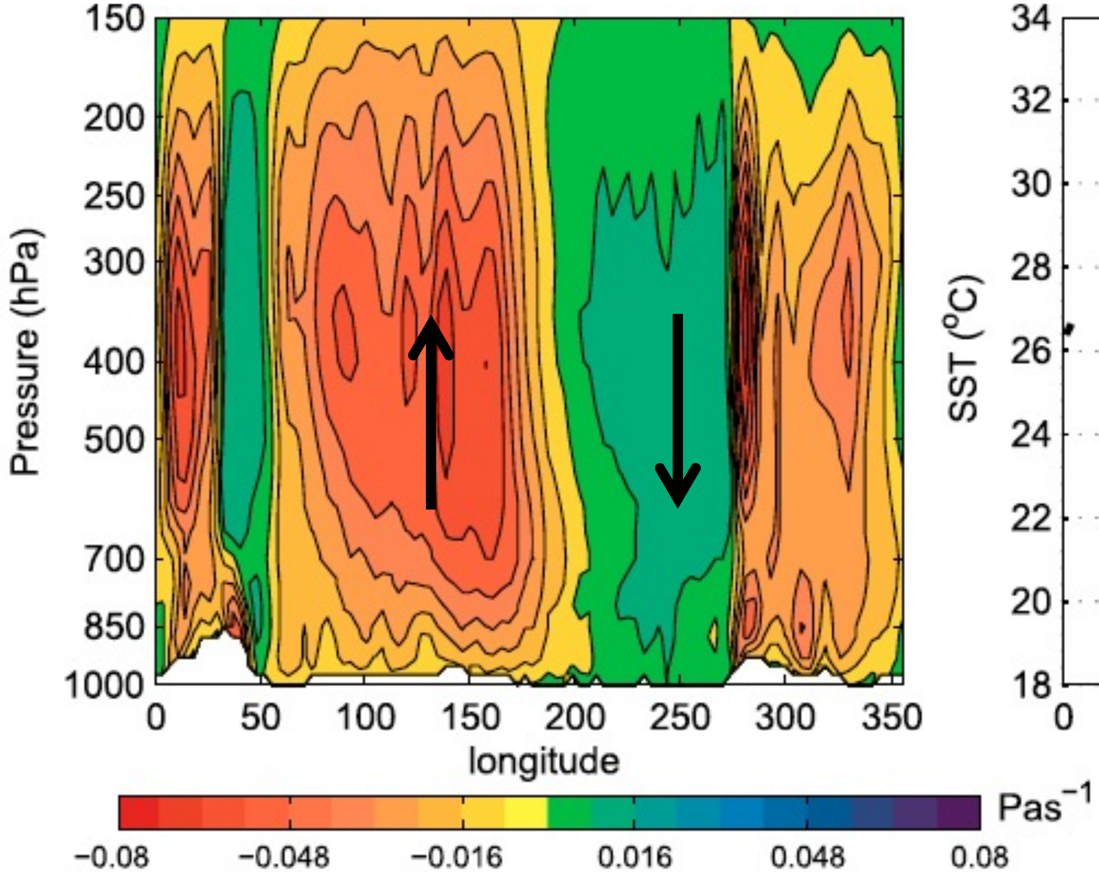
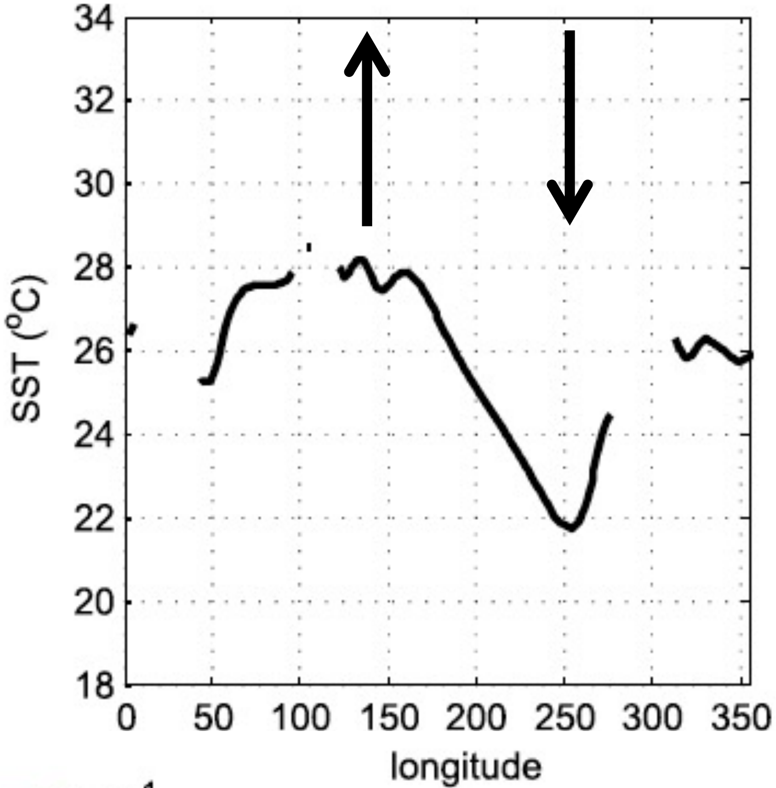
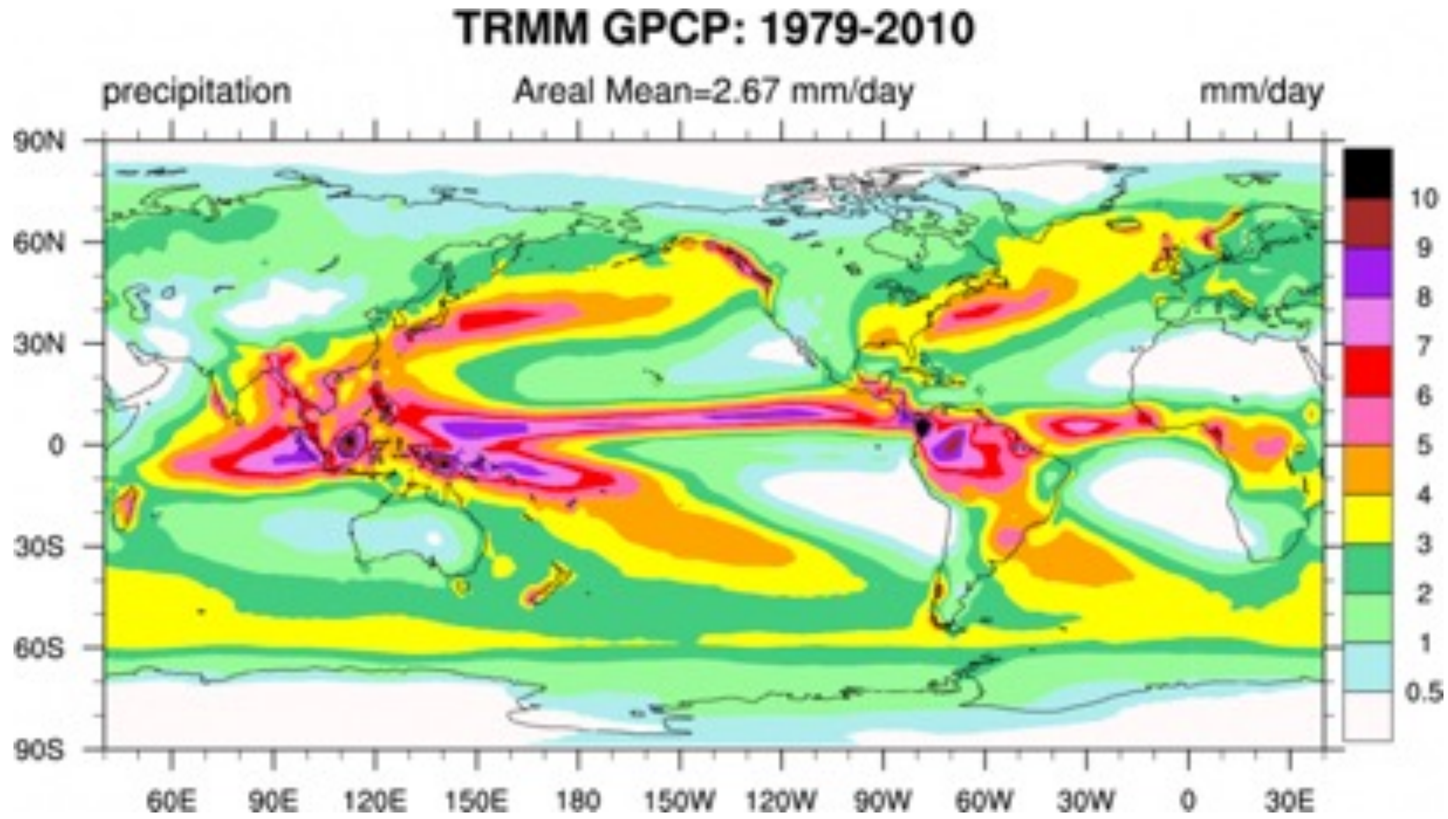
The Walker Circulation



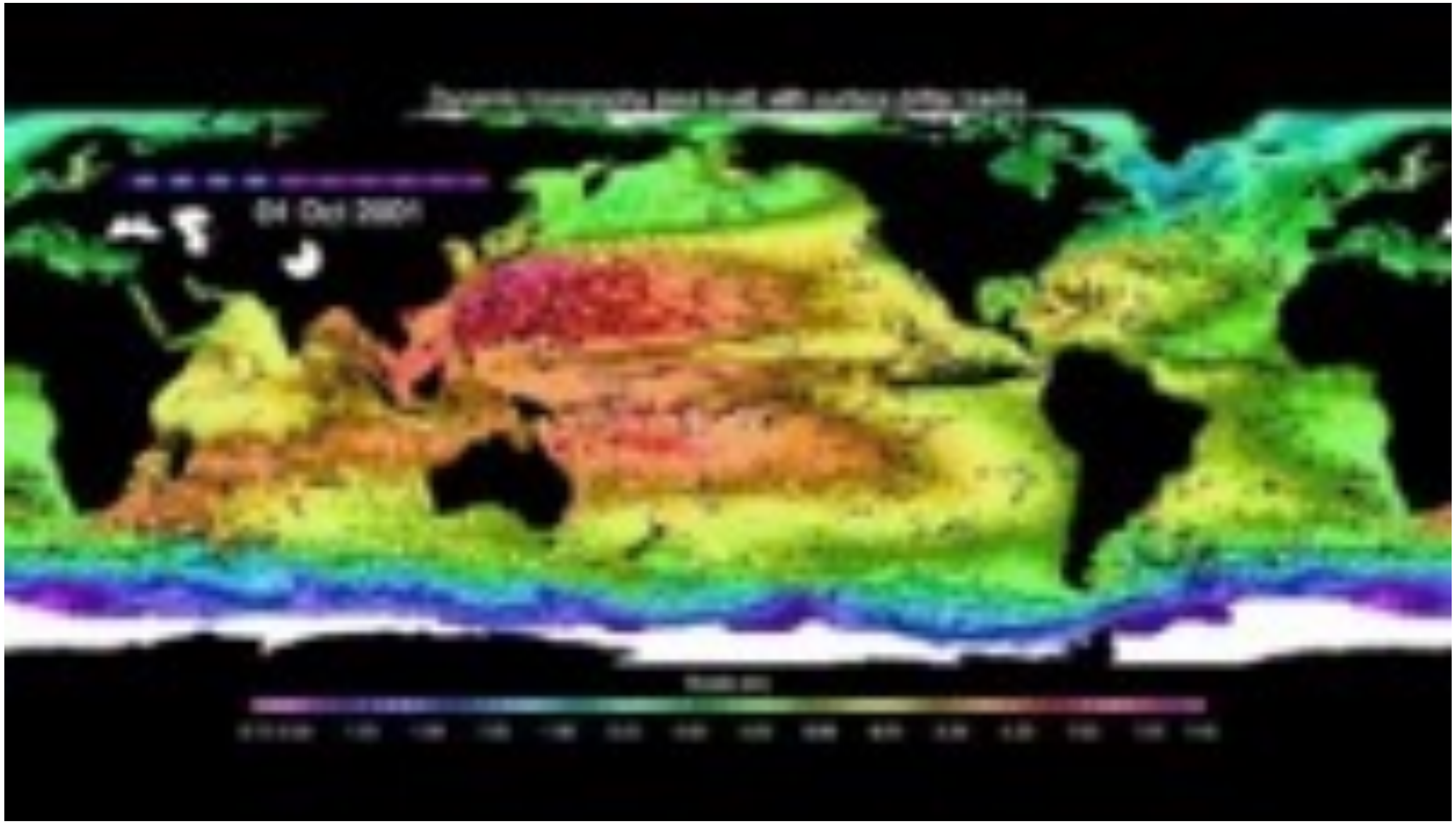


Burls and Fedorov, 2014

Atmospheric Circulation Patterns evidenced by Precipitation Patterns



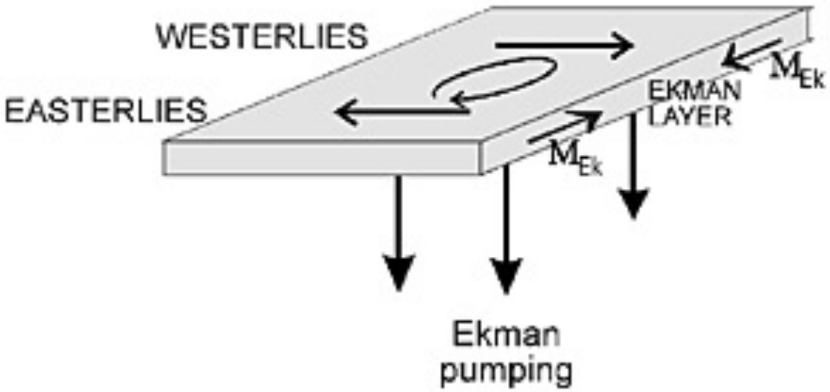
The Tropical Ocean



Chris Hughes, https://www.youtube.com/watch?v=2Om93b1OgBk

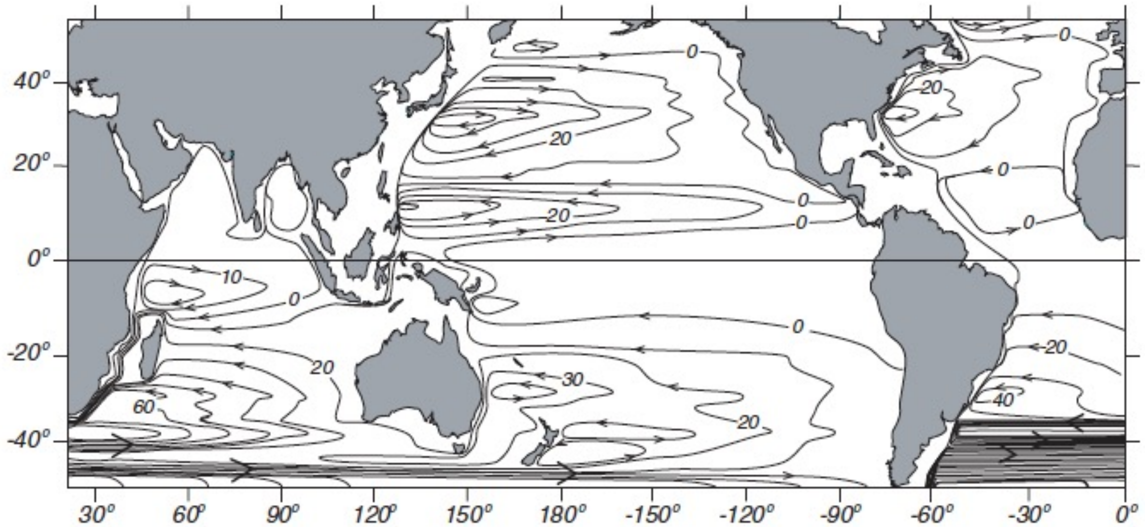
The Wind Driven Gyres

Relating the curl of the wind stress to mass transport within the upper ocean



Marshall and Plumb

Depth-integrated Sverdrup Transport from Wind Stress

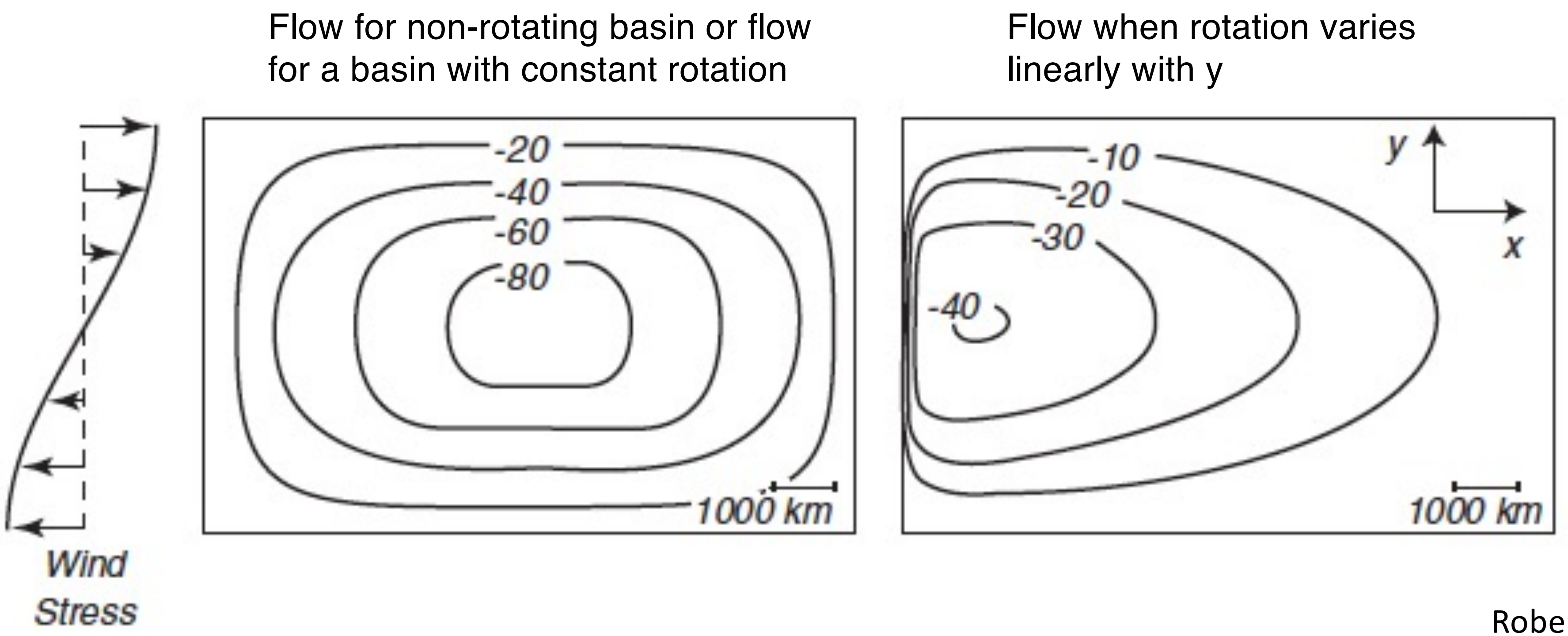


$$M_y \approx -\frac{1}{\beta}\frac{\partial T_x}{\partial y}$$

Robert H Steward

The Wind Driven Gyres

Variation of Coriolis force with latitude is required for the existence of the western boundary current - Stommel



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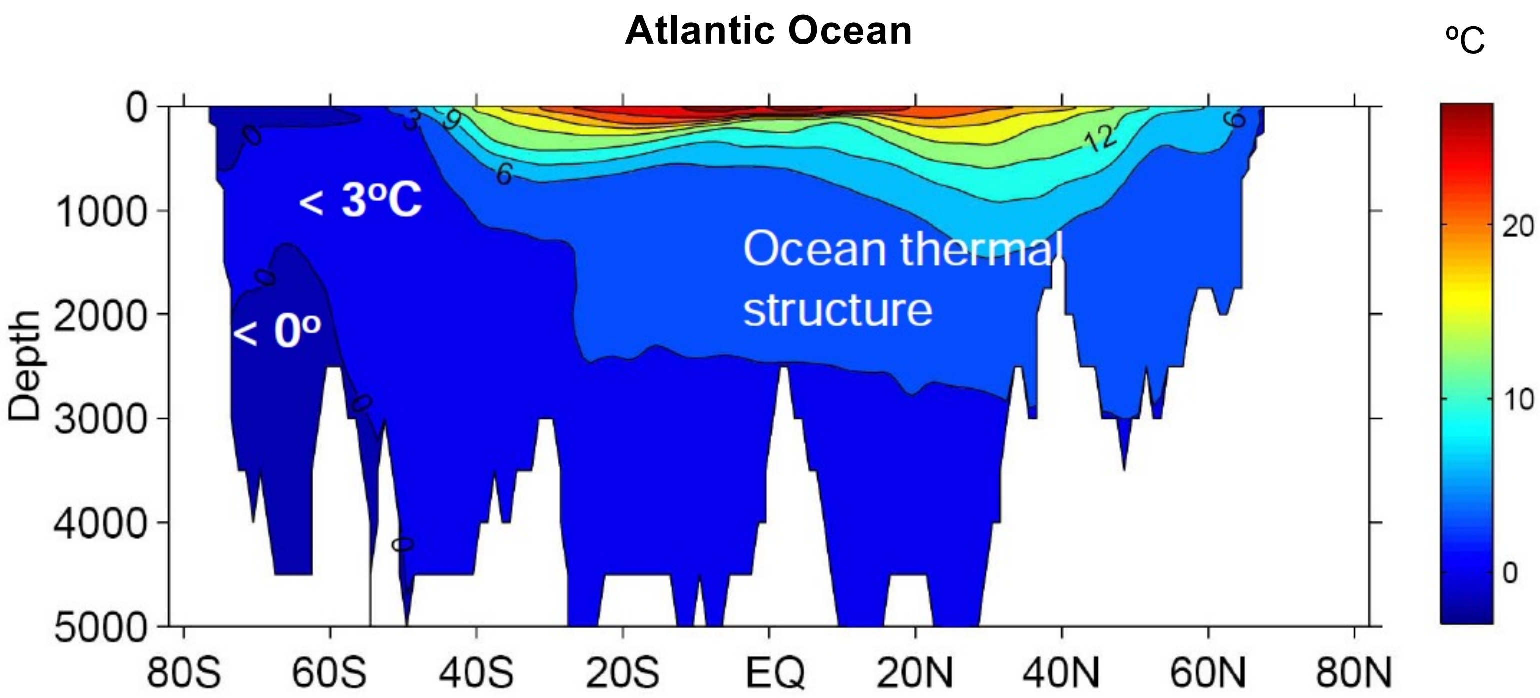
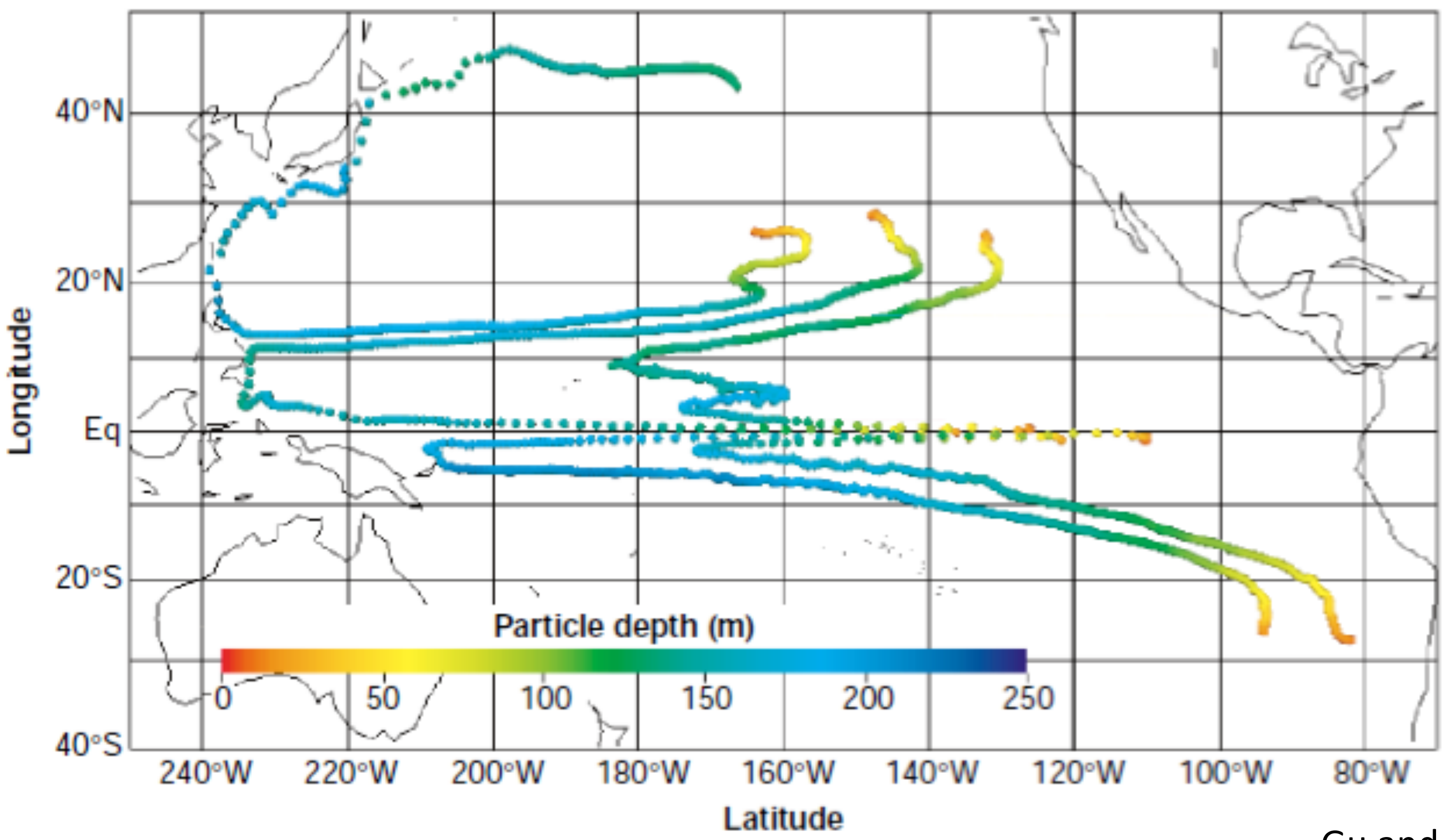
The Thermal Structure of the Tropical Ocean



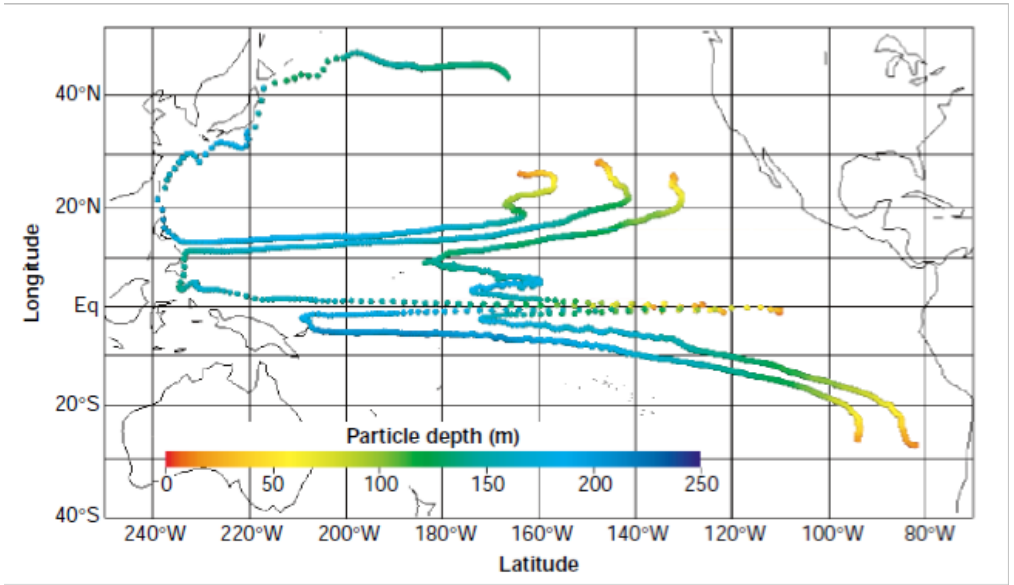
Unlike the atmosphere, the ocean is primarily heated from above

Subtropical Wind Driven Overturning Cells + the Thermal Structure of the Tropical Ocean



Gu and Philander, 1997

Subtropical Wind Driven Overturning Cells + the Thermal Structure of the Tropical



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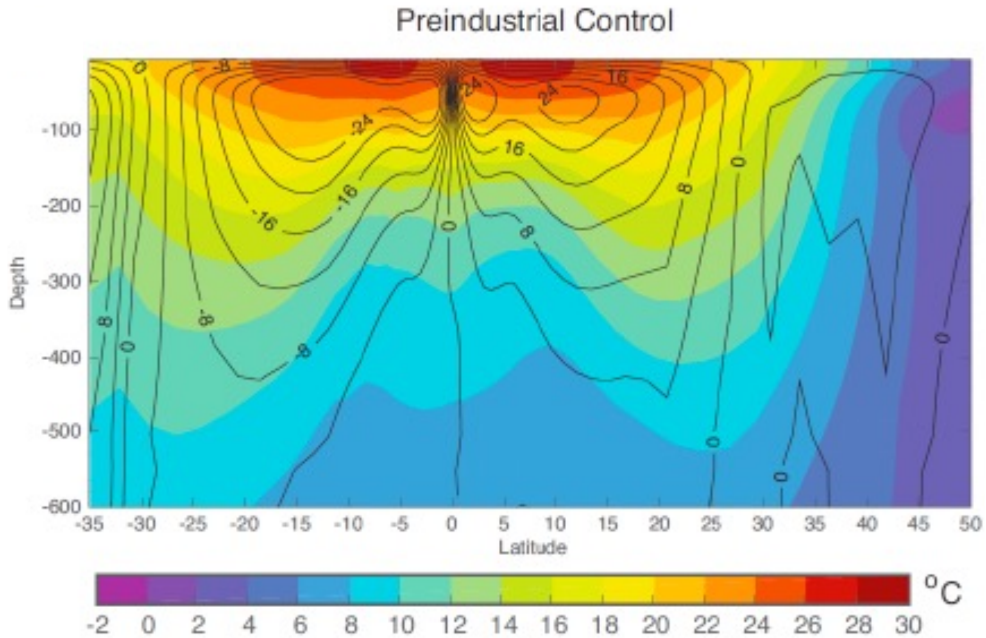
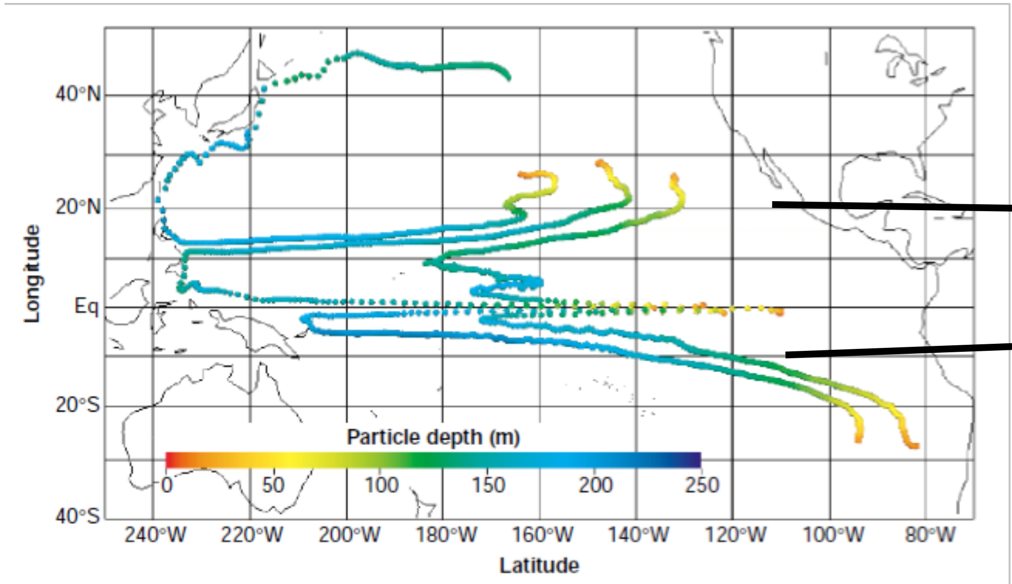


Burls and Fedorov, 2014

Subtropical Wind Driven Overturning Cells + the Thermal Structure of the Tropical Ocean = **Poleward Energy Transport**



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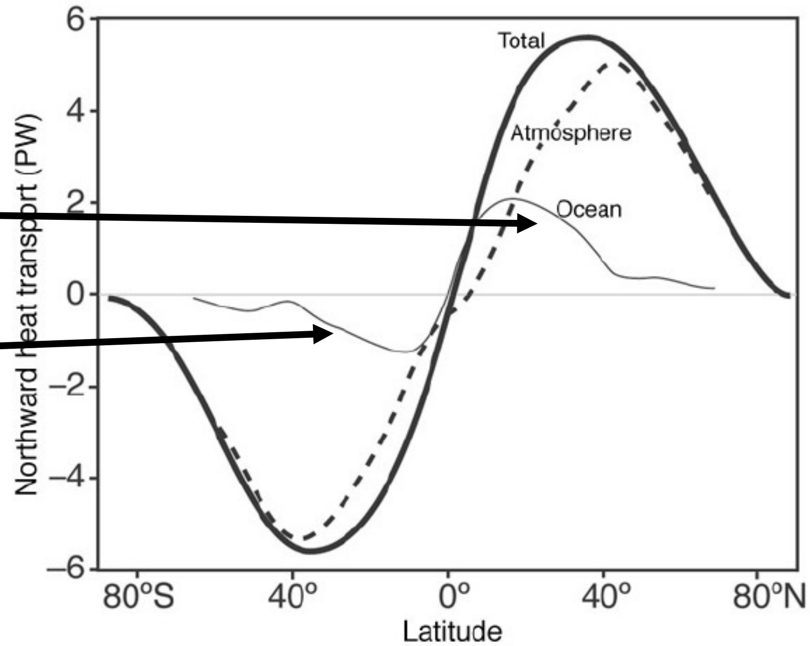
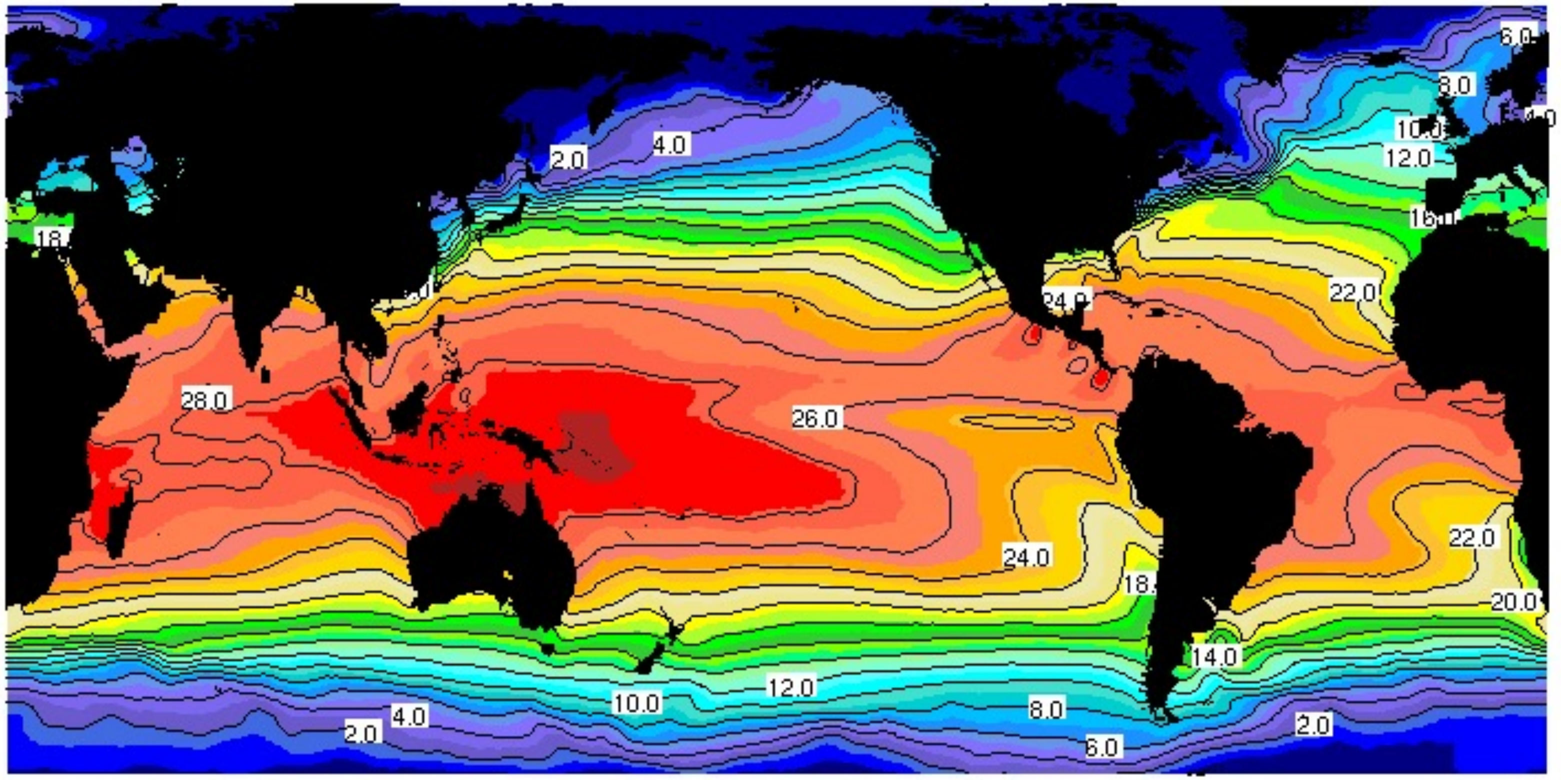
Poleward energy transport



Marshall and Plumb

Tropical Ocean-Atmosphere Interactions



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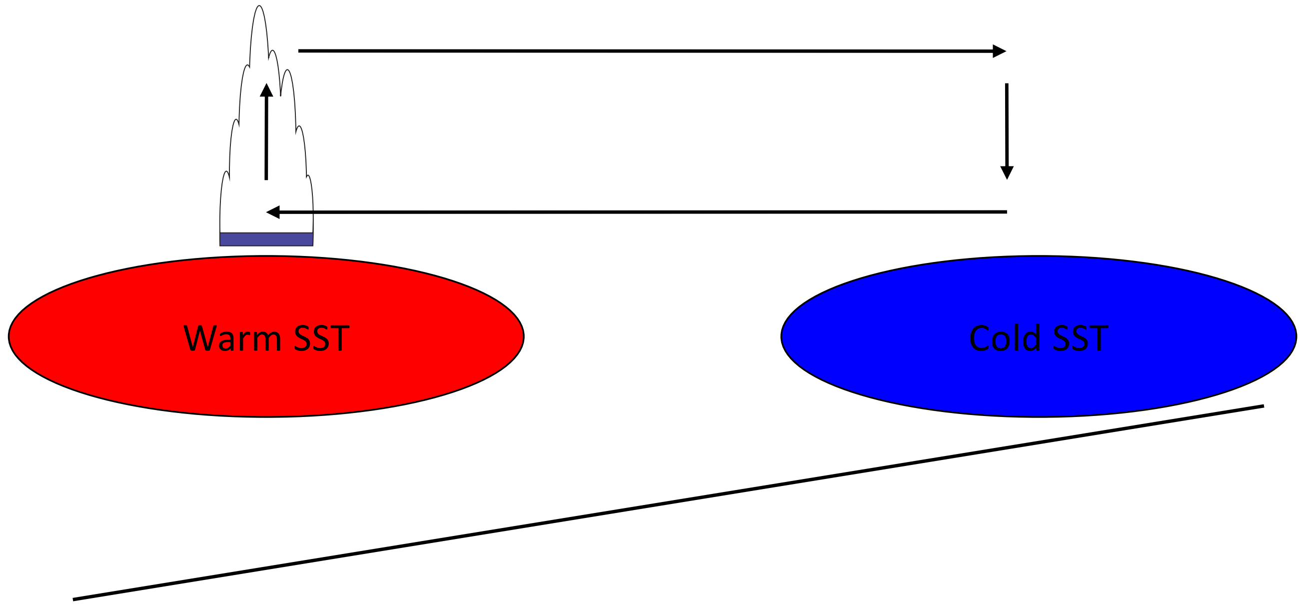
Tropical Ocean-Atmosphere Interactions

The Tropical Oceans are particularly susceptible to Ocean-Atmosphere Interactions.

Firstly, atmospheric circulation exhibits a strong dependence on underlying SST in the tropics



Deep atmospheric convection is driven by the warmer (>27°C) SSTs which reside in the tropics

Tropical Ocean-Atmosphere Interactions

Secondly, while extra-tropical SSTs are predominately determined by the magnitude of the surface heat flux, with oceanic advection tending to play a relatively small role, the oceanic response to wind forcing (both local and remote) tends to have a much stronger influence on SST in the tropics.

$$SST_t = uT_x + vT_y + wT_z + Q + D$$

Over most of the ocean, changes in SST are driven primarily by changes in the surface flux.

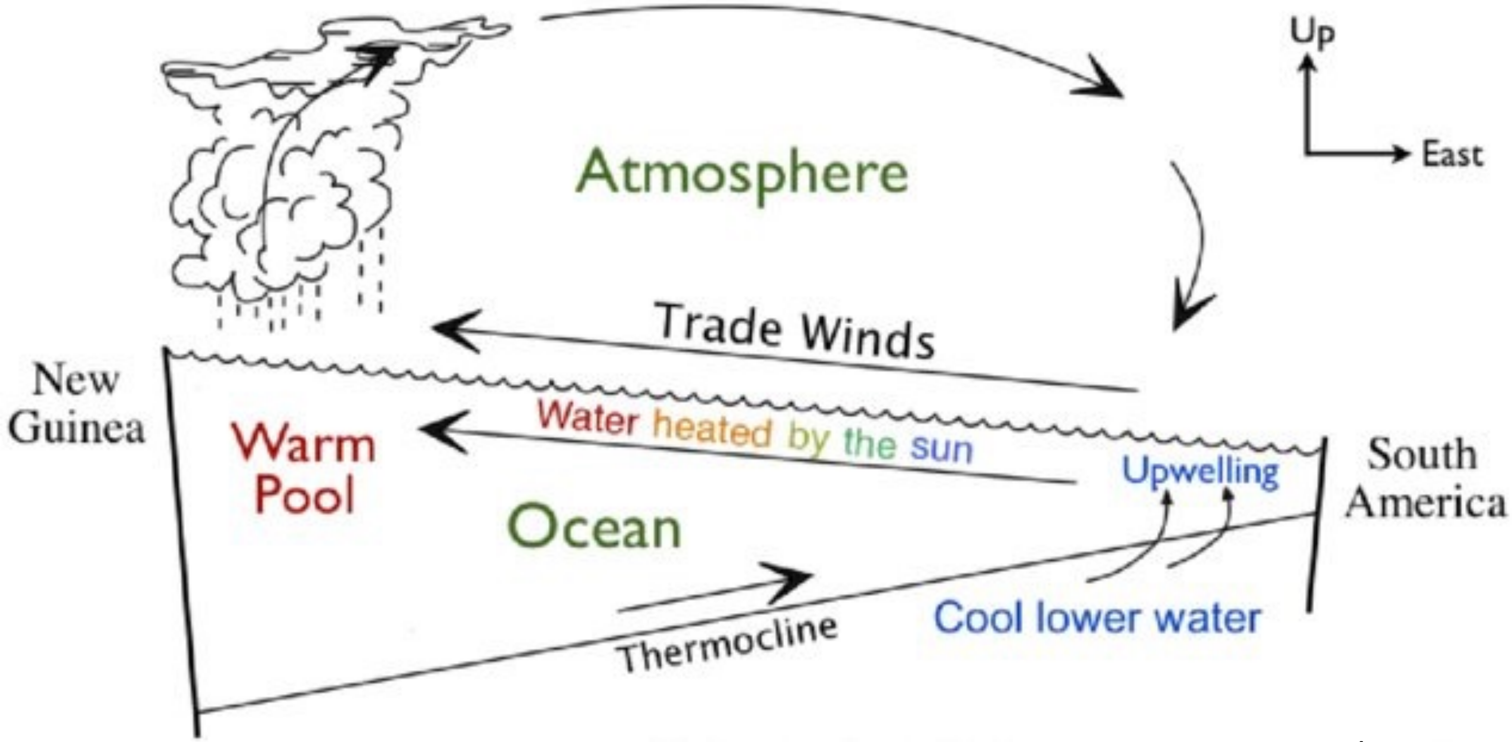
$$Q$$

In upwelling and equatorial regions however advection (particulary vertical advection) becomes a dominant term.

$$wT_z$$

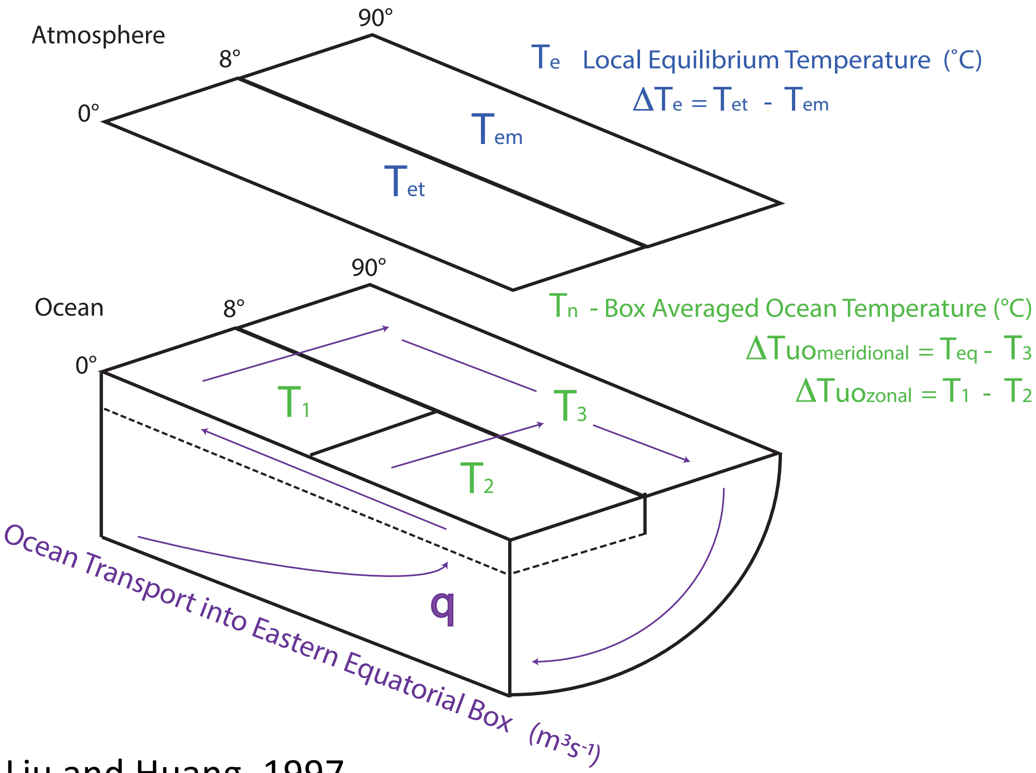
because the depth of the surface mixed layer is not determined locally over most of the tropics due to the presence of a sharp, shallow thermocline, the depth of which is remotely forced by large scale oceanic adjustment in response to changes in atmospheric forcing involving oceanic Kelvin and Rossby waves. "the Ocean mixed layer is tightly coupled to the subthermocline ocean, allowing changes in the subsurface ocean to have a direct impact on SST" Change et al. 2006

The Walker Circulation

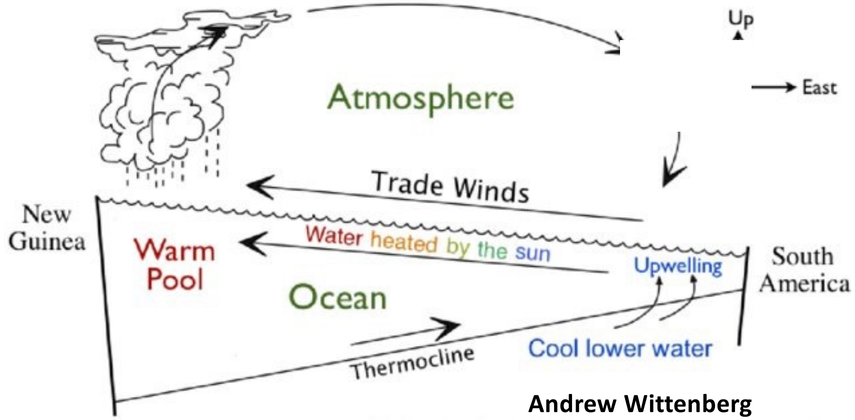


Andrew Wittenberg

Coupled Theory



Liu and Huang, 1997



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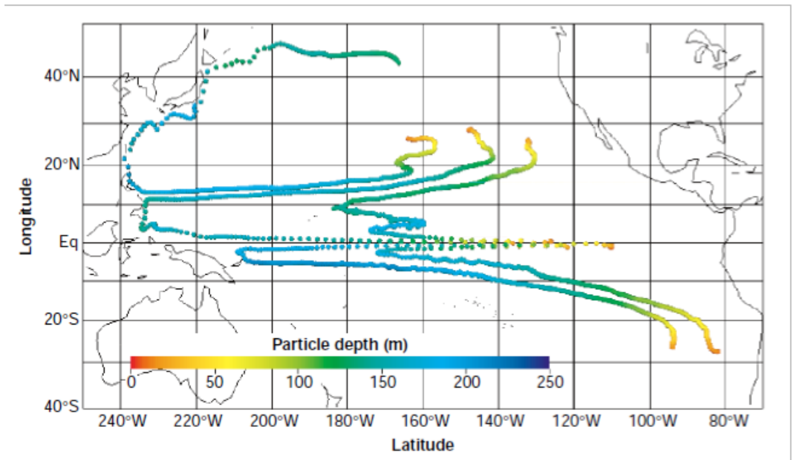
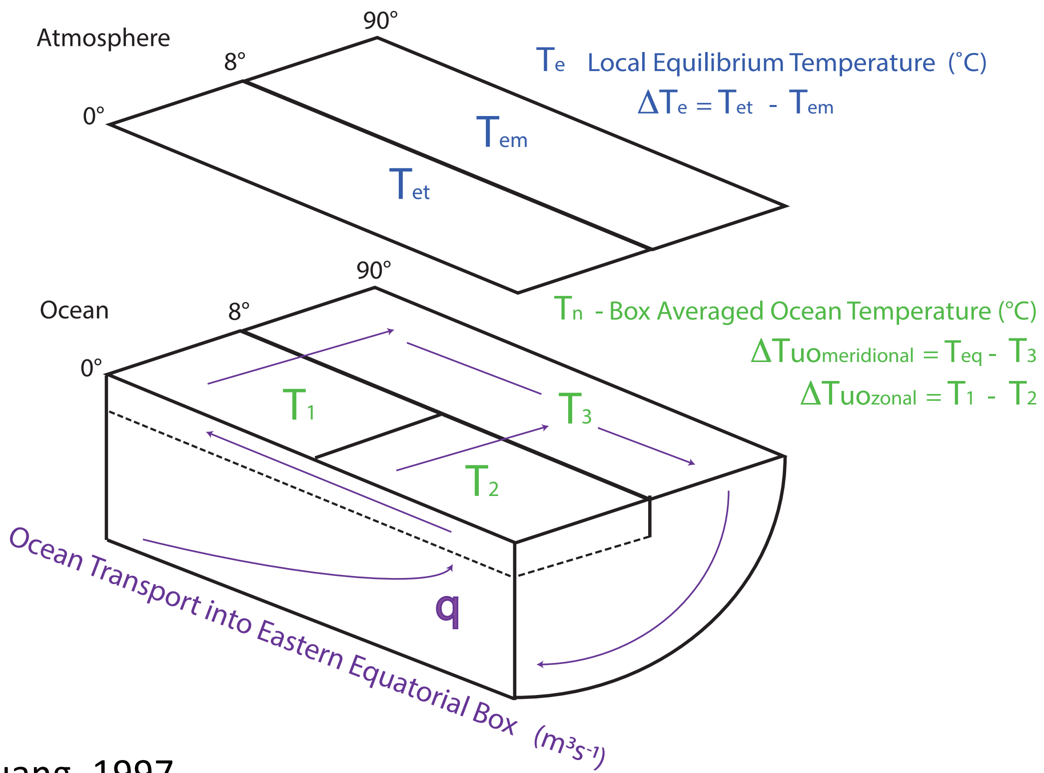


Gu and Philander, 1997

"A Coupled Theory of Tropical Climatology: Warm Pool, Cold Tongue, and Walker Circulation"



Liu and Huang, 1997

m_n The volume of each Box (m^3)

$m = m_3/m_1$

τ_r Restoring time of local negative air-sea feedback (s)

A_w Walker Coupling Parameter ($m^3s^{-1}K^{-1}$)

A_h Hadley Coupling Parameter ($m^3s^{-1}K^{-1}$)

ϵ Branching Parameter

$T_{eq} = 1/2(T_1 + T_2)$

$Q = q\tau_r/m_1$ Nondimensionalized volume transport

Q_i 1/Q

$$q = A_h(T_{eq} - T_3) + A_w(T_1 - T_2)$$

$$m_1 dT_1/dt = m_1(T_{et} - T_1)/\tau_r + (1-\epsilon)q(T_2 - T_1)$$

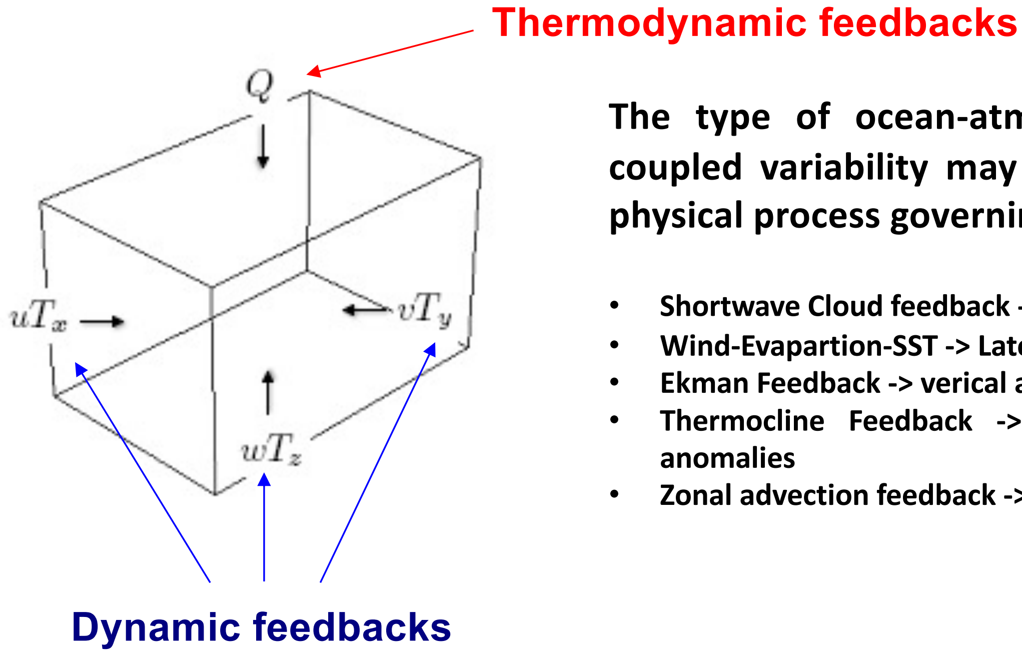
$$m_2 dT_2/dt = m_2(T_{et} - T_2)/\tau_r + q(T_3 - T_2)$$

$$m_3 dT_3/dt = m_3(T_{em} - T_3)/\tau_r + \epsilon q(T_2 - T_3) + (1-\epsilon)q(T_1 - T_3)$$

Framework for Diagnosing Coupled Processes

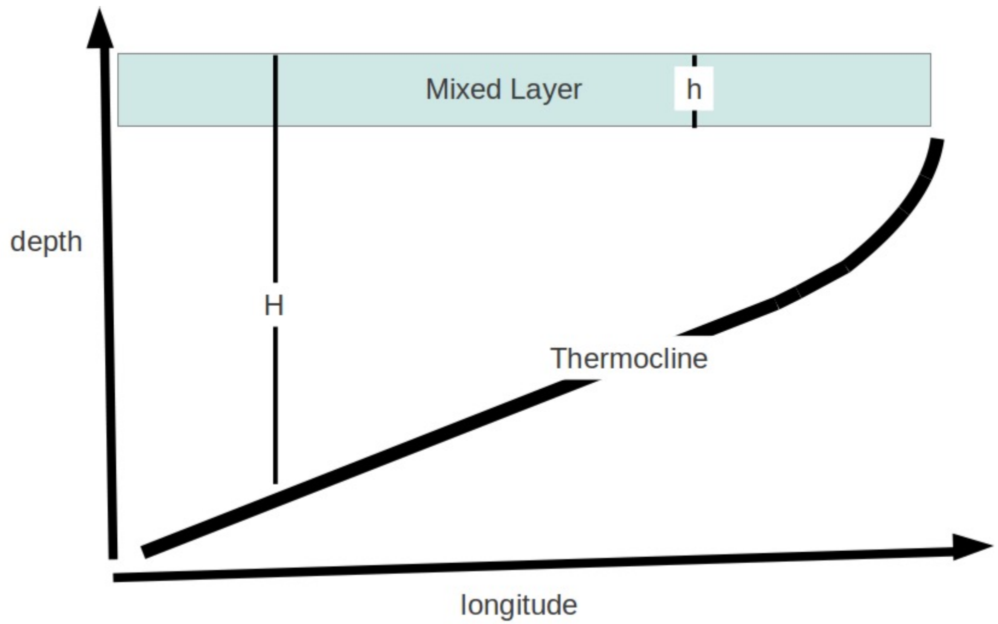
Coupled variability is grown via a coupled feedback mechanism

SST changes represent variability at the interface between each component of the coupled ocean-atmosphere system, one can gain great insight into the mechanisms driving coupled variability by understanding the primary processes controlling the evolution of SST



The type of ocean-atmosphere feedback mechanism behind coupled variability may be identified according to the primary physical process governing SST changes e.g.

- **Shortwave Cloud feedback -> Shortwave heat flux anomalies**
- **Wind-Evapartion-SST -> Latent heat flux anomalies**
- **Ekman Feedback -> verical advection change due to Ekman pumping anomalies**
- **Thermocline Feedback -> verical advection change due to thermocline anomalies**
- **Zonal advection feedback -> zonal horizonal advection anomalies**



$$\frac{\partial \bar{T}}{\partial t} = \underbrace{-\frac{1}{h}\int_{-h}^{0} u\frac{\partial T}{\partial x}dz}_{A_x} \underbrace{-\frac{1}{h}\int_{-h}^{0} v\frac{\partial T}{\partial y}dz}_{A_y} \underbrace{-\frac{1}{h}\int_{-h}^{0} w\frac{\partial T}{\partial z}dz}_{A_z}$$
$$+\underbrace{\frac{1}{h}\int_{-h}^{0} K_{th}\nabla^2 T dz}_{D_h} \underbrace{-\frac{1}{h}(K_{tv}\frac{\partial T}{\partial z})_{z=-h}}_{V} \underbrace{-\frac{1}{h}\frac{\partial h}{\partial t}(\bar{T} - T_{z=-h})}_{E} + \underbrace{\frac{q_* + q_s(1 - f_{z=-h})}{h\rho_o Cp}}_{F} \quad (1)$$

where $T_{z=-h}$ is the temperature at the base of the chosen surface layer, K_{th} represents the horizontal temperature diffusion coefficient, K_{tv} the vertical temperature diffusion coefficient, u and v the horizontal velocity components, w the vertical velocity component, q_s the surface solar radiative flux, $f(z)$ the fraction of solar radiation reaching depth z and q_* is the non penetrative part of the surface heat flux that consists of the net long-wave radiative flux, the latent heat flux and the sensible heat flux components.

The Seasonal Cycle in the Tropical Pacific

The Pacific

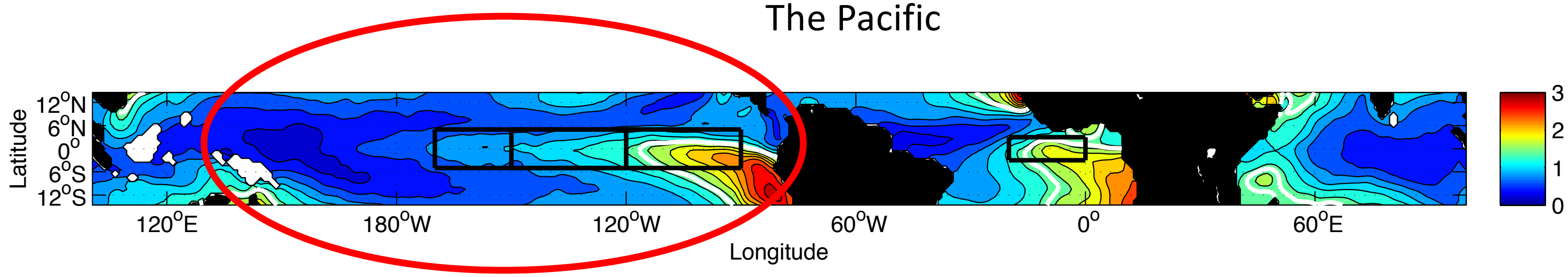


Figure: Based on 1° resolution, monthly, Hadley OI SST data (Rayner et al., 2003), this figure shows the standard deviation of SST variations spanning 1958-2004. The thick white line represents the 1.5°C contour. The black boxes indicate the Niño 3.4 (5°N-5°S 170°W-120°W), Niño 3 (5°N-5°S 150°W-90°W) and Atl3 (3°N-3°S 20°W-0°W) regions.

The Mean State of the Equatorial Pacific

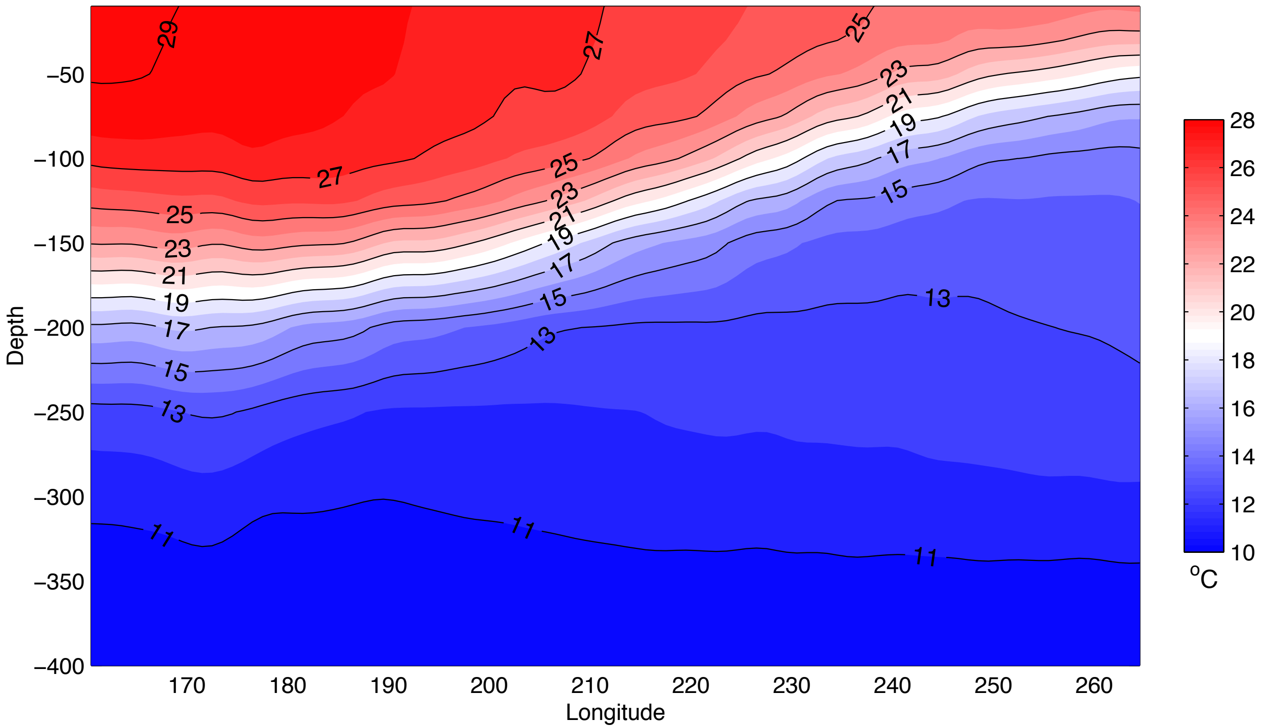
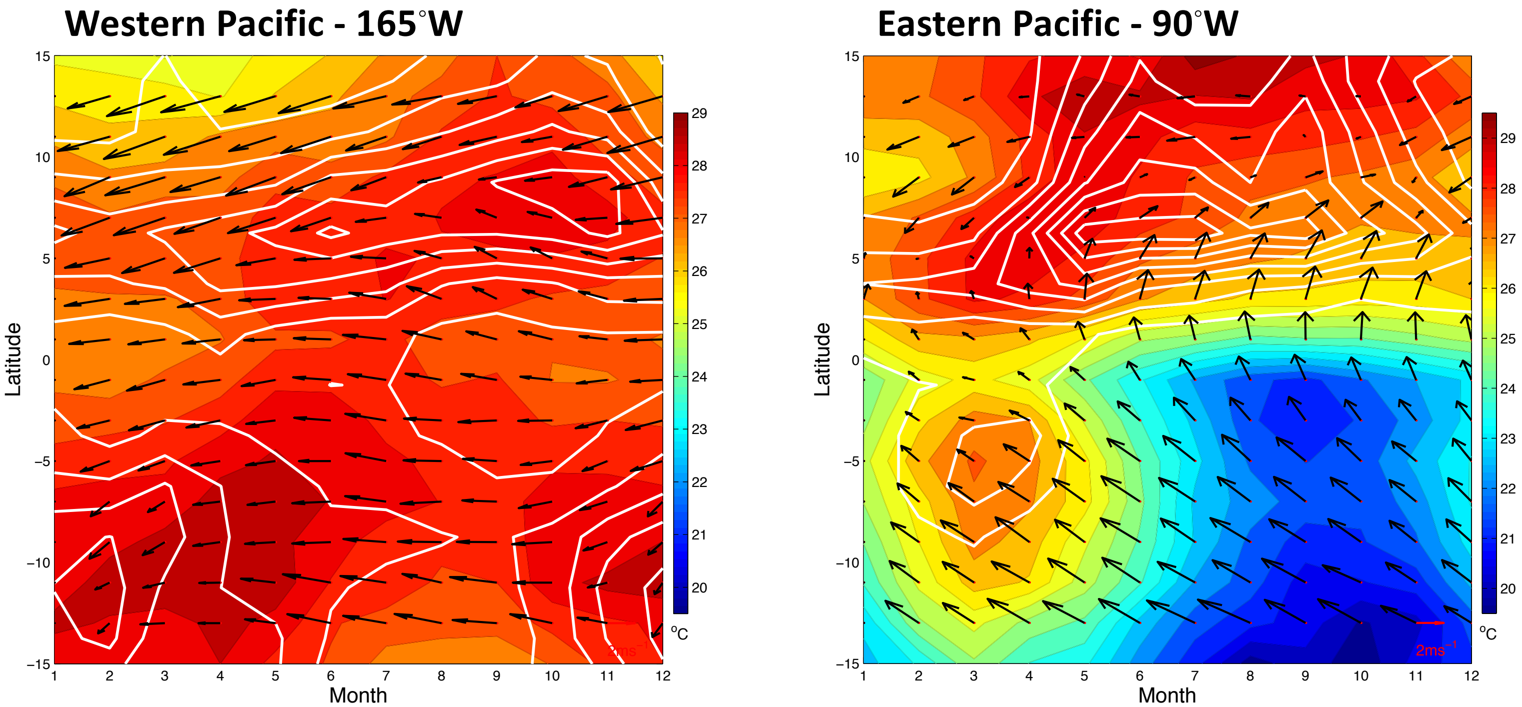


Figure: A cross-section of the mean temperature structure along the equator (3°S-3°N), based on climatological temperature data from the World Ocean Atlas 2005 (Locarnini et al., 2006).

Seasonal Variability within the Pacific

The distinct annual cycle in **eastern Pacific** is due to the integral role played by ocean-atmosphere interactions.



Seasonal SST, wind stress, and rainfall fluctuations. The color filled contours represent SST values in °C as indicated by the corresponding colorbar. The white contours represent precipitation with a contour interval of 2mm/day. The black vectors represent surface winds in m/s. Climatological SST and wind stress values from ICOADS v2.5 and climatological precipitation values from the CMAP dataset.

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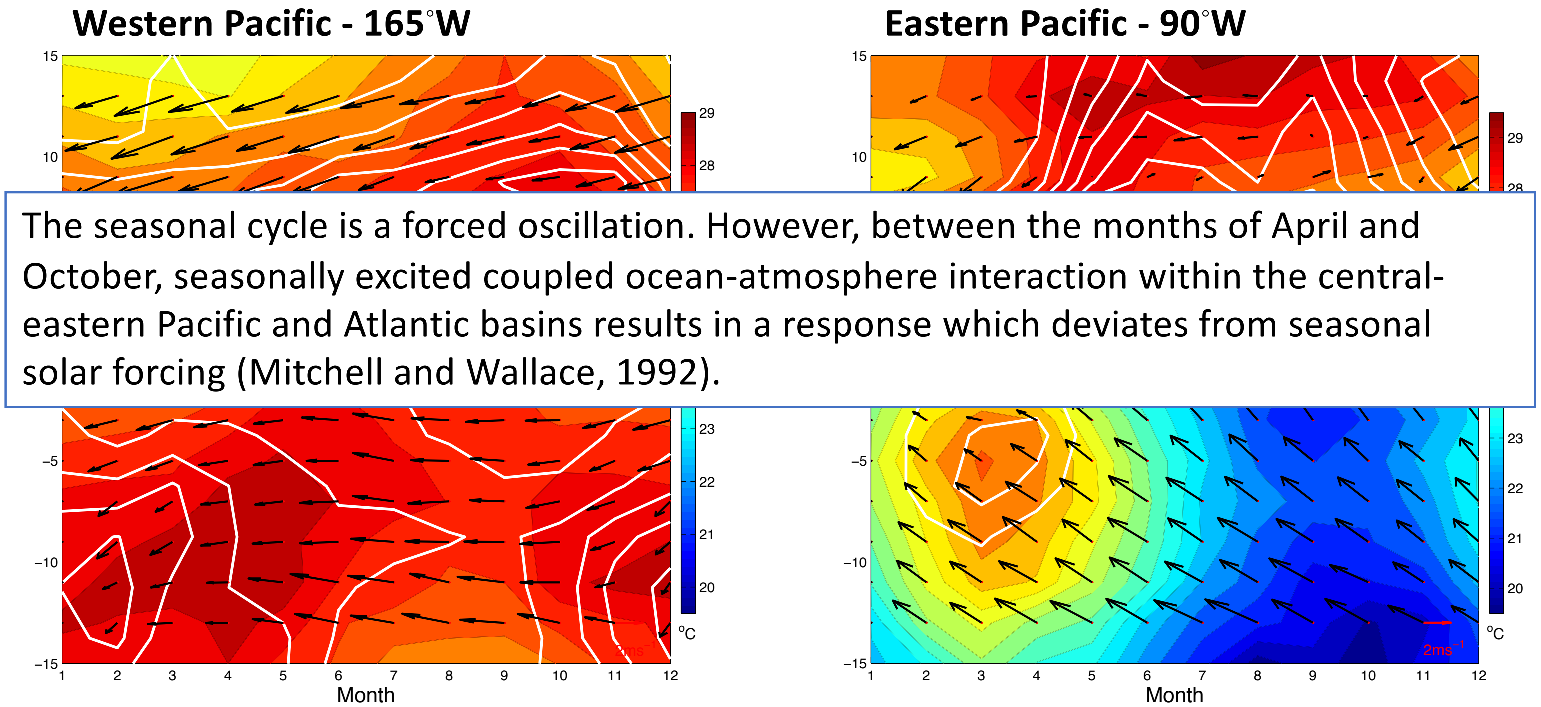

The seasonal cycle is a forced oscillation. However, between the months of April and October, seasonally excited coupled ocean-atmosphere interaction within the central-eastern Pacific and Atlantic basins results in a response which deviates from seasonal solar forcing (Mitchell and Wallace, 1992).

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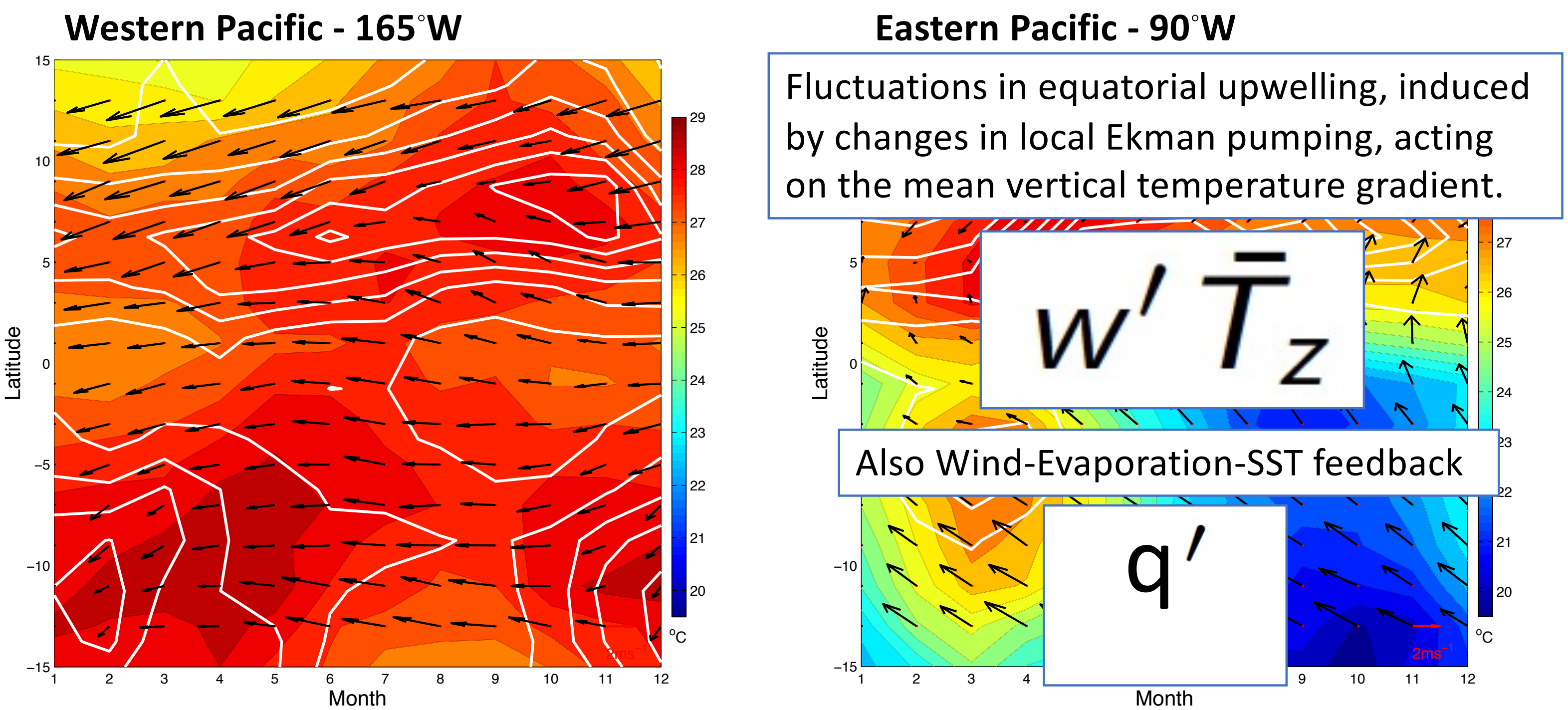

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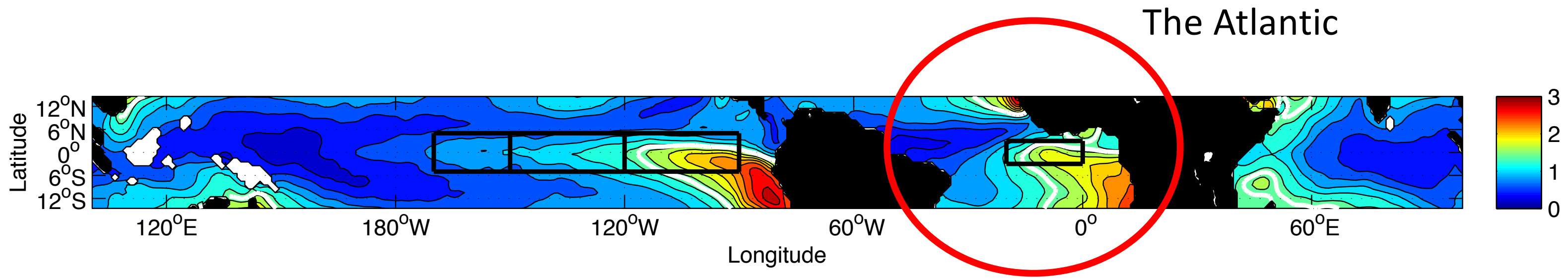
The Seasonal Cycle in the Tropical Atlantic



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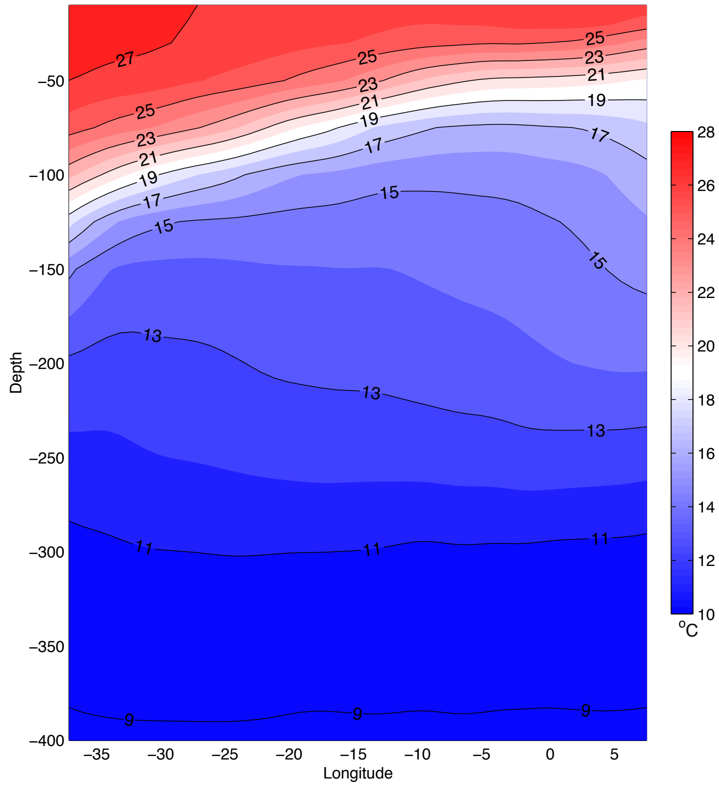

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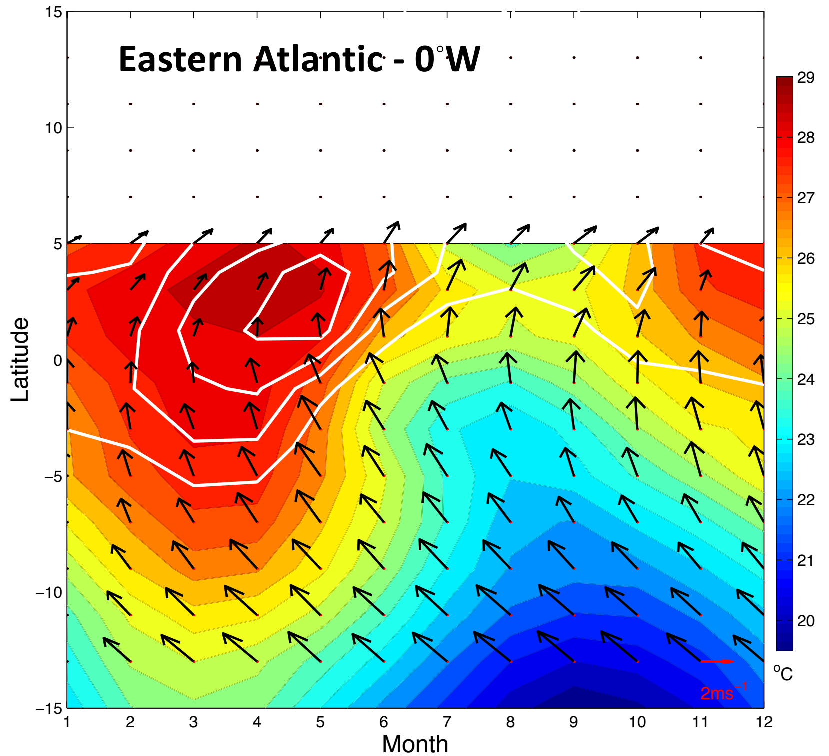

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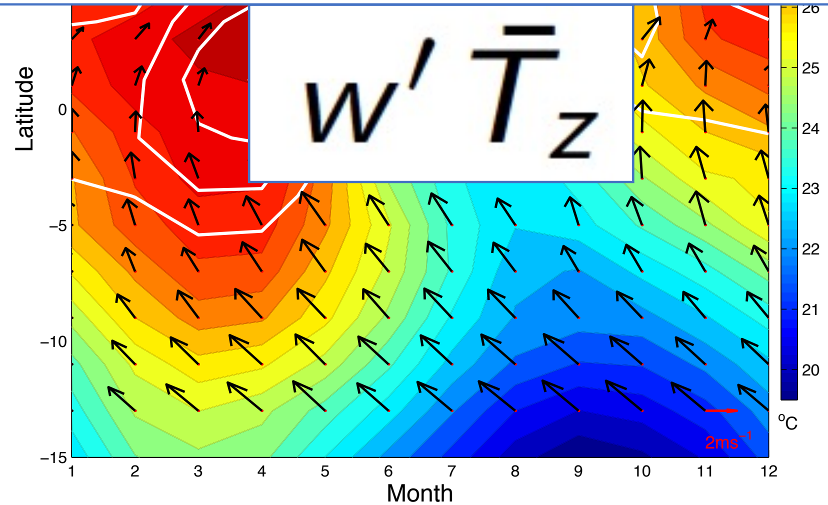
Seasonal Variability within the Eastern Atlantic

The primary feedback mechanism deemed responsible for the seasonal evolution of coupled conditions and the development of the cold tongue in the Atlantic is thought to be equivalent to that responsible for the seasonal development of the cold tongue in the Pacific (Mitchell and Wallace, 1992), namely seasonally excited SST modes and their associated Ekman feedback (Chang and Philander, 1994).

$$w' \bar{T}_z$$



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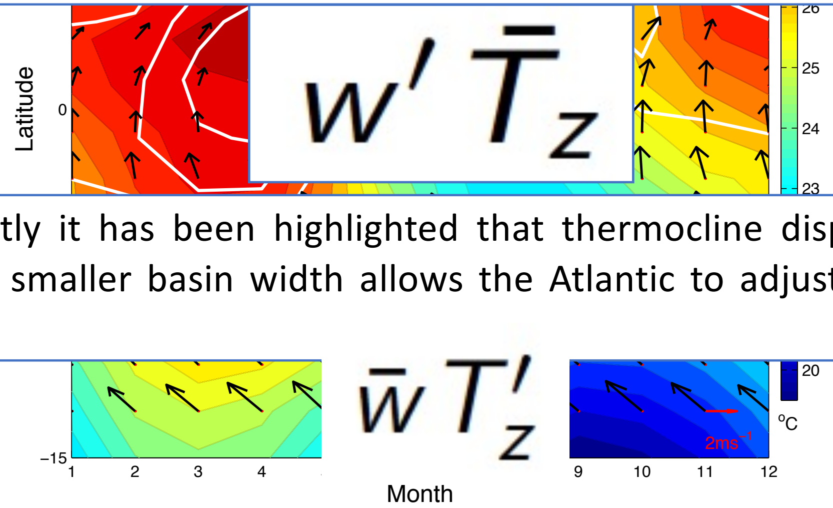

$$w' \bar{T}_z$$

However, more recently it has been highlighted that thermocline displacements also play an important role as the smaller basin width allows the Atlantic to adjust on seasonal timescales (Burls et al. 2011).

$$\bar{w} T'_z$$

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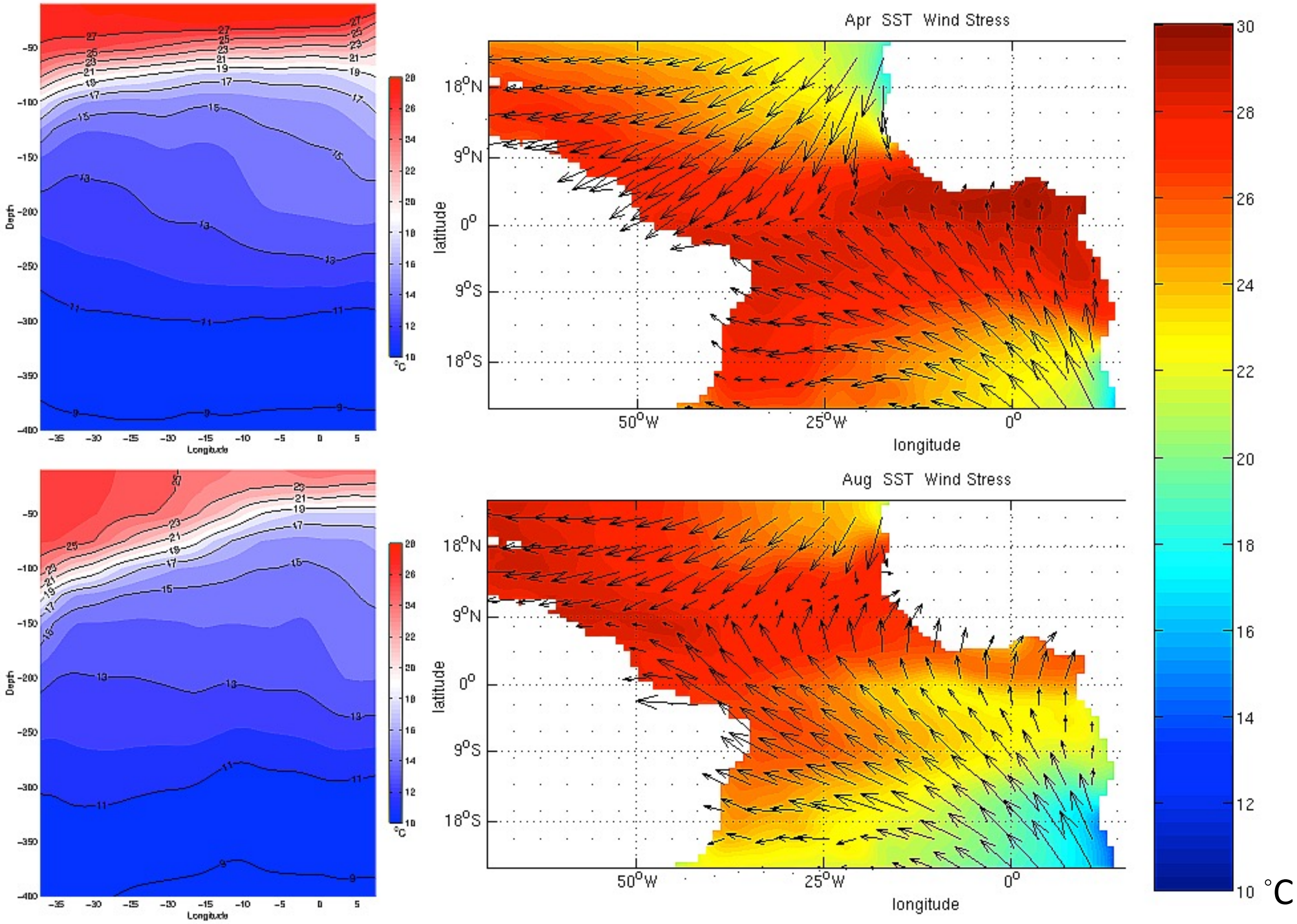
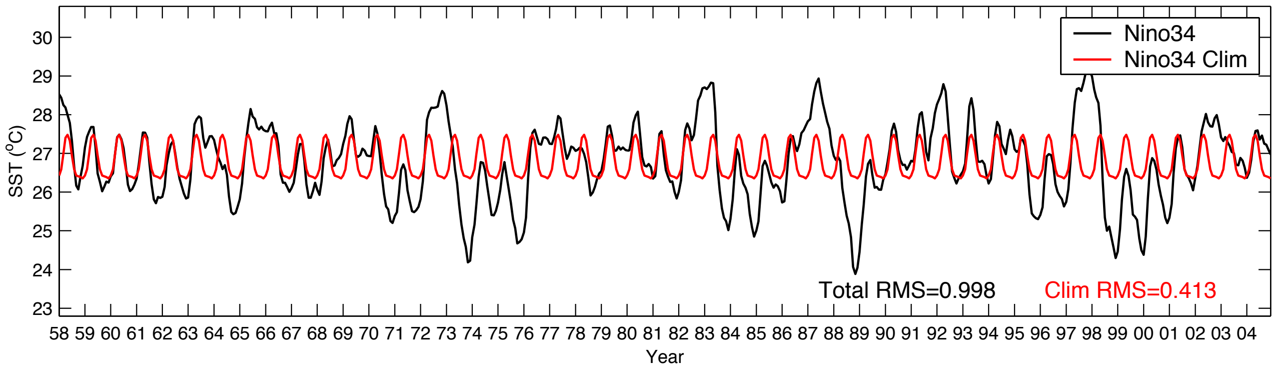
Seasonal Thermocline Adjustment

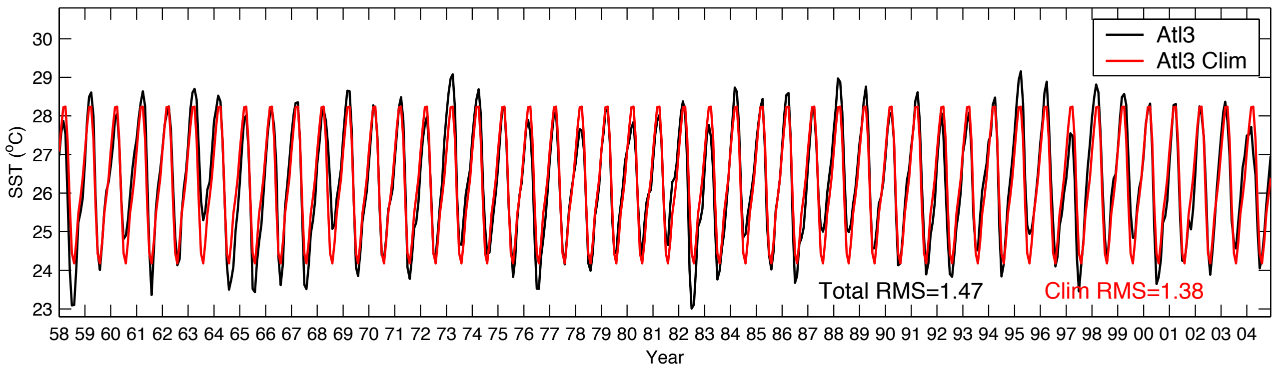


Equatorial Atlantic versus Pacific SST Variability

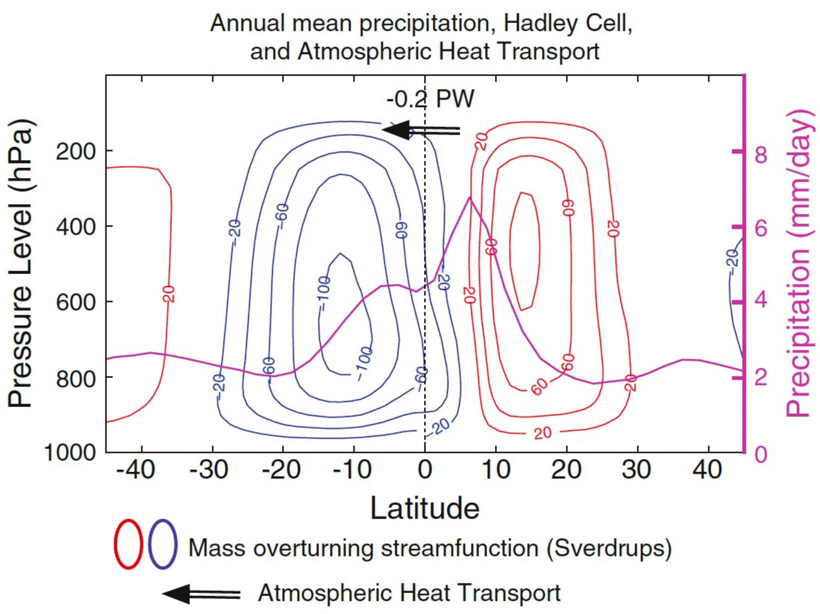
Pacific – Nino3.4 Region

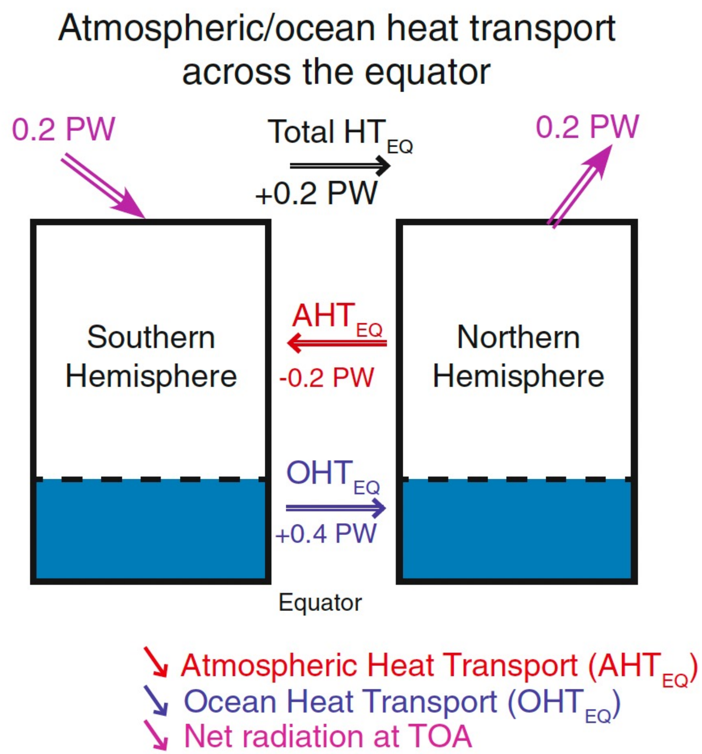


Atlantic – Atl3 Region



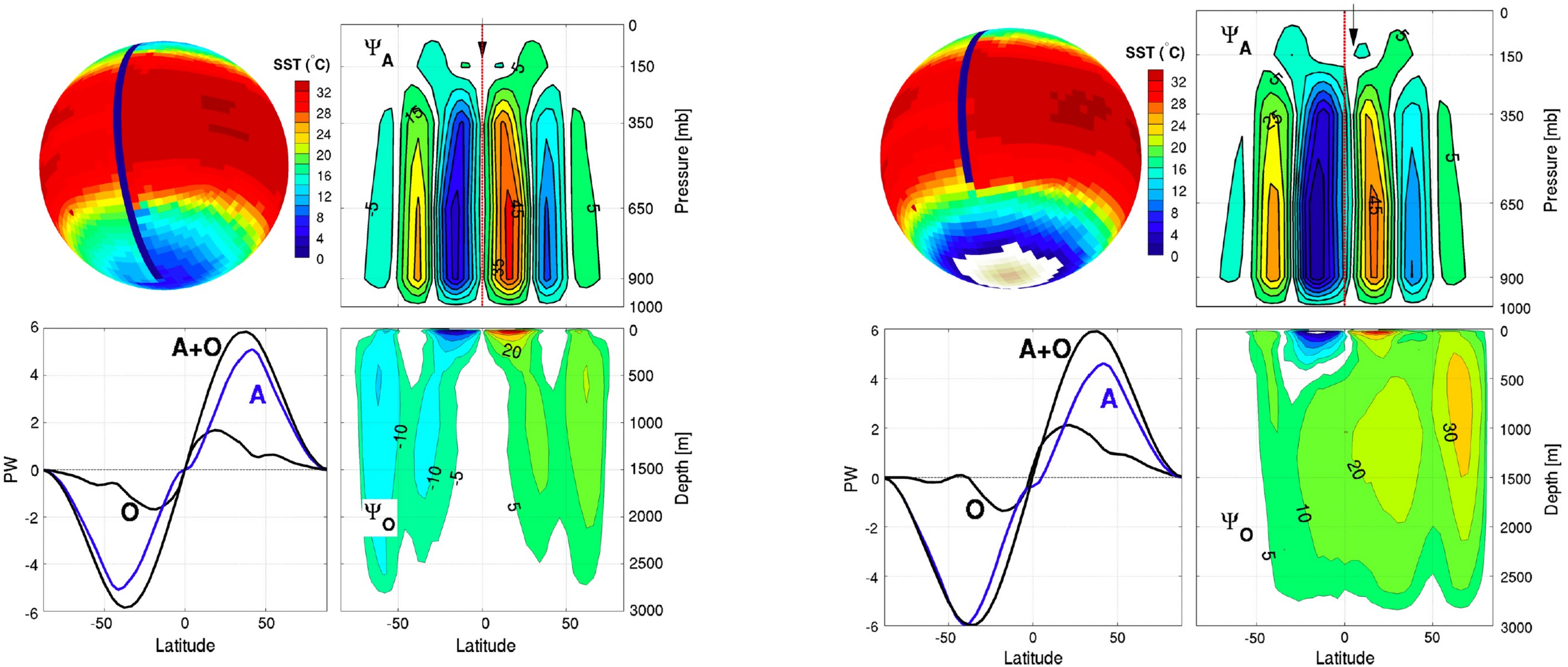
The ocean's role in setting the mean position of the Inter-Tropical Convergence Zone





Kang et al., (2008), Marshal et al., (2014)

The ocean's role in setting the mean position of the Inter-Tropical Convergence Zone



Marshal et al., (2014)

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Extra slides

Bjerknes Stability Index

A measure of the growth rate of SST anomalies due to individual feedback mechanisms

Linear equation for mixed-layer

$$\frac{\partial T}{\partial t} = -\left(\bar{u}\frac{\partial T}{\partial x} + \bar{v}\frac{\partial T}{\partial y} + u\frac{\partial \bar{T}}{\partial x} + v\frac{\partial \bar{T}}{\partial y} + \bar{w}\frac{\partial T}{\partial z} + w\frac{\partial \bar{T}}{\partial z}\right) + Q,$$

"average over that region where the dominating SST variability of ENSO resides"

$$\frac{\partial \langle T\rangle}{\partial t} \approx -\left(\frac{\langle \bar{u}\rangle}{L_x} + \frac{\langle -2y\bar{v}\rangle}{L_y^2} + \frac{\langle H(\bar{w})\bar{w}\rangle}{H_m}\right)\langle T\rangle - \langle u\rangle\left\langle\frac{\partial \bar{T}}{\partial x}\right\rangle + \langle H(\bar{w})\bar{w}\rangle\frac{\langle T_{sub}\rangle}{H_m} - \langle w\rangle\left\langle H(\bar{w})\frac{\partial \bar{T}}{\partial z}\right\rangle + \langle Q\rangle,$$

where $\langle\ \rangle$ denotes the area average; L_x and L_y are the longitude and latitude extents of the equatorial box; and $H(x)$ is a step function which ensures that only upstream vertical advection is taken into consideration. In equation (2), the factor $(-2y/L_y)$ comes from our assumption that the meridional structure of ENSO SST anomalies is Gaussian-like with an e-folding decay scale of L_y; T_{sub} denotes the subsurface ocean temperature anomalies; and H_m is the effective depth for the vertical advection. We have omitted the small term $v\partial\bar{T}/\partial y$ for the advection of the climate temperature by the meridional current perturbation.

$$2I_{BJ} = -\left(\frac{\langle \bar{u}\rangle}{L_x} + \frac{\langle -2y\bar{v}\rangle}{L_y^2} + \frac{\langle H(\bar{w})\bar{w}\rangle}{H_m}\right) - \alpha + \mu_a\beta_u\left\langle -\frac{\partial \bar{T}}{\partial x}\right\rangle + \mu_a\beta_w\left\langle\frac{\partial \bar{T}}{\partial z}H(\bar{w})\right\rangle + \mu_a^*\beta_h\left\langle\frac{H(\bar{w})\bar{w}}{H_m}a\right\rangle,$$

$$\beta_u = \beta_{um} + \beta_{us}, \quad F = -\left\langle\frac{\partial \bar{T}}{\partial x}\right\rangle\beta_{uh} + \left\langle\frac{H(\bar{w})\bar{w}}{H_m}a\right\rangle.$$

$$\frac{\partial \langle T\rangle}{\partial t} = 2I_{BJ}\langle T\rangle + F[h],$$

F[h] represents the effects of the delayed ocean adjustment

[*] denotes the zonal mean

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Jin et al. 2006

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Mean Advection | Mean Upwelling | Thermal Damping

$$2I_{BJ} = -\left(\frac{\langle \bar{u}\rangle}{L_x} + \frac{\langle -2y\bar{v}\rangle}{L_y^2} + \frac{\langle H(\bar{w})\bar{w}\rangle}{H_m}\right) - \alpha$$
$$+ \mu_a\beta_u\left\langle -\frac{\partial \bar{T}}{\partial x}\right\rangle + \mu_a\beta_w\left\langle \frac{\partial \bar{T}}{\partial z}H(\bar{w})\right\rangle$$
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Zonal Advection Feedback

Ekman Feedback

Thermocline Feedback

$$2I_{BJ} = -\left(\frac{\langle \bar{u} \rangle}{L_x} + \frac{\langle -2y\bar{v} \rangle}{L_y^2} + \frac{\langle H(\bar{w})\bar{w} \rangle}{H_m}\right) - \alpha + \mu_a \beta_u \left\langle -\frac{\partial \bar{T}}{\partial x} \right\rangle + \mu_a \beta_w \left\langle \frac{\partial \bar{T}}{\partial z} H(\bar{w}) \right\rangle + \mu_a^* \beta_h \left\langle \frac{H(\bar{w})\bar{w}}{H_m} a \right\rangle,$$

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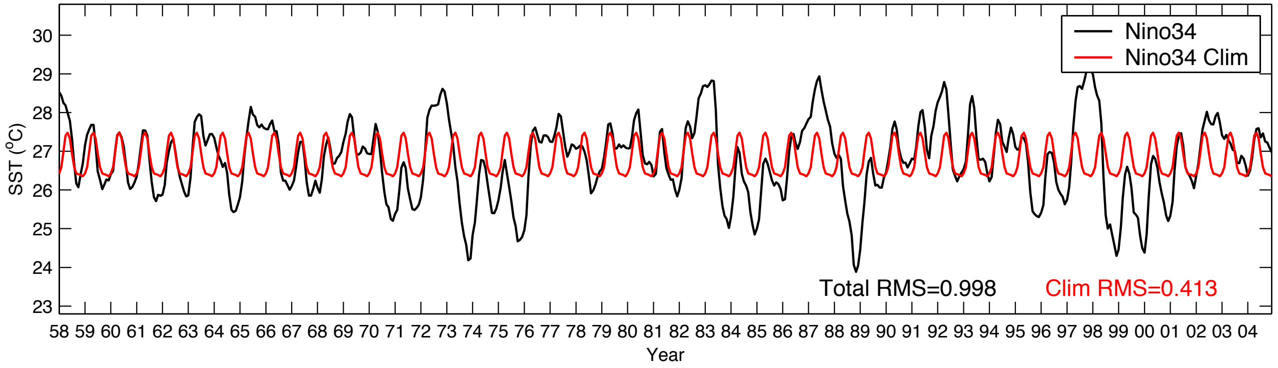
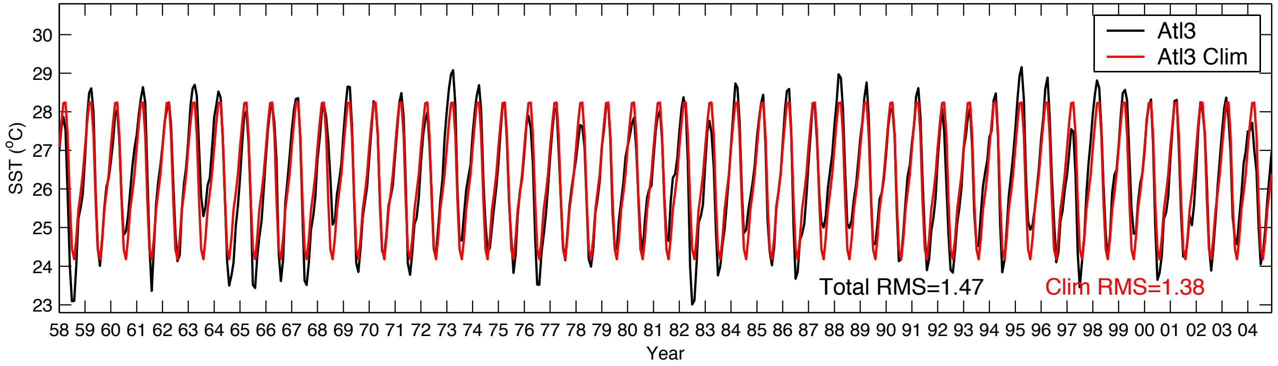
Atlantic versus Pacific SST Variability

Pacific – Nino3.4 Region



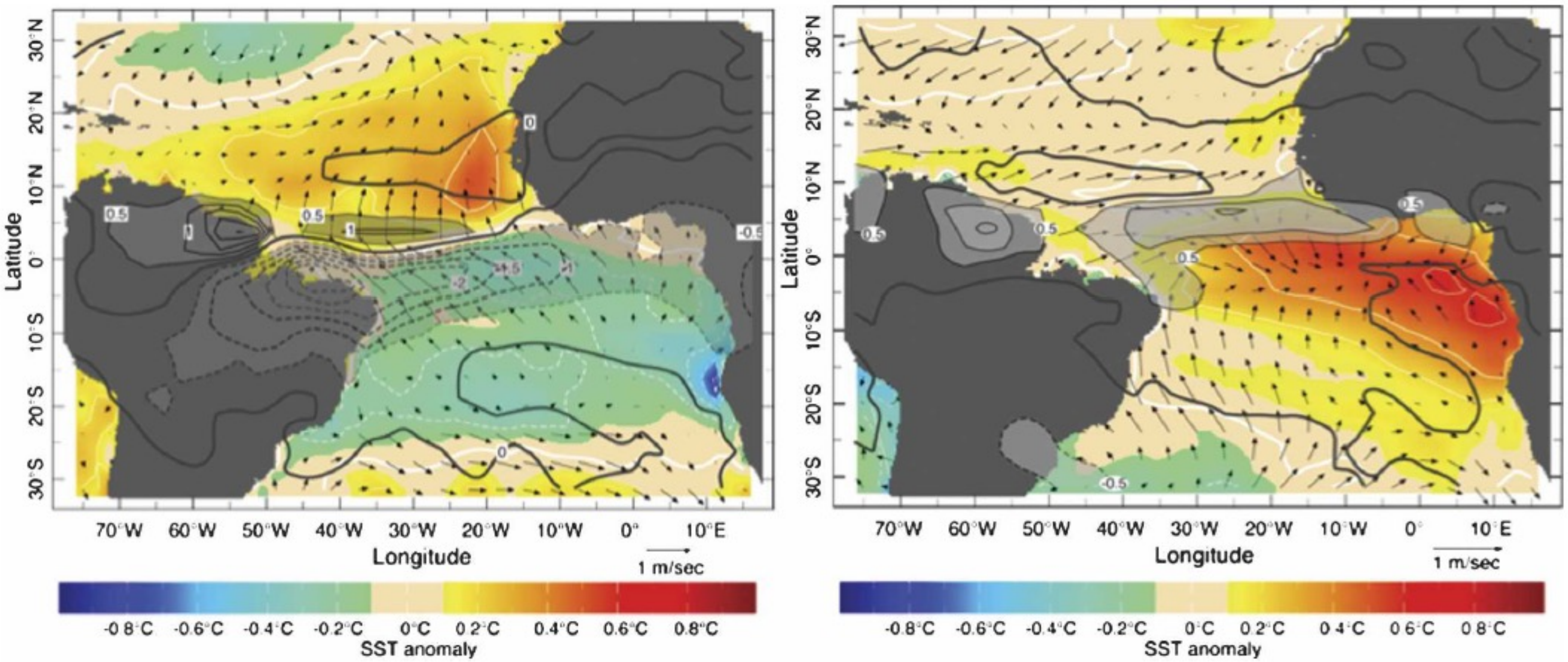
Atlantic – Atl3 Region



Tropical Atlantic Coupled Variability

Dominant patterns of surface ocean–atmosphere variability in the tropical Atlantic region

Boreal spring (March–April) **Boreal summer (June–August)**



The black contours depict the first EOF of regional rainfall anomalies in mm/day (from GPCP data 1979–2001). The colored field is SST anomalies regressed on the principal component time series of the rainfall EOF [(°C), see scale below; white contours every 0.2° are added for further clarity]. Arrows depict the seasonal mean surface wind vector in m/s, regressed on the same time series (see arrow scale below frame). (From Kushnir et al. 2004. and Chang et al. 2006)

Tropical Atlantic Meridional Mode

Boreal spring (March–April)