Today's Lecture (Lecture 9): Internal variability

Reference

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

6.3 – 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)

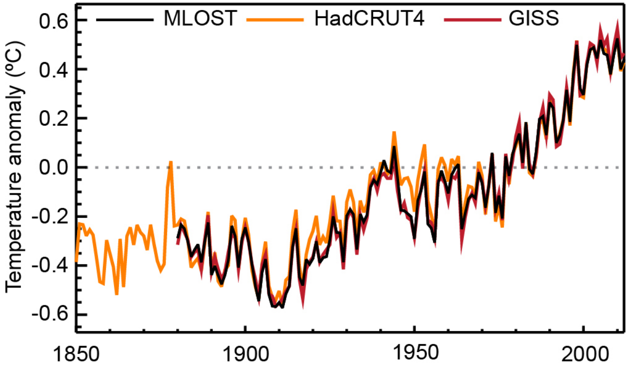


Figure: IPCC AR5

ENSO and global mean surface temperature

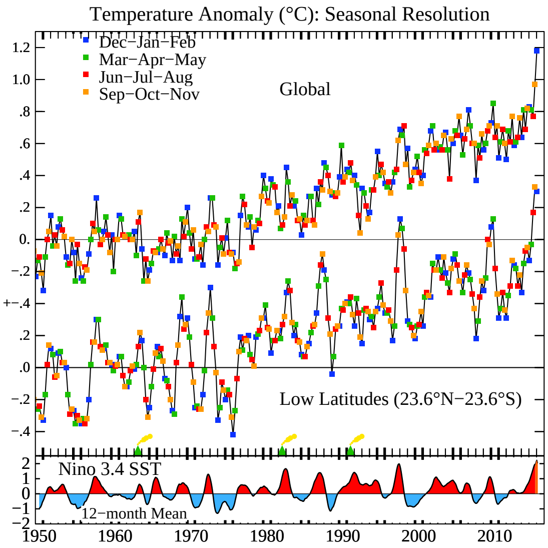
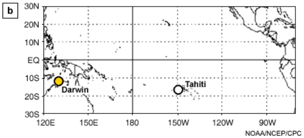


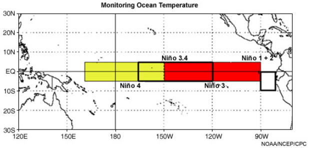
Figure: NASA GISS

El Niño–Southern Oscillation

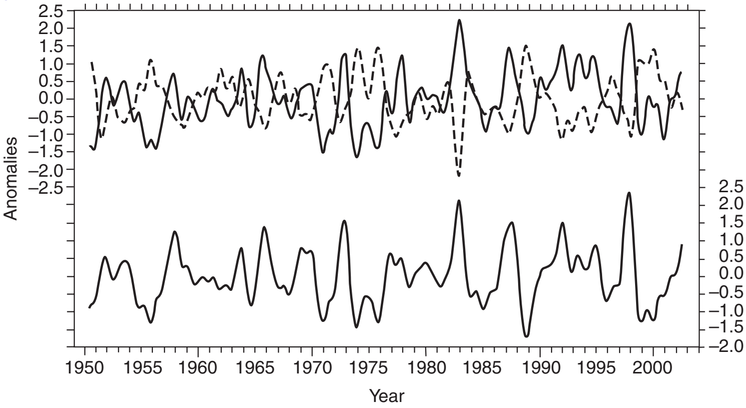
Southern oscillation – an atmospheric phenomenon



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

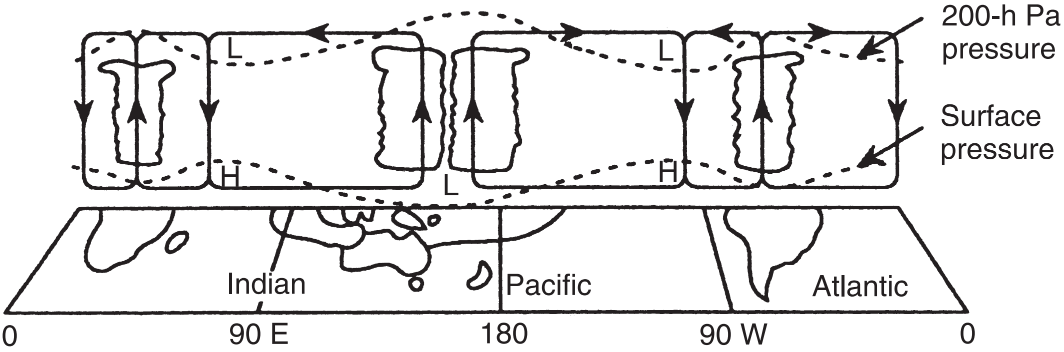


Figure: Holton

Oceanic and atmospheric circulation are coupled through convection

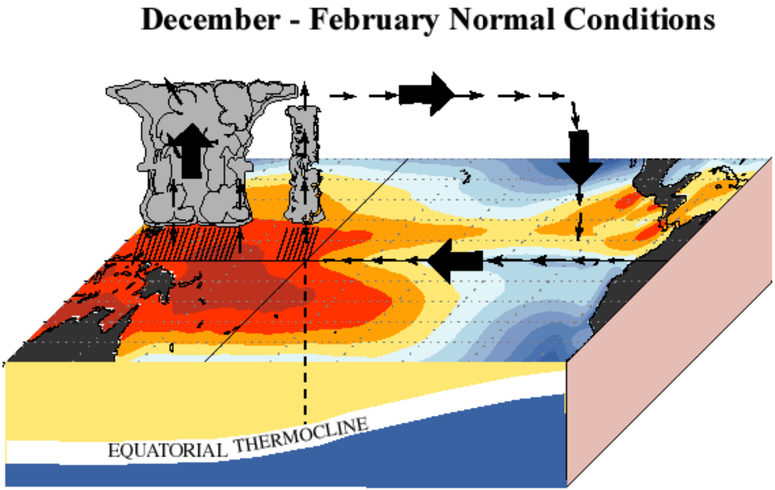
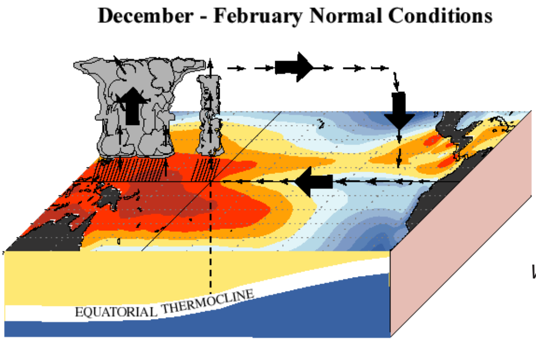
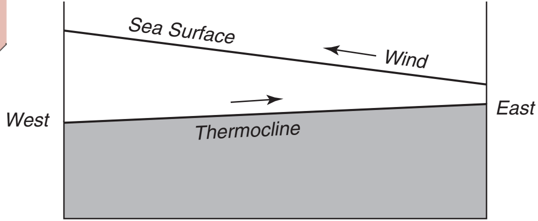


Figure: COMET

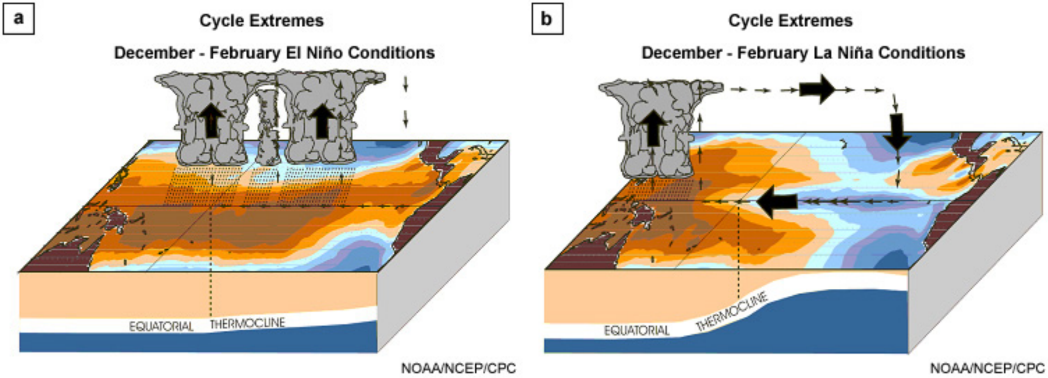
Mean state of the equatorial ocean – SST, thermocline depth, sea surface elevation





Figures: COMET, Stewart

El Niño–La Niña cycle



6.4 – 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

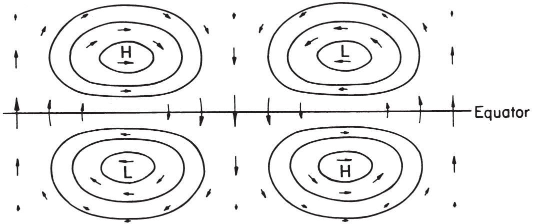
explains why La Niña follows El Niño

Recharge–discharge of ocean heat

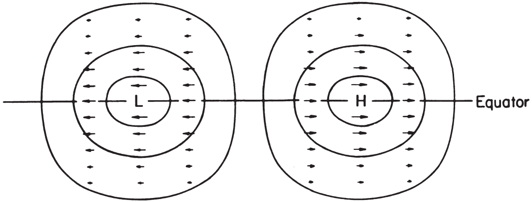
explains why El Niño causes a spike in global mean temperature (by releasing heat stored in the ocean)

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*):

$$f = \beta y \tag{6.1}$$

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

$$\frac{\partial u'}{\partial t} - \beta y v' = -\frac{\partial \Phi'}{\partial x} \qquad \text{equation of motion} \tag{6.2}$$

$$\frac{\partial v'}{\partial t} + \beta y u' = -\frac{\partial \Phi'}{\partial y} \qquad \text{note: not geostrophic at equator} \tag{6.3}$$

$$\frac{\partial \Phi'}{\partial t} + g w' = -g h_e \left(\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} \right) \qquad \text{hydrostatic equilibrium + continuity} \tag{6.4}$$

These linearized equations assume that $\bar{u} = 0$, $u' \partial u' / \partial x \ll \partial u' / \partial t$ 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:

$$\begin{pmatrix} u' \\ v' \\ \Phi' \end{pmatrix} = \begin{pmatrix} \hat{u}(y) \\ \hat{v}(y) \\ \hat{\Phi}(y) \end{pmatrix} \exp(i(kx - \nu t)) \tag{6.5}$$

Insert into (6.2)– (6.4):

$$-i\nu\hat{u} - \beta y\hat{v} = -ik\hat{\Phi} \tag{6.6}$$

$$-i\nu\hat{v} + \beta y\hat{u} = -\frac{\partial\hat{\Phi}}{\partial y} \tag{6.7}$$

$$-i\nu\hat{\Phi} + gh_e\left(ik\hat{u} + \frac{\partial\hat{v}}{\partial y}\right) = 0 \tag{6.8}$$

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

$$\left(\beta^2 y^2 - \nu^2\right)\hat{v} = ik\beta y\hat{\Phi} + i\nu\frac{\partial\hat{\Phi}}{\partial y} \tag{6.9}$$

$$\left(\nu^2 - gh_e k^2\right)\hat{\Phi} + i\nu gh_e\left(\frac{\partial\hat{v}}{\partial y} - \frac{k}{\nu}\beta y\hat{v}\right) = 0 \tag{6.10}$$

or

$$\frac{\partial^2\hat{v}}{\partial y^2} + \left(\frac{\nu^2}{gh_e} - k^2 - \frac{k}{\nu}\beta - \frac{\beta^2 y^2}{gh_e}\right)\hat{v} = 0 \tag{6.11}$$

Equatorial wave theory

(6.11) has solutions of the form

$$v(\xi) = v_0 \mathrm{H}_n(\xi) \exp\left(-\frac{\xi^2}{\nu}\right), \quad \text{where} \quad \xi = \left(\frac{\beta}{\sqrt{gh_e}}\right)^{\frac{1}{2}} y, \quad n = 0, 1, 2, \ldots \tag{6.12}$$

and H_n are the hermite polynomials,

$$\mathrm{H}_0(\xi) = 1, \quad \mathrm{H}_1(\xi) = 2\xi, \quad \mathrm{H}_2(\xi) = 4\xi^2 - 2 \tag{6.13}$$

Rossby–gravity waves

Consider the $n = 0$ solution. Substituting this $\hat{v}$ into (6.11) leads to a dispersion relation:

$$\nu = k\sqrt{gh_e}\left(\frac{1}{2} \pm \frac{1}{2}\sqrt{1 + \frac{4\beta}{k^2\sqrt{gh_e}}}\right) \tag{6.14}$$

This type of wave is called *Rossby–gravity wave*. The two solutions (6.14) 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 (6.11). This solution is called a *Kelvin wave*. In this case the system of equations (6.6)– (6.8) simplifies to

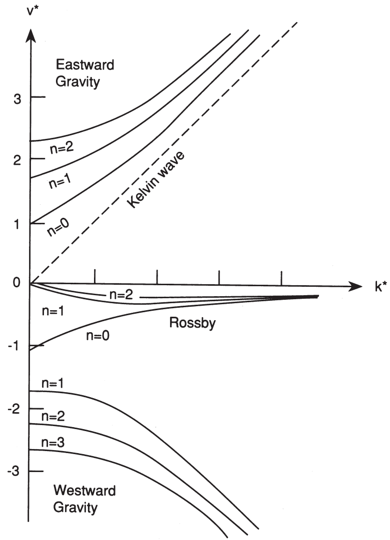
$$\beta y\hat{u} = -\frac{\nu}{k}\frac{\partial\hat{u}}{\partial y} \tag{6.15}$$

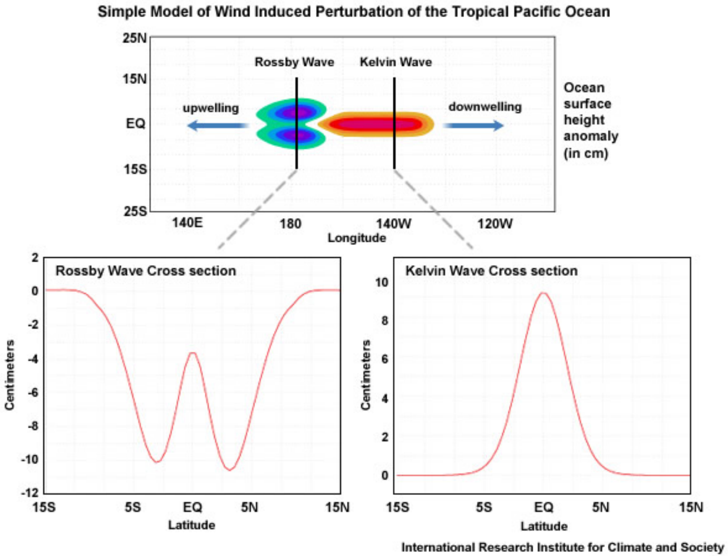
which has the solution

$$\hat{u} = u_0 \exp\left(-\frac{\beta y^2}{2c}\right) \tag{6.16}$$

From (6.16) it is evident that only Kelvin waves with $c = \nu/k > 0$, i.e., eastward-traveling Kelvin waves, are equatorially trapped.

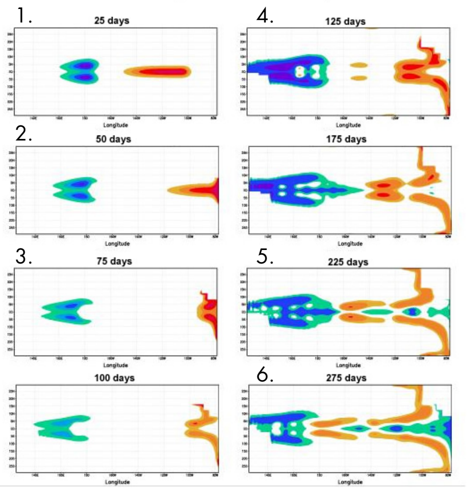
Dispersion relations





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

Time Evolution for the Idealized Experimental Kelvin and Rossby Waves Across the Pacific



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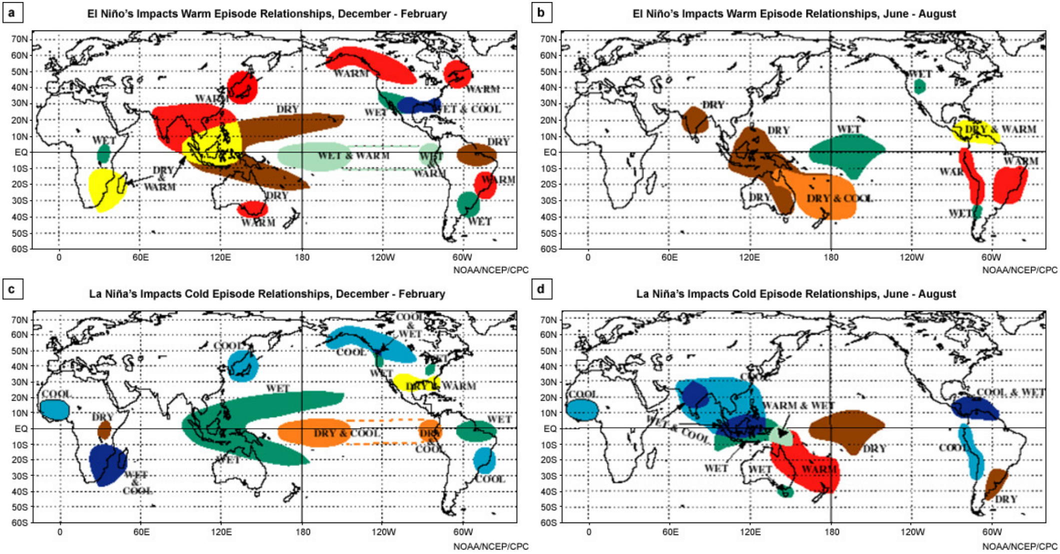
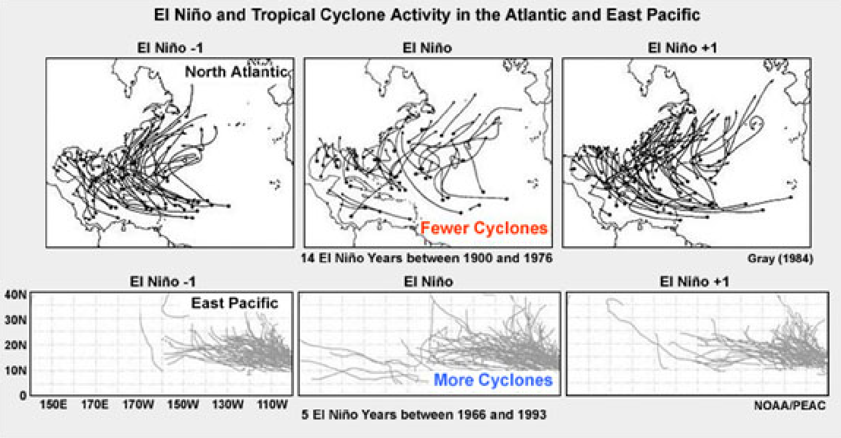
1. Downwelling Kelvin wave (KW) forms in response to westerly wind anomaly; KW propagates eastward with 2–3 m s^{-1} speed (2–3 months to cross Pacific)
2. The downwelling KW deepens the thermocline and warms the eastern Pacific
3. Upwelling Rossby wave (RW) propagates westward (1 m s^{-1}), leading 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 crossd 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)

ENSO teleconnections are nearly global



Tropical teleconnections include cyclone frequency



7 – Forcing and feedbacks

1. Introduction
2. Atmosphere
3. Ocean
4. Land, biosphere, cryosphere
5. The climate system
6. Internal variability
7. Forcing and feedbacks
7.1 Radiative forcing
7.2 Feedbacks
7.3 Adjustments
8. Anthropogenic climate change

Reference

- Hartmann, Ch. 9 and 12 (caution: note that Hartmann's sensitivity parameter λ_R is the reciprocal of the feedback parameter λ that we use)
- IPCC AR5, Ch. 7–8

7.1 – Radiative forcing

- Change in net energy exchange between the climate system and the environment
- Examples:
  - Solar intensity cycles
  - Orbital parameter cycles
  - Volcanic eruptions
  - Anthropogenic
    - Greenhouse gases
    - Aerosols
    - Ozone depletion
    - Land-use change
- Utility: intercomparability of the different forcing agents; condenses the problem to a global number
- Drawbacks: ambiguity in definition; rapid adjustments; reference state; condenses the problem to a global number