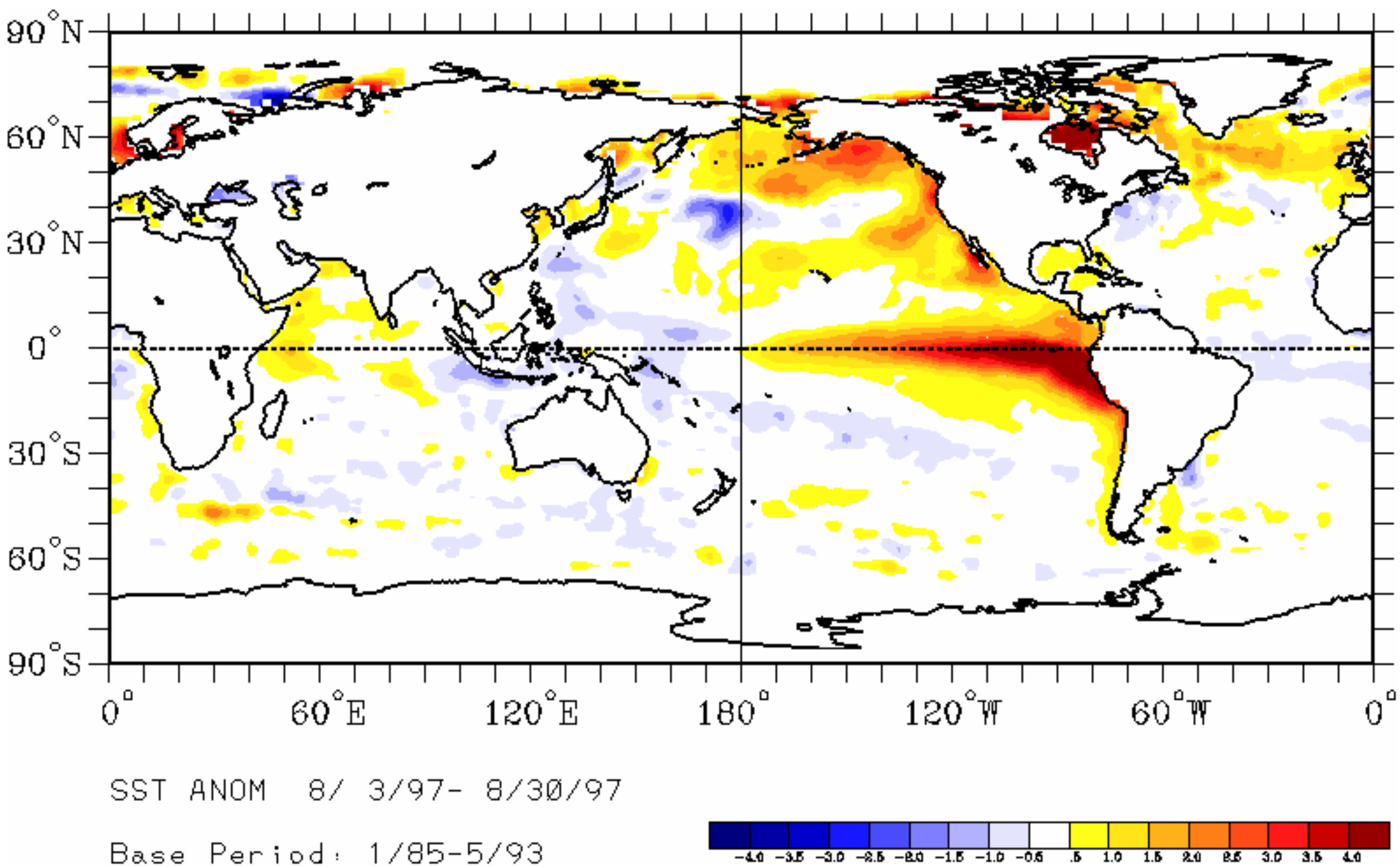
El Niño

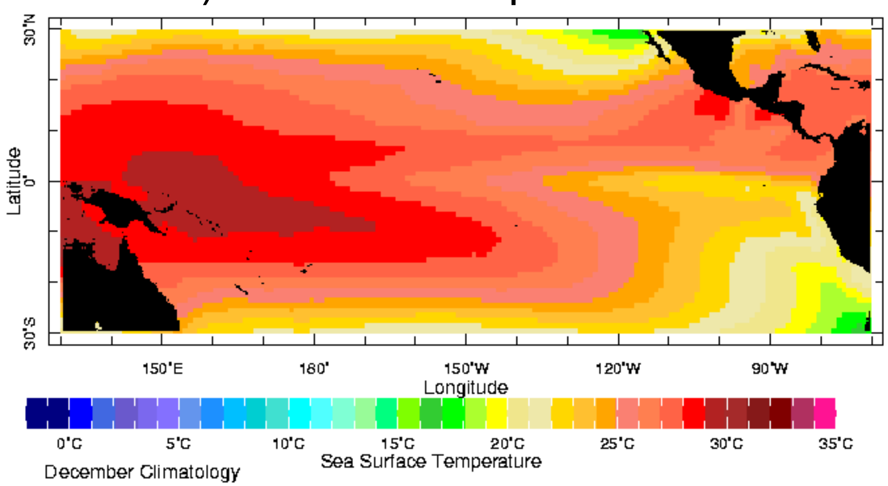
EPS131, Introduction to Physical Oceanography and Climate
EPS 231 Climate dynamics
Dept of Earth and Planetary Sciences, Harvard University
Eli Tziperman

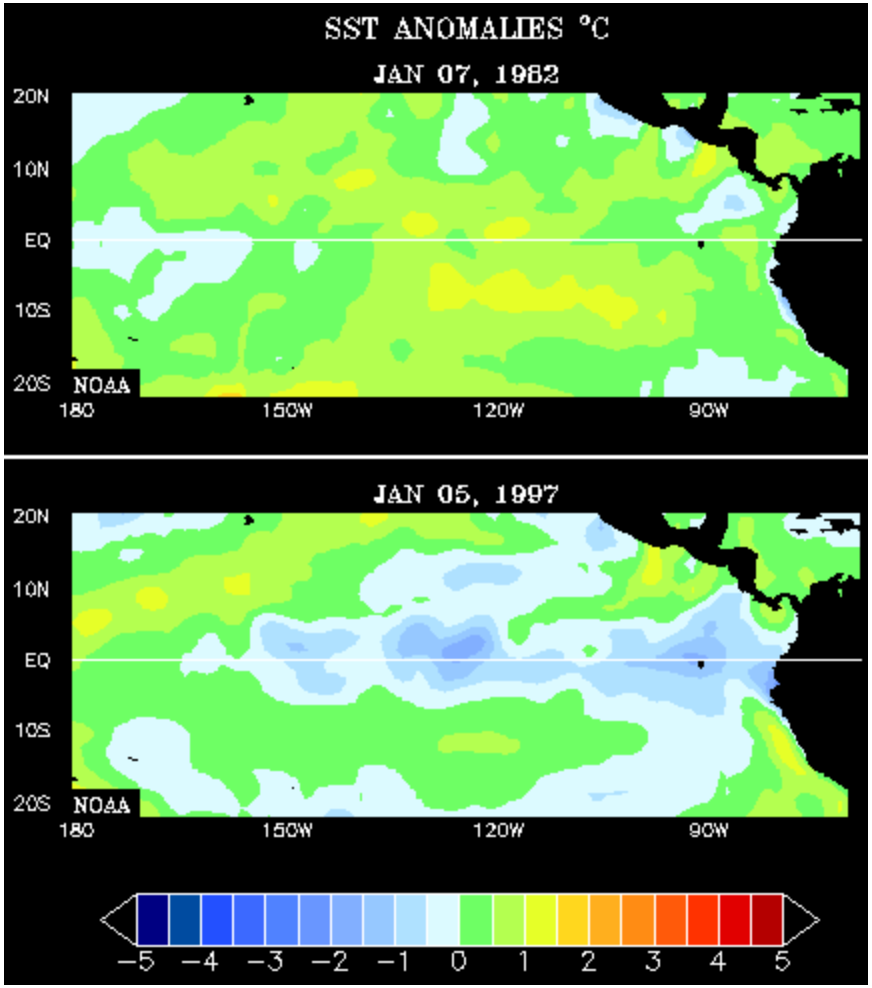


Development of an El Nino event: comparison of two major El Nino events

SST=Sea Surface Temperature

Climatological (long term time-mean) SST in tropical Pacific





SST: deviation from climatology for 1982 & 1997 events

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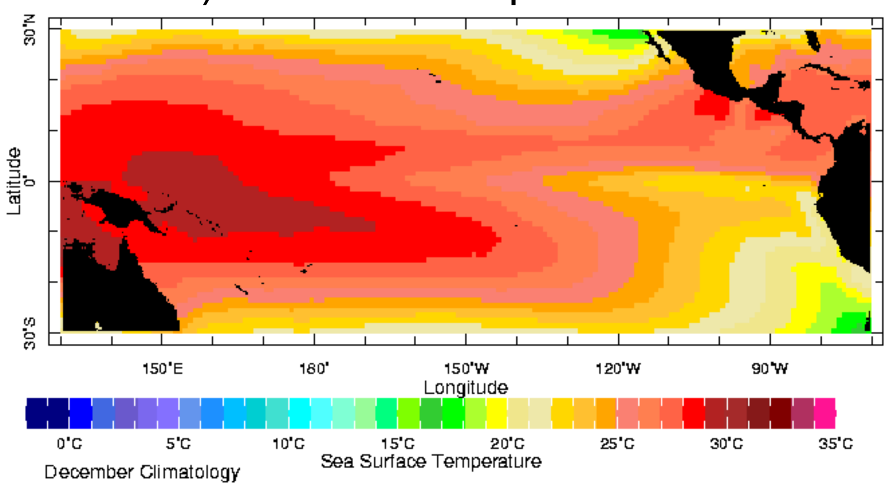
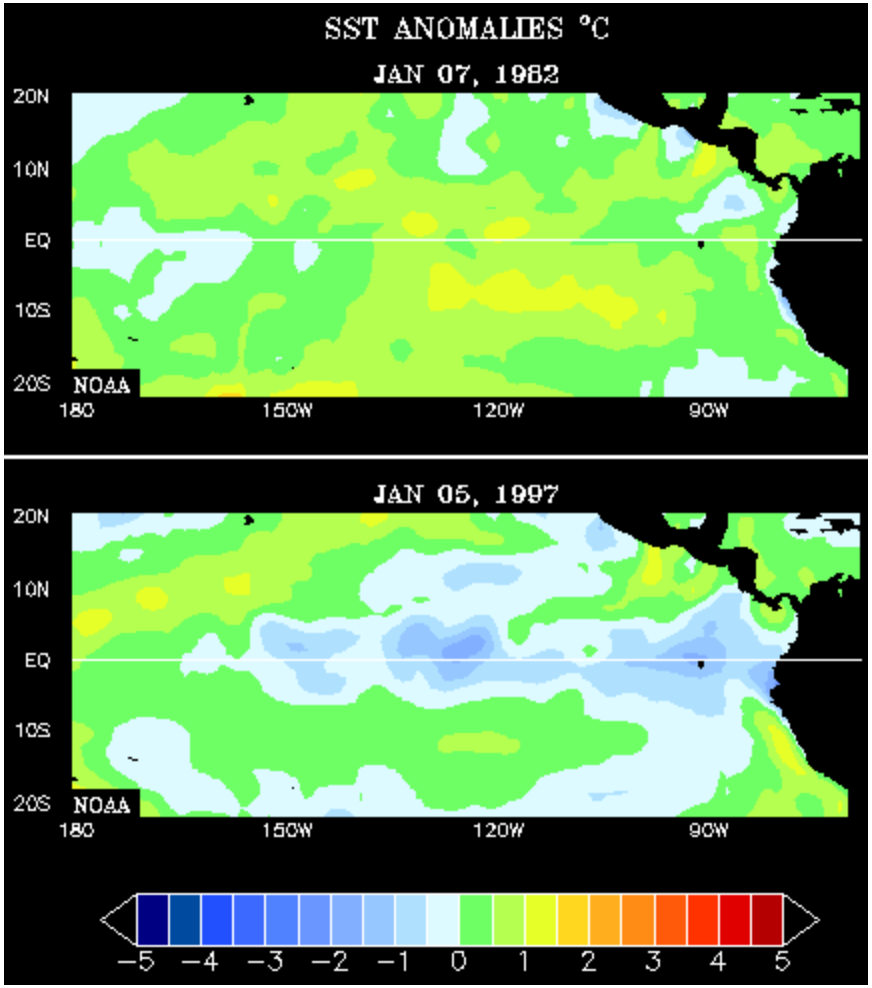
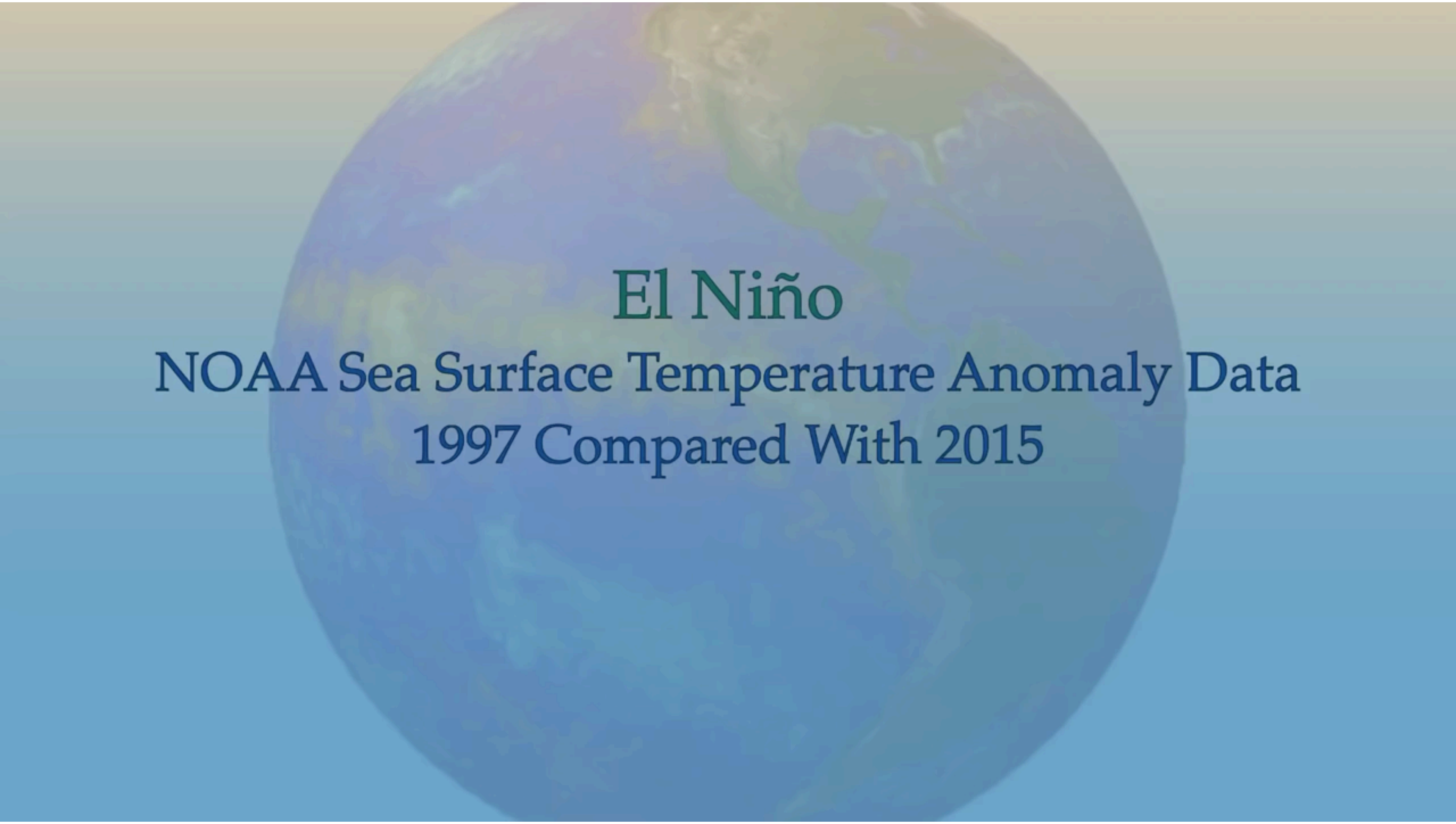




SST: deviation from climatology for 1982 & 1997 events

Development of an El Nino event: comparison of two major El Nino events – 1997, 2015



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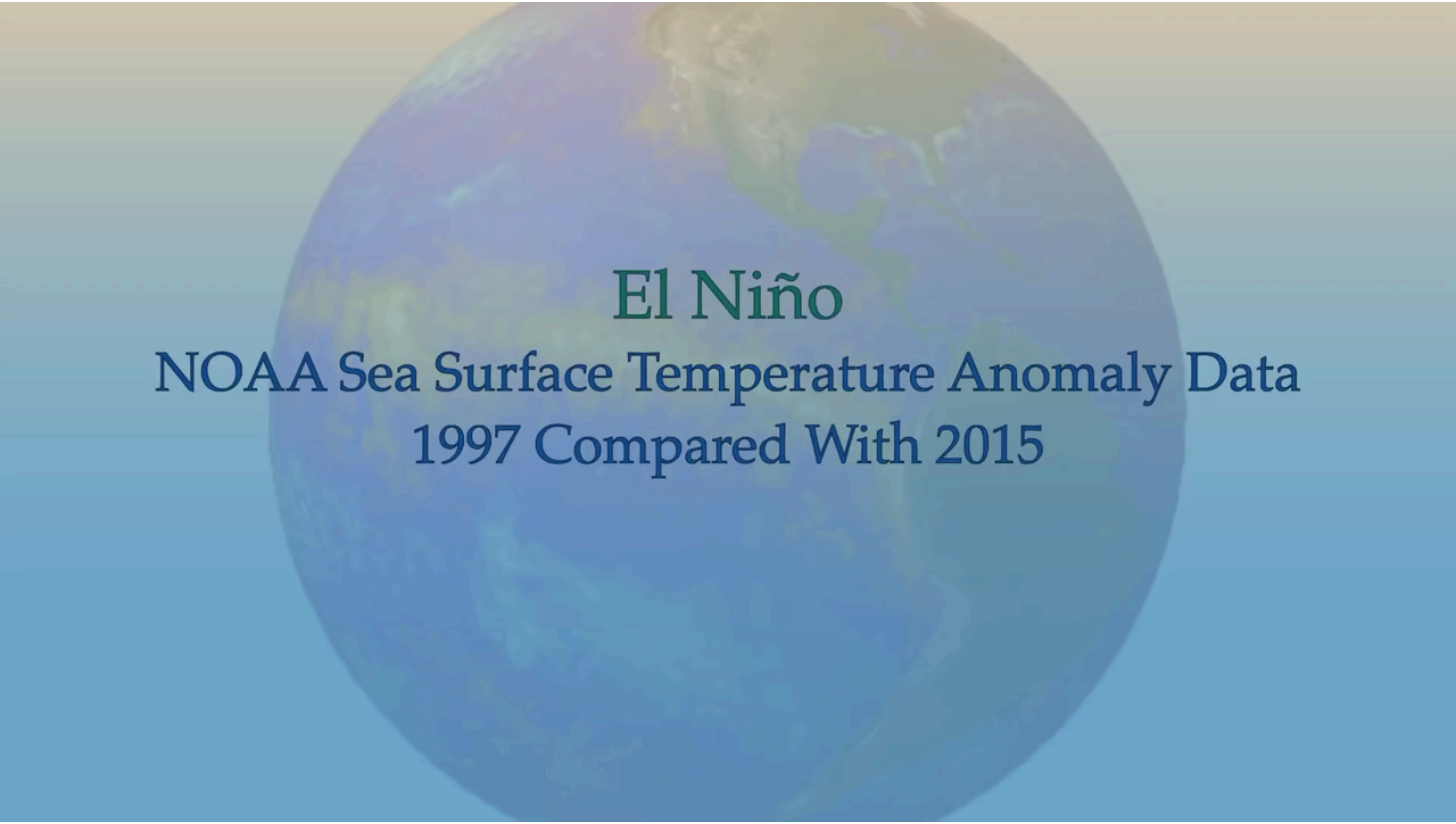

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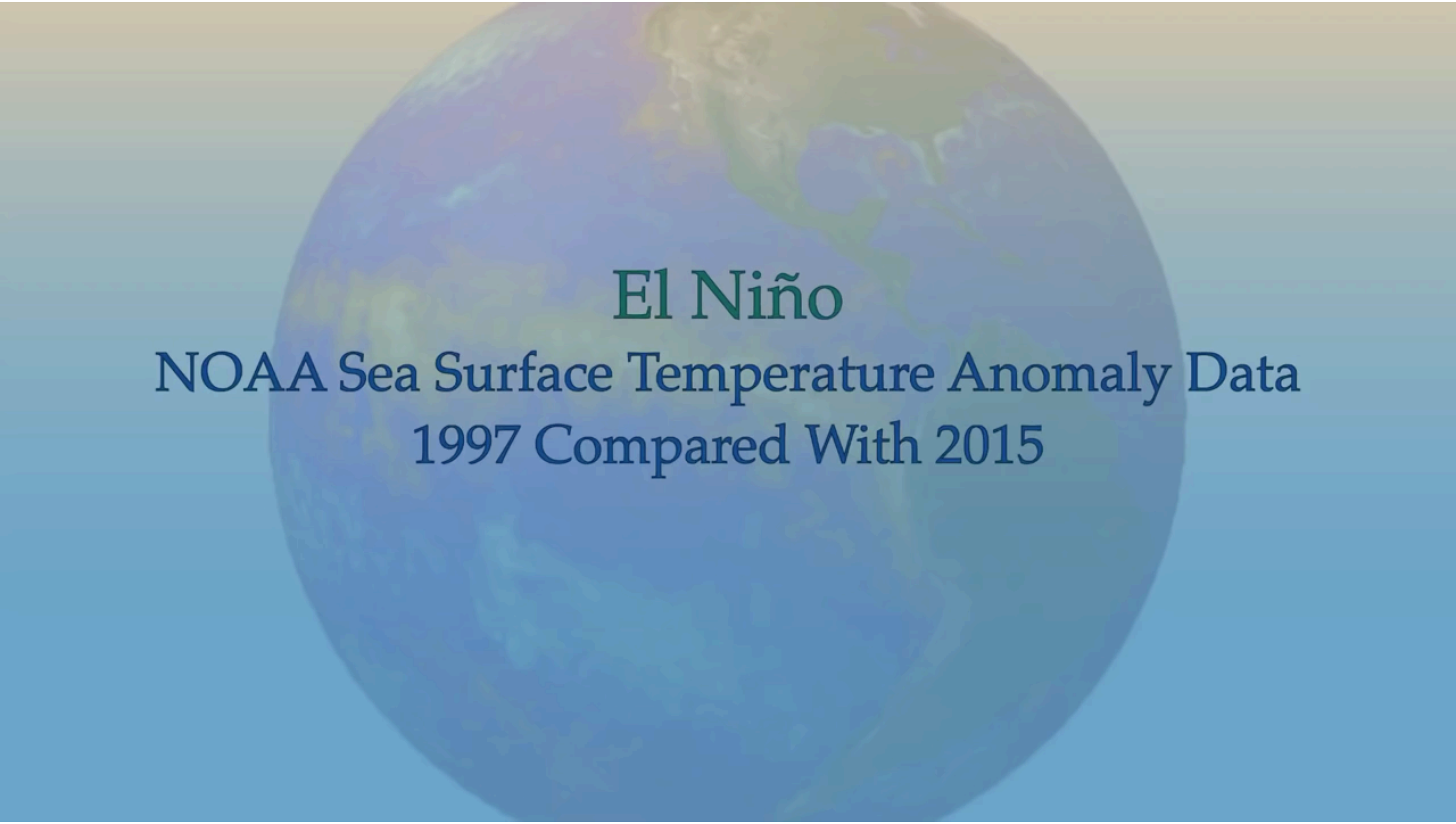
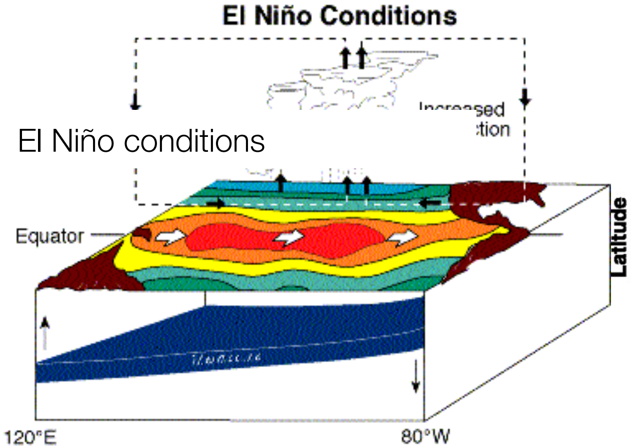
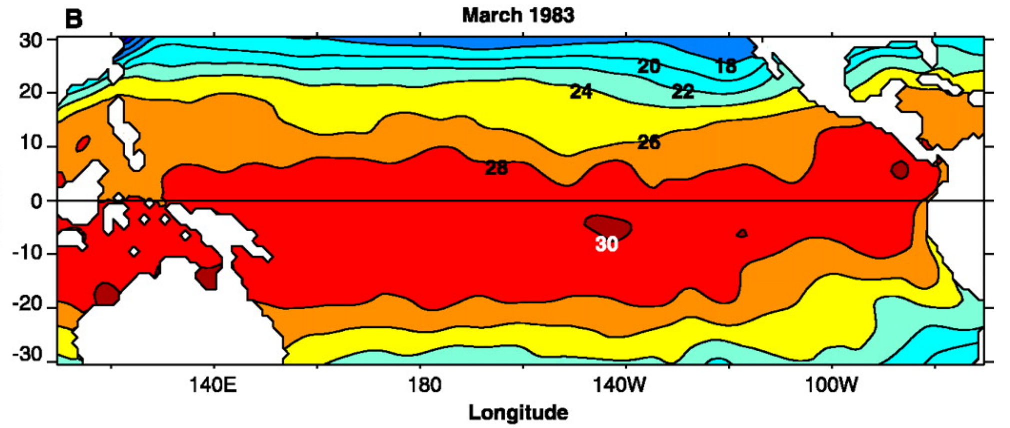


Mechanism: transitions between two states: El Niño & La Niña

El Niño:

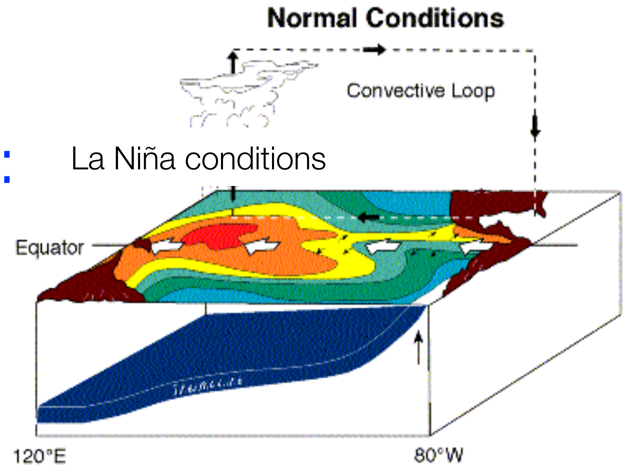
El Niño conditions

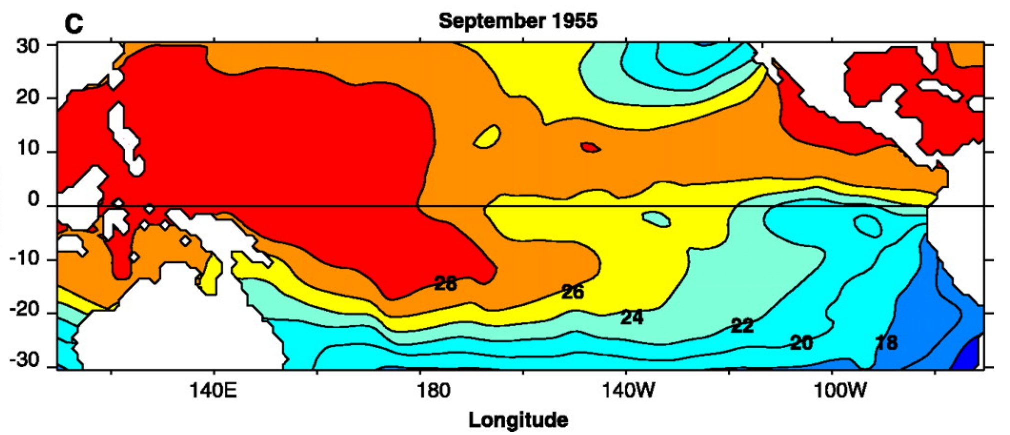




La Niña:

La Niña conditions





The major players:

Easterly Trade Winds → Thermocline;

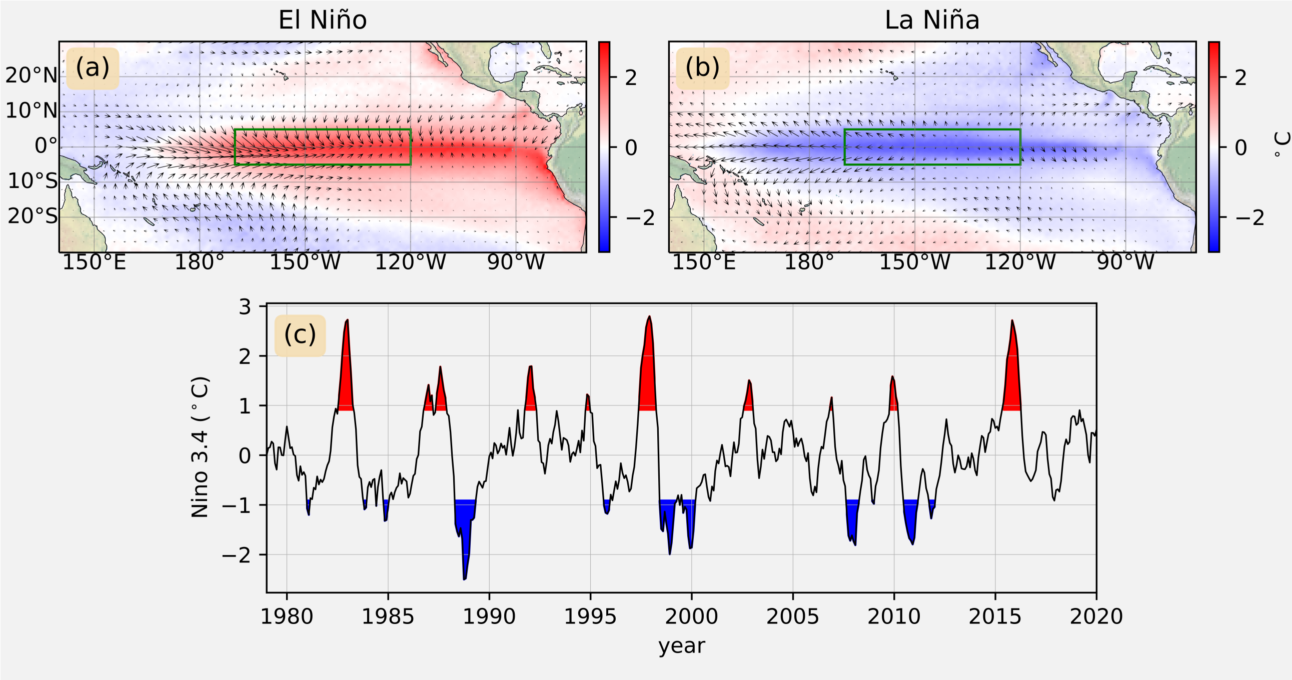
Thermocline → sea surface temperature.

Eastward propagating Kelvin waves, westward Rossby Waves

Mechanism: transitions between two states: El Niño & La Niña

Transitions between two states

Period: 3-6 years



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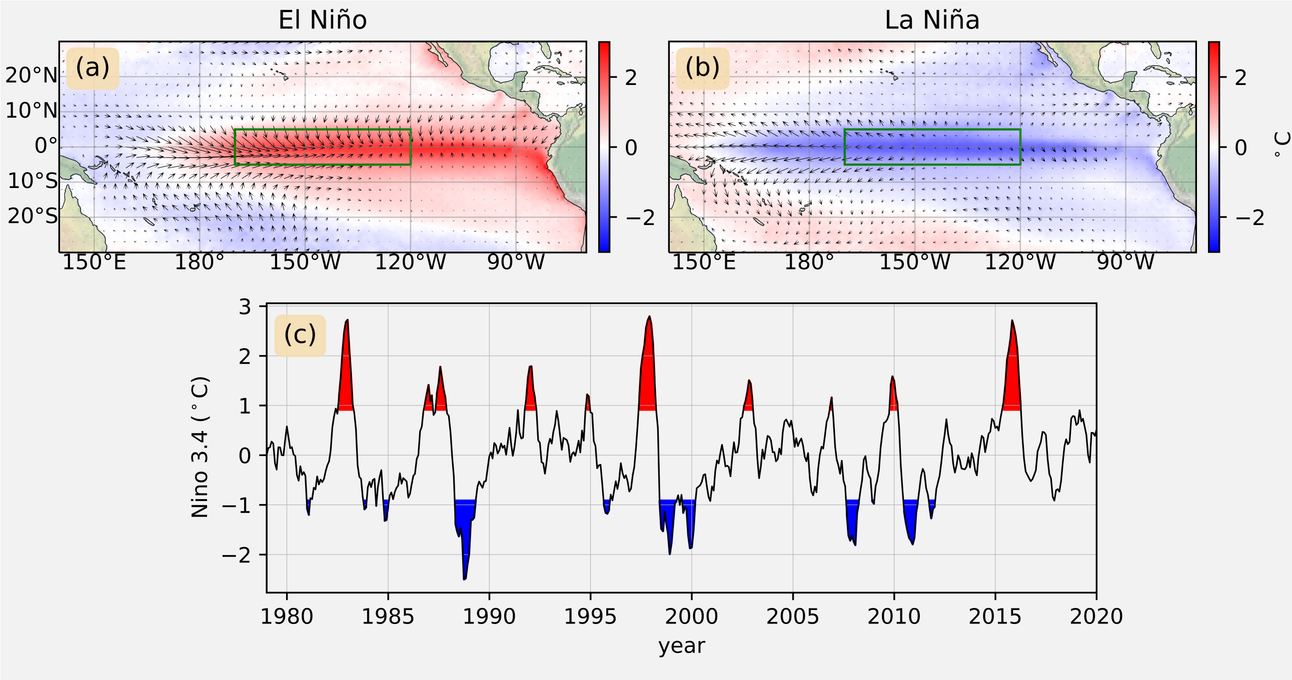
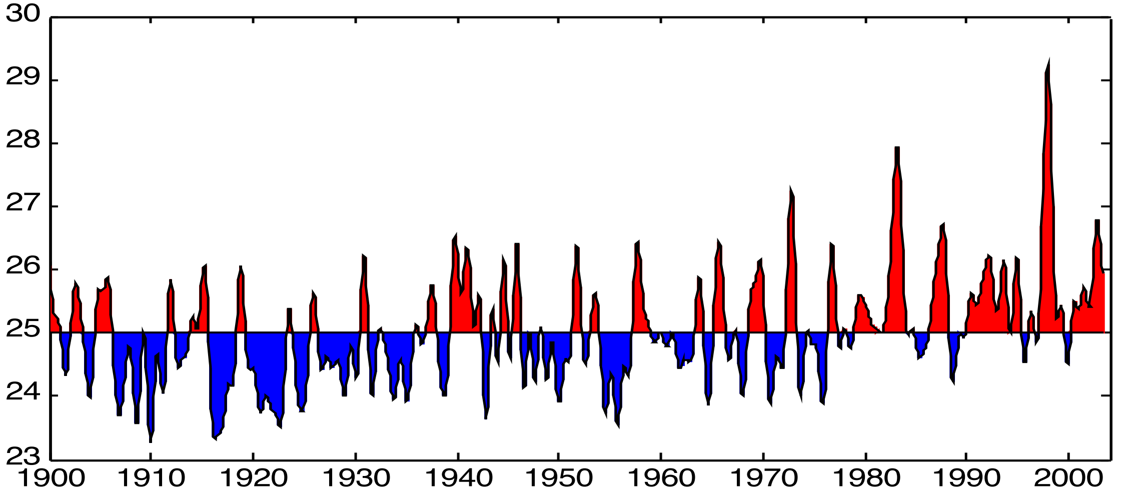


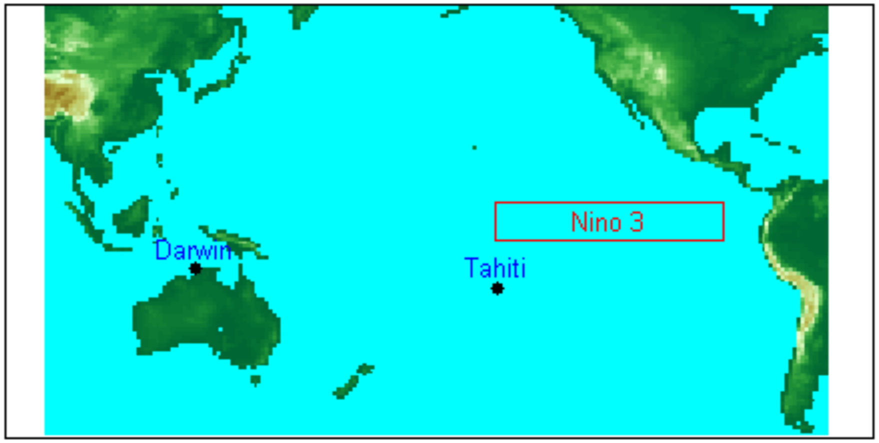
A longer record:

Decadal variability of El Nino Characteristics, possibly due to interaction with mid-latitudes

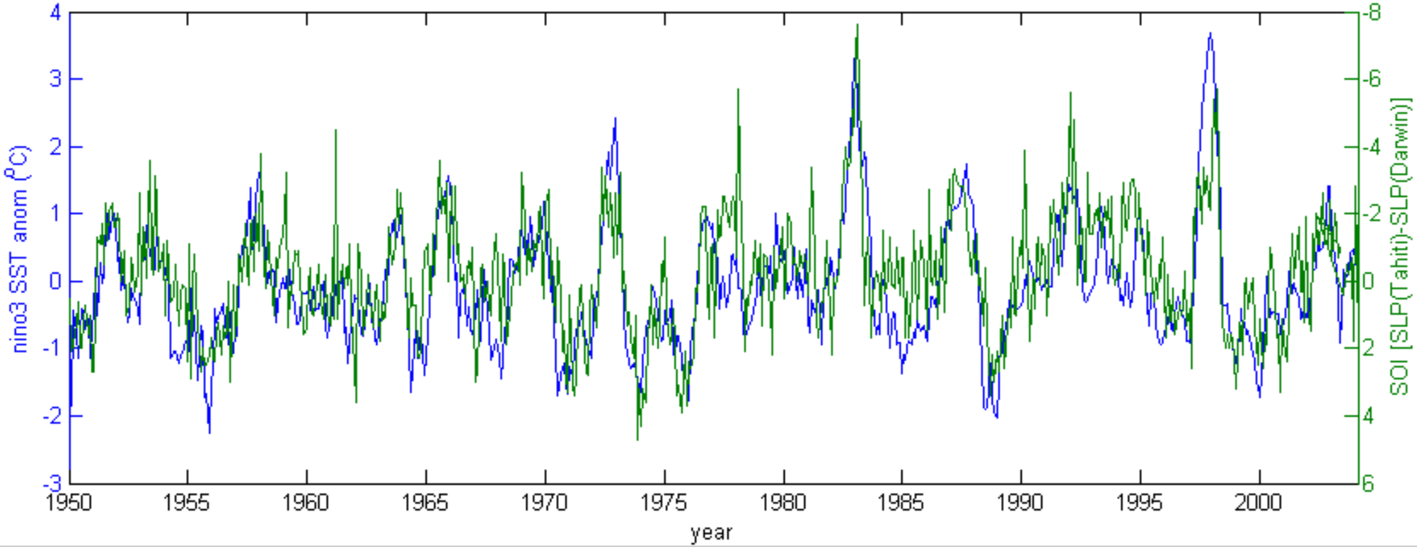


El Nino is a coupled ocean-atmosphere phenomenon

"ENSO": El Nino (warming of ocean) and the Southern Oscillation (in atmospheric pressure difference between Darwin and Tahiti) are well correlated

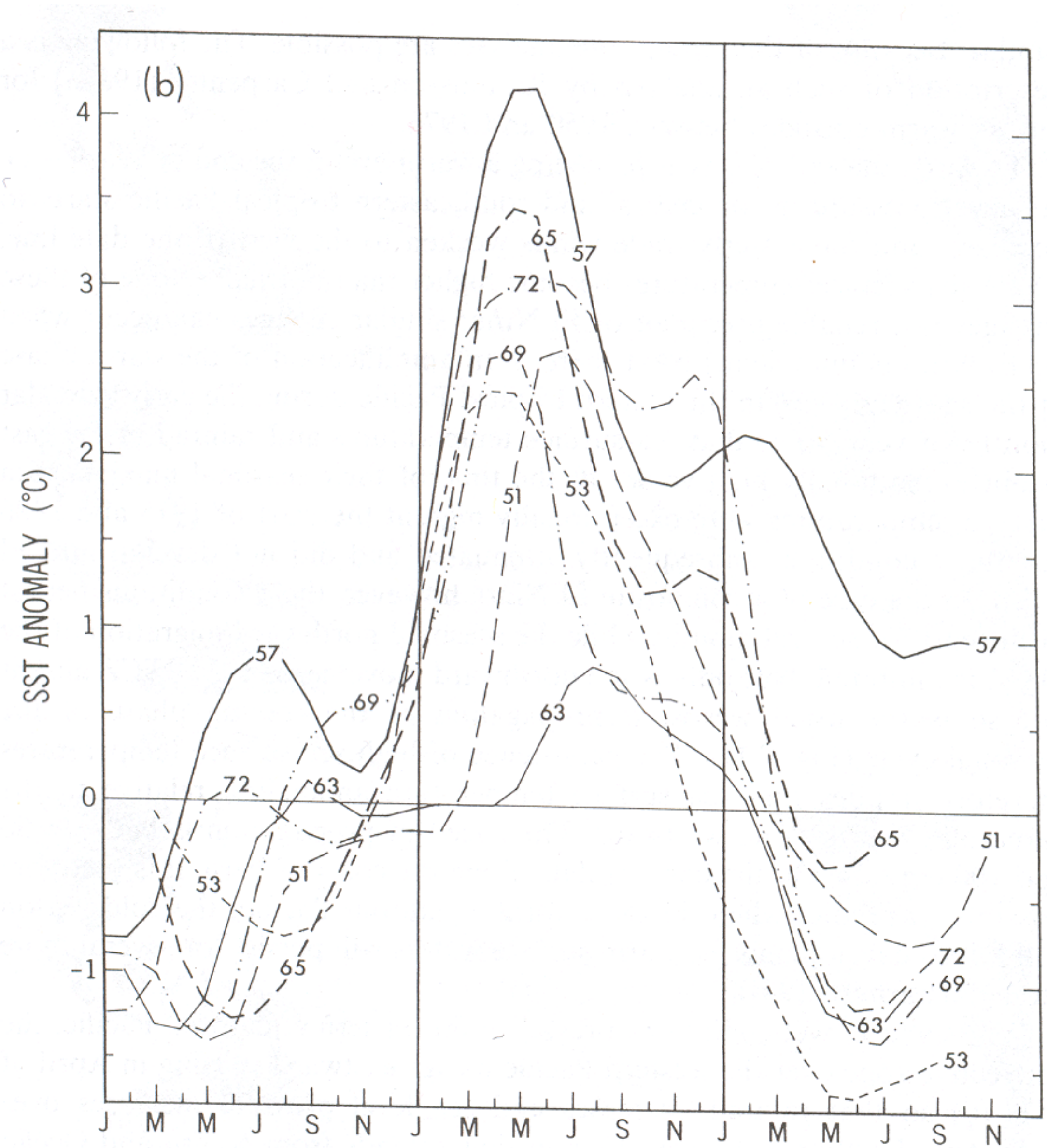


SST (blue) and atmospheric pressure difference (green)



While irregular, all El Nino episodes still look similar, and tend to peak at end of calendar year

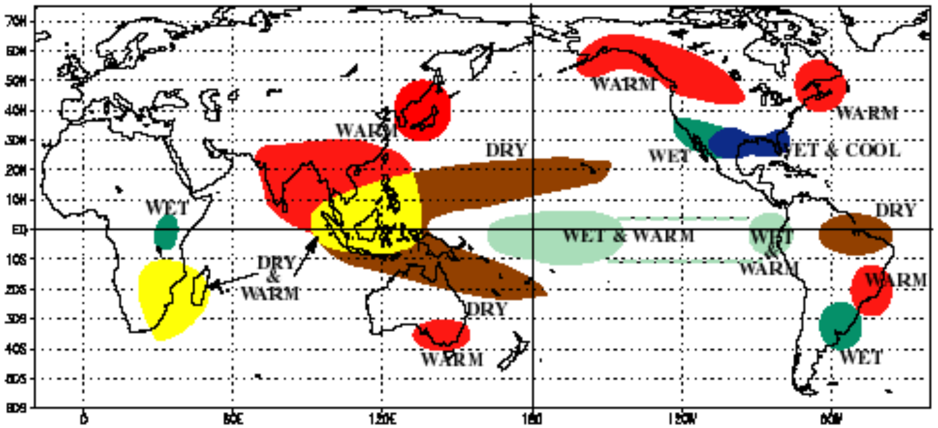
Sea surface temperature averaged over the eastern equatorial pacific during several El Nino events, as function of month (over two years):



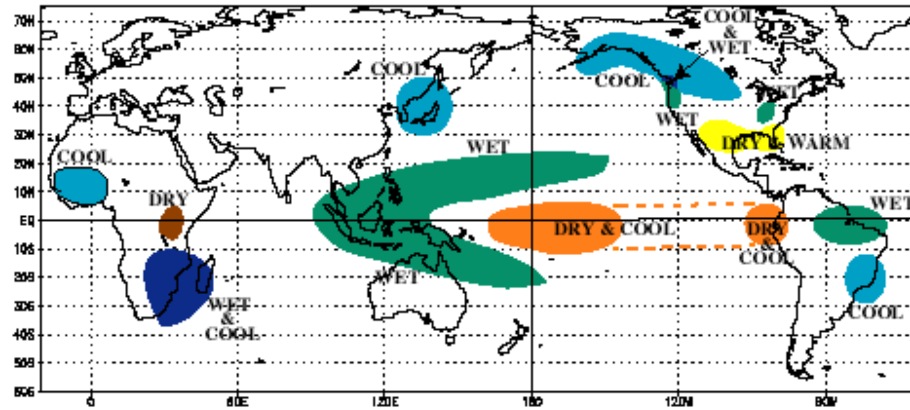
Why do we care: Global impacts

ENSO is the largest inter-annual signal in global climate

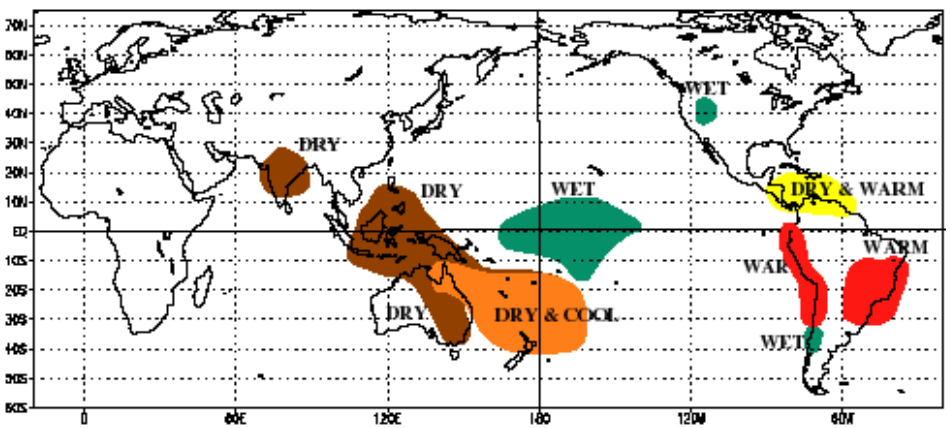
WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



COLD EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



WARM EPISODE RELATIONSHIPS JUNE - AUGUST



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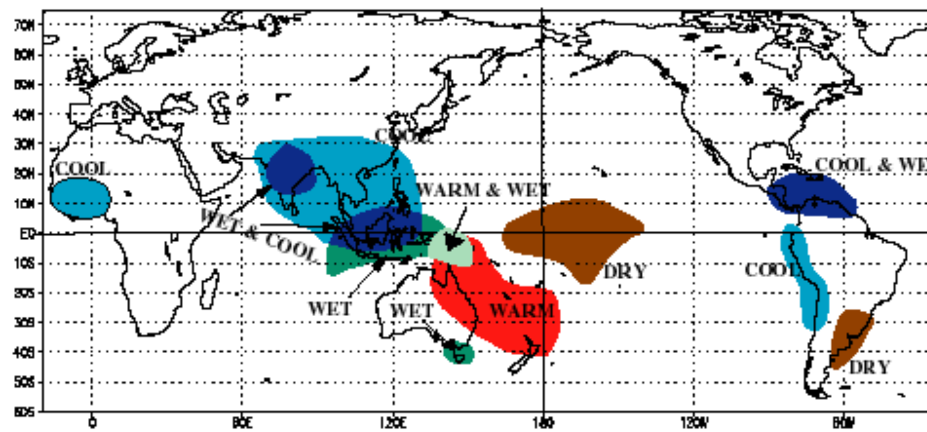


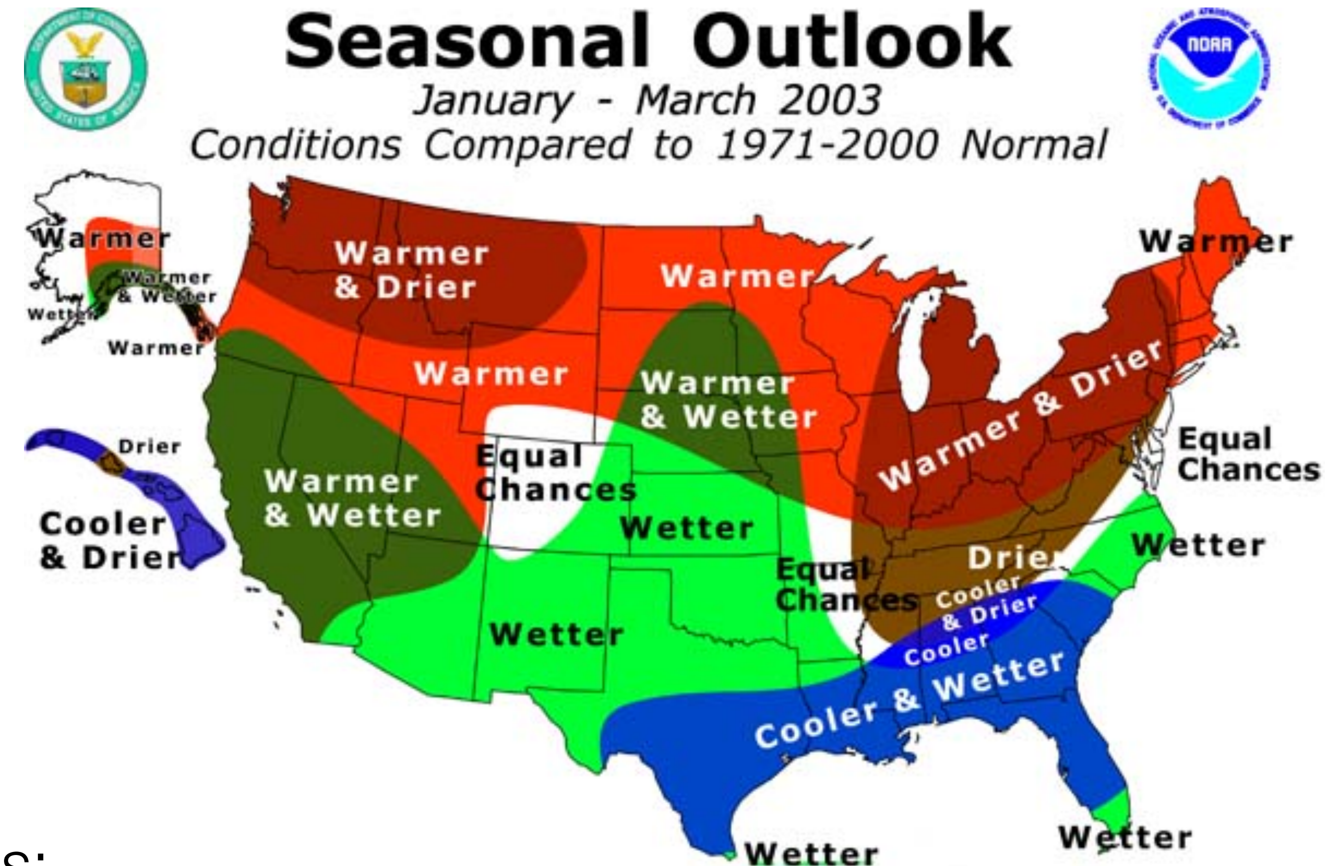
El Nino

Climate Prediction Center
NCEP

La Nina

Climate Prediction Center
NCEP

Why do we care: El Nino Impacts, it's not all bad news



"El Niño's Benefits:

In recent weeks, El Niño has contributed much-needed precipitation to many parched areas of the country. For example, fall and winter storms along the Gulf and East Coasts have nearly ended the drought from Texas to Georgia, and along the entire East Coast."

http://www.noaanews.noaa.gov/stories/s1080.htm

Why do we care: ENSO's Global climate impacts

Floods

Lakeport, California (1998)

Fires

Australia (1998)

Making Observations: monitoring systems

Satellites:
SST (infrared),
wind speed (scatterometer),
SSH (altimeter)

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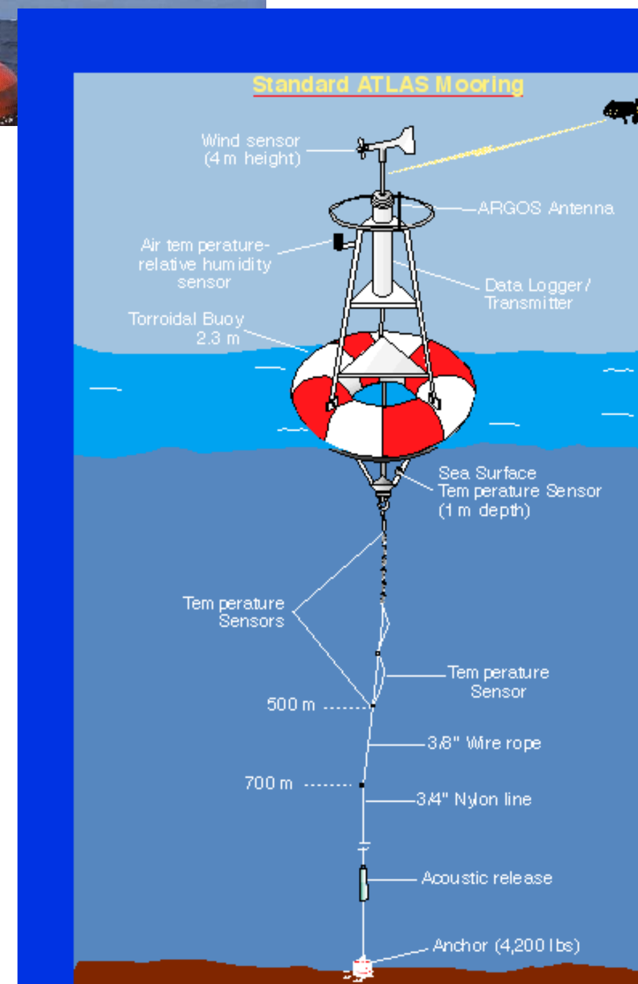
Moored buoys
temperature
profile, wind
speed, currents



Making Observations: monitoring systems

Satellites:
SST (infrared),
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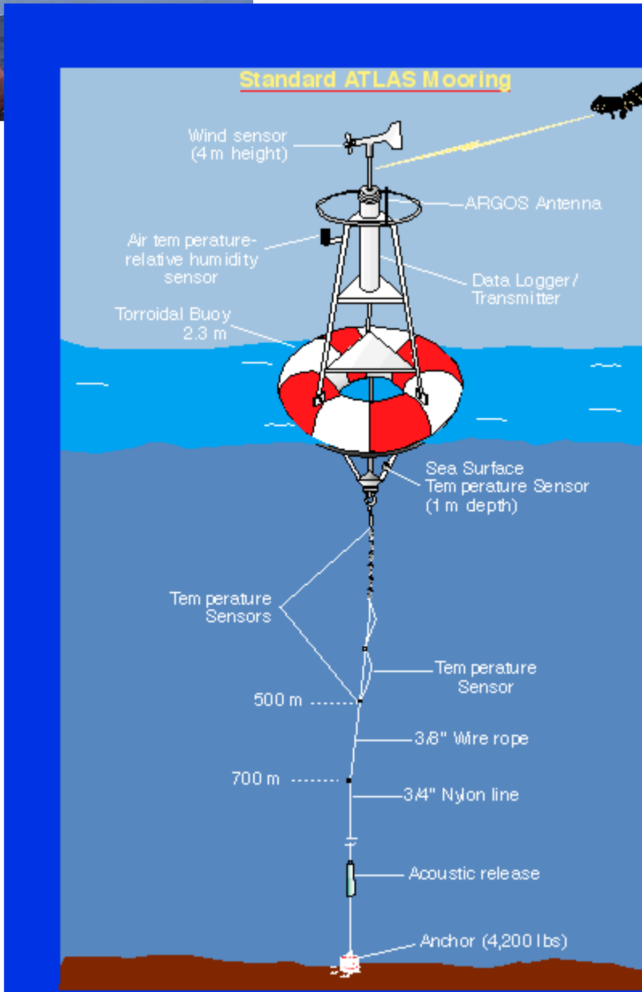
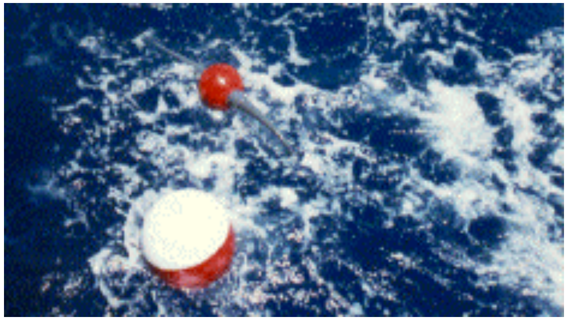
Moored buoys
temperature profile, wind speed, currents





Drifting buoys
SST & surface currents
"Lagrangian drifters"

Making Observations: monitoring systems

Sate
SST
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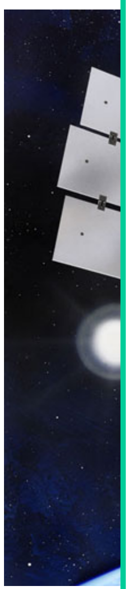
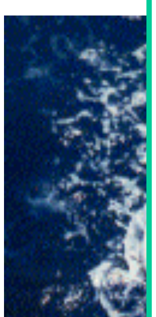
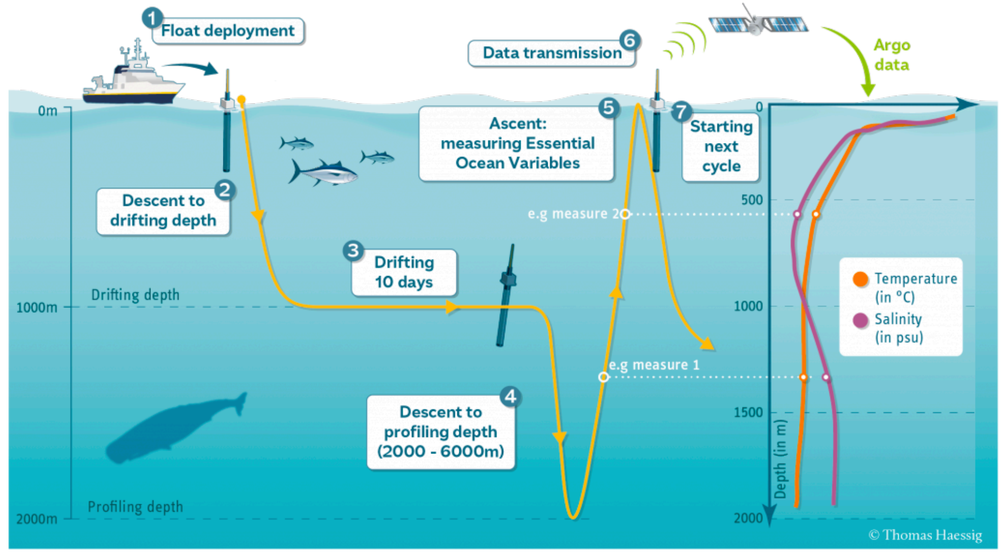
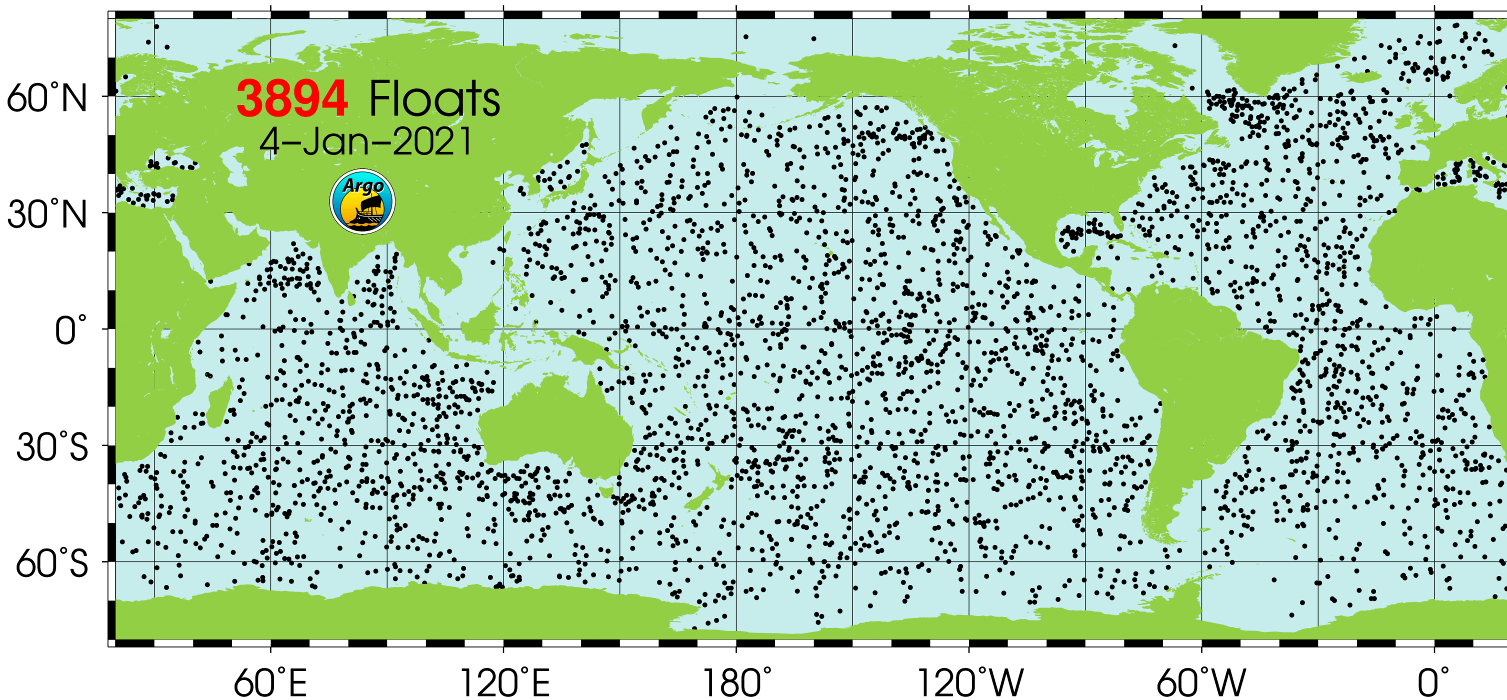


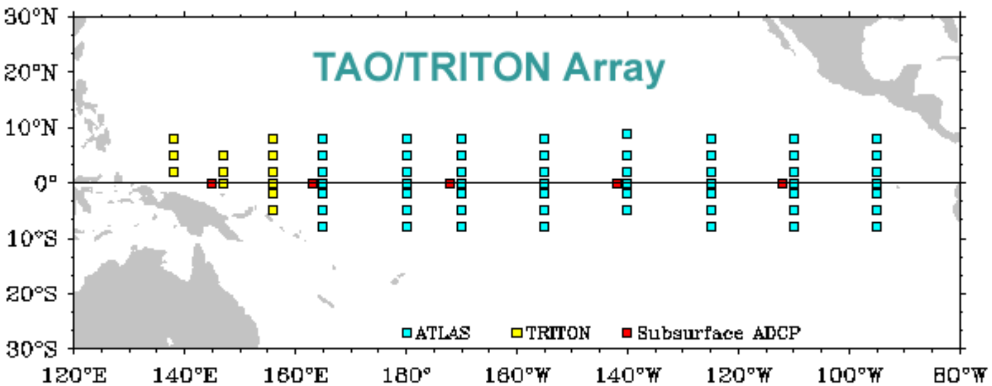


Argo floats



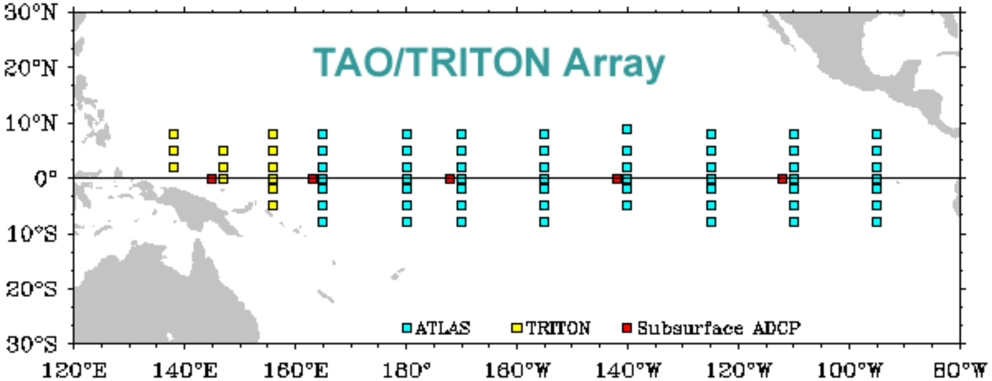


Making Observations: TAO array



Large observational buoy array, dedicated research vessel, international consortium

Making Observations: TAO array



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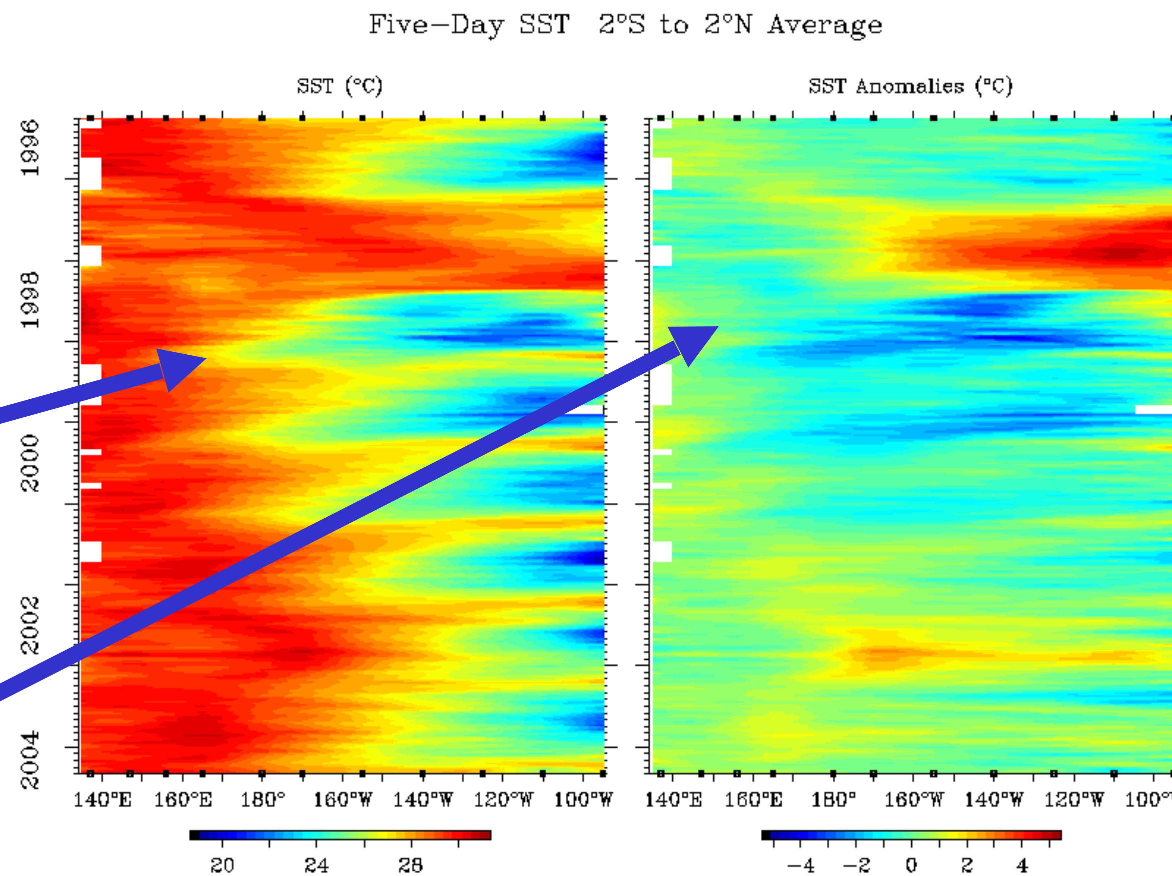


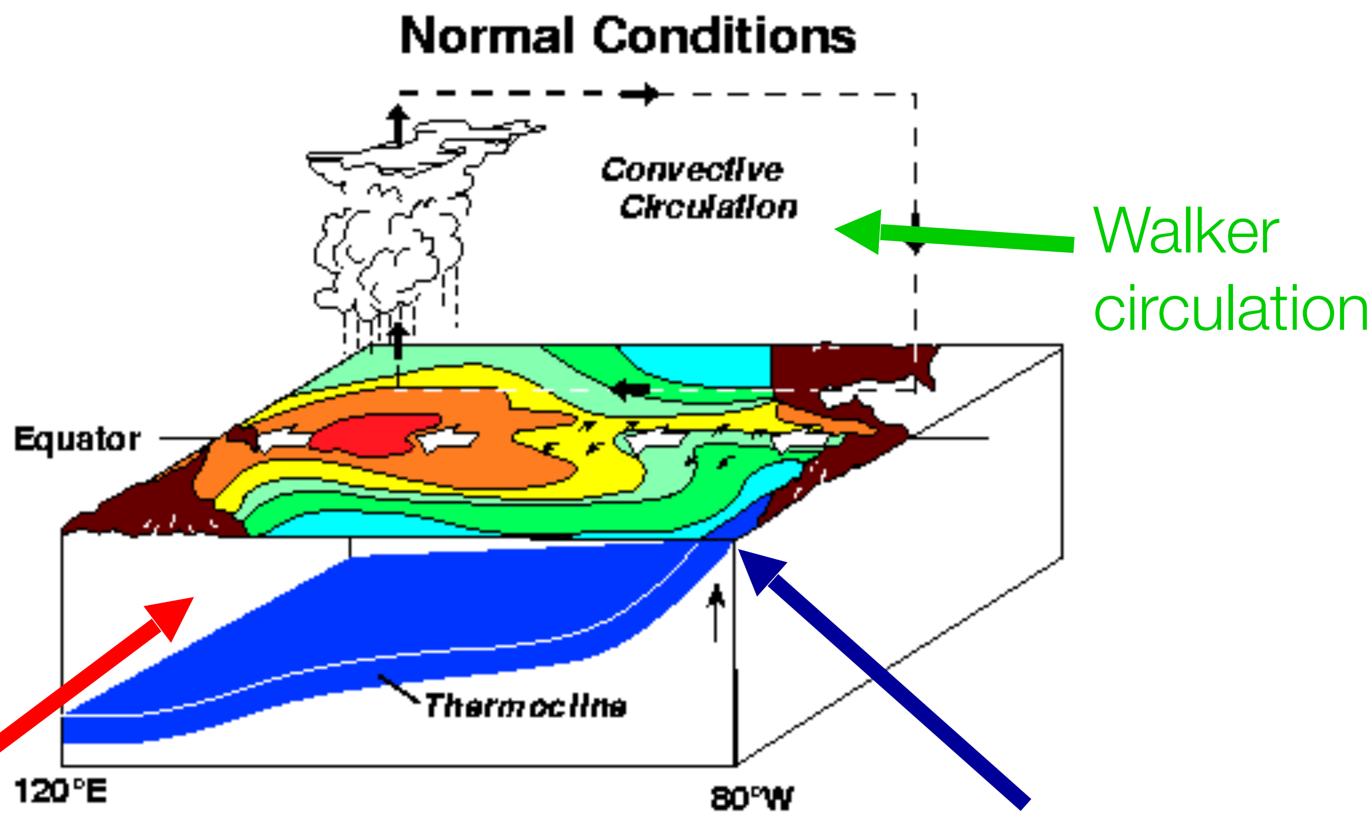
Equatorial Sea Surface Temperature (SST) as function of longitude & time [from TAU data]

Same, but deviation of SST from mean

Mechanism, Normal background conditions first:

Zonal wind ➔ Thermocline slope ➔ Warm pool/ cold tongue

State of the ocean during normal conditions:



West Pacific: Deep thermocline, warm pool

East Pacific: Shallow thermocline, cold tongue

Notes:

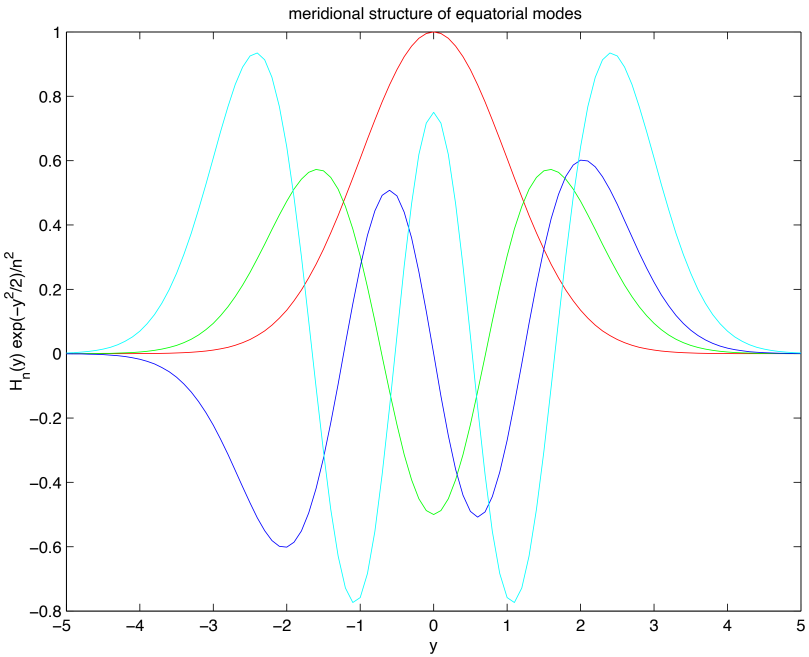
1. Kelvin wave reminder
2. Notes: equatorial Kelvin wave
3. Rossby wave reminder
4. Ekman pumping reminder
5. Delayed oscillator mechanism (next few slides)

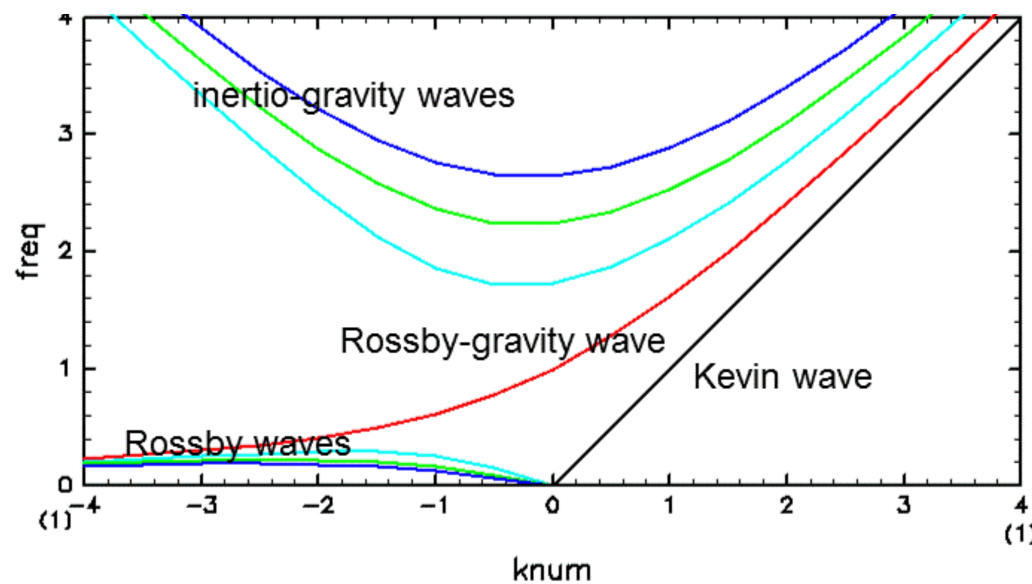
undergraduate level

Notes:

1. Shallow water equations and the equatorial beta plane (section 1.2.1, equations 1-3)
2. Equatorial Kelvin wave (section 1.2.3)
3. equatorial Rossby/Poincare/Yanai waves (section 1.2.3)

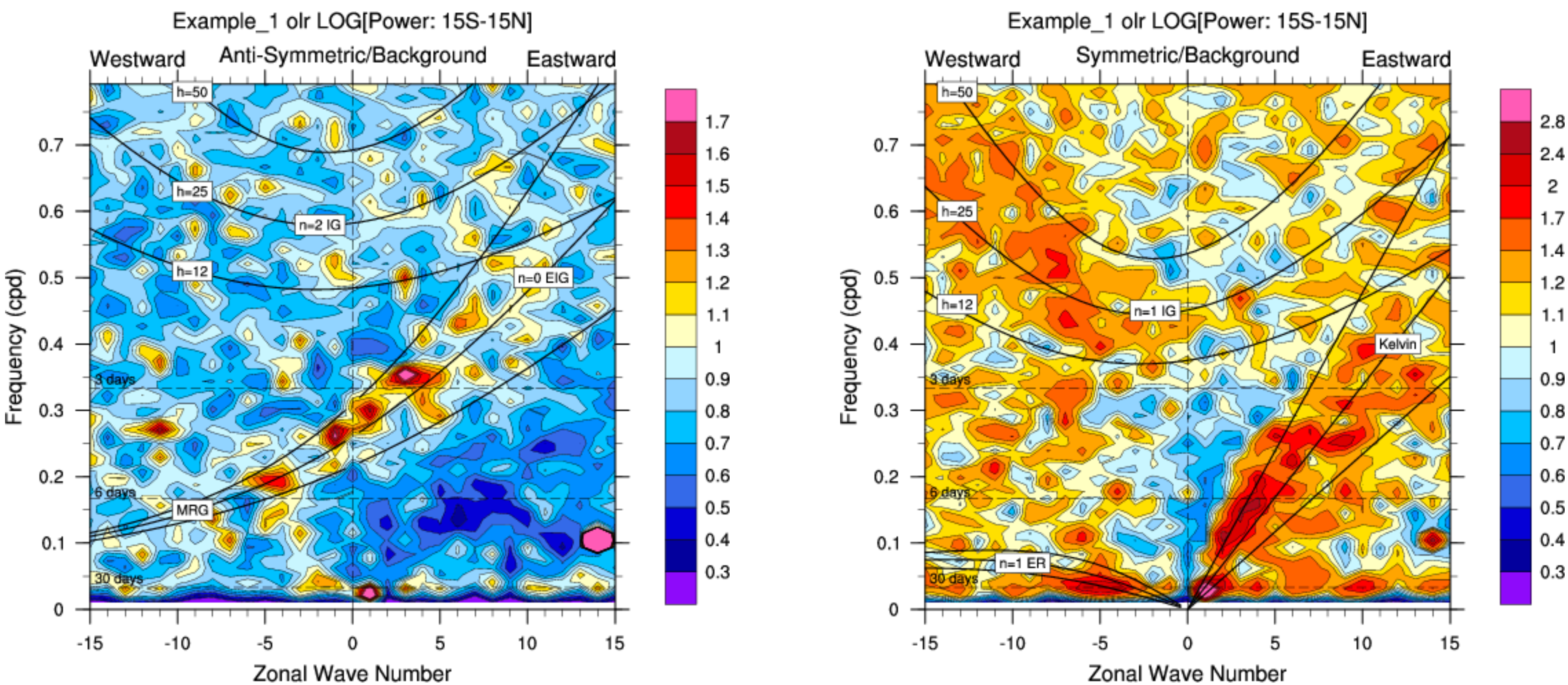
Equatorial wave modes





The latitudinal structure of the first few equatorial modes: $H_n(y)\exp(-y^2/2)/n^2$.

Observations of **atmospheric** Equatorial wave modes



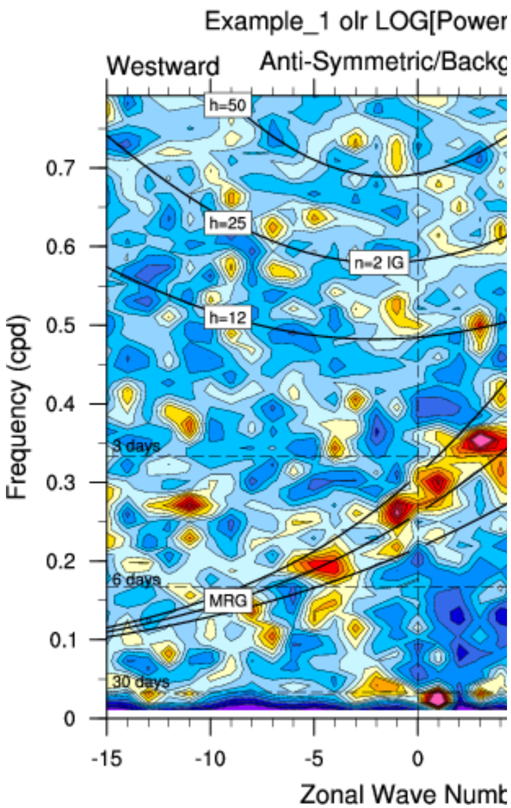
Atmospheric equatorial waves

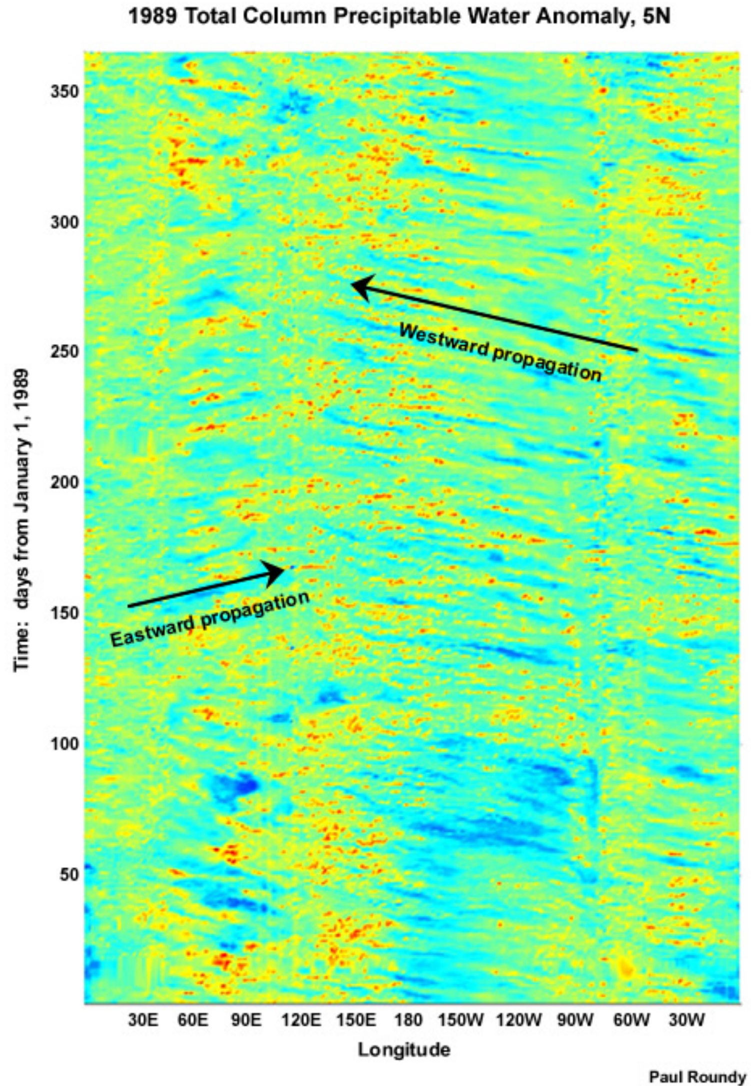
(Wheeler-Kiladis Space-Time Spectra)

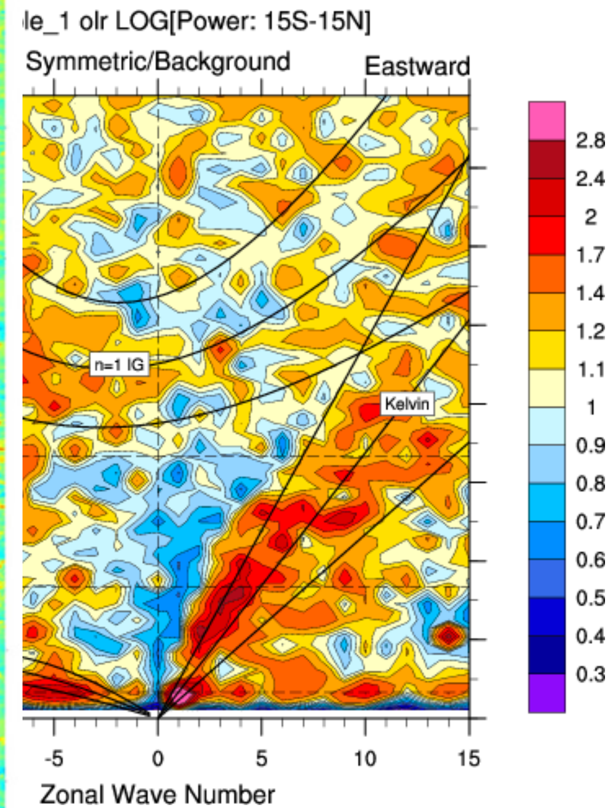
https://www.ncl.ucar.edu/Applications/space_time.shtml

graduate level

Observations of **atmospheric** Equatorial wave modes







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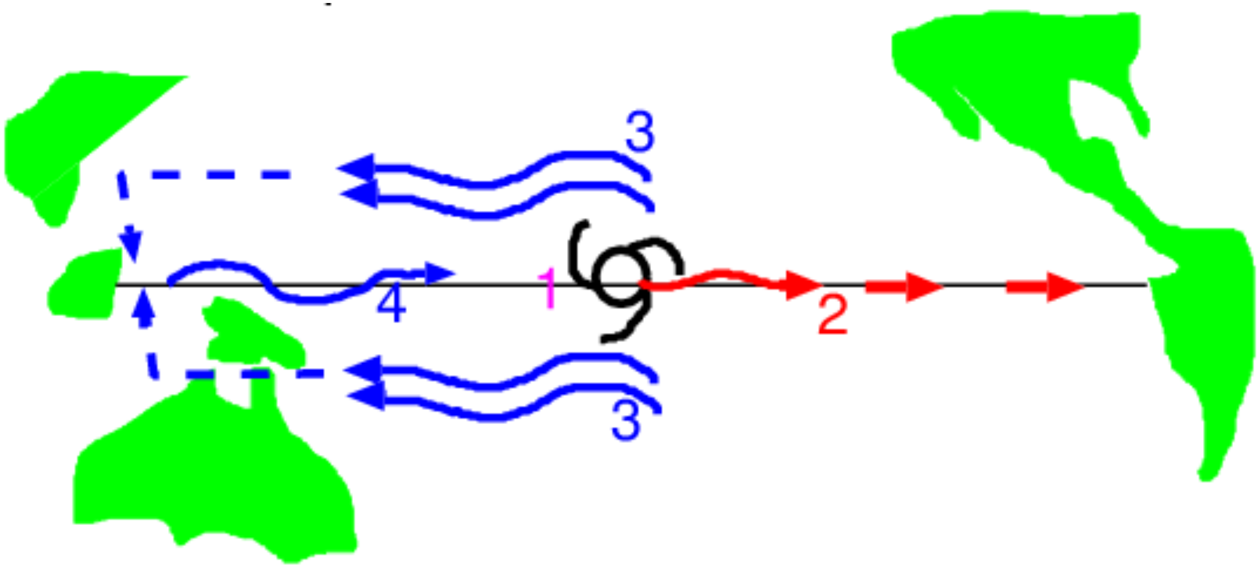
(Wh pectra)

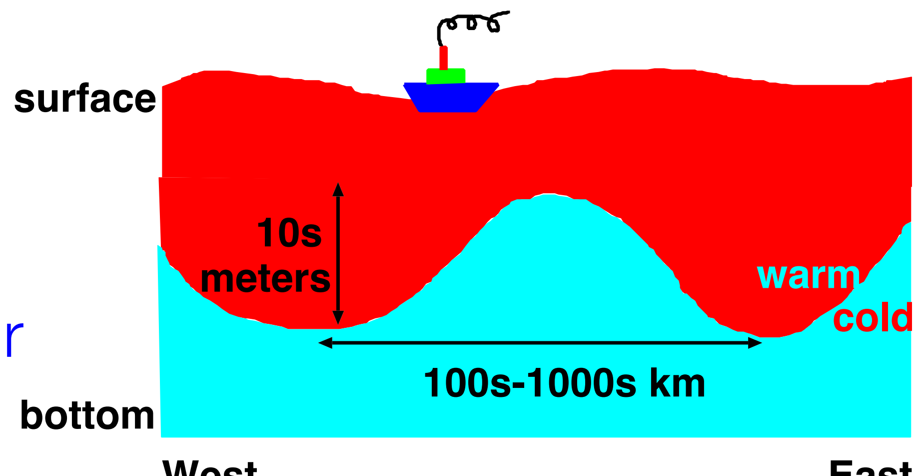
https://www.ncl.ucar.edu/Applications/space_time.shtml

graduate level

Mechanism: Kelvin & Rossby waves, and the delayed oscillator (Schopf & Suarez, Battisti 1988)

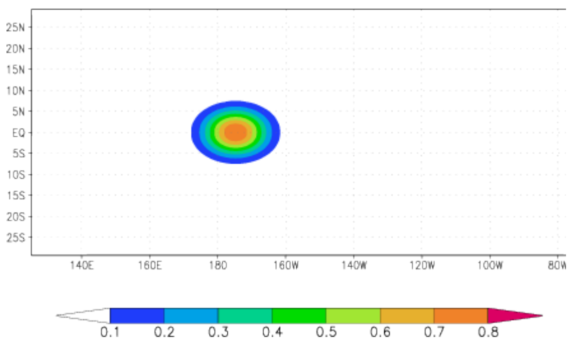


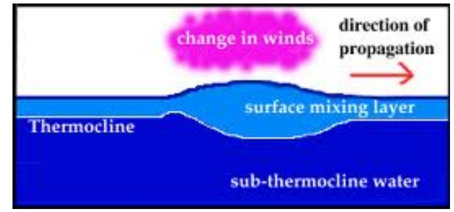
1. An initial weakening of trades
2. Warm Kelvin wave, positive feedback, El Nino peaks
3. Cold Rossby waves making their way to the west pacific
4. Reflecting from western boundary, ending the event, start a cooling
5. All repeats with opposite signs…



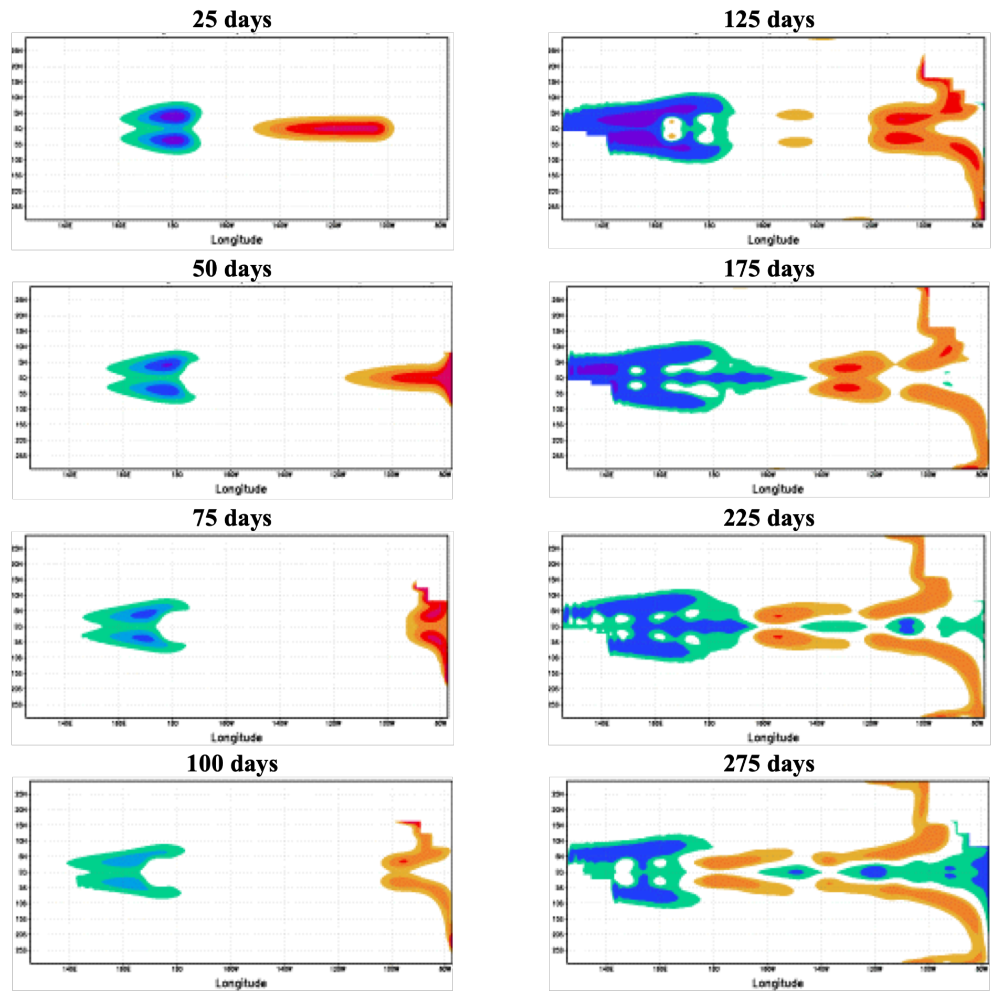
Kelvin and Rossby waves and boundary reflections

1. Force ocean with a westerly wind stress pulse





Kelvin wave schematic



2. Warm Kelvin waves propagate east along equator ➔ Event starts!

3. Cold Rossby waves propagate west at higher latitude & reflect eastward as Kelvin waves ➔ Event ends

http://iri.columbia.edu/climate/ENSO/theory/

notes

delayed oscillator derivation

use also next side

Delayed oscillator equations

East Pacific temperature, *T(t),* depends on thermocline depth there:

$$\frac{dT(t)}{dt} = \hat{a}h_{eq}(x_c, t - \frac{1}{2}\tau_K) + \hat{b}h_{off-eq}(x_c, t - [\frac{1}{2}\tau_R + \tau_K]) - cT(t)^3$$

Schopf & Suarez 1989

Delayed oscillator equations

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wind at eq, x_c,
directly affects h

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graduate level

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$$\boxed{h_{\mathrm{off-eq}} \propto -w^{Ekman}_{\mathrm{off-eq}} \propto -\mathrm{curl}(\tau_{\mathrm{off-eq}}) \approx \partial_y \tau^{(x)}_{\mathrm{off-eq}} \approx (\tau^{(x)}_{\mathrm{off-eq}} - \tau^{(x)}_{\mathrm{eq}})/L \propto -\tau^{(x)}_{\mathrm{eq}}.}$$

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Schopf & Suarez 1989

graduate level

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$$\frac{dT(t)}{dt} = aT(t - \frac{1}{2}\tau_K) - bT(t - [\frac{1}{2}\tau_R + \tau_K]) - cT(t)^3$$

Schopf & Suarez 1989

graduate level

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wind at eq, x_c, directly affects h

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$$\frac{dT(t)}{dt} = \underline{\bar{a}\tau_{eq}(x_c, t - \frac{1}{2}\tau_K)} - \underline{\bar{b}\tau_{eq}(x_c, t - [\frac{1}{2}\tau_R + \tau_K])} - cT(t)^3$$

$$\boxed{-\tau_{\text{eq}}^{(x)}(t - [\frac{1}{2}\tau_R + \tau_K])/L \propto -T(t - [\frac{1}{2}\tau_R + \tau_K]).}$$

$$\frac{dT(t)}{dt} = aT(t - \frac{1}{2}\tau_K) - \underline{bT(t - [\frac{1}{2}\tau_R + \tau_K])} - cT(t)^3$$

Schopf & Suarez 1989

graduate level

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$$\frac{dT(t)}{dt} = \hat{a}h_{eq}(x_c, t - \frac{1}{2}\tau_K) + \hat{b}h_{off-eq}(x_c, t - [\frac{1}{2}\tau_R + \tau_K]) - cT(t)^3$$

wind at eq, x_c, directly affects h

$$h_{\text{off-eq}} \propto -w^{Ekman}_{\text{off-eq}} \propto -\text{curl}(\tau_{\text{off-eq}}) \approx \partial_y \tau^{(x)}_{\text{off-eq}} \approx (\tau^{(x)}_{\text{off-eq}} - \tau^{(x)}_{\text{eq}})/L \propto -\tau^{(x)}_{\text{eq}}.$$

$$\frac{dT(t)}{dt} = \bar{a}\tau_{eq}(x_c, t - \frac{1}{2}\tau_K) - \bar{b}\tau_{eq}(x_c, t - [\frac{1}{2}\tau_R + \tau_K]) - cT(t)^3$$

$$-\tau^{(x)}_{\text{eq}}(t - [\frac{1}{2}\tau_R + \tau_K])/L \propto -T(t - [\frac{1}{2}\tau_R + \tau_K]).$$

$$\frac{dT(t)}{dt} = aT(t - \frac{1}{2}\tau_K) - bT(t - [\frac{1}{2}\tau_R + \tau_K]) - cT(t)^3$$

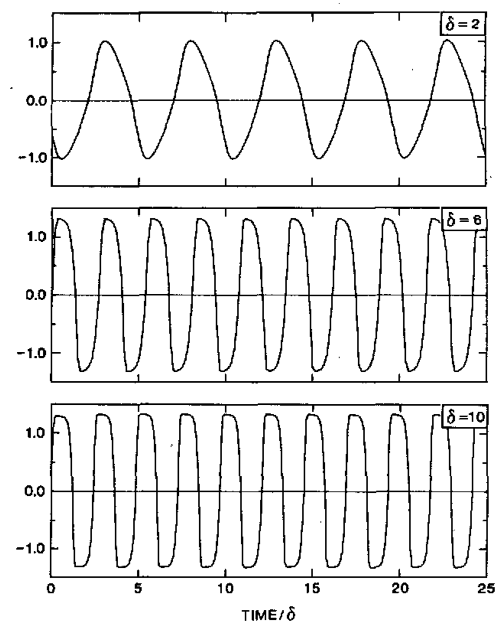
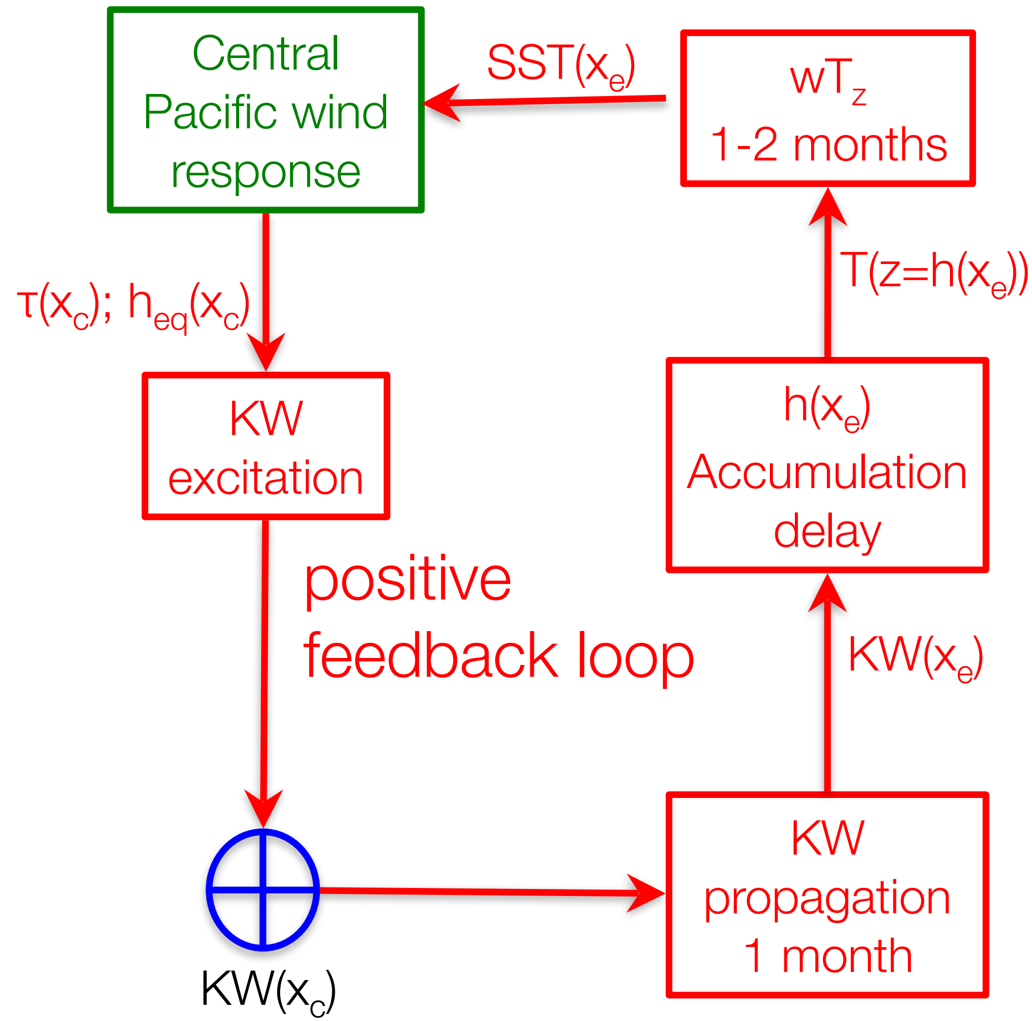


FIG. 4. Behavior of the nonlinear oscillator. (a) $\alpha = 0.75$, $\delta = 2$, (b) $\alpha = 0.75$, $\delta = 6$, and (c) $\alpha = 0.75$, $\delta = 10$. The time axis is scaled in units of the delay.

Schopf & Suarez 1989

graduate level

Delay oscillator mechanism (Schopf-Suarez, Battisti, 1989)



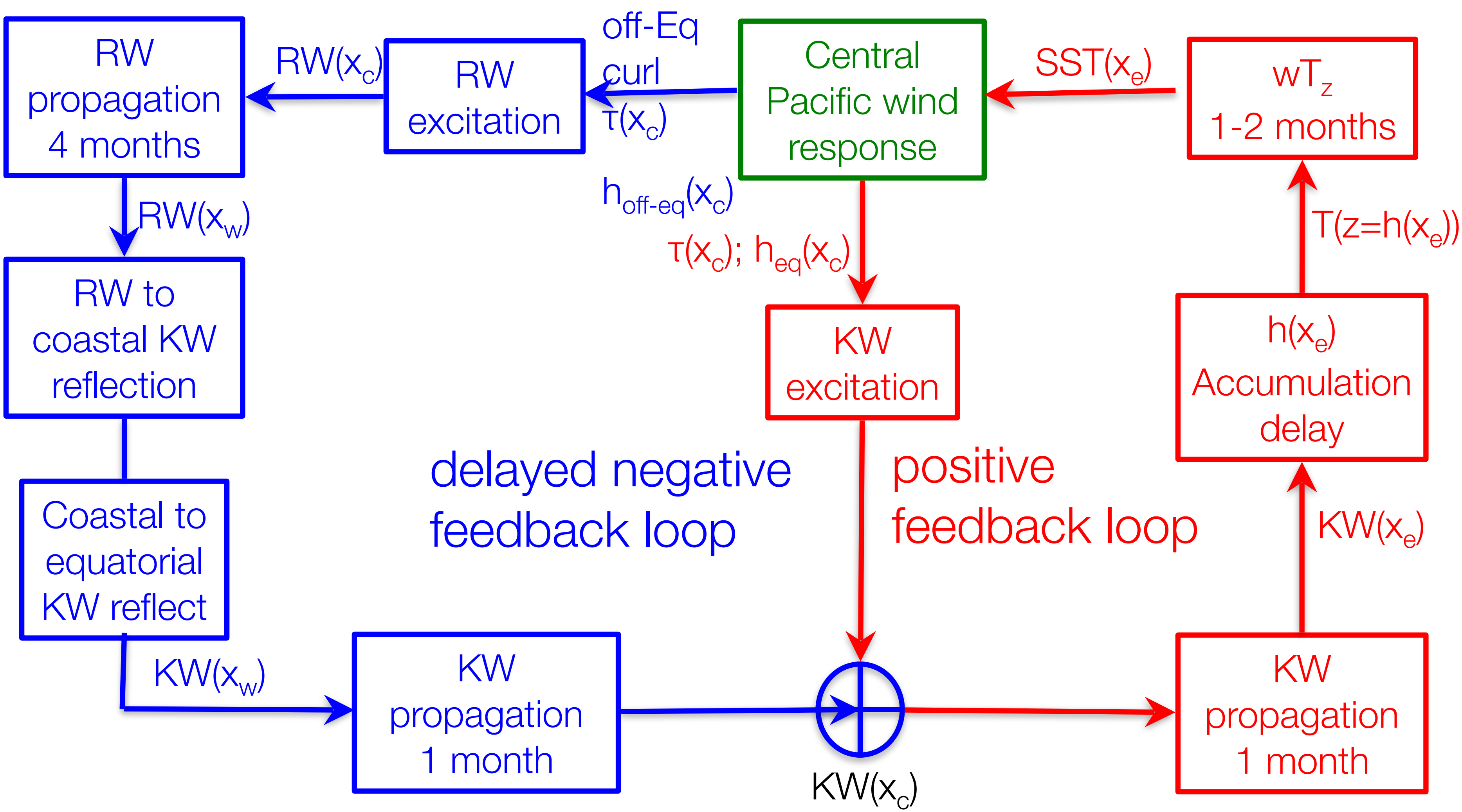
Each block represents a physical process relating input and output.

Right loop: eastern-Pacific positive feedback.

Left loop: negative feedback due to delayed Rossby waves.

Delay oscillator mechanism

(Schopf-Suarez, Battisti, 1989)



Each block represents a physical process relating input and output.

Right loop: eastern-Pacific positive feedback.

Left loop: negative feedback due to delayed Rossby waves.

Delayed oscillator analysis

neglect Kelvin delay for simplicity

$$\frac{dT(t)}{dt} = T(t) - \alpha T(t - \delta_T) - T^3(t).$$

Schopf & Suarez 1989

Delayed oscillator analysis

neglect Kelvin delay for simplicity

$$\frac{dT(t)}{dt} = T(t) - \alpha T(t - \delta_T) - T^3(t).$$

steady states: $\bar{T} = 0, \pm\sqrt{1-\alpha}.$

Schopf & Suarez 1989

Delayed oscillator analysis

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$$\frac{dT(t)}{dt} = T(t) - \alpha T(t - \delta_T) - T^3(t).$$

steady states: $\bar{T} = 0, \pm\sqrt{1-\alpha}.$

Linearize: $T = \bar{T} + \tilde{T}$ to find $\dfrac{d\tilde{T}(t)}{dt} = \tilde{T}(t)(1 - 3\bar{T}^2) - \alpha\tilde{T}(t - \delta_T).$

Schopf & Suarez 1989

graduate level

Delayed oscillator analysis

neglect Kelvin delay for simplicity

$$\frac{dT(t)}{dt} = T(t) - \alpha T(t-\delta_T) - T^3(t).$$

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Finding eigen solutions: $\text{Letting } \tilde{T} = e^{\sigma t} \text{ where } \sigma = \sigma_r + i\sigma_i$

Schopf & Suarez 1989

Delayed oscillator analysis

neglect Kelvin delay for simplicity

$$\frac{dT(t)}{dt} = T(t) - \alpha T(t-\delta_T) - T^3(t).$$

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Finding eigen solutions: Letting $\tilde{T} = e^{\sigma t}$ where $\sigma = \sigma_r + i\sigma_i$

need to solve transcendental equation: $\sigma = 1 - 3\bar{T}^2 - \alpha e^{-\sigma\delta_T}$

Schopf & Suarez 1989

graduate level

Delayed oscillator analysis

neglect Kelvin delay for simplicity

$$\frac{dT(t)}{dt} = T(t) - \alpha T(t - \delta_T) - T^3(t).$$

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Finding eigen solutions: Letting $\tilde{T} = e^{\sigma t}$ where $\sigma = \sigma_r + i\sigma_i$

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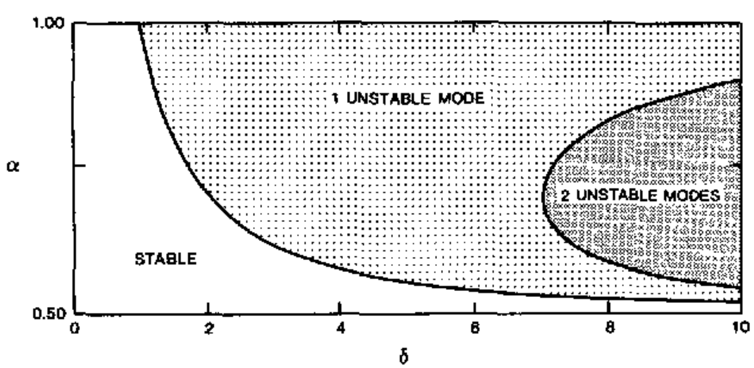


solution

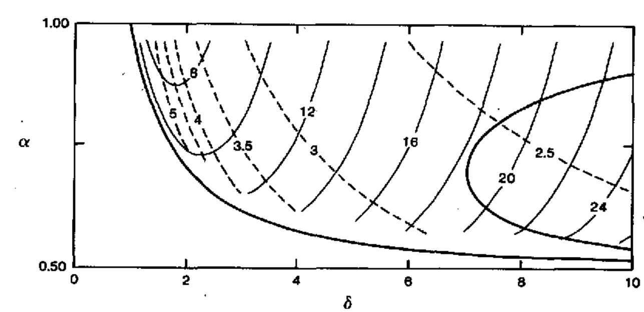


FIG. 5. The fundamental period of the nonlinear oscillator found numerically. The heavy solid lines are the neutral curves of the linear problem, reproduced from Fig. 2. The light solid contours give the period of the oscillation ($2\pi/\sigma_i$), while the dashed contours present the period in multiples of the delay.

Schopf & Suarez 1989

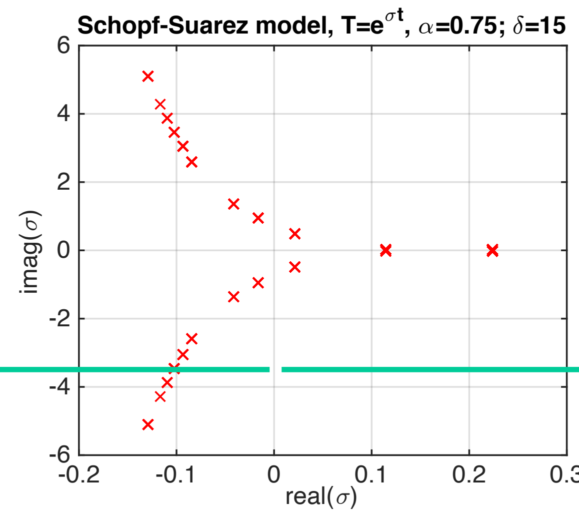
graduate level

notes

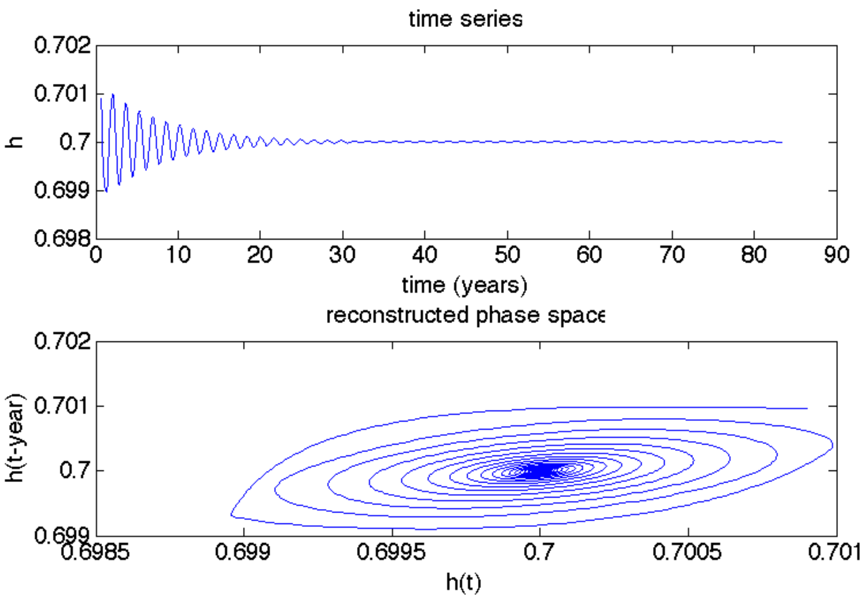
Hopf bifurcation, see also next slide

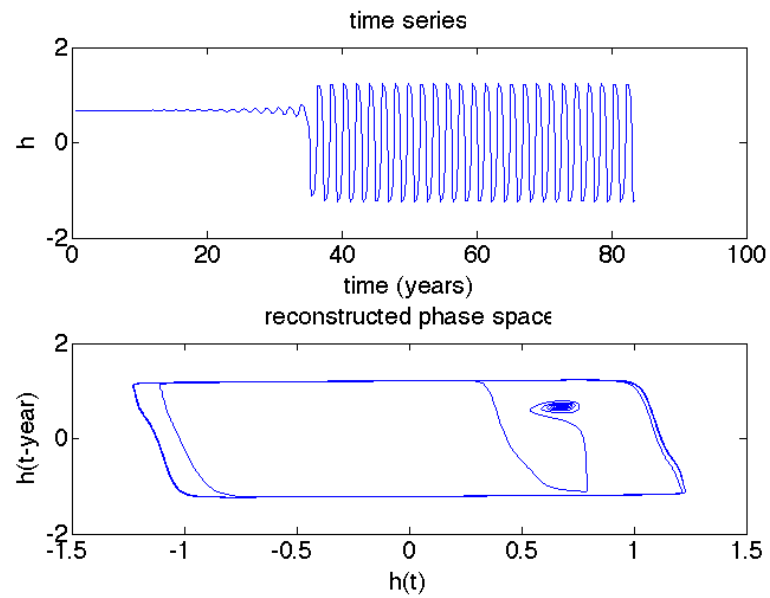
Delayed oscillator analysis

roots of linearized delayed oscillator equation:



damped ⟵ ⟶ self-sustained





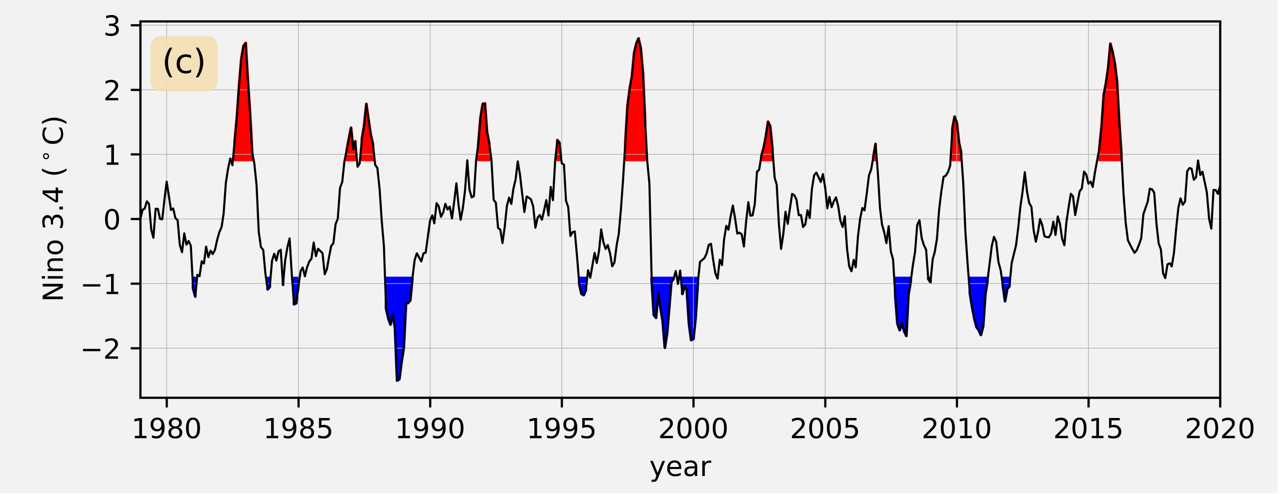
Time series and phase space of nonlinear solution, damped and self-sustained regimes

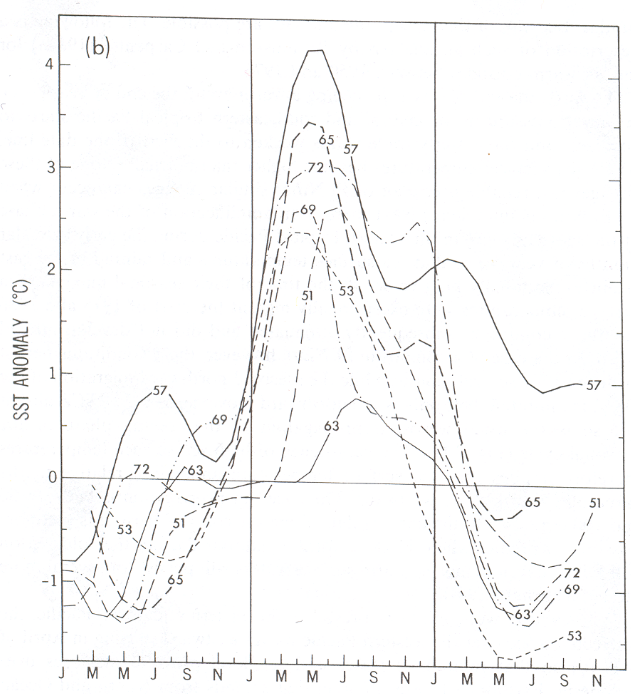
graduate level

Irregularity: chaos

1a- notes:

A. nonlinear synchronization example: fireflies (pp 75,77)
B. nonlinear phase locking video in following slide
C. circle map and quasi-periodicity route to chaos (pp 79, 81)





graduate level

Irregularity: chaos

Nonlinear phase locking

graduate level

Irregularity: chaos

Nonlinear phase locking

graduate level

Transition to chaos of an ENSO model

$(x, y, z) =$ (east,north,up) coordinates;

$[u, v, w]/[u_a, v_a]$: corresponding ocean water/atmospheric wind velocity;

$T(x, y, t)$ sea surface temperature; $h(x, y, t)$: depth of warm water.

- Ocean momentum and mass conservation:

$$\begin{aligned} u_t - \beta y v &= -g' h_x + \tau^{(x)}[u_a, v_a] - ru \\ \beta y u &= -g' h_y + \tau^{(y)}[u_a, v_a] - rv \\ h_t + H\nabla\mathbf{v} &= -rh. \end{aligned}$$

- Atmospheric momentum and mass:

$$\begin{aligned} \beta y v_a &= -\phi_x - r u_a \\ \beta y u_a &= -\phi_y - r v_a \\ \phi_t + H\nabla\mathbf{v} &= Q[T, \nabla\mathbf{v}_a] \end{aligned}$$

- Sea surface temperature equation:

$$T_t + \overline{\mathbf{v}}\nabla T + \mathbf{v}\nabla(\overline{T} + T) + w\overline{T}_z + (\overline{w} + w)T_z = -\alpha T \quad (1)$$

An “Intermediate” coupled ocean-atmosphere model, first to successfully predict El Niño events

graduate level

Transition to chaos of an ENSO model

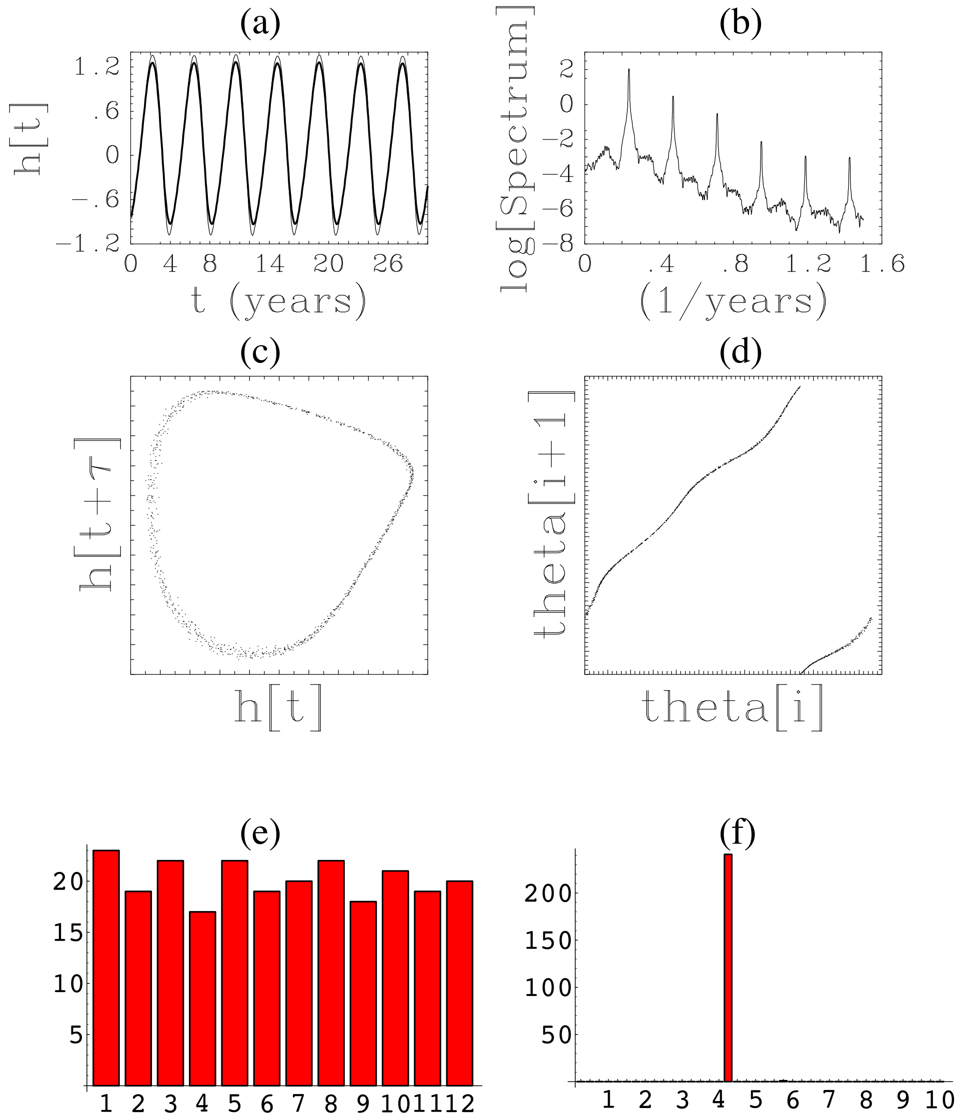
SST

Spectrum

Delay coordinates reconstructed phase space

Number of events per month

Time between events



Weak seasonal cycle: quasi-periodic, ENSO period is 4.X years

Transition to chaos of an ENSO model

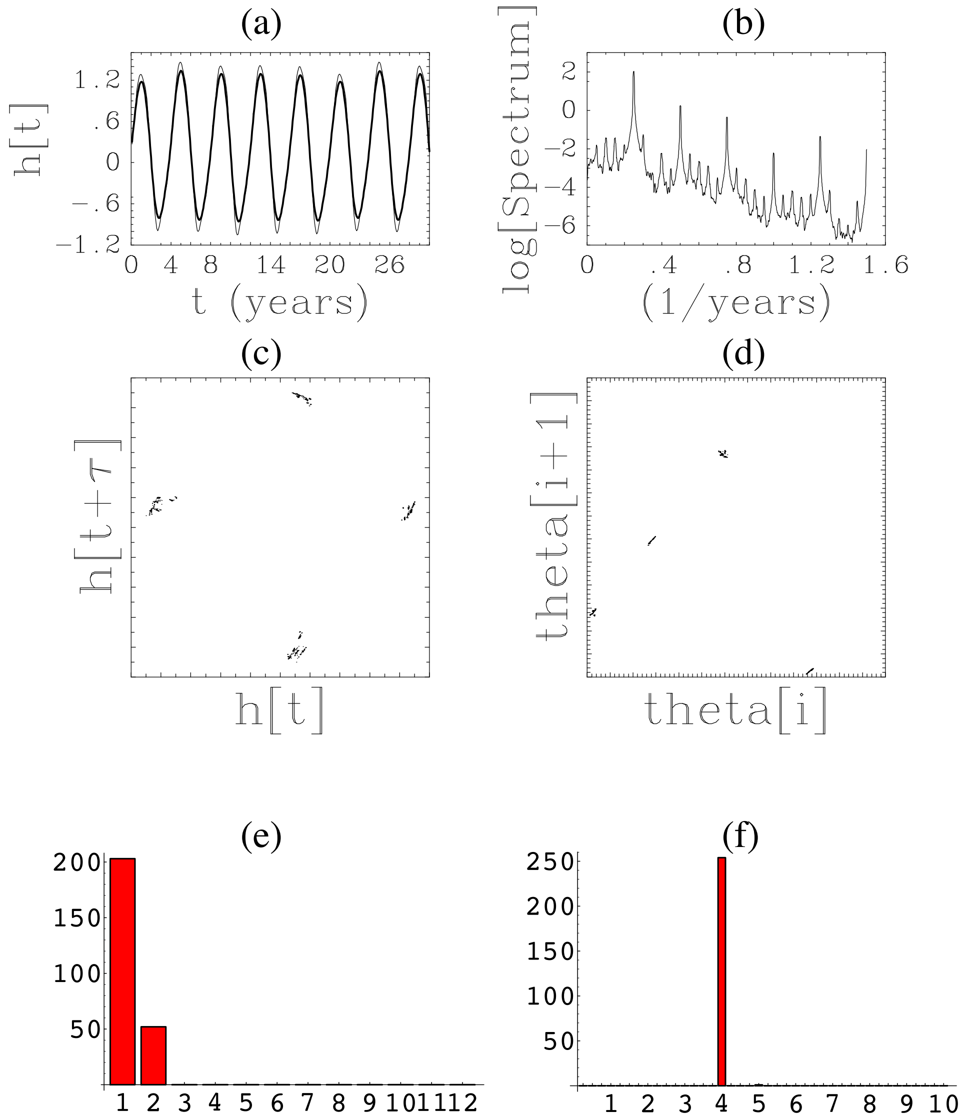
SST

Spectrum

Delay coordinates reconstructed phase space

Number of events per month

Time between events



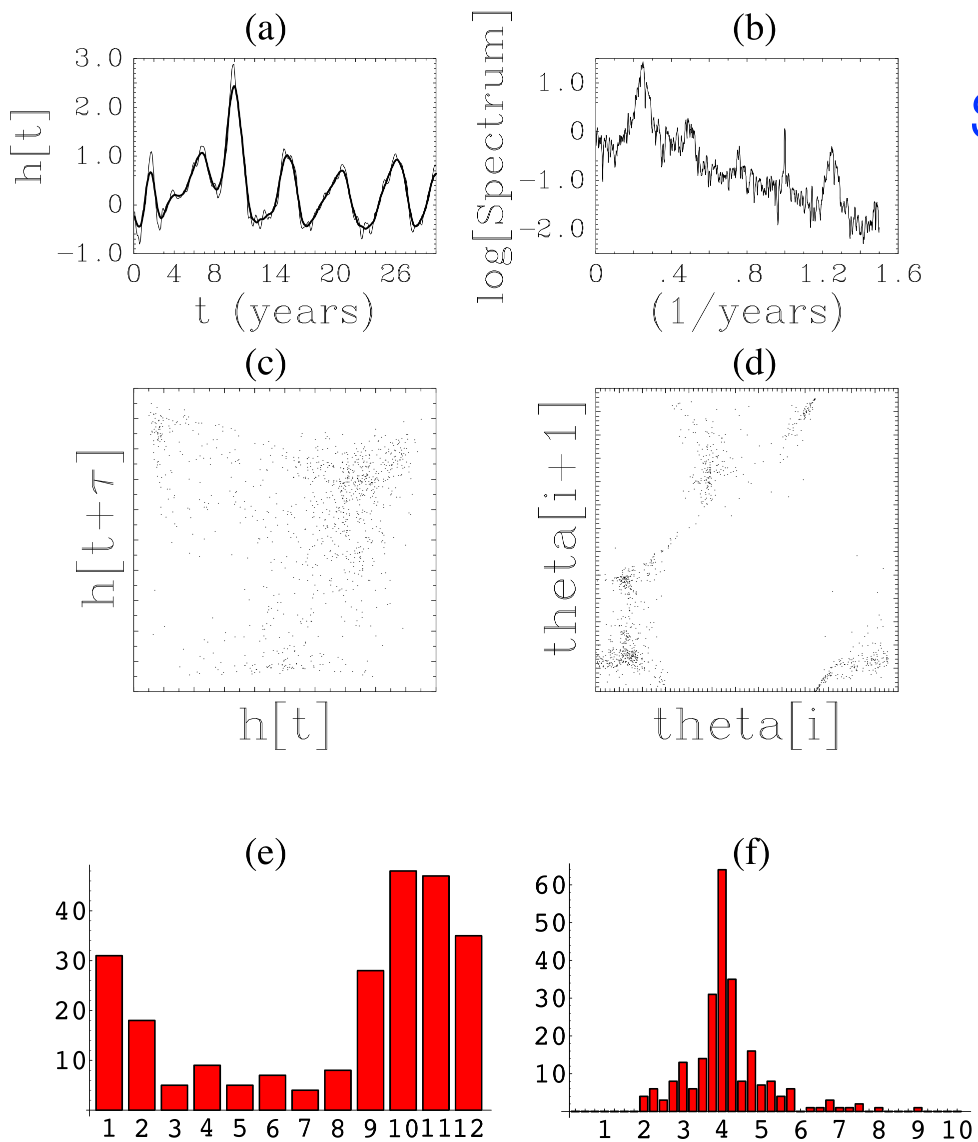
Moderate amplitude seasonal cycle: phase-locked

graduate level

Transition to chaos of an ENSO model

SST

Spectrum



Delay coordinates reconstructed phase space

Number of events per month

Time between events

Strong seasonal cycle: chaotic

graduate level

Irregularity: noise, transient growth

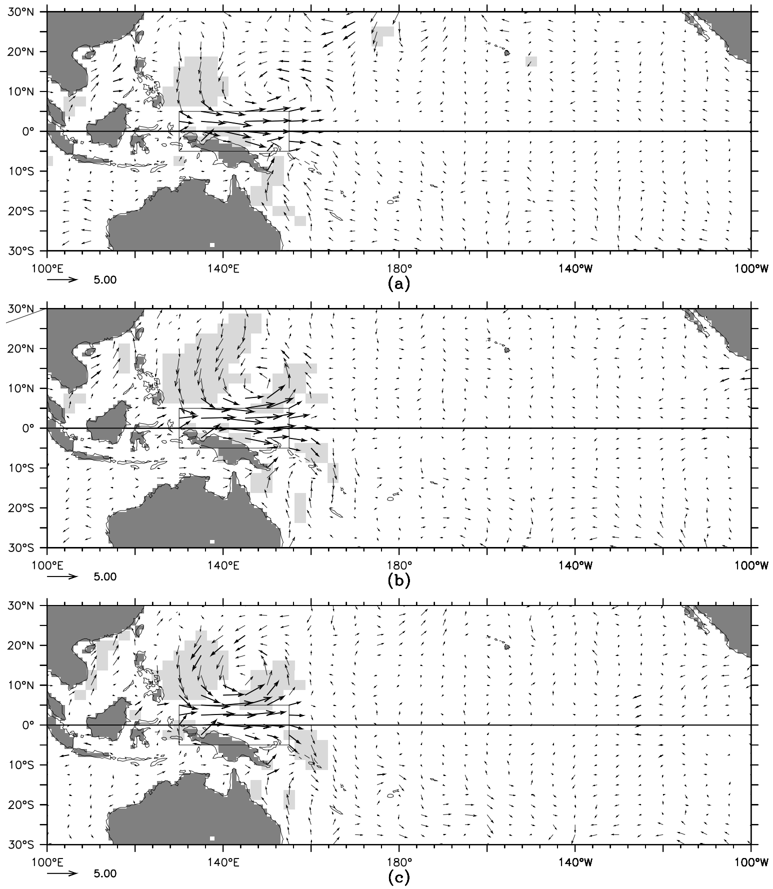
Outline:

1- notes: non-normal transient growth, optimal initial conditions
(stochastic optimals will be covered in AMOC section)

2- WWBs as stochastic optimals

3- WWBs do not seem stochastic, they depend on the mean state and occur more frequently during El Nino conditions

Irregularity: observed Westerly Wind Bursts

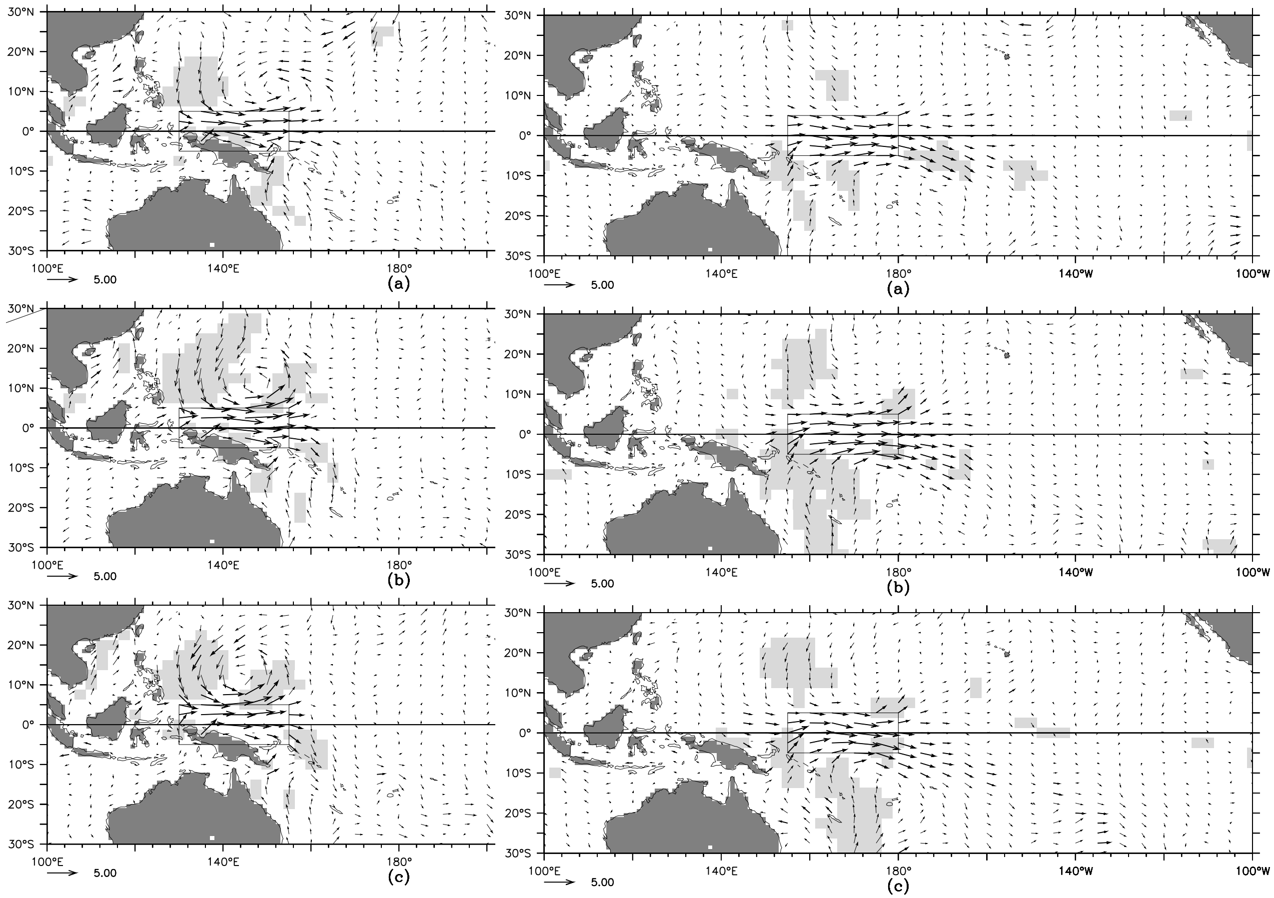


Figs 68, 69, 70: composite WWE 10-m wind anomaly vector map, for (a) day(–1), (b) day(0) and (c) day(1). The classifying region is indicated by the thin lined box. The scale vector is 5m/s. Zonal wind anomalies statistically significant at 99% are indicated by bold vectors, meridional wind anomalies significant at 99% are indicated by shaded background.

Vecchi and Harrison 1997

graduate level

Irregularity: observed Westerly Wind Bursts



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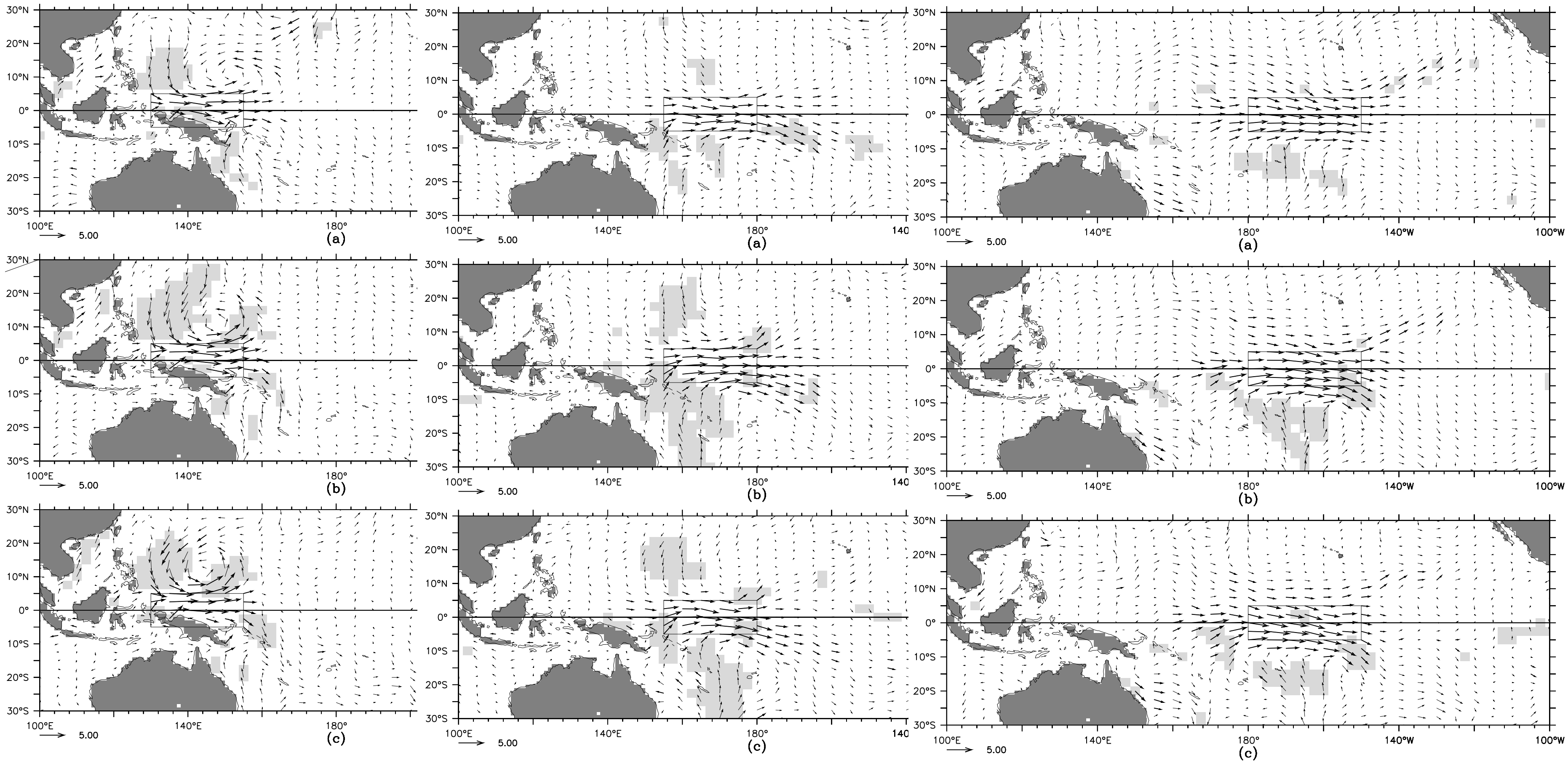
Vecchi and Harrison 1997

graduate level

Irregularity: observed Westerly Wind Bursts



Figs 68, 69, 70: composite WWE 10-m wind anomaly vector map, for (a) day(–1), (b) day(0) and (c) day(1). The classifying region is indicated by the thin lined box. The scale vector is 5m/s. Zonal wind anomalies statistically significant at 99% are indicated by bold vectors, meridional wind anomalies significant at 99% are indicated by shaded background.

Vecchi and Harrison 1997

graduate level

Irregularity: Westerly Wind Bursts excite Kelvin waves

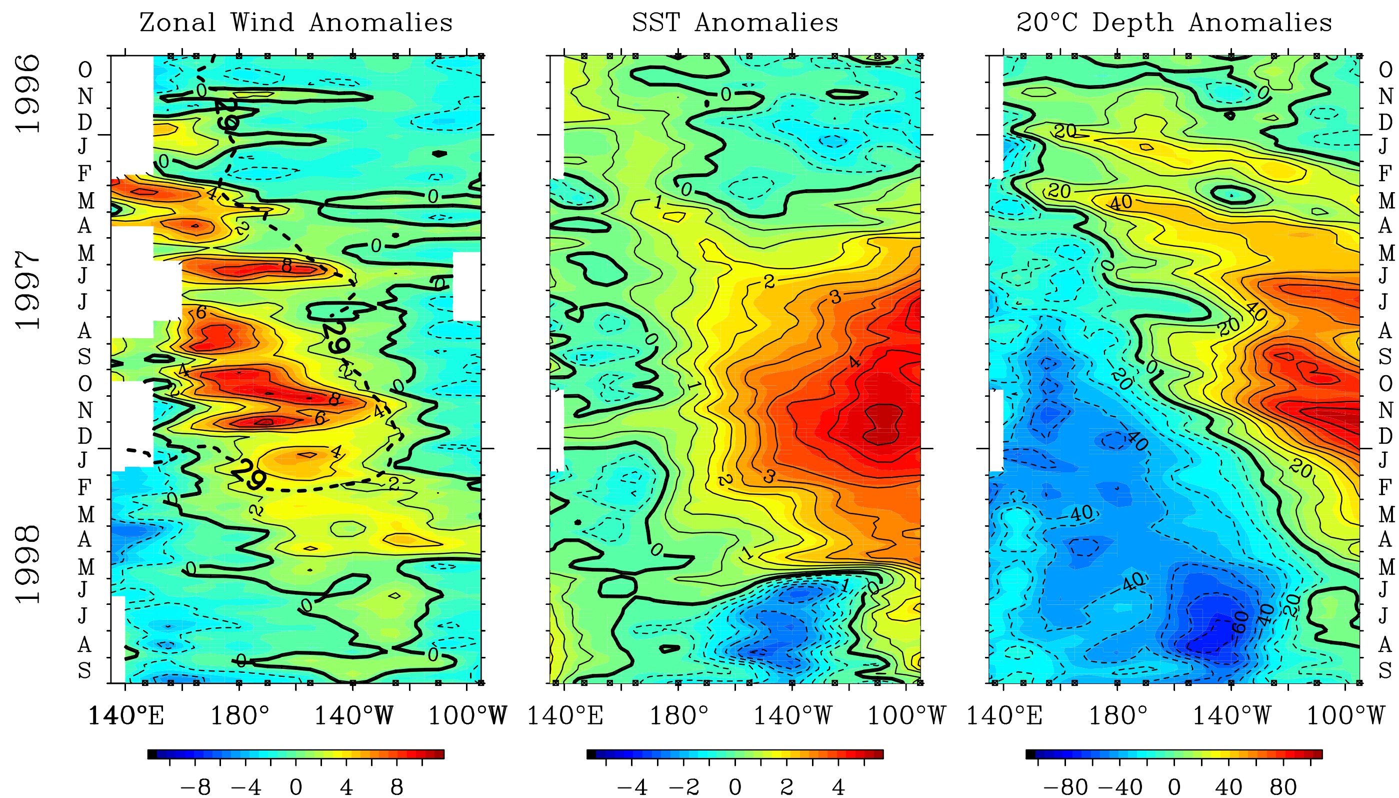
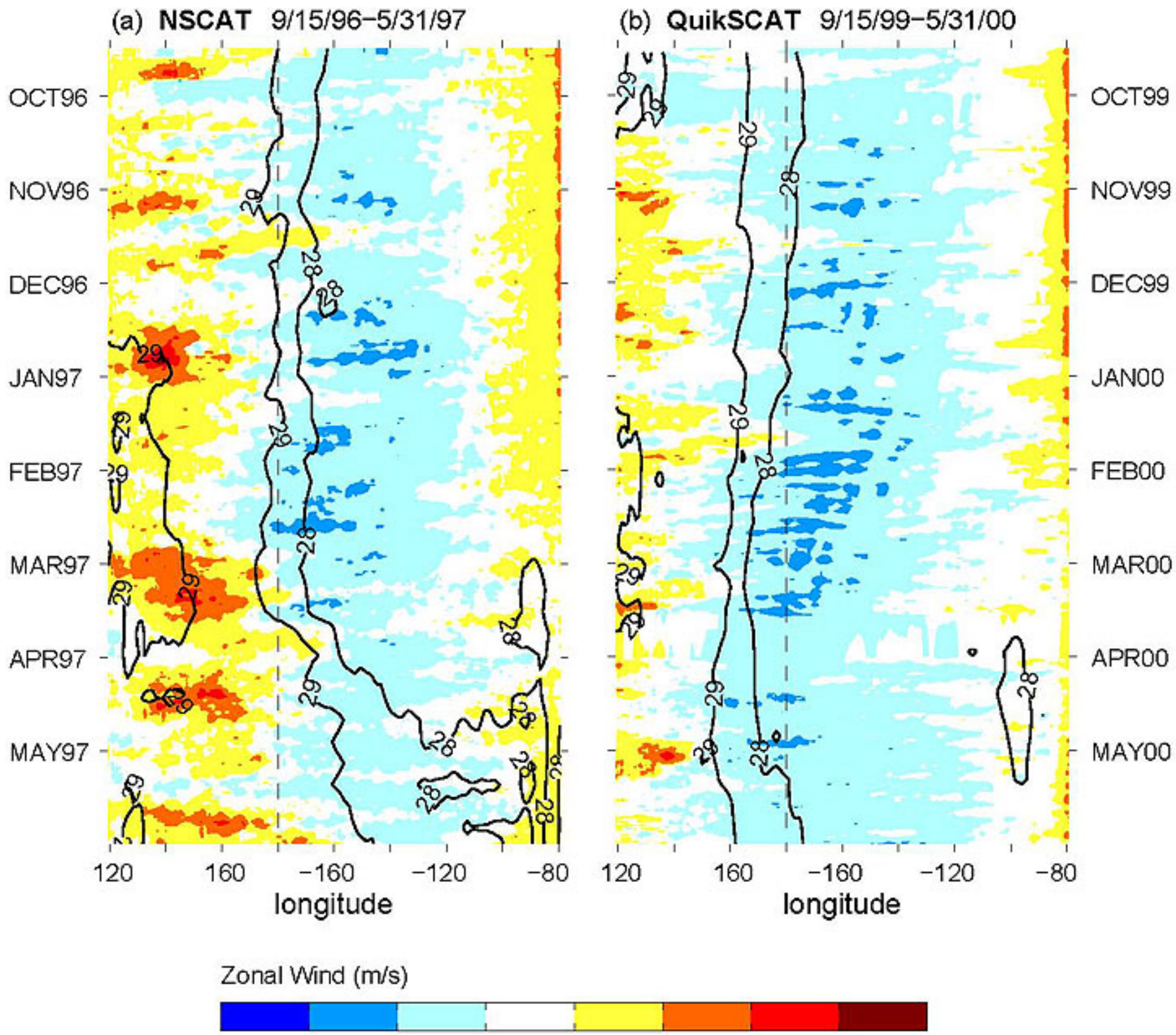


Figure 2. Heat content anomalies averaged between 2°N and 2°S along the equator from TAO data (in 10^{10} J m^{-3}, left), sea level anomalies along the equator from the TOPEX/Poseidon altimeter (in cm, middle), and modeled sea level anomalies along the equator (in cm, right). Temporal resolution is 5-days for TAO data and the model, 10-days for the altimeter data. A mean seasonal cycle has been removed from each time series.

McPhaden and Yu 1999

graduate level

Irregularity: WWBs precede major El Ninos

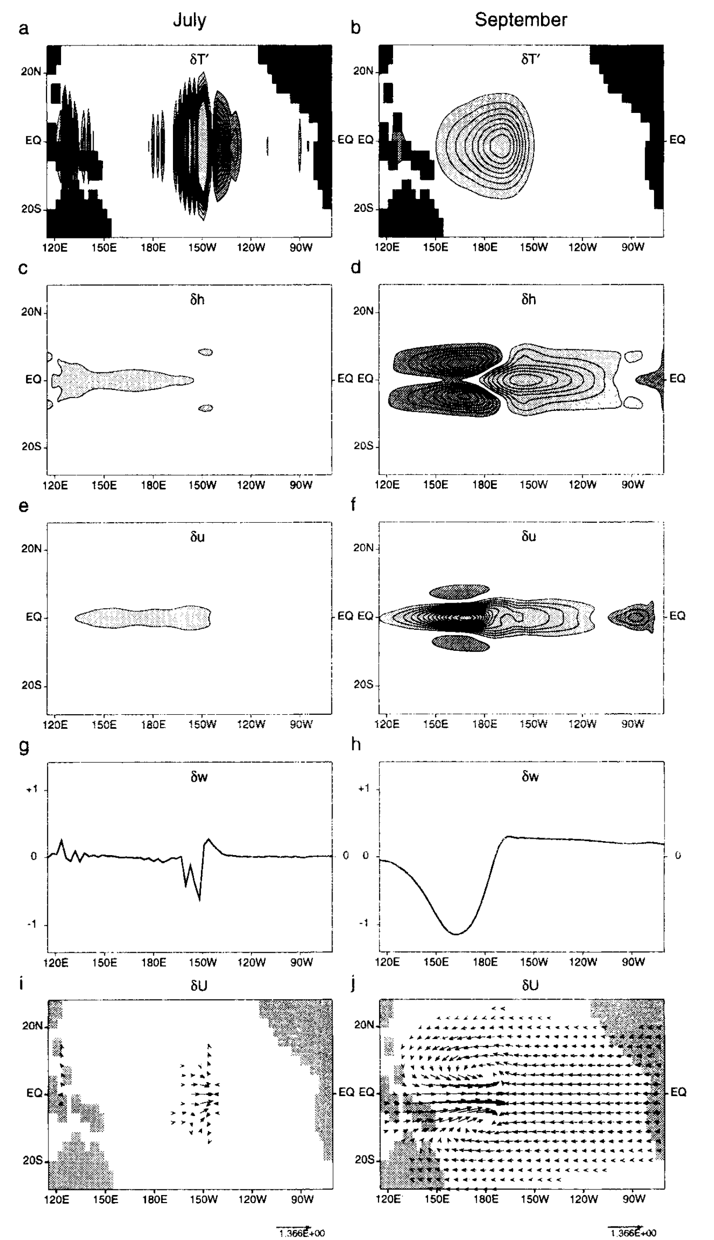


Lisan Yu: observed SST (contours) and WWBs (colors)

graduate level

Irregularity: Westerly Wind Bursts as optimal initial conditions

Figure 6: the structure of the fastest growing all terms singular factor (TAUSV) over the tropical pacific. during the July, August and September (JAS) quarter. Maps detailing the structure of the perturbation SST (delta T) , perturbation thermocline depth (delta h),perturbation zonal ocean current (delta u),equatorial perturbation vertical velocity (delta w),and vectors of the perturbation wind (delta U) are shown at the end of July and September. Light shading represents positive values of each quantity, while dark shading indicates negative values. Because the SVs are the result of a linear analysis, the scaling of the various fields is arbitrary.



Moore and Kleeman 1997

graduate level

Irregularity: WWBs are not stochastic, depend on mean state

WWBs as a gaussian perturbation: $$\tau = A\exp\left[-\frac{(x-x_0)^2}{L_{\mathrm{EW}}^2}-\frac{(y-y_0)^2}{L_{\mathrm{NS}}^2}-\frac{(t-t_0)^2}{T^2}\right].$$

with parameters: $$\mathbf{R}(t) = (A, x_0, y_0, L_{\mathrm{EW}}, L_{\mathrm{NS}}, T, p)^{\mathrm{T}},$$

covariance matrix with SST $$\mathbf{C}_{ij} = \frac{1}{N_{\mathrm{wwb}}-1}\sum_{t=1}^{N_{\mathrm{wwb}}} T_i(t)\mathbf{R}_j(t).$$

and singular vectors are:

Tziperman and Yu 2007

Irregularity: WWBs are not stochastic, depend on mean state

WWBs as a gaussian perturbation:

$$\tau = A \exp\left[-\frac{(x-x_0)^2}{L_{\mathrm{EW}}^2} - \frac{(y-y_0)^2}{L_{\mathrm{NS}}^2} - \frac{(t-t_0)^2}{T^2}\right].$$

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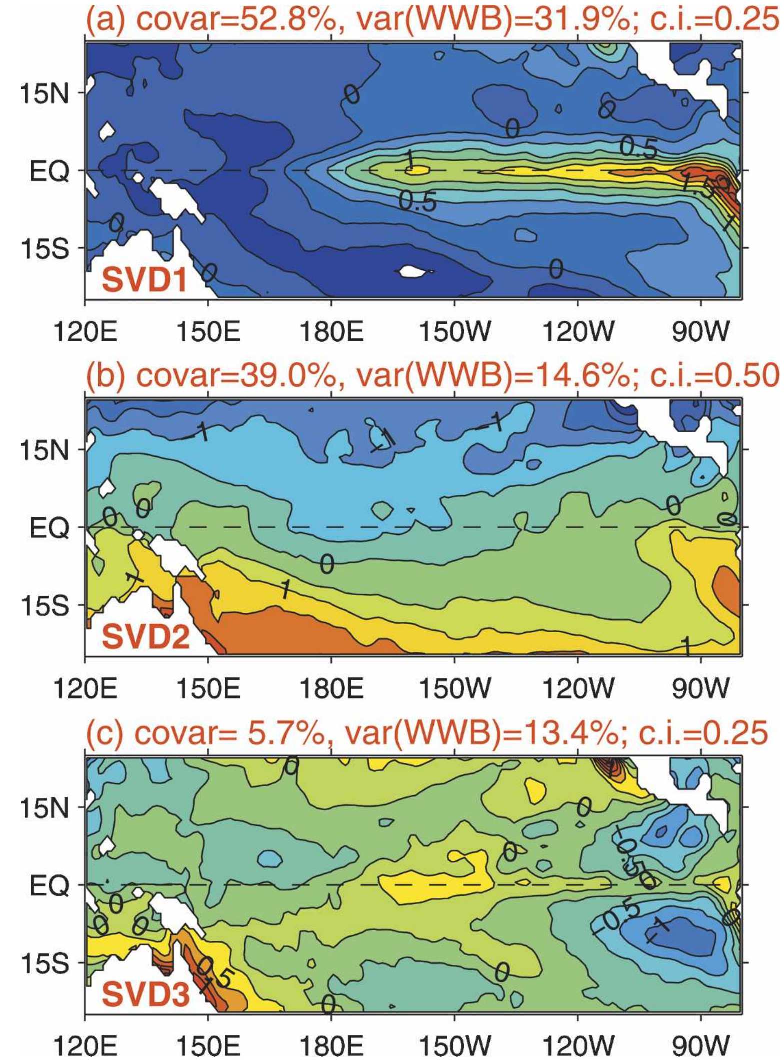

Tziperman and Yu 2007

graduate level

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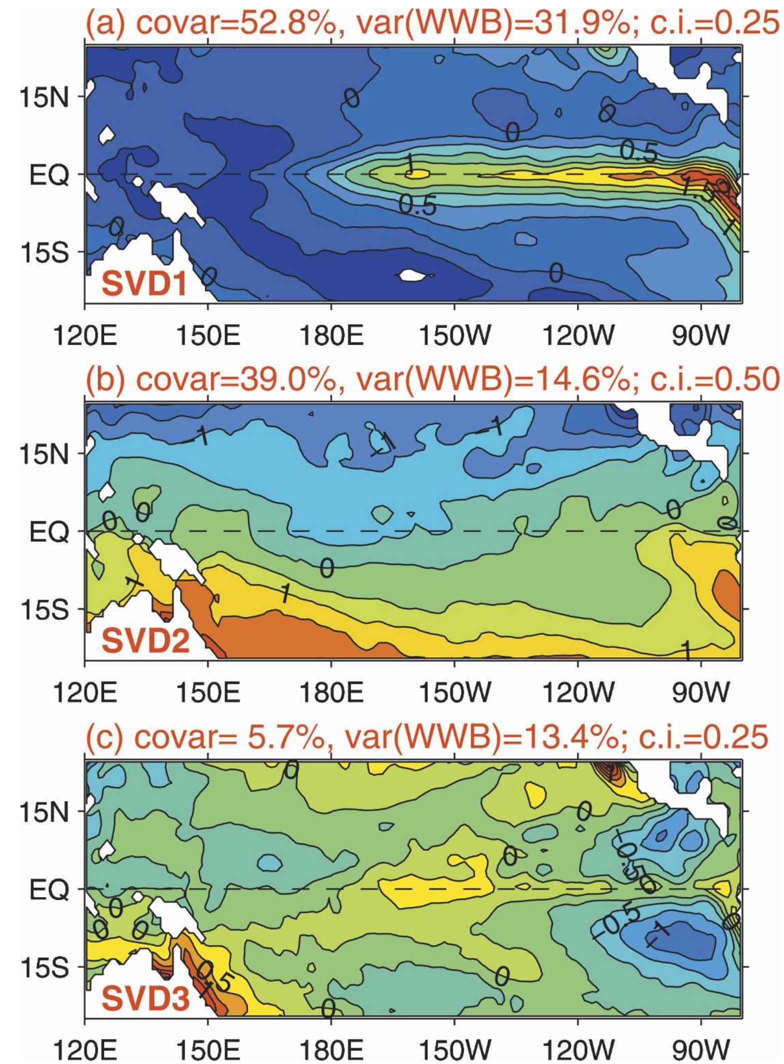
with parameters: $$\mathbf{R}(t) = (A, x_0, y_0, L_{EW}, L_{NS}, T, p)^{T},$$

covariance matrix with SST $$\mathbf{C}_{ij} = \frac{1}{N_{wwb}-1}\sum_{t=1}^{N_{wwb}} T_i(t)\mathbf{R}_j(t).$$

and singular vectors are:

TABLE 1. The first seven rows of this table give the seven SVD vectors for the WWB parameters shown in Eq. (1). The entries are all multiplied by 100. The row marked "%covar" contains the percentage of the covariance between the SST and the WWB parameters explained by each SVD vector [using the singular values, Eq. (9)]. The last row, marked "%var(τ)," is the percentage of the variance of the WWB parameter vector explained by each SVD vector [using Eq. (11)].

	1	2	3	4	5	6	7
A	18	81	2	35	0	2	43
x_0	58	−20	27	−49	−23	0	51
L_{EW}	49	4	−7	17	−11	−75	−39
L_{NS}	11	−13	31	6	91	−15	14
T	27	1	67	30	−14	43	−43
P	47	−33	−56	43	11	38	8
y_0	−28	−41	27	57	−27	−29	44
%covar	53	39	6	1	1	0	0
%var(τ)	32	15	13	15	12	7	6



Tziperman and Yu 2007

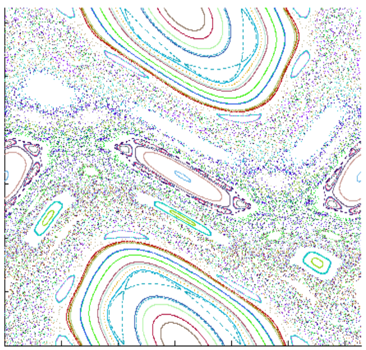
graduate level

Summary of ENSO irregularity: Chaos or stochastic forcing
Why can't we predict El Nino well in advance?

Two possible paradigms

Chaos: the butterfly effect

- Irregularity from deterministic chaos driven by seasonal cycle



- ENSO oscillator irregularly jumps between nonlinear resonances with the seasonal cycle.
- reproduces major ENSO features
- Deterministic system but sensitive to initial conditions – 6-9 month predictability

Summary of ENSO irregularity: Chaos or stochastic forcing
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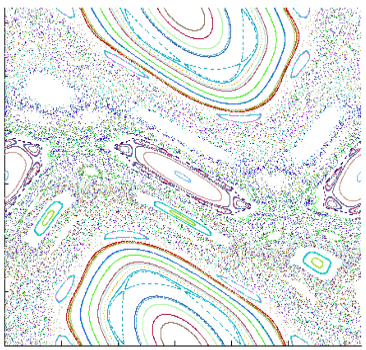
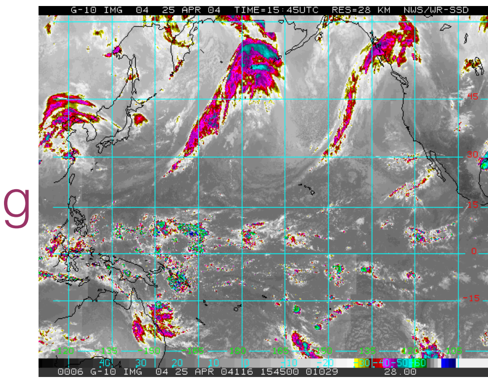


- ENSO oscillator irregularly jumps between nonlinear resonances with the seasonal cycle.
- reproduces major ENSO features
- Deterministic system but sensitive to initial conditions – 6-9 month predictability

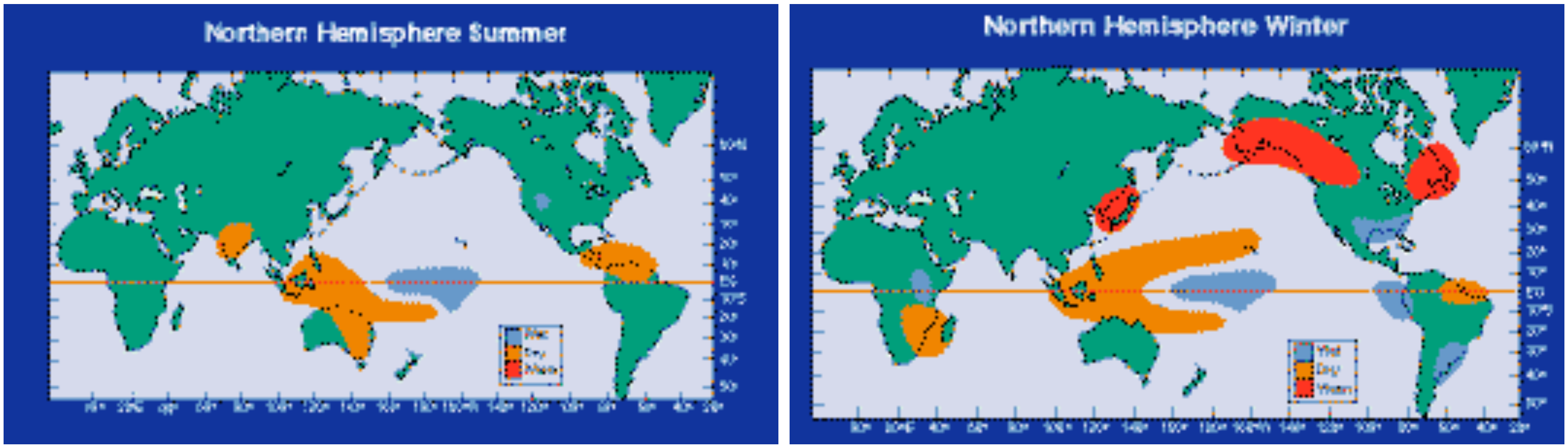
Noise (Stochastic forcing):



- Irregularity from weather forcing on inter-annually varying components
- Nonlinearity is not crucial. Damped oscillations are randomized by stochastic forcing
- Models reproduce major ENSO features
- Insensitive to initial conditions, but stochastic forcing effects add up – 6-9 month predictability

ENSO teleconnections

Reminder: ENSO teleconnections, precipitation:



Precipitation anomalies during El Niño in (a) Summer and (b) Winter

http://www.pmel.noaa.gov/tao/elnino/impacts.html

ENSO teleconnections

example wave teleconnection patterns

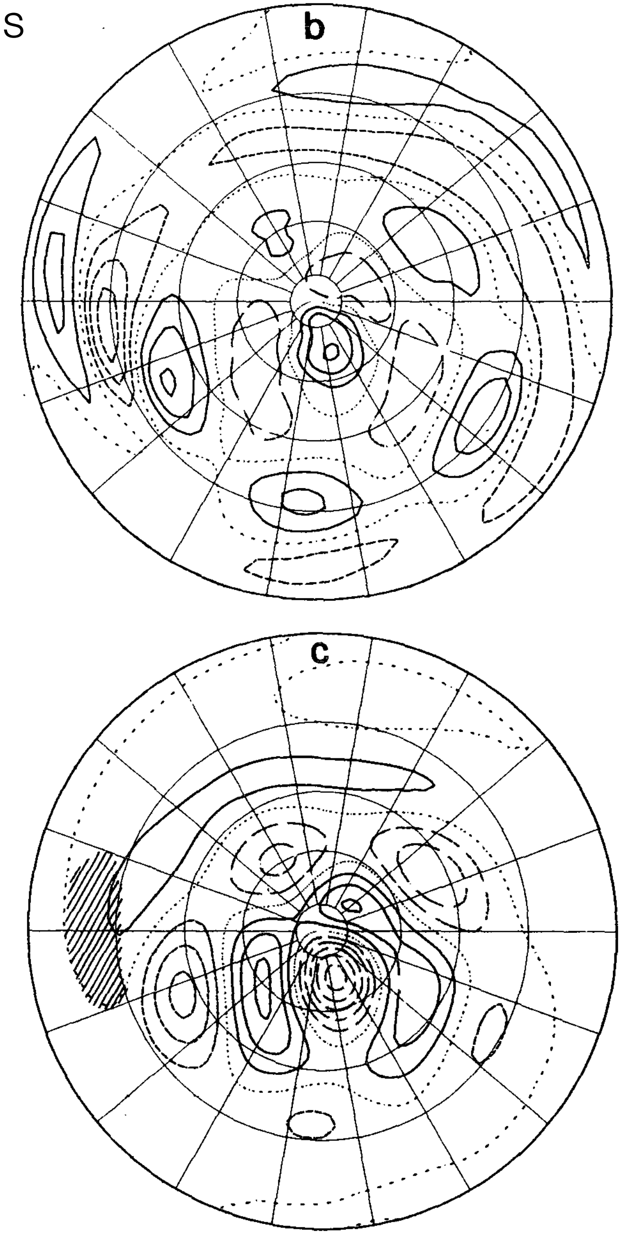


FIG. 3. Steady state, linear solution of a five-layer baroclinic model for a deep elliptical heat source at 15° perturbing the Northern Hemisphere winter zonal flow. Shown are (a) height field in a longitude-height section at 18.1°N (contour interval 1 dam), (b) 300 mb vorticity perturbation (contour interval 0.05Ω), and (c) 300 mb height field perturbation (contour interval 2 dam). The contour convention is as in Fig. 1 except that the zero contours in (a) are thick continuous lines. The center of the source is indicated by a cross in (a) and the region of heating larger than 0.5 K day^{-1} by hatching in (c). Tick marks in (a) are at 100, 300, 500, 700 and 900 mb in the vertical and every 30° of longitude.

Hoskins and Karoly 1981

ENSO teleconnections

notes, use also following slides

ENSO teleconnections: spherical coordinates, mercator projection

sphere. It is convenient to use a Mercator projection of the sphere (e.g., Phillips, 1973):

$$x = a\lambda, \tag{5.1}$$

$$y = a \ln[(1 + \sin\phi)/\cos\phi]. \tag{5.2}$$

Then

$$\frac{1}{a\cos\phi}\frac{\partial}{\partial\lambda} = \frac{1}{\cos\phi}\frac{\partial}{\partial x}, \tag{5.3}$$

$$\frac{1}{a}\frac{\partial}{\partial\phi} = \frac{1}{\cos\phi}\frac{\partial}{\partial y}, \tag{5.4}$$

$$\nabla^2 = \frac{1}{\cos^2\phi}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right), \tag{5.5}$$

$$\cos\phi = \operatorname{sech} y/a, \tag{5.6}$$

$$\sin\phi = \tanh y/a. \tag{5.7}$$

The Mercator basic zonal velocity

$$\bar{u}_M = \bar{u}/\cos\phi \tag{5.8}$$

is proportional to the angular velocity. The equation for the horizontal streamfunction perturbation ψ, on multiplying by $\cos^2\phi$, takes the form

$$\left(\frac{\partial}{\partial t} + \bar{u}_M\frac{\partial}{\partial x}\right)\left(\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2}\right) + \beta_M\frac{\partial\psi}{\partial x} = 0, \tag{5.9}$$

where

$$\beta_M = \frac{2\Omega}{a}\cos^2\phi - \frac{d}{dy}\frac{1}{\cos^2\phi}\frac{d}{dy}(\cos^2\phi\,\bar{u}_M) \tag{5.10}$$

is $\cos\phi$ times the meridional gradient of the absolute vorticity on the sphere.

The dispersion equation for plane wave solutions $\exp i(kx + ly - \omega t)$ of (5.9)

$$\omega = \bar{u}_M k - \frac{\beta_M k}{k^2 + l^2}. \tag{5.11}$$

Hoskins and Karoly 1981

graduate level

ENSO teleconnections

Ray tracing for idealized “constant angular momentum” mean flow:

$$\bar{u}_M = a\tilde{\omega}$$

$$\beta_M = \frac{2\cos^2\phi}{a}(\Omega + \tilde{\omega})$$

$$K_s \doteq (\epsilon a)^{-1}\cos\phi$$

and an analytic solution for x(t), y(t) is possible:

Hoskins and Karoly 1981

graduate level

ENSO teleconnections

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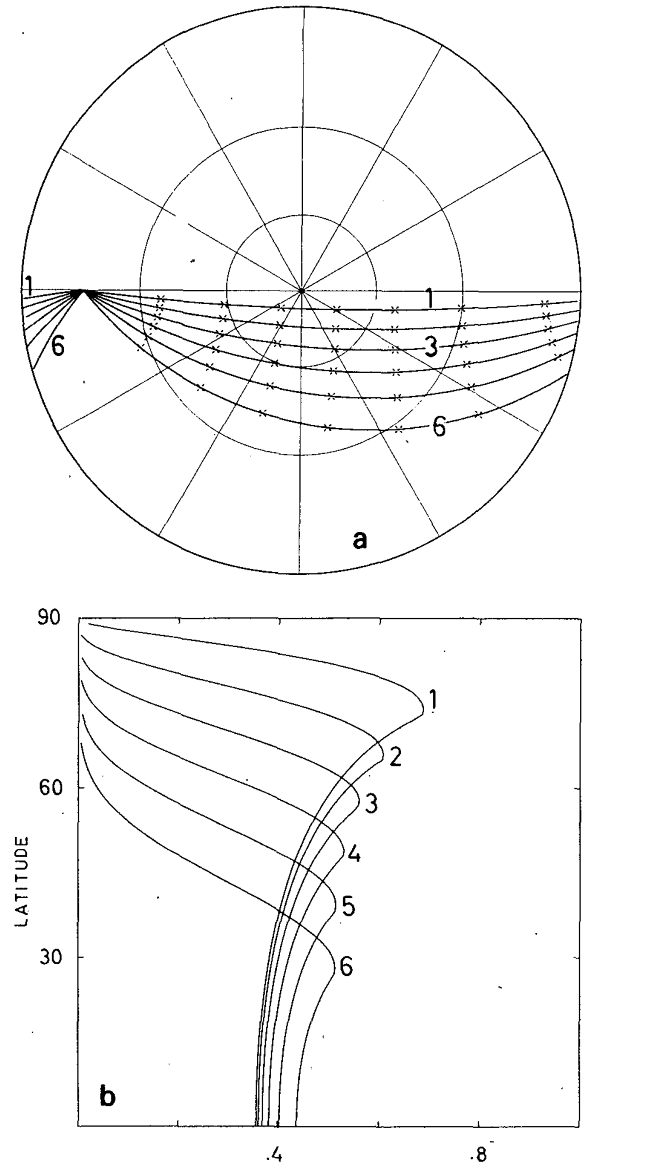

FIG. 12. (a) Rays and phases marked by a cross every 180° for a source at 15° in a super-rotation flow. If all wavelengths give a negative extremum at the source, the crosses mark the positions of successive positive and negative extrema. Lines of latitude and longitude are drawn every 30° and the zonal wavenumbers associated with the rays are indicated. (b) Amplitudes of the extrema on the rays for the different zonal wavenumbers, on the super-rotation flow shown as a function of latitude. The relative amplitudes of the different wavenumbers depend on the position and nature of the source.

Hoskins and Karoly 1981

graduate level

ENSO teleconnections

example teleconnection patterns

$a\,K_s$

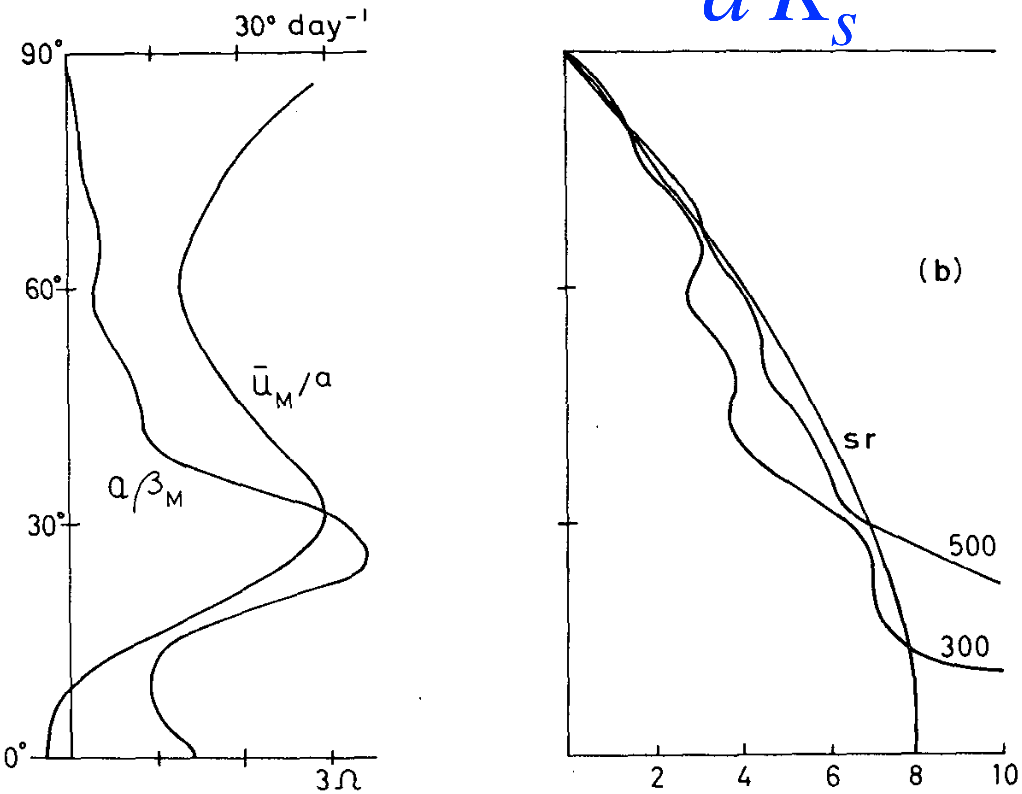

FIG. 13. (a) $\bar{u}_M/a$ (deg day^{-1}) and $a\beta_M$ for the 300 mb NH winter flow used in the model. (b) Stationary wavenumbers aK_s for the super-rotation flow, and the 500 and 300 mb NH winter flow.

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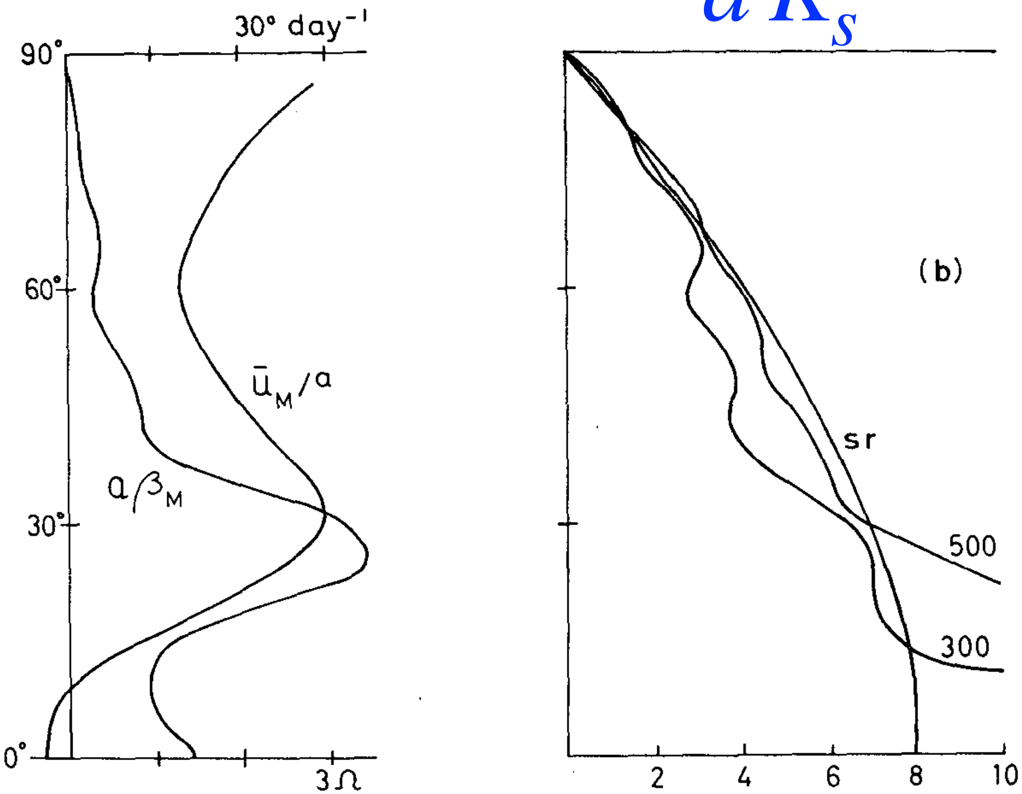

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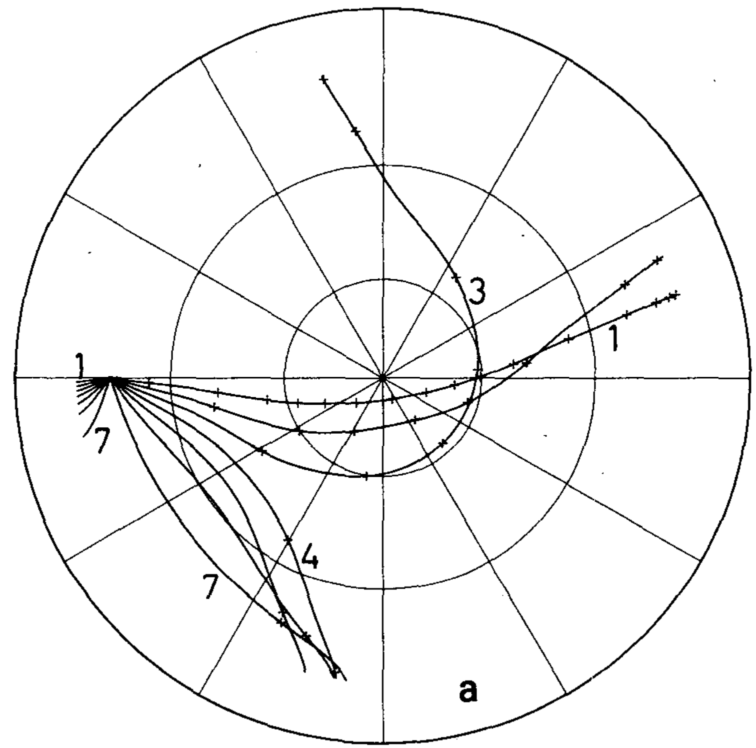


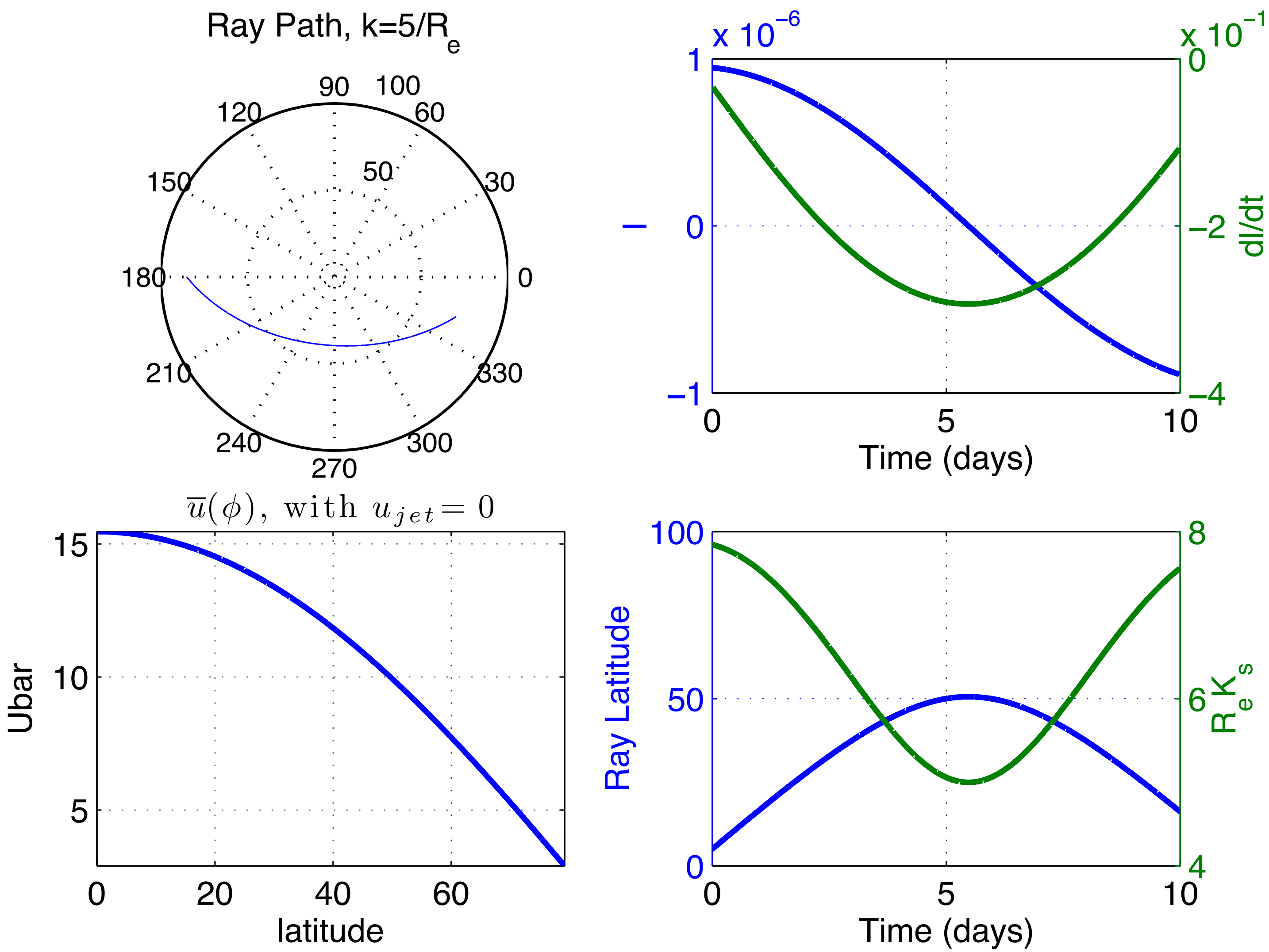
FIG. 15. A 15° source in the NH 300 mb zonal flow: (a) rays and propagation time marked by crosses every 2 days, and

Hoskins and Karoly 1981

graduate level

ENSO teleconnections

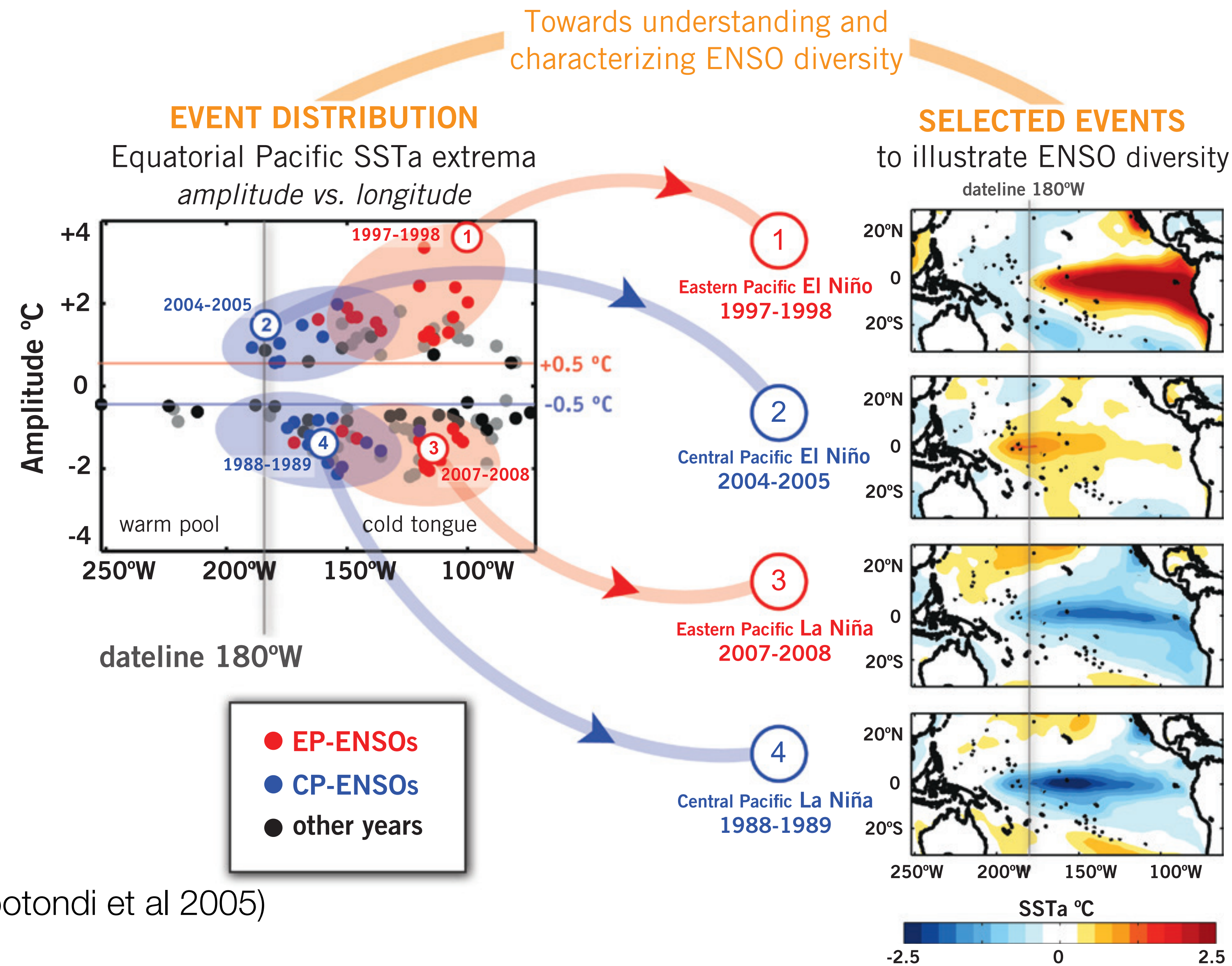
an example using the python code on course web page, should be useful for HW



graduate level

ENSO diversity/ complexity

Examples of different El Nino/ La Nina types



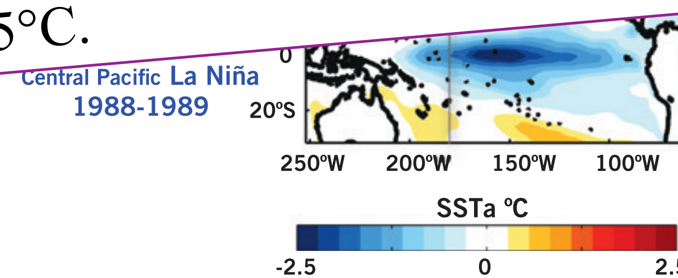
(Capotondi et al 2005)

Large events are EP (East Pacific) El Niños…

graduate level

Examples of different El Nino/ La Nina types

Fig. 1. (left) Distribution of boreal winter [Nov–Jan (NDJ)] SSTA extrema in the longitude–amplitude plane. Anomalies were obtained from the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST dataset (Smith and Reynolds 2004) over the period 1900–2013, as departures from the 1945–2013 climatology. Each dot corresponds to the extreme positive or negative value over the NDJ of each year in the region 2°S–2°N, 110°E–90°W. Events prior to 1945 are colored in gray. Events after 1945 are considered EP (red dots) when the Niño-3 index exceeds one standard deviation. CP events are identified using the leading principal component of the SSTA residual after removing the SSTA regression onto the Niño-3 index. Blue dots in the left panel correspond to events for which the leading principal component (used as CP index) exceeds one standard deviation. (right) The spatial patterns of SSTA for specific warm and cold events of either type are shown, with a contour interval of 0.25°C.



(Capotondi et al 2005)

Large events are EP (East Pacific) El Niños…

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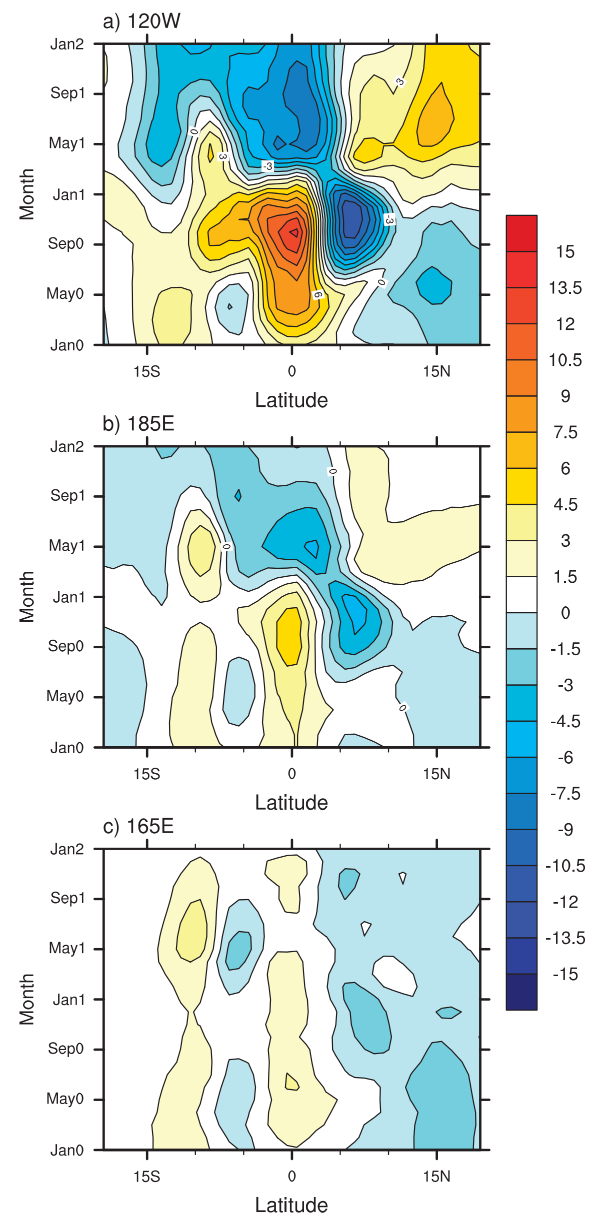
Thermocline feedback is weaker for CP (Central Pacific) events

Composite evolution of zonally averaged thermocline depth, as a func of latitude & time, for El Niño events in a 500-yr preindustrial simulation from CCSM4. The selected events peak in **(a)** Niño-3 region (5°S–5°N, 150°–90°W), **(b)** Niño-4 region (5°S–5°N, 160°E–150°W), & **(c)** 20° to west of the Niño-4 area.

(Capotondi et al 2005)

Thermocline depth evolution



Zonal advective feedback: Positive feedback, particularly effective in the central Pacific, in which a positive (negative) equatorial SSTA weakens (strengthens) equatorial trade winds, reducing (enhancing) the oceanic transport of cold waters from the eastern Pacific. (Timmermann et al 2018)

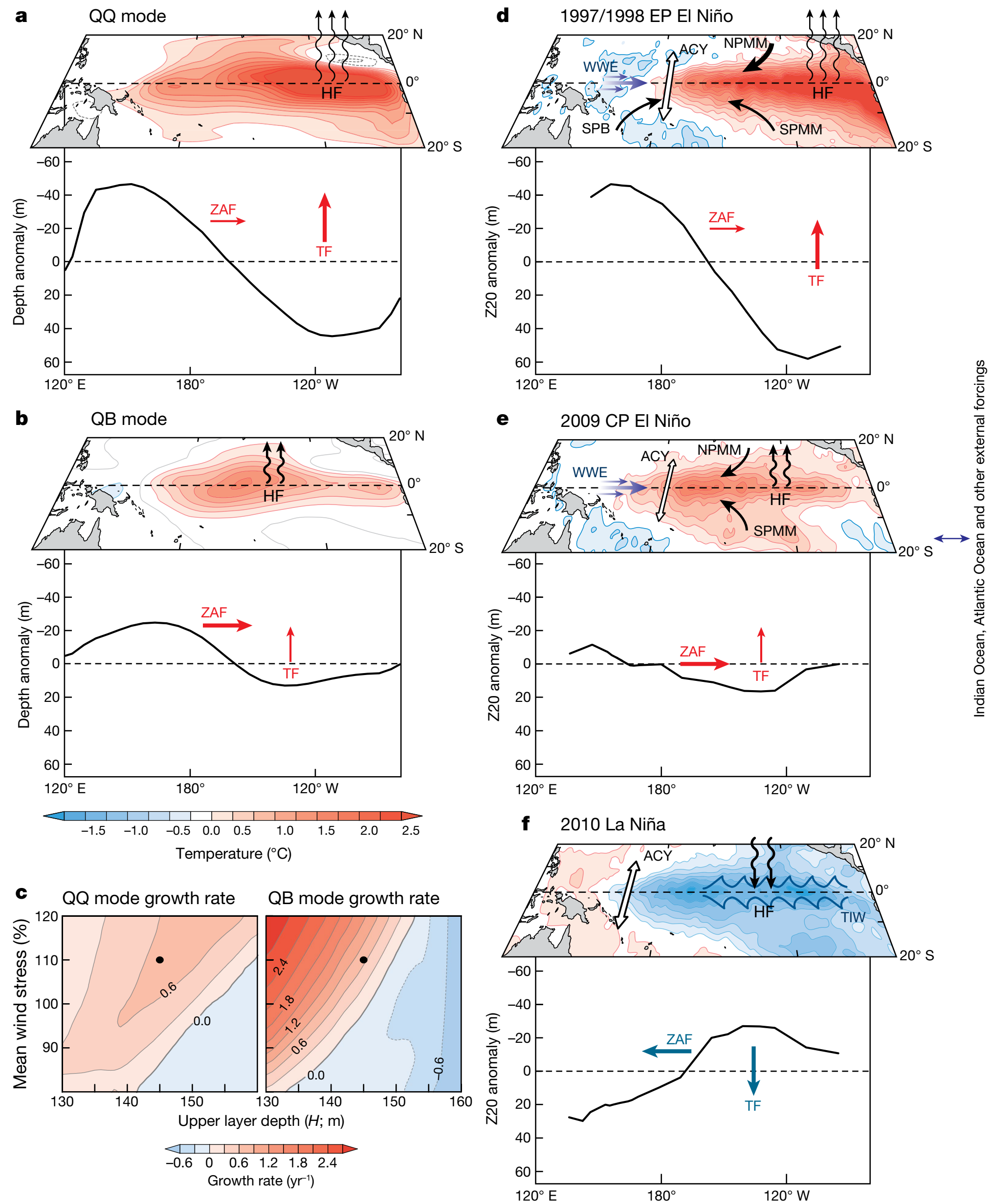
EP & CP ENSO mechanisms: Thermocline vs zonal advection feedbacks

a, b, Leading two eigenmodes of SSTA & thermocline depth anomalies w/periods of 4 yr (QQ) and 2 yr (QB), from CZ model. Different roles of zonal advective feedback (ZAF) and thermocline feedback (TF).

[analysis: d**X**/dt=*A***X**, *A* has 2 main eigenmodes, rest are strongly damped]

c, Growth rates of 2 modes as func of mean thermocline depth H & mean wind strength. 2 dots: mean state for modes.

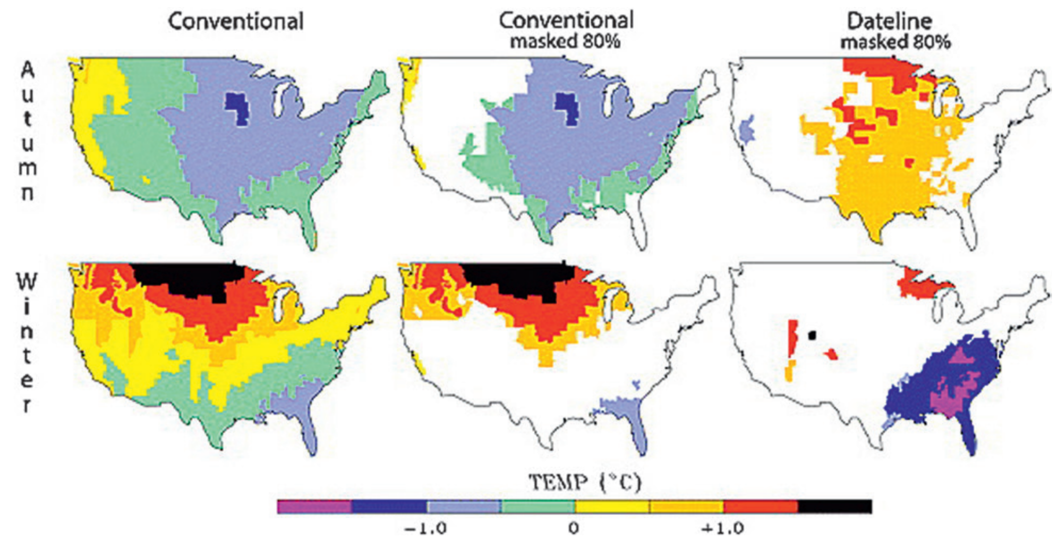
d–f, obs of SSTAs & 20°C depth for EP & CP El Niños & La Niñas, w/ key mechanisms: annual cycle (ACY), WWEs, South Pacific booster (SPB), North/South Pacific meridional modes (NPMM/ SPMM), tropical instabilty waves (TIW). Curly arrows: damping net surface heat flux (HF) feedback.



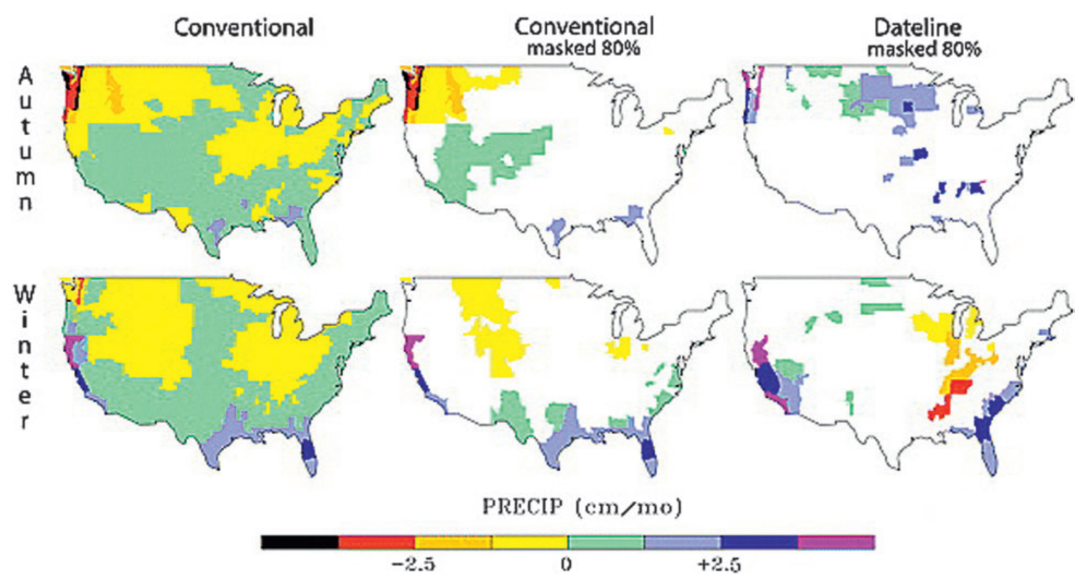
(Timmermann et al 2018; Xie and Jin 2018)

Different teleconnections for EP and CP ENSOs

Composites of U.S. temperature anomalies during autumn [Sep–Nov (SON)] and winter (DJF) for conventional (i.e., EP) and dateline (i.e., CP) El Niños during 1950–2003.



same, for U.S. precipitation anomalies.



(Capotondi et al 2005)

Summary

- Observed features of El Niño:

Eastern tropical Pacific warms & trade winds weaken for nearly a year, every 3-6 years; affects weather worldwide: fires in Australia, floods in South America, droughts in Africa, weather in the US

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- Future projections: unclear how frequency/ amplitude will change

The End