UNIVERSITÄT LEIPZIG

Climate Dynamics (Summer Semester 2019)

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Today's Lecture (Lecture 10): Internal variability

Reference

IPCC AR5, Ch. 14
Holton, Ch. 11
COMET *Introduction to tropical meteorology*, linked from course webpage

3 – Internal variability

1. Introduction

2. The climate system

3. Internal variability
   - 3.1 Departures from temporal average
   - 3.2 Modes of internal variability
   - 3.3 El Niño–Southern Oscillation
   - 3.4 Modeling ENSO
   - 3.5 ENSO teleconnections

4. Forcing and feedbacks

5. Anthropogenic climate change

Reference

IPCC AR5, Ch. 14
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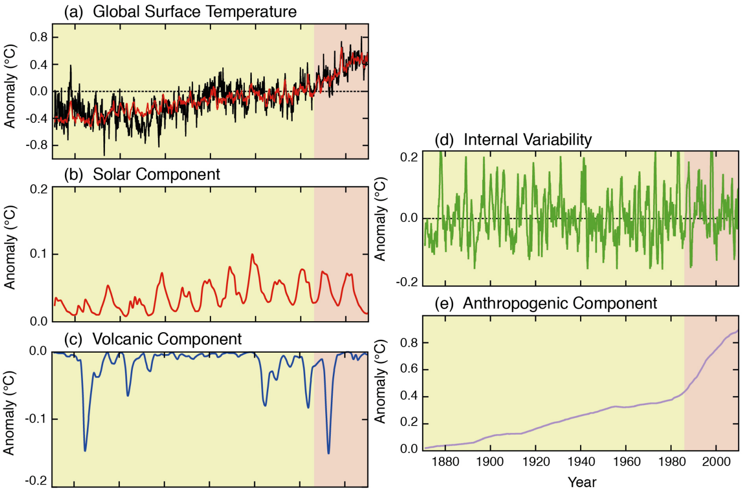
3.1 – Departures from temporal average



Classification of fluctuations about the climatological mean:

- Time scale: for example, diurnal, annual cycles in solar forcing
- Periodic or trend?
- Natural or anthropogenic?
- Forcing or internal variability?

Figures: IPCC AR5, Holton (unless otherwise noted)

Forcing or internal variability?

Forcing

- Change in net energy exchange between the climate system and the environment
- Examples:
  - Solar intensity cycles
  - Orbital parameter cycles
  - Volcanic eruptions
  - Anthropogenic emissions of greenhouse gases, aerosols

Internal variability

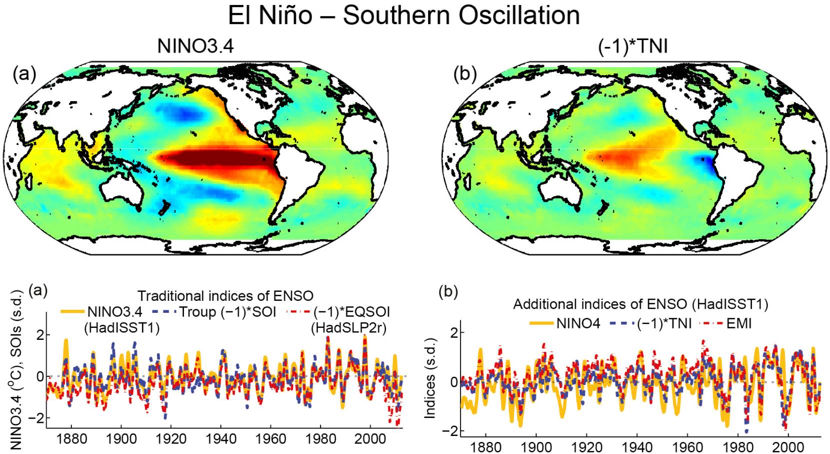
- Many aspects of the climate system
  - are described by nonlinear differential equations
  - couple systems with different time scales
  - have positive feedback
- This leads to transitions between states (example: the attractors in the Lorenz system) on various time scales
- Examples (with time scales):

Days–weeks	Midlatitude storm systems
Months	Madden–Julian oscillation (MJO)
Interannual	El Niño–southern oscillation (ENSO)
Decadal	Pacific decadal oscillation (PDO)
Multidecadal	Atlantic multidecadal oscillation (AMO)

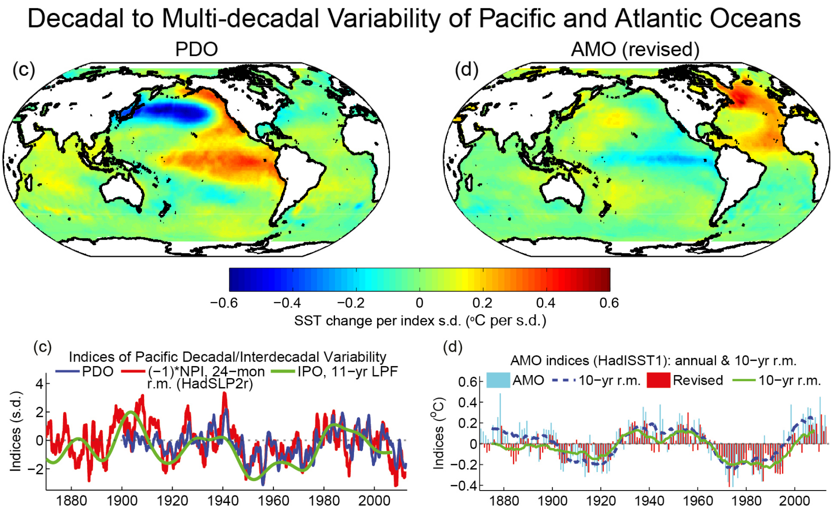
3.2 – Modes of internal variability

What is a mode?

A *mode* describes the space–time structure of the variability. Often it is defined as a product of a characteristic spatial *pattern* (of one or more variables) and a time-varying *index*. In next week's homework, we will have a hands-on exercise on determining a mode.



Modes of internal variability



3.3 – El Niño–Southern Oscillation

- ENSO describes cyclical changes in the state of the tropical Pacific Ocean and the overlying atmosphere
- Through *teleconnections*, ENSO influences not only the tropical Pacific but most other regions, including the Arctic
- Strong influence on regional climates (temperature and precipitation) and on global-mean temperature
- On interannual time scales, ENSO is the most important mode of variability globally
- Strong El Niños are visible in the global-mean temperature time series (e.g., 1998)

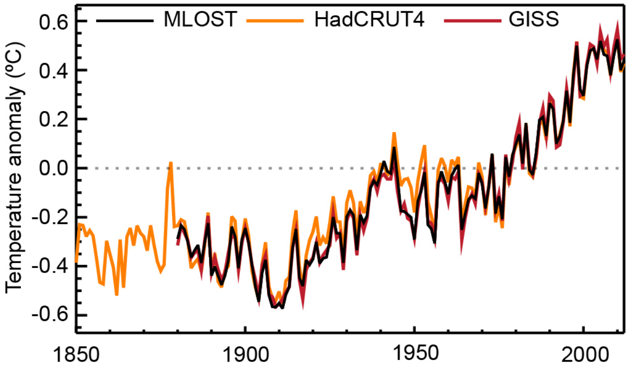


Figure: IPCC AR5

ENSO and global mean surface temperature

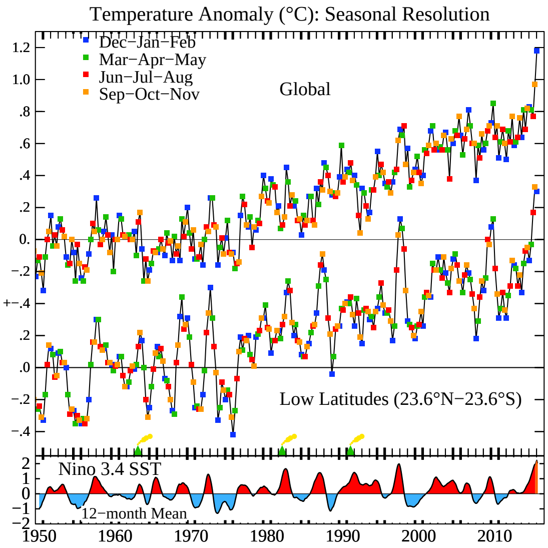
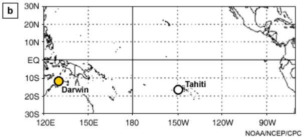


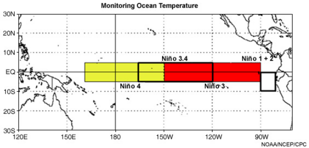
Figure: NASA GISS

El Niño–Southern Oscillation

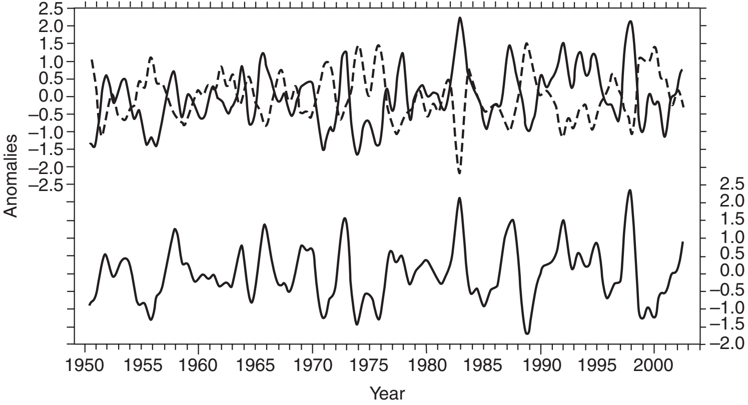
Southern oscillation – an atmospheric phenomenon



El Niño – an ocean phenomenon



But the underlying process is a combined ocean–atmosphere phenomenon (ENSO)



Figures: COMET, Holton

Mean state of the equatorial atmosphere – Walker circulation

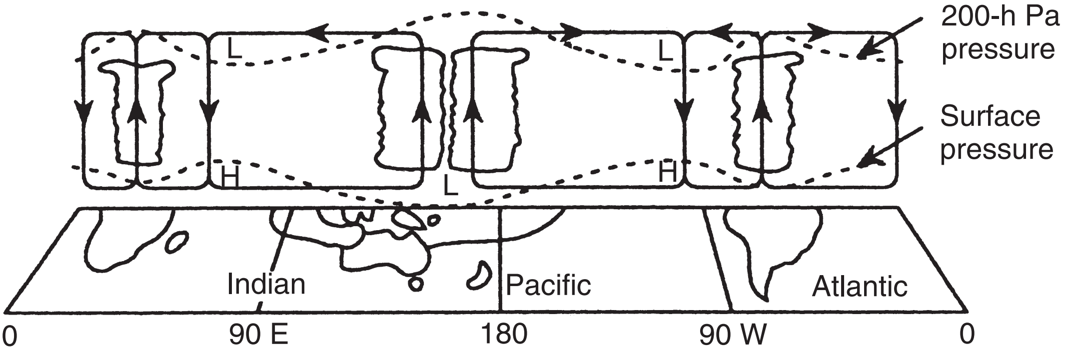


Figure: Holton

Oceanic and atmospheric circulation are coupled through convection

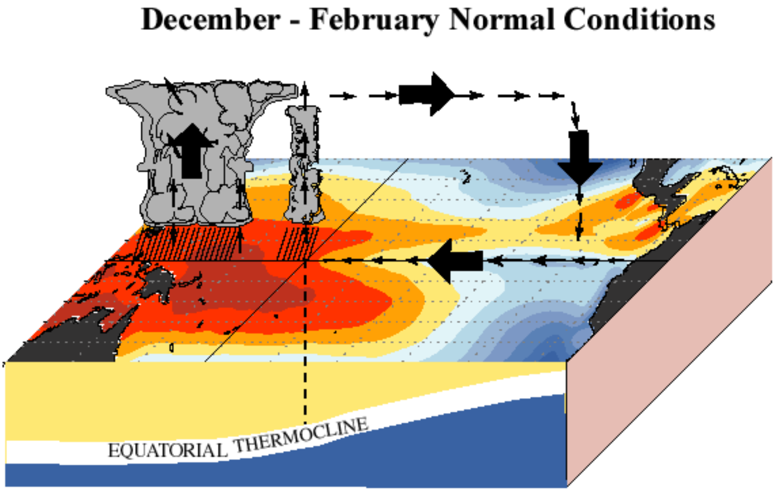
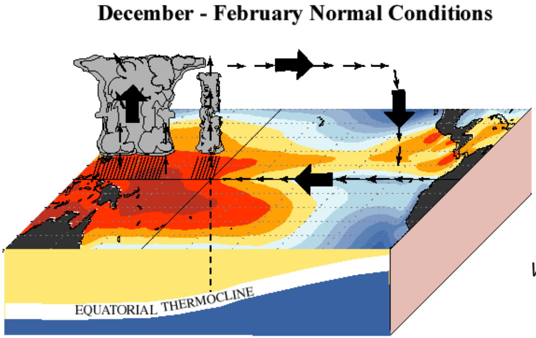
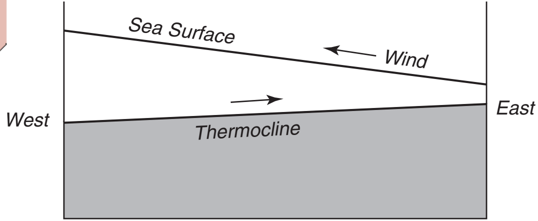


Figure: COMET

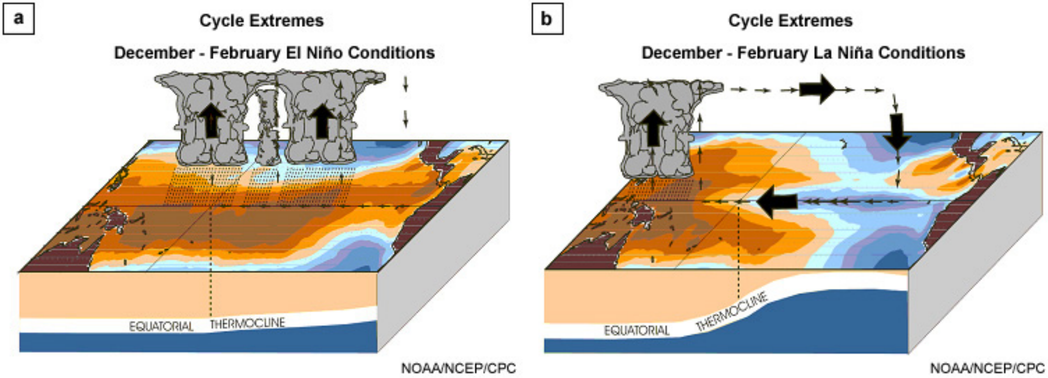
Mean state of the equatorial ocean – SST, thermocline depth, sea surface elevation





Figures: COMET, Stewart

El Niño–La Niña cycle



Walker circulation: normal (top) and El Niño (bottom)

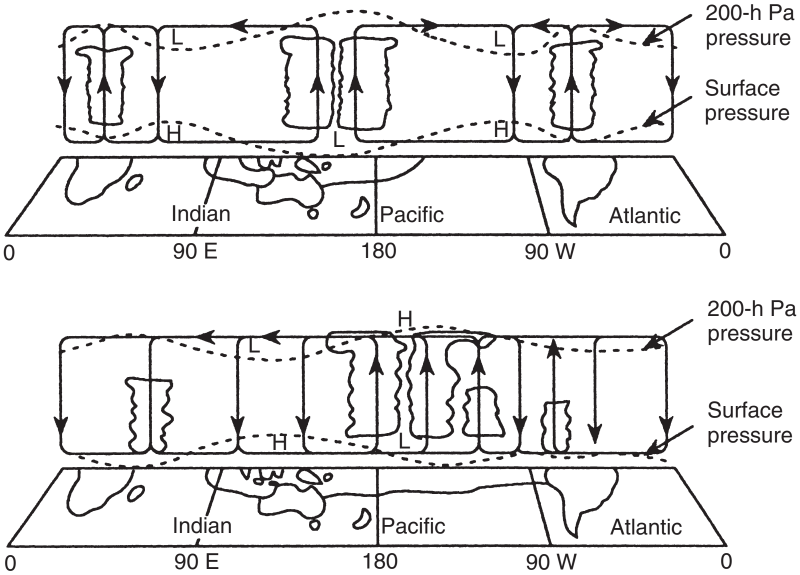


Figure: Holton

3.4 – Modeling ENSO

- A satisfactory model of ENSO must explain
  1. Formation of the El Niño pattern
  2. Collapse of El Niño and transition to La Niña
  3. Collapse of La Niña pattern and return to neutral conditions

  There are many models that accomplish this (more or less).
- The irregular temporal cycle (which is in part due to interactions with other modes) is hard to forecast
- For climate models, the important features are
  - Realistic time spectrum
  - Realistic teleconnections (export of energy from tropical ocean)

Conceptual models

The purpose of conceptual models is to simplify the ENSO problem to just those characteristics that explain the observed behavior. Two examples of conceptual models for ENSO are:

Delayed oscillator

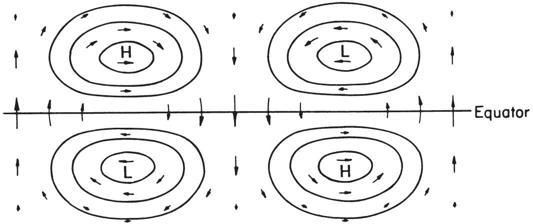
explains why La Niña follows El Niño

Recharge–discharge of ocean heat

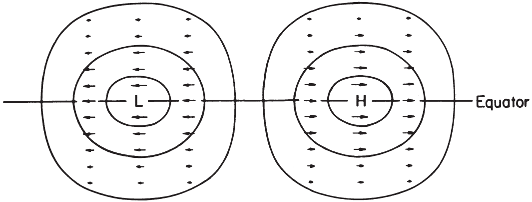
explains why El Niño causes a spike in global mean temperature (by releasing heat stored in the ocean)

Some tropical dynamics – tropical waves

Rossby–gravity wave velocity anomaly field



Kelvin wave velocity anomaly field



These wave disturbances (horizontal velocity perturbations sketched in the figures) are *equatorially trapped* (group velocity is zonal along the equator)

Figure: Holton, Ch. 11

Equatorial wave theory

Near equator, to good approximation (*equatorial beta plane*):

$$f = \beta y \tag{3.1}$$

For an incompressible fluid of mean depth h_e, we can write the following linearized set of equations for perturbation u, v and Φ:

$$\frac{\partial u'}{\partial t} - \beta y v' = -\frac{\partial \Phi'}{\partial x} \qquad \text{equation of motion} \tag{3.2}$$

$$\frac{\partial v'}{\partial t} + \beta y u' = -\frac{\partial \Phi'}{\partial y} \qquad \text{note: not geostrophic at equator} \tag{3.3}$$

$$\frac{\partial \Phi'}{\partial t} + g w' = -g h_e \left(\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} \right) \qquad \text{hydrostatic equilibrium + continuity} \tag{3.4}$$

These linearized equations assume that $\overline{u} = 0$, $u' \partial u' / \partial x \ll \partial u' / \partial t$ etc. (terms second-order and higher in the perturbation $\ll$ first-order). They apply to ocean and atmosphere.

Equatorial wave theory

Ansatz for zonally propagating waves:

$$\begin{pmatrix} u' \\ v' \\ \Phi' \end{pmatrix} = \begin{pmatrix} \hat{u}(y) \\ \hat{v}(y) \\ \hat{\Phi}(y) \end{pmatrix} \exp(i(kx - \nu t)) \tag{3.5}$$

Insert into (3.2)– (3.4):

$$-i\nu\hat{u} - \beta y\hat{v} = -ik\hat{\Phi} \tag{3.6}$$

$$-i\nu\hat{v} + \beta y\hat{u} = -\frac{\partial\hat{\Phi}}{\partial y} \tag{3.7}$$

$$-i\nu\hat{\Phi} + gh_e\left(ik\hat{u} + \frac{\partial\hat{v}}{\partial y}\right) = 0 \tag{3.8}$$

which yields two first-order differential equations in two variables (after elimination of $\hat{u}$):

$$\left(\beta^2 y^2 - \nu^2\right)\hat{v} = ik\beta y\hat{\Phi} + i\nu\frac{\partial\hat{\Phi}}{\partial y} \tag{3.9}$$

$$\left(\nu^2 - gh_e k^2\right)\hat{\Phi} + i\nu gh_e\left(\frac{\partial\hat{v}}{\partial y} - \frac{k}{\nu}\beta y\hat{v}\right) = 0 \tag{3.10}$$

or

$$\frac{\partial^2\hat{v}}{\partial y^2} + \left(\frac{\nu^2}{gh_e} - k^2 - \frac{k}{\nu}\beta - \frac{\beta^2 y^2}{gh_e}\right)\hat{v} = 0 \tag{3.11}$$

(3.11) has solutions of the form

$$v(\xi) = v_0 \mathrm{H}_n(\xi) \exp\left(-\frac{\xi^2}{\nu}\right), \quad \text{where} \quad \xi = \left(\frac{\beta}{\sqrt{gh_e}}\right)^{\frac{1}{2}} y, \quad n = 0, 1, 2, \ldots \tag{3.12}$$

and H_n are the hermite polynomials,

$$\mathrm{H}_0(\xi) = 1, \quad \mathrm{H}_1(\xi) = 2\xi, \quad \mathrm{H}_2(\xi) = 4\xi^2 - 2 \tag{3.13}$$

Equatorial wave theory

Rossby–gravity waves

Consider the $n = 0$ solution. Substituting this $\hat{v}$ into (3.11) leads to a dispersion relation:

$$\nu = k\sqrt{gh_e}\left(\frac{1}{2} \pm \frac{1}{2}\sqrt{1 + \frac{4\beta}{k^2\sqrt{gh_e}}}\right) \tag{3.14}$$

This type of wave is called *Rossby–gravity wave*. The two solutions (3.14) have opposite signs of group velocity ($c_g = \partial\nu/\partial k$) and phase velocity ($c = \nu/k$), representing a westward-traveling and eastward-traveling wave.

Kelvin waves

Note that $\hat{v} = 0$ is a (trivial) solution of (3.11). This solution is called a *Kelvin wave*. In this case the system of equations (3.6)– (3.8) simplifies to

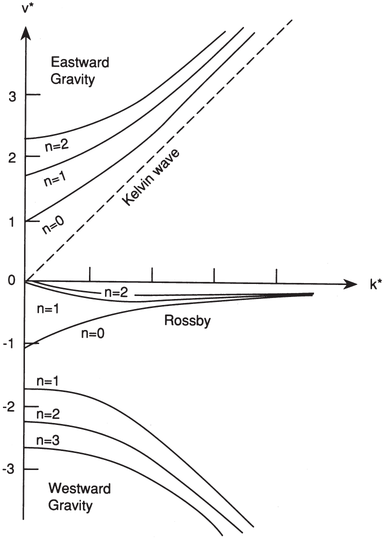
$$\beta y \hat{u} = -\frac{\nu}{k}\frac{\partial \hat{u}}{\partial y} \tag{3.15}$$

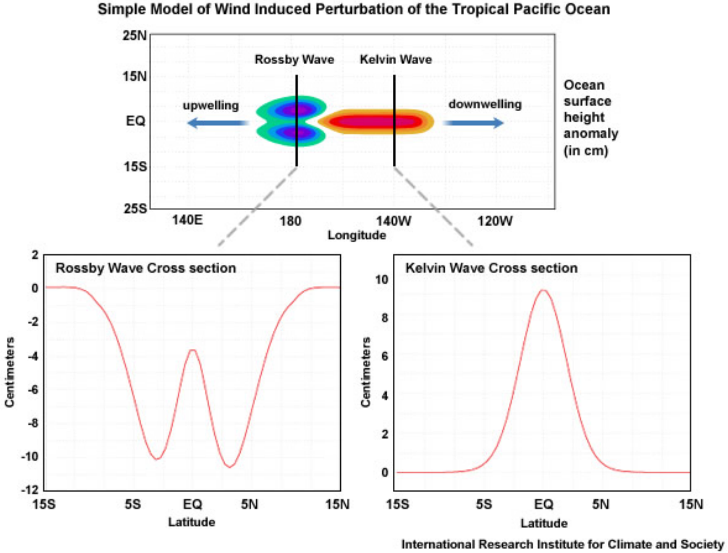
which has the solution

$$\hat{u} = u_0 \exp\left(-\frac{\beta y^2}{2c}\right) \tag{3.16}$$

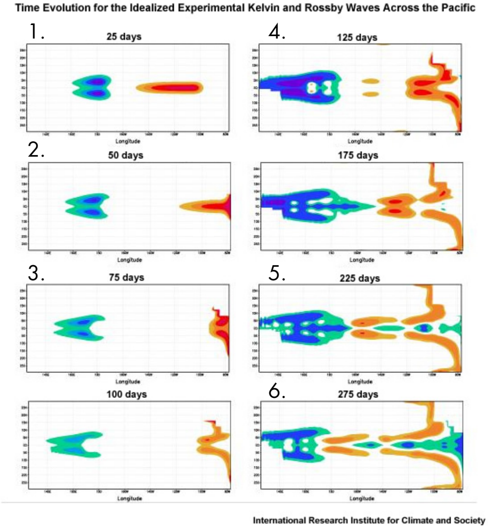
From (3.16) it is evident that only Kelvin waves with $c = \nu/k > 0$, i.e., eastward-traveling Kelvin waves, are equatorially trapped.

Dispersion relations





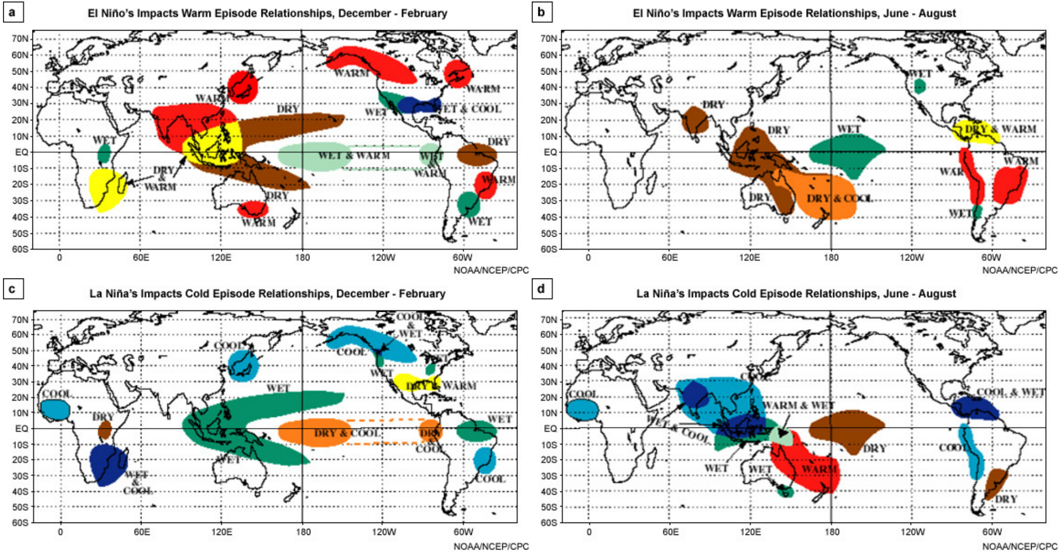
Delayed oscillator model: ENSO disturbance modeled as Kelvin and Rossby–gravity waves



1. Downwelling Kelvin wave (KW) forms in response to westerly wind anomaly; KW propagates eastward with 2–3 m s^{-1} speed (2–3 months to cross Pacific)
2. The downwelling KW deepens the thermocline and warms the eastern Pacific
3. Upwelling Rossby wave (RW) propagates westward (1 m s^{-1}), leading to a shallower thermocline in the western Pacific
4. Reflection of the upwelling RW leads to upwelling eastward-propagating KW + RW
5. After $\sim$ 8 months, the upwelling KW has crossed the Pacific and reversed the thermocline deepening in the eastern Pacific
6. KW at eastern boundary is partly reflected as RW, partly as KW. Recall that only eastward-propagating KW are equatorially trapped; the reflected KW propagates poleward (as coastal KW)

Schopf and Suarez (1988); Battisti and Hirst (1989)

3.5 – ENSO teleconnections: they are nearly global



Tropical teleconnections include cyclone frequency