An Analytical Framework for Understanding Tropical Meridional Modes

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The Atlantic and Pacific Meridional Modes

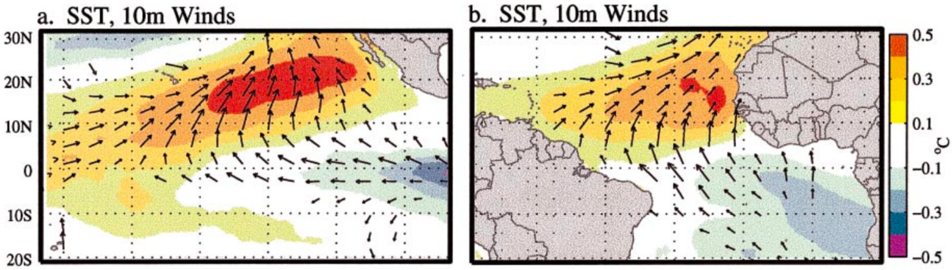
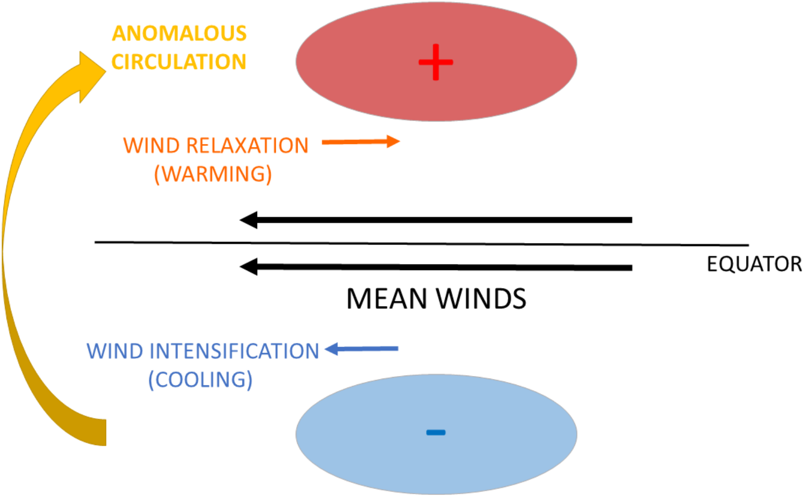


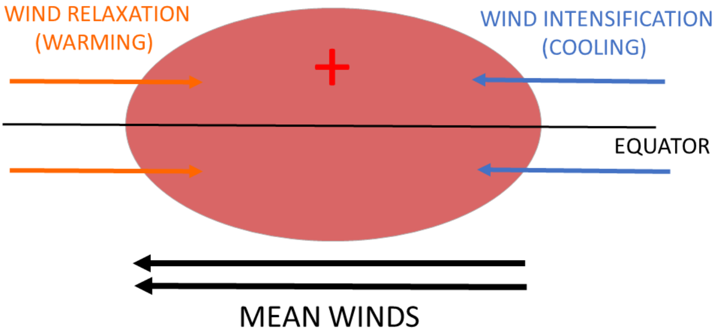
Figure: Pacific Meridional Mode (PMM) and Atlantic Meridional Mode (AMM). Chiang and Vimont 2004

- **AMM**: Equatorially antisymmetric dipole
- **AMM**: Flow from cold to warm hemisphere
- **PMM**: Analogous to AMM
- **PMM**: Important Equatorially Symmetric Part
- Wind-Evaporation-SST (WES) feedback.

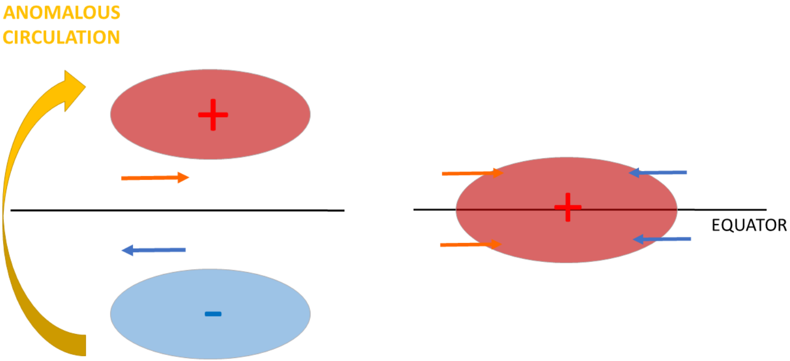
The WES feedback (Xie and Philander 1994)



In addition... Equatorially symmetric case.



Equatorially Antisymmetric and Symmetric patterns supported by the WES feedback



Take home messages I

- Both equatorially symmetric and antisymmetric structures may arise through the WES feedback interaction.
- Symmetric and antisymmetric modes will interact differently with other components of the climate system (e.g. ENSO)

WES feedback simple model

Slab Ocean

$$\frac{\partial T}{\partial t} = \alpha u - \epsilon_T T$$

- Mean easterly trades ($\alpha > 0$)
- $u > 0$ ->Relaxation of trades, positive SST tendency
- ϵ_T Thermal relaxation time

Gill-Matsuno Atmosphere

$$\epsilon u - yv = -\frac{\partial \phi}{\partial x}$$

$$yu = -\frac{\partial \phi}{\partial y}$$

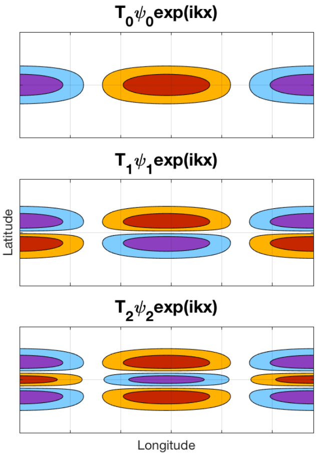
$$\epsilon \phi + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -K_q T$$

- Long wave approximation

- Effective coupling of the system $K_q \alpha$. (Martinez-Villalobos and Vimont 2016)
- Atmosphere determined by SSTs
- K_q, α homogeneous coupling

Separation onto Parabolic Cylinder Function Space

$$T(t, y, x) = \sum_{m=0}^{\infty} T_m(t)\psi_m(y)exp(ikx)$$



- m even -> equatorially symmetric SST structures
- m odd -> equatorially antisymmetric SST structures
- low m -> loadings preferentially close to the equator
- high m -> peak farther from equator

SST evolution under the WES feedback in parabolic cylinder function space

$$\frac{\partial T_m}{\partial t} = \frac{1}{2}K_q\alpha[\frac{\sqrt{(m-1)m}}{-(2m-1)\epsilon+ik}T_{m-2} + (\frac{m-1}{-(2m-1)\epsilon+ik} - \frac{m+2}{-(2m+3)\epsilon+ik})T_m - \frac{\sqrt{(m+1)(m+2)}}{-(2m+3)\epsilon+ik}T_{m+2}] - \epsilon_T T_m. \quad (1)$$

- Interaction between contiguous m modes mediated by equatorial atmospheric Rossby ($c_R \propto (-(2m+1)\epsilon + ik)^{-1}$)) and Kelvin waves ($c_K \propto (\epsilon + ik)^{-1}$)
- Equatorial Symmetry preserving evolution.
- Equatorward Propagation
- Dynamics of antisymmetric and symmetric modes the same for $m \geq 2$ modes.
- Difference only on most equatorially confined structures.

SST evolution under the WES feedback in parabolic cylinder function space

- $\frac{\partial T_m}{\partial t}$ equation same for $m \geq 2$
- $m = 0$

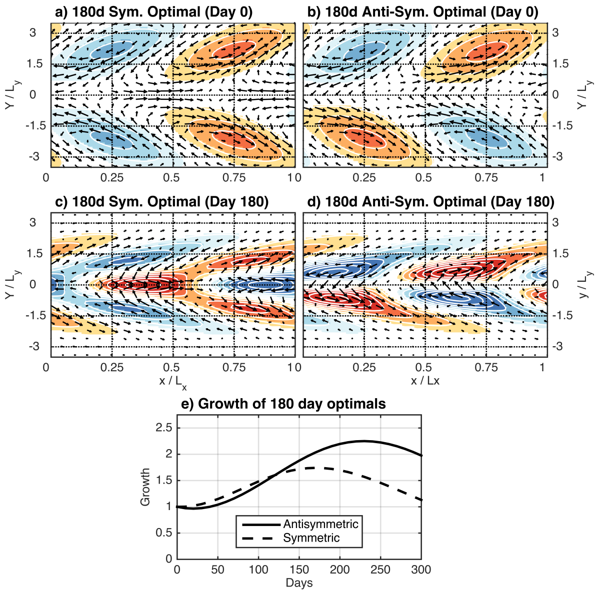
$$\frac{\partial T_0}{\partial t} = \frac{1}{2} K_q \alpha [(\frac{-1}{\epsilon + ik} - \frac{2}{-3\epsilon + ik}) T_0 - \frac{\sqrt{2}}{-3\epsilon + ik} T_2] - \epsilon_T T_0 \quad (2)$$

- $m = 1$

$$\frac{\partial T_1}{\partial t} = \frac{1}{2} K_q \alpha [(\frac{-3}{-5\epsilon + ik} T_1 - \frac{\sqrt{6}}{-5\epsilon + ik} T_3] - \epsilon_T T_1 \quad (3)$$

- Key role of atmospheric Kelvin wave in T_0 equation
- No analogous term in T_1 evolution

Equatorially symmetric and antisymmetric example



Take home messages II

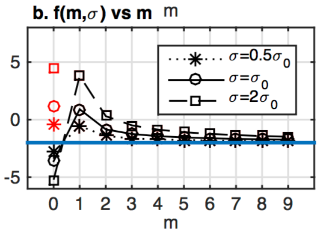
- Both equatorially symmetric and antisymmetric modes emerge naturally from the same framework.
- WES feedback interaction recast as the interaction between different SST modes mediated by Equatorial atmospheric waves.
- Both symmetric and antisymmetric modes propagate equatorward
- Equatorially symmetric and antisymmetric modes dynamics differ only for the most equatorially confined SST patterns. (**Atmospheric Kelvin Wave Role**).

Zonally homogeneous SST patterns ($\frac{\partial}{\partial x} = 0$ or $k = 0$)

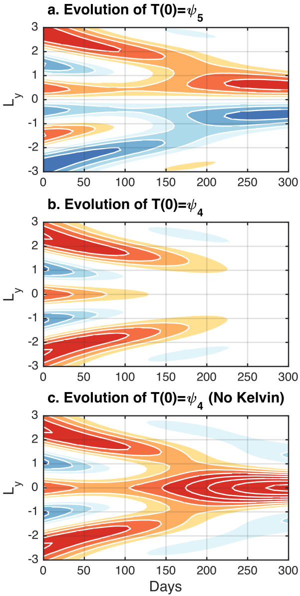
- $k \rightarrow 0$
- $\sigma = \frac{K_q \alpha}{\epsilon_T \epsilon}$ Ratio of coupling to damping ("stability parameter")

$$\frac{\partial T_m}{\partial t} = \frac{1}{2}\epsilon_T(-h(m-1)\sigma T_{m-2} + (g(m)\sigma - 2)T_m + h(m+1)\sigma T_{m+2})$$

- $h(m)$ ->WES feedback propagation
- $g(m)$ ->WES feedback growth
- $g > 0$ WES feedback positive, $g < 0$ WES feedback negative
- $f(m,\sigma) = g(m)\sigma - 2$-> Balance between WES feedback and thermal damping



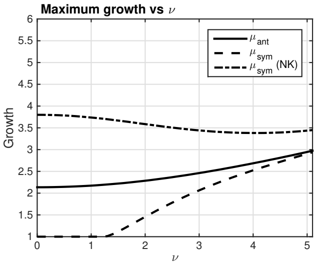
Symmetric and antisymmetric propagation



- Equatorward propagation
- a. Decay until $\psi_1(y)$ projection.
- b. Decay
- c. Similar to b at the beginning
- c. No Kelvin -> Growth

Zonally inhomogeneous SSTs ($k \neq 0$)

- $\nu = \frac{k}{\epsilon}$



- Kelvin wave reduced damping compared to $k = 0$.
- More growth of equatorially symmetric modes.

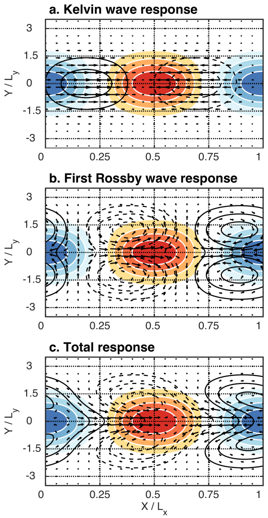


Figure: **a**. (**b**). Kelvin (first Rossby) wave response to $T = \psi_0(y)$. **c** Total

Take home messages III

- WES feedback is positive for all T_m modes, with the exception of the most equatorially confined SST mode (T_0 **Kelvin wave affect**)
- WES feedback favors growth of equatorially antisymmetric SST structures
- **Finite zonal wavelength** There are regimes in the parameter space where equatorially symmetric structures can grow through the WES feedback.

Relevant Publications

- Vimont, D. J. (2010). Transient growth of thermodynamically coupled variations in the tropics under an equatorially symmetric mean state. *Journal of Climate*, 23(21):5771-5789.
- Martinez-Villalobos, C. and Vimont, D. J. (2016). The Role of the Mean State in Meridional Mode Structure and Growth. *Journal of Climate*, 29(10):3907-3921.
- Martinez-Villalobos, C. and Vimont, D. J. (2017). An analytical framework for understanding Tropical Meridional Modes. *Journal of Climate*, In Press.