

The ocean in climate El Niño

We live in the atmosphere: where is it sensitive to the ocean?

What I won't talk about (very much):

- The ocean as a heat reservoir (passive)
- The thermohaline circulation (very long timescales)
- High latitudes: ice edge sensitivity, and

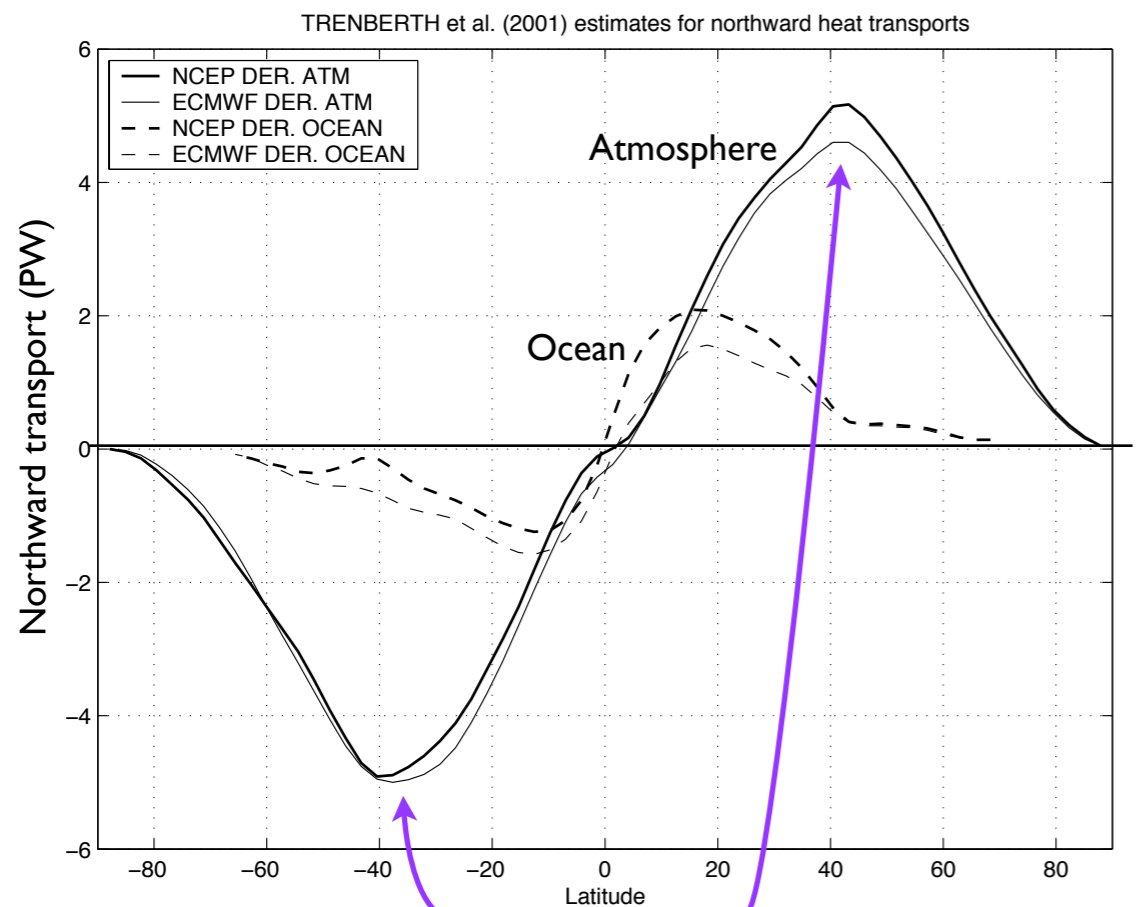
The tropics and El Niño

Introduction and lead-in to Jadranka and Maristella's talks

Talk on line at: <http://faculty.washington.edu/kessler> → LATEST TALK

Most of the poleward heat transport is by the atmosphere (except in the tropics)

Ocean and atmosphere heat transports



Trenberth et al (2001)

Most of the poleward transport is associated with mid-latitude winter storms

Ocean heat transport estimates (small north of 40°N)

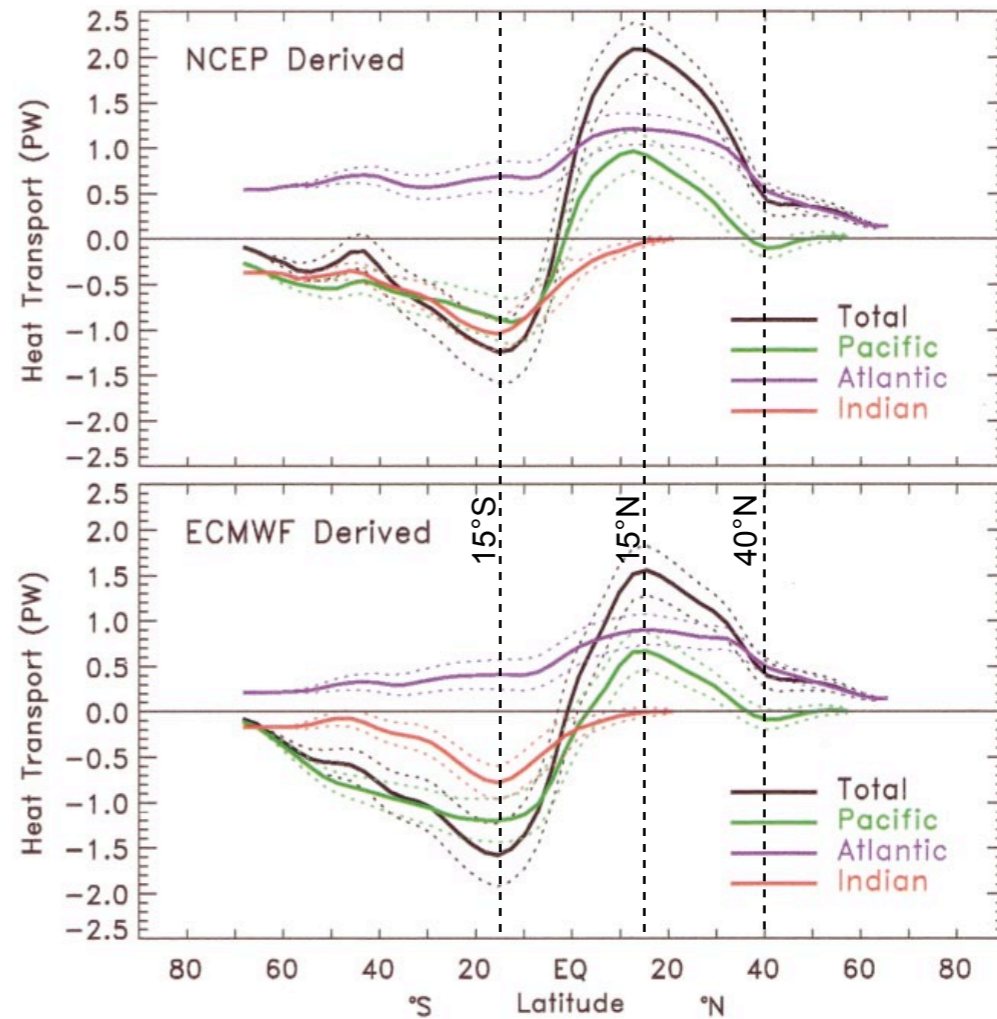


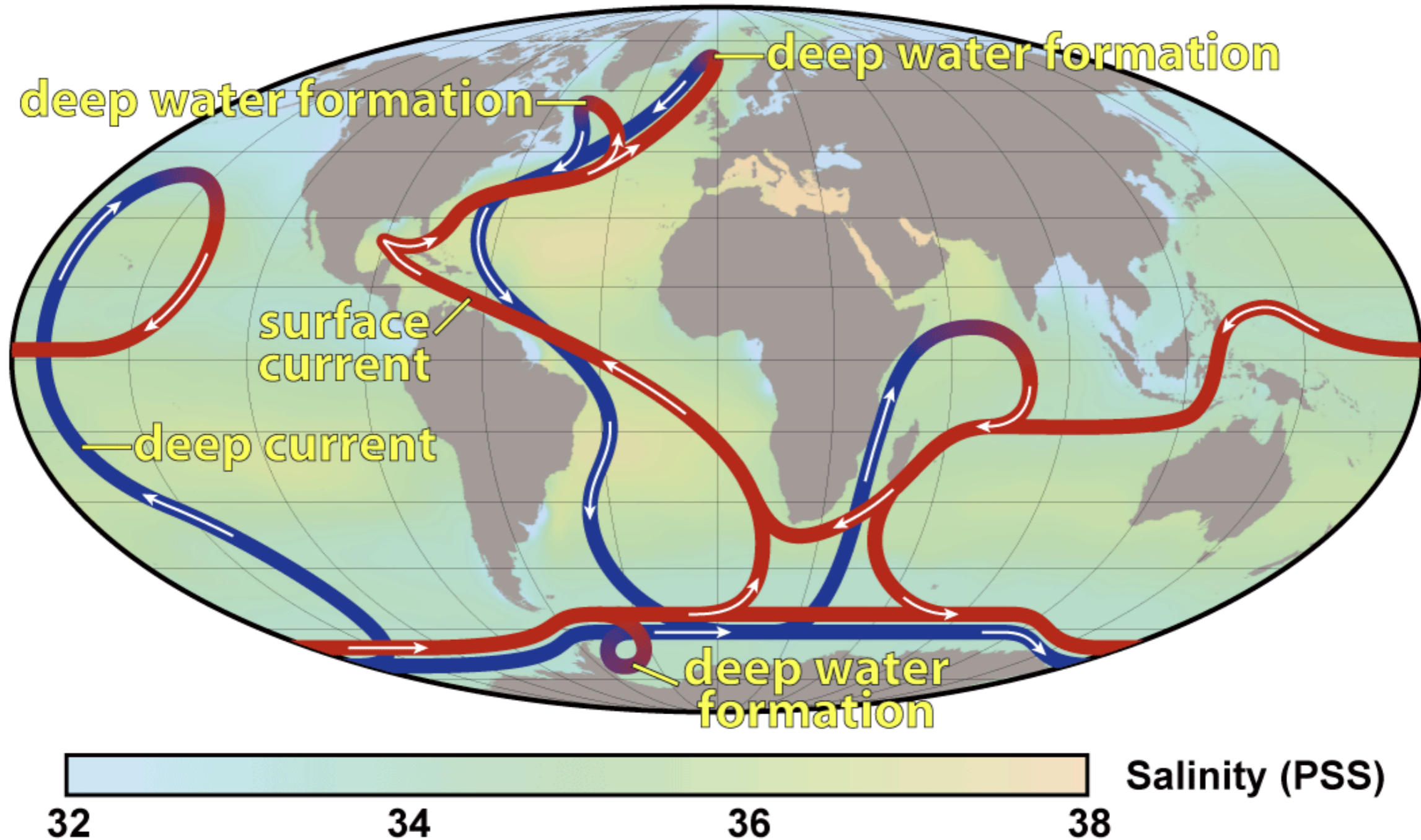
FIG. 5. Implied zonal annual mean ocean heat transports based upon the surface fluxes for Feb 1985–Apr 1989 for the total, Atlantic, Indian, and Pacific basins for NCEP and ECMWF atmospheric fields (PW). The 1 std err bars are indicated by the dashed curves.

Trenberth and Caron (2001)

Much recent interest in the “global conveyor belt”

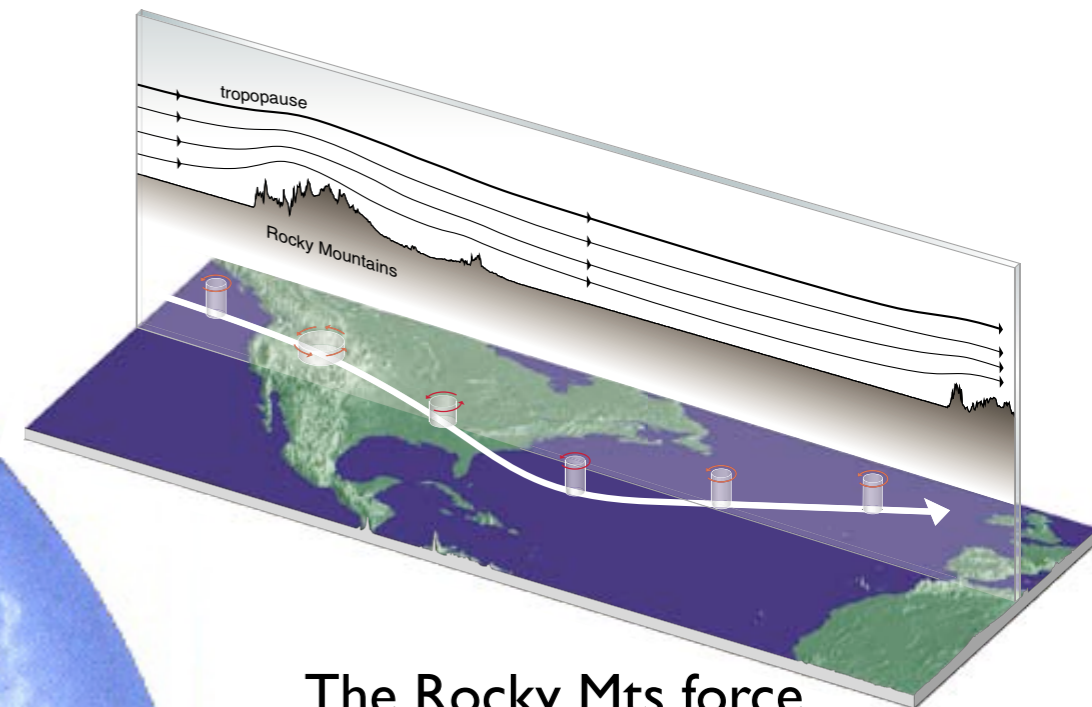
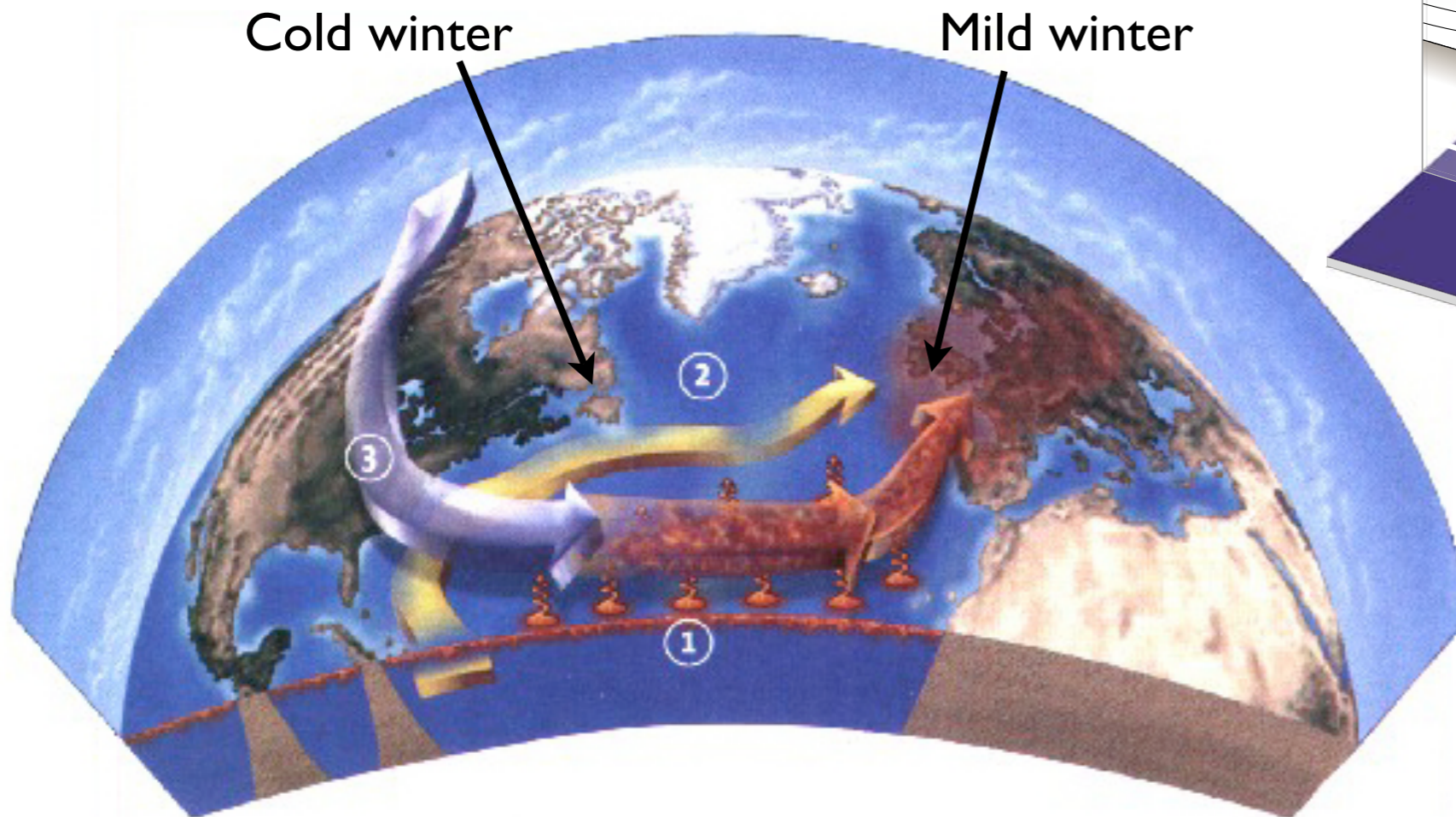
But the timescales are probably slow

Thermohaline Circulation



Does the Gulf Stream warm Europe?

An example of the (largely) passive effect of the ocean



The Rocky Mts force the jet stream to make a 5000-km bend to the south. As a result, mid-latitude westerlies approach Europe from the southwest.

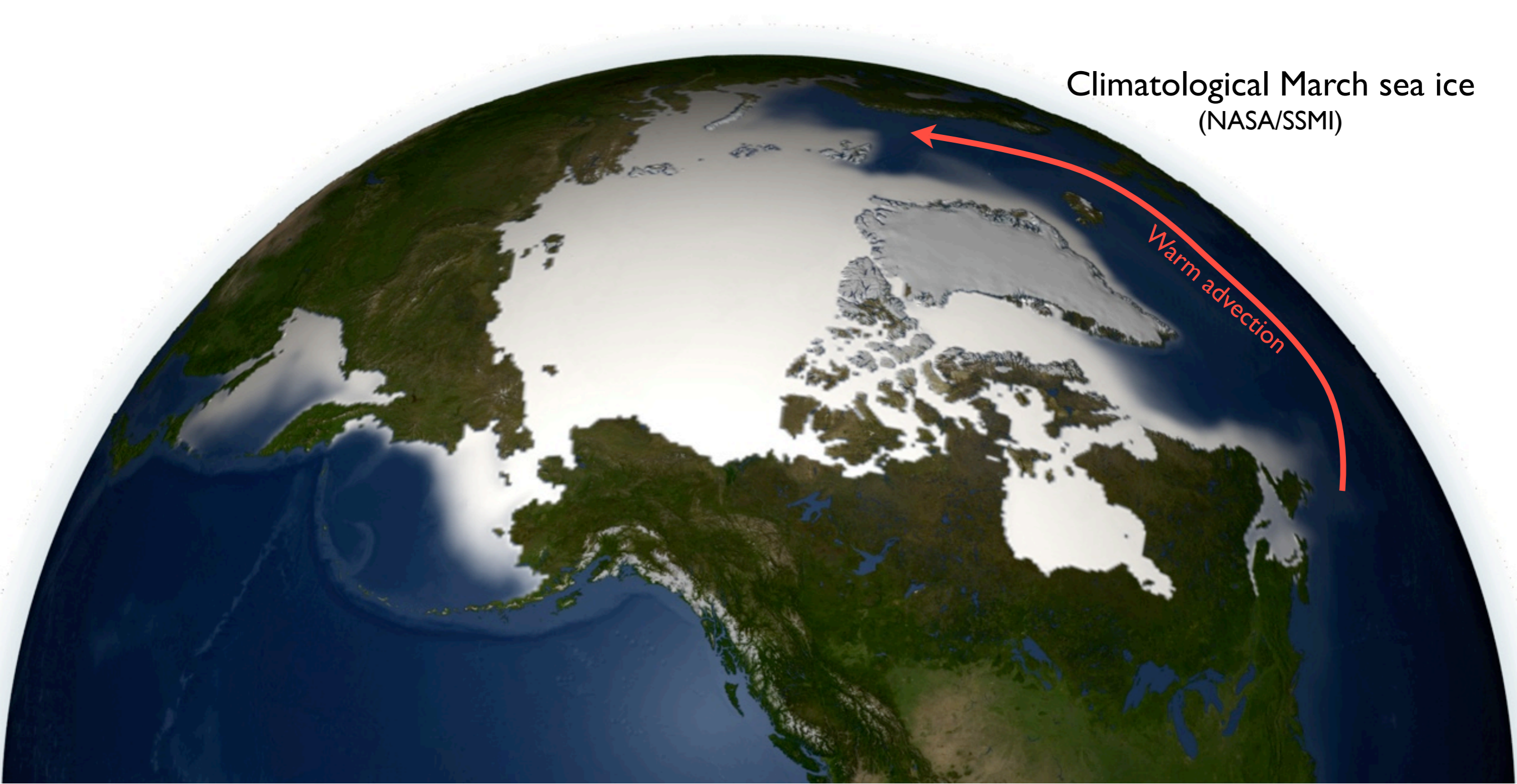
The east-west temperature contrast depends on three phenomena:

- 1) Summer heating regained by the atmosphere during winter carried east by the mid-latitude westerly winds;
- 2) Stationary atmospheric waves forced by the Rocky Mountains ;
- 3) Heat transport by the Gulf Stream.

Seager et al (2001, QJRM)

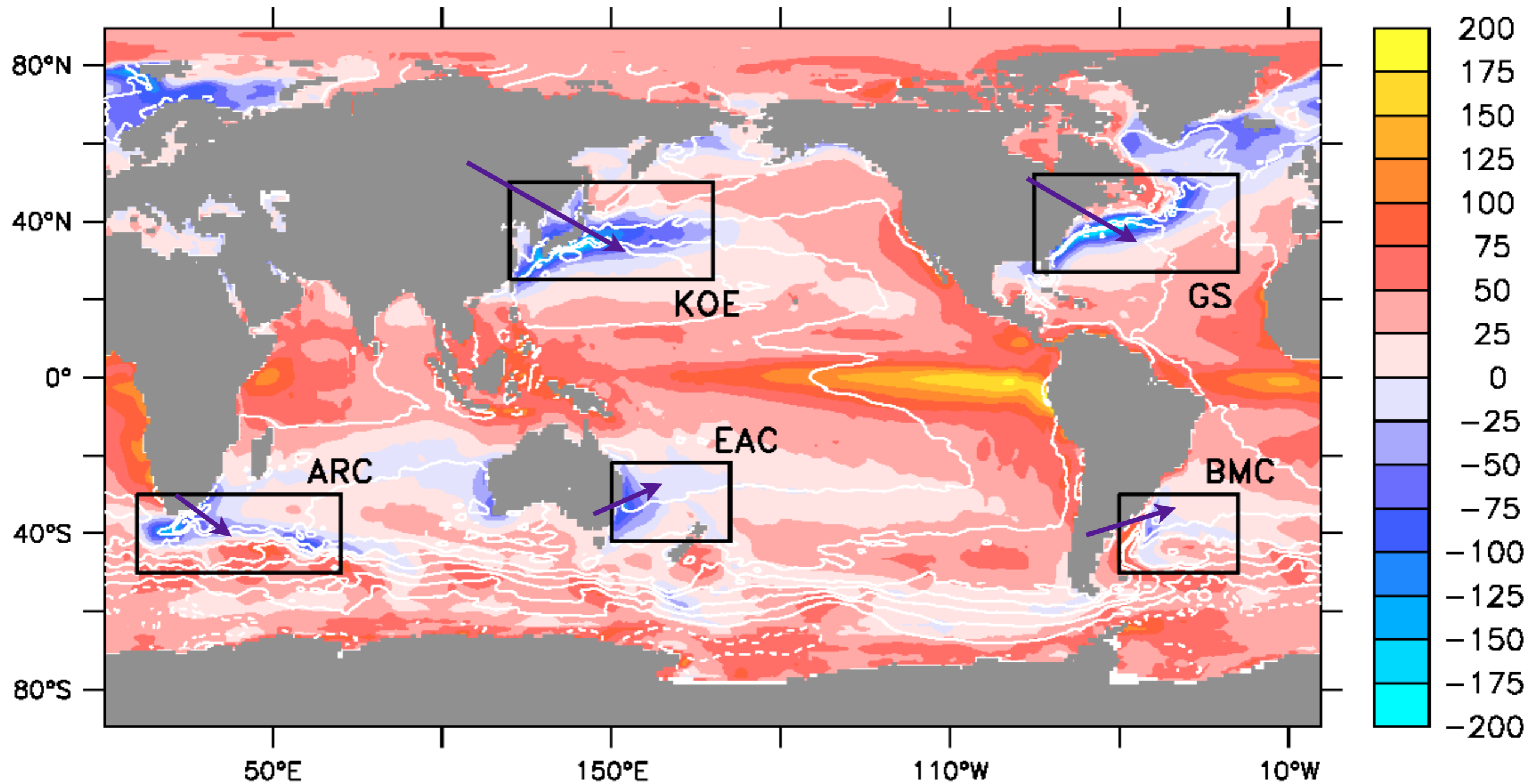
However, even the small effect of Gulf Stream warm advection is important for the ice edge

And the salty surface water carried into the Arctic affects the convection that controls the formation of deep water



Western boundary currents do matter regionally

Winter continental cold air flows over warm WBC water: significant heat flux to atmosphere



Mean Net Surface Heat Flux (Wm⁻²)

Yu and Weller (2007)
Rio (2004)

What's special about the tropics?

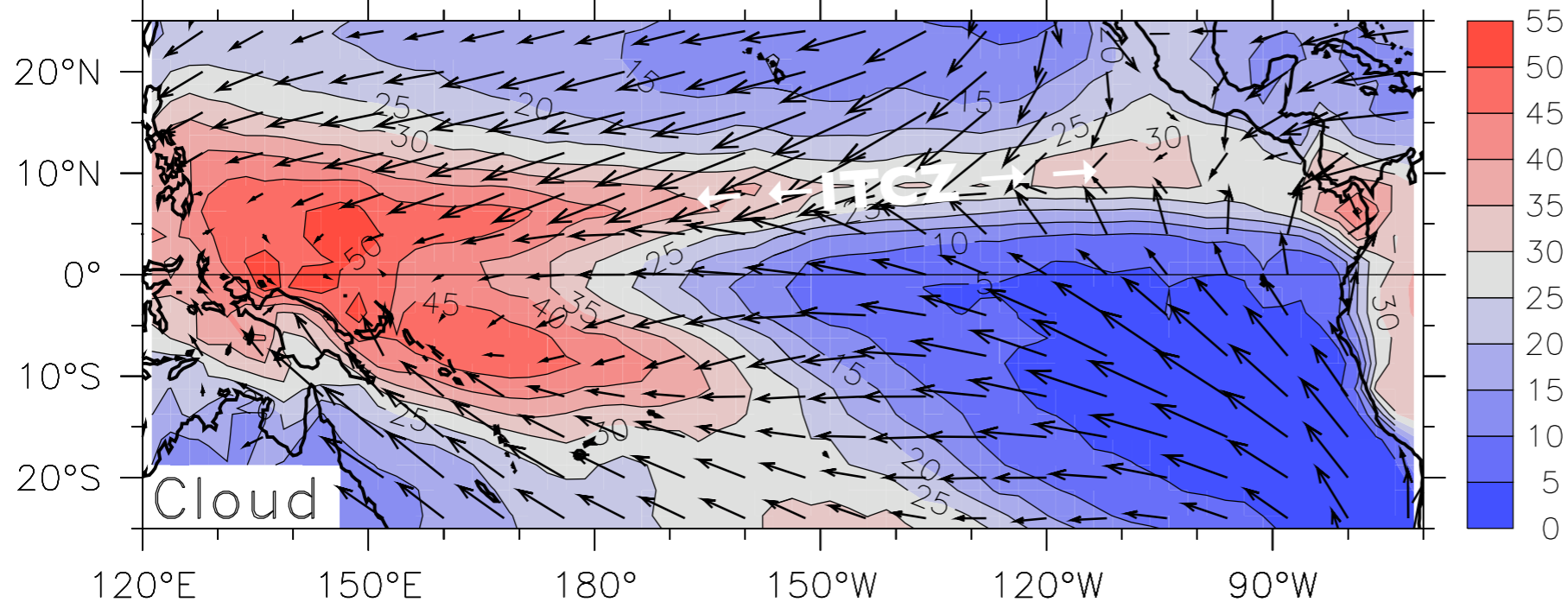
- Surface air temperature is always near the threshold for convection ($\sim 27^{\circ}\text{C}$).
- Equatorial zonal winds respond rapidly to the SST gradient.
- The close connection between thermocline depth and SST means the tropical ocean varies rapidly.
- The high speed and large zonal scale of equatorial waves allows efficient basinwide transmission of signals.

Thus, small SST changes can greatly affect the atmosphere in the tropics, and conversely small changes in the wind can greatly affect the SST pattern: **coupling**.

- All this is less true of the extra-tropics:
other mechanisms by which SST affects the atmosphere are less effective.

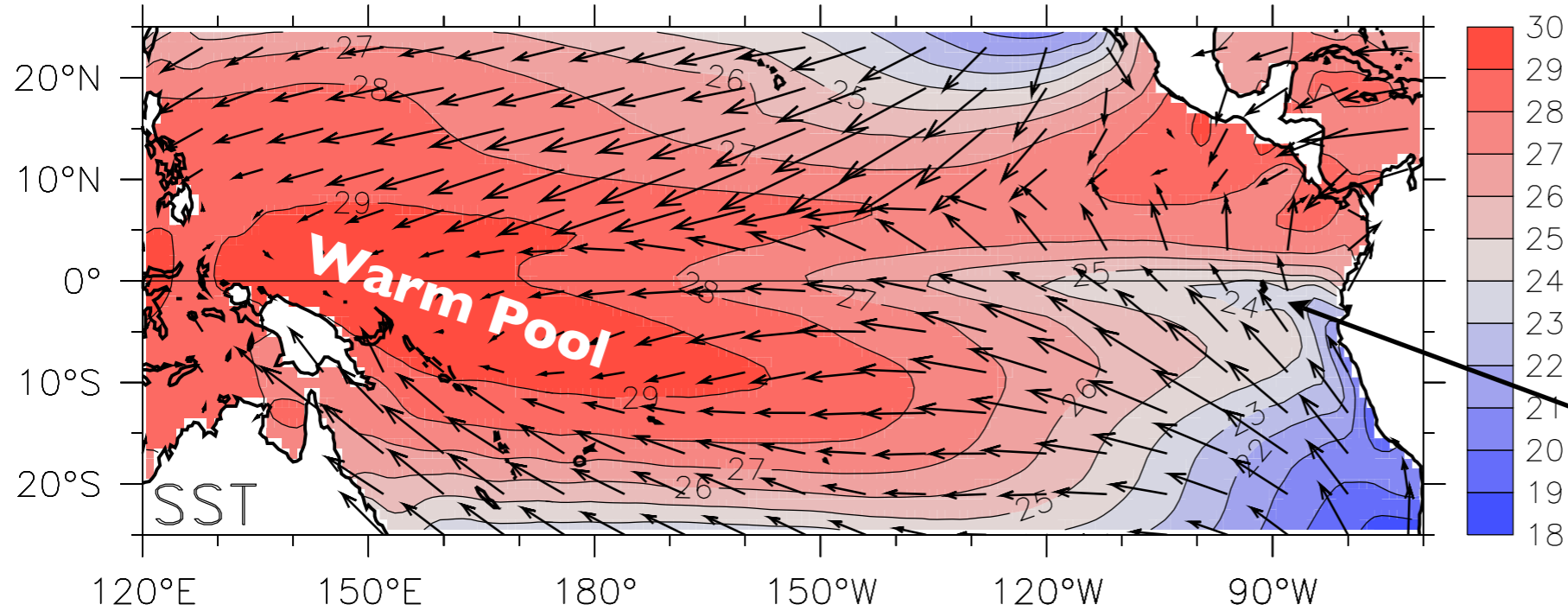
Close relation among SST, convection and winds

High cloud fraction (deep convection) and surface winds



In the tropics, convection coincides with warm SST and surface wind convergence.

SST and surface winds



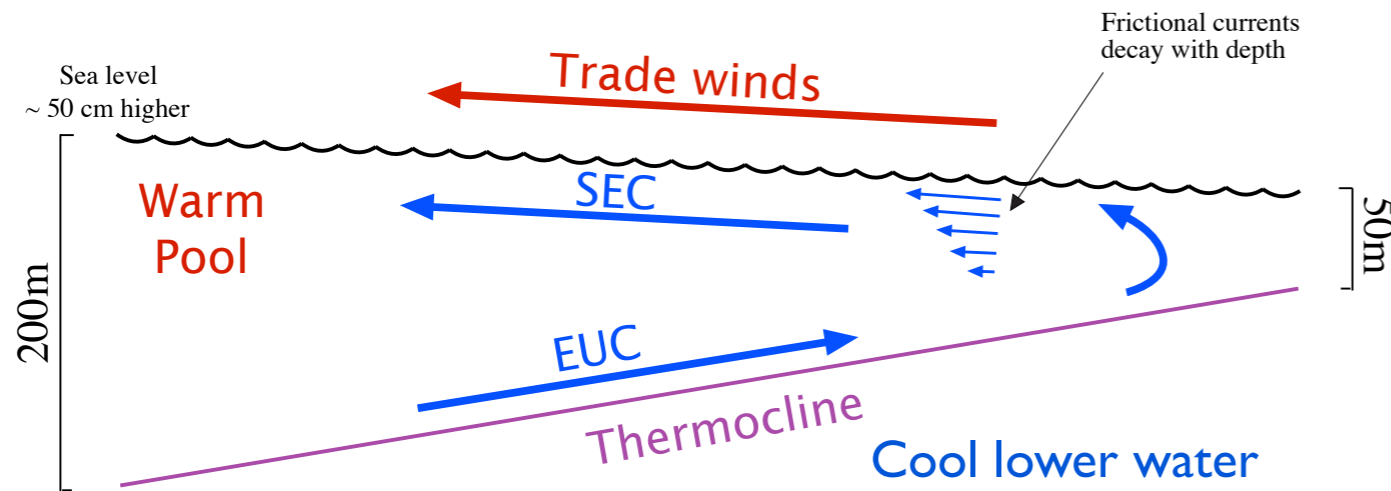
All three define the West Pacific warm pool and the Intertropical Convergence Zone (ITCZ).

East Pacific Cold Tongue

→ $10 \times 10^{-2} \text{ N m}^{-2}$

(Reynolds SST, ISCCP high clouds, Quikscat winds)

Currents and temperature on the equator

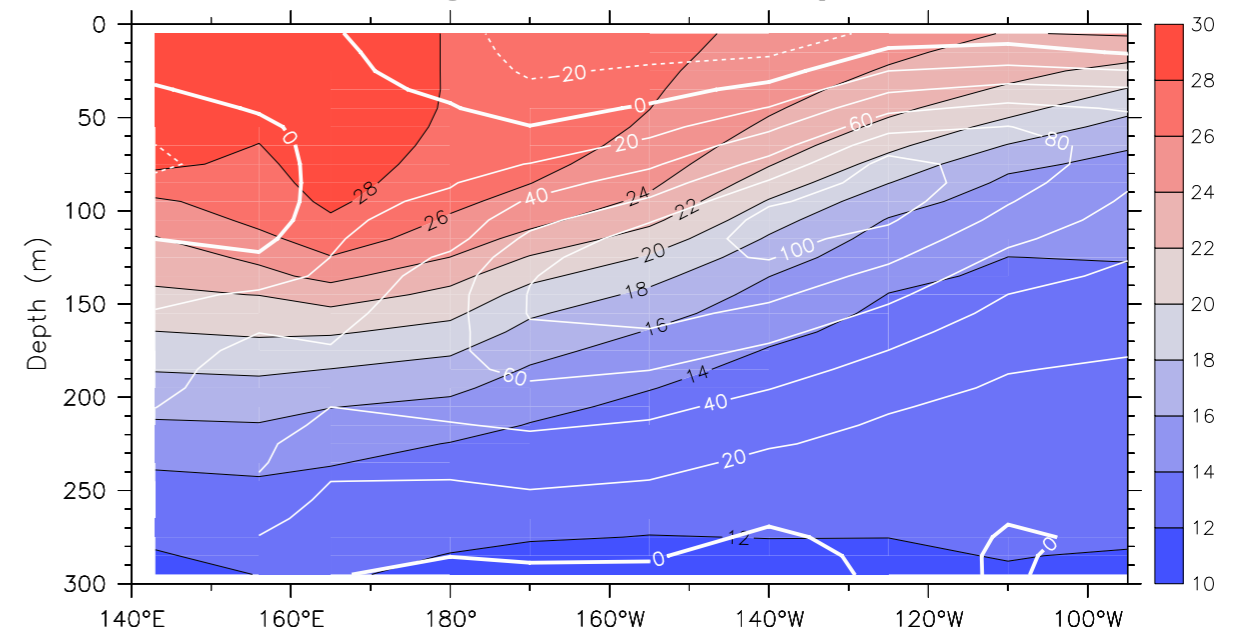


The trade winds 1) Pile up water in the west.
2) Drive the SEC by direct friction.

Below the frictional layer (25m?) pressure due to the high sea level in the west pushes the EUC eastward below the surface.

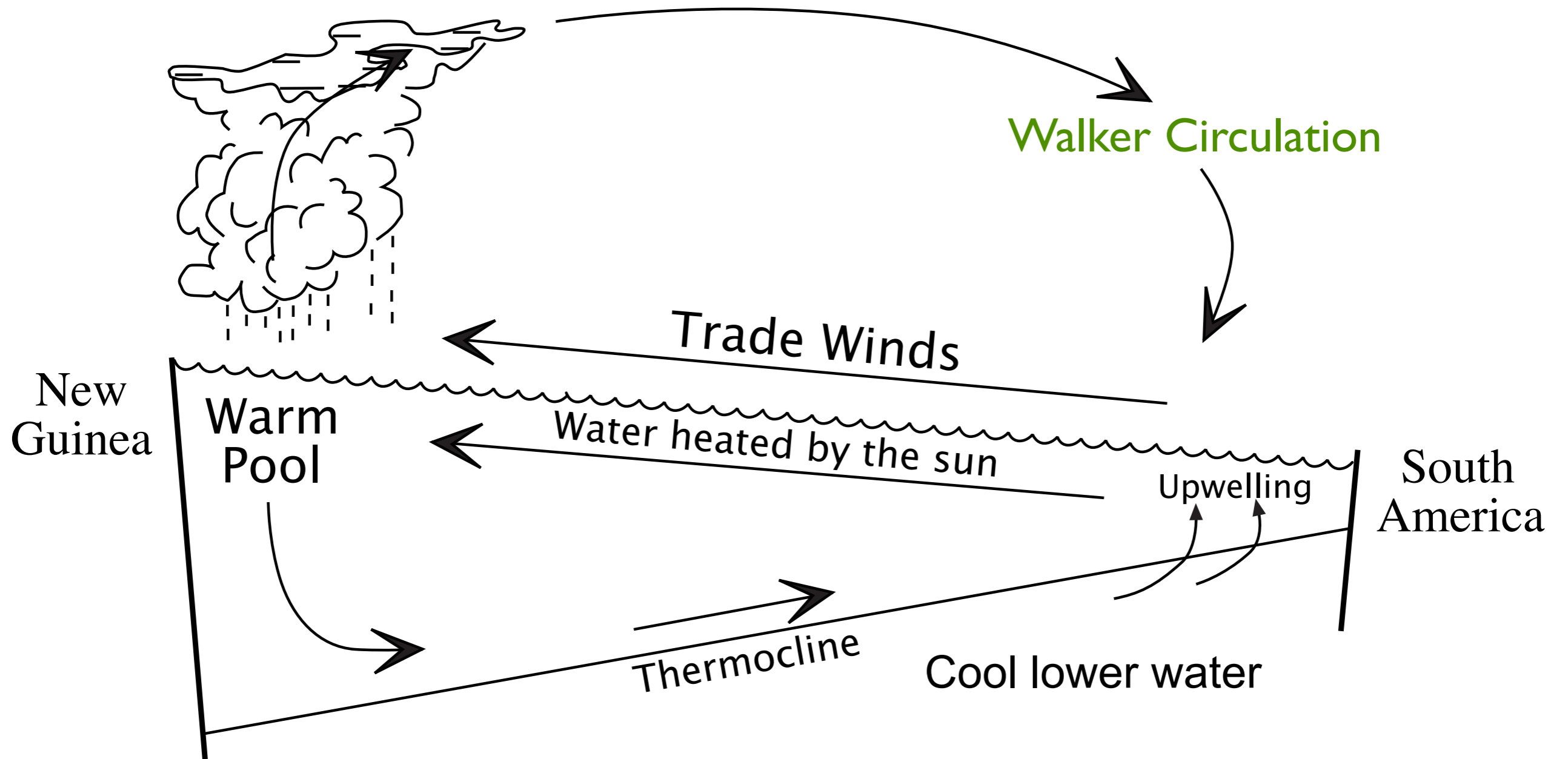
(SEC = South Equatorial Current)
(EUC = Equatorial Undercurrent)

Observed mean temperature and currents along the Pacific equator



Johnson et al (2001)

The tropical climate is coupled

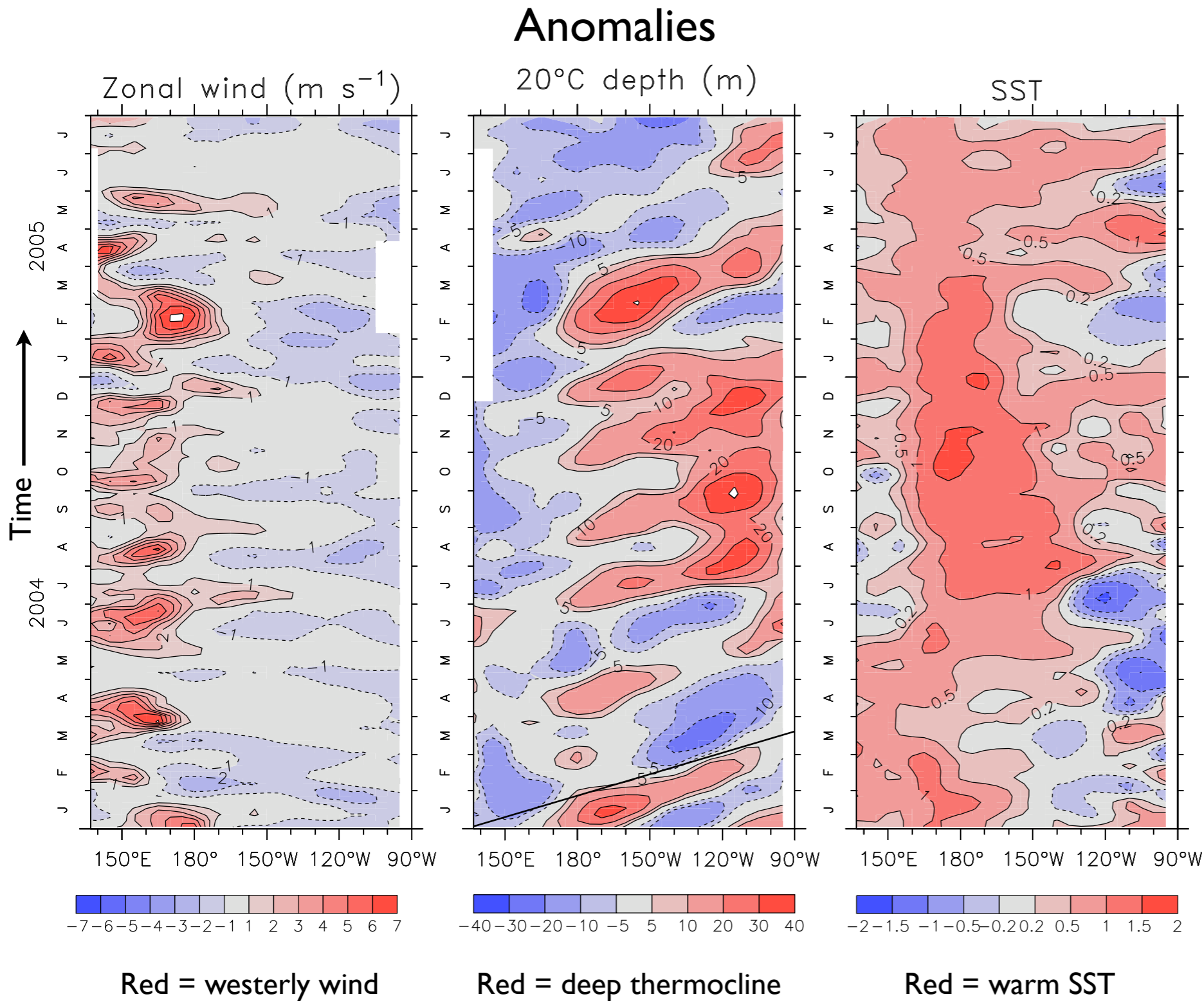


A positive feedback!

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.

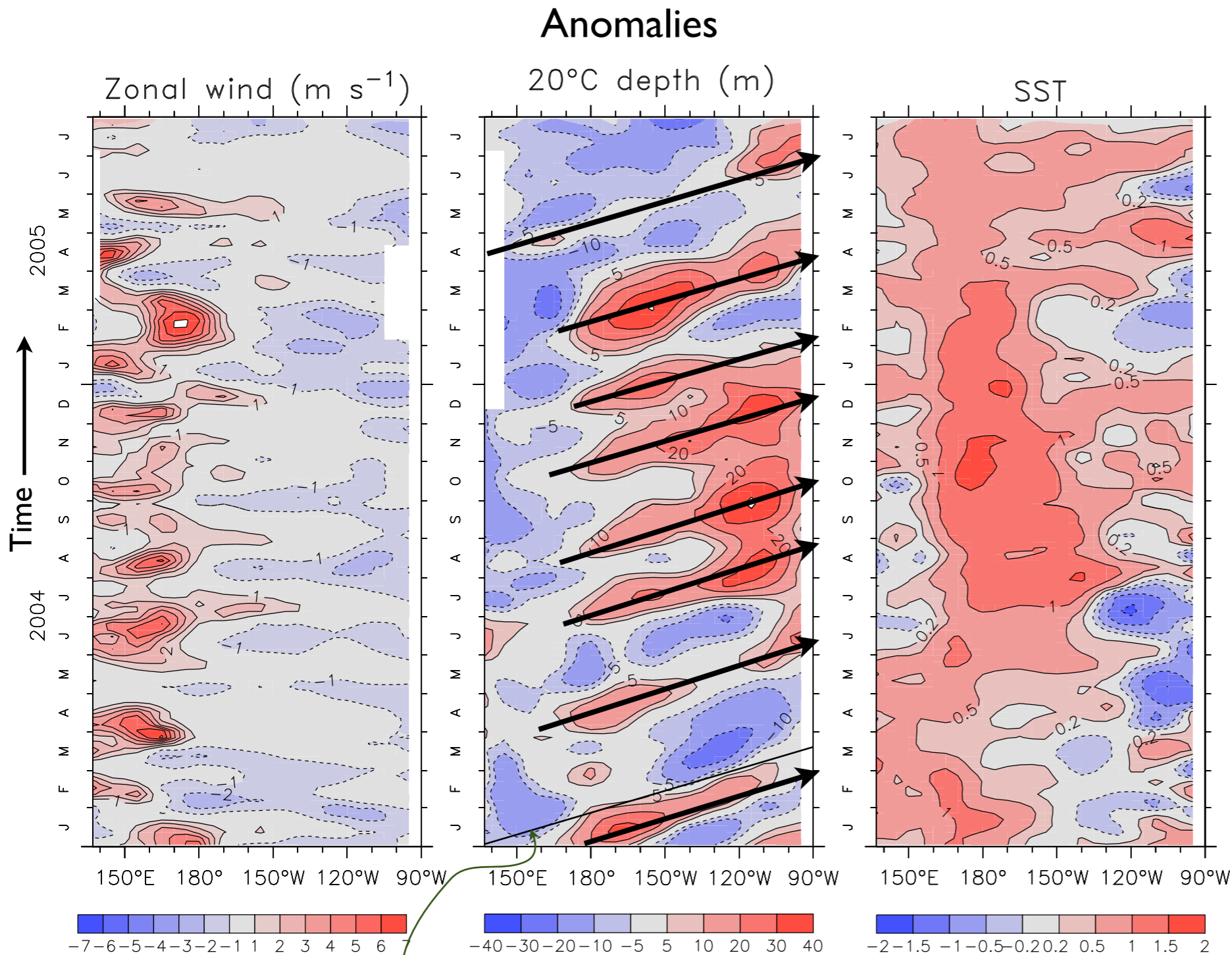
Signals spread efficiently across the Pacific equator



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

- Winds blow into warm SST.
 - Westerly winds come in bursts lasting ~30 days. (Maristella's talk to follow)
 - 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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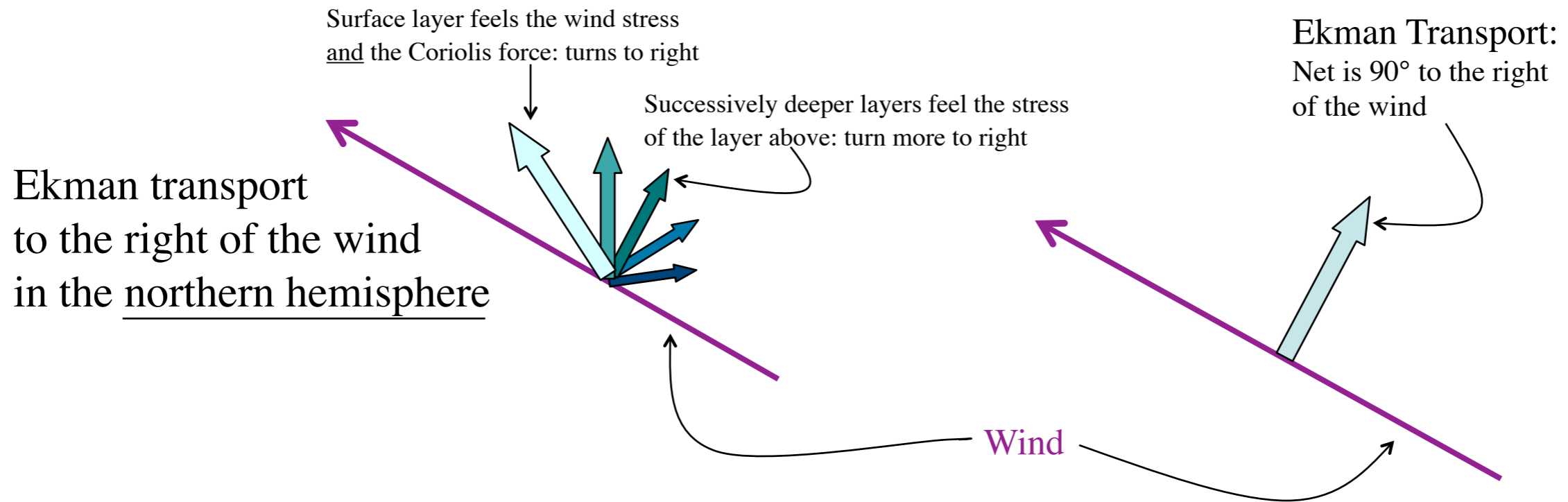
Red = westerly wind

Red = deep thermocline

Red = warm SST

Linear Kelvin wave speed
($\sim 2.3 \text{ m s}^{-1}$)

Fundamental wind-driven dynamics: Ekman Transport

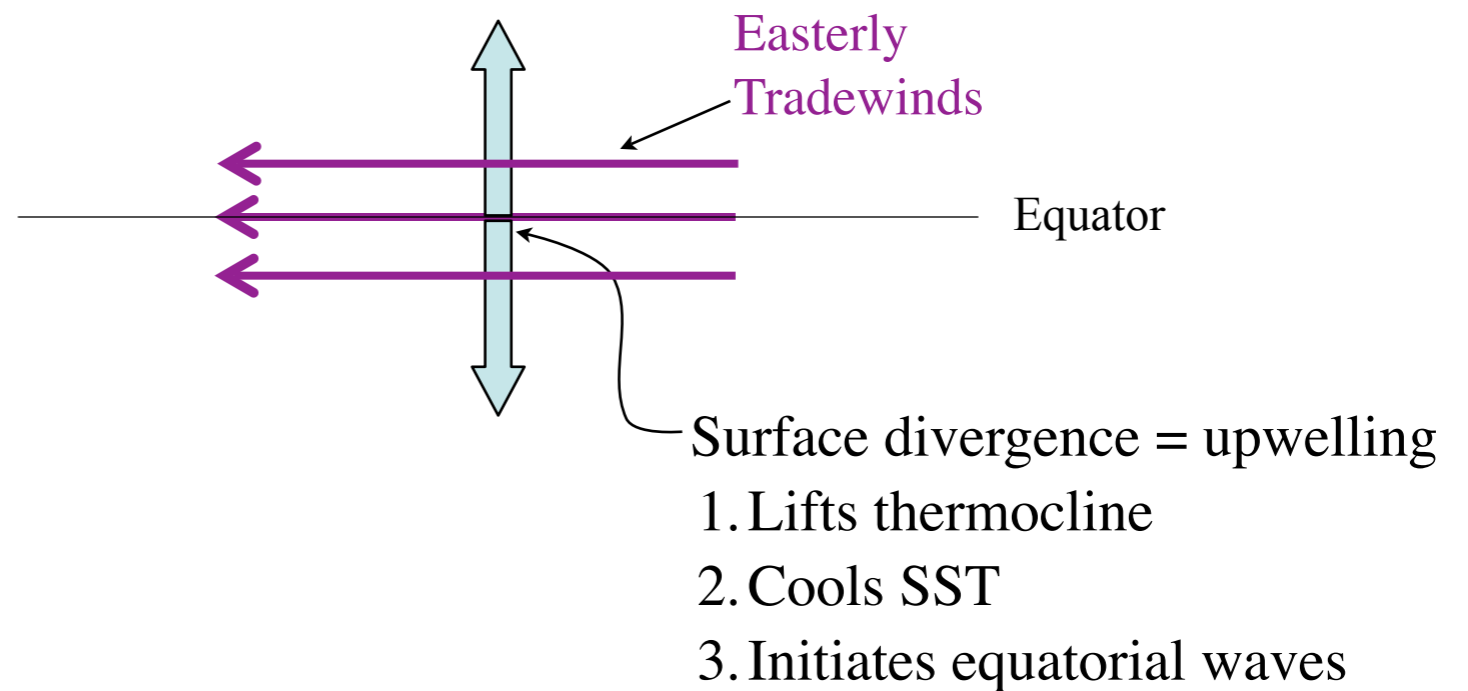


Wind along the equator produces opposite Ekman transport on each side of the equator.

Easterly winds (normal tradewinds) give divergent Ekman transport, with consequent upwelling.

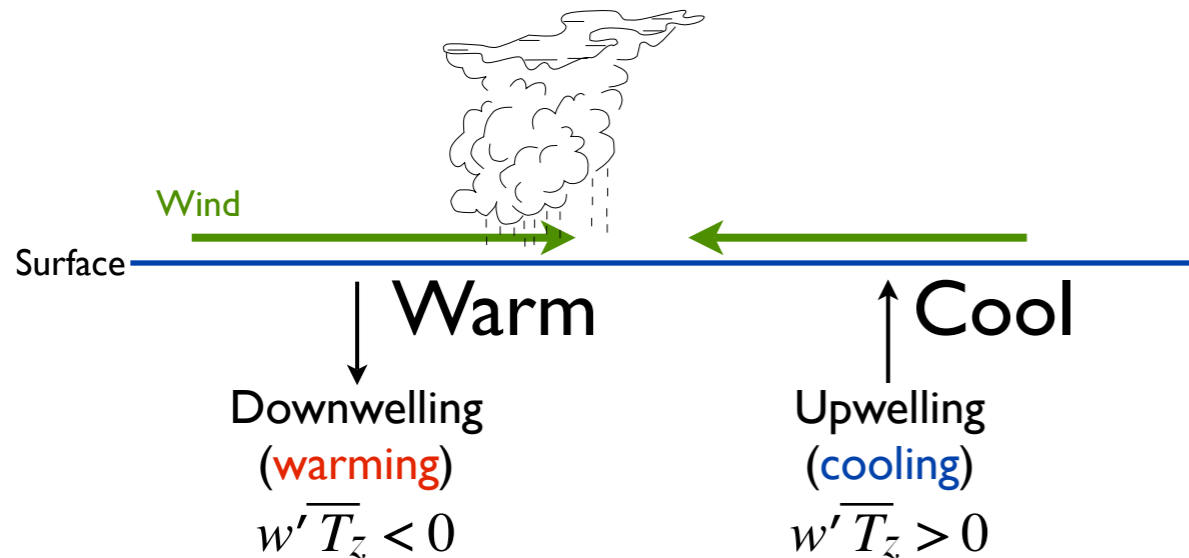
As the thermocline is lifted to the surface, SST will usually cool.

Westerly anomalies do the opposite.



SST modes: eastward or westward propagation along the equator

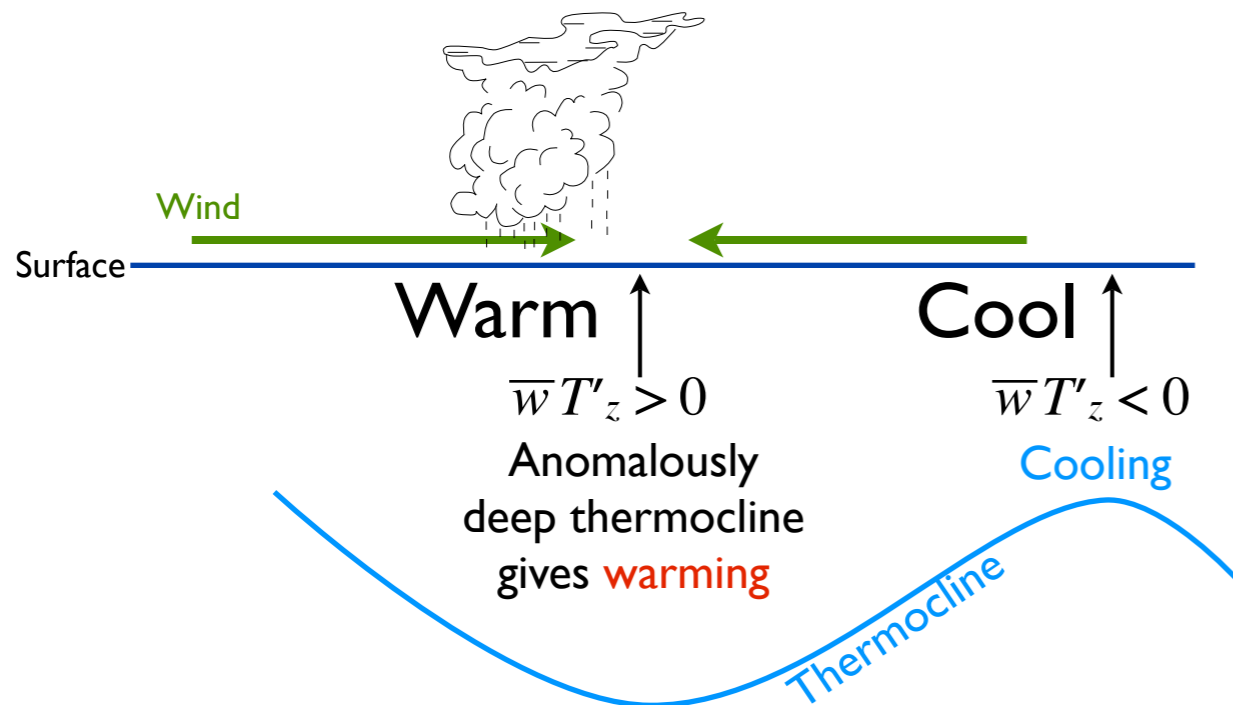
Convection occurs over warm SST → rising air converges → westerlies extend over warm anomaly



“Slow SST mode”

Local feedbacks (upwelling/downwelling)
 w' (vertical velocity) anomalies dominate.

→ Anomalies propagate **WEST**



“Fast-wave limit”

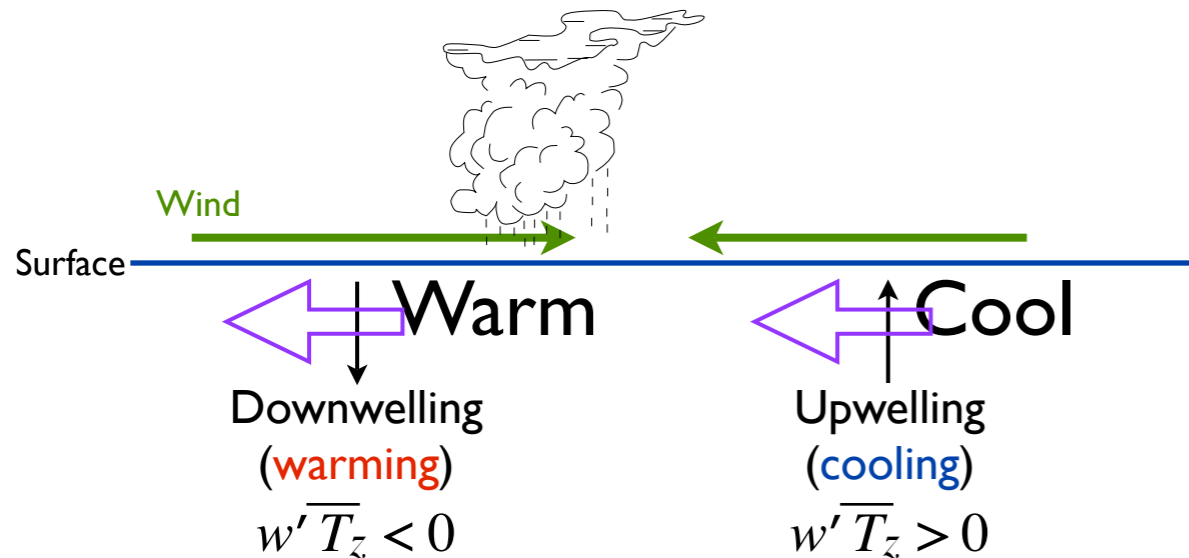
Waves assumed to have brought thermocline into equilibrium with the wind. ($P_x = \tau^x$)

Assume mean background upwelling ($w = \bar{w}$).
 T'_z (vertical T gradient) anomalies dominate.

→ Anomalies propagate **EAST**

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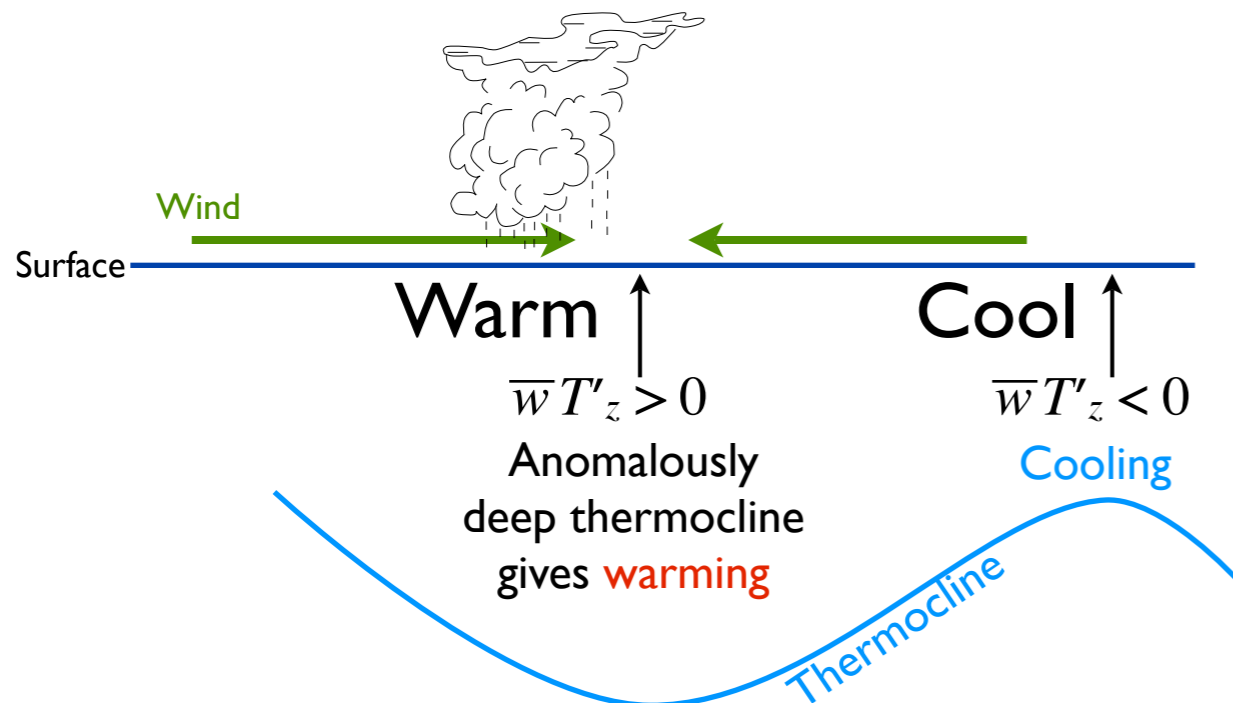
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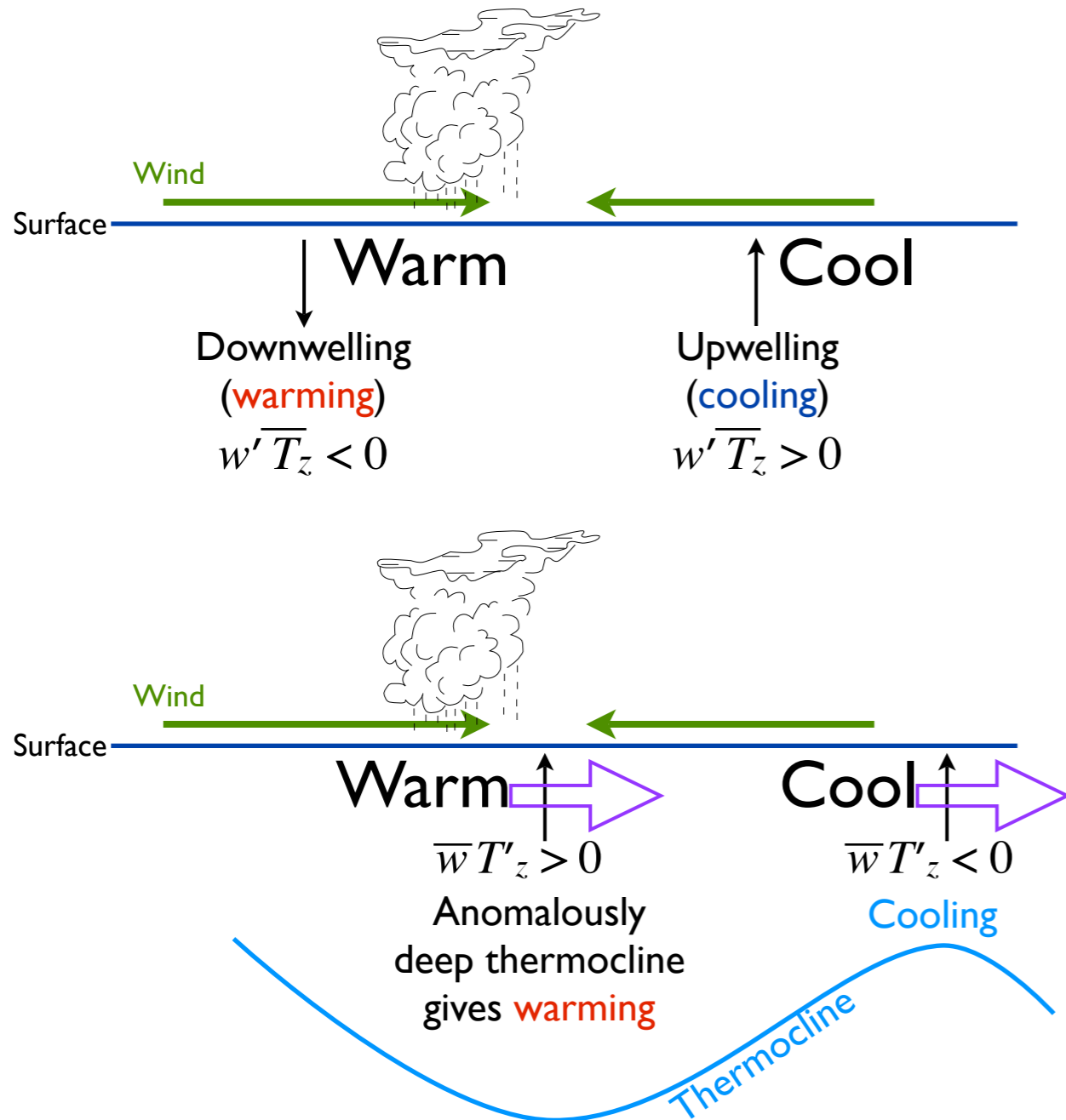
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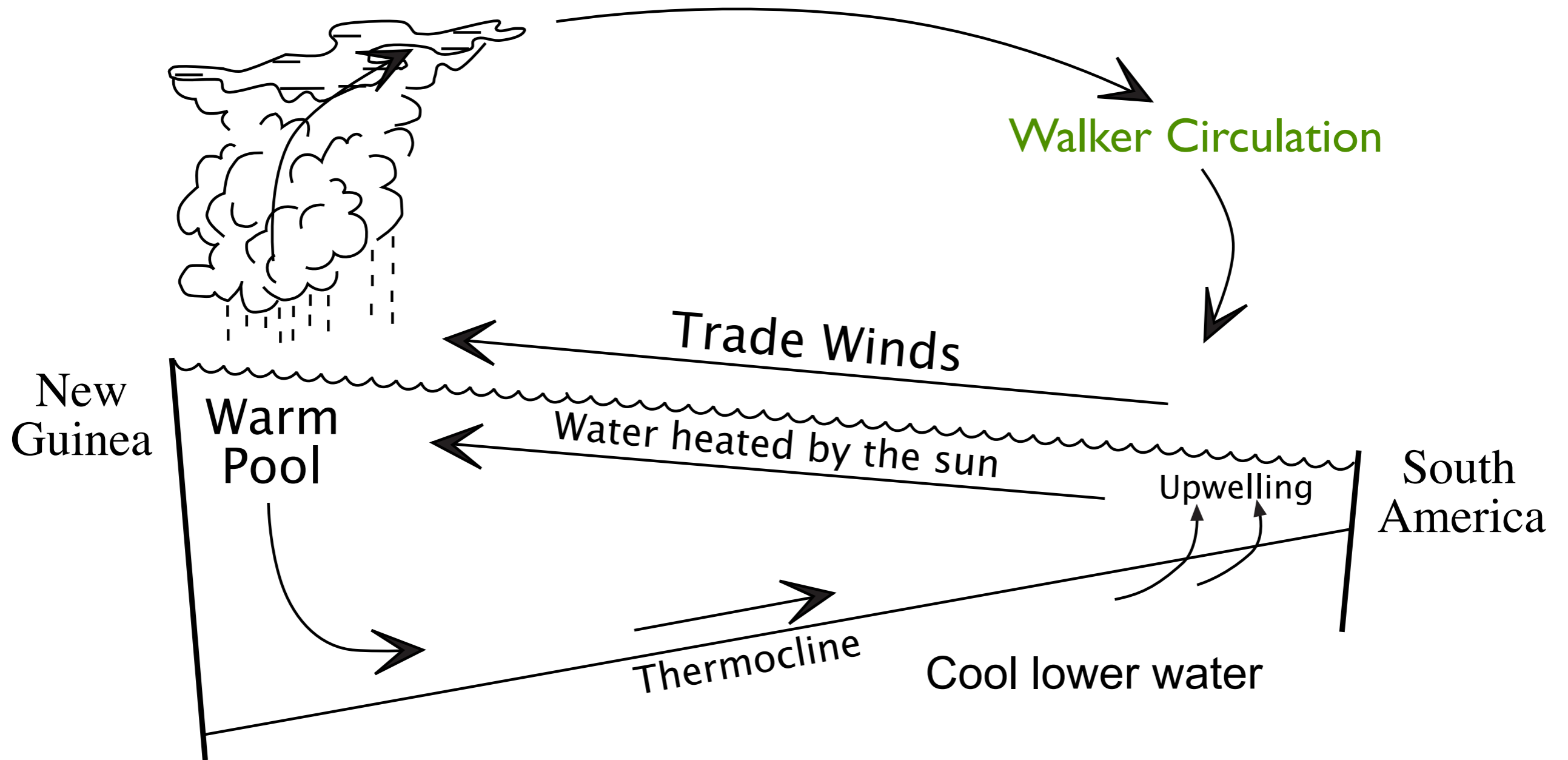
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Evolution of El Niño: The “normal” situation



Positive feedback: should be stable, but

We don't know why El Niños begin!

Theories fall roughly into two categories:

- The Pacific ocean-atmosphere system has a natural frequency of oscillation (perturbed by weather to be slightly irregular),
- The system is stable until an event is triggered by outside forcing.

This is a major subject of debate in the climate community today.

(Jadranka and Maristella's talks, to follow)

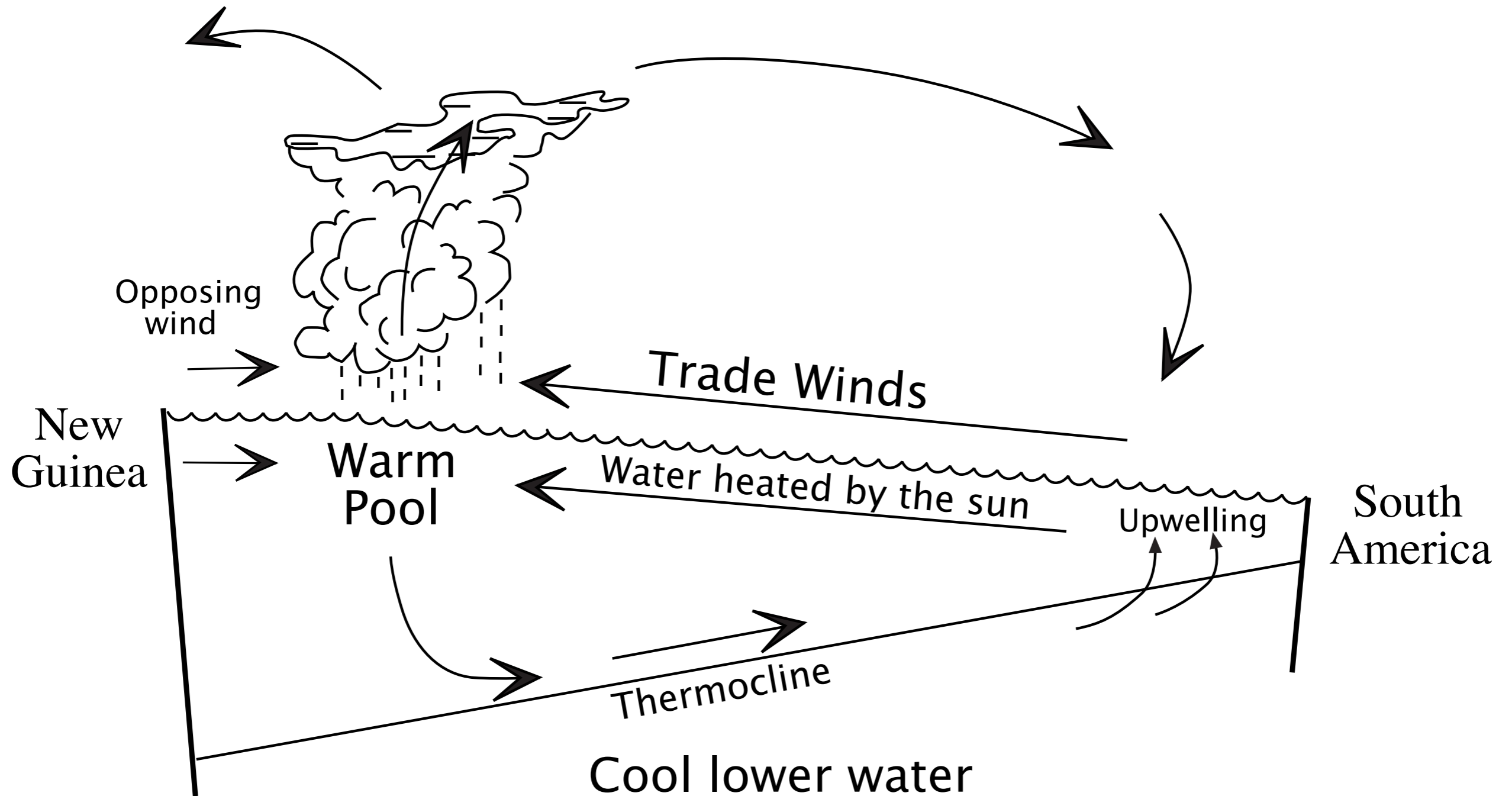
No one has ever predicted an El Niño before it has begun.

However, once an event begins, we have a good idea of how it evolves, which allows us to make socially-useful forecasts.

The effects of El Niños radiate outward from the tropical Pacific as waves through the atmosphere. These take relatively predictable paths, and are the basis for the forecasts you hear in the media.

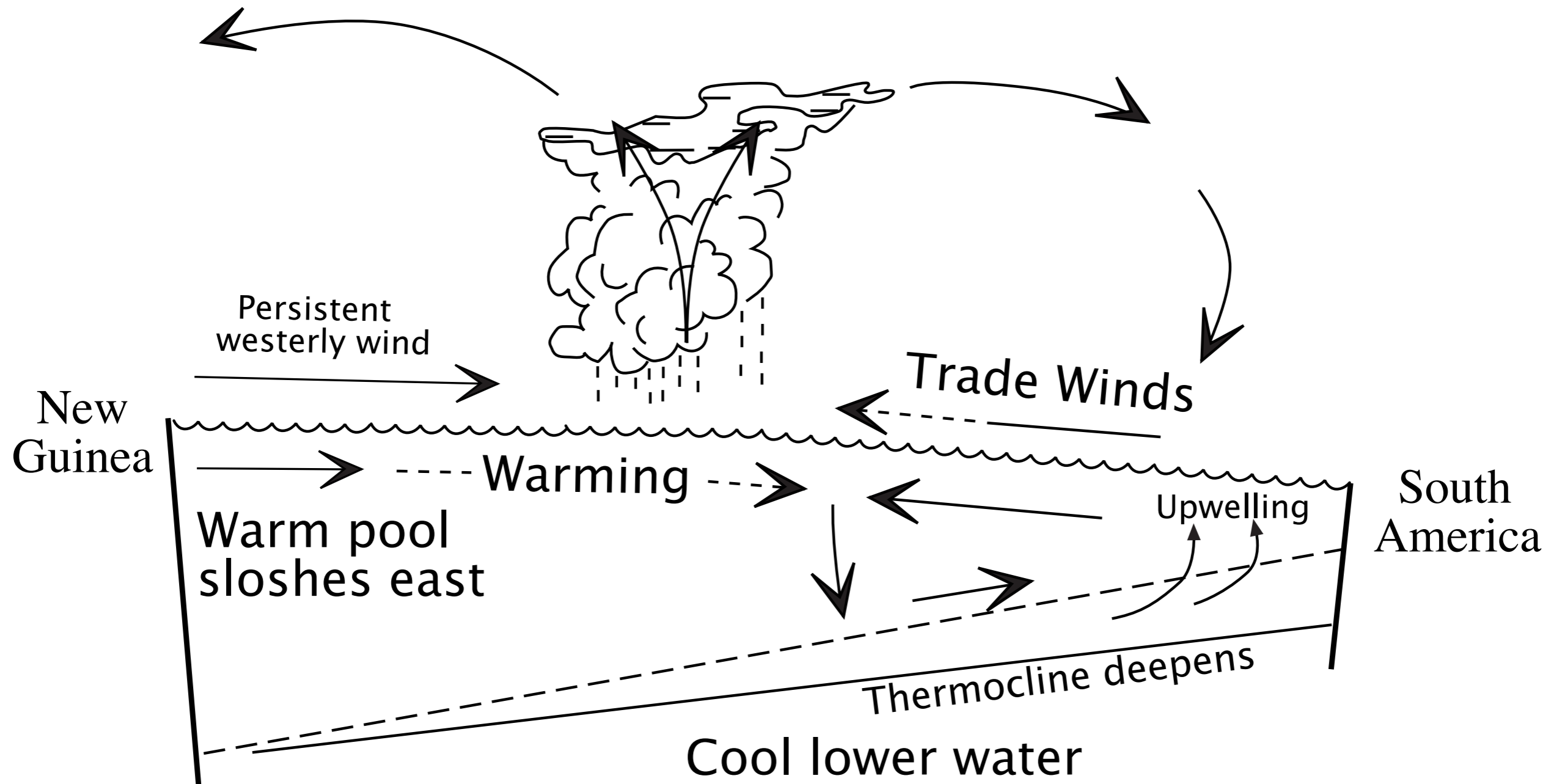
Schematic ocean-atmosphere interaction during El Niño onset:

A “coupled collapse” as the warm pool sloshes east



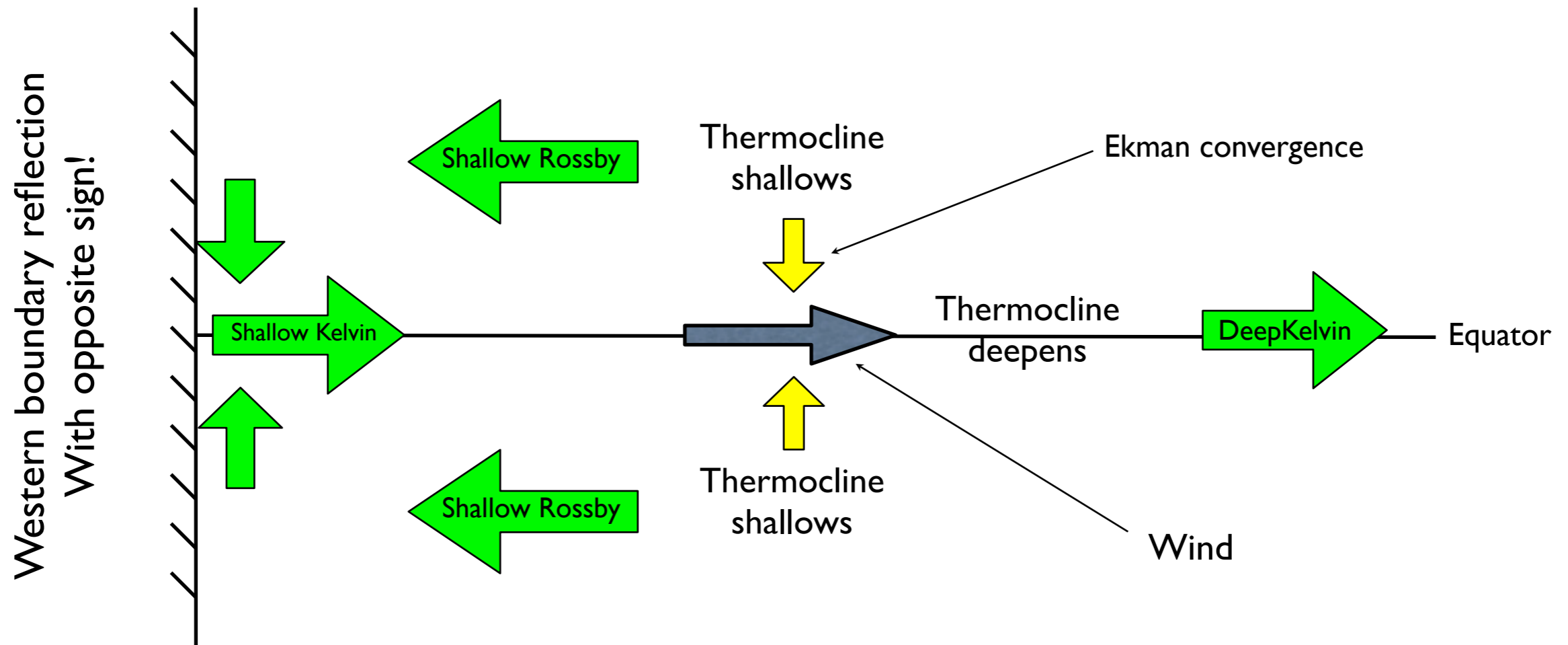
We don't know why El Niños start!

The peak of El Niño



Again a positive feedback. Why does it end?

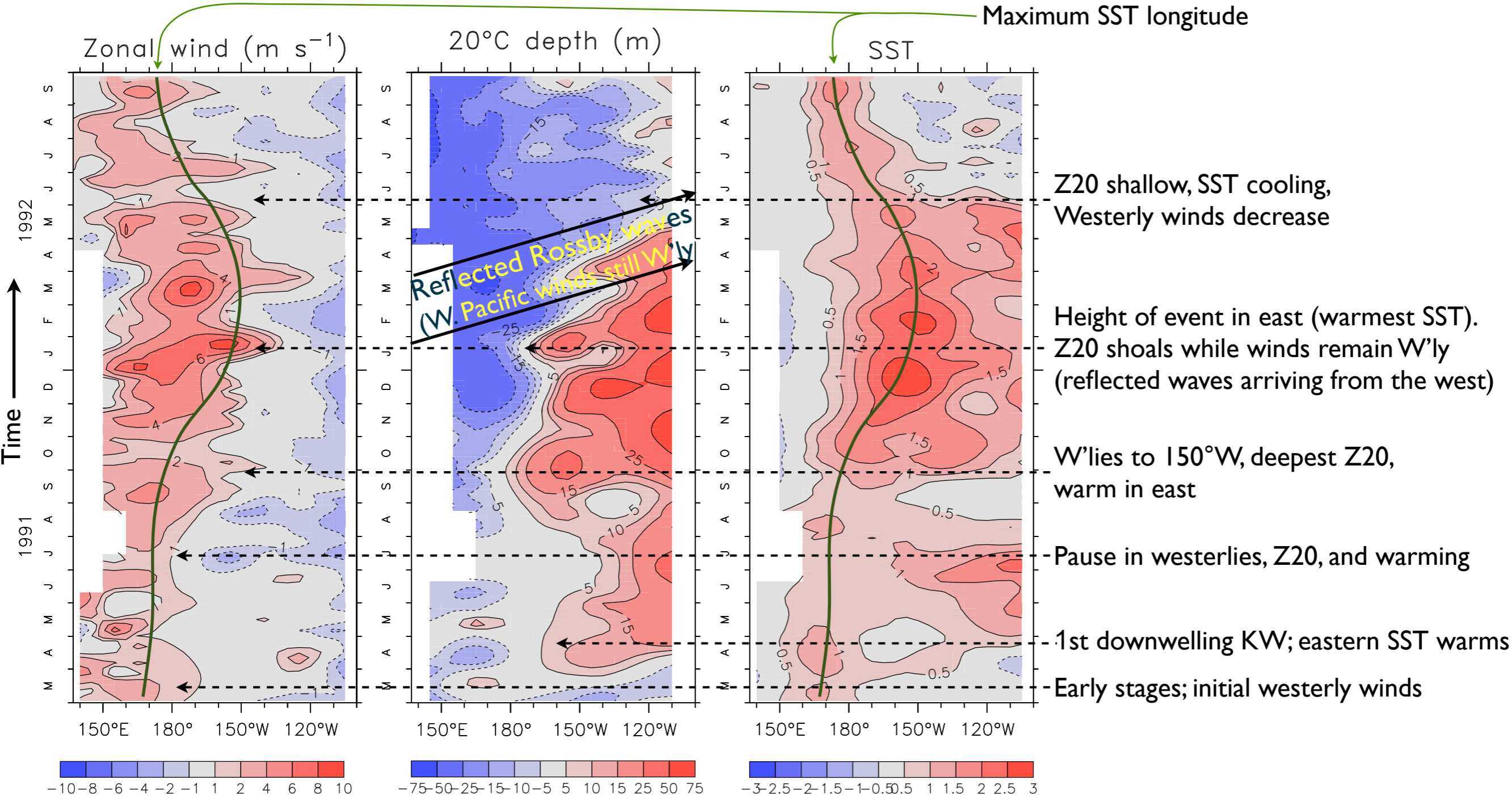
El Niño creates the seeds of its own destruction



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

(Jadranka's talk to follow)

Sequence of events during the El Niño of 1991-92



Why do El Niños end? Can the warm state just persist?

An El Niño event contains the **seeds of its own demise** (wave reflection).

Once the warm upper layer water has sloshed east, it leaks out, poleward along the American coast and also into the off-equatorial interior ocean.

(One might say that the climate “function” of El Niño events is to drain excess heat from the west Pacific warm pool.)

As the equatorial upper layer drains and thins, the thermocline comes closer to the surface and begins to cool the SST again.

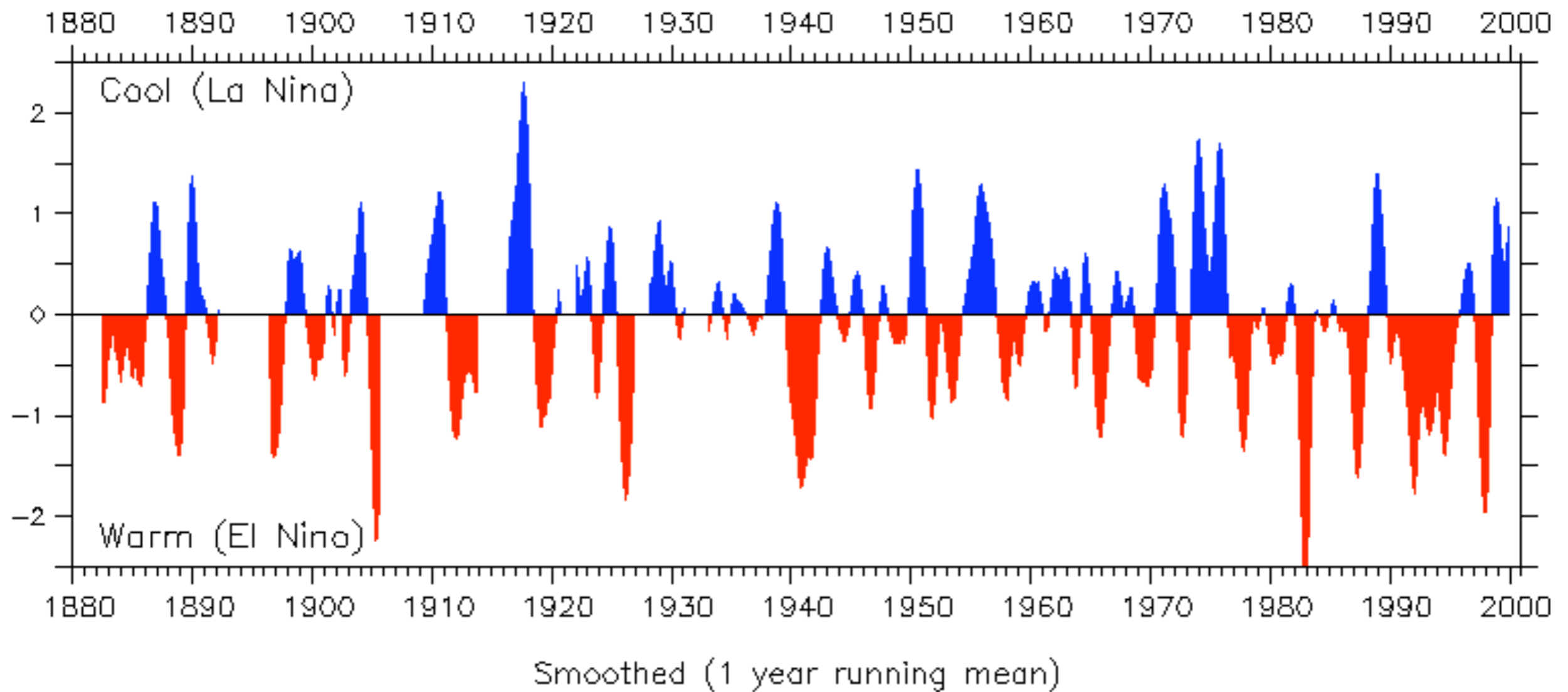
Cool SST reestablishes the trade winds, restoring the normal pattern.

(Jadranka's talk to follow)

Because the amount of warm water in the warm pool is limited, El Niños have a finite duration (9-12 months).

El Niño occurrences are irregular

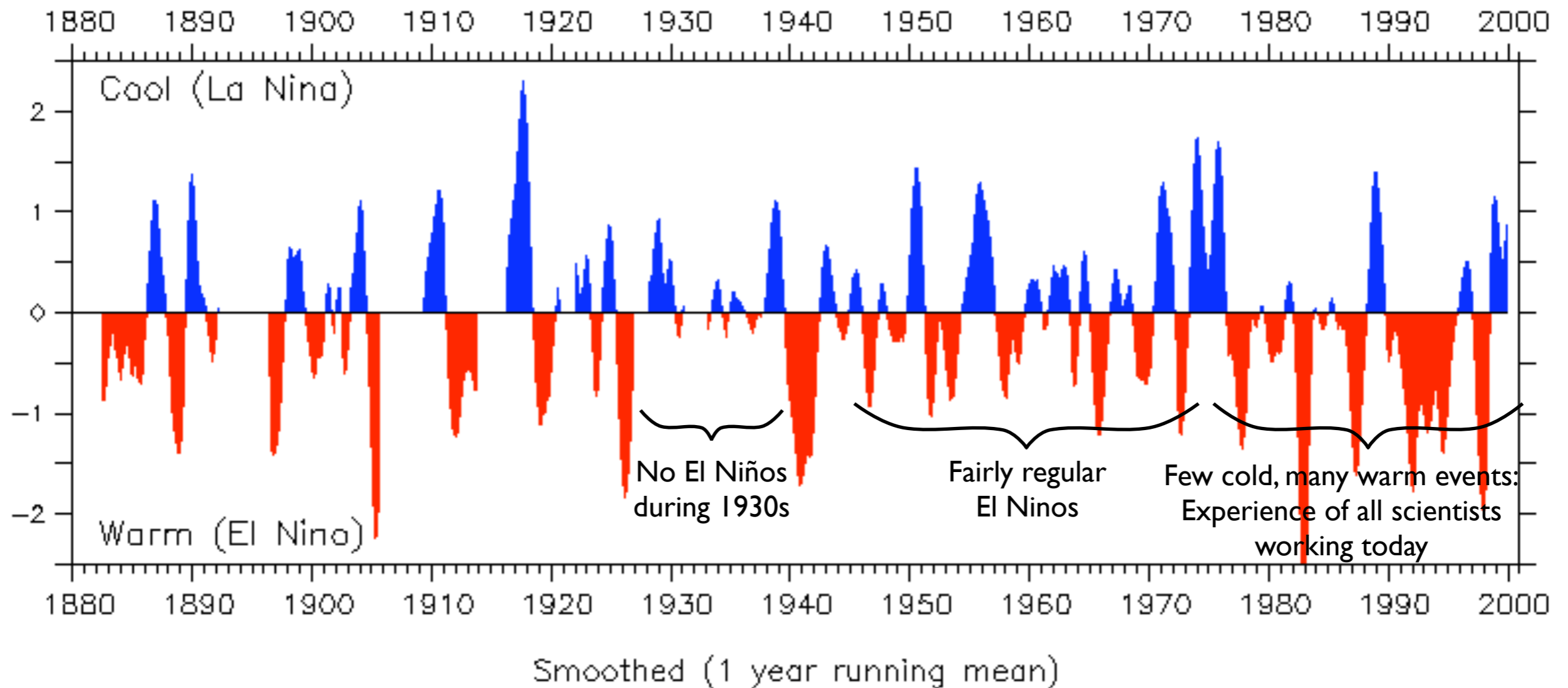
Southern Oscillation Index



Jadranka's talk to follow

El Niño occurrences are irregular

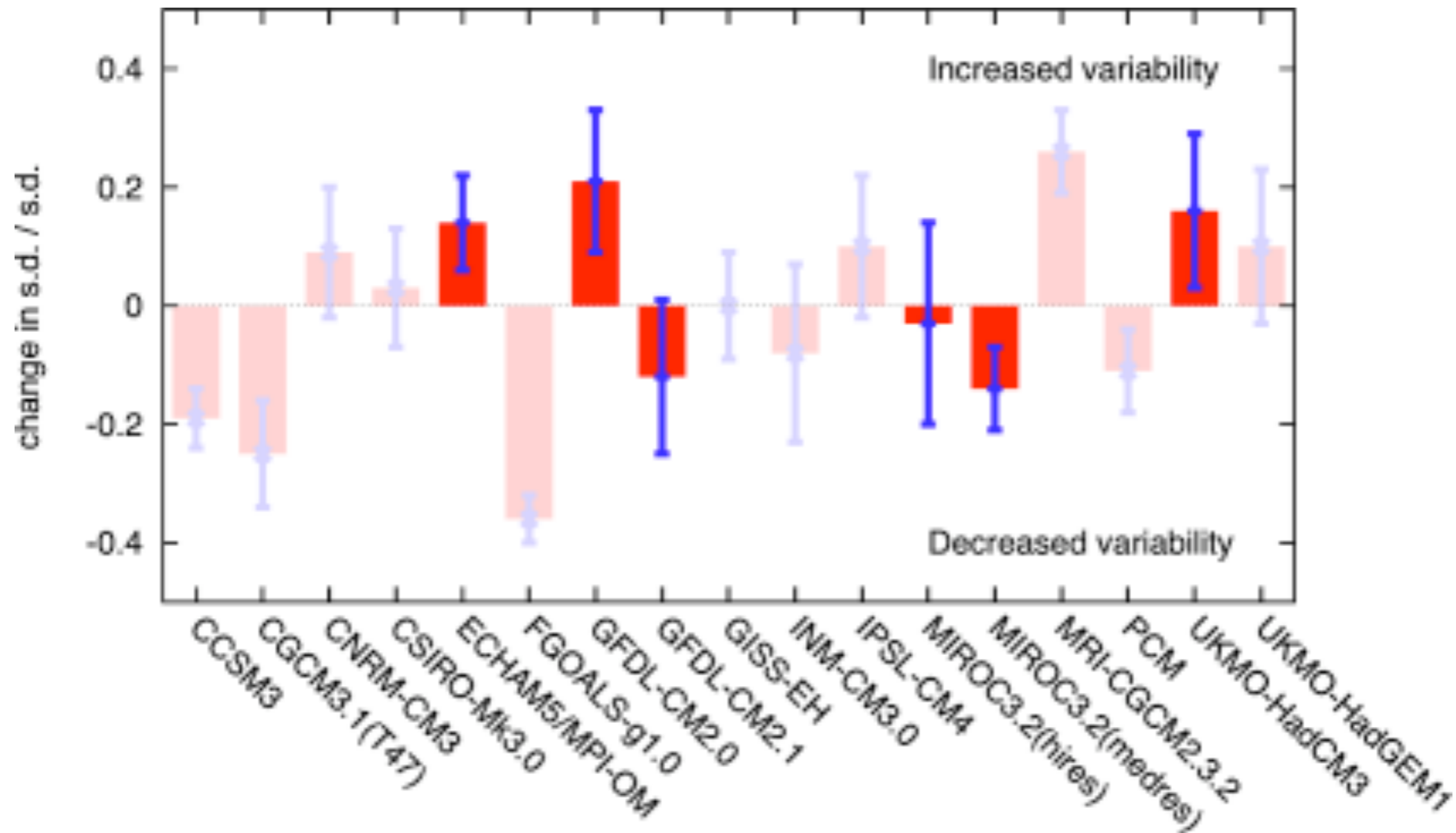
Southern Oscillation Index



Some caution on opinions ... bias due to personal experience???

ENSO variability in IPCC models

Relative change in ENSO variability in the IPCC 4AR models.
The most reliable models for the current climate are shaded red.



van Oldenborgh &
Collins (2007)
(KNMI & U.K. Met Office)

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.
- No one has ever predicted an El Niño in advance.
- El Niño events are self-limited, but the connection, if any, between events remains unclear.

(Jadranka's talk to follow)

- El Niños have occurred for at least $O(10^5)$ years, but we don't know if or how they have changed, nor if they will change under global warming.

Extra

Figures

Follow ...

The ocean absorbs less than 1 W/m² net

(About 0.5PW goes into the ocean)

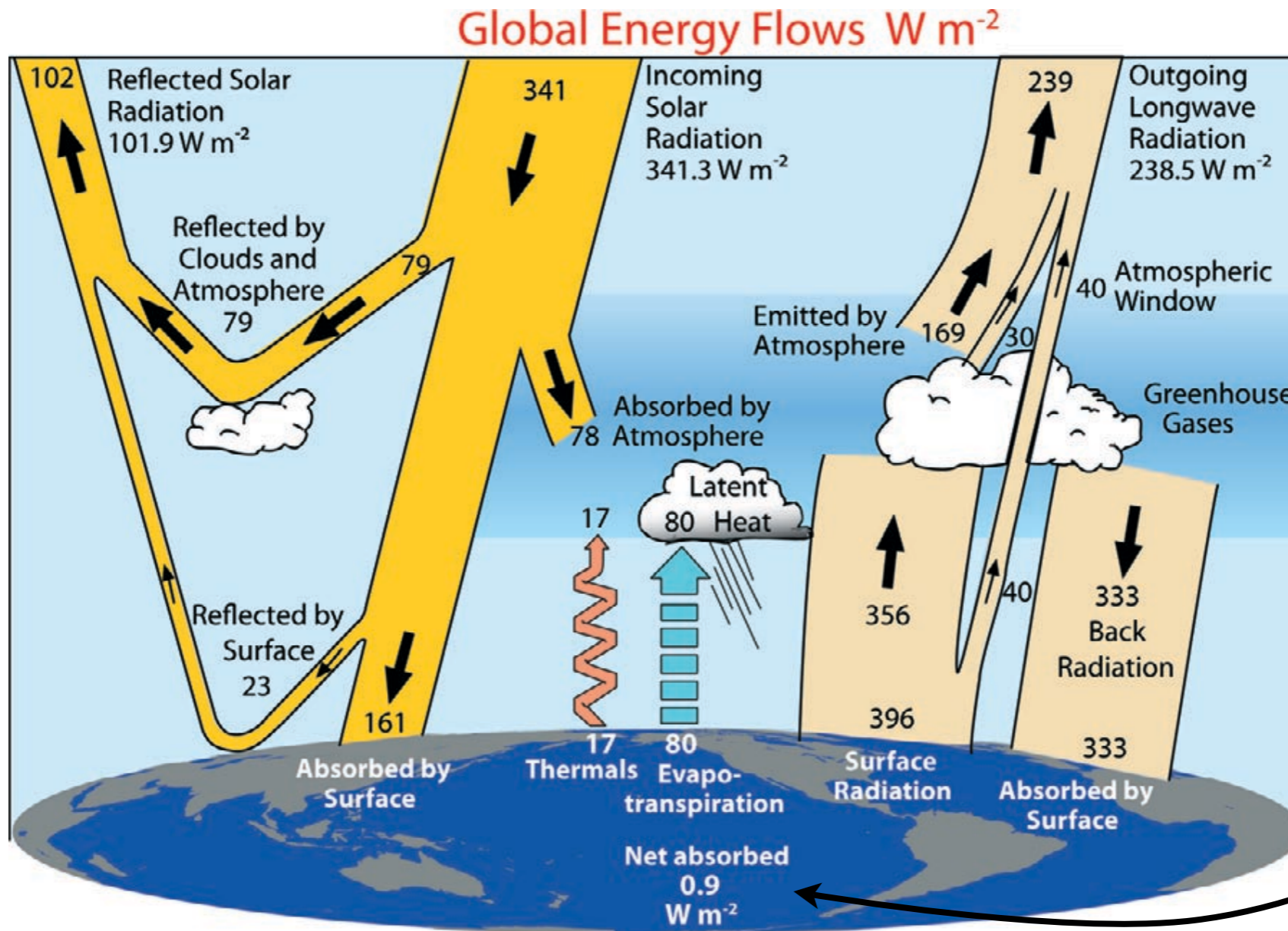
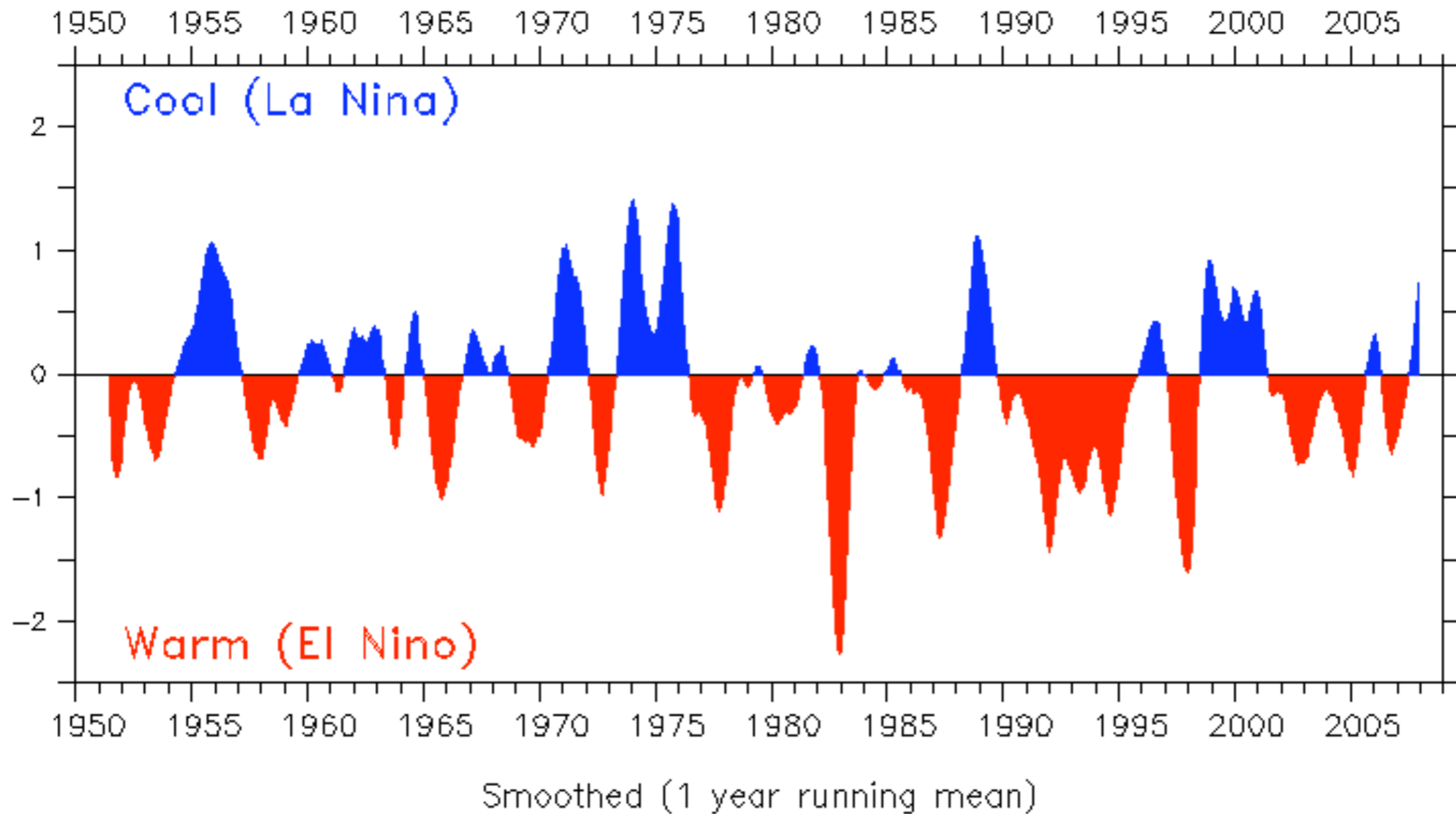


FIG. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m⁻²). The broad arrows indicate the schematic flow of energy in proportion to their importance.

Trenberth (2009)

El Niño occurrences are irregular

Southern Oscillation Index

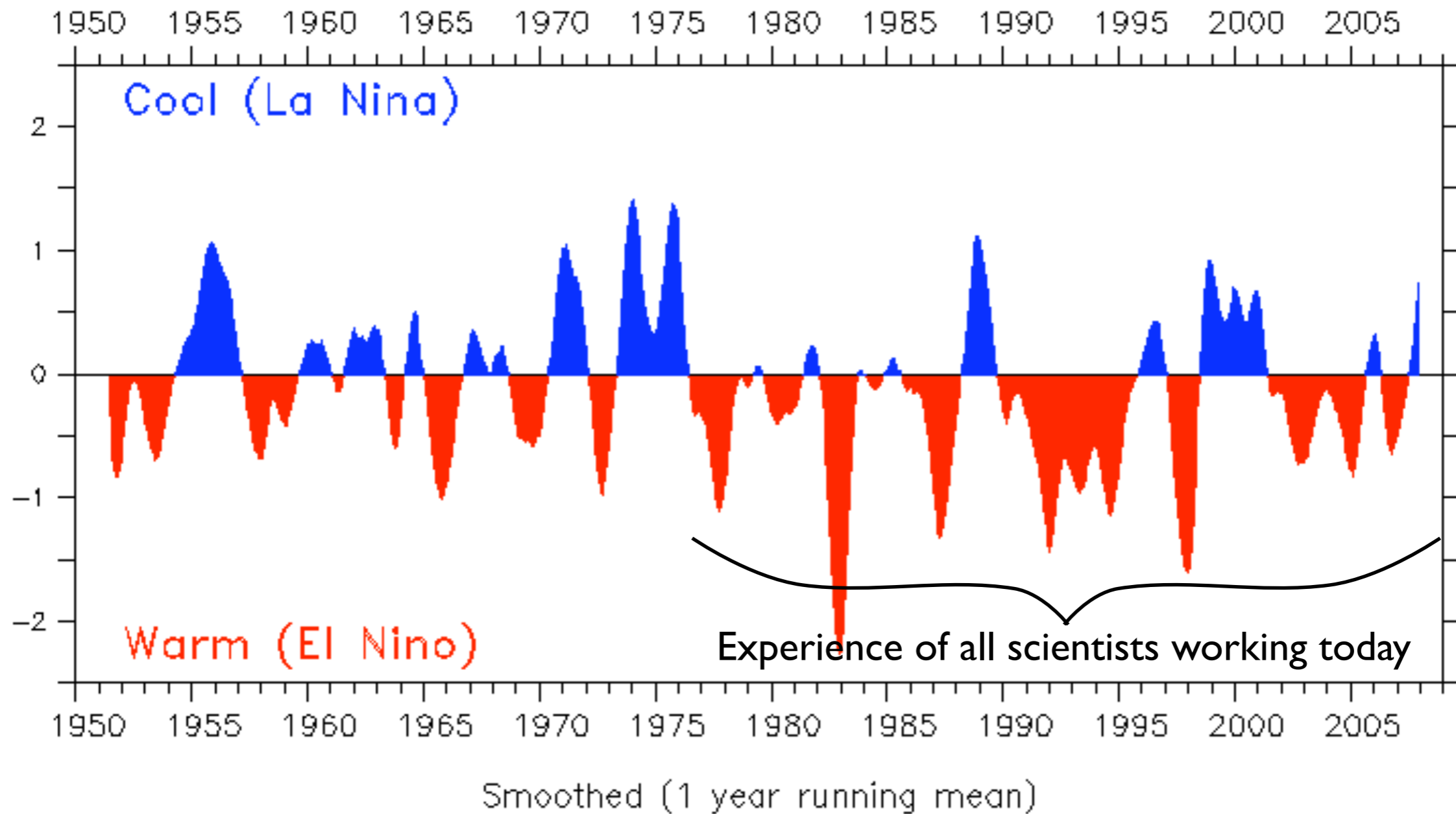


Jadranka's talk to follow ...



El Niño occurrences are irregular

Southern Oscillation Index



Jadranka's talk to follow ...



Remarks by Señor Federico Alfonso Pezet at the Sixth International Geographical Congress (London, 1895):

In the year 1891, Señor Dr Luis Carranza, President of the Lima Geographical Society, contributed a small article to the Bulletin of the Society, calling attention to the fact that a countercurrent flowing from north to south had been observed between the ports of Paita and Pascamayo.

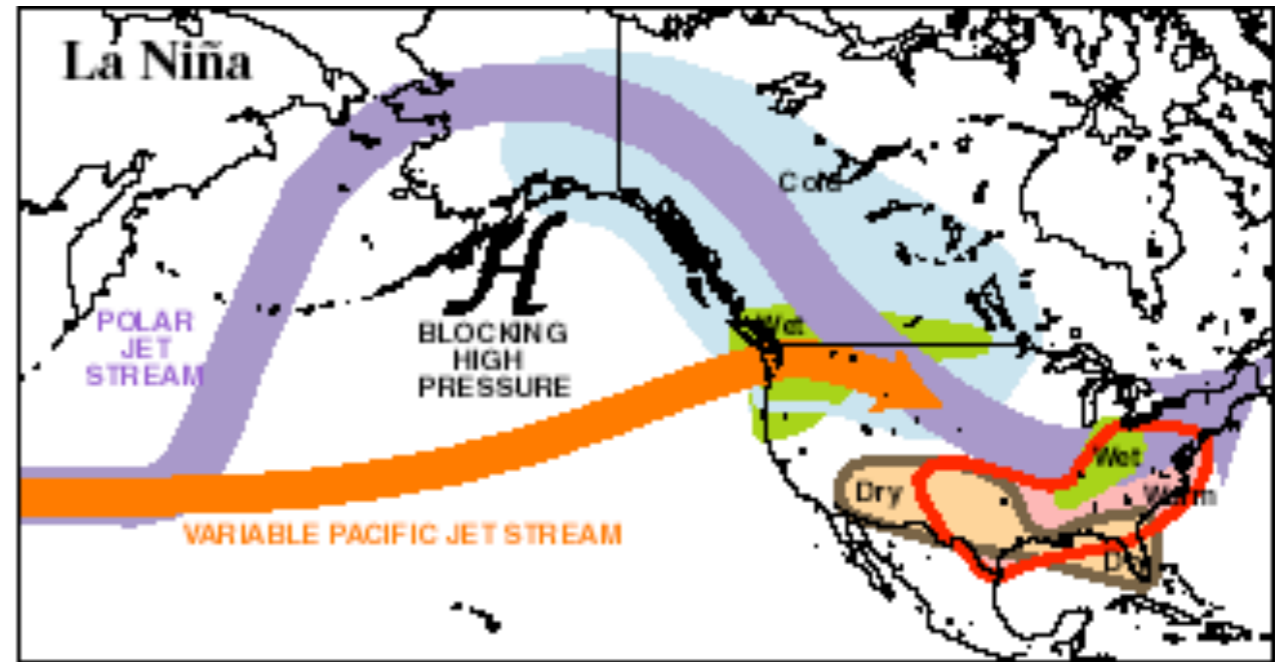
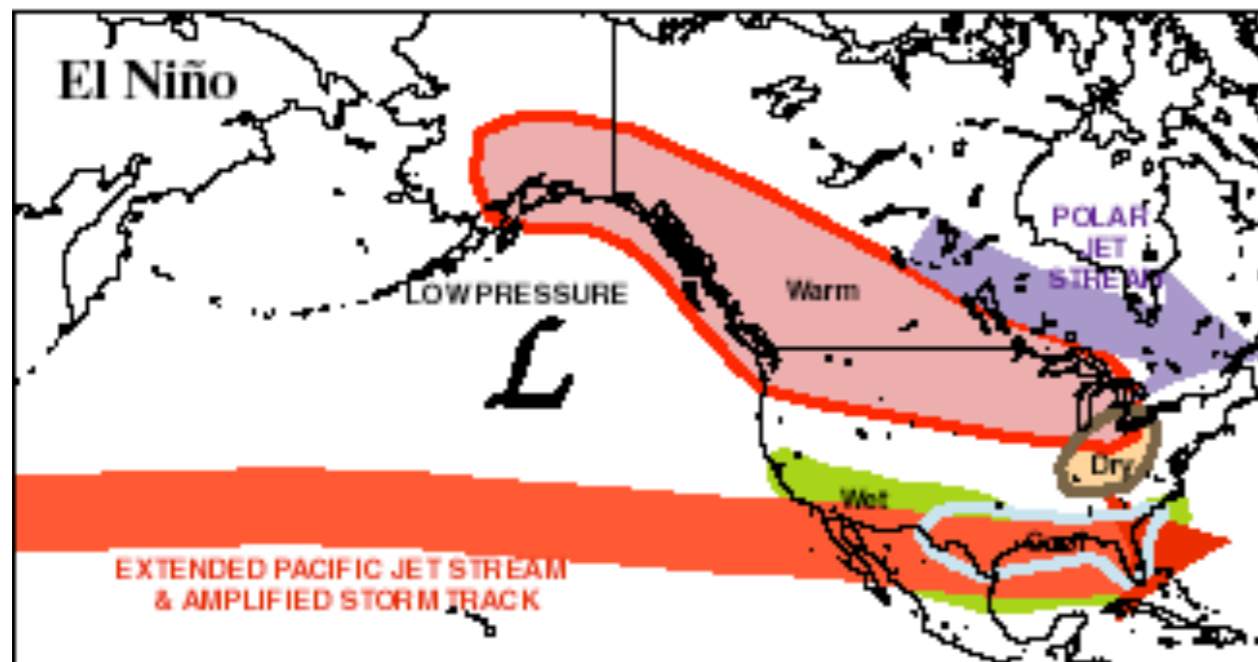
The Paita sailors, who frequently navigate along the coast in small craft, either to the north or south of that port, name this countercurrent the current of “El Niño” because it has been observed to appear immediately after Christmas.

During the mid-20th century, the usage of the term “El Niño” changed. The name for a local, seasonal phenomenon was adopted for the basin-scale, interannual phenomenon.

Recently, the term “La Niña” has been used to refer to the opposite (cold) phase, though it is unclear that this is really an oscillation (it may be more like a series of events).

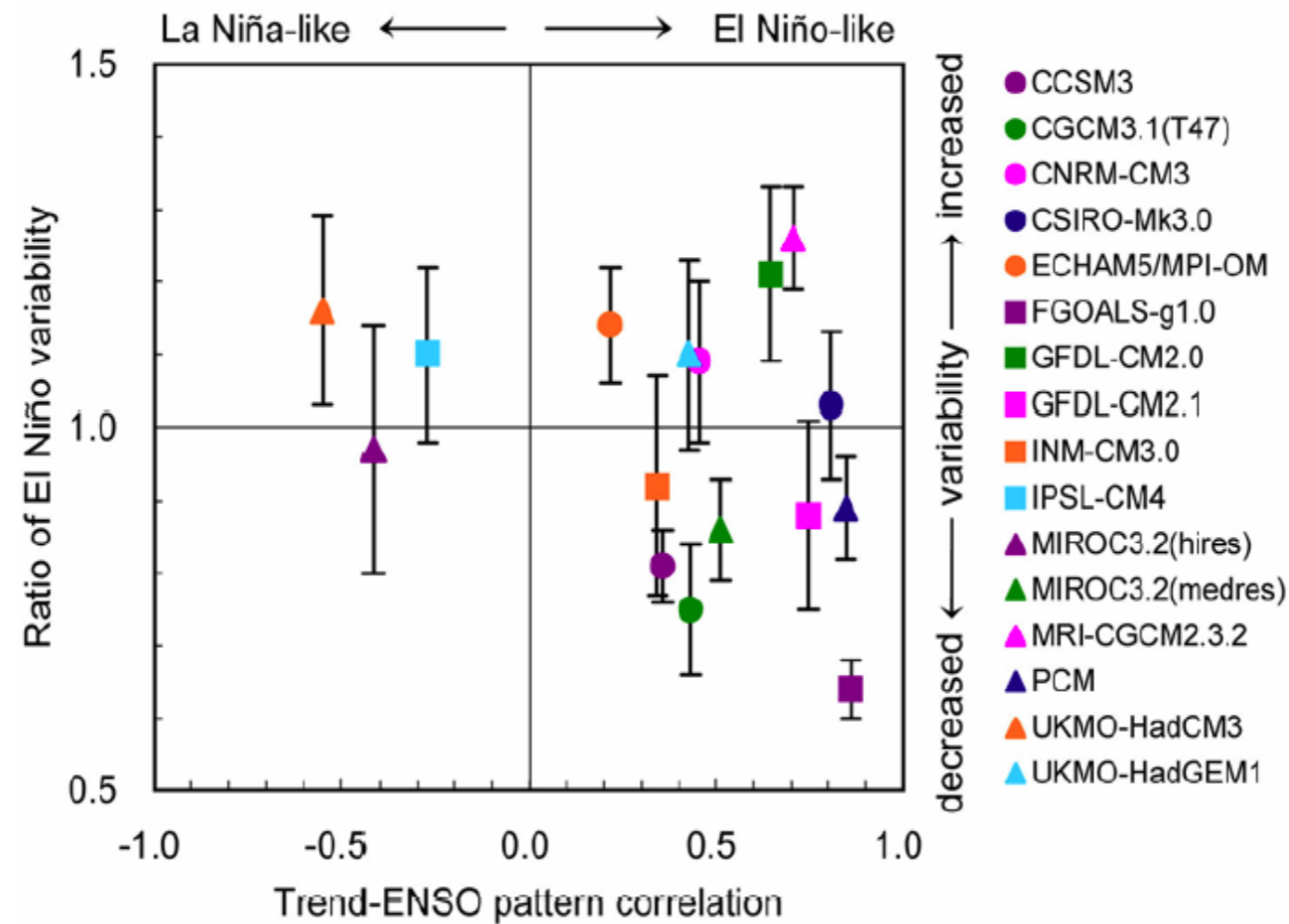
How are El Niño's effects spread from the tropics?

The west Pacific warm pool is a principal heat source driving much of the global winds. When it shifts east, it distorts the jet streams, much as a rock placed in a creek causes waves that extend well downstream from the rock itself.



In North America, the effects of the warm SST during El Niño are not felt directly. Instead, mid-latitude weather is modified because the eastward-shifted warm water changes the path of the winter jet streams that bring us our weather systems.

More El Niño-like mean state, but no signal for El Niño variability change



Mean tropical Pacific climate change

a weak shift towards average background conditions which may be described as "El Niño-like" with sea surface temperatures in the central and east equatorial Pacific warming more than those in the west, with weakened tropical circulations and an eastward shift in mean precipitation

El Niño

there is no consistent indication at this time of discernable changes in projected ENSO amplitude or frequency in the 21st century

ENSO climate change forecasts are highly uncertain!

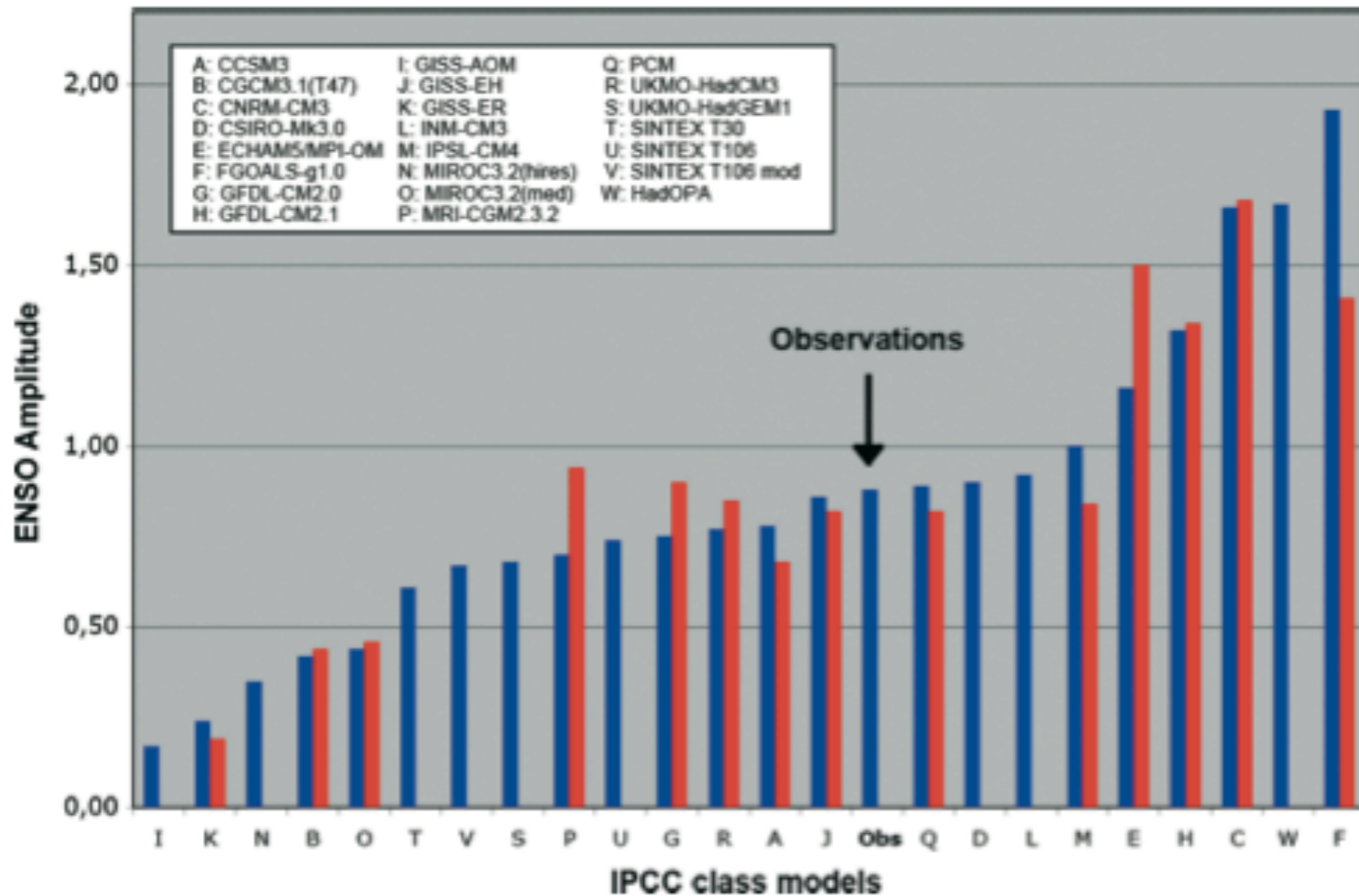
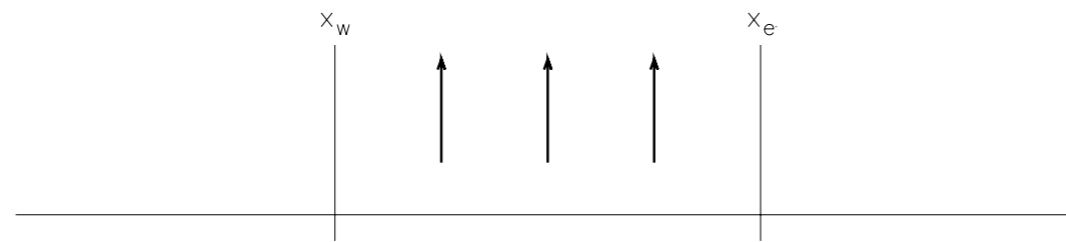


FIG. 5. ENSO amplitude in 23 coupled CGCMs, including those used for the IPCC AR4, as measured by the Niño-3 SST anomaly std dev in preindustrial simulations (blue bars) and equilibrated $2 \times \text{CO}_2$ scenarios (red bars).

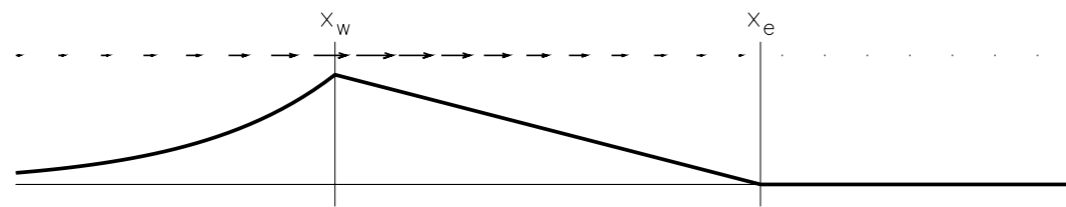
Winds are westerly under convection

The Clarke (1994) mechanism works as follows. Consider an imposed patch of rising air over an equatorial ocean (say it is convection over a patch of warm SST).



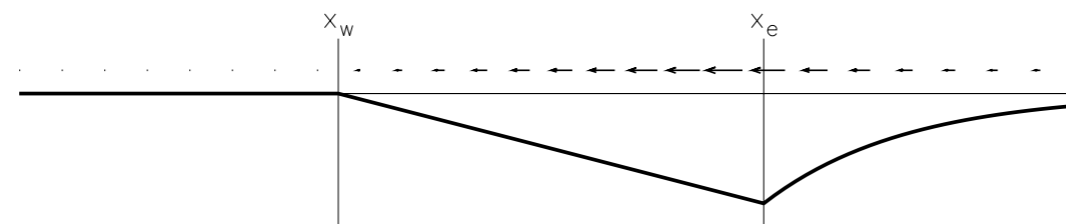
The patch is located between longitudes x_w and x_e . Within the patch: $w_z > 0$, so $u_x < 0$.

Since the system is linear, consider the Rossby and Kelvin responses separately, integrating along wave characteristics. For the Rossby response, there is no signal east of x_e . From x_e to x_w , the Rossby zonal wind increases westerly, since $u_x < 0$. West of x_w , the Rossby westerlies decay exponentially to the west:

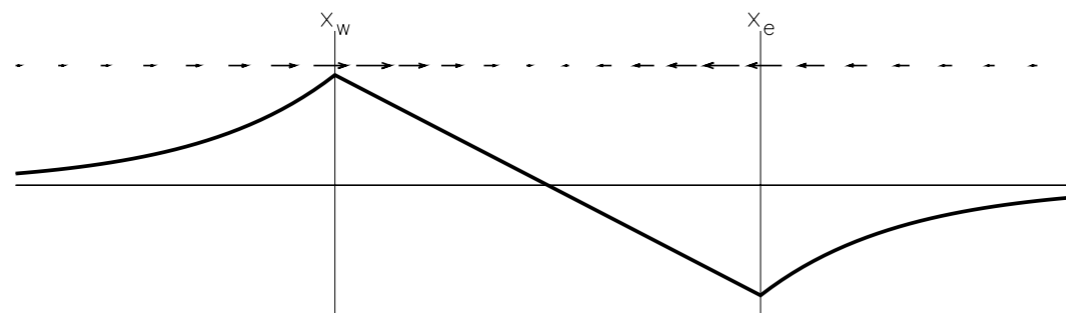


The line graphs the zonal winds, and the vectors display the same winds.

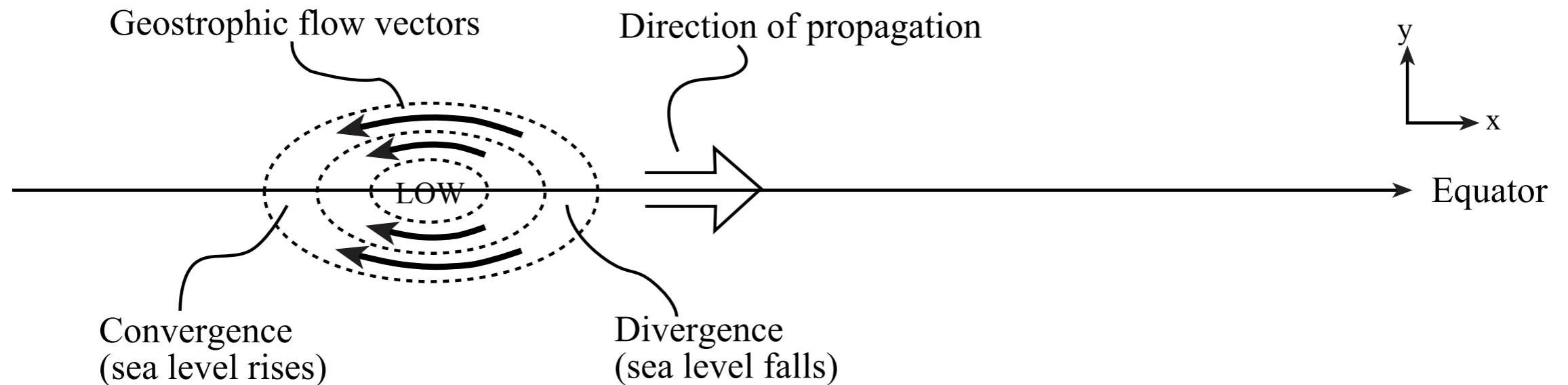
For the Kelvin response, do the same kind of integration, but from the west. There is no Kelvin response west of x_w . From x_w to x_e , the Kelvin zonal wind increases easterly, since $u_x < 0$. East of x_e , the Kelvin easterlies decay exponentially:



If the Kelvin and Rossby responses are equal, the sum is symmetric. Winds converge equally from both sides into the center of the box:



The mechanism of equatorial Kelvin wave propagation



For a sea level depression (shallow thermocline; dashed contours) spanning the equator, the geostrophic flow is westward in both northern and southern hemispheres (dark arrows). These currents move mass from the east side of the depression to the west. As a result, sea level falls in the east (deepening the depression there), and rises in the west (filling in the depression there). Some time later, the depression has moved east. This mechanism works similarly for a sea level hump (deep thermocline): The flow directions and convergence/divergence patterns are reversed, but the propagation direction is always eastward.

⇒ Equatorial Kelvin waves are the result of the change of sign of f across the equator.

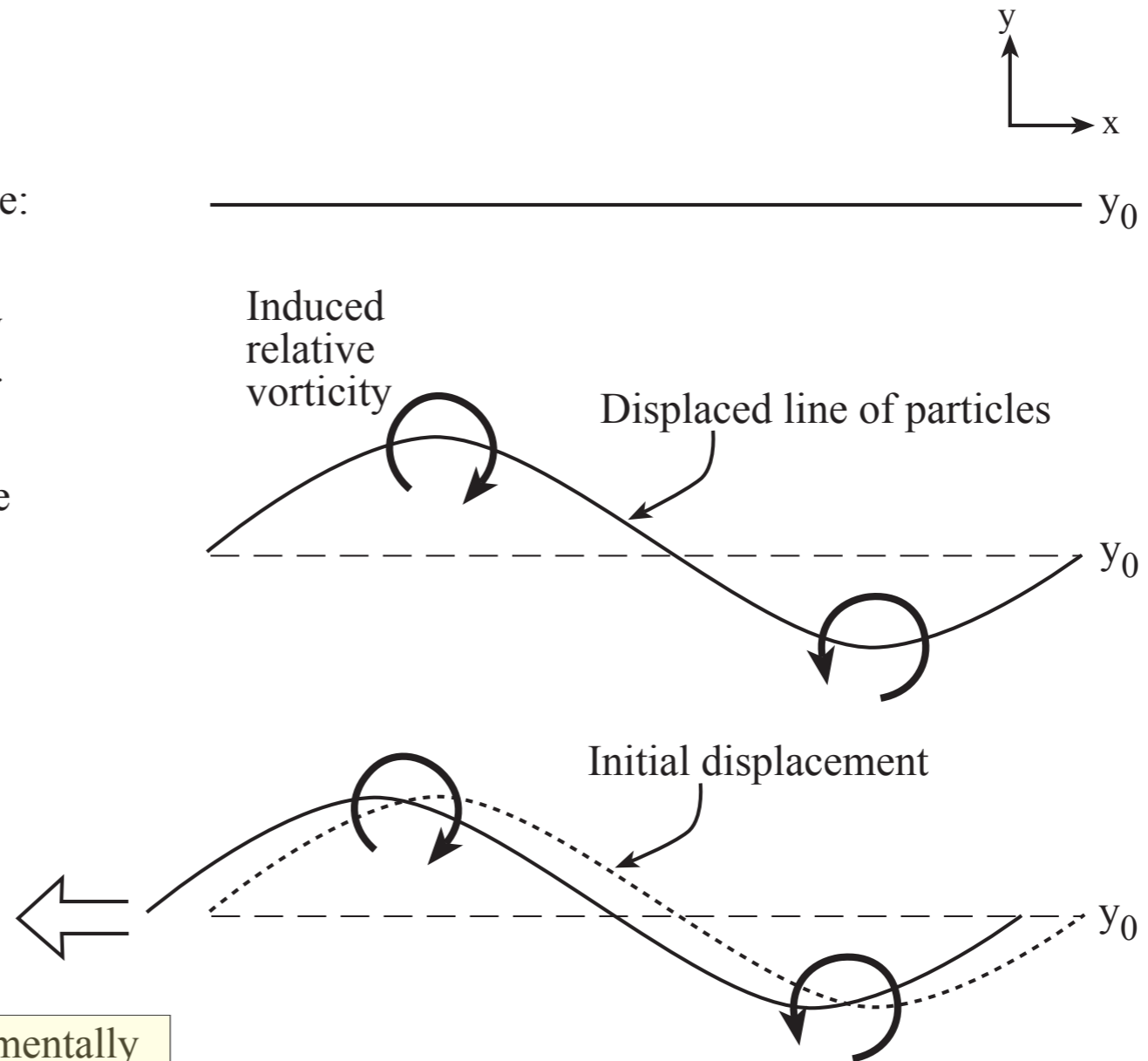
The mechanism of Rossby wave propagation

Consider a line of fluid particles, initially at rest along a line of latitude in the northern hemisphere:

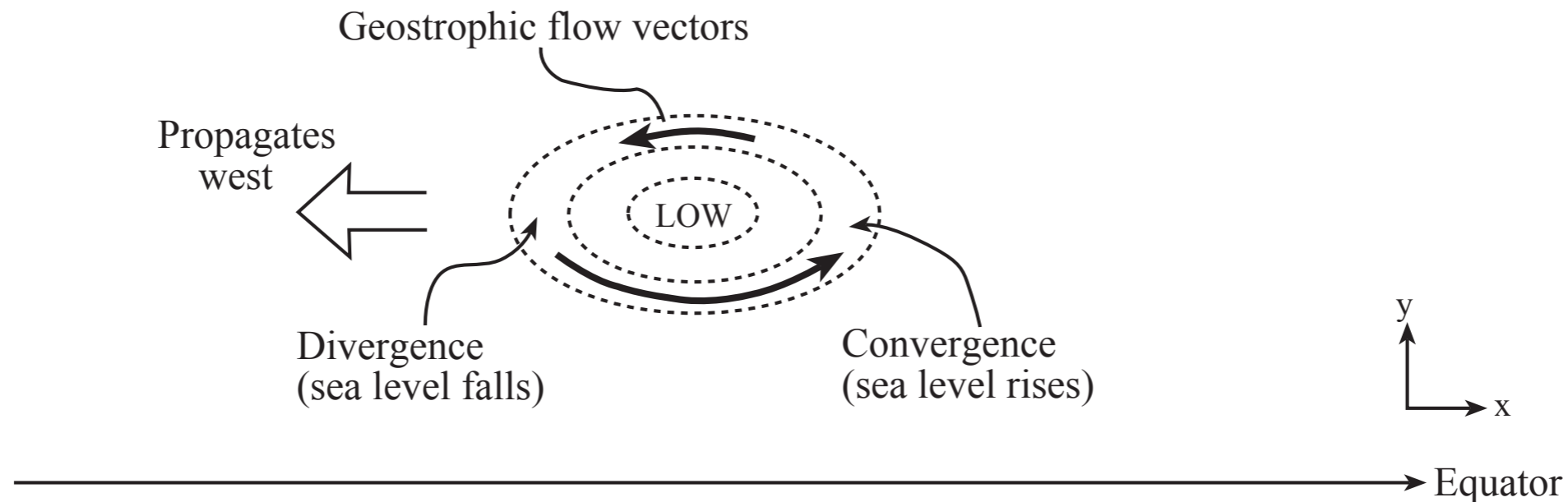
The line is displaced meridionally by an external forcing (solid line). Conserving total vorticity ($\zeta+f$), particles displaced northward, where f is larger, acquire negative (clockwise) vorticity relative to surrounding water, while those displaced southward acquire positive relative vorticity:

The acquired relative velocities move the displaced line of particles to the west:

⇒ Rossby waves depend fundamentally on the variation of f with latitude.



Rossby propagation of a sea level depression (North)



For a sea level depression (shallow thermocline; dashed contours) in the northern hemisphere, the geostrophic flow is counterclockwise (dark arrows).

The transport is stronger on the equatorial side, because f is smaller there.

Thus, the net transport moves mass from the west side of the depression to the east.

As a result, sea level falls in the west (deepening the depression there), and rises in the east (filling in the depression there).

Some time later, the depression has moved west.

This mechanism works similarly for a sea level hump (deep thermocline):

The flow directions and convergence/divergence patterns are reversed, but the propagation direction is always westward.

⇒ The $1/f$ dependence of geostrophic transport makes off-equatorial anomalies propagate west.

Equatorial Kelvin reflection to Rossby waves at an eastern boundary

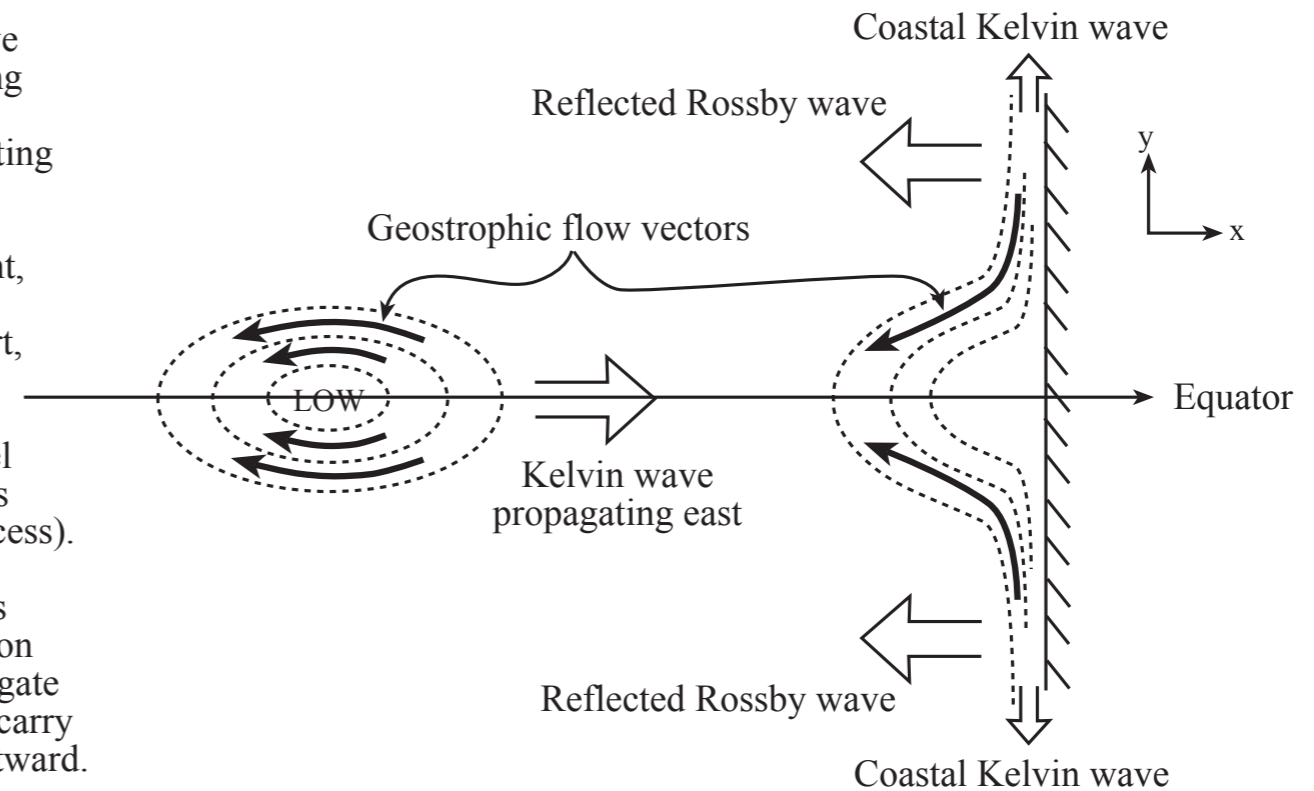
The constraint is mass conservation:

$$\int_{-\infty}^{\infty} u dy = 0$$

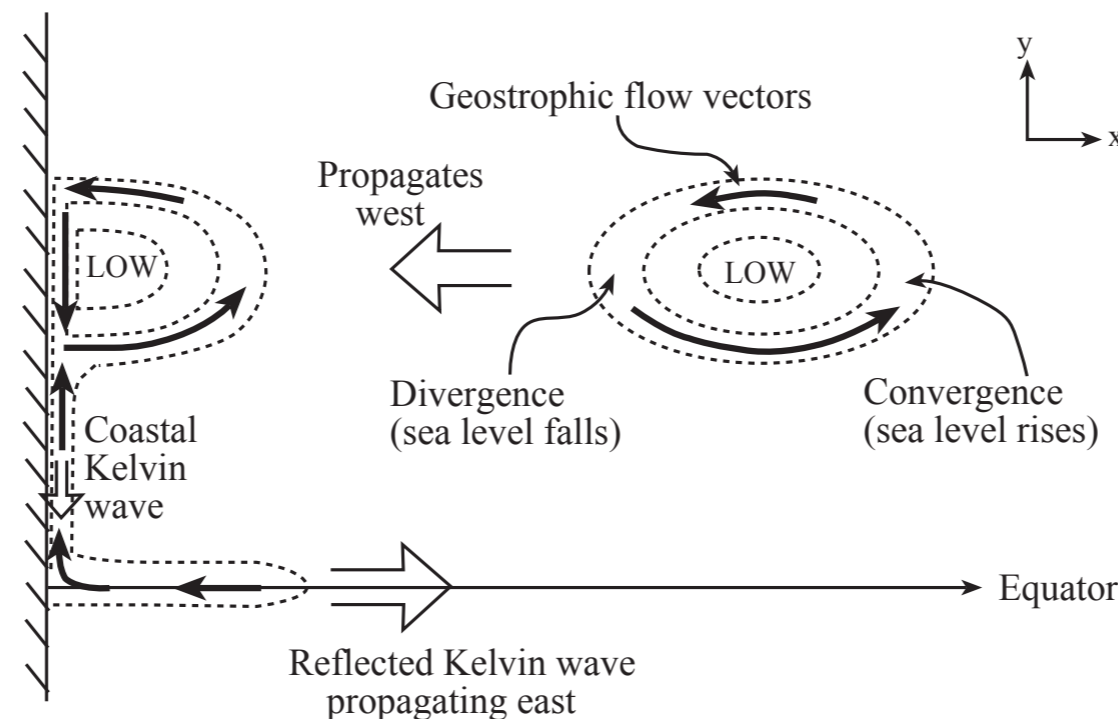
An example of a Kelvin wave (sea level depression) arriving at an eastern boundary. The Kelvin wave is transporting mass westward.

To satisfy the mass constraint, the needed inflow comes via equatorward coastal transport, which propagates poleward as coastal Kelvin waves. These carry the low-sea-level signal poleward. (Some mass "leaks" poleward in this process).

The coastal signal also forms the eastern boundary condition for Rossby waves that propagate west, off the equator. These carry the low-sea-level signal westward.



Rossby reflection to equatorial Kelvin waves at a western boundary

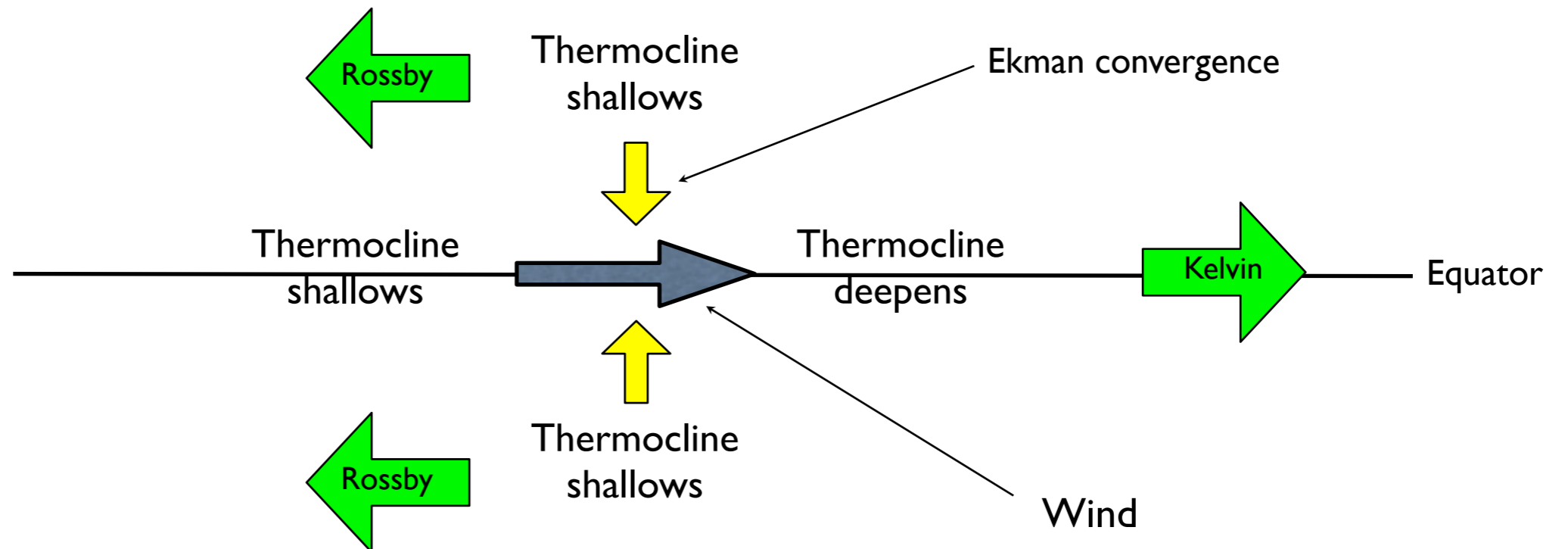


An example of a Rossby wave (sea level depression) arriving at a western boundary. The Rossby wave is transporting mass eastward.

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).

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)