El Niño: The ocean in climate

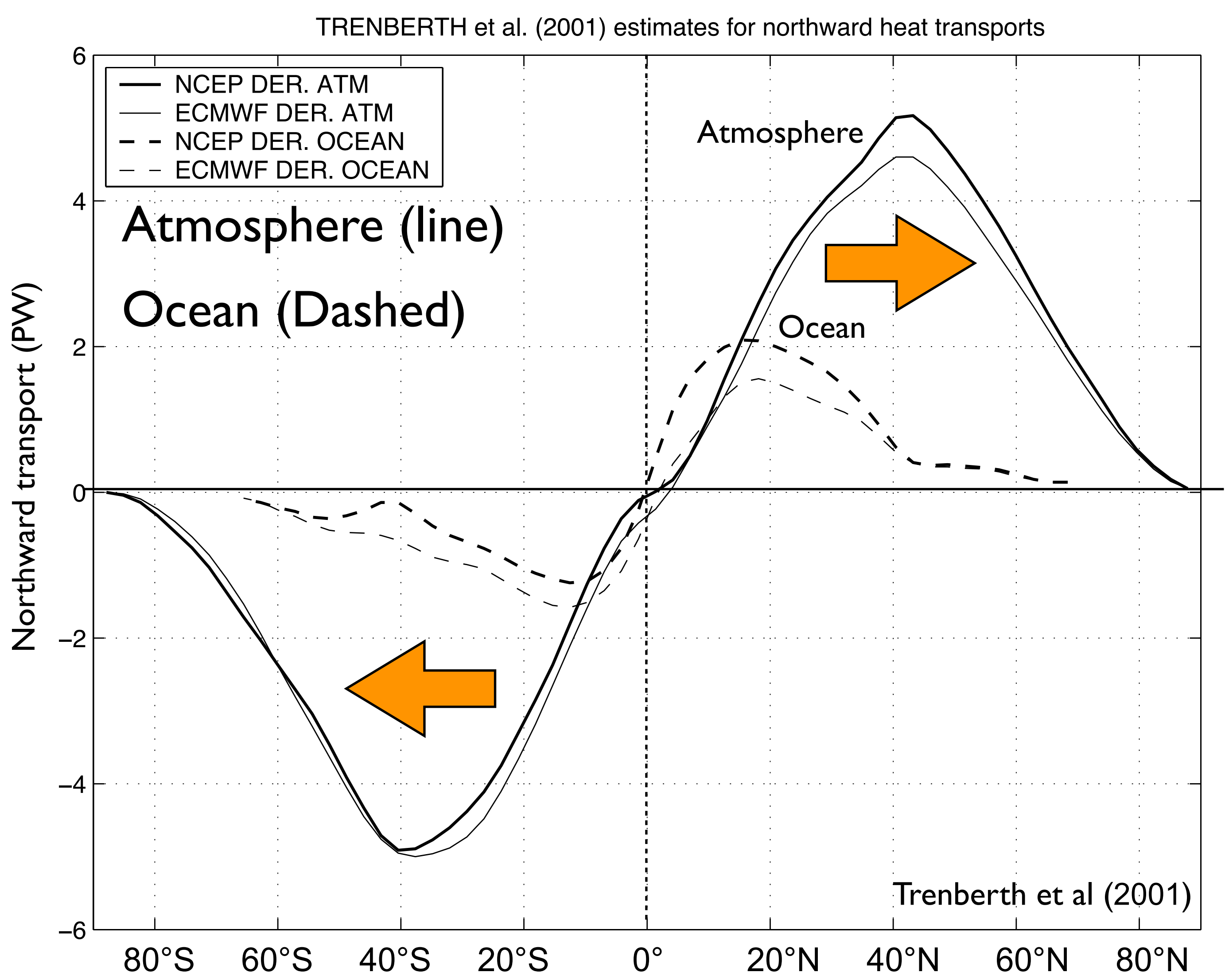
We live in the atmosphere: where is it sensitive to the ocean?

→ The tropics!

El Niño is the most spectacular short-term climate oscillation.
It affects weather around the world,
and illustrates the many aspects of O-A interaction

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

Ocean and atmosphere heat transports



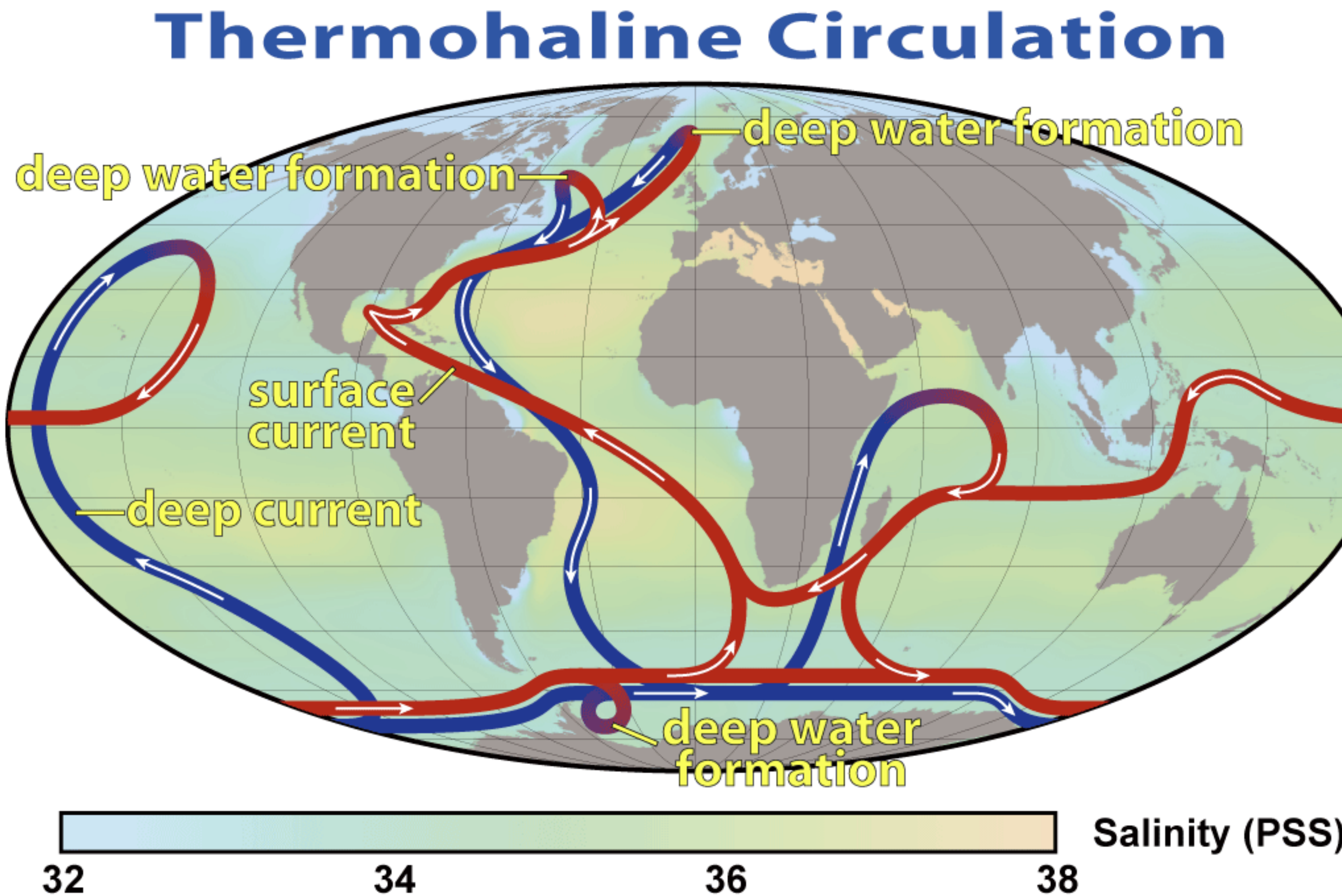
Most of the poleward transport
occurs in mid-latitude winter storms near 40°S/N.
Only in the tropics is the ocean really important.

Heat transport is poleward in both ocean and atmosphere:

The role of the O-A system is to move excess heat from the tropics to the poles, where it is radiated to space.

Much recent interest in the "global conveyor belt"

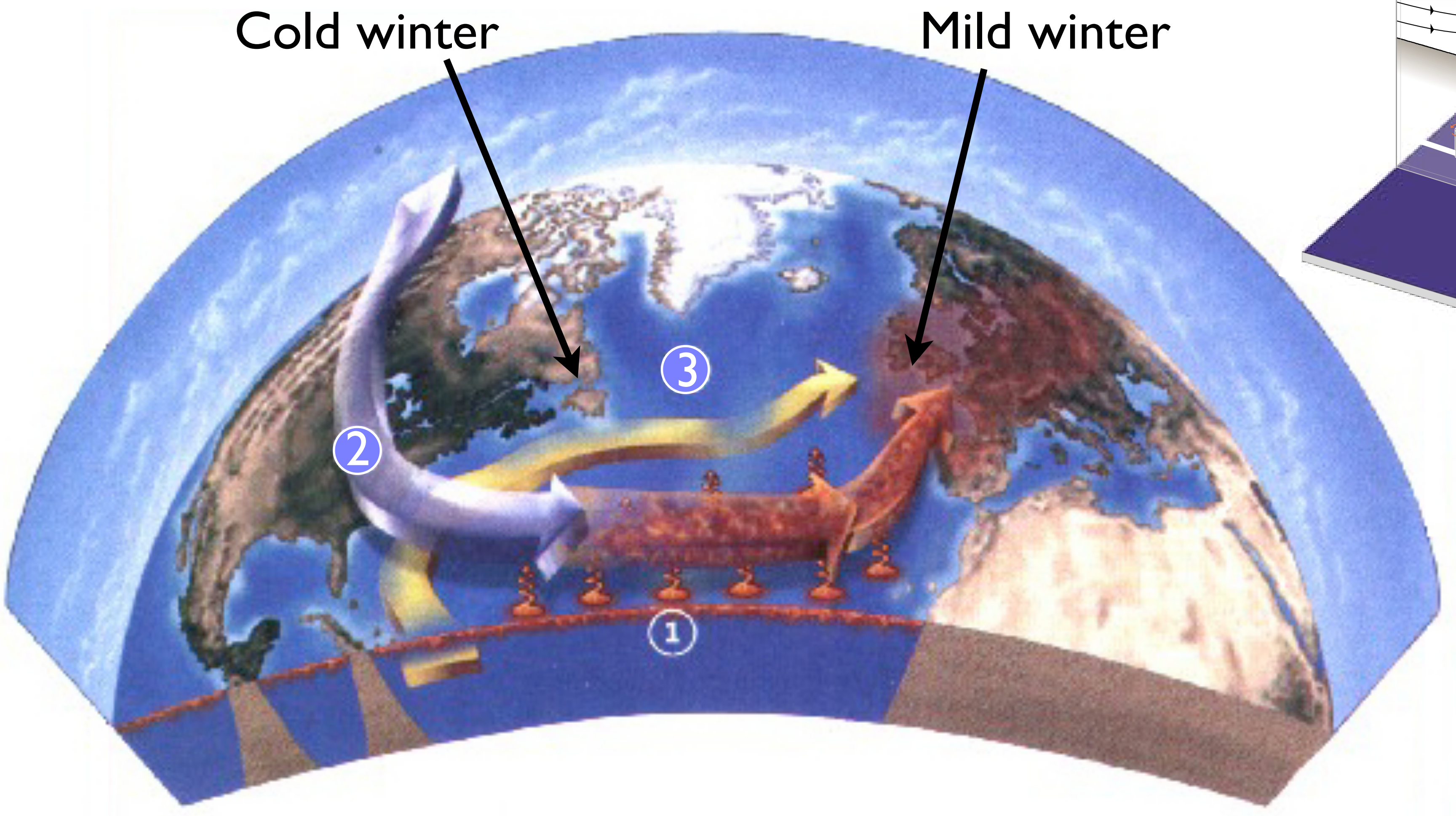
But the timescales are very slow

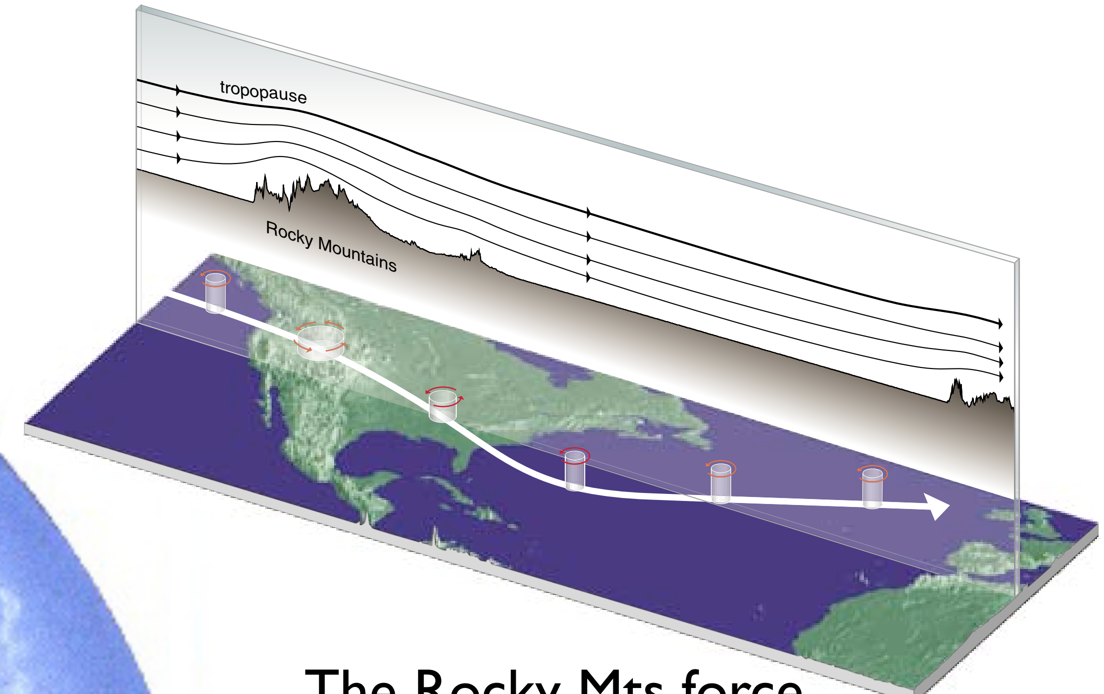


Does the Gulf Stream warm Europe?

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

Why is Ireland warmer than Labrador in winter?





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:

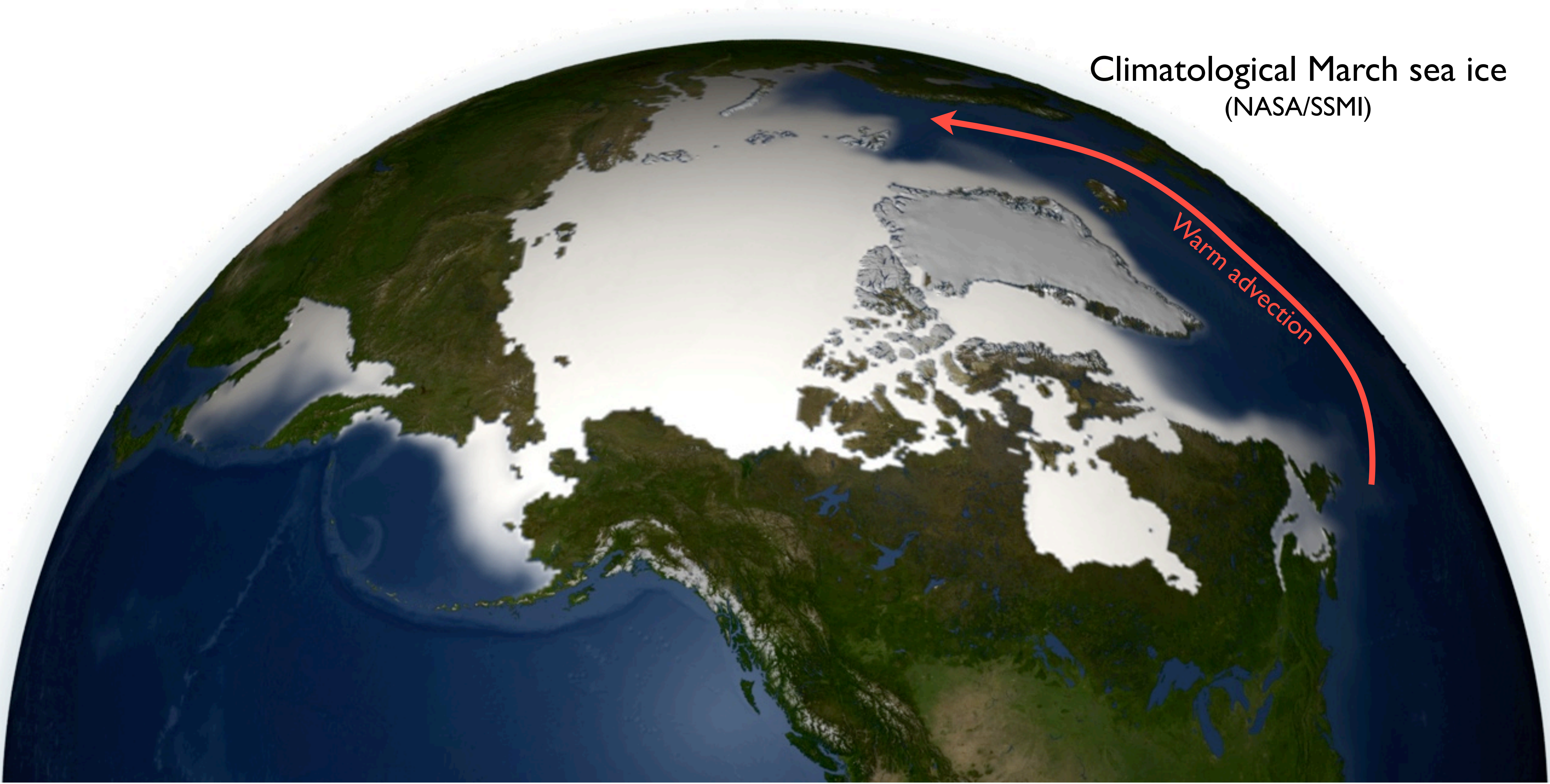
1) Summer heating regained by the atmosphere during winter carried east by the mid-latitude westerly winds;
2) Stationary atmospheric waves forced by the Rocky Mountains ;
3) Heat transport by the Gulf Stream.

Seager et al (2001, QJRMS)

http://la.climatologie.free.fr/ocean/ocean1.htm

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

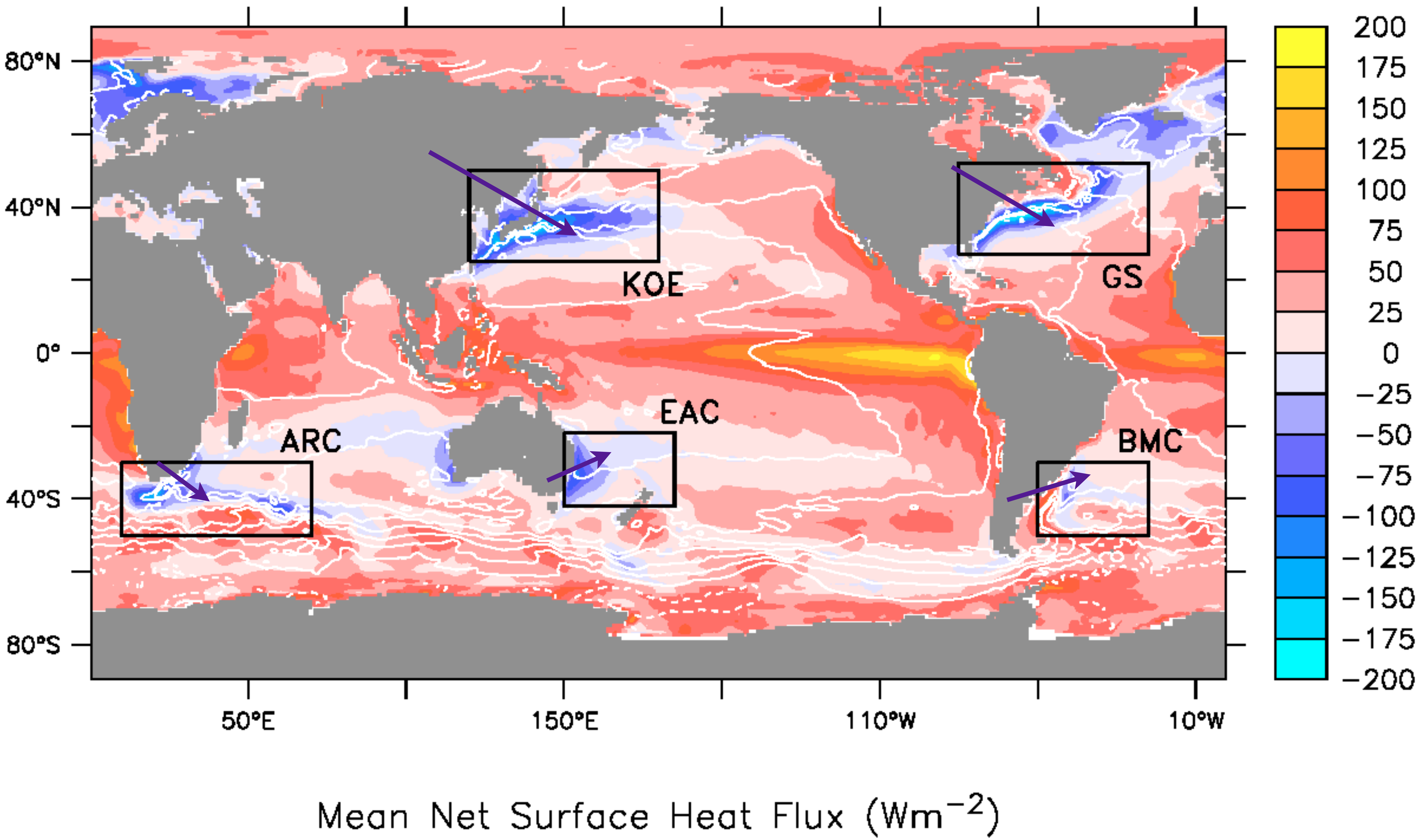
And the salty surface water carried into the Arctic affects the convection that controls the formation of deep water



Climatological March sea ice
(NASA/SSMI)

Western boundary currents do matter regionally

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

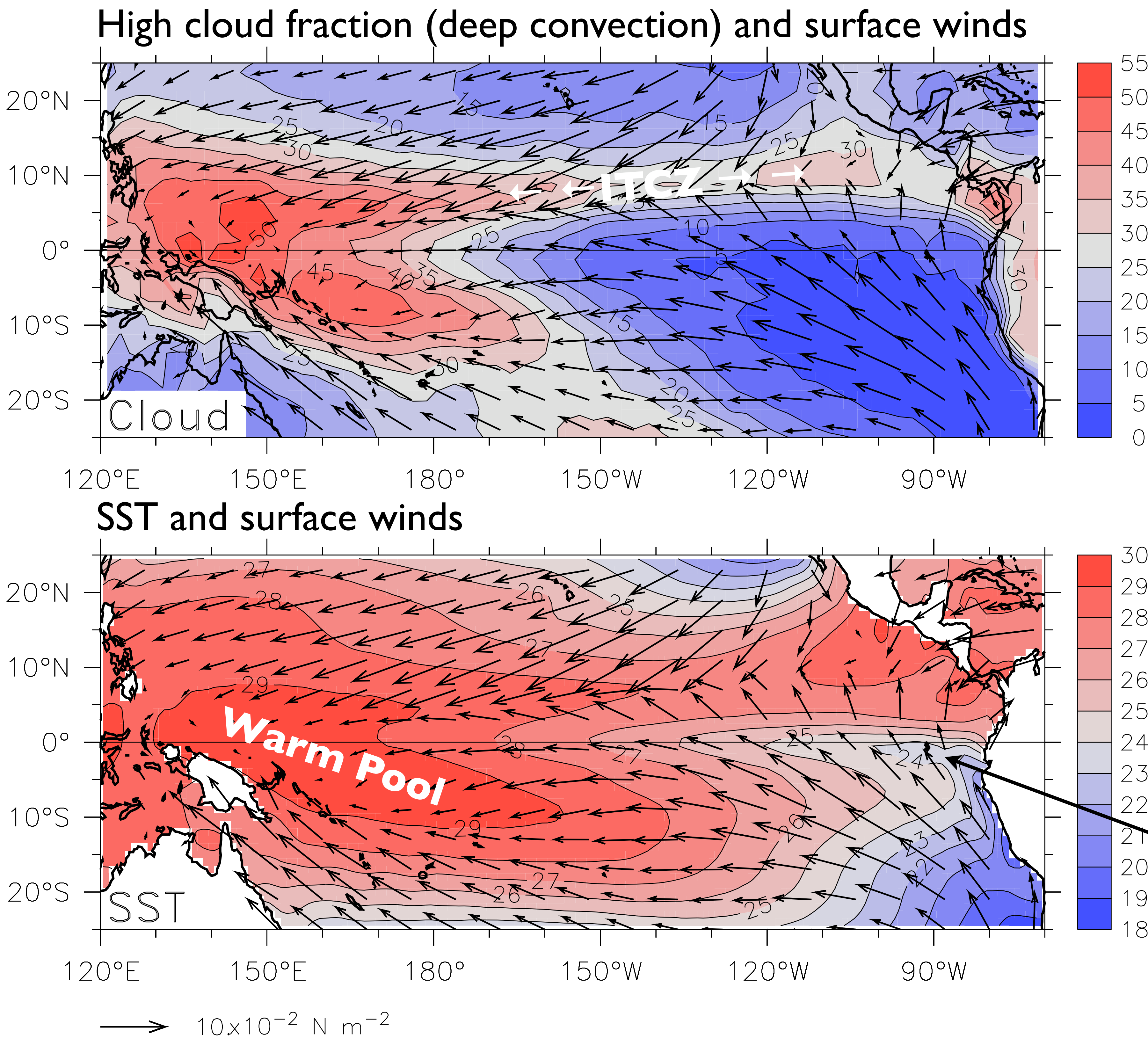


Yu and Weller (2007)
Rio (2004)

What's special about the tropics?

(Sea Surface Temperature)

Close relation among SST, convection and winds



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

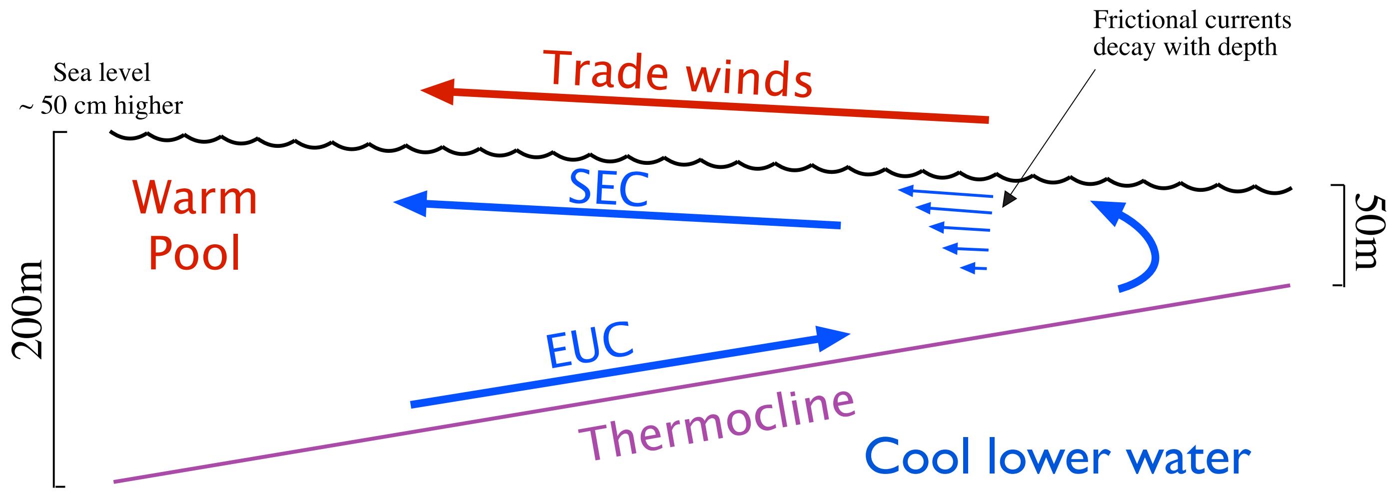
All three define the West Pacific warm pool and the Intertropical Convergence Zone (ITCZ).

Tropical winds blow directly towards warm SST.

East Pacific Cold Tongue

(Reynolds SST, ISCCP high clouds, Quikscat winds)

Currents and temperature on the equator

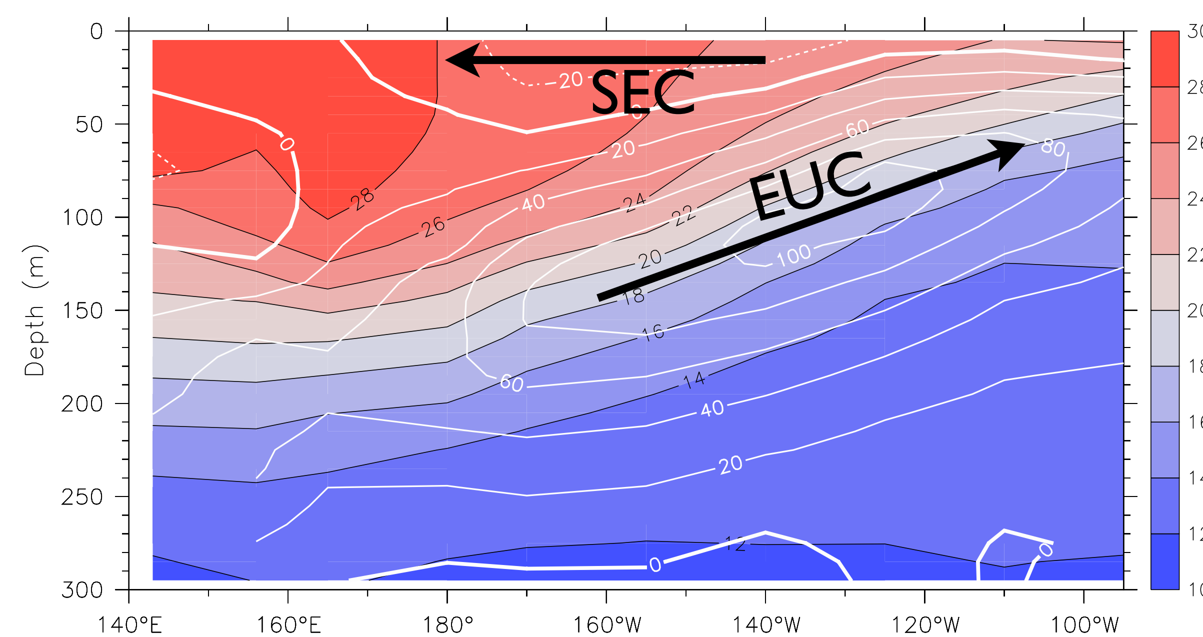


The trade winds 1) Pile up water in the west.
2) Drive the SEC by direct friction.

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 (colors) and currents (white contours) along the Pacific equator

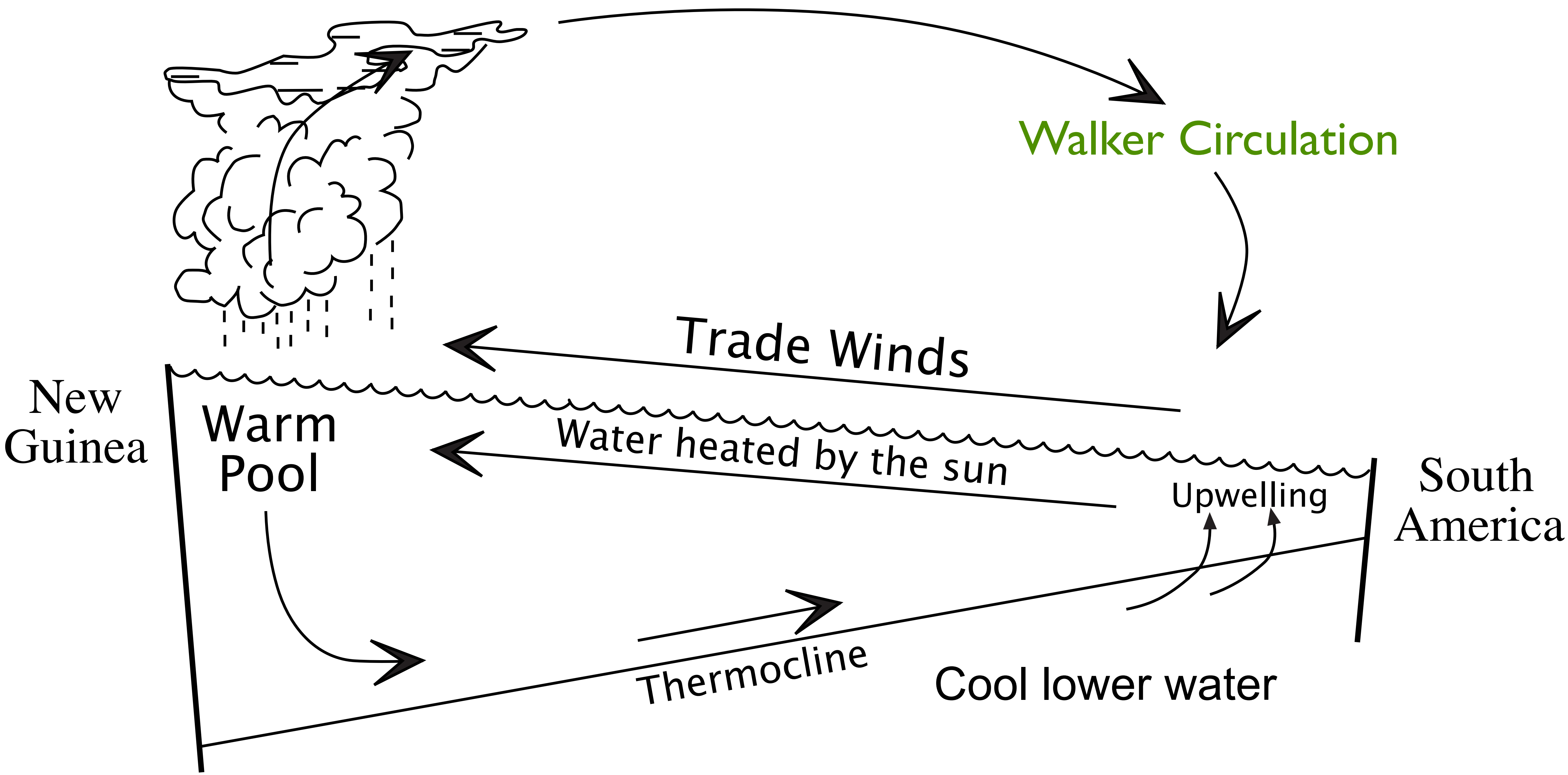


Johnson et al (2001)

Close connection between thermocline depth ⟺ SST

The tropical climate is coupled

Vertical slice along the equator



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.

Bjerknes (1965)

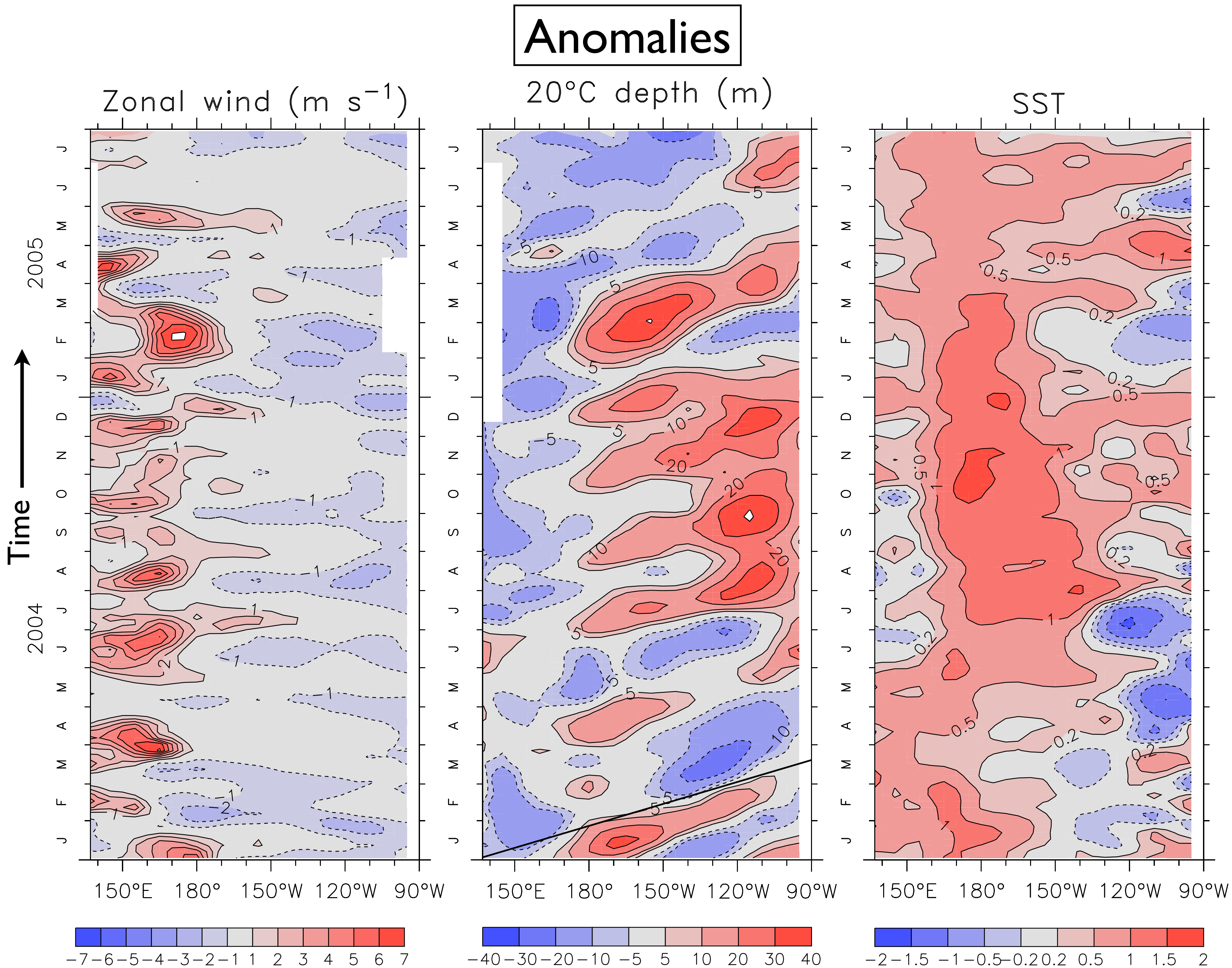
What's special about the tropics?

- Surface air temperature is always near the threshold for convection (~27°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.

Signals spread efficiently across the Pacific equator



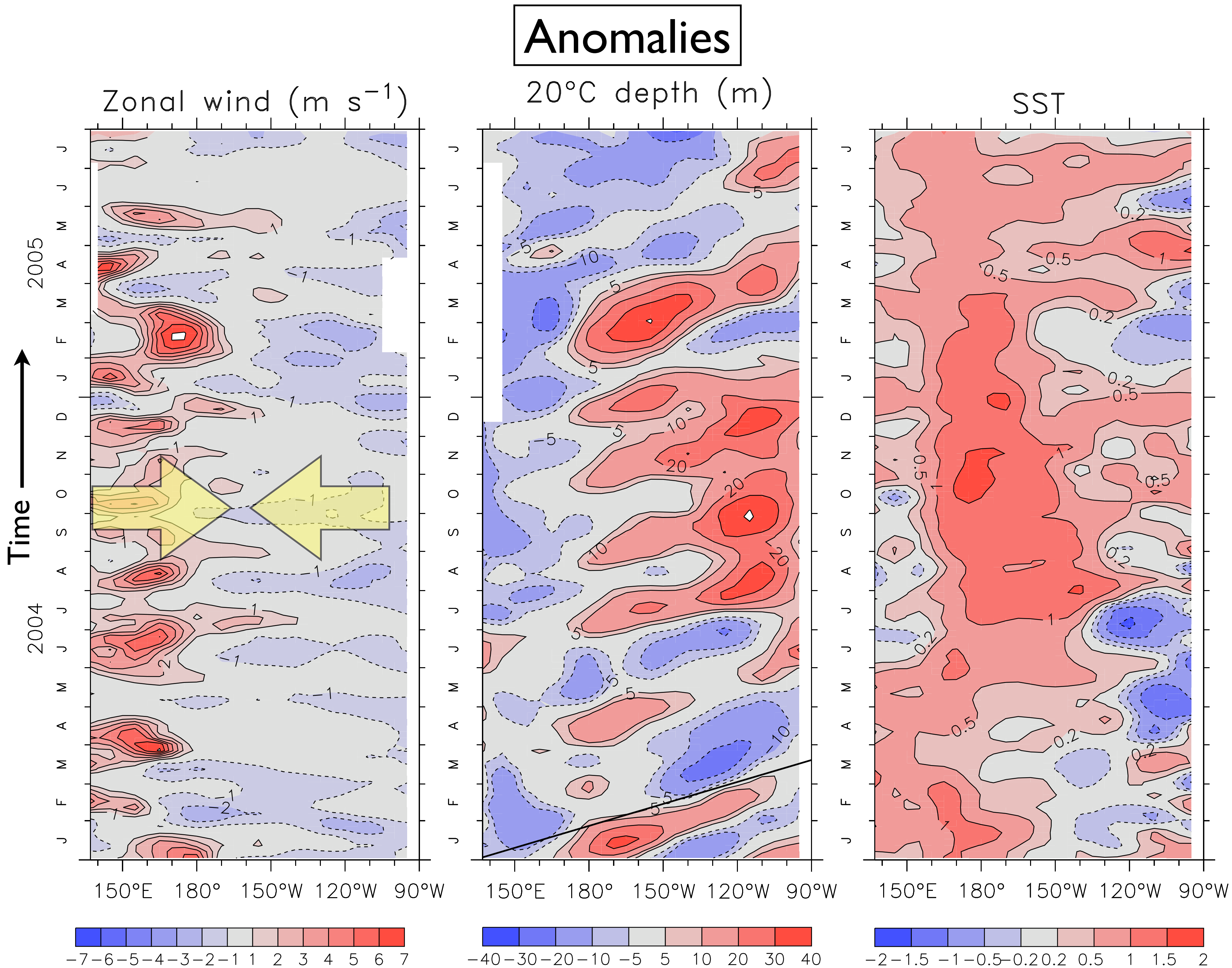
Red = westerly wind   Red = deep thermocline   Red = warm SST

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 <u>remote forcing</u>.
- Shallow eastern thermocline cools local SST.

Signals spread efficiently across the Pacific equator



Red = westerly wind | Red = deep thermocline | Red = warm SST

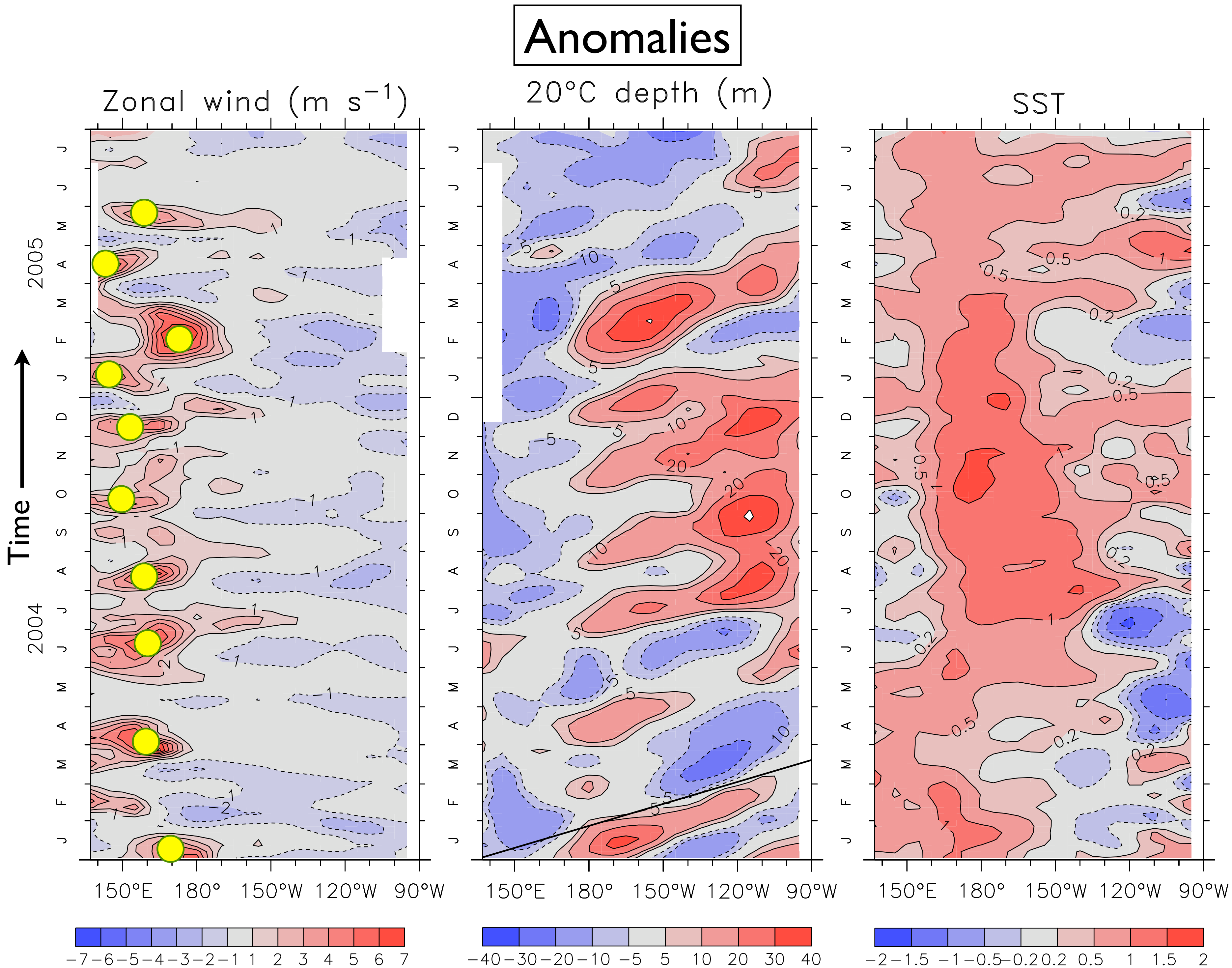
The response to episodic westerly wind anomalies in the western Pacific:

- 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.

Signals spread efficiently across the Pacific equator



Red = westerly wind   Red = deep thermocline   Red = warm SST

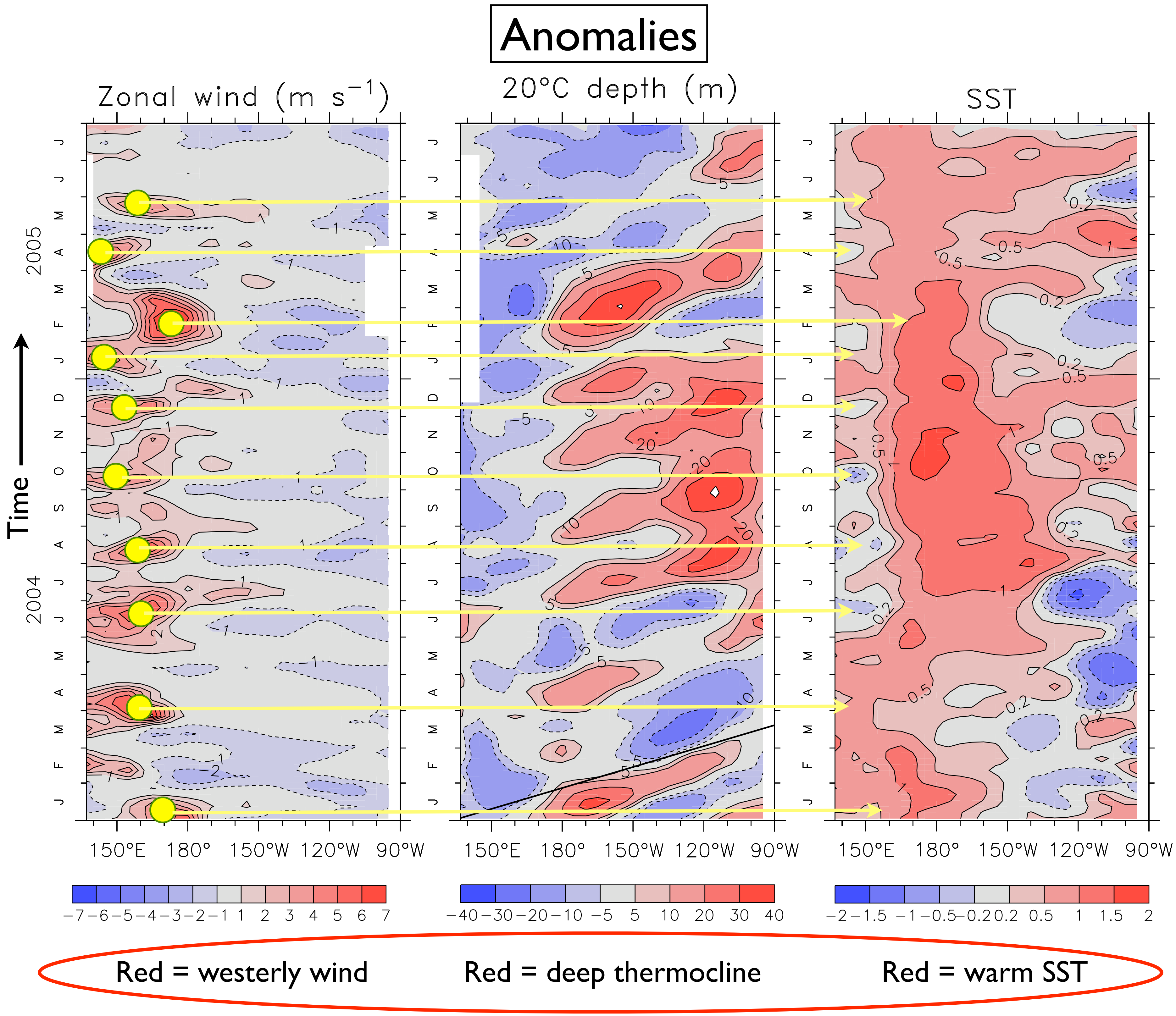
The response to episodic westerly wind anomalies in the western Pacific:

- 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.

Signals spread efficiently across the Pacific equator



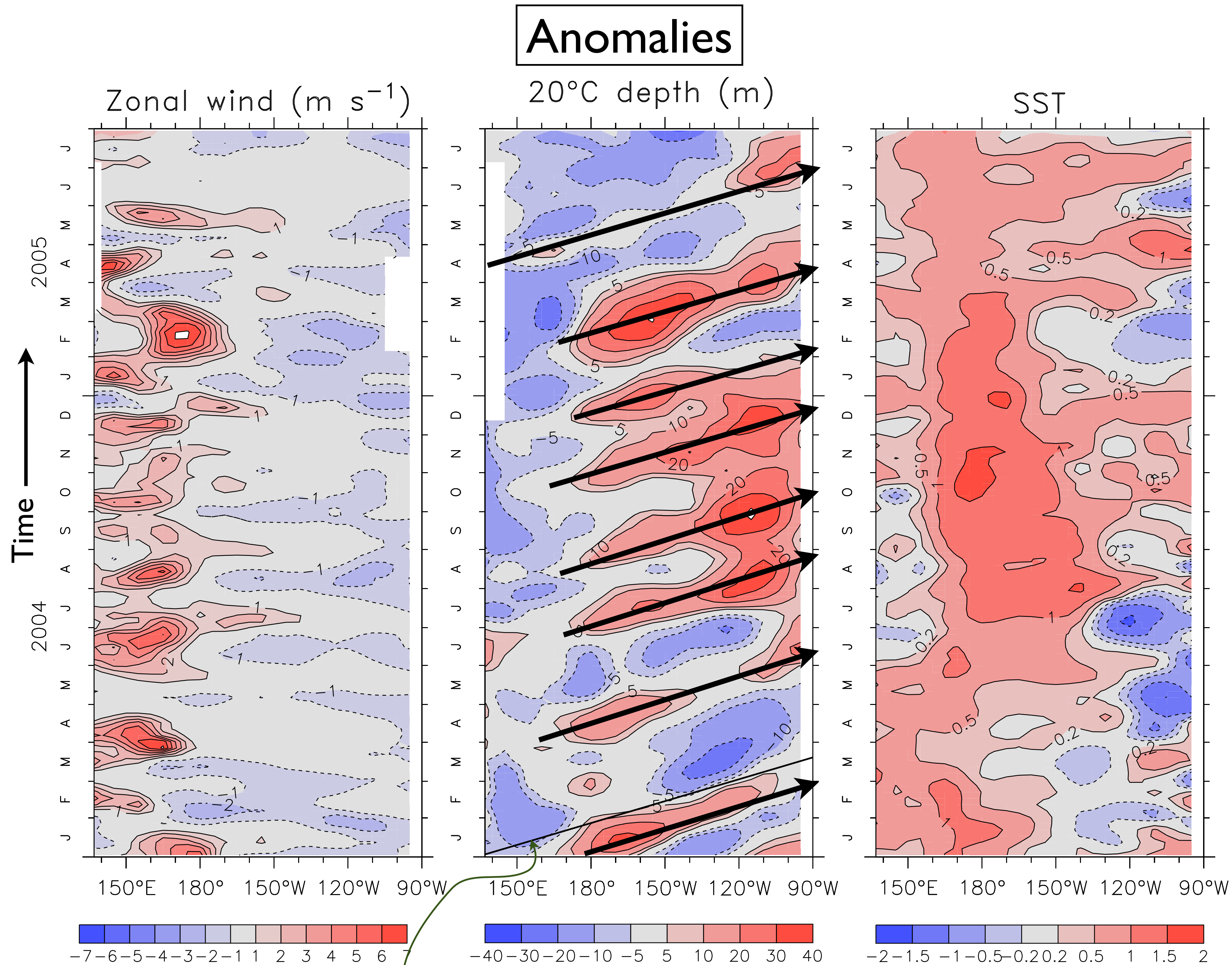
The response to episodic westerly wind anomalies in the western Pacific:

- Winds blow into warm SST.
- Westerly winds come in bursts lasting ~30 days.
- 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.

Signals spread efficiently across the Pacific equator



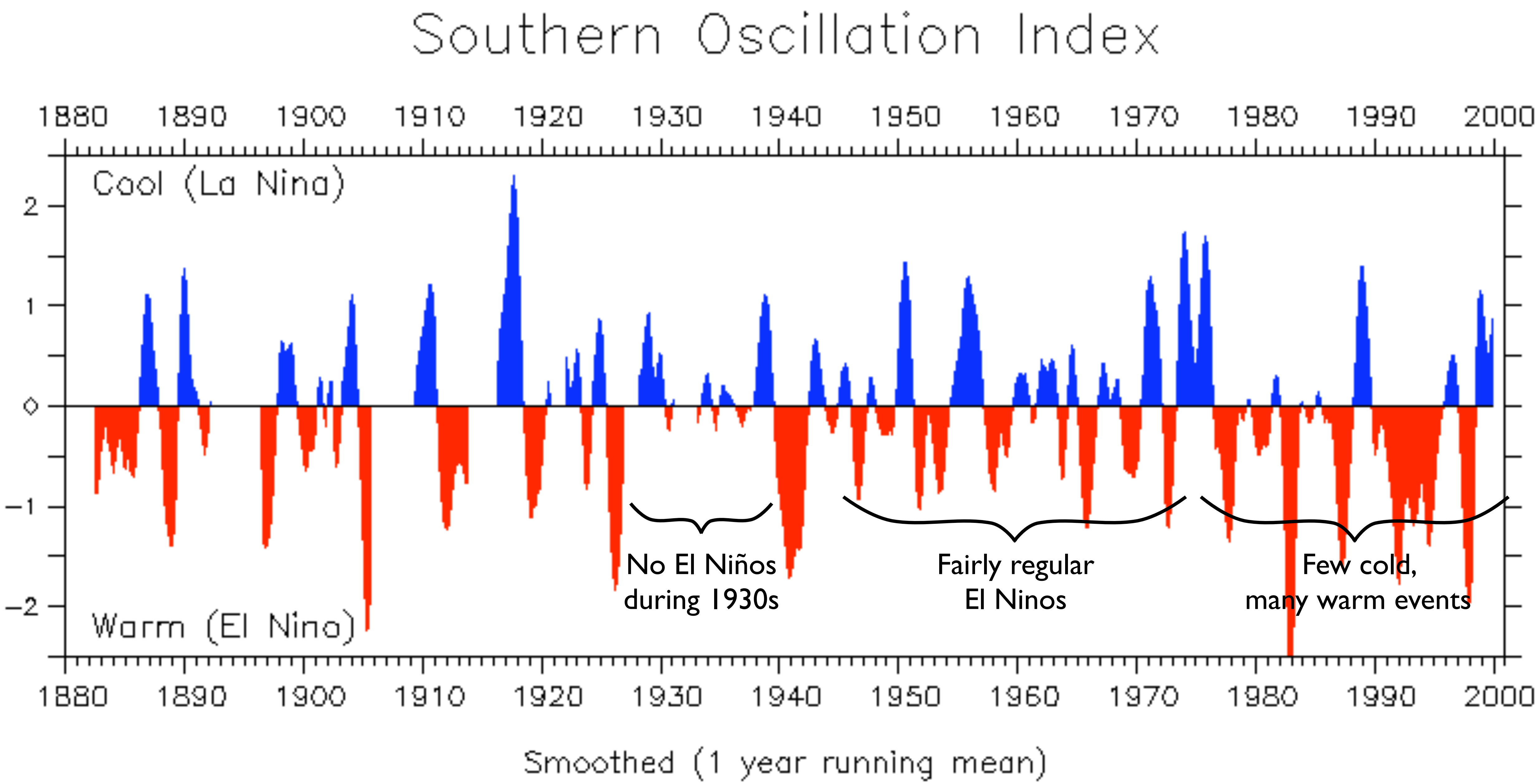
Red = westerly wind   Red = deep thermocline   Red = warm SST

Linear Kelvin wave speed
(~2.3 m s^{-1})

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 <u>eastward-propagating</u> Kelvin wave.
  Although eastern Pacific winds remain easterly throughout, the thermocline deepens due to persistent <u>remote forcing</u>.
- Shallow eastern thermocline cools local SST.

El Niño occurrences are irregular



We don't know why El Niños begin!

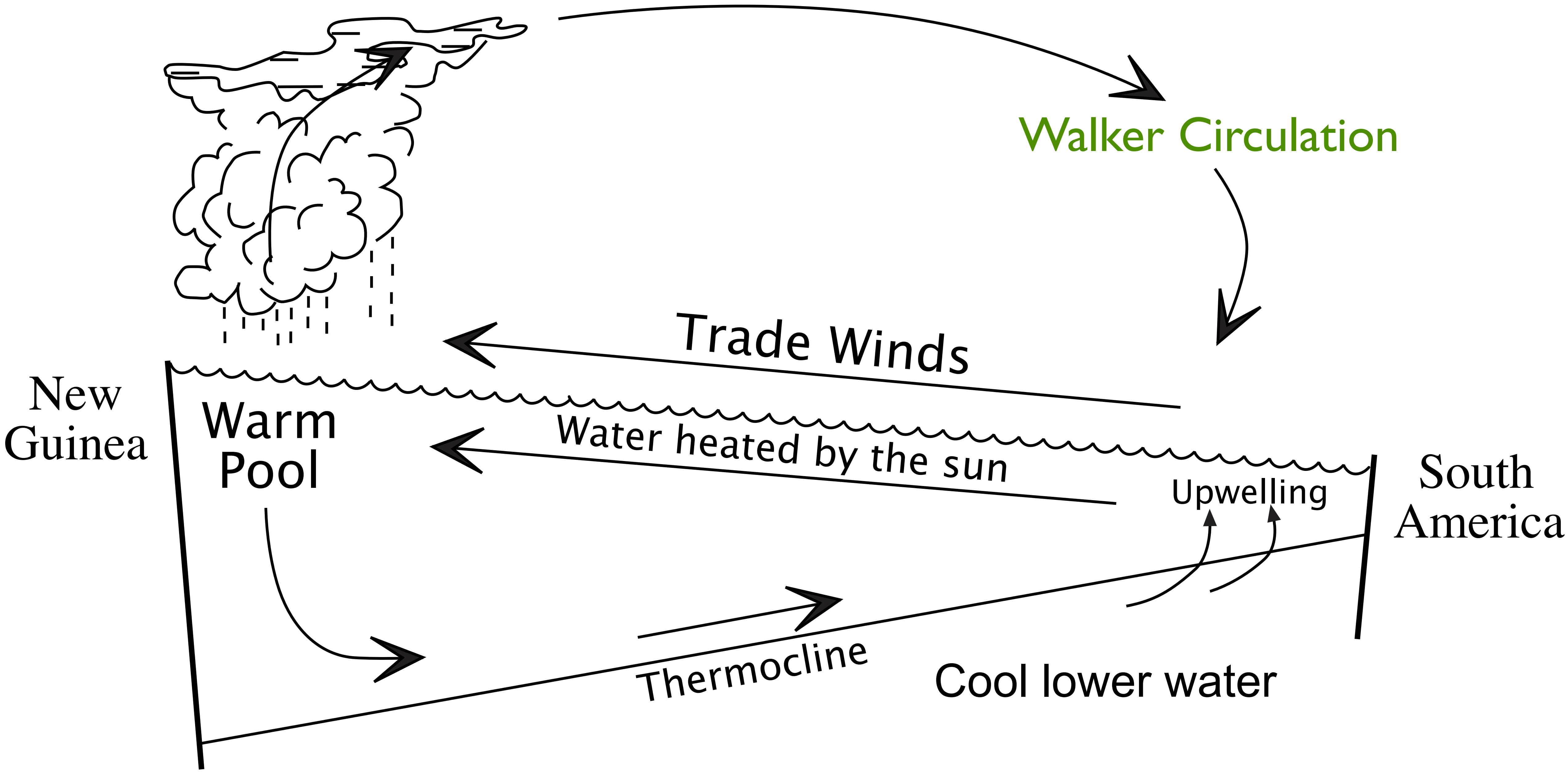
Theories fall roughly into two categories:

- 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, and it is not just academic: predictability.

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.

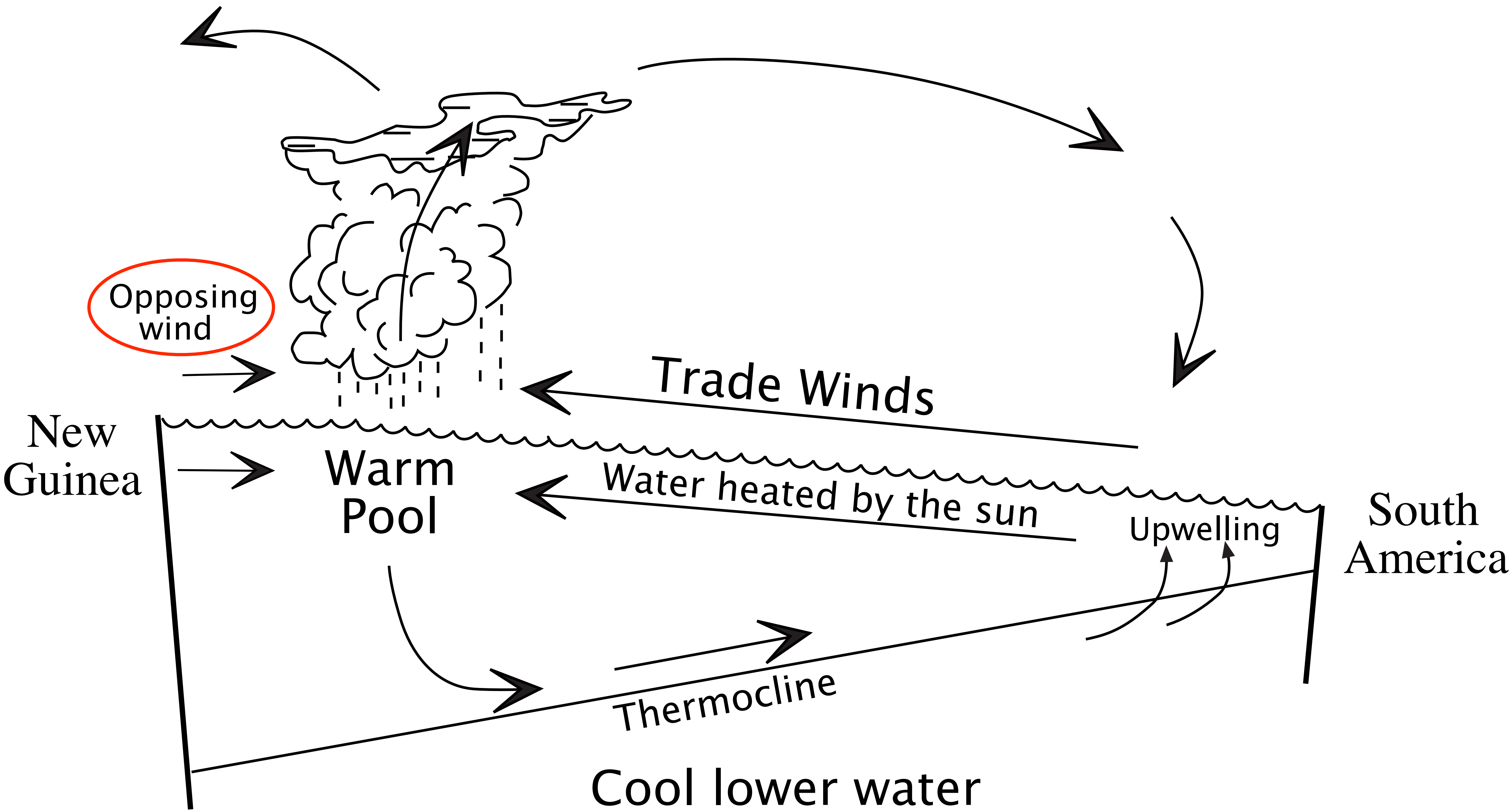
Evolution of El Niño: The "normal" situation



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

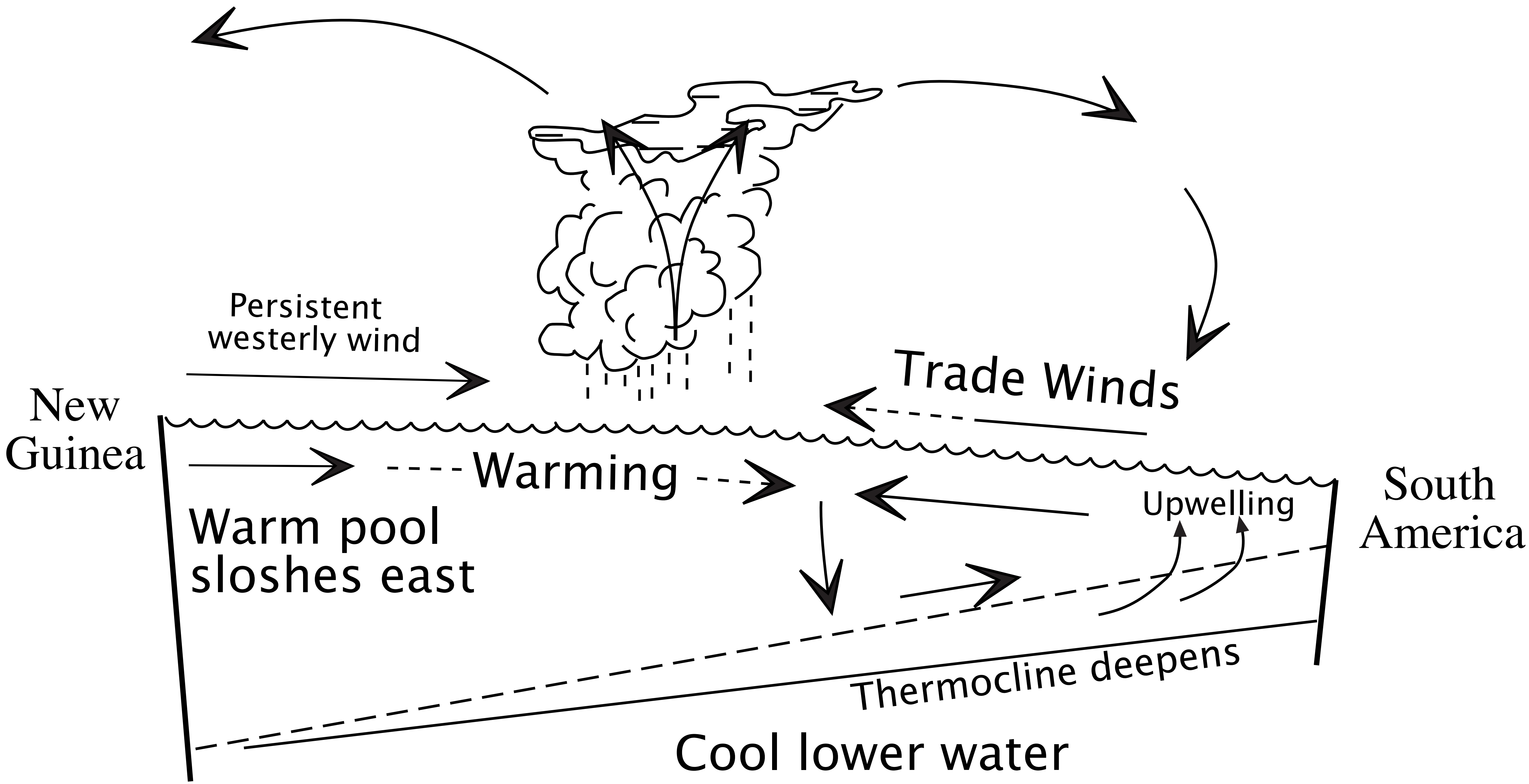
Schematic ocean-atmosphere interaction during El Niño onset:

A "coupled collapse" as the warm pool sloshes east



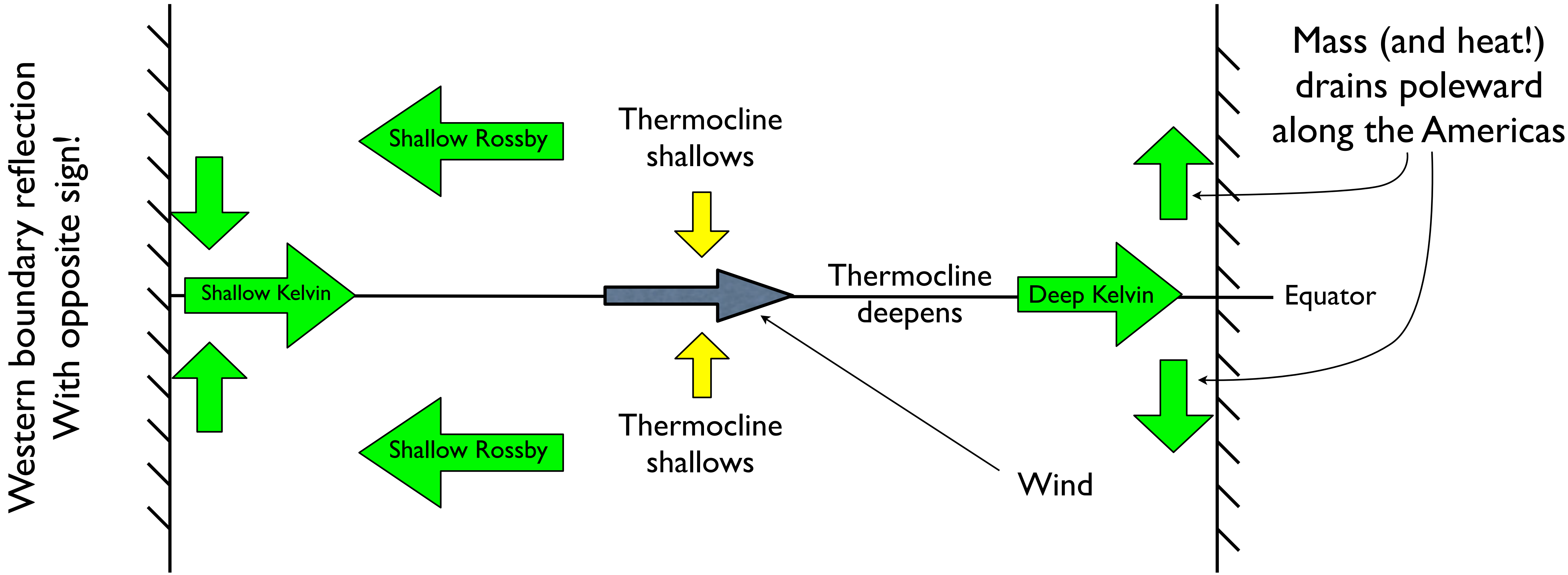
We don't know why El Niños start!

The peak of El Niño



Again a positive feedback. Why does it end?

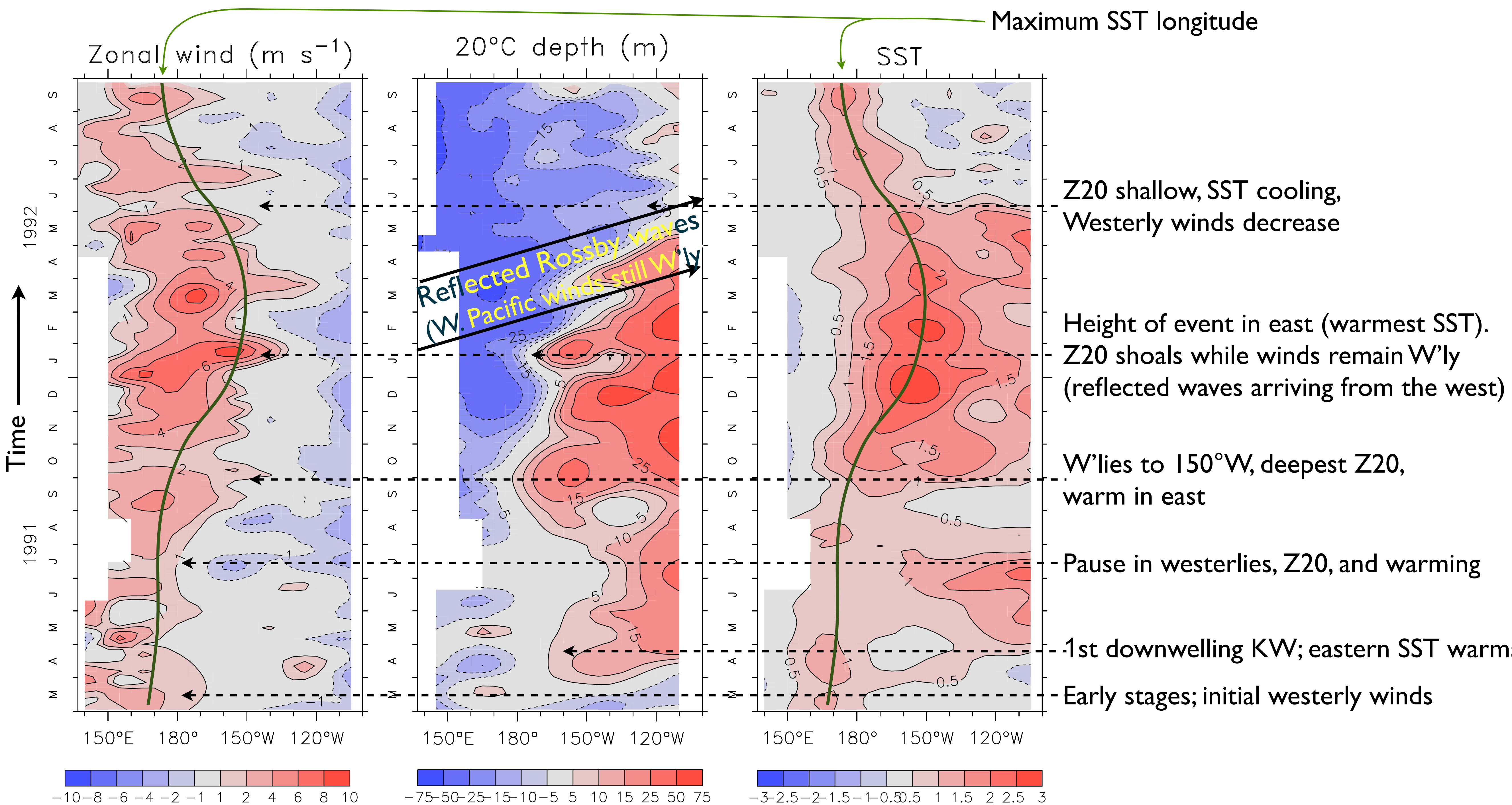
El Niño creates the seeds of its own destruction



Kelvin waves: ~2.5 m/s <u>eastward</u> (6500 km/month)
Rossby waves: ~0.8 m/s <u>westward</u> (2000 km/month)

Sequence of events during the El Niño of 1991-92

"Seeds of its own destruction"



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.)

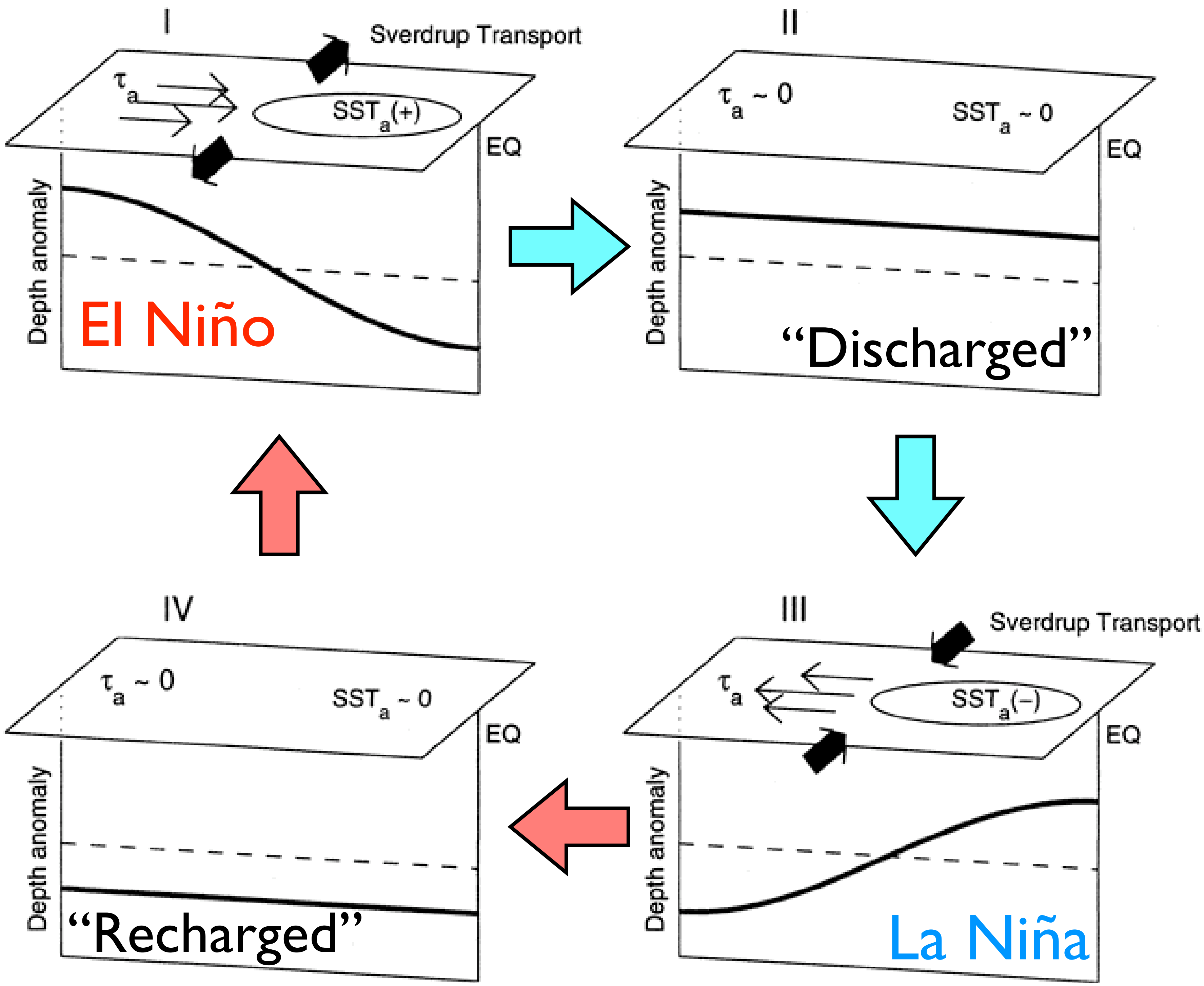
As the equatorial upper layer drains and thins, the thermocline comes closer to the surface and begins to cool the SST again.
Cool SST reestablishes the trade winds, restoring the normal pattern.

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

The big picture: meridional redistribution of mass and heat

ENSO as a cycle, accumulating and then discharging heat and mass from the equator

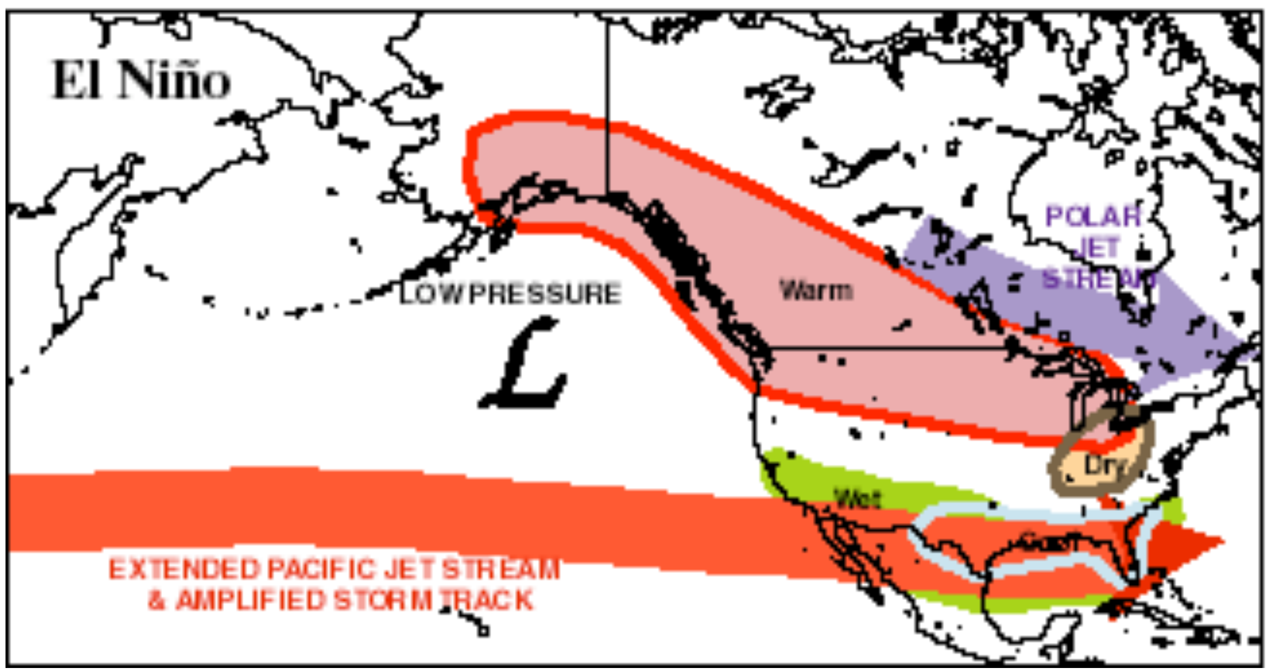
(Jin 1997)

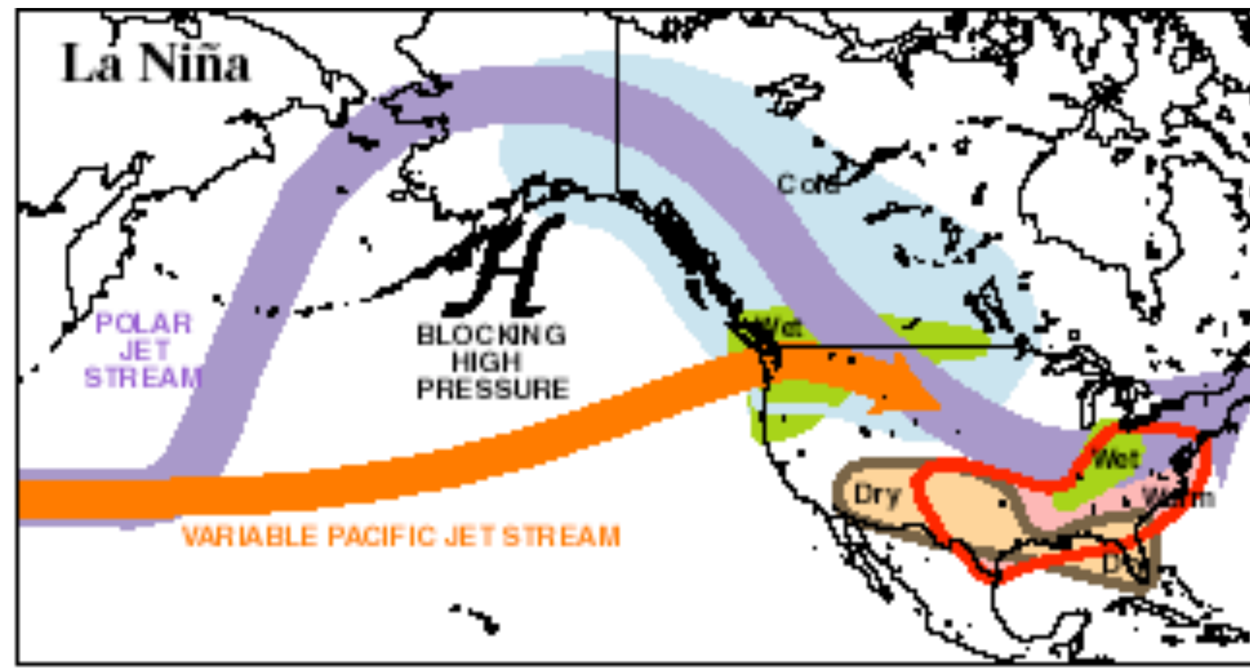


(After Meinen and McPhaden (2000))

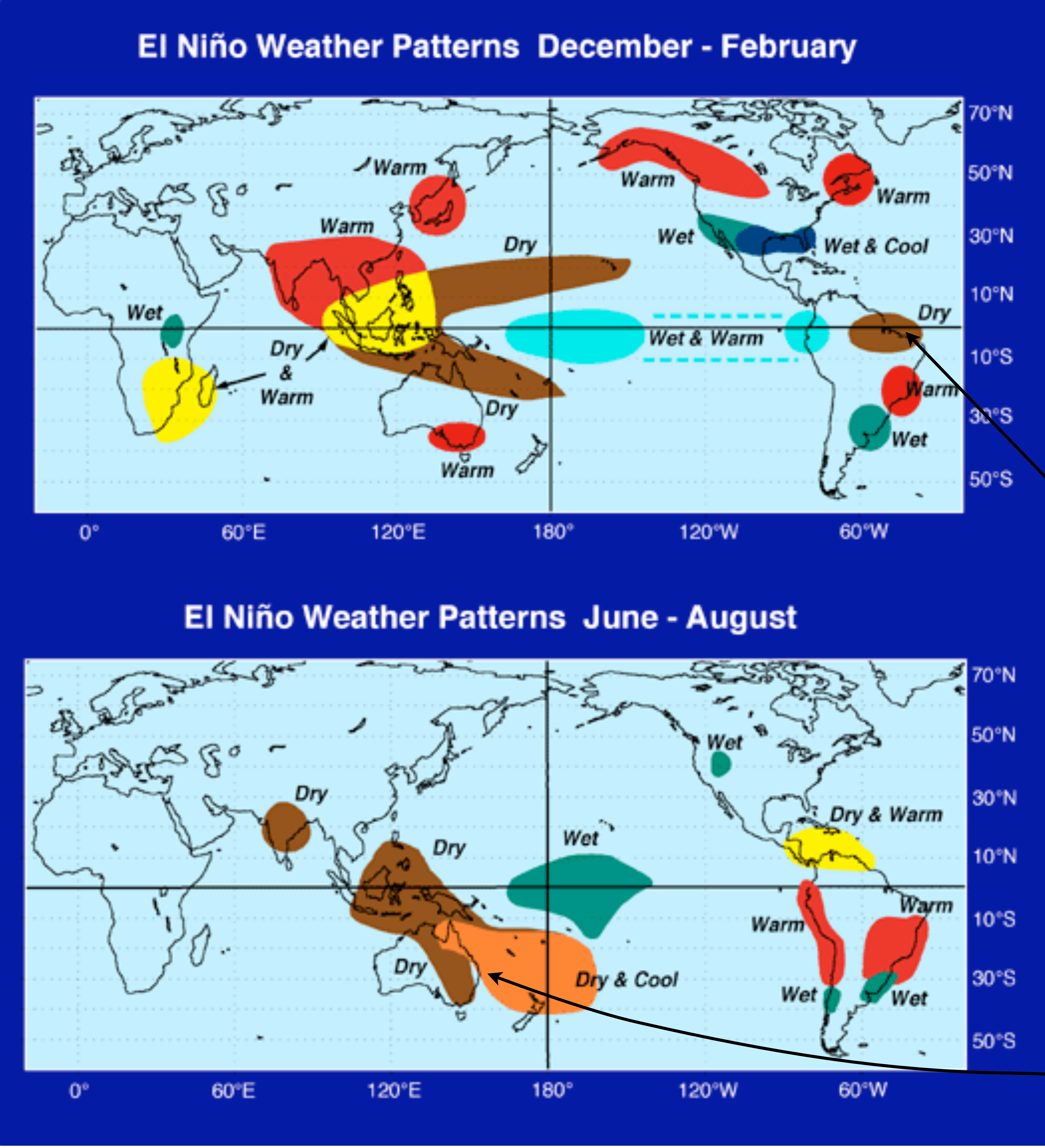
How are El Niño's effects spread from the tropics?

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.



Great benefit around the world if these events (and their subsequent effects) could be accurately predicted.

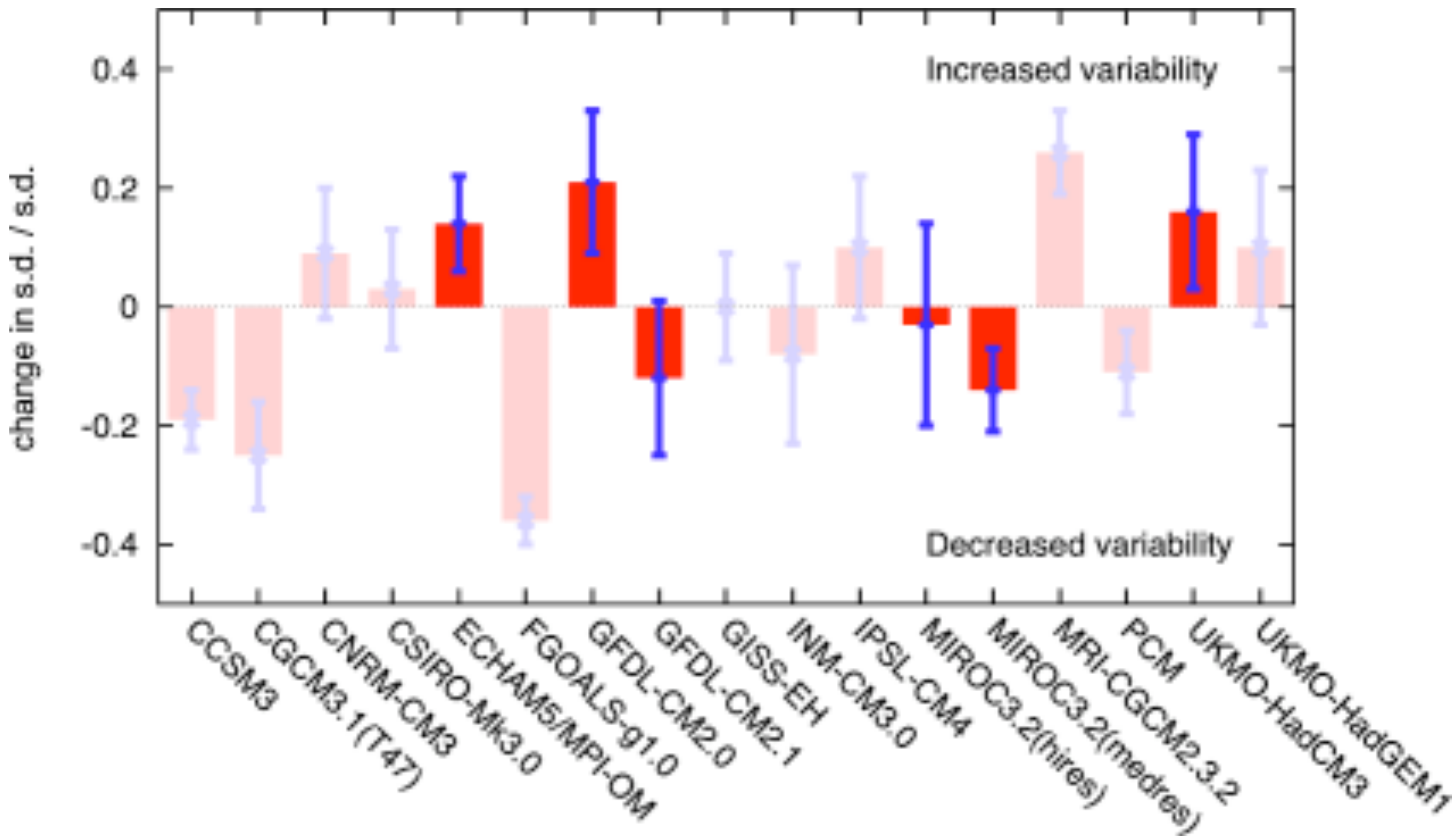
NE Brazil

El Niño droughts used to reduce crop yields by 75%. With predictions, famers plant drought-tolerant beans and crop losses are much less.

On the other hand, predictions are not always correct (Australia 1997).

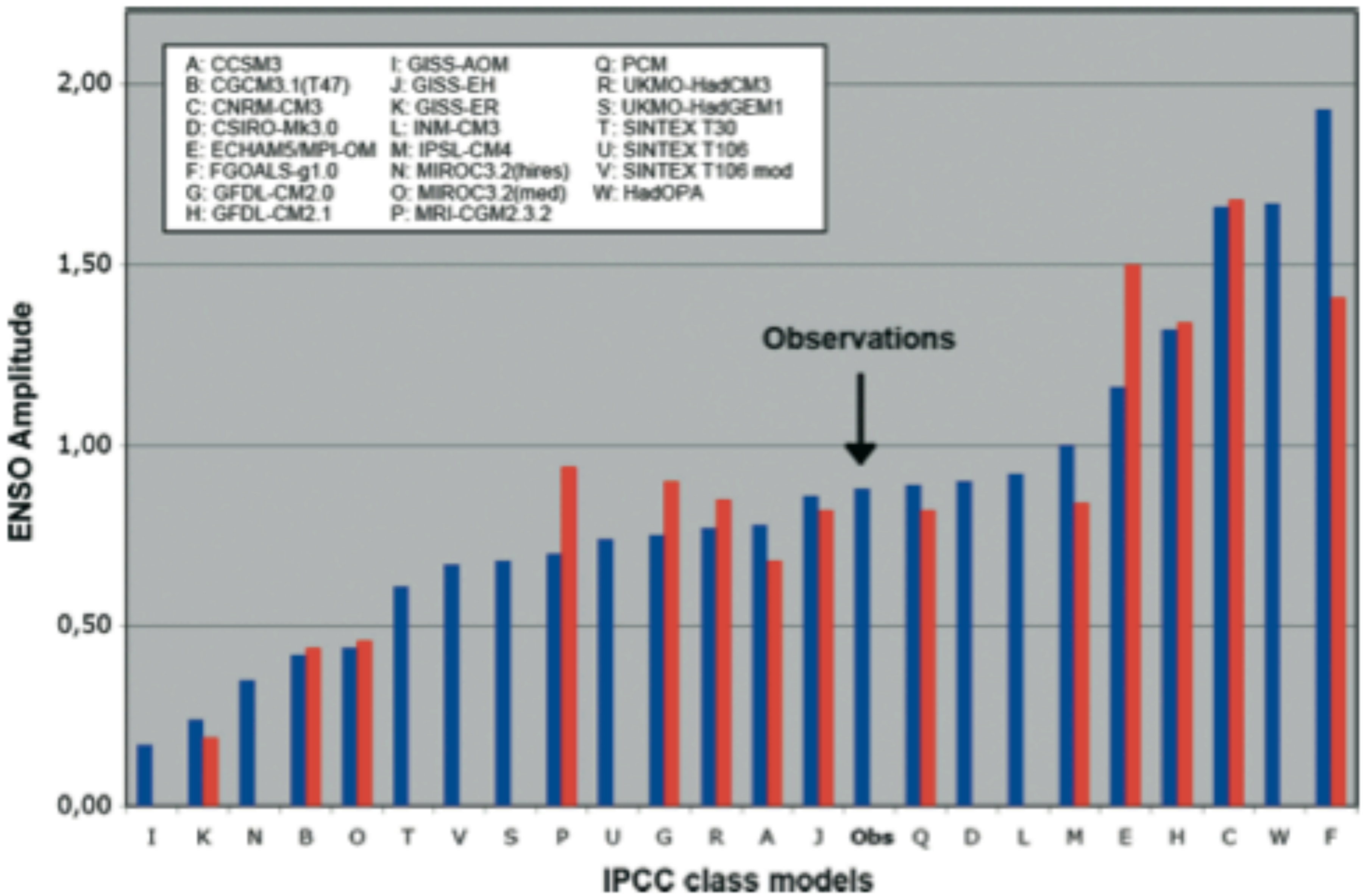
ENSO variability in IPCC models

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)

ENSO climate change forecasts are highly uncertain!



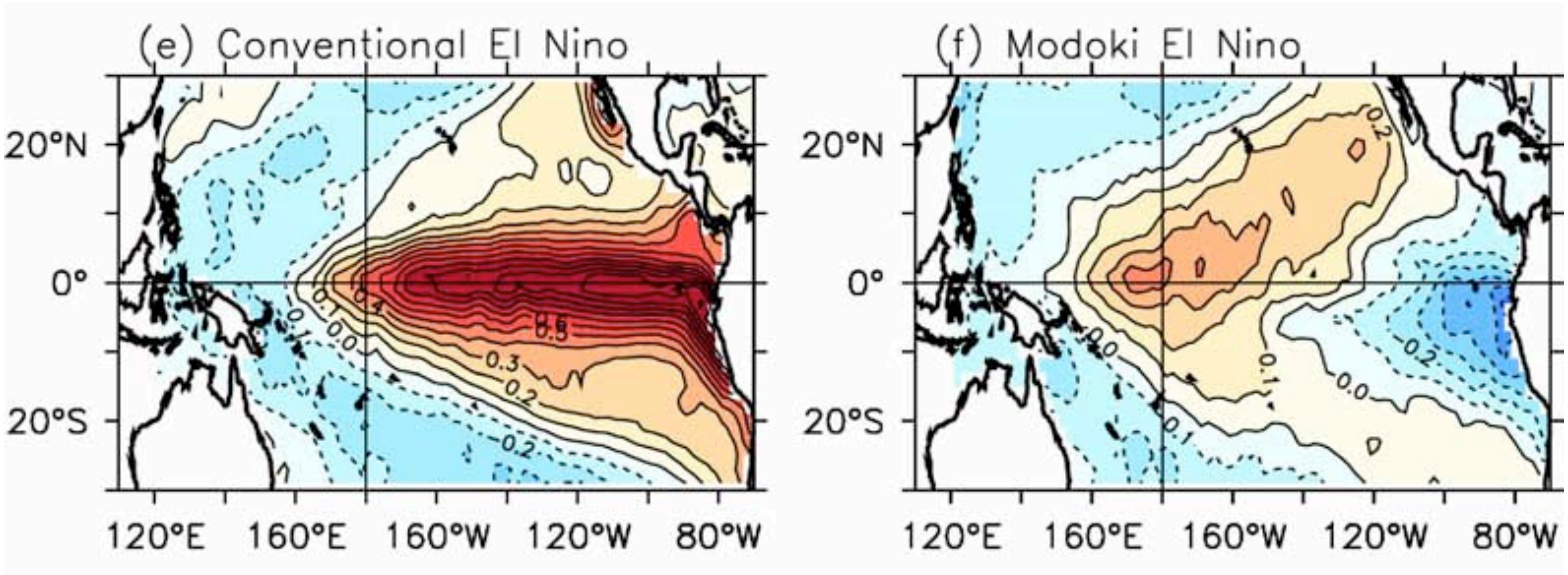
Blue = Pre-industrial

Red = 2 x CO_2

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 × CO_2 scenarios (red bars).

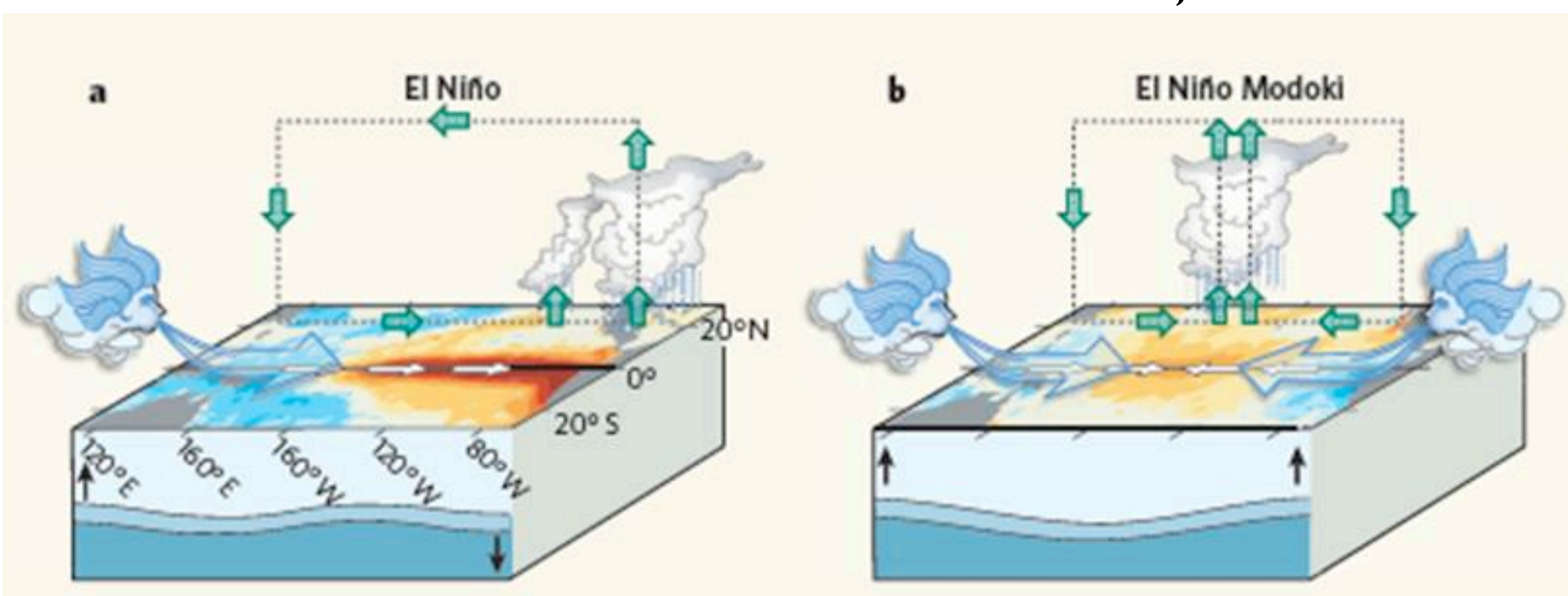
Guilyardi (2009)

Confusing new issues: "Modoki El Niño"



Clement et al.

Winds blow towards the warm water, as usual ...



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.
- 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.

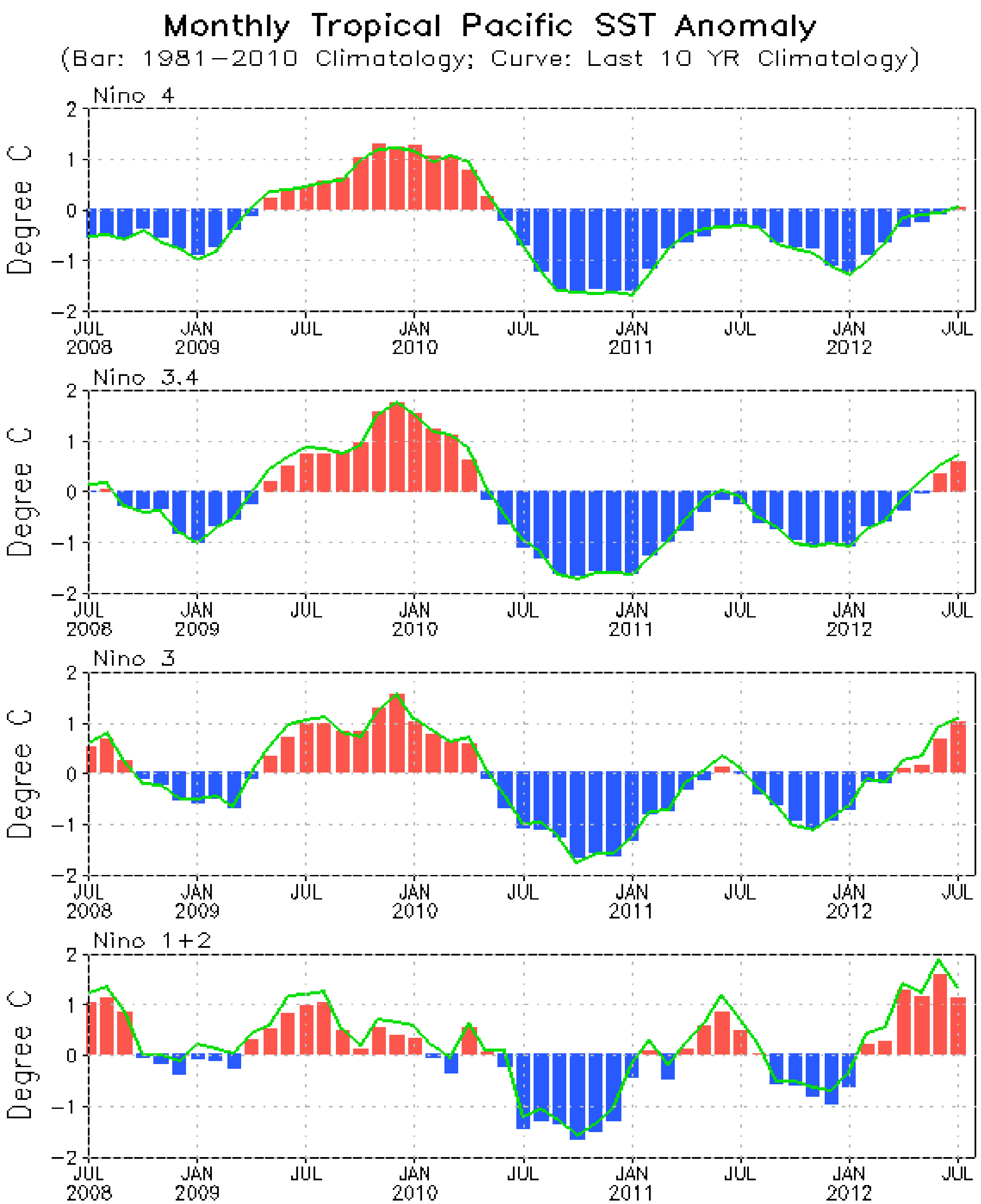
Talk on line at: http://faculty.washington.edu/kessler → LATEST TALK

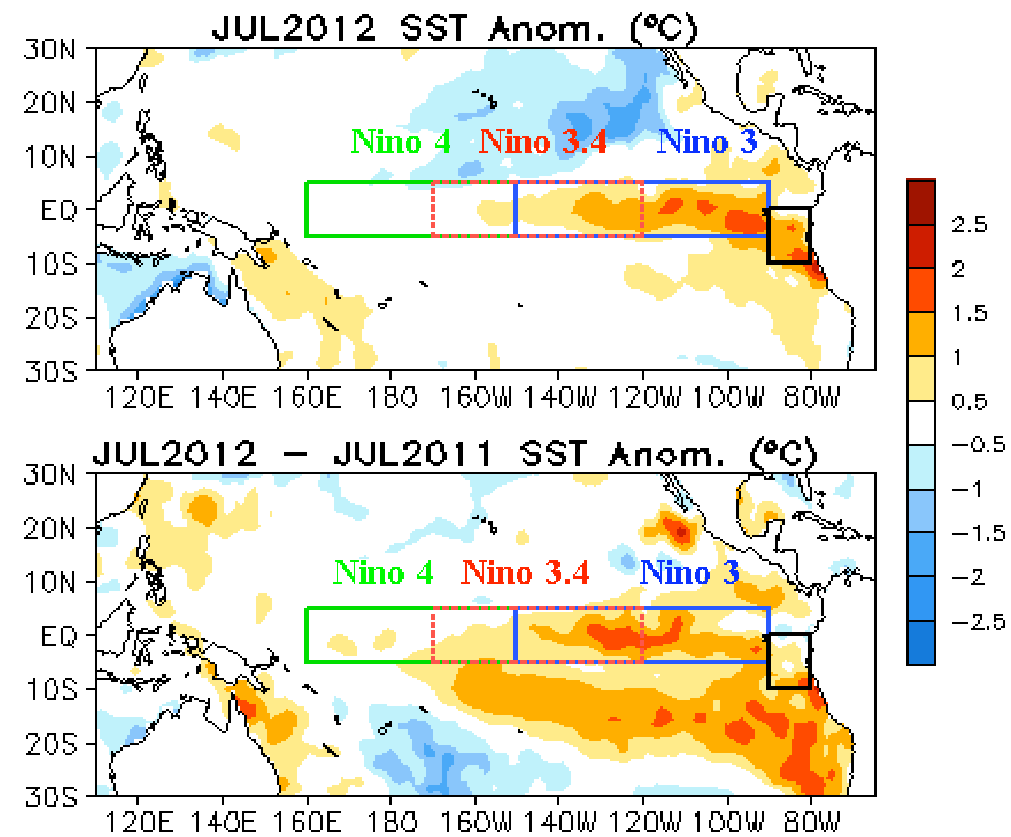
Extra

Figures

Follow ...

Evolution of Pacific NINO SST Indices



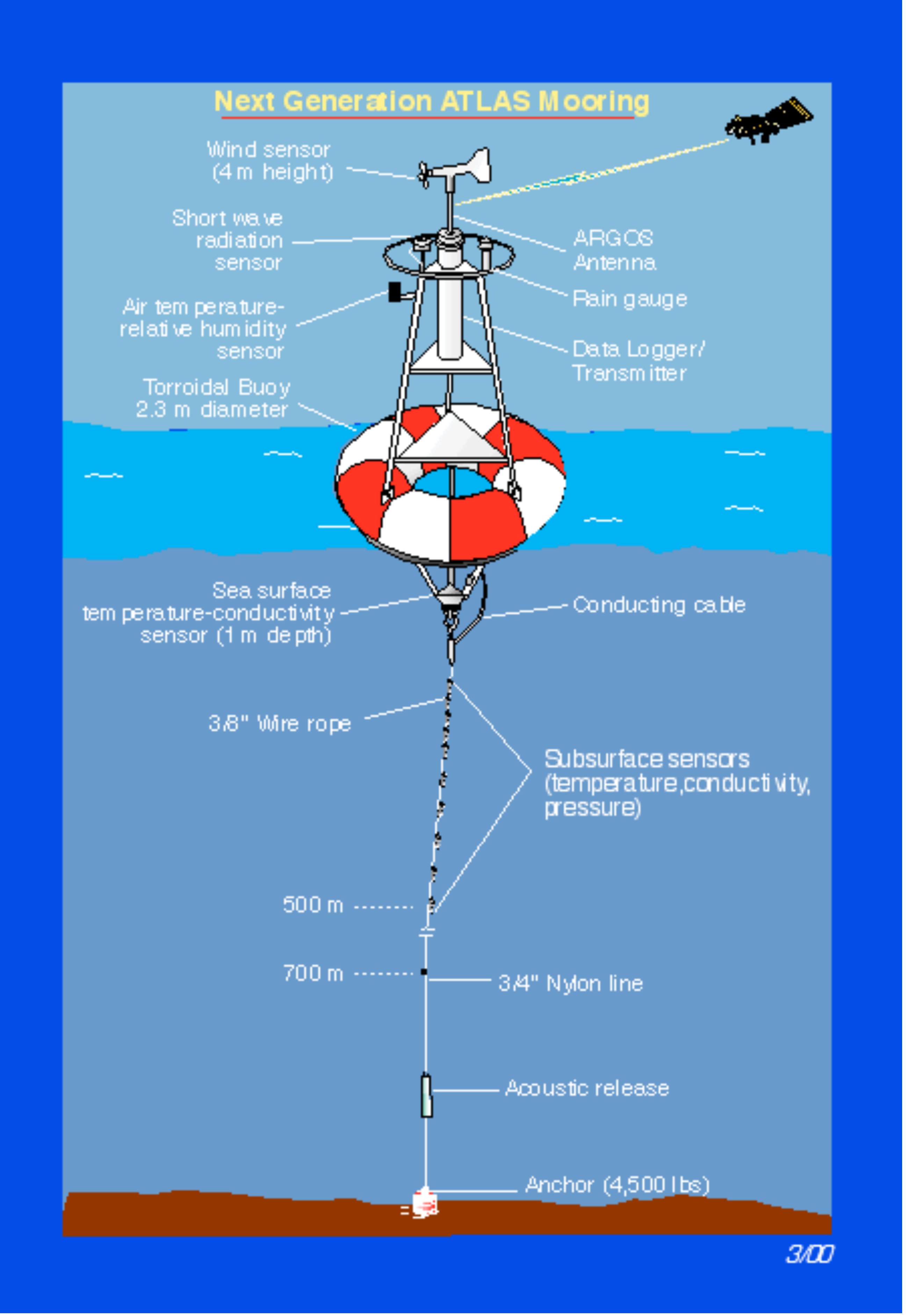


- Nino indices were above normal, with Nino 3.4 index = 0.6°C in July 2012 .

- The distribution of SSTA was asymmetric between the north and south Pacific. Compared with last June, SST was much warmer in the tropical-subtropical S. Pacific in July 2012.

- The indices were calculated based on OISST. They may have some differences compared with those based on ERSST.v3b.

Fig. P1a. Nino region indices, calculated as the area-averaged monthly mean sea surface temperature anomalies (°C) for the specified region. Data are derived from the NCEP OI SST analysis, and anomalies are departures from the 1981-2010 base period means.



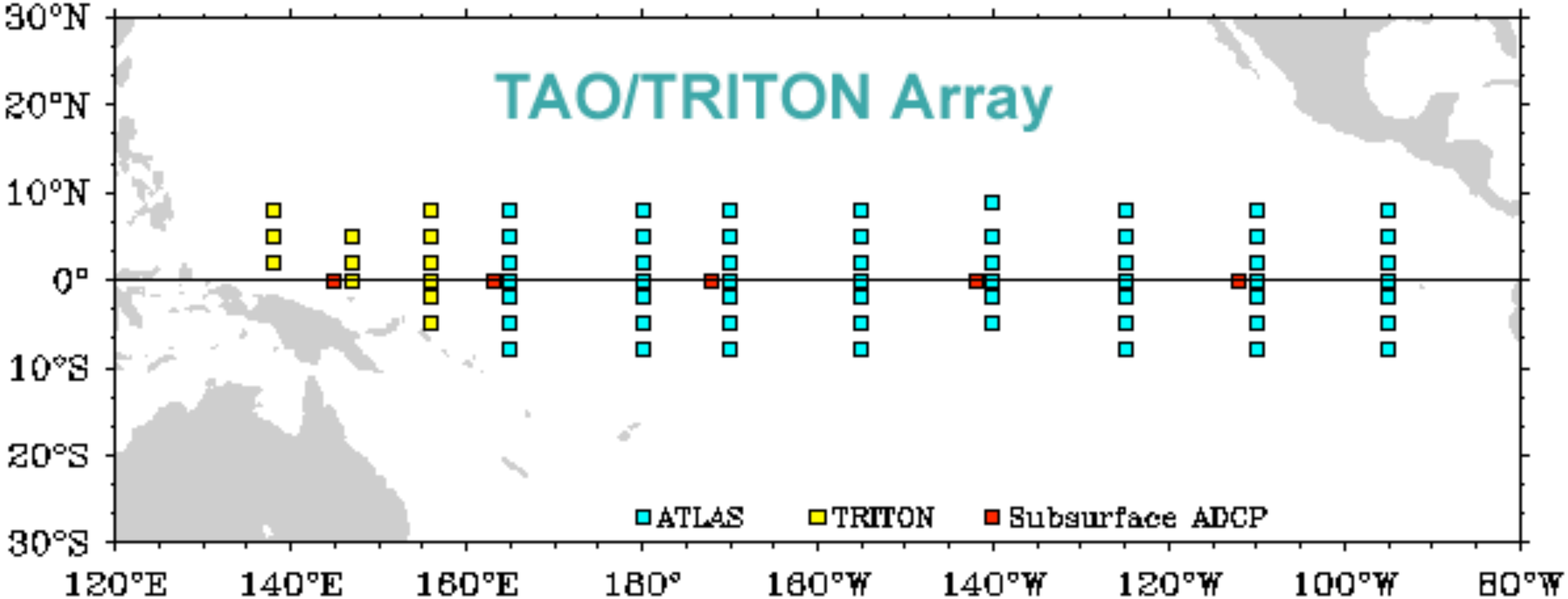
ATLAS mooring

A principal mission of my laboratory is to develop techniques that describe the state of the tropical Pacific for input into the forecast models.

The ATLAS mooring was developed at PMEL in the 1980s and is our primary tool. The moorings last for a year or more (and the parts are reusable), and all data are received in near-real time.


ATLAS

The TAO-TRITON network is a US-Japan project.
There are 70 moorings maintained continuously.

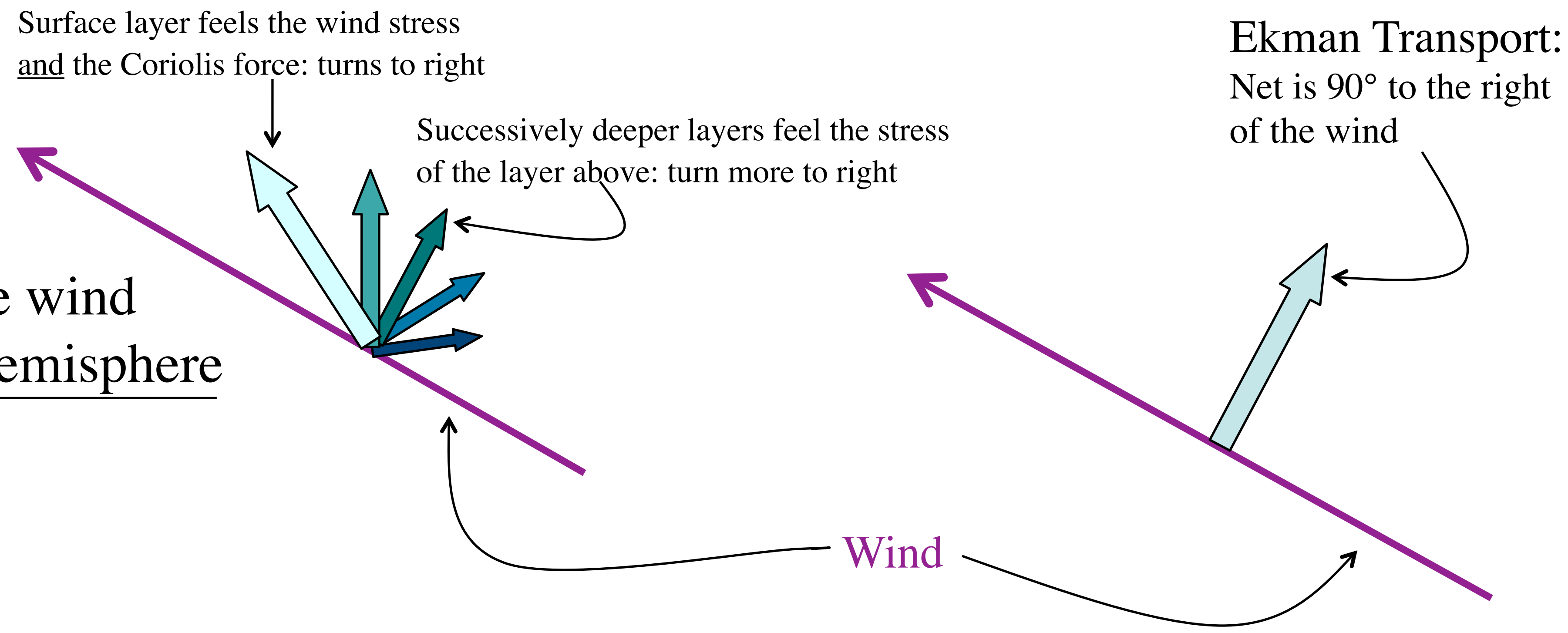


Data plots from the array are available in near-real time:

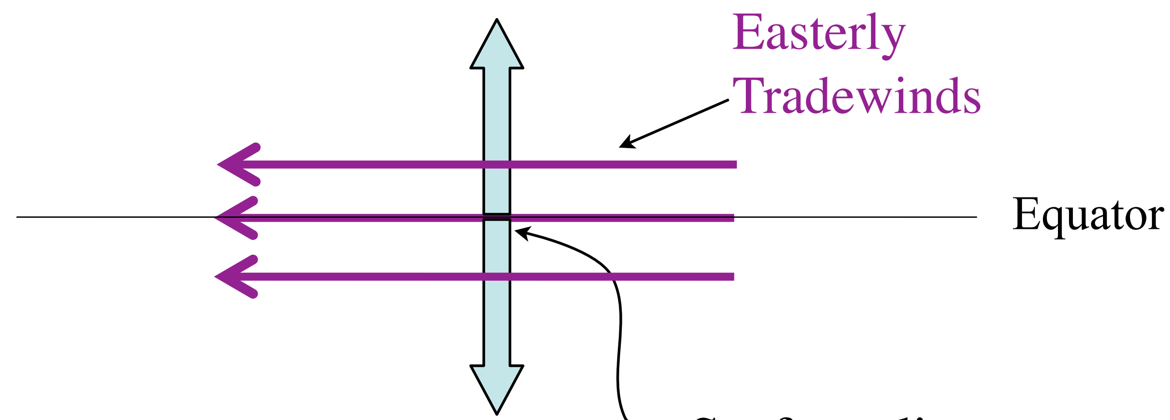
http://www.pmel.noaa.gov/tao/jsdisplay

Fundamental wind-driven dynamics: Ekman Transport

Ekman transport
to the right of the wind
in the northern hemisphere



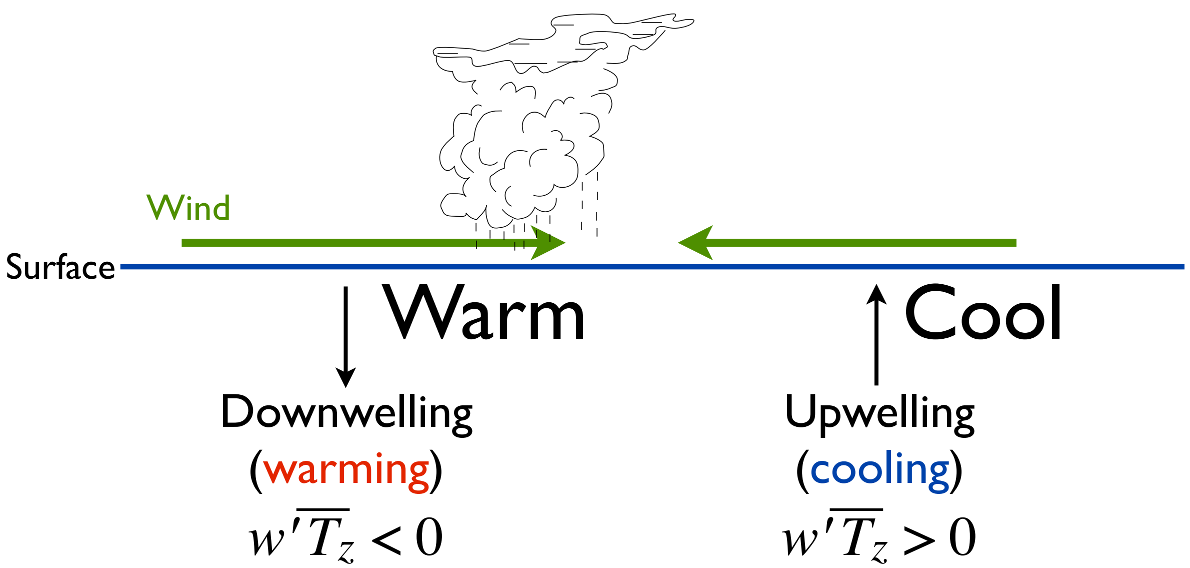
Wind along the equator produces opposite Ekman transport on each side of the equator.
Easterly winds (normal tradewinds) give divergent Ekman transport, with consequent upwelling.
As the thermocline is lifted to the surface, SST will usually cool.
Westerly anomalies do the opposite.



Surface divergence = upwelling
1. Lifts thermocline
2. Cools SST
3. Initiates equatorial waves

SST modes: eastward or westward propagation along the equator

<u>Convection occurs over warm SST → rising air converges → westerlies extend over warm anomaly</u>

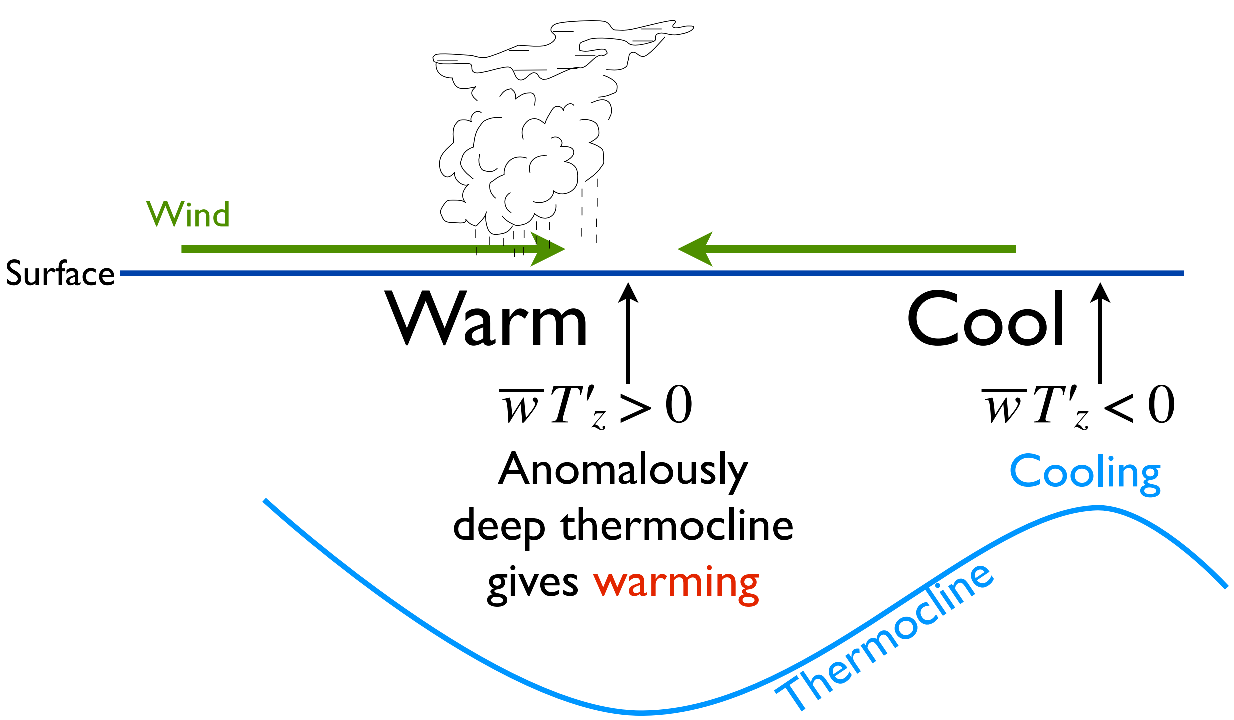


"Slow SST mode"

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 ($w = \overline{w}$).

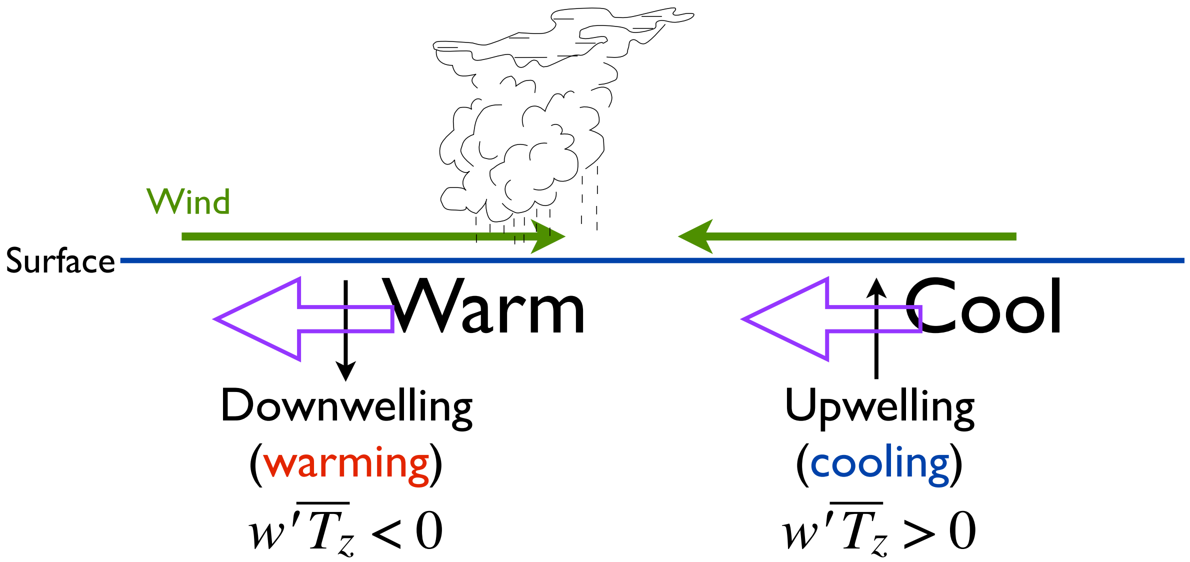
T'_z (vertical T gradient) anomalies dominate.

→ Anomalies propagate EAST

Neelin (1991, 97)

SST modes: eastward or westward propagation along the equator

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

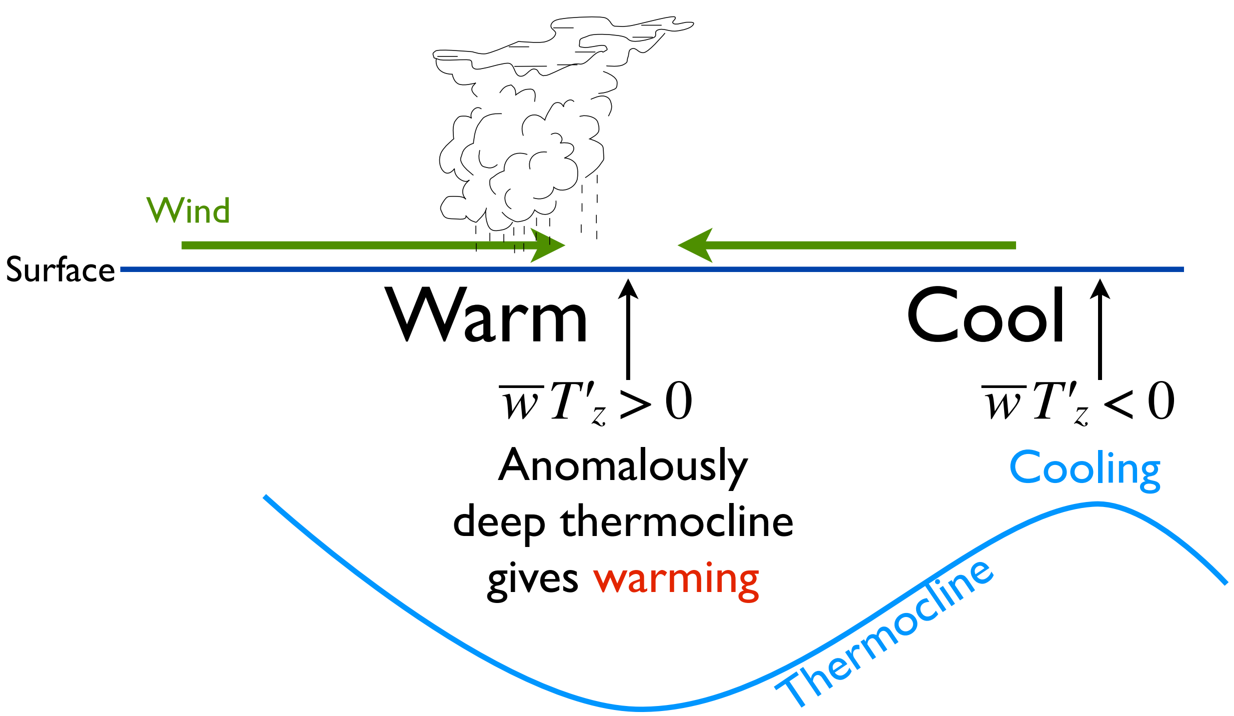


"Slow SST mode"

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 ($w = \overline{w}$).

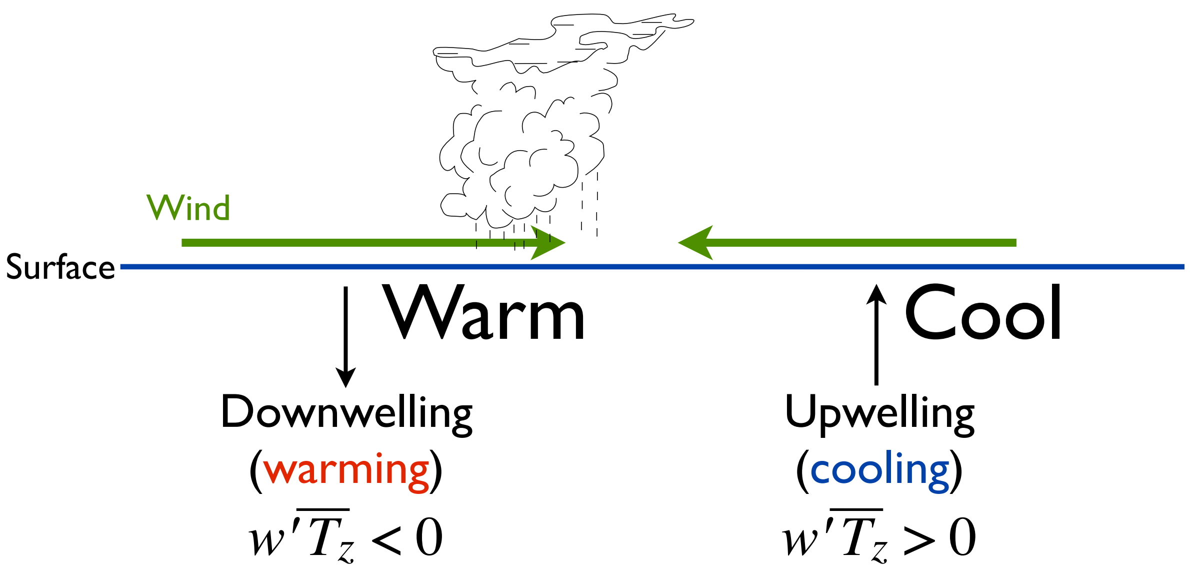
T'_z (vertical T gradient) anomalies dominate.

→ Anomalies propagate EAST

Neelin (1991, 97)

SST modes: eastward or westward propagation along the equator

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

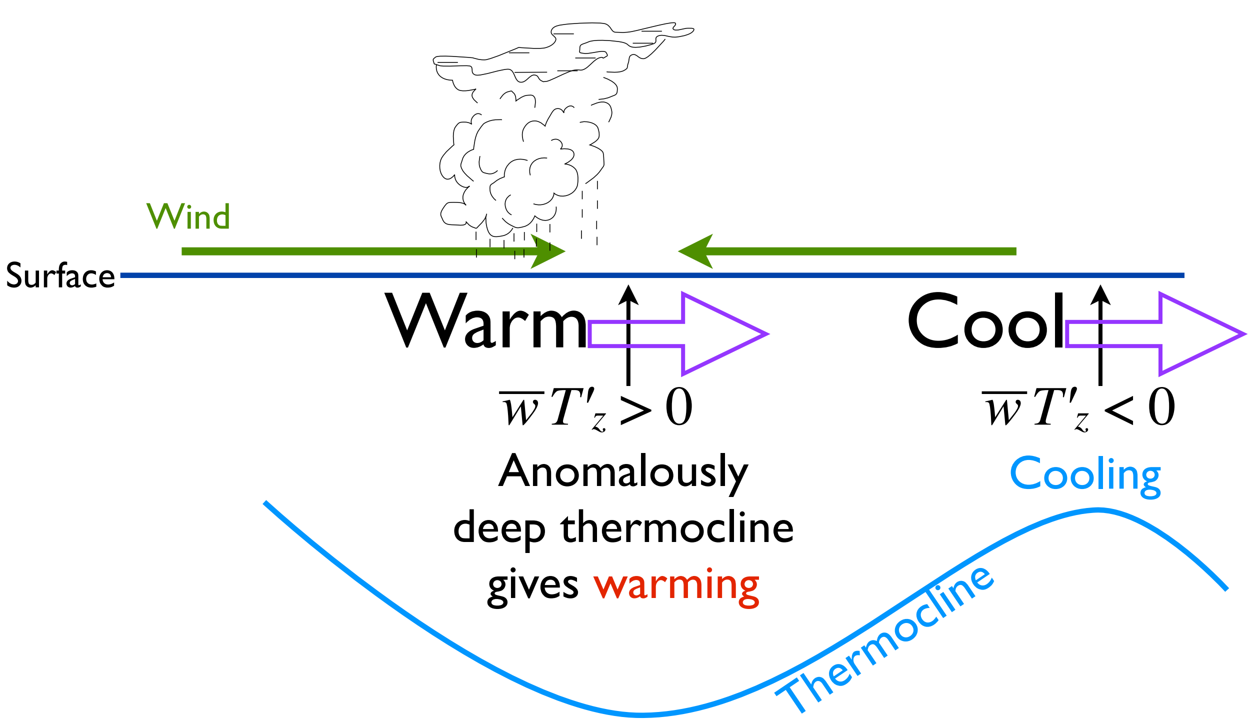


"Slow SST mode"

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 ($w=\overline{w}$).

T'_z (vertical T gradient) anomalies dominate.

→ Anomalies propagate EAST

Neelin (1991, 97)

The ocean absorbs less than 1 W/m² net

(About 0.5PW goes into the ocean)

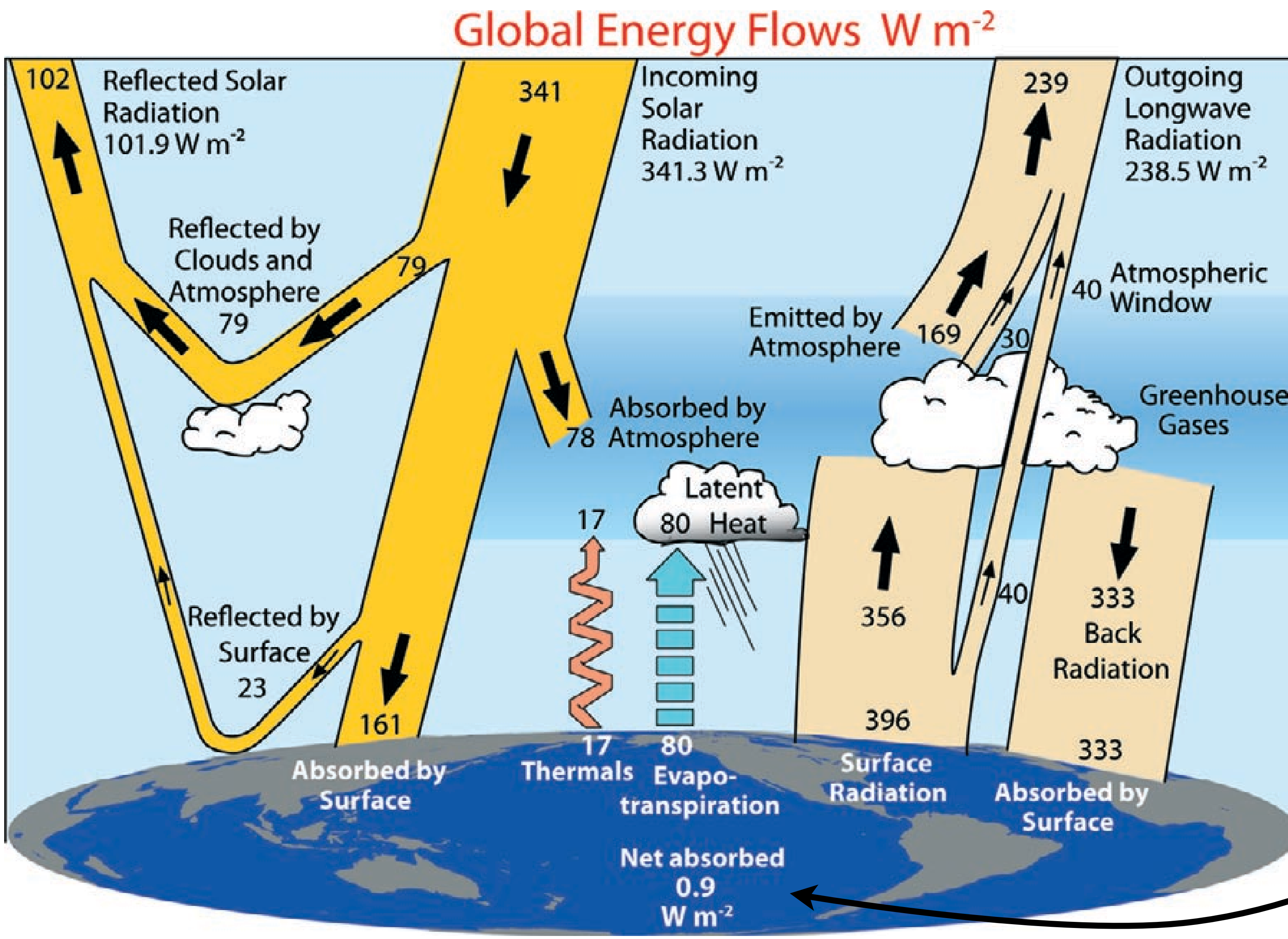
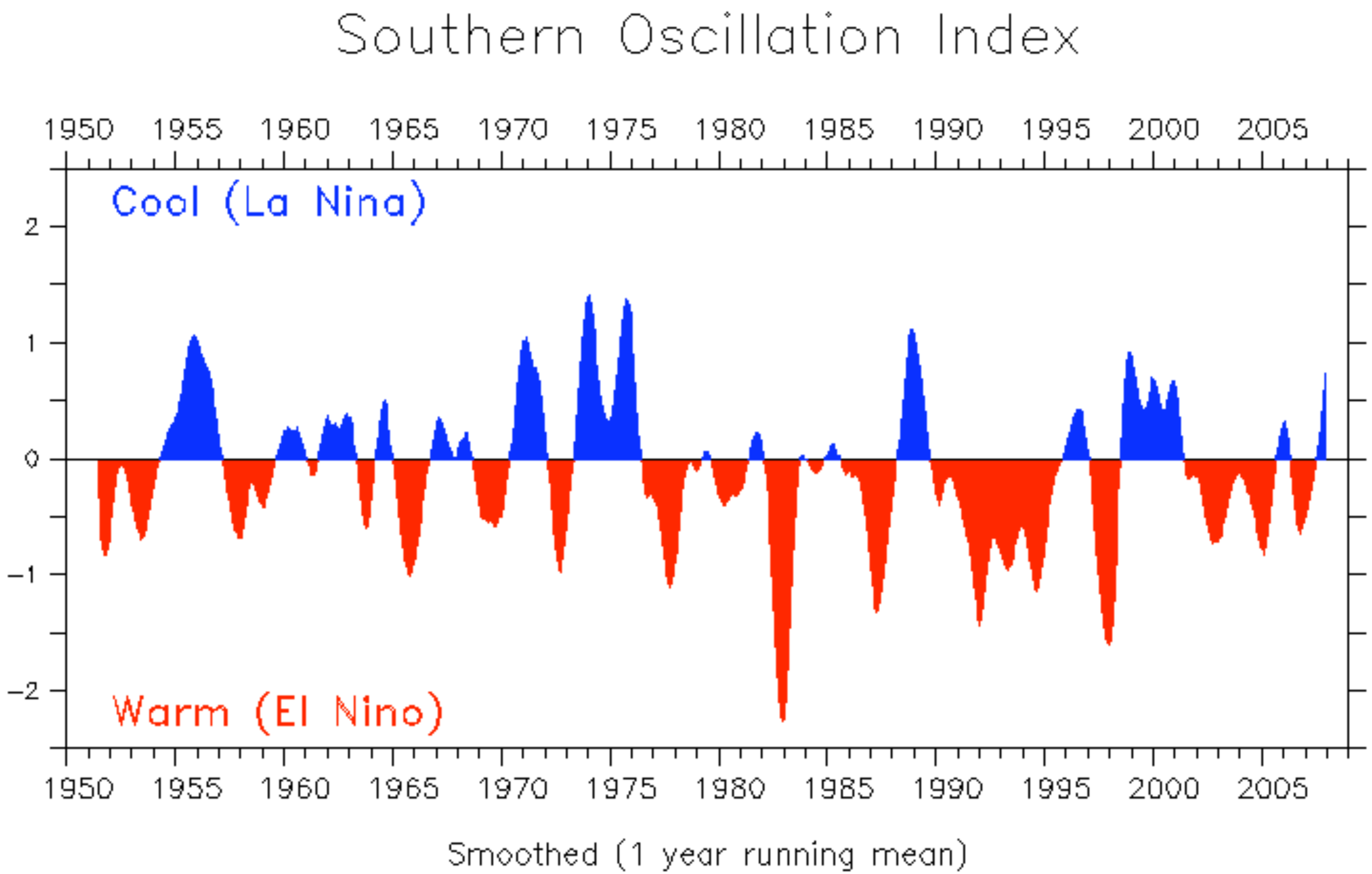


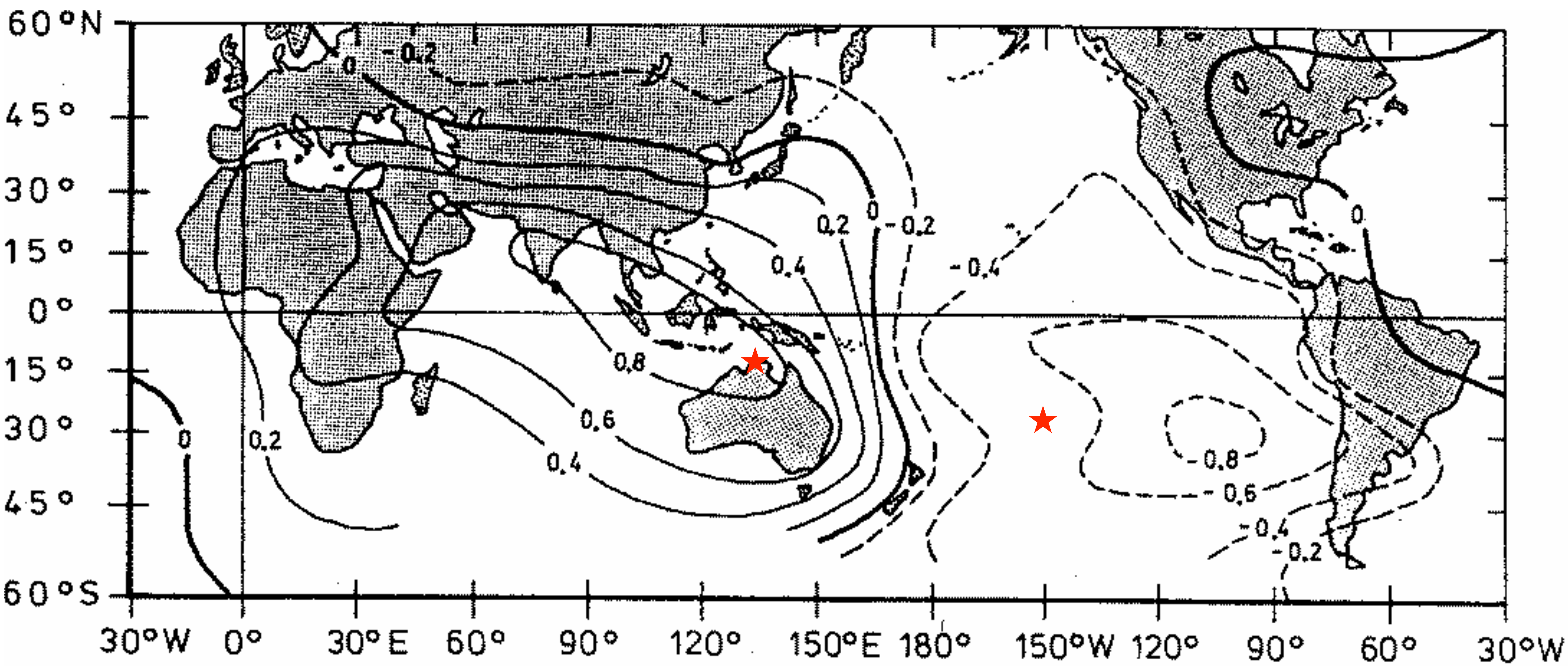
Fig. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m⁻²). The broad arrows indicate the schematic flow of energy in proportion to their importance.

Trenberth (2009)

El Niño occurrences are irregular



A widely-used indicator of El Niño is the Southern Oscillation Index, first used in 1923 by Sir Gilbert Walker, Director of Observatories in British India, who noted that "when pressure is high in the Pacific Ocean it tends to be low in the Indian Ocean from Africa to Australia".



The Southern Oscillation Index is the air pressure difference between Darwin, Australia and Tahiti

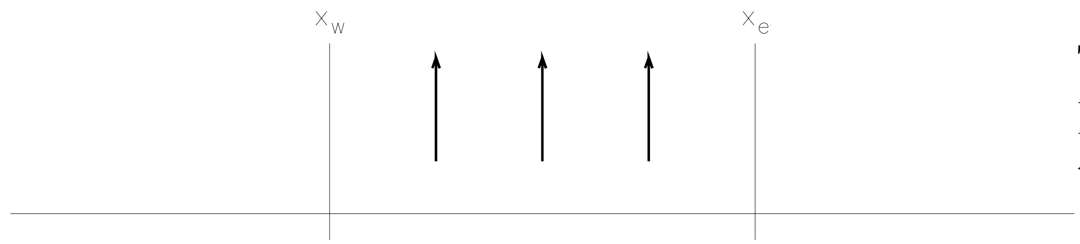
Remarks by Señor Federico Alfonso Pezet at the Sixth International Geographical Congress (London, 1895):

> 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).

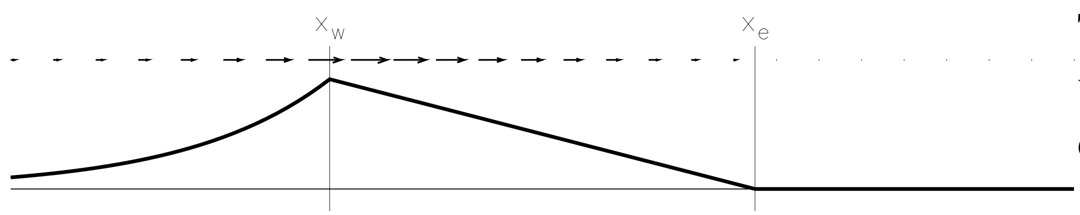
Winds are westerly under convection

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).



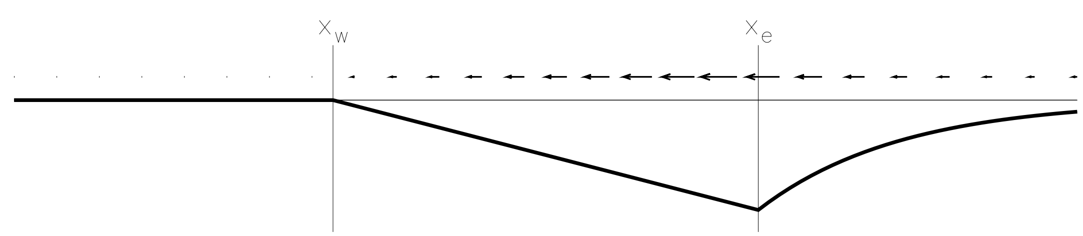
The patch is located between longitudes x_w and x_e. Within the patch: $w_z > 0$, so $u_x < 0$.

Since the system is linear, consider the Rossby and Kelvin reponses separately, integrating along wave characteristics. For the Rossby reponse, 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:

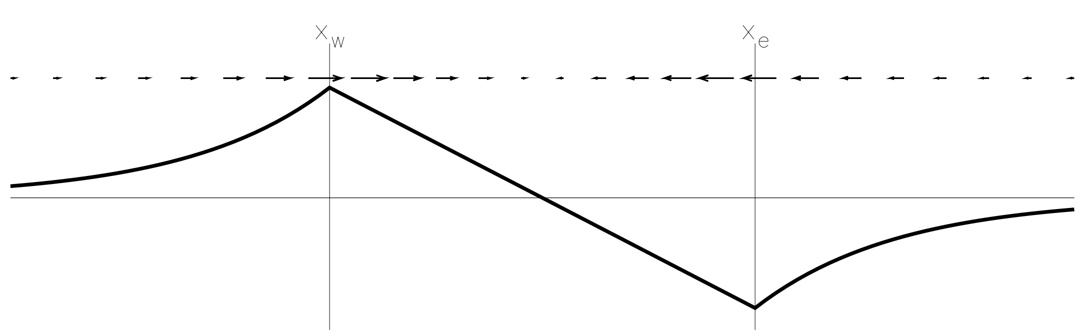


The line graphs the zonal winds, and the vectors display the same winds.

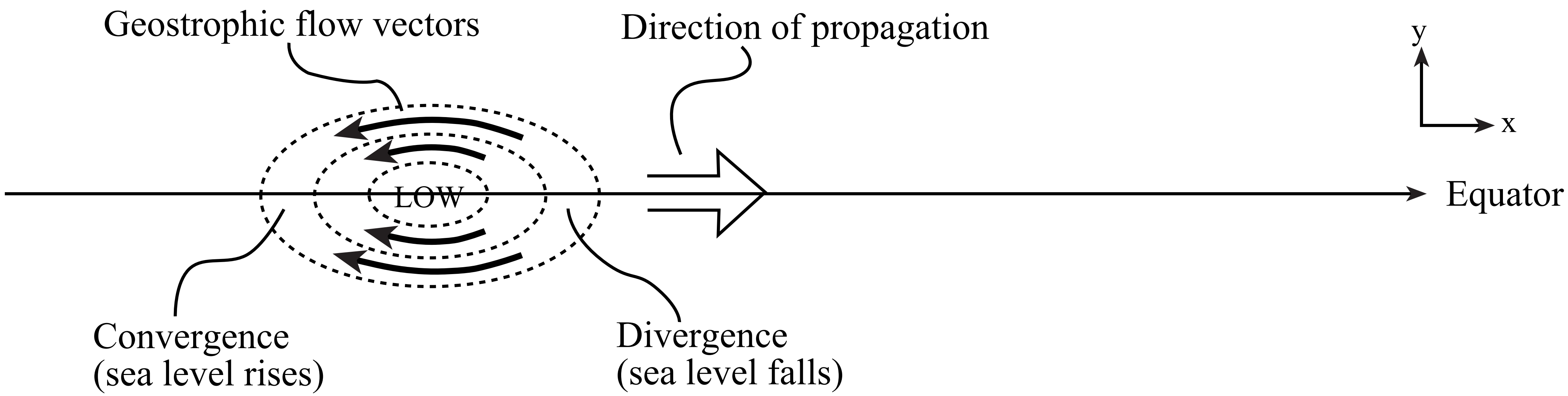
For the Kelvin response, do the same kind of integration, but from the west. There is no Kelvin response west of x_w. From x_w to x_e, the Kelvin zonal wind increases easterly, since $u_x < 0$. East of x_e, the Kelvin easterlies decay exponentially:



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



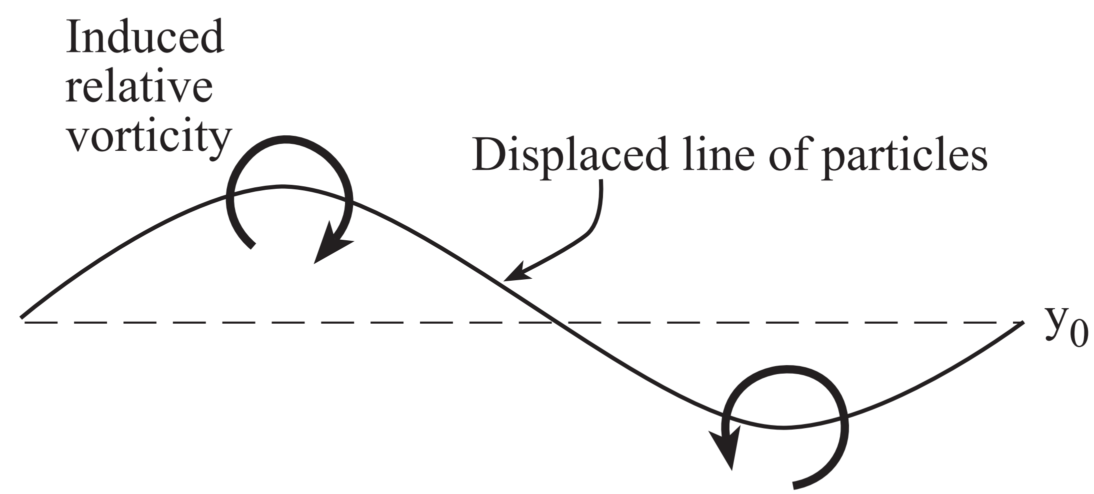
For a sea level depression (shallow thermocline; dashed contours) spanning the equator,
the geostrophic flow is westward in both northern and southern hemispheres (dark arrows).
These currents move mass from the east side of the depression to the west.
As a result, sea level falls in the east (deepening 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.

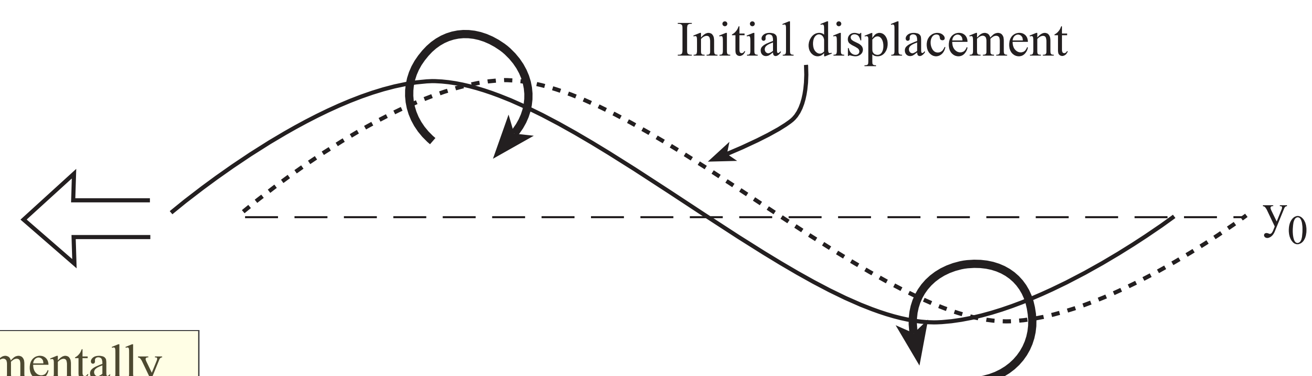
The mechanism of Rossby wave propagation

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 :

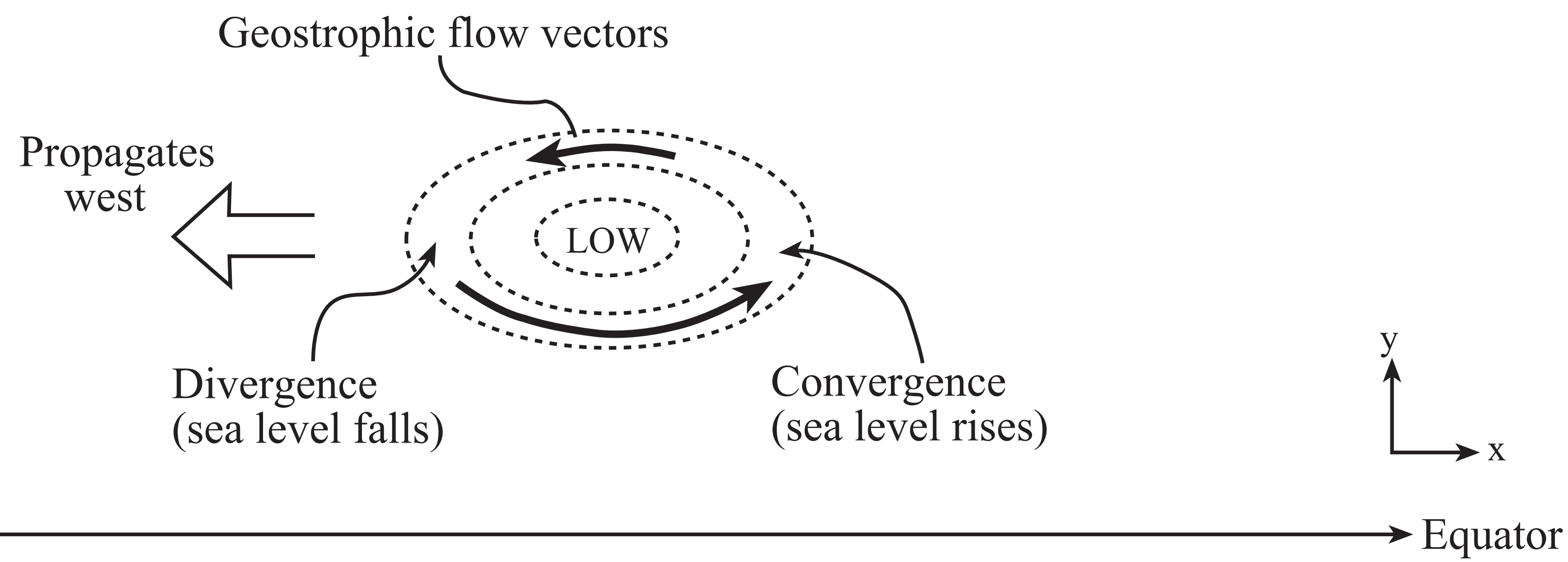


The acquired relative velocities move the displaced line of particles to the west:



⇨ 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.

The constraint is mass conservation:

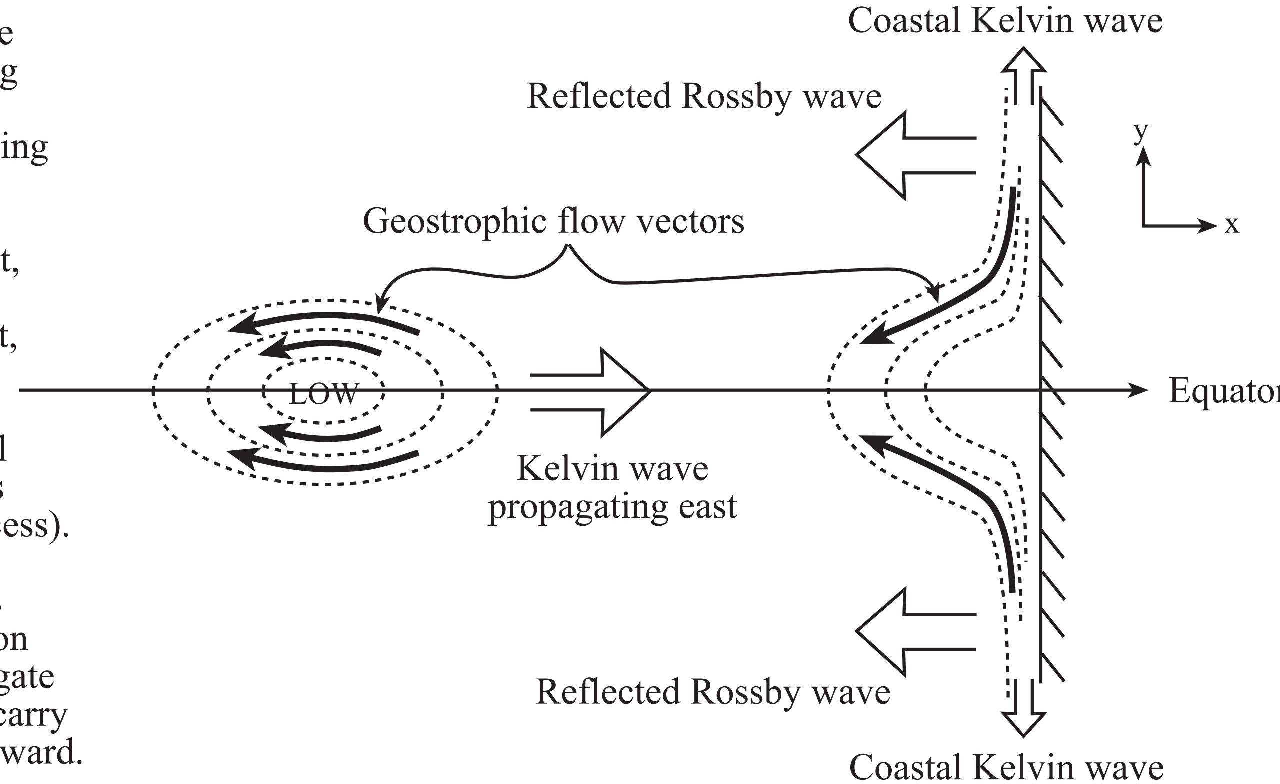
$$\int_{-\infty}^{\infty} u dy = 0$$

Equatorial Kelvin reflection to Rossby waves at an eastern boundary

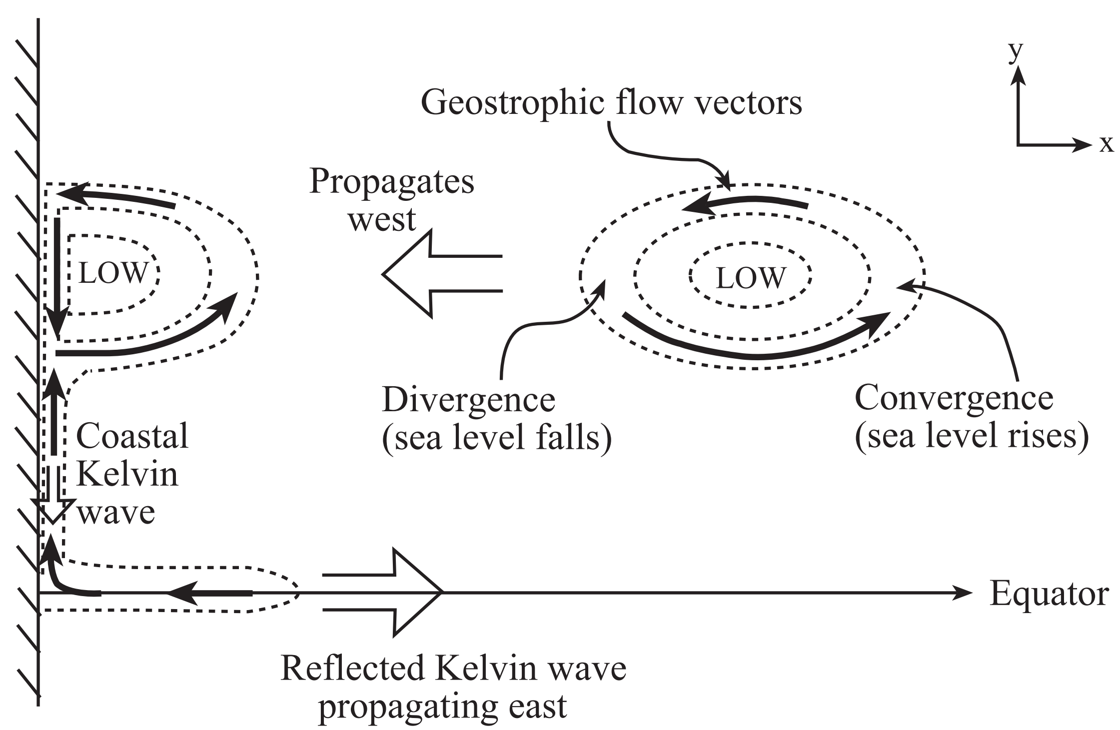
An example of a Kelvin wave (sea level depression) arriving at an eastern boundary. The Kelvin wave is transporting mass westward.

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

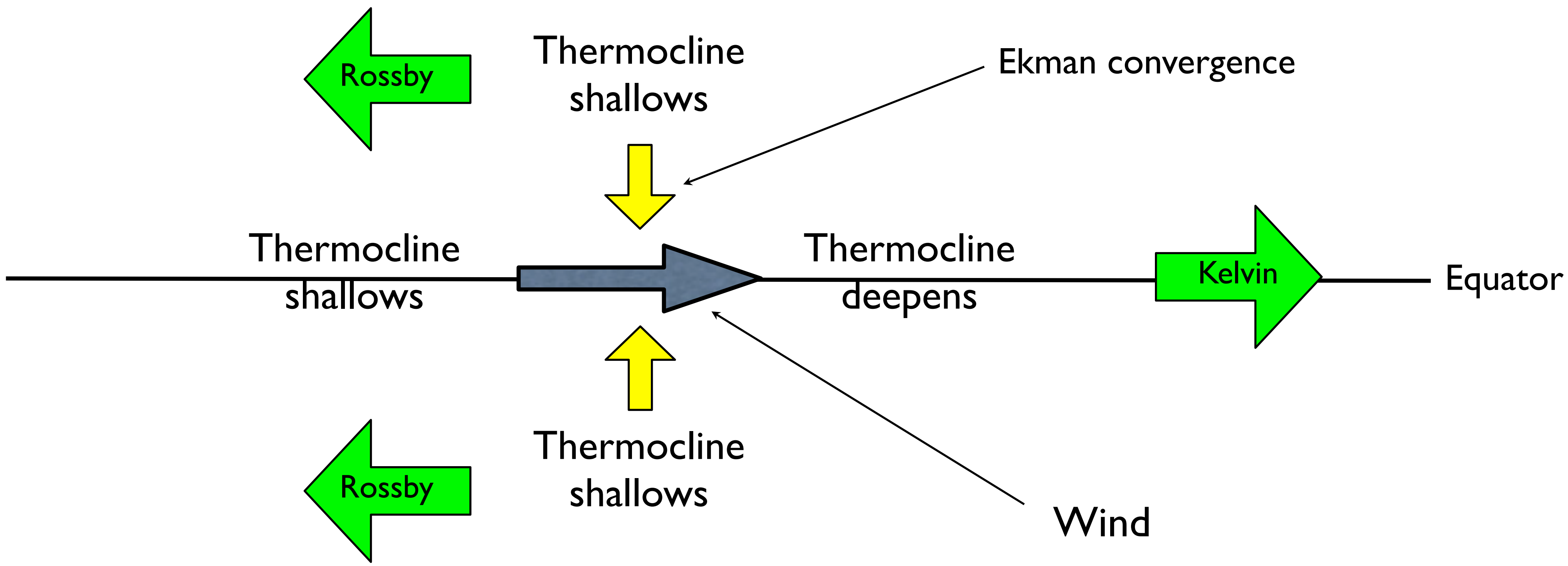


An example of a Rossby wave (sea level depression) arriving at a western boundary. The Rossby wave is transporting mass eastward.

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)