Tropical Pacific climate mechanisms

(a very partial and personal view!!!)

Use ENSO as a "laboratory" to explore mechanisms

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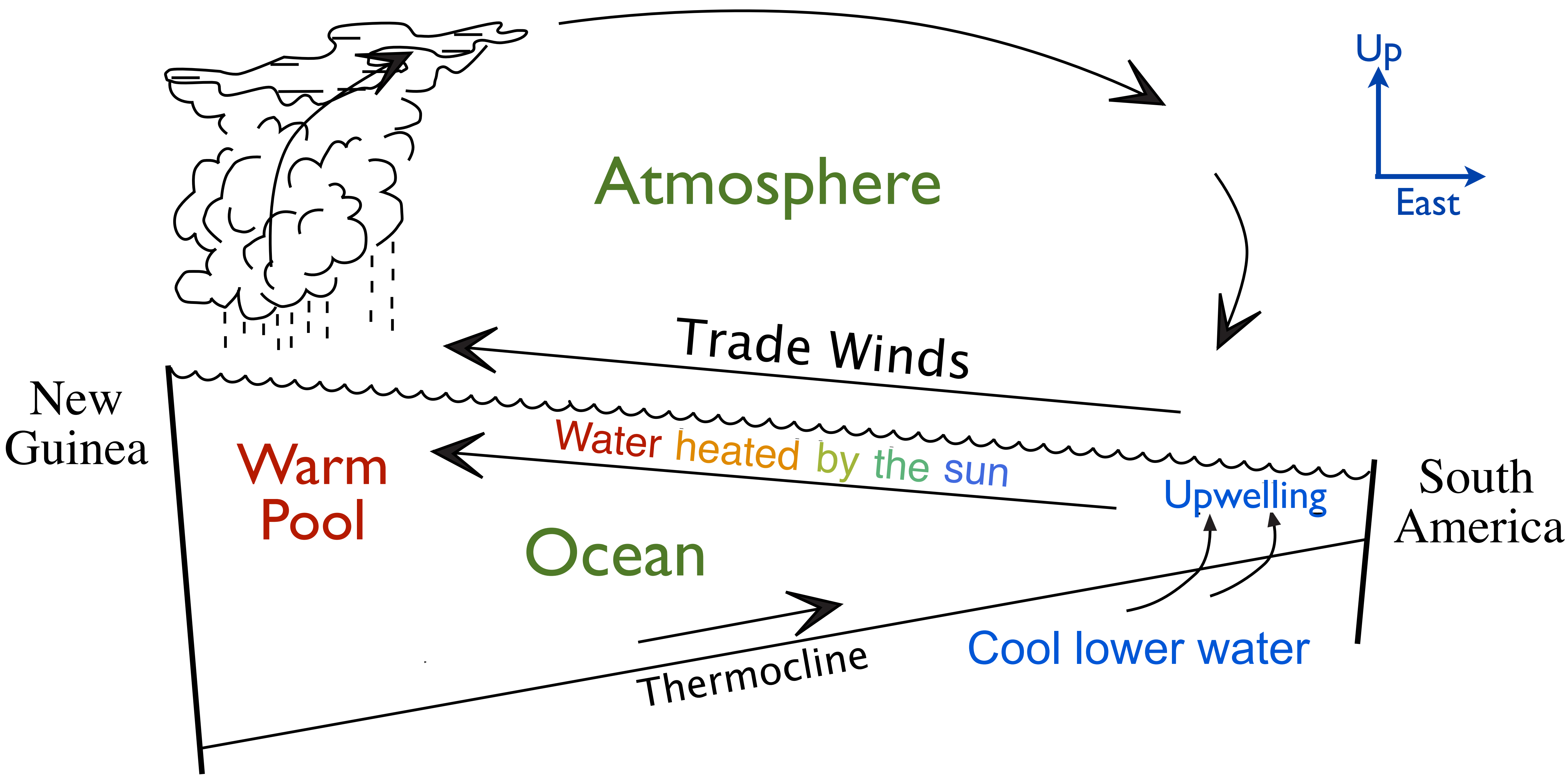
What's special about the tropics?

- Air temperature is near the threshold for convection (~27°C)
  ⇒ The tropical atmosphere responds rapidly to SST
- Tropical ocean currents can spin up rapidly (downwind on Eq!)
  ⇒ Wind changes produce rapid ocean changes
- The high speed and long zonal scale of equatorial waves allows efficient basinwide transmission of thermocline depth anomalies
- The close connection between thermocline depth and the surface means SST can vary rapidly

Thus, small SST changes greatly affect the atmosphere,
and small wind changes greatly affect the SST pattern: Coupling

➢ All this is less true of the extra-tropics:
Other mechanisms by which SST affects the atmosphere - and winds affect the ocean - are slower and less effective.

The tropical climate is coupled



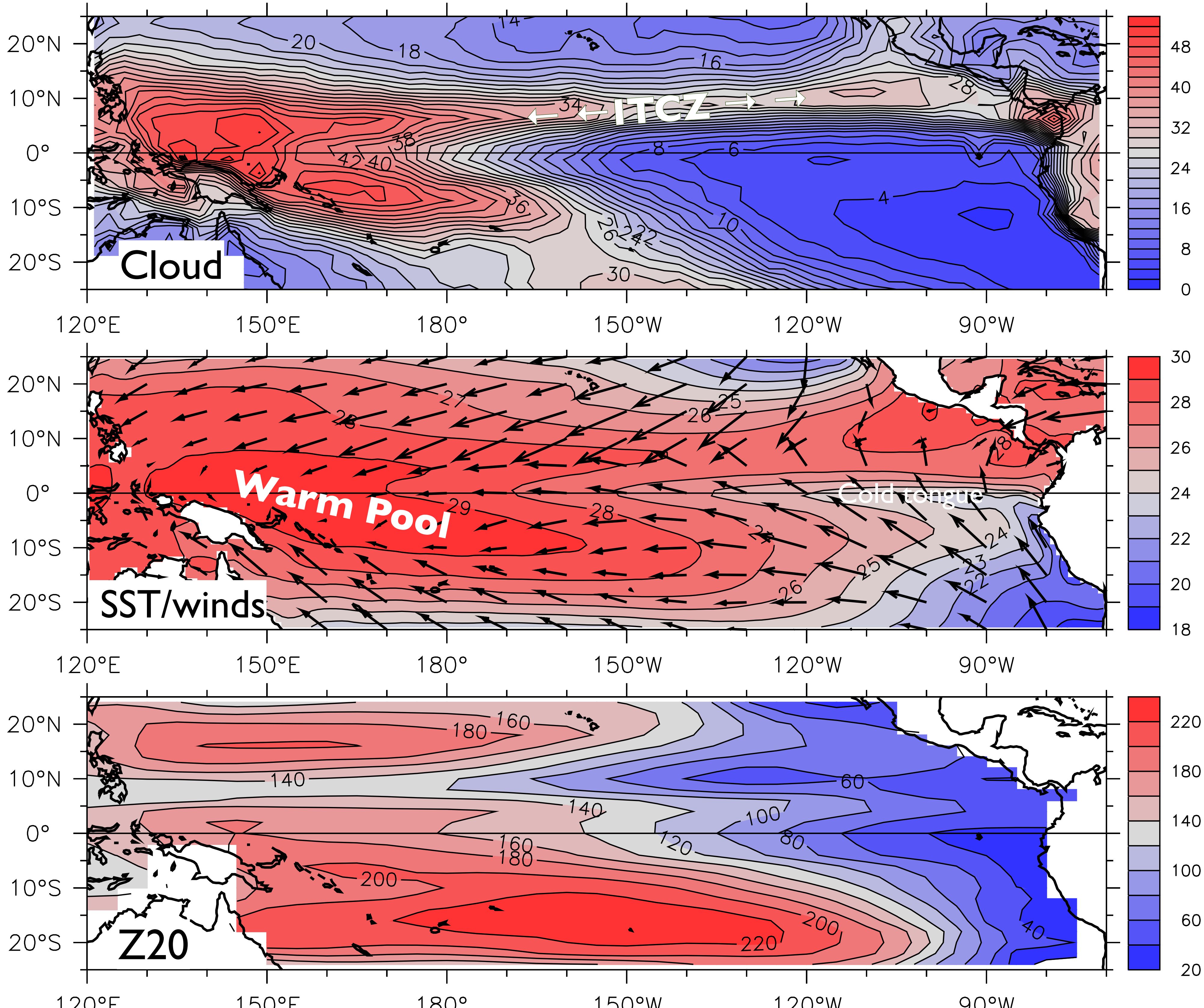
A positive feedback!

Why are there trade winds? Because the warmest water is in the west.

Why is the warmest water in the west? Because there are trade winds.

Close relation among SST, convection, winds, thermocline

High cloud fraction (deep convection) and surface winds



Warm air rises.

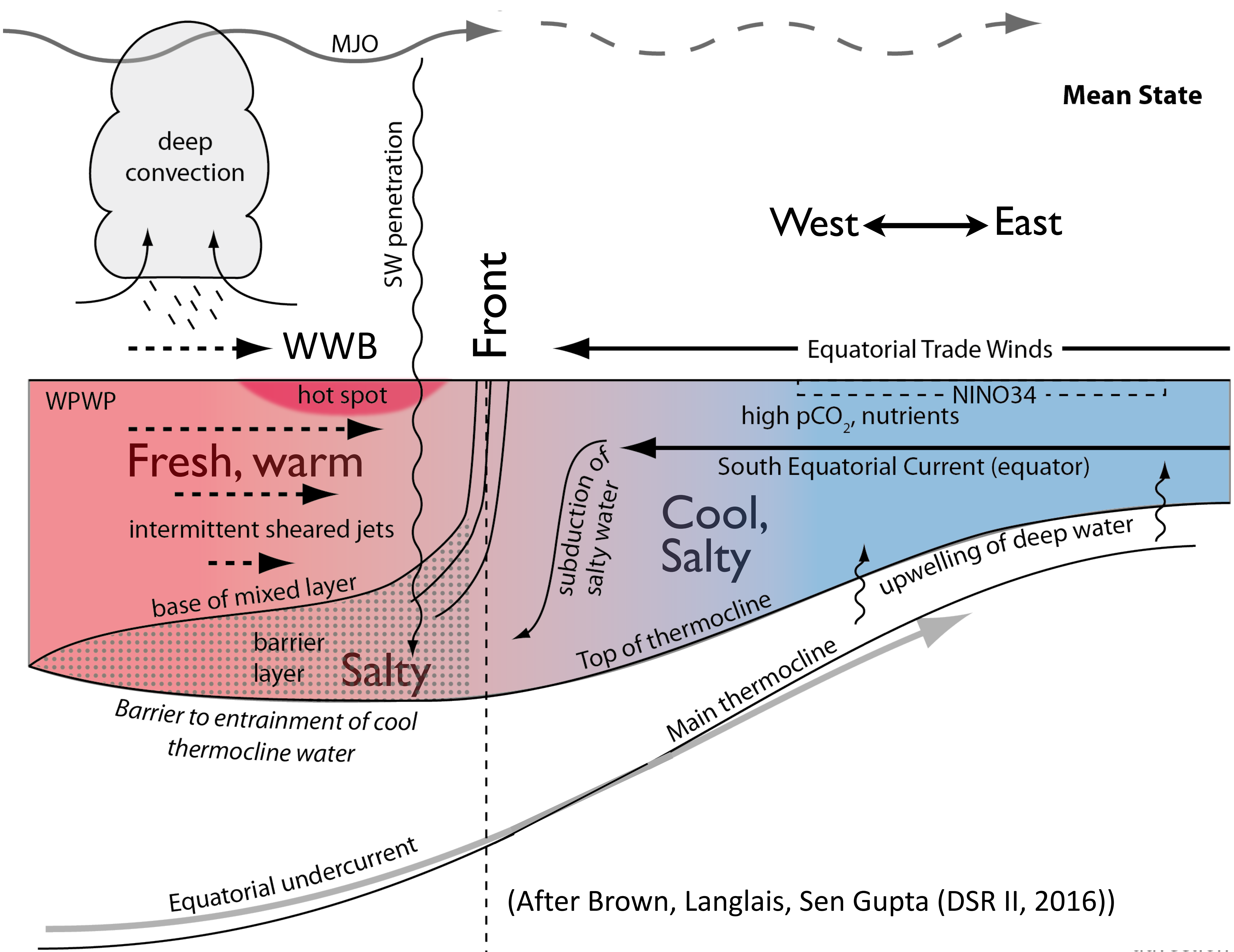
⇒ Surface winds blow into warm SST.

⇒ Rising air produces convection and rainfall.

That happens everywhere, but the SST pattern organizes it over large regions in the tropics.

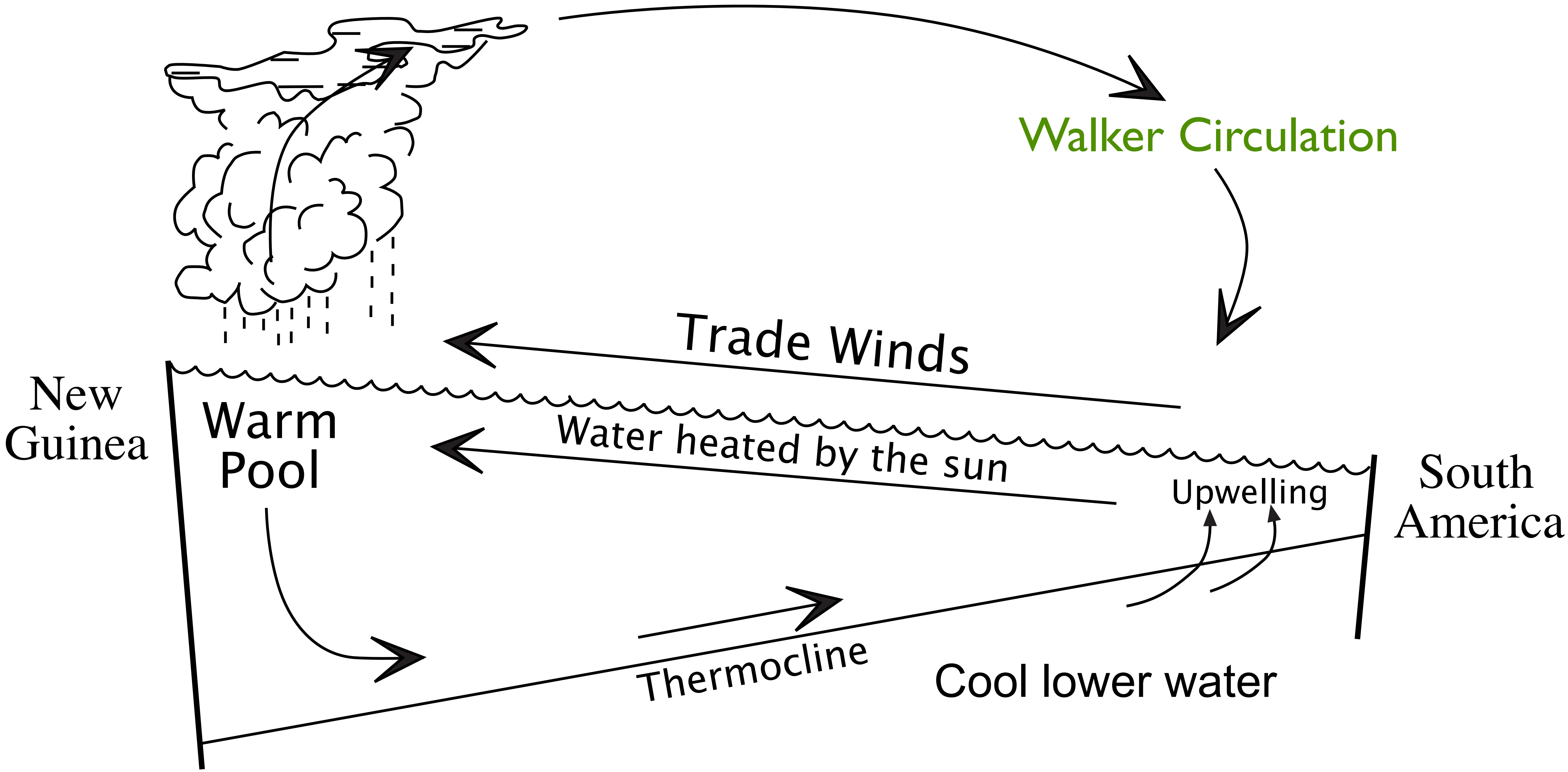
(Reynolds SST, ISCCP high clouds, Quikscat winds, XBT Z20)

Lots of interesting stuff in an equatorial section …



(After Brown, Langlais, Sen Gupta (DSR II, 2016))

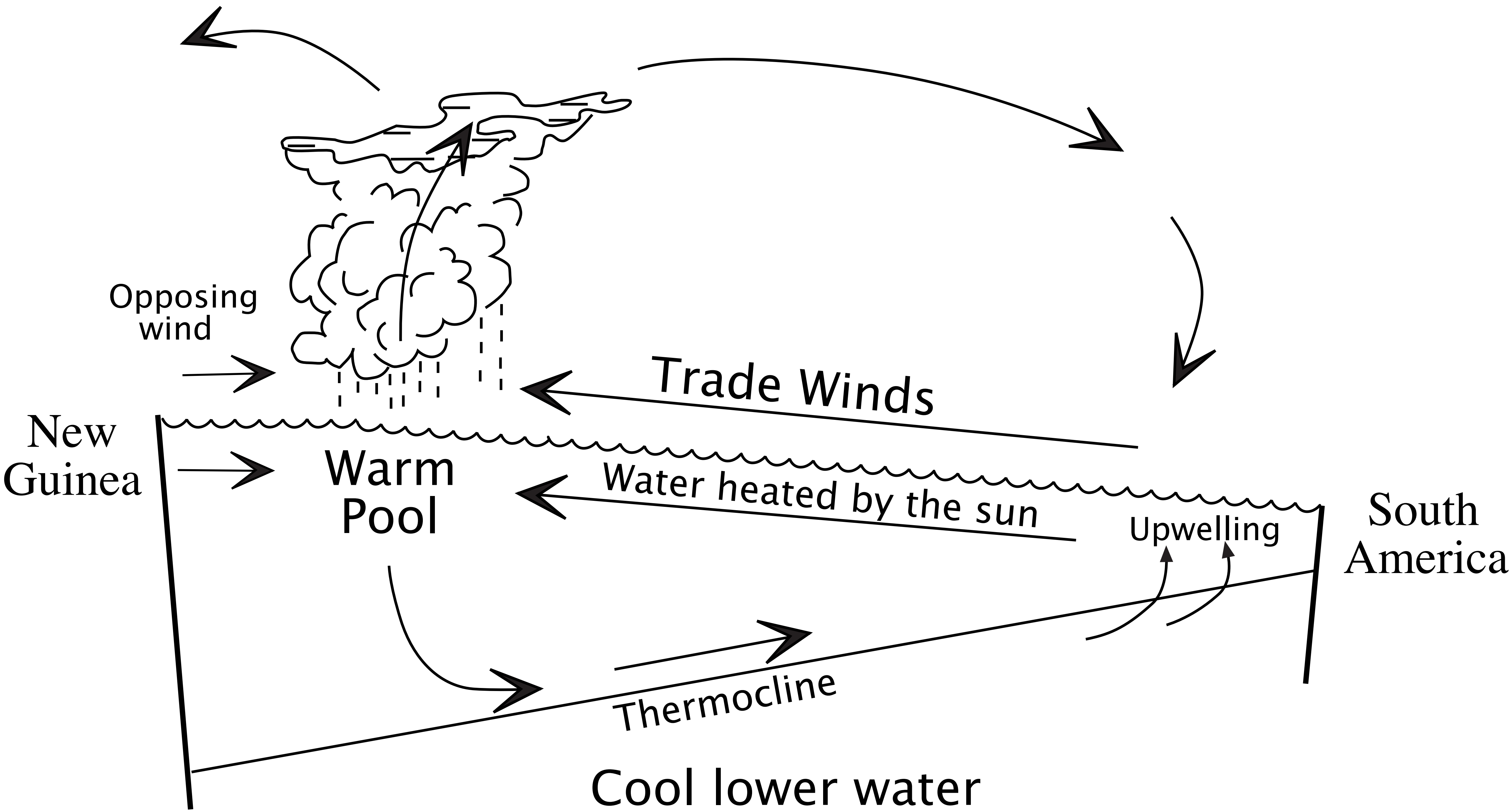
Evolution of El Niño: The "normal" situation



Positive feedback: should be stable, but ....

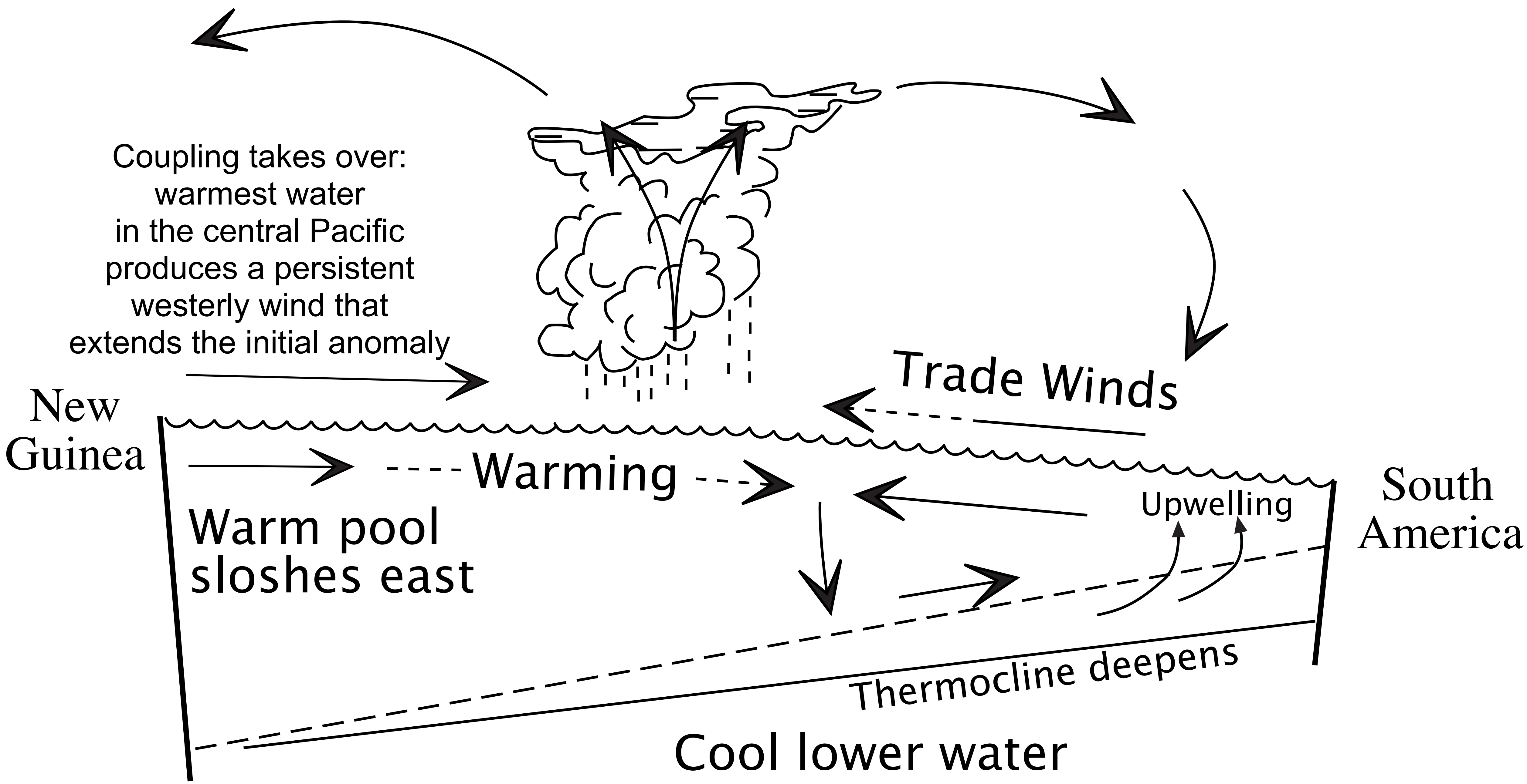
Schematic ocean-atmosphere interaction during El Niño onset:

A "coupled collapse" as the warm pool sloshes east



Several hypotheses for the opposing winds (MJO), but once the warmest water shifts east, coupling takes over

The peak of El Niño



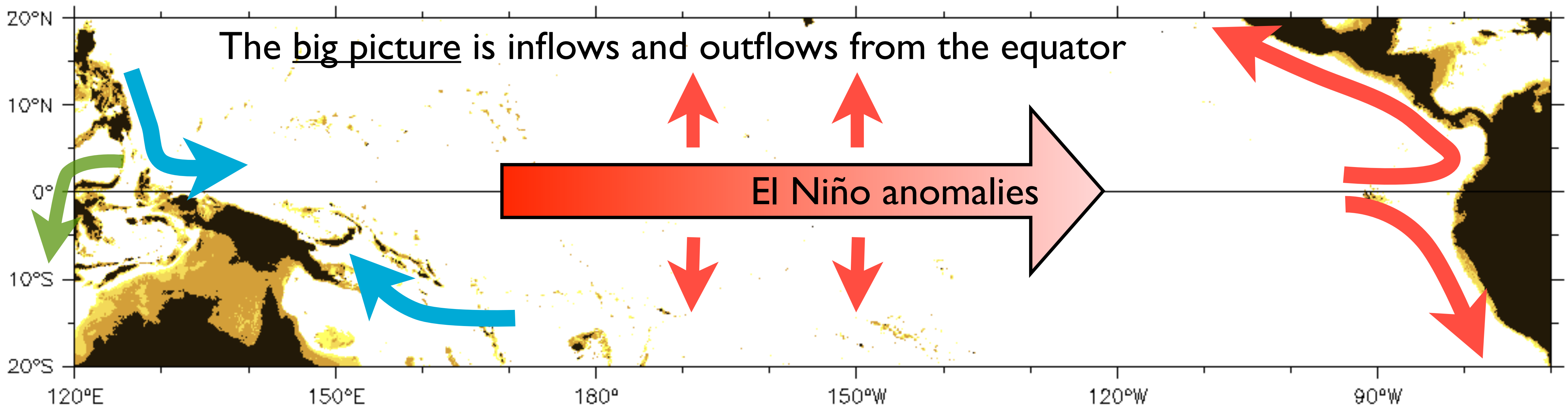
Again a positive feedback. Why does it end?

The big picture of ENSO isn't zonal, it's inflows and outflows from the equator

The big picture is the accumulation (recharge) and discharge of mass and heat in the equatorial strip:

→ Exchanges of heat and mass with the subtropics

Most discharge during El Niño occurs in the east and central Pacific, but most recharge occurs in the LLWBCs.



Two over-arching hypotheses

- Cyclic ENSO (McCreary ➙ Cane/Zebiak ➙ Jin)

⇨ ENSO is a self-sustained oscillation.

The Pacific ocean-atmosphere system has a natural frequency of oscillation (slightly perturbed by "weather")

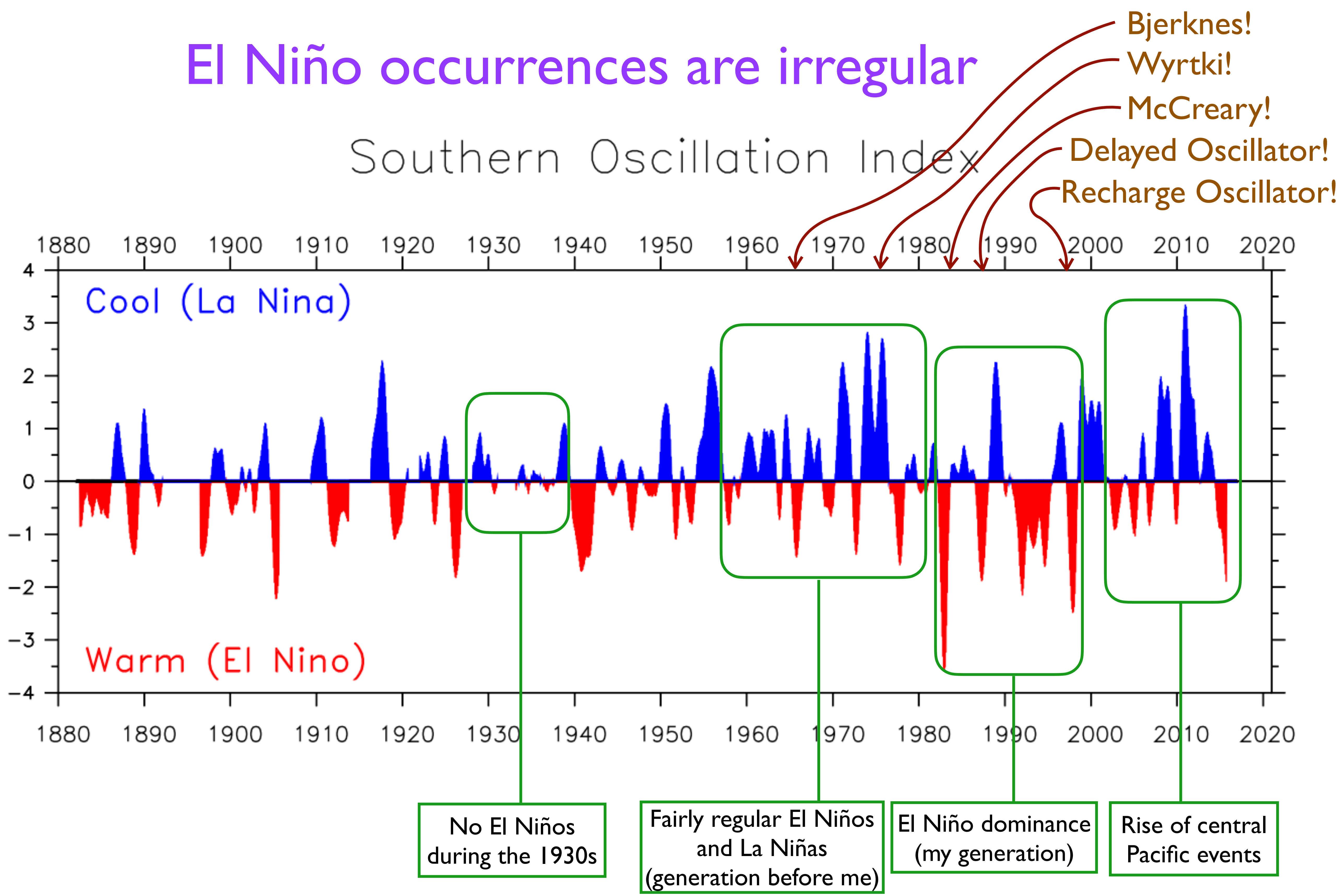
⇨ Predictability!

- Event-like ENSO (Wyrtki ➙ Kessler?)

⇨ The basic state is stable, thus each event requires an external trigger. No persistent memory.

⇨ Implies limited predictability.

El Niño occurrences are irregular



History of ideas about the physics of ENSO

Bjerknes (1969)	Positive feedbacks maintain each state.
Wyrtki (1975, 86)	Buildup in the west Pacific precedes events. Other than that, events are independent.
McCreary (1983)	Oscillation can occur via western boundary reflection delay. Time-lagged negative feedback
Schopf/Suarez (88) Battisti/Hirst (89)	Delayed Oscillator paradigm. More realistic delay via coupled growth on the equator.
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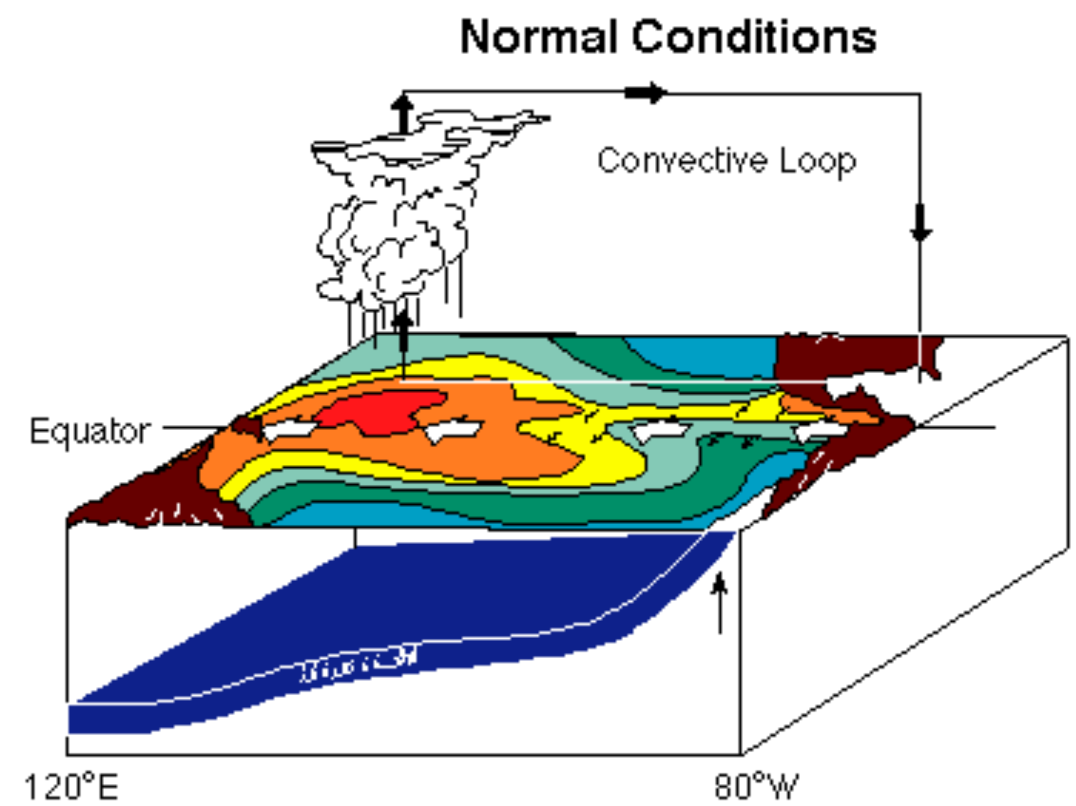
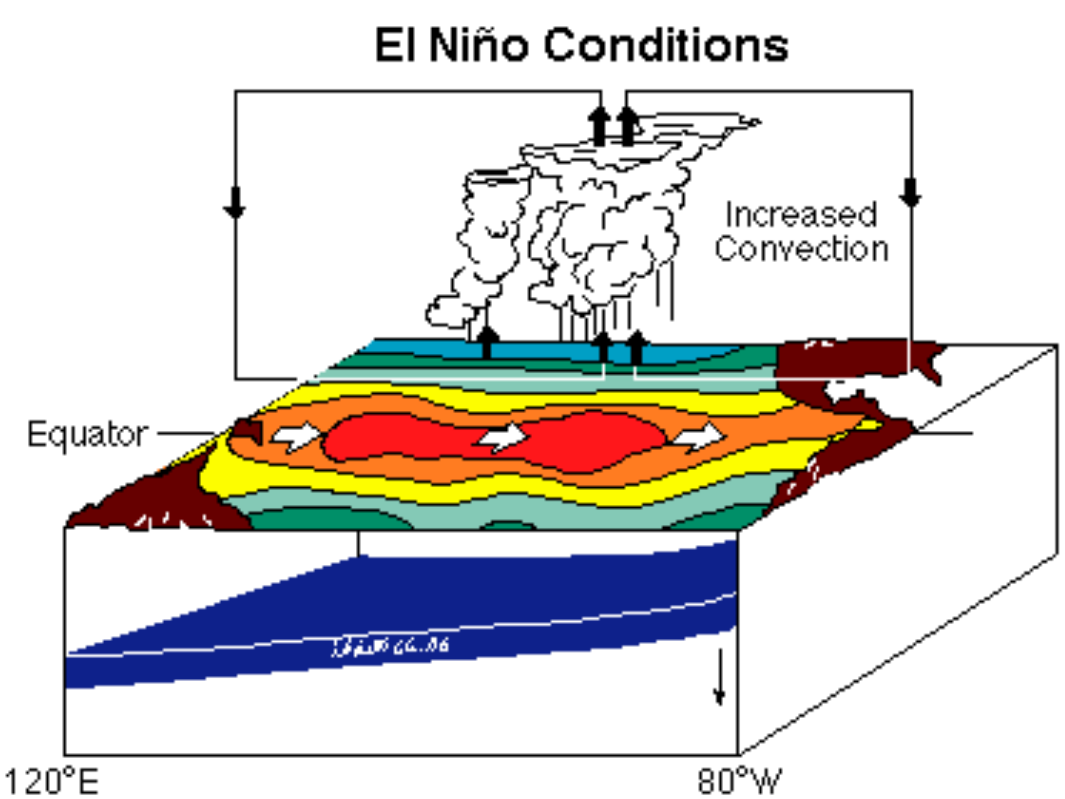
Bjerknes: positive feedbacks

Convection occurs over warm SST
→ Winds blow towards warm SST

During normal conditions,
SST is warm in the west:
→ produces convection there
→ strengthens the trade winds
→ strong upwelling in the east
→ cools the surface: eastern Cold Tongue



During El Niño conditions,
SST is warm across the basin:
→ produces generalized convection
→ weakens the trade winds
→ suppresses upwelling



But, Bjerknes did not know how the phase could reverse.

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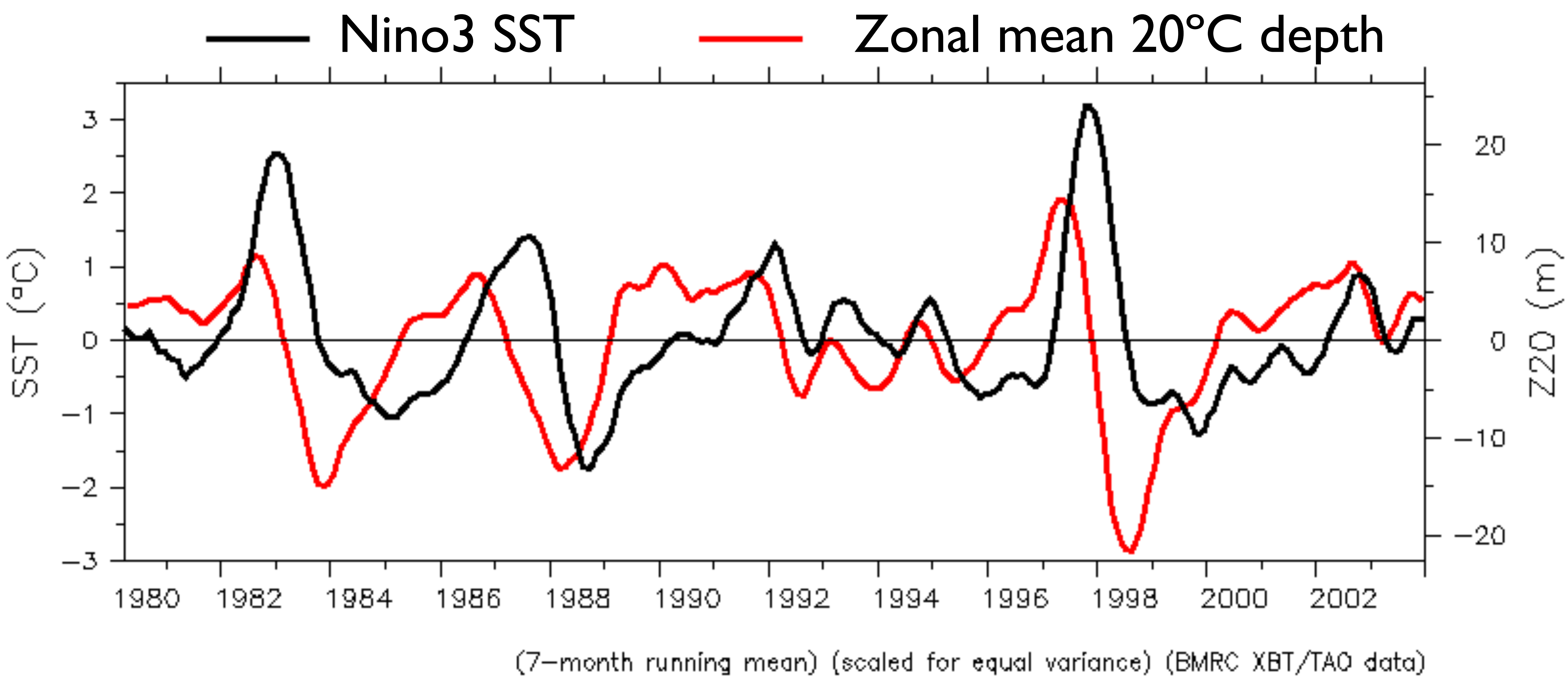
Warm water volume increases before each event



Trade winds pile up warm water in the west Pacific. El Niño serves the climate "purpose" of episodically draining the warm pool.

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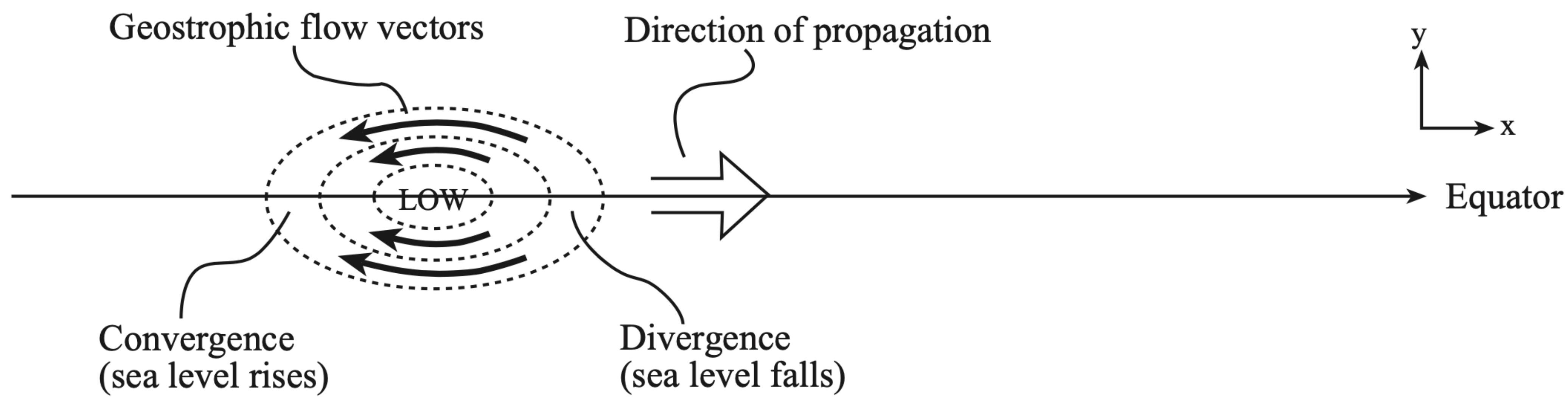
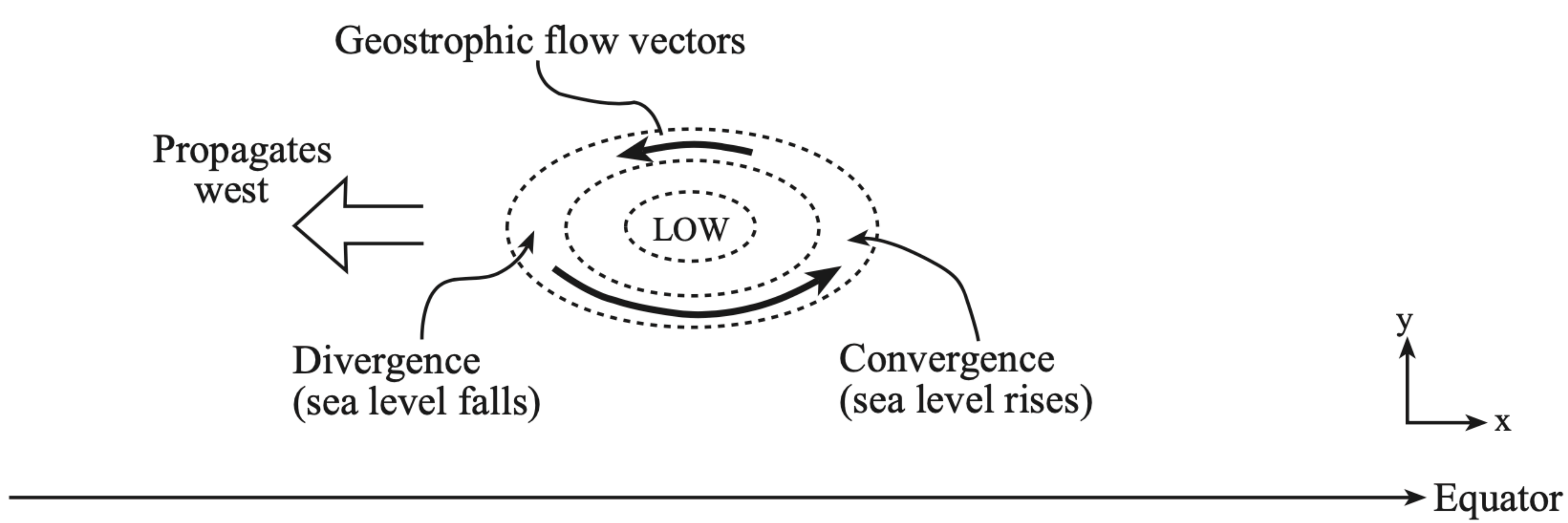
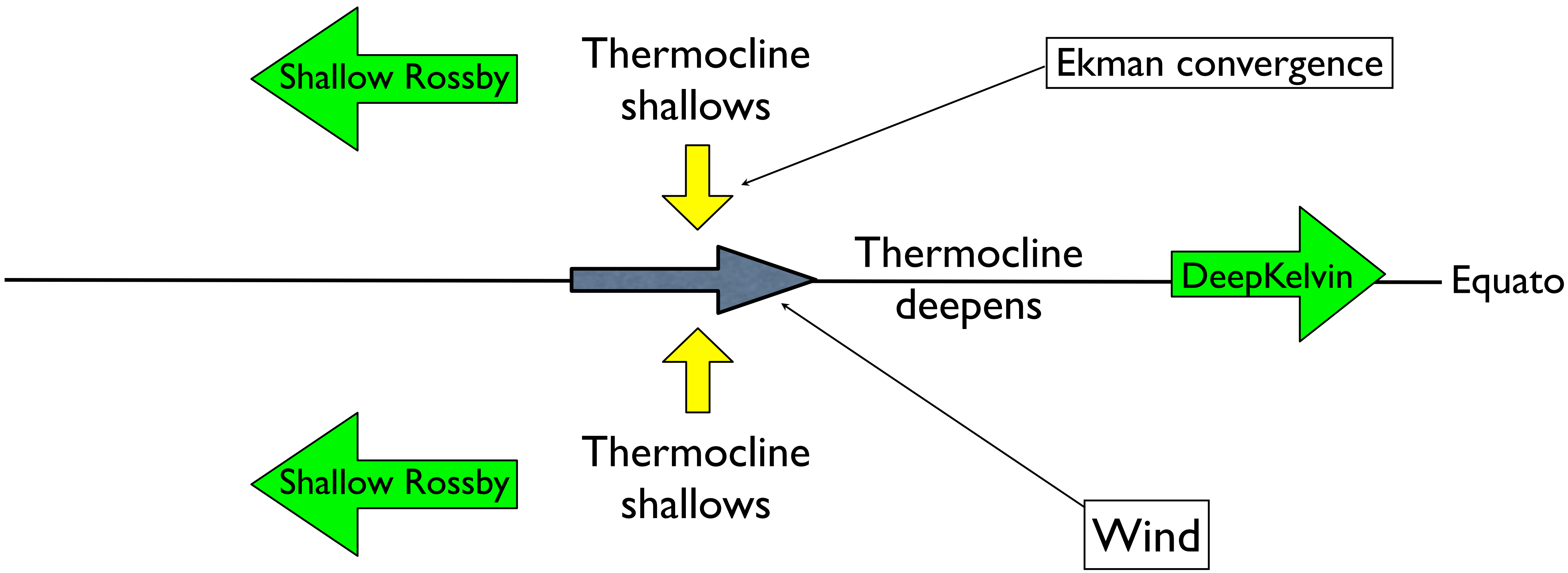
The mechanism of equatorial Kelvin wave propagation



Rossby propagation of a sea level depression (North)



Equatorial winds generate both Kelvin and Rossby waves



Kelvin waves: ~2.5 m/s (6500 km/month)
Rossby waves: ~0.8 m/s (2000 km/month)

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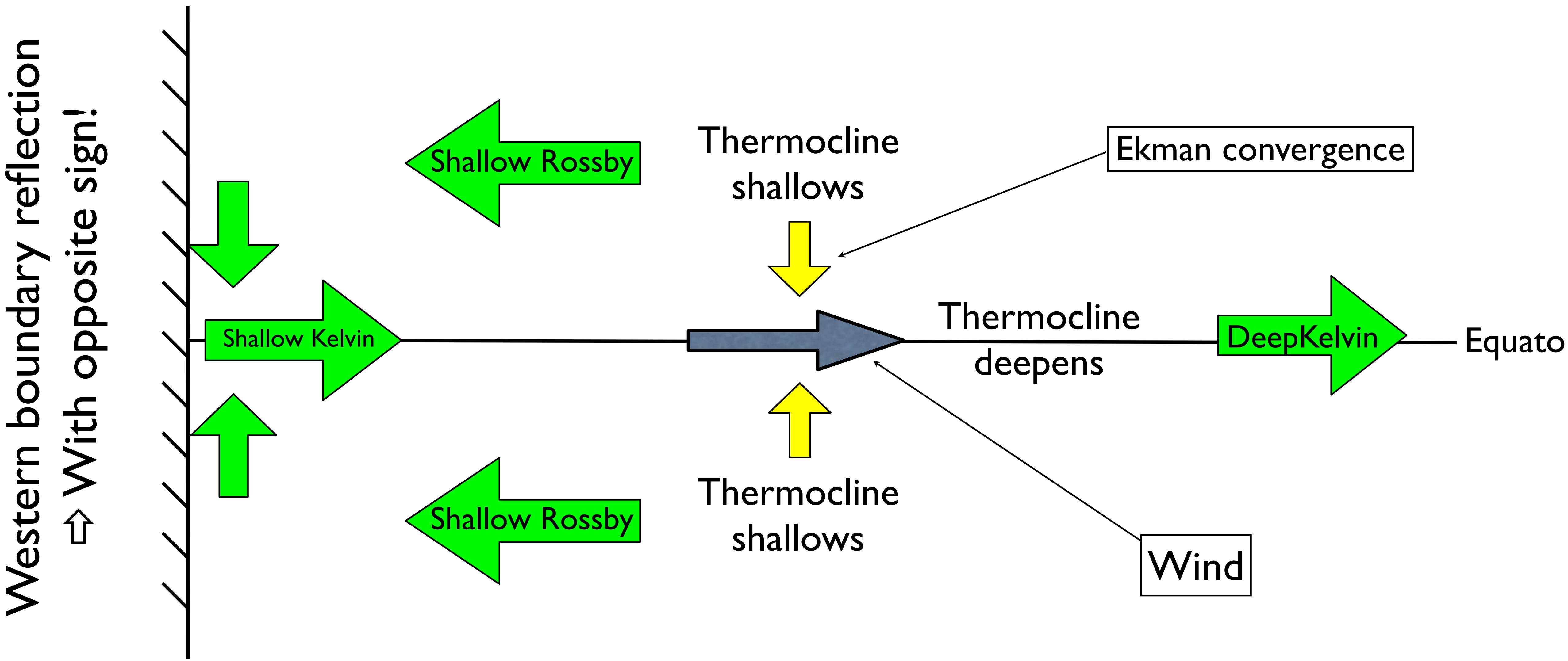

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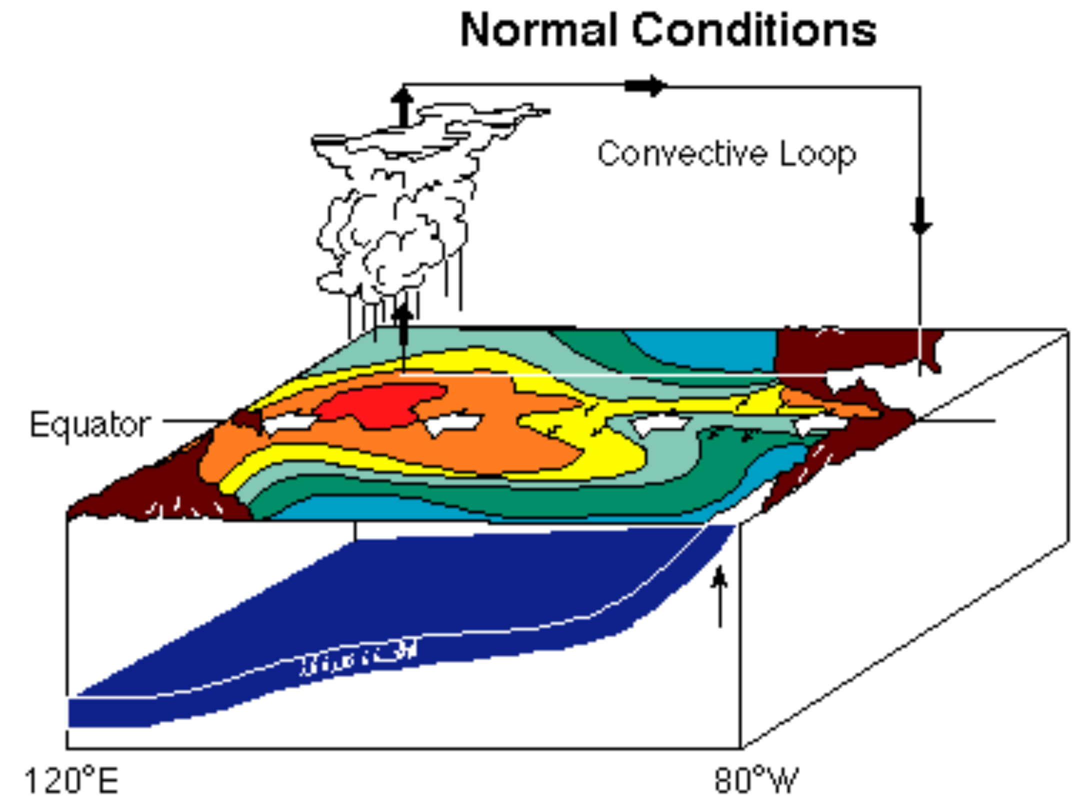
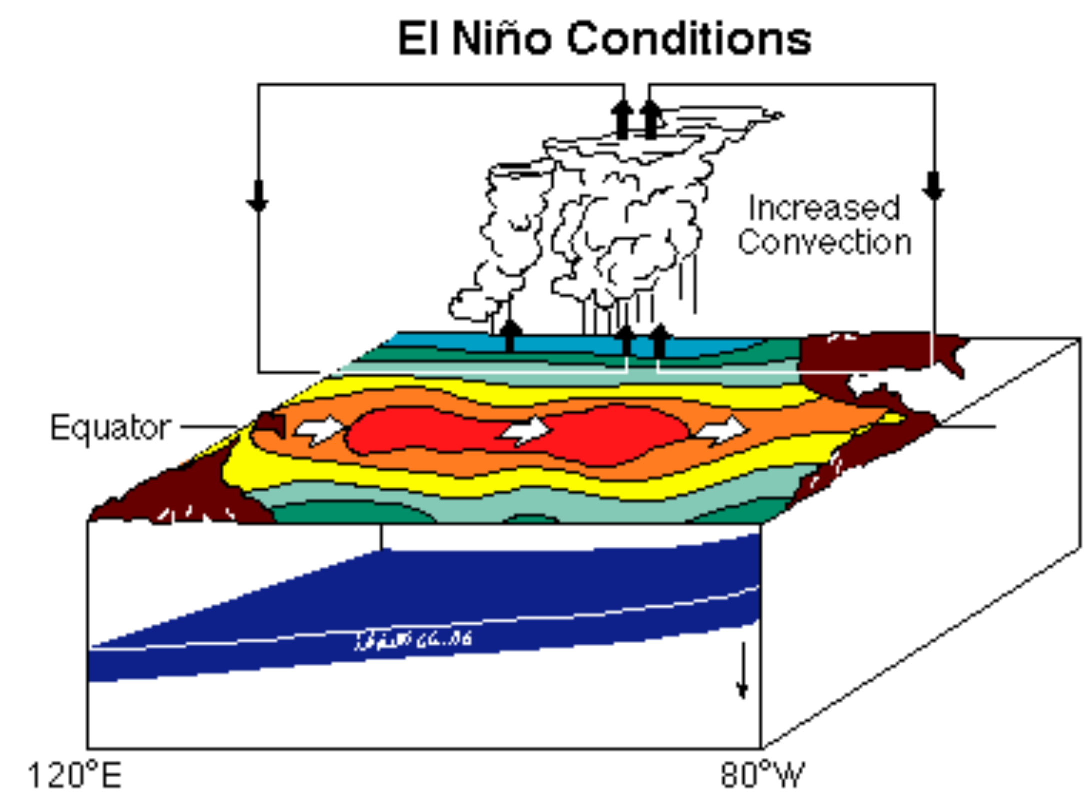
Delayed Oscillator Models incorporate both western boundary reflection and Bjerknes positive feedbacks

During normal conditions, easterly winds give Ekman divergence from the equator

→ shallow the equatorial thermocline
→ deepen the off-equatorial thermocline
→ produce downwelling Rossby waves that propagate west
→ reflect to deepen the equatorial thermocline
→ begin to warm equatorial SST
→ Bjerknes positive feedbacks increase the warming (slowly)
→ system moves *gradually* towards El Niño: 3-4 year timescale





Delayed Oscillator models

- Fundamental mechanism is the reflection of Rossby waves at the western boundary, returning to initiate the reversal of phase on the equator.
- Have forecast skill comparable to advanced GCMs. (Which is to say, not so much).
- Allow exploration of the parameter space of tropical climate: a useful paradigm for thinking about ENSO.
- Produce nearly symmetric and regular El Niños and La Niñas (unrealistic). Observational studies have shown that the D.O. mechanism works for the termination of an El Niño but not for its initiation.

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The Recharge-Discharge Oscillator

- More general than the delayed oscillator since it does not depend on wave reflection times.
- Similar to Wyrtki's "buildup", but each event leads explicitly to the opposite phase.
- Memory of the system contained in the zonal mean thermocline depth.
- Points to a convenient set of variables that can be evaluated from observations.

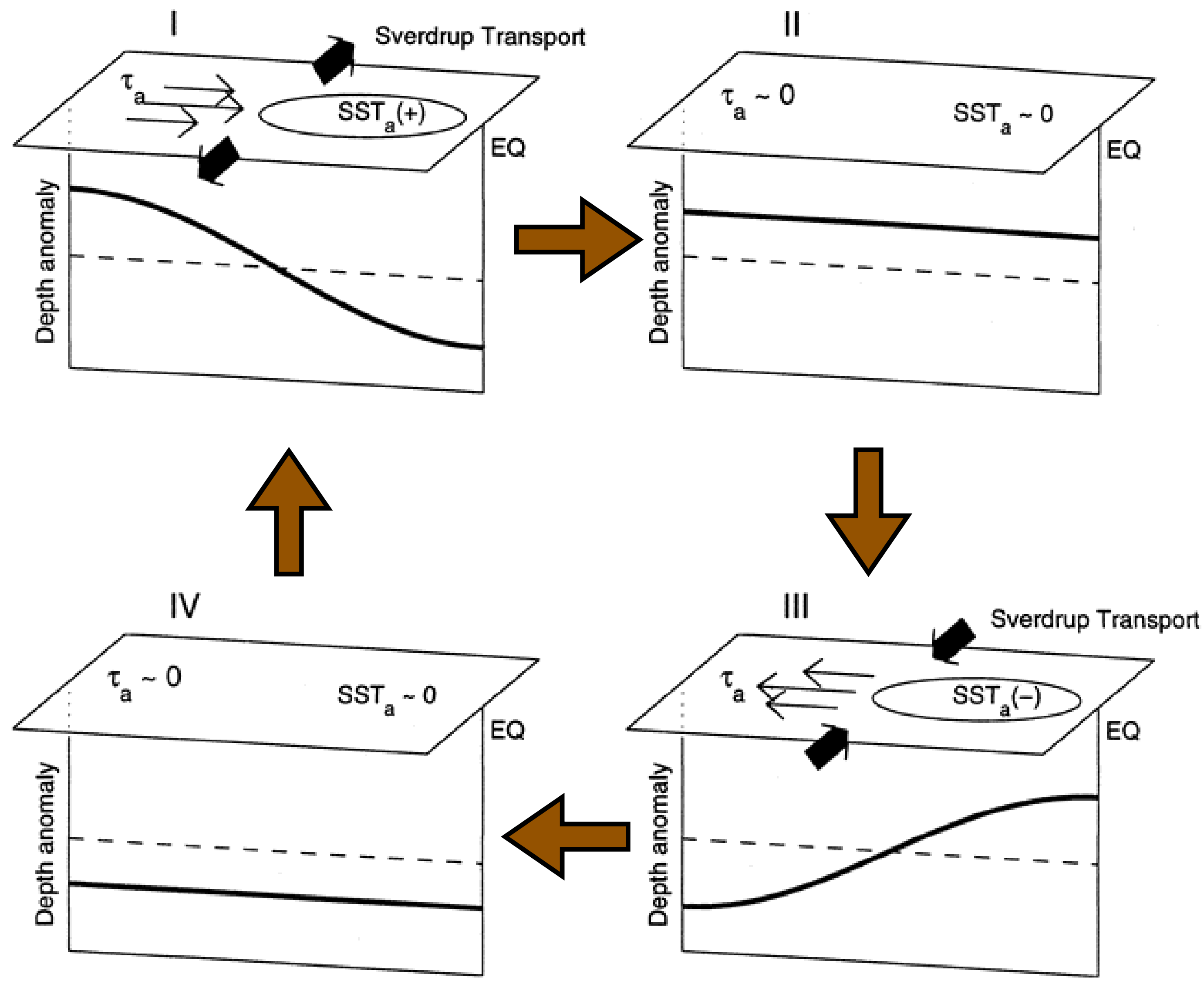
The Jin (1997) recharge-discharge mode

El Niño

1. Warm SST in east
→ westerly winds
→ thermocline slope
→ poleward transport

Discharged

2. Poleward transport
→ shoals thermocline
→ weakens SST anomalies
→ westerlies cease
→ eastern SST begins to cool



La Niña

3. Cool SST in east
→ easterly winds
→ thermocline slopes down to west
→ equatorward transport

Recharged

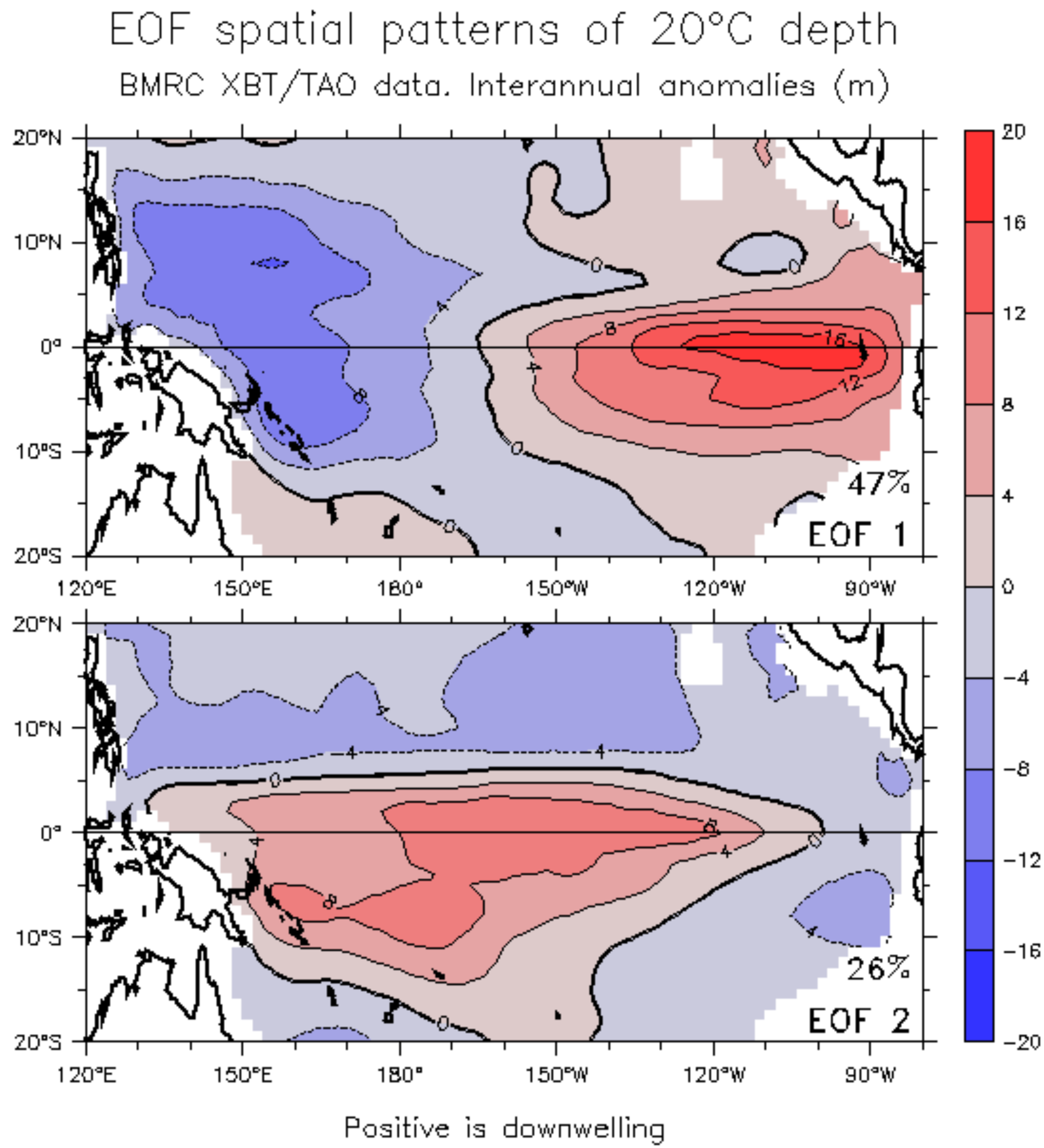
4. Equatorward transport
→ deepens thermocline
→ weakens SST anomalies
→ easterlies cease
→ eastern SST begins to warm

(After Meinen and McPhaden (2000))

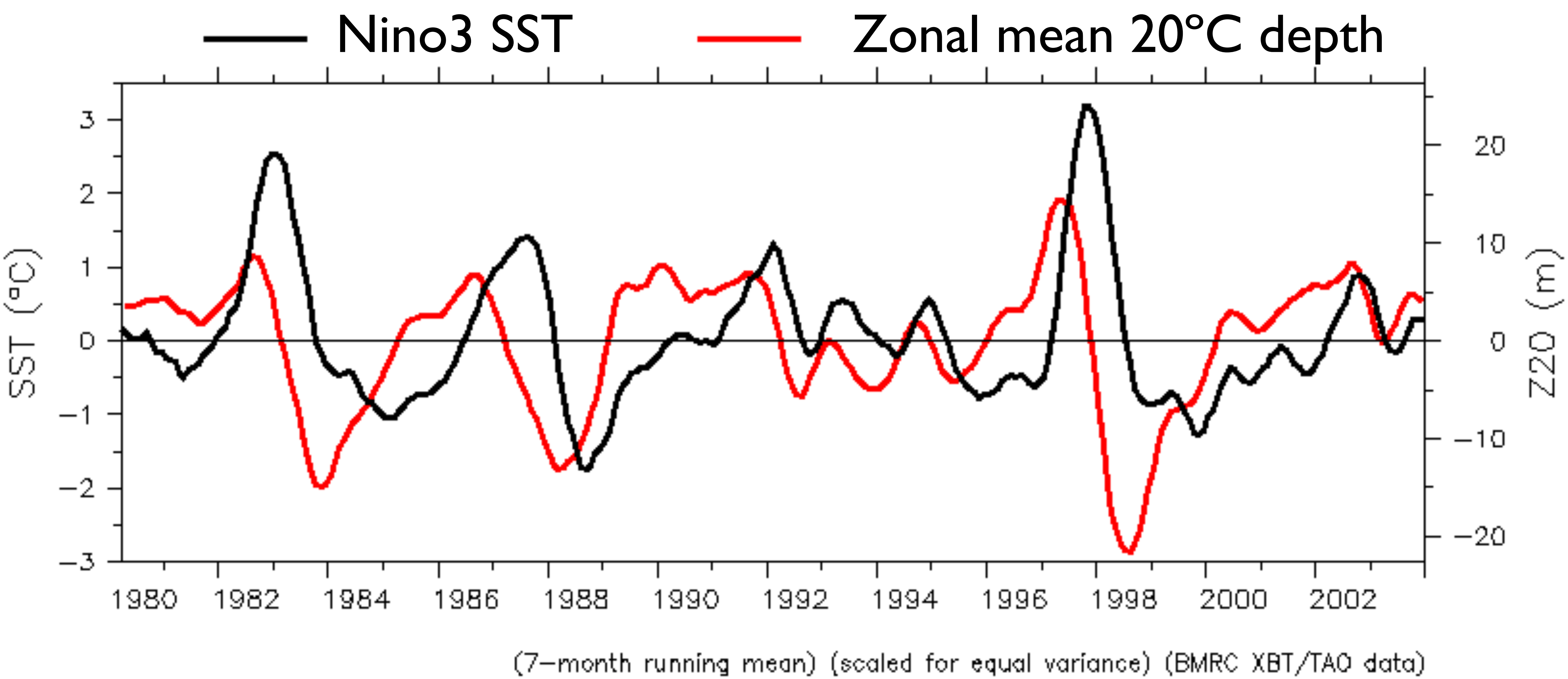
Another symmetric oscillator

Like the D.O. but considers steady balances, ignores wave transients.
Delay comes from adjustment and advective timescales, not waves.

Spatial pattern of thermocline variability is called the "tilting mode" (EOF 1) and "zonal mean mode" (EOF 2).



Warm water volume increases before each event



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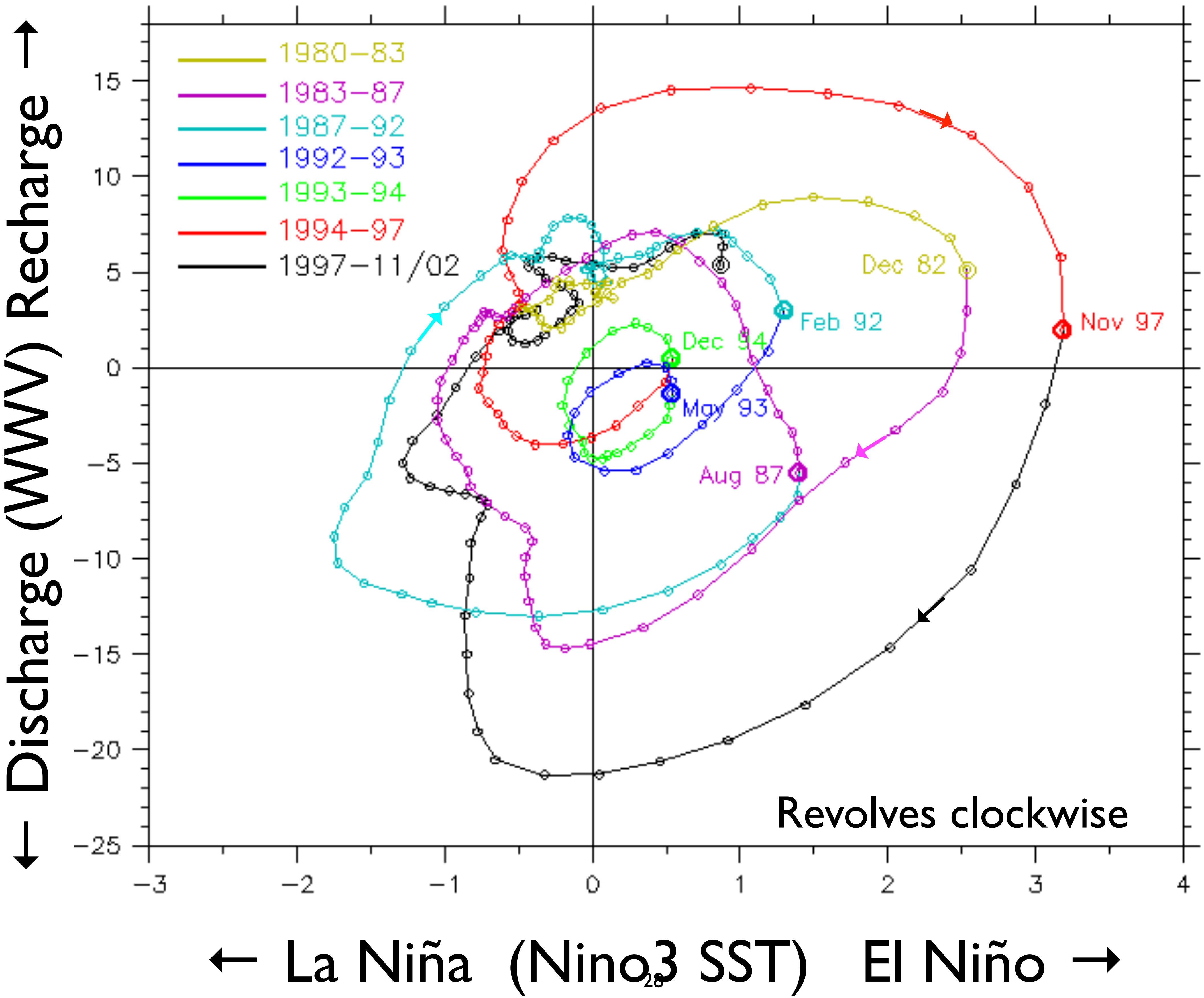
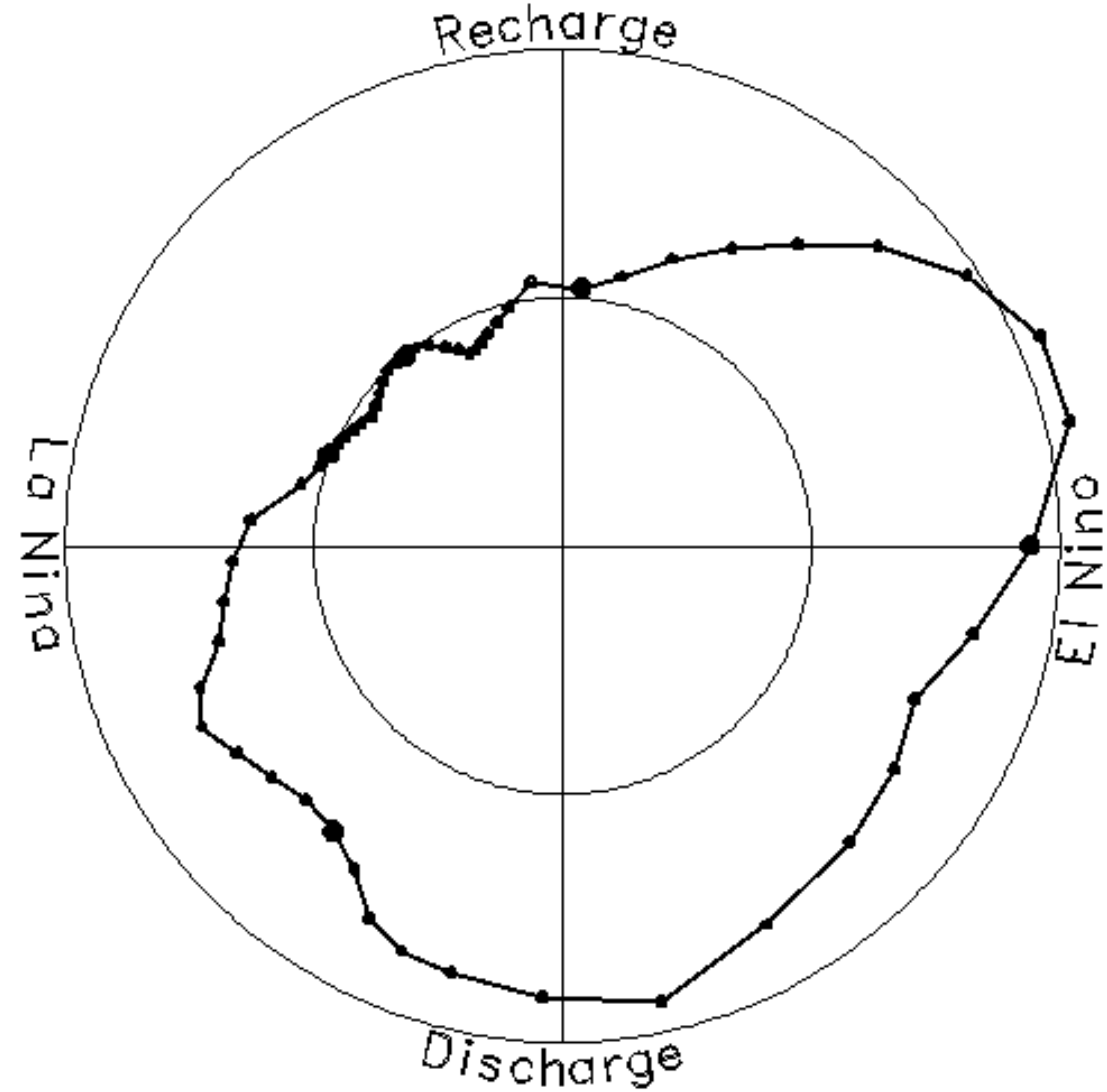
Wyrtki (1975)

Nino3 SST and Warm Water Volume Phase Ellipses



A mean ENSO cycle. Nino3 SST vs Upper Layer Volume



Observed mean amplitude and angular speed. Monthly and yearly tics
Mean cycle length is 4.75 years. Circles are 1 and 2 Std Dev

Conclude:

Observations suggest that an El Niño event leaves the system in a cool state with slightly increased warm water volume, and this state can persist for years, losing memory of previous conditions.

⇨ ENSO is not a self-sustained oscillation.

The evolution of ENSO since 1980 appears consistent with the idea that the basic state is stable or nearly so, thus warm events must be produced by forcing external to the cycle itself.

Possibilities include:

- MJO (generated over the Indian Ocean, propagates east to Pacific)
- Events triggered in the trade-wind system of the central N. Pacific
- Stochastic events within the equatorial Pacific

Overall conclusion

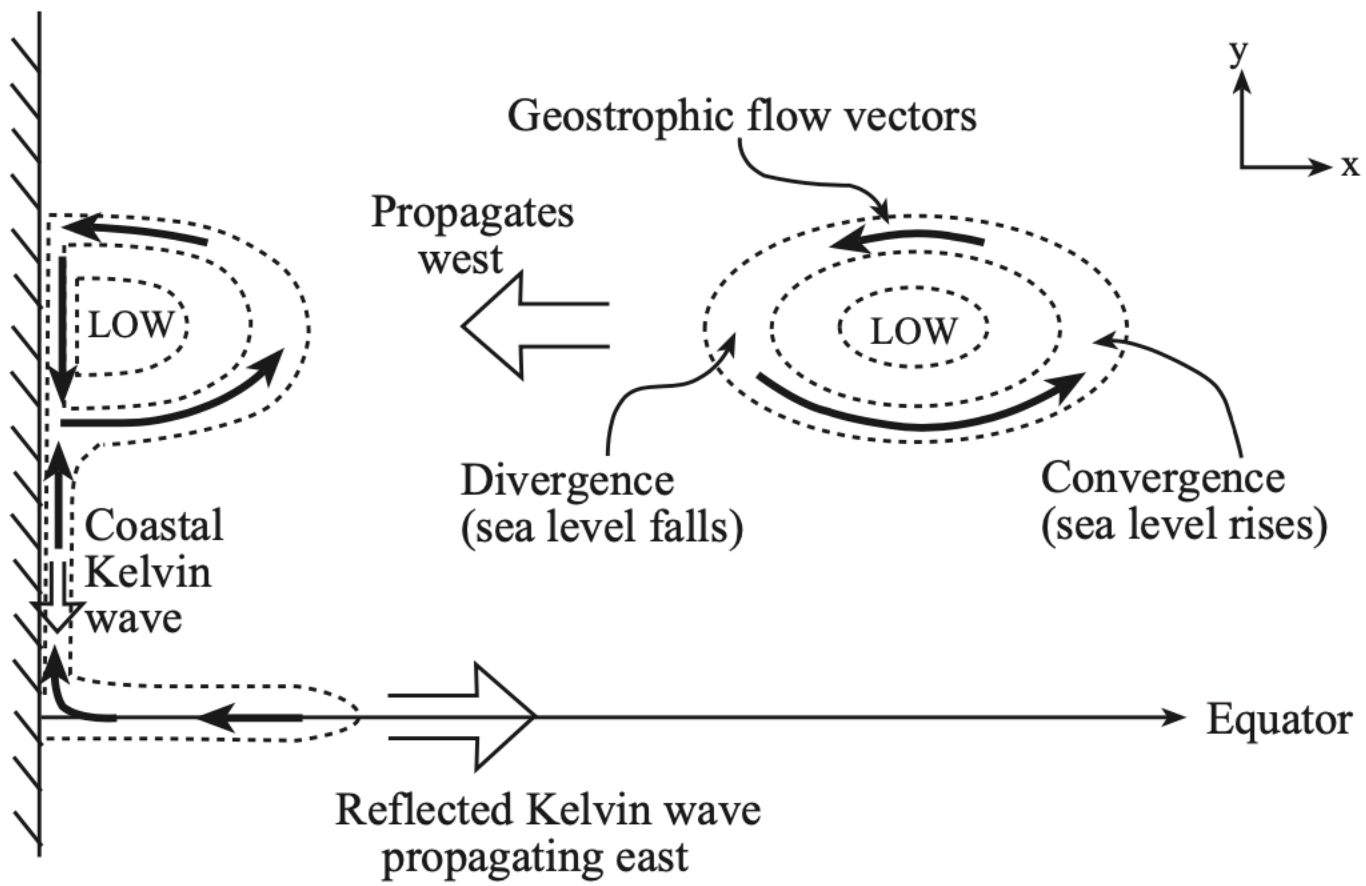
- The tropical climate system is coupled (much less true of extra-tropics)

  Small SST changes can greatly affect the atmosphere in the tropics; conversely, small changes in the wind can greatly affect the SST pattern.

- The tropical climate system is coupled
- El Niño events are self-limited, but the connection, if any, between events remains unclear
- Many important processes omitted here! MJO, extra-tropical forcing mechanisms, other kinds of feedbacks, processes of thermocline-surface communication, role of the diurnal cycle, …

Extra slides below

Rossby reflection to equatorial Kelvin waves at a western boundary



An example of a Rossby wave (sea level depression) arriving at a western boundary.
The Rossby wave is transporting mass eastward.

To satisfy the mass constraint, the needed inflow comes via northward coastal transport as a coastal Kelvin wave, which carries the signal equatorward.

Arriving at the equator, this forms the western boundary condition for an equatorial Kelvin wave that propagates east along the equator. (With no damping, this would then reflect again at the eastern boundary as above).

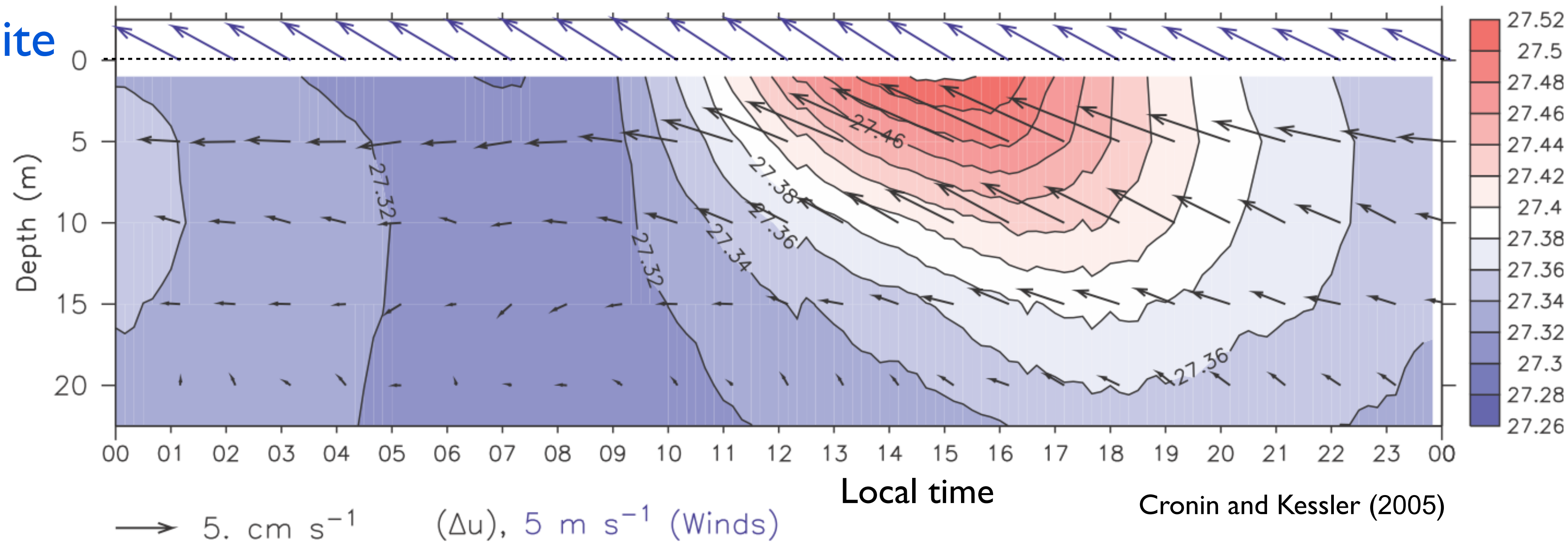
How does the thermocline communicate with the atmosphere? (b)

The diurnal cycle is surprisingly important

Diurnal cycle composite at 2°N,140°W.

Wind and current vectors, temperature shading.

Afternoon trapping, then downward propagation of T and u (and implied mixing) into the evening.

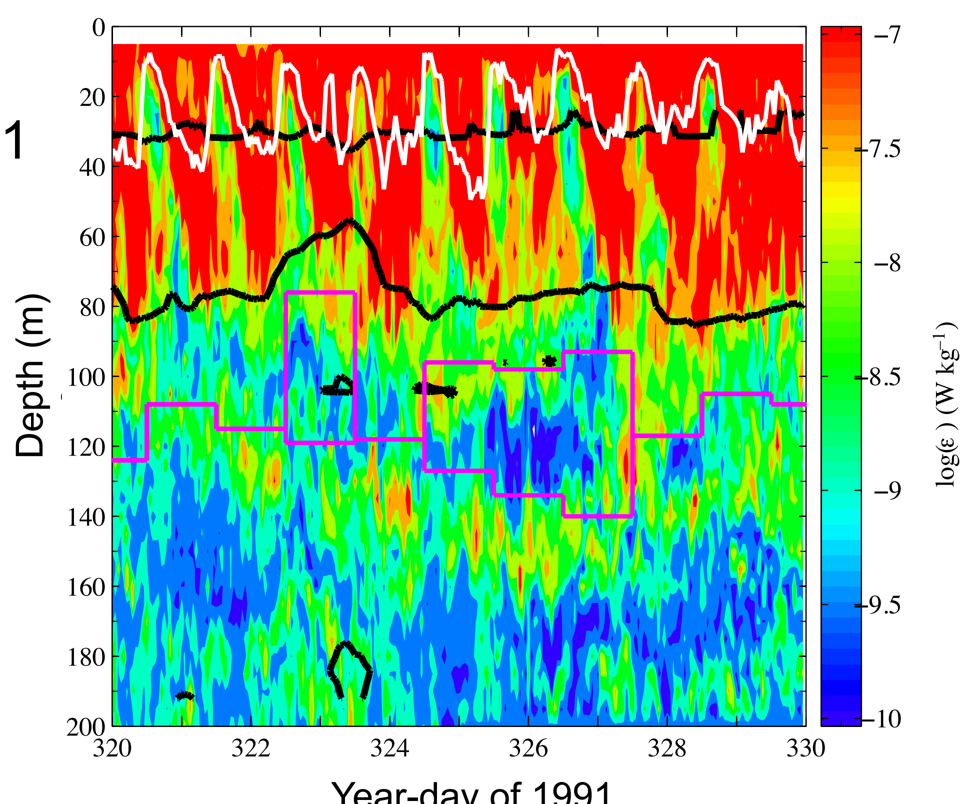


Cronin and Kessler (2005)

FIG. 5. Mean diurnal composite (24 May 2004–7 Oct 2004) of wind (blue vectors), temperature (color shading), and currents relative to 25 m (black vectors). The vector scale is shown at the bottom.

Turbulent dissipation during 10 days of 1991
White = Mixed layer
Red = Turbulent ϵ

TIWE (Lien)

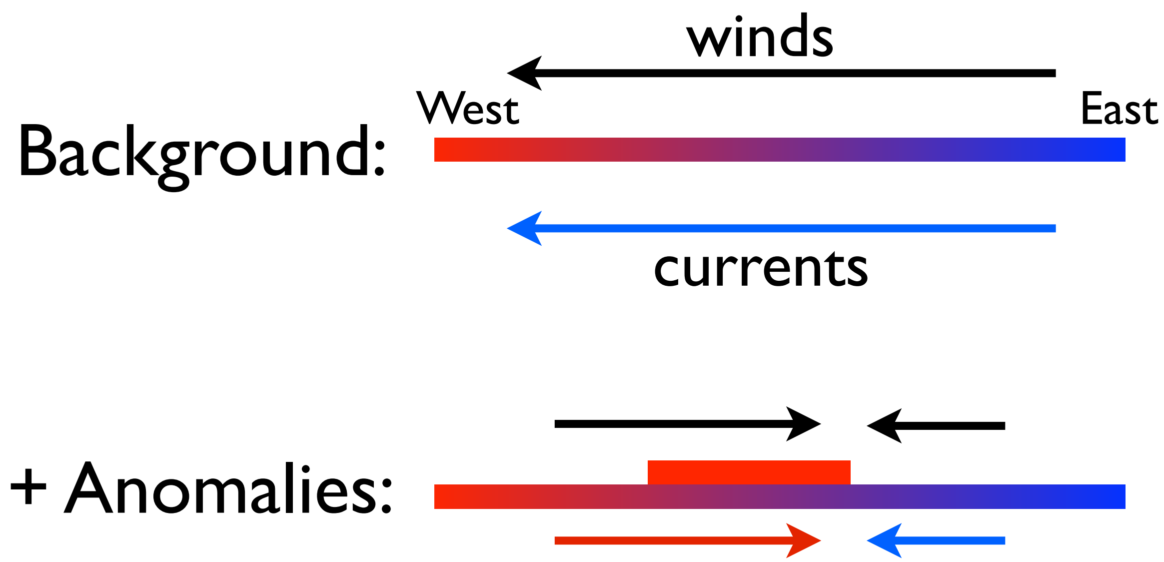


Much of the work of heat and momentum transmission to the thermocline is accomplished by the diurnal cycle.

(Schudlich, Danabasoglu,/Large, Lien/D'Asaro, Cronin/Kessler)

Other feedbacks: Some examples

Zonal advective and WES feedbacks



In response to a (warm) SST anomaly (however created):

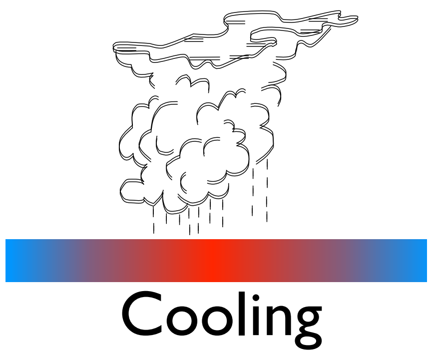
Zonal advection: anomalous currents advect the background cooler-to-east SST, amplifying the original anomaly.

Wind-Evaporation-SST: wind anomalies due to a warm SST patch also mean that the wind speed is smaller than the background, reducing evaporation and warming SST locally.

Heat flux damping

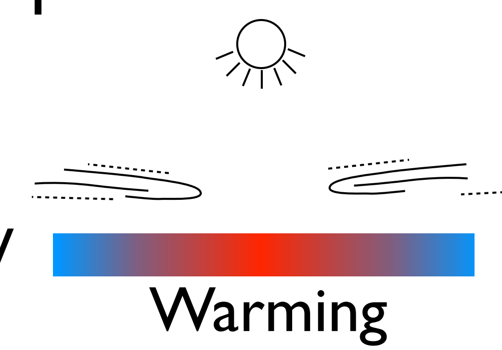
In an unstable (warm) atmosphere:

A warm SST patch leads to convection, increased cloudiness, reduced SW flux, decreased SST. (Negative feedback)



In a stable (cool) atmosphere:

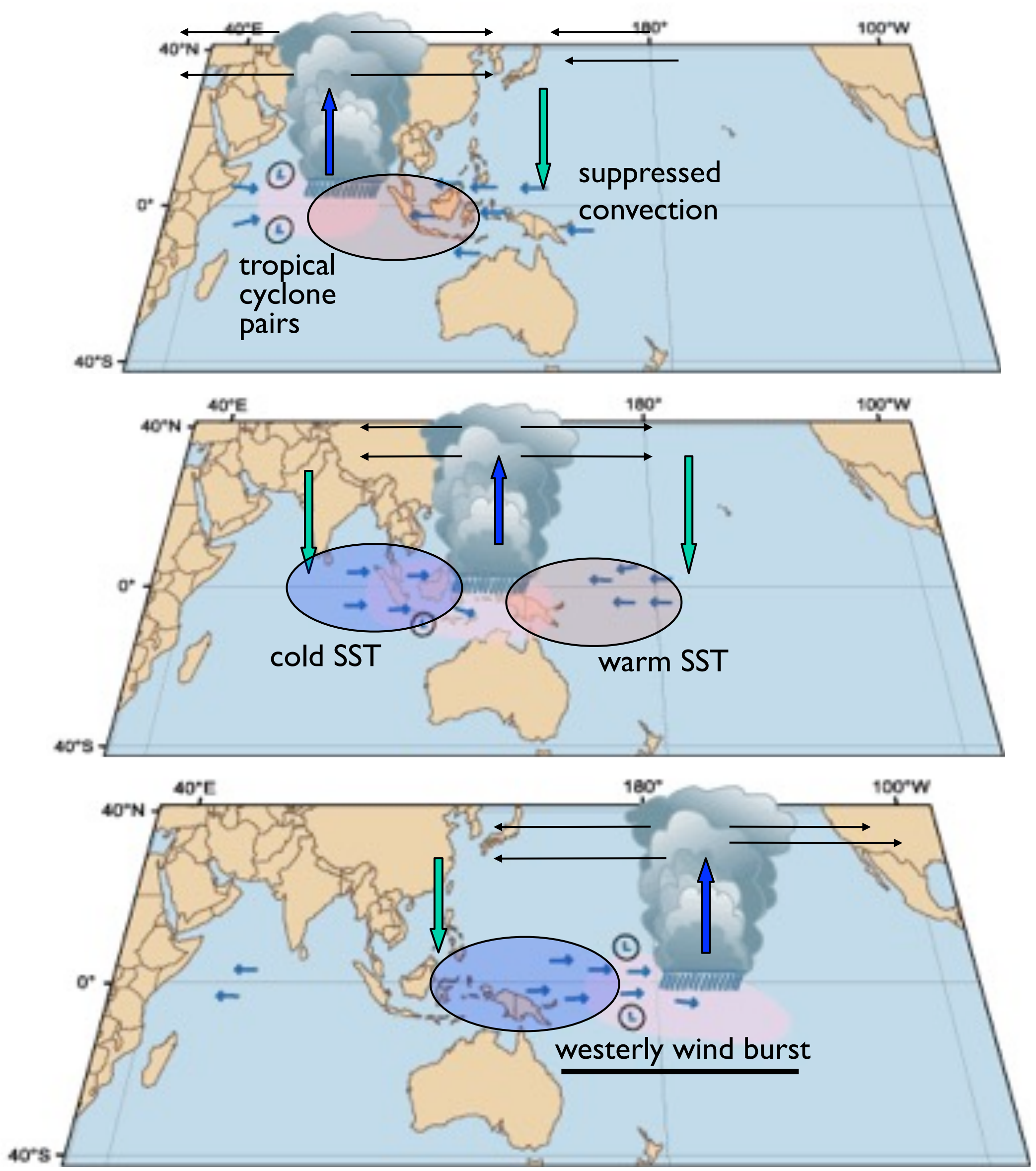
A warm SST patch leads to reduced stratiform cloudiness, increased SW flux, increased SST. (Positive feedback)

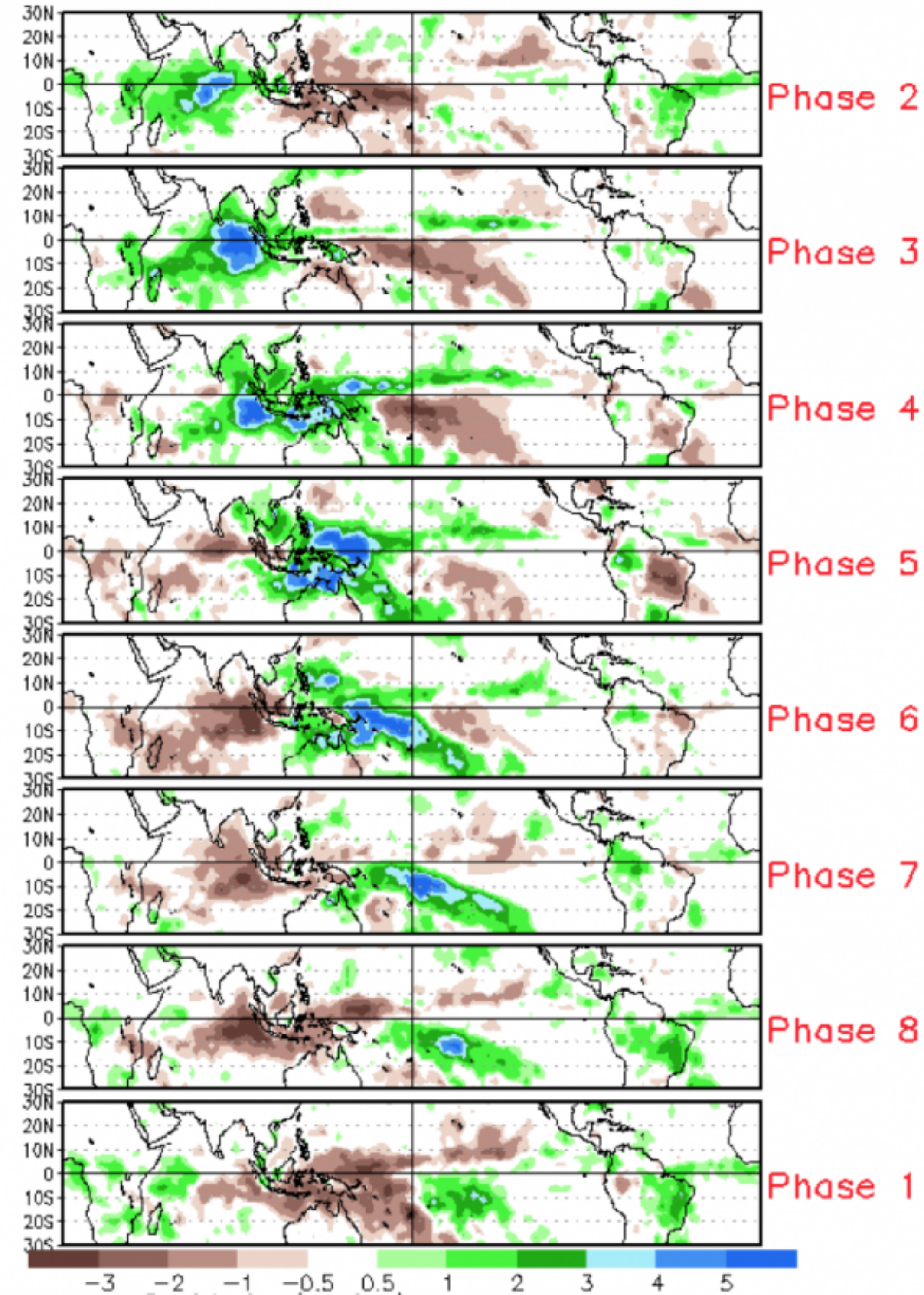


HF "damping" can be a positive or negative feedback

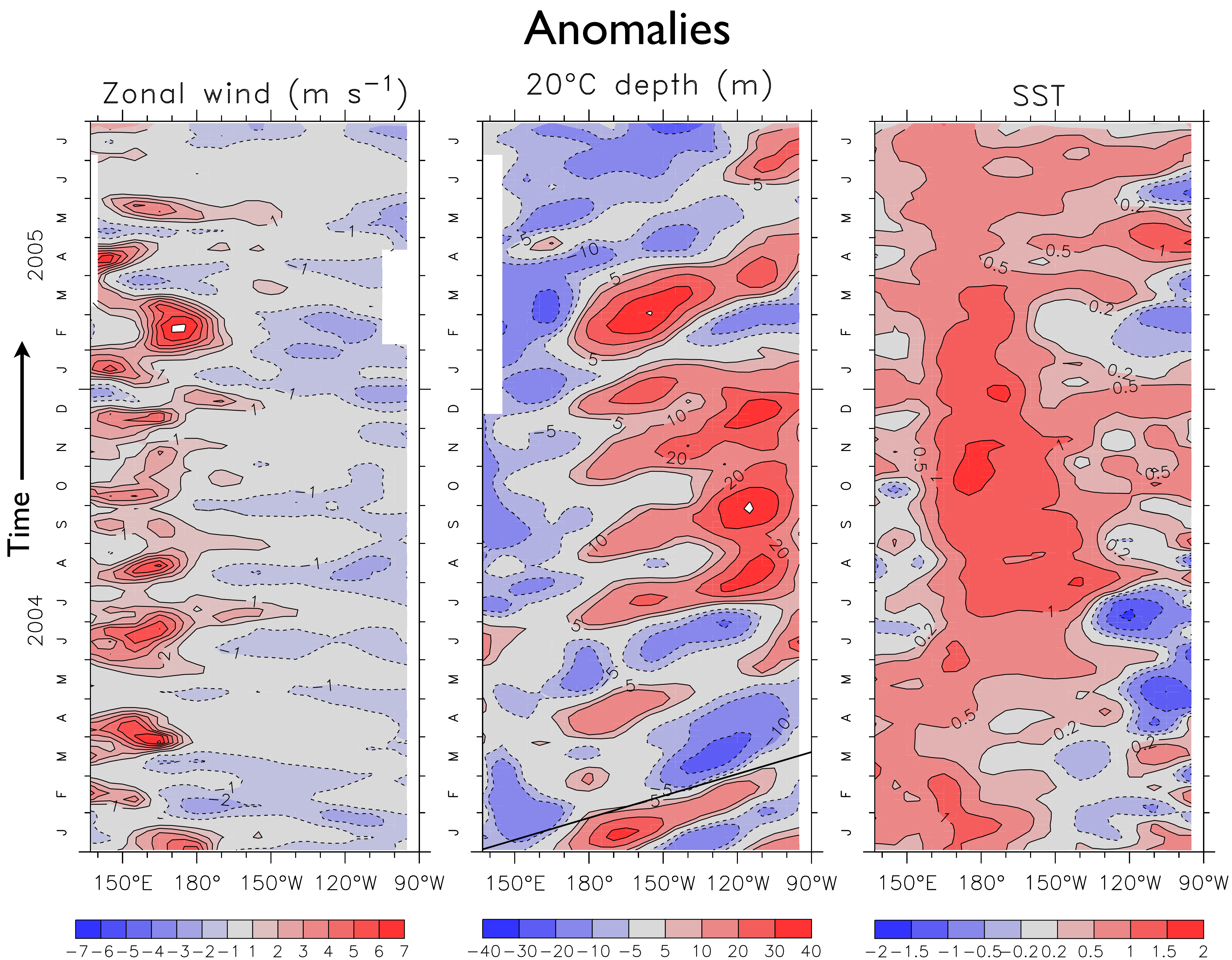
The Madden-Julian Oscillation (MJO)

30-50 day convection event
propagating from the Indian Ocean into the western Pacific.
Brings heavy rain and strong westerly winds.
El Niño trigger?





Signals spread efficiently across the Pacific equator



Red = westerly wind

Red = deep thermocline

Red = warm SST

The response to episodic westerly wind anomalies in the western Pacific:

- Winds blow into warm SST.
- Westerly winds come in bursts lasting ~30 days.
- Each wind event cools locally (mostly by evaporation).
- Each event also generates an eastward-propagating Kelvin wave.
  Although eastern Pacific winds remain easterly throughout, the thermocline deepens due to persistent remote forcing.
- Shallow eastern thermocline cools local SST.

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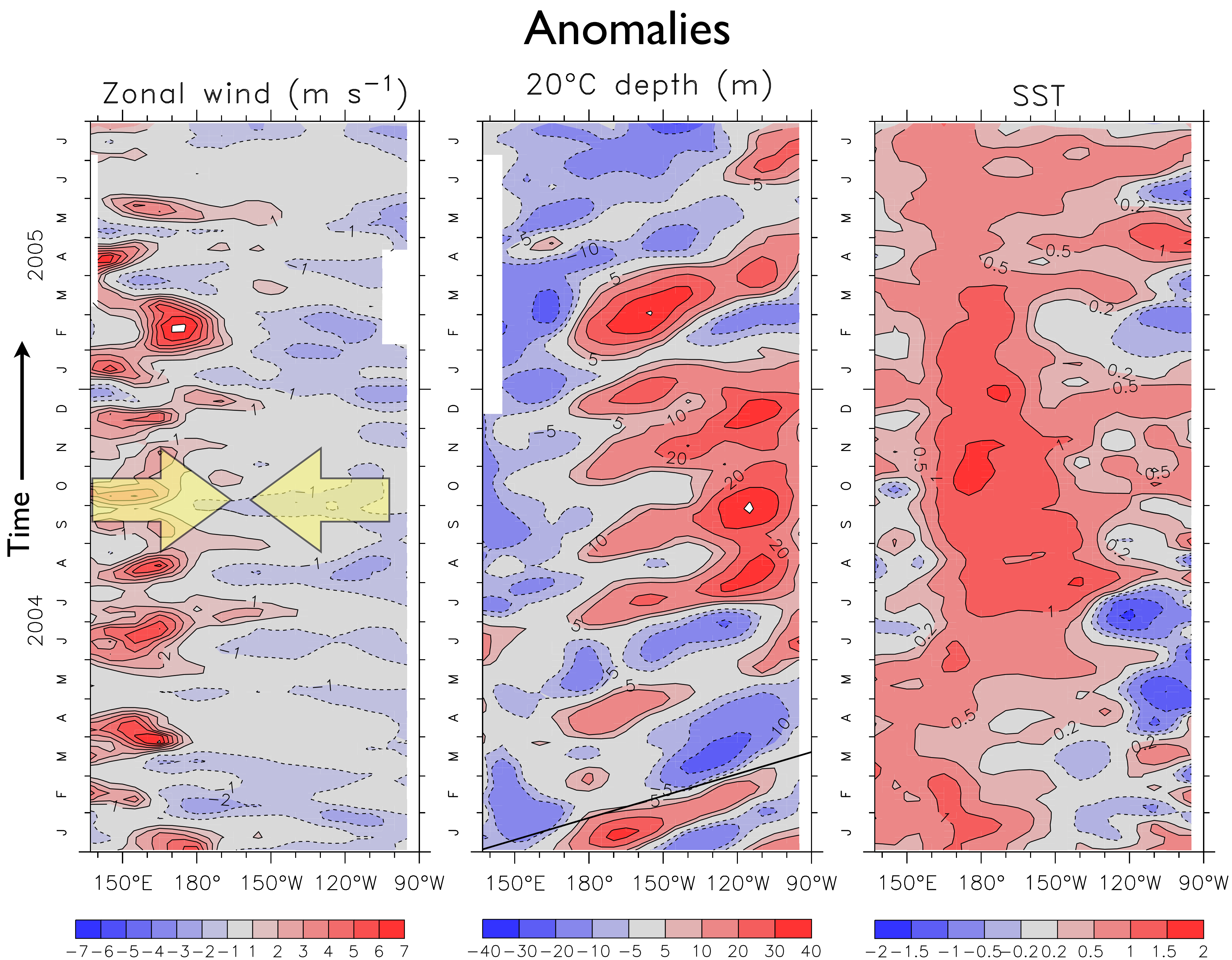

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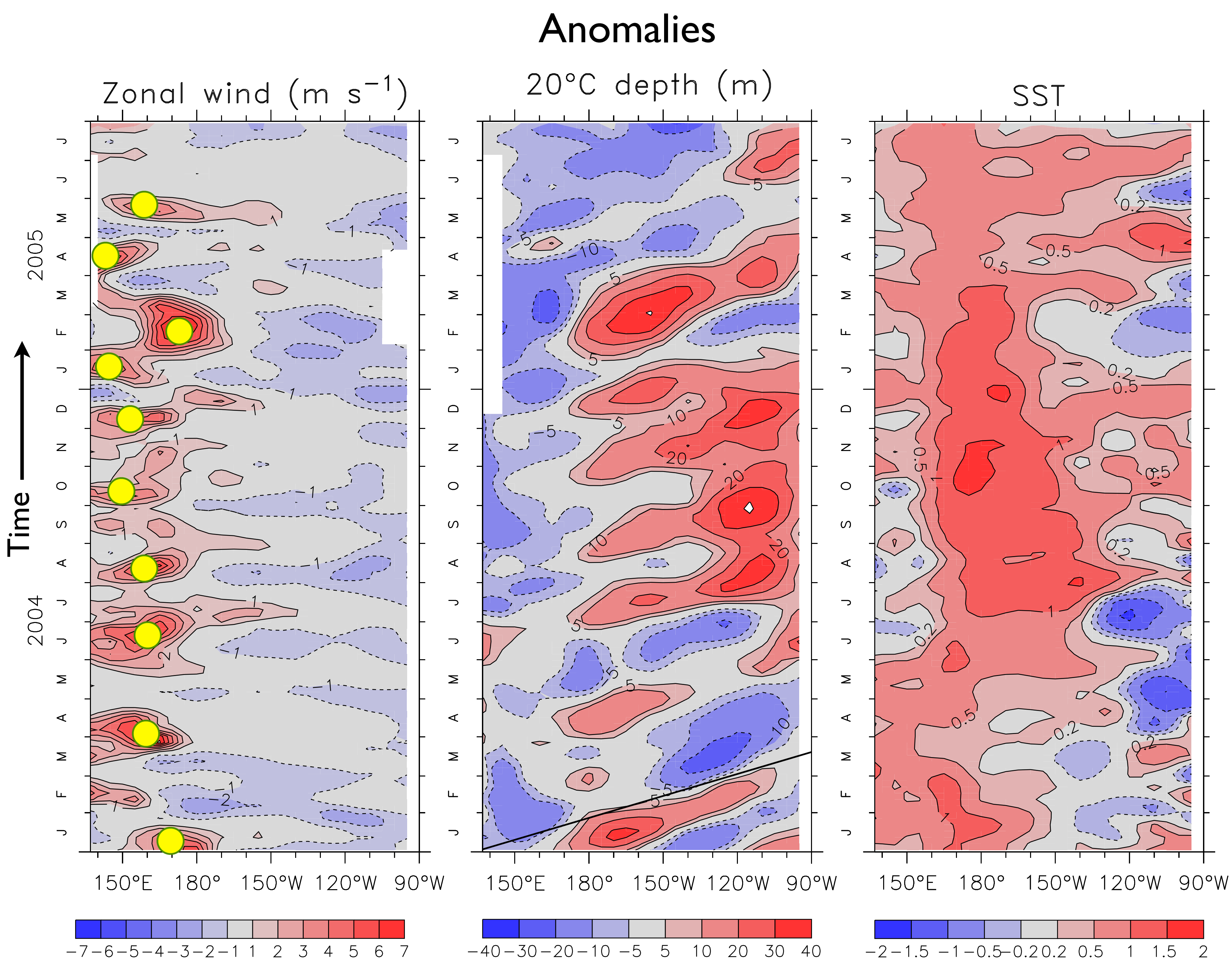

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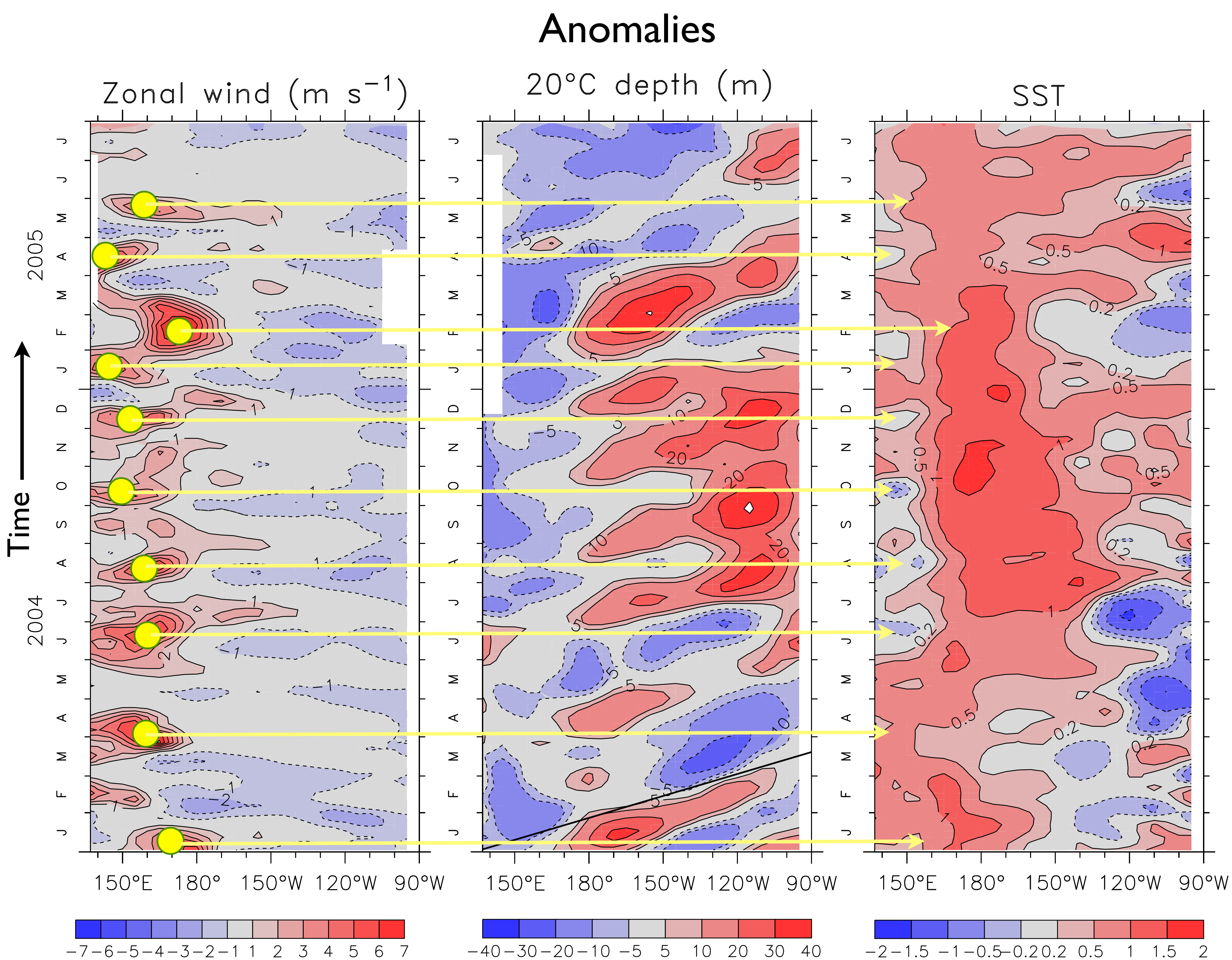

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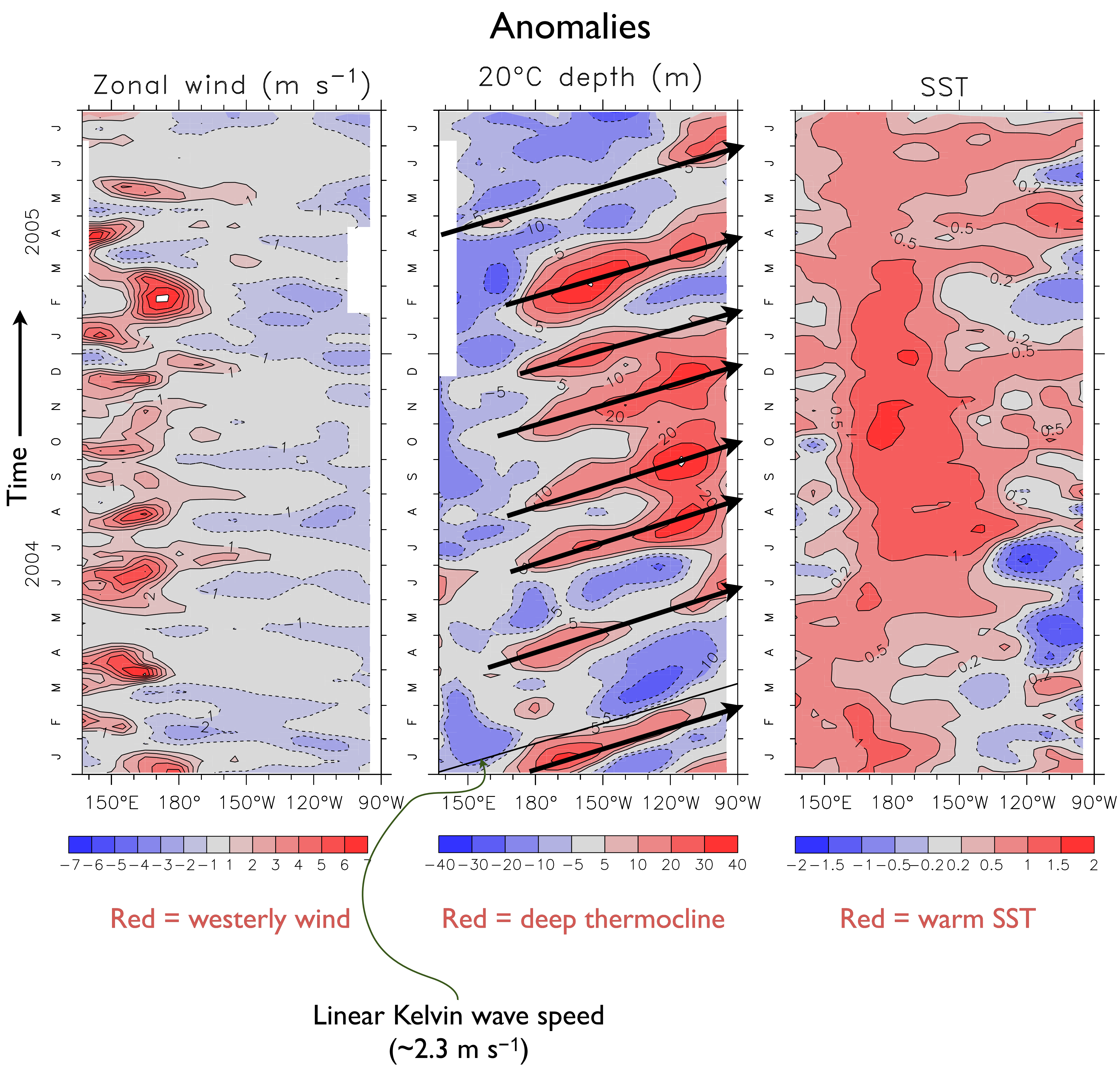

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