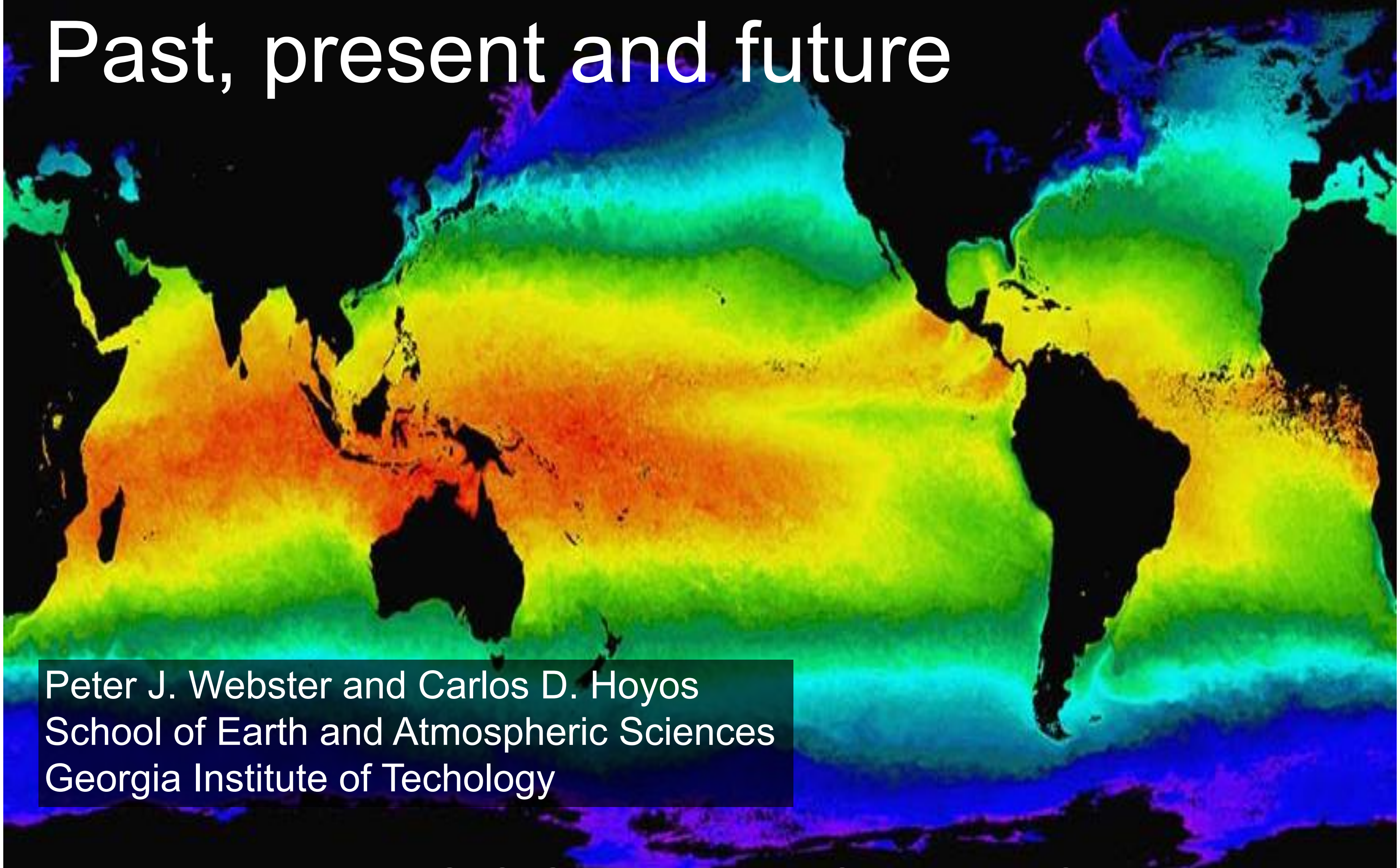
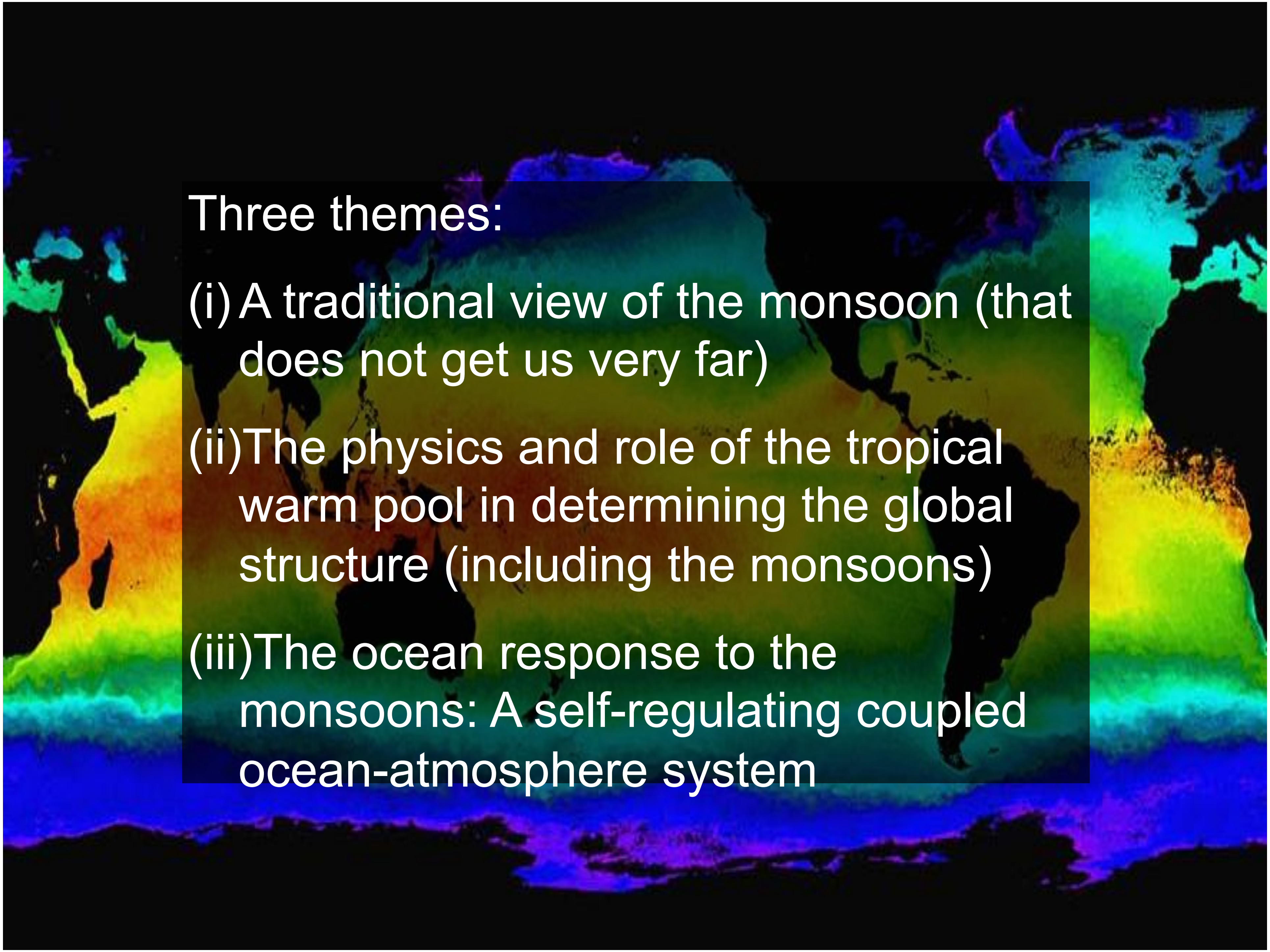
The evolving monsoon: Past, present and future



Peter J. Webster and Carlos D. Hoyos
School of Earth and Atmospheric Sciences
Georgia Institute of Techology

PAGES Global Monsoon Symposium, Shanghai 2010



Three themes:

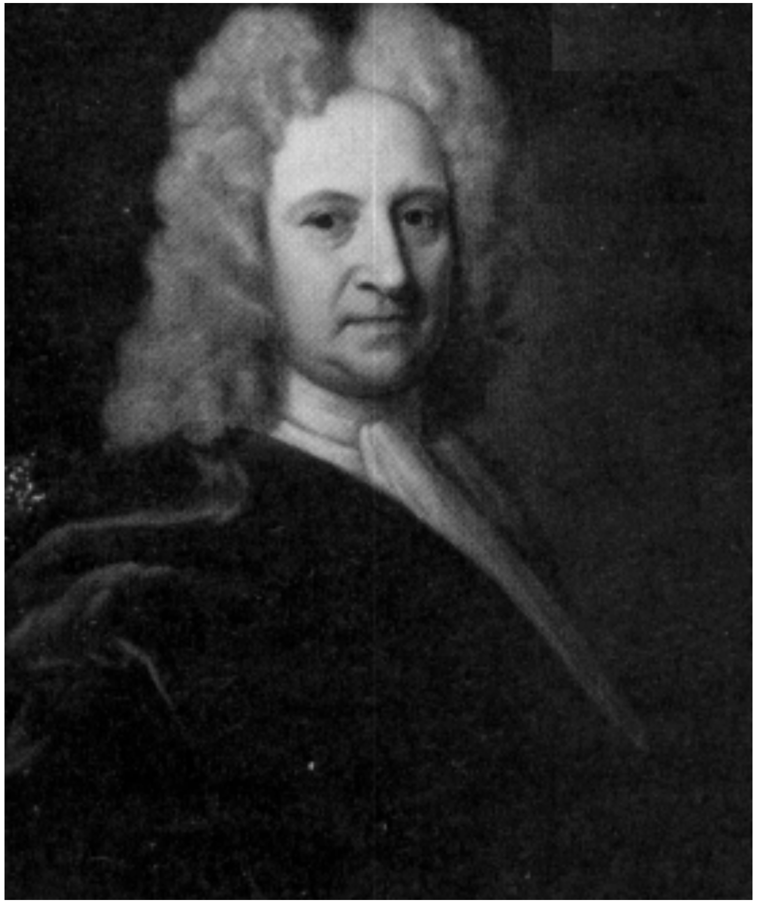
(i) A traditional view of the monsoon (that does not get us very far)

(ii) The physics and role of the tropical warm pool in determining the global structure (including the monsoons)

(iii) The ocean response to the monsoons: A self-regulating coupled ocean-atmosphere system

Edmund Halley (1656-1742)

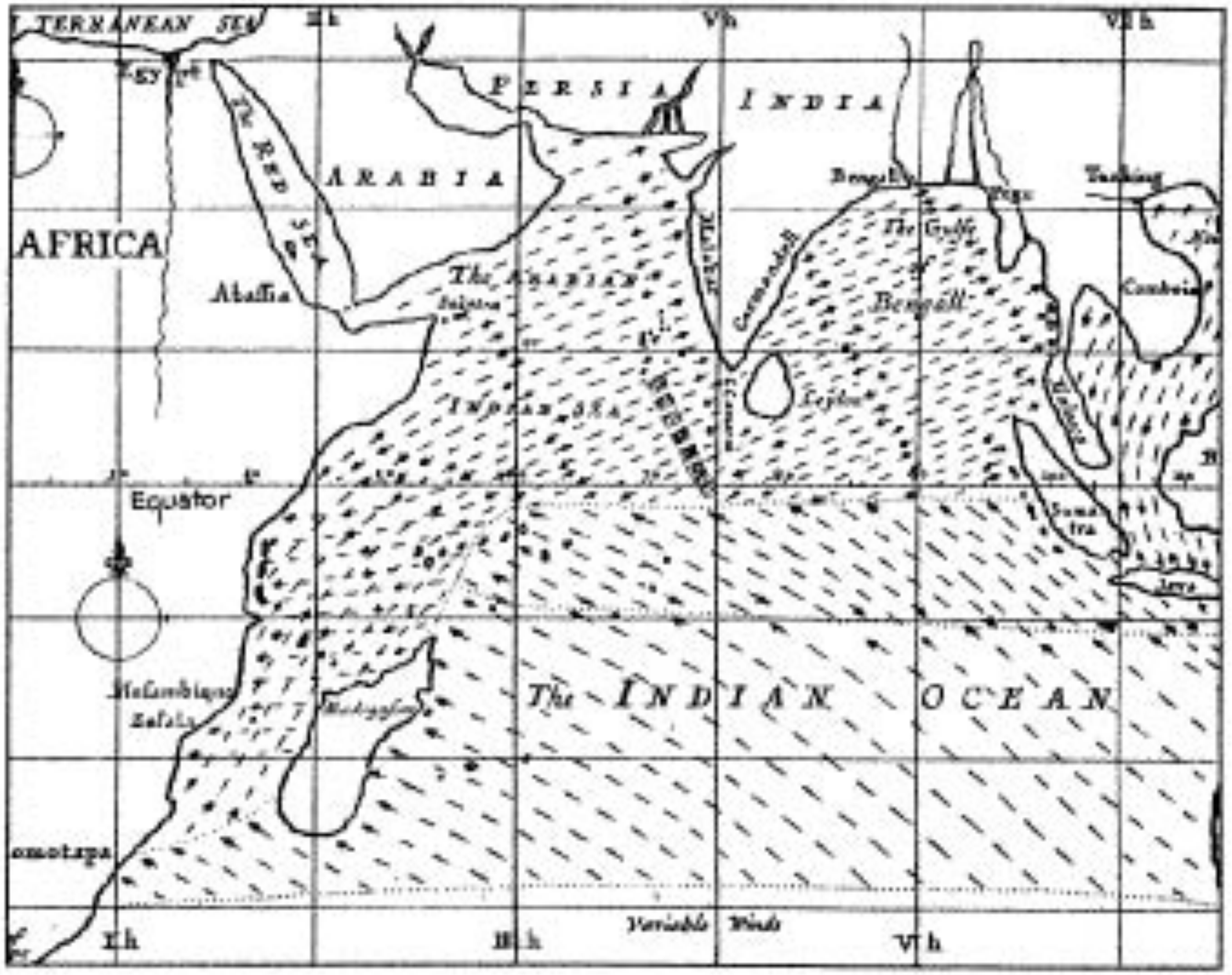
- Mathematician & physicist



George Hadley 1685-1768

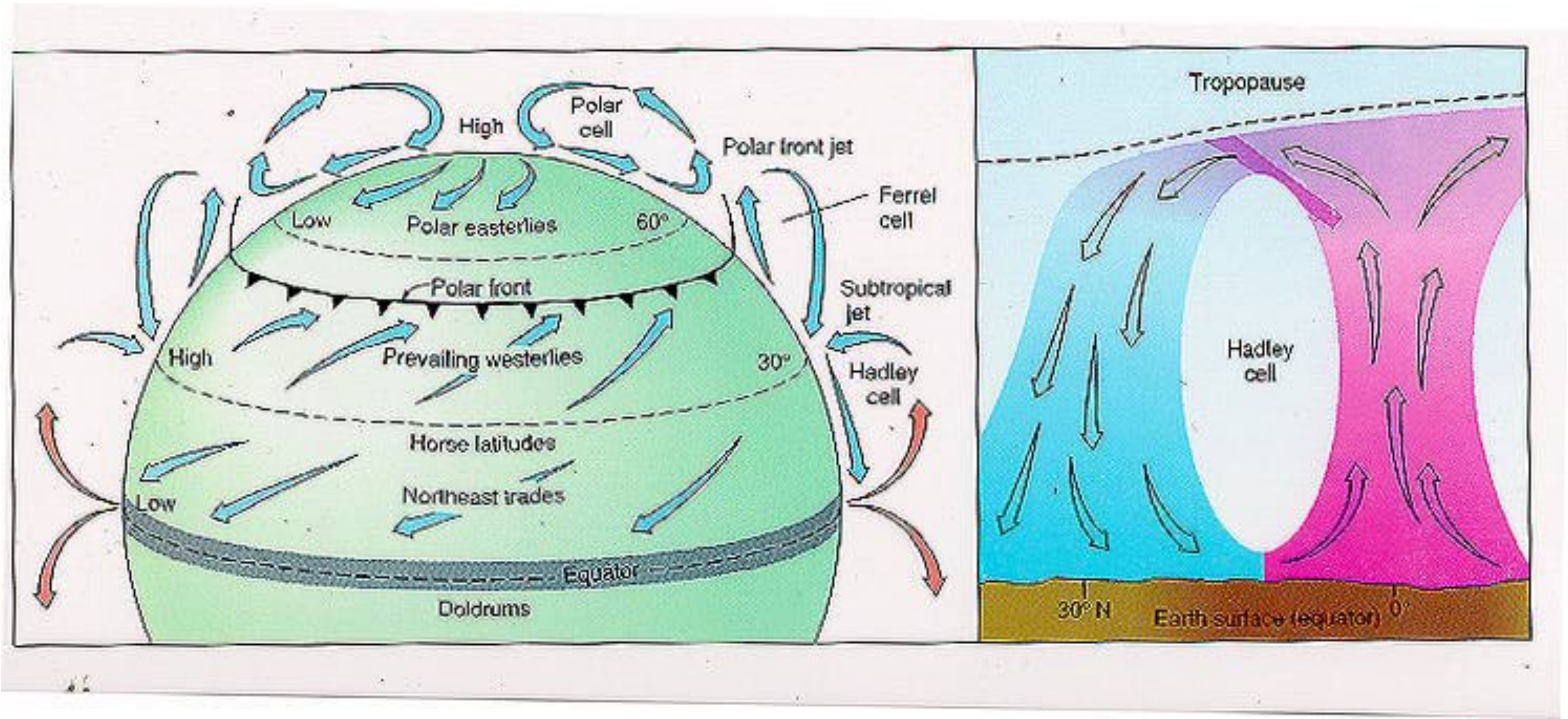
- Laywer and meterologist

Halley (of comet fame) was the first to describe monsoon and attribute differential heating between land and ocean as the cause



Section of Halley's global surface wind map

Unfortunately, the ideas of Halley and Hadley were interpreted to provide incorrect and over simplistic views of the climate system such as…

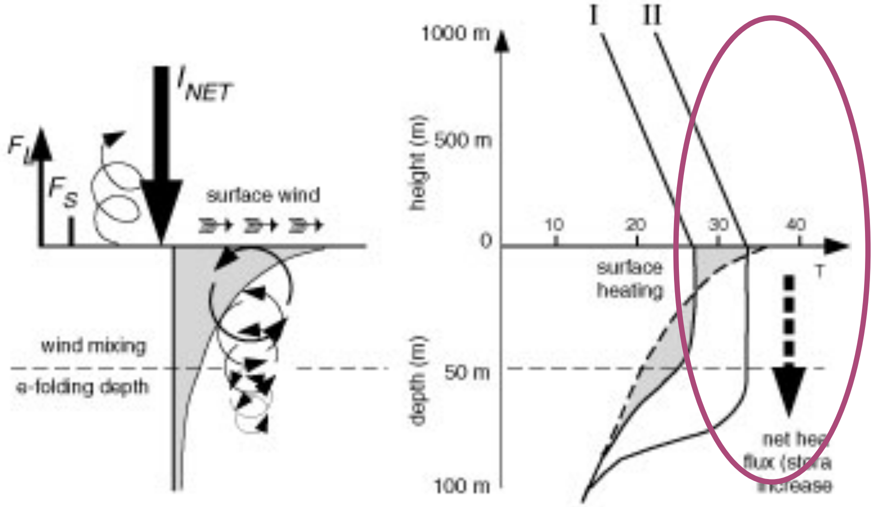


A meteorological epicycle theory!

OCEAN

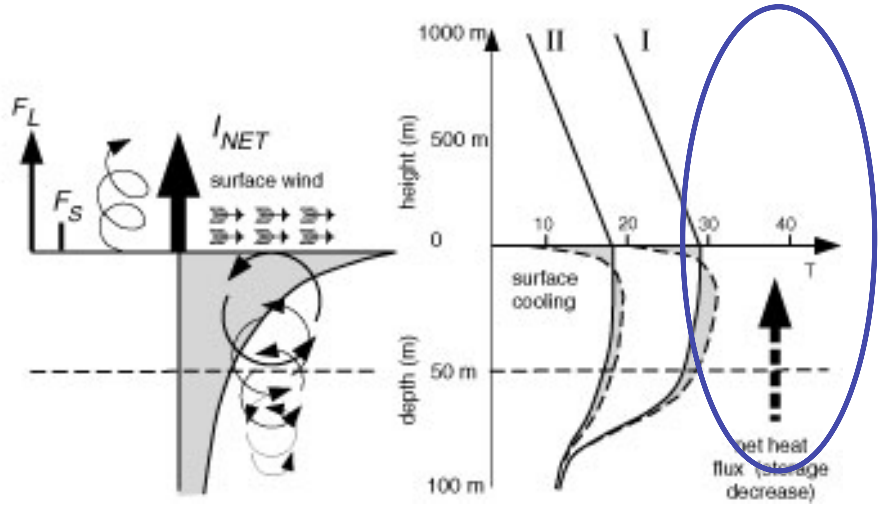
Spring to summer

- Increase storage by deepening & warming mixed layer
- Induce delay of maximum SST

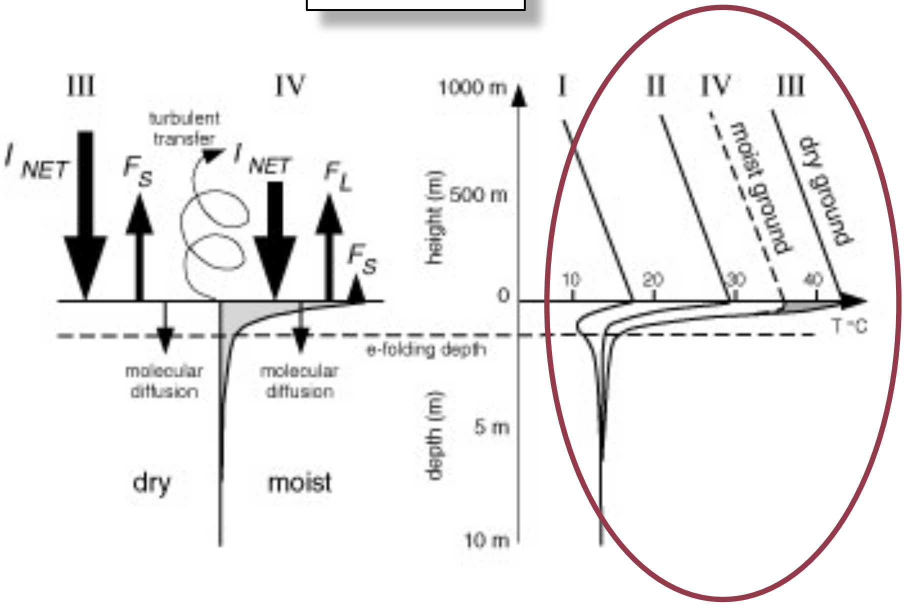


Autumn to winter

- Decrease storage by cooling of mixed layer & mixing upwards of warm water
- Delay in SST minimum

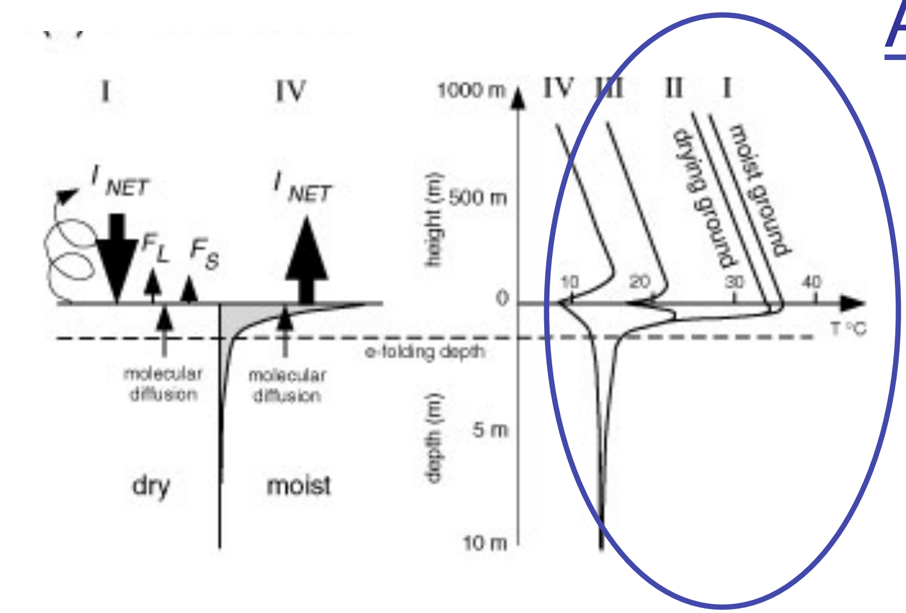


LAND



Spring to summer

- Initial rapid increase in surface temperature (SH>>LH) reduced by wetting
- Land becomes evaporation source with LH>SH
- Storage and climatic memory
- Decrease in albedo

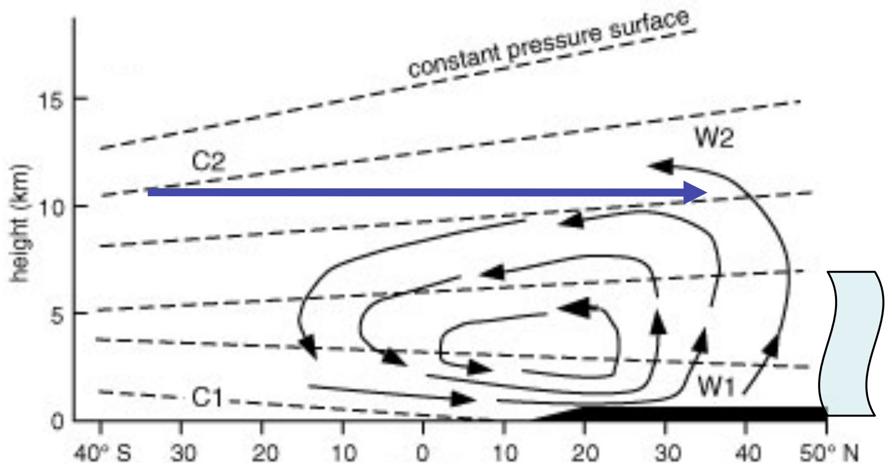


Autumn to winter

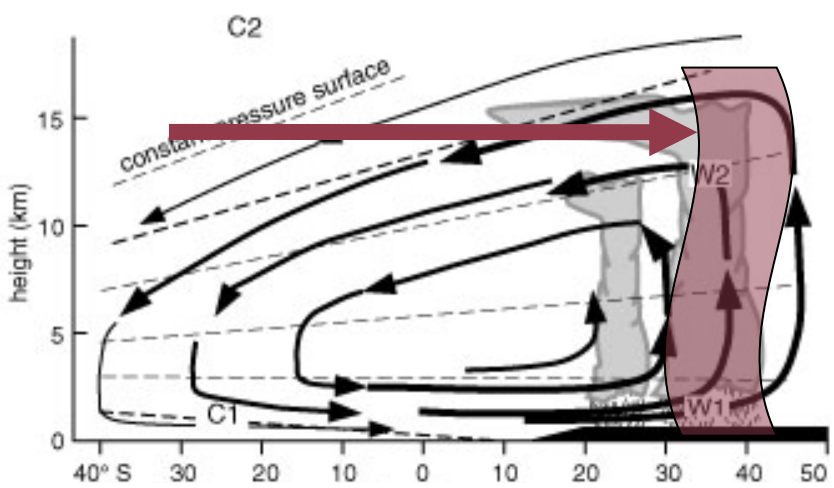
- Delay of cooling of surface by moist soil followed by rapid cooling

moisture sets the vertical scale of the circulation

DRY CIRCULATION

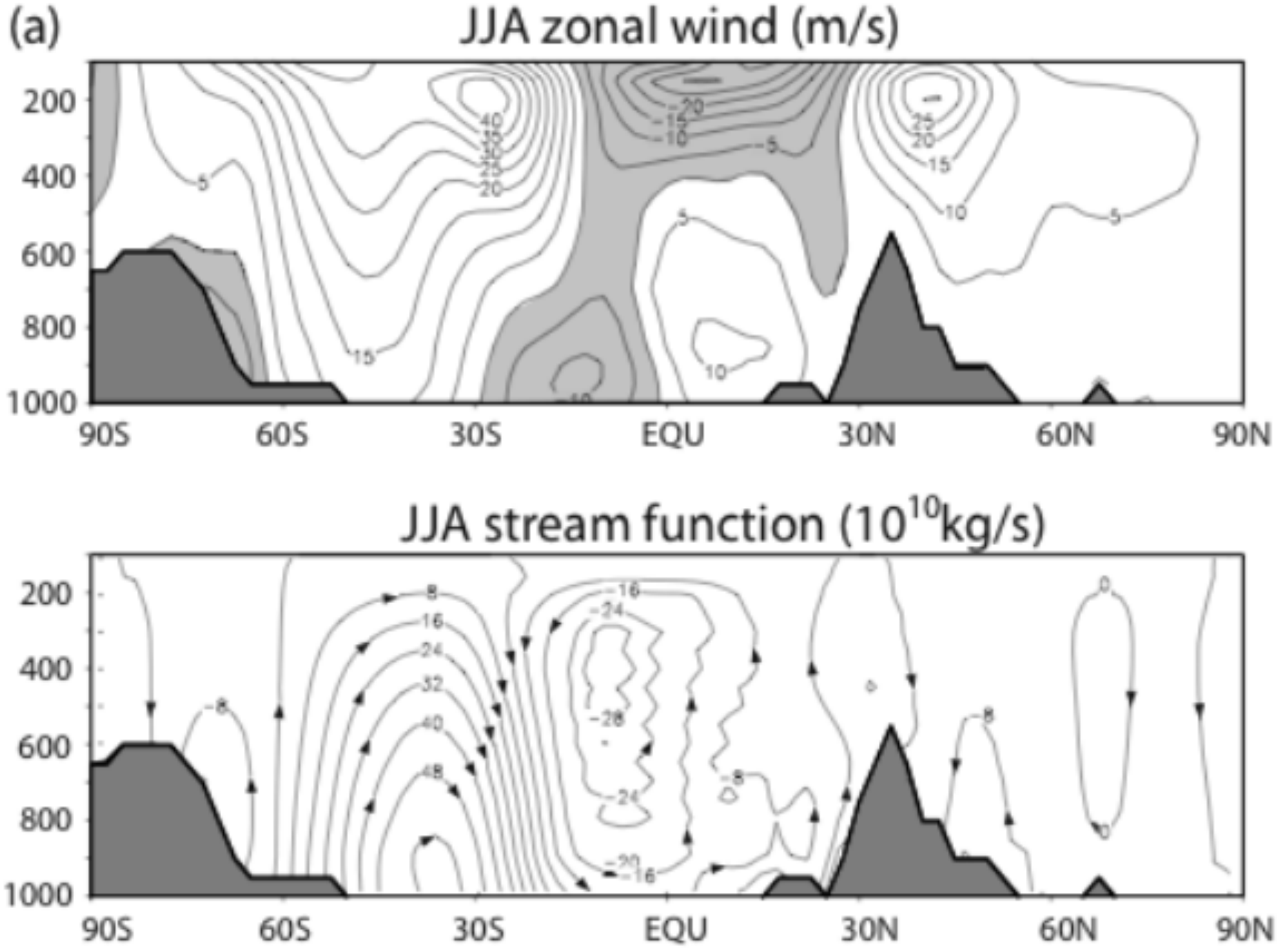


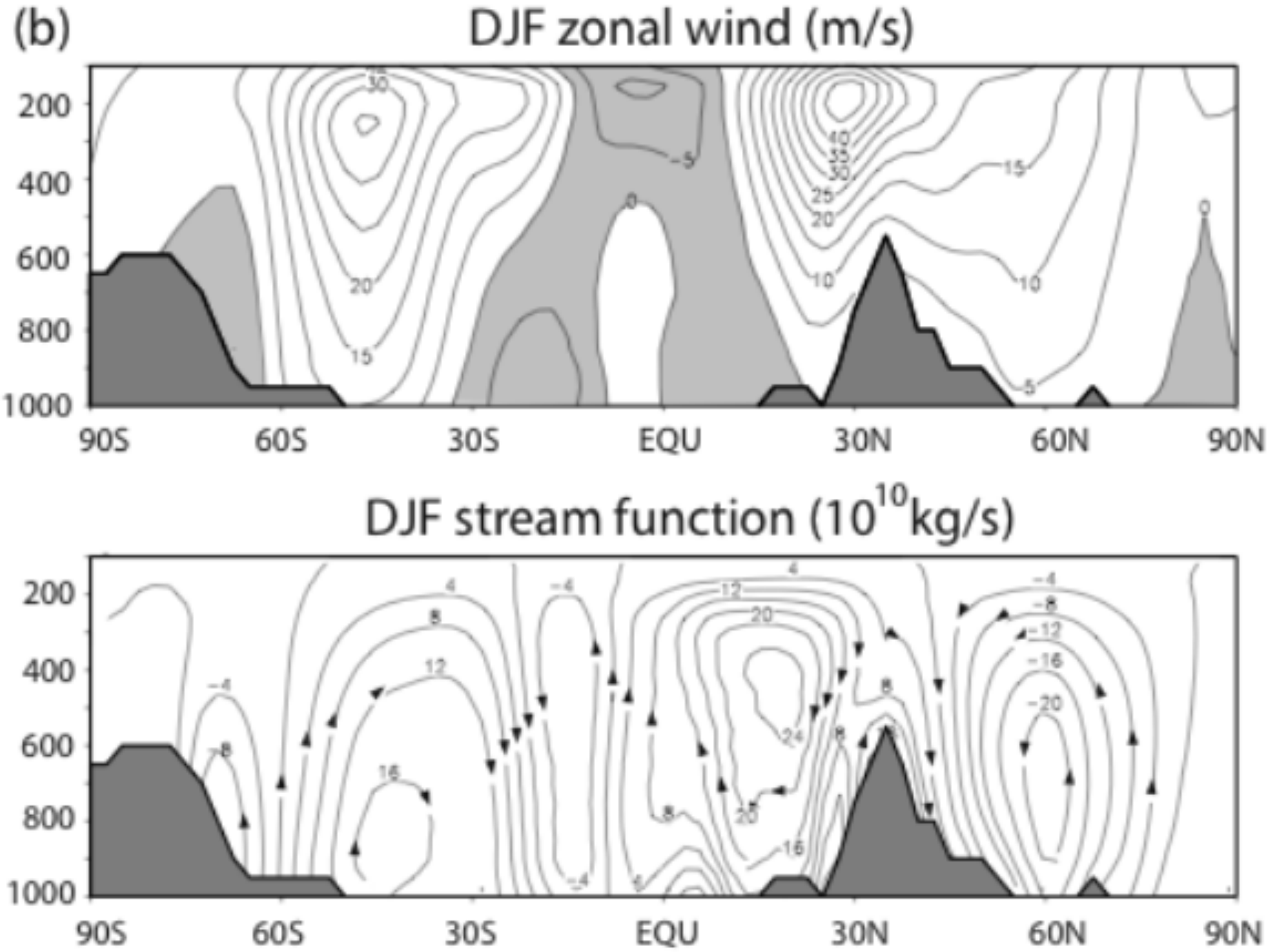
MOIST CIRCULATION



- Weak amplitude (Rad, SH).
- T(z) dry adiabatic so that upper pressure gradient force weak
- Vertical scale given by equivalent depth of mode (2-4 km)

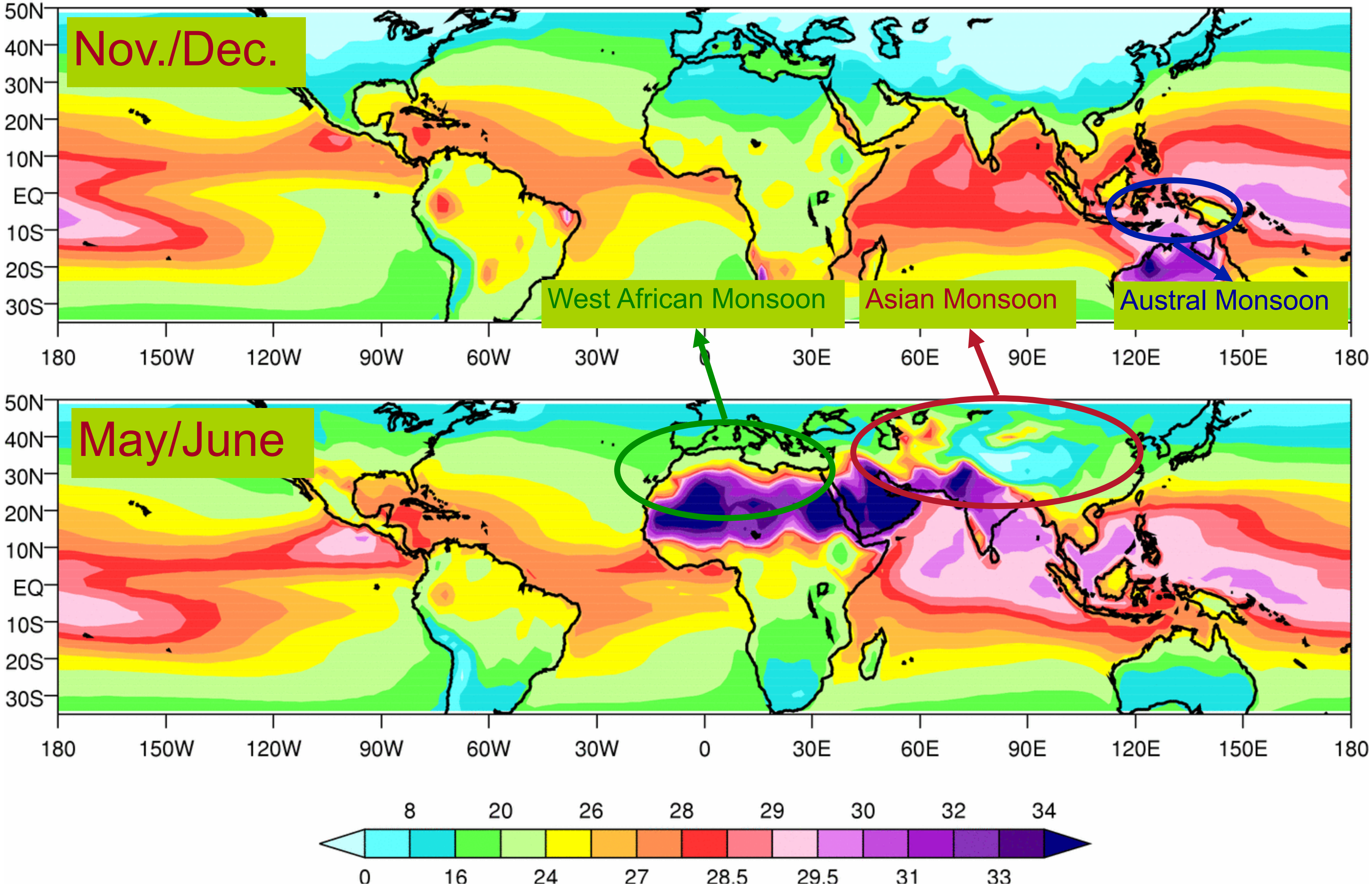
- Stronger amplitude (SH->LH, Rad)
- T(z) moist over land, more abiabatic over cold ocean creating large upper-trop pressure gradient
- Vertical scale given by convection


(a)
JJA zonal wind (m/s)
200
400
600
800
1000
90S
60S
30S
EQU
30N
60N
90N
JJA stream function (10^{10}kg/s)
200
400
600
800
1000
90S
60S
30S
EQU
30N
60N
90N

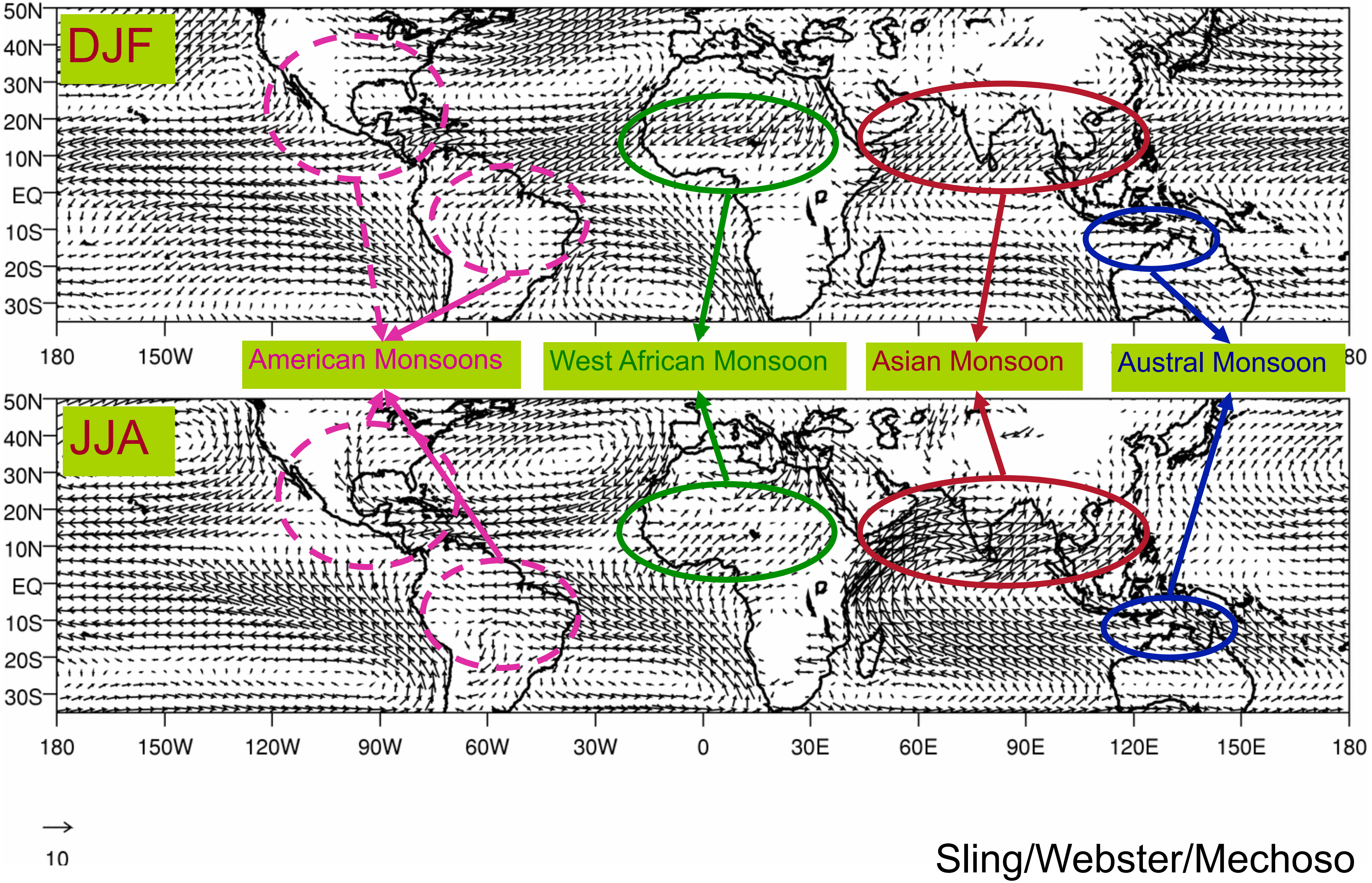


(b)
DJF zonal wind (m/s)
200
400
600
800
1000
90S
60S
30S
EQU
30N
60N
90N
DJF stream function (10^{10}kg/s)
200
400
600
800
1000
90S
60S
30S
EQU
30N
60N
90N

Land/Ocean temperature/SST contrasts

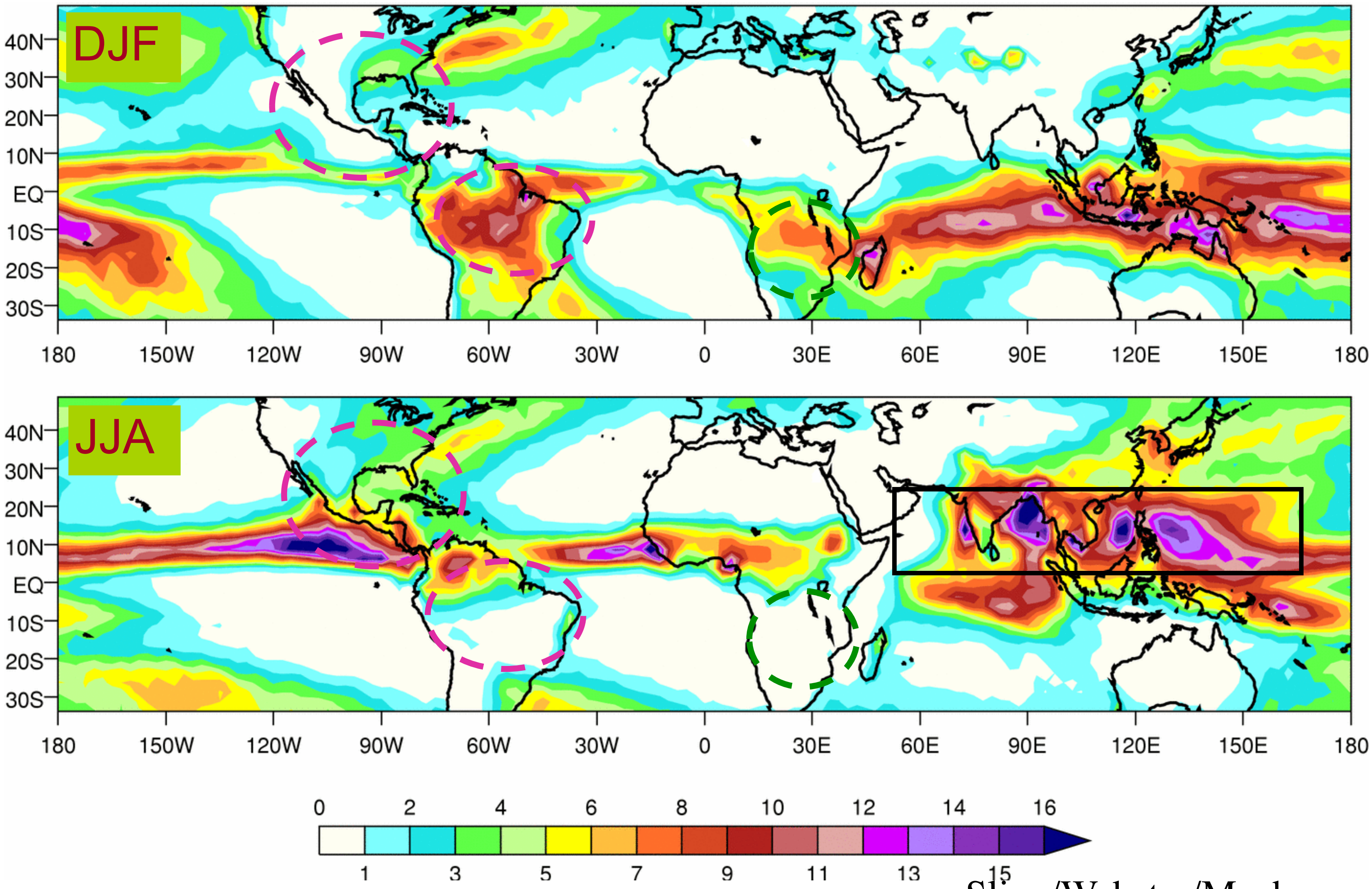


925 mb winds



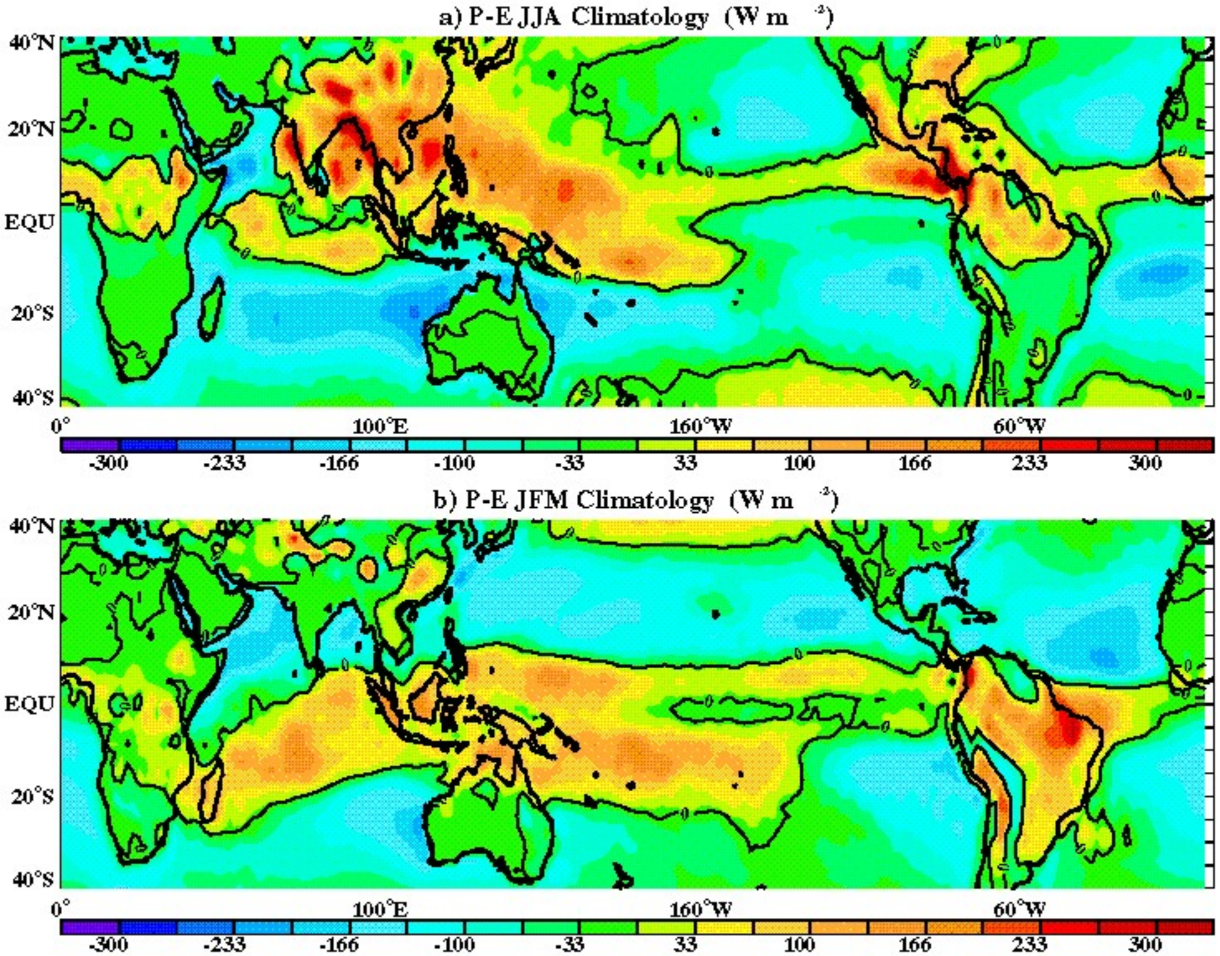
Sling/Webster/Mechoso

Precipitation (mm/day) not all rain over land!



Sling/Webster/Mechoso

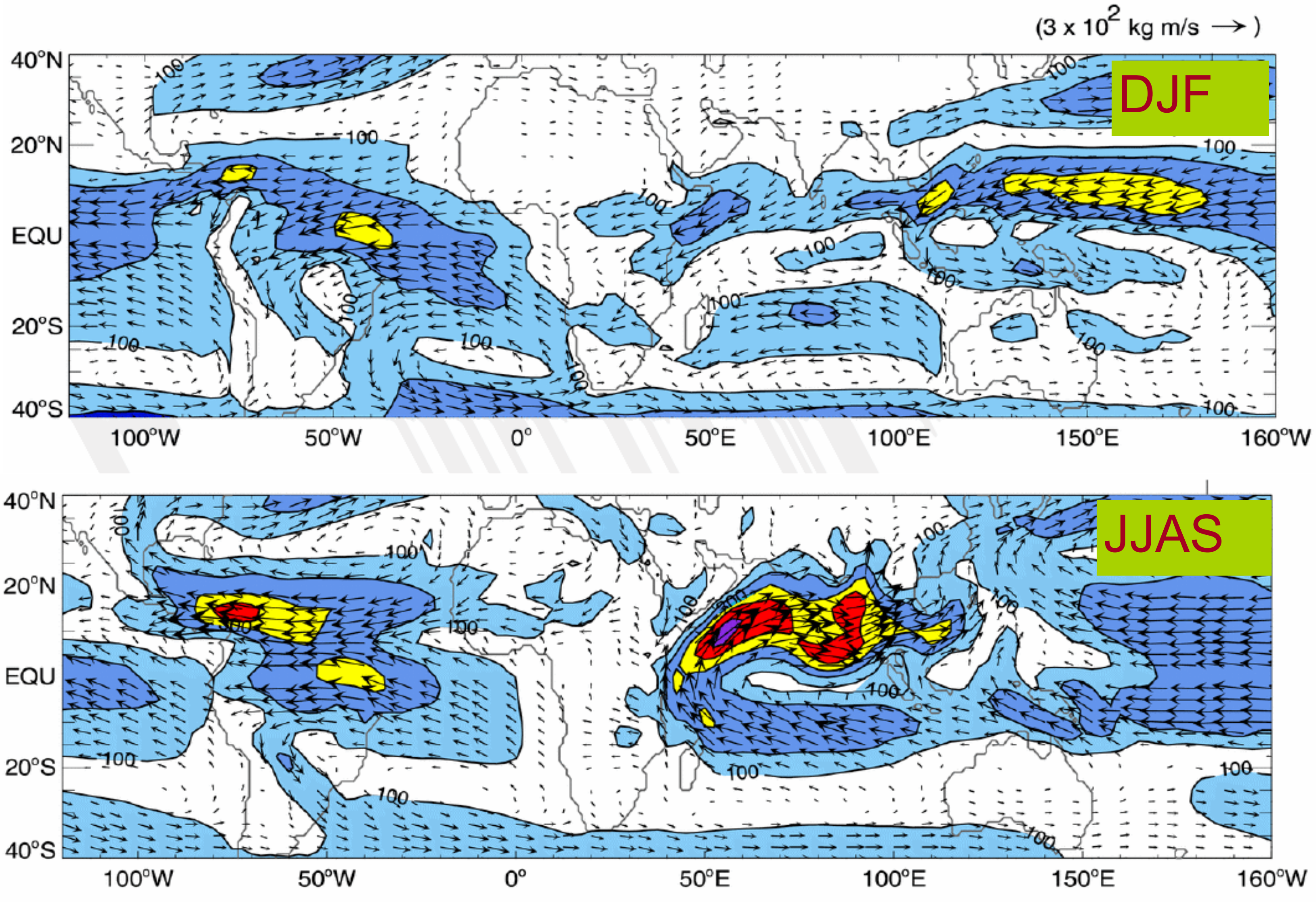
What determines the (P-E) distribution?



This question led to TOGA COARE

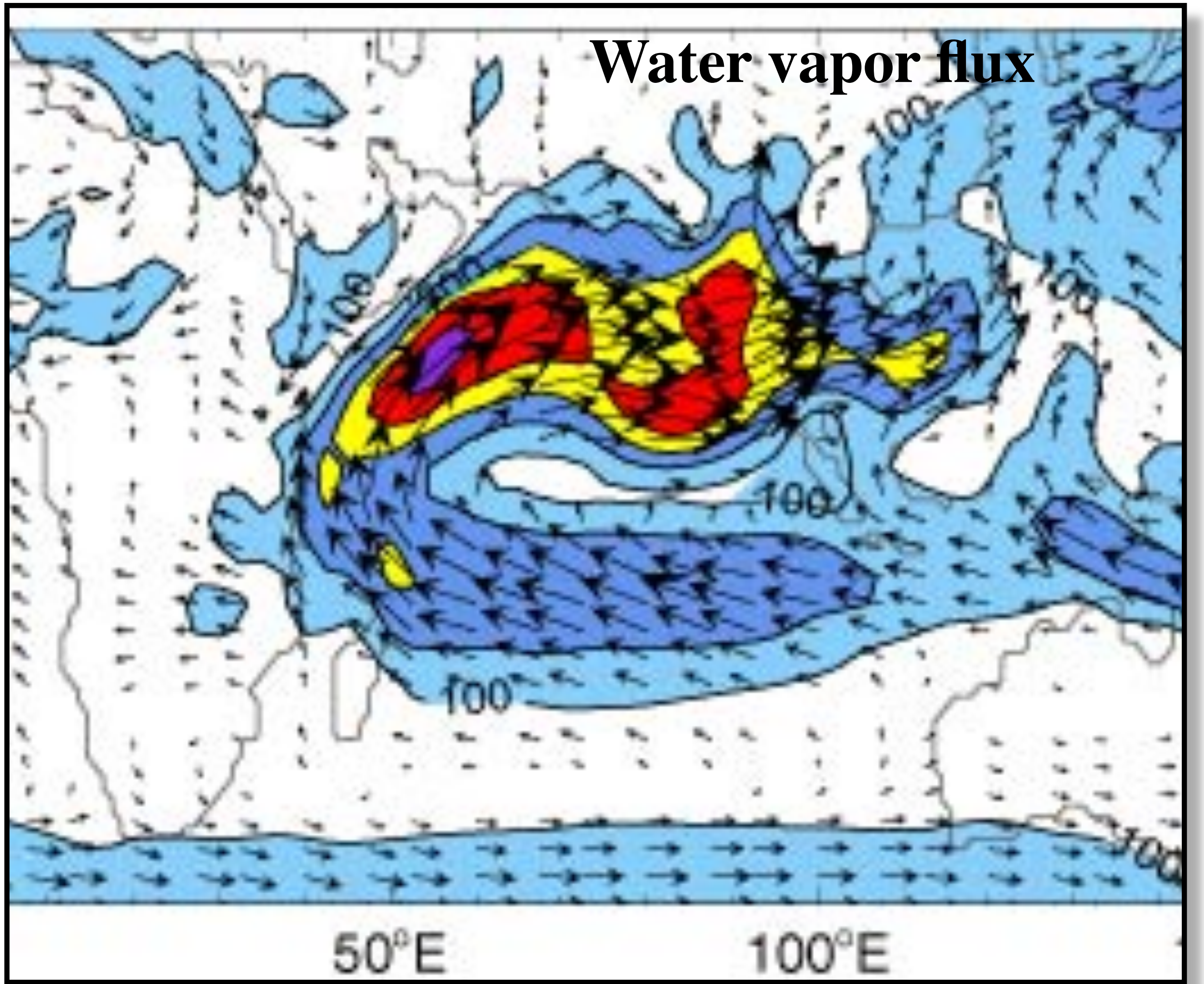
Monsoon's moisture supply

Vertically integrated moisture flux



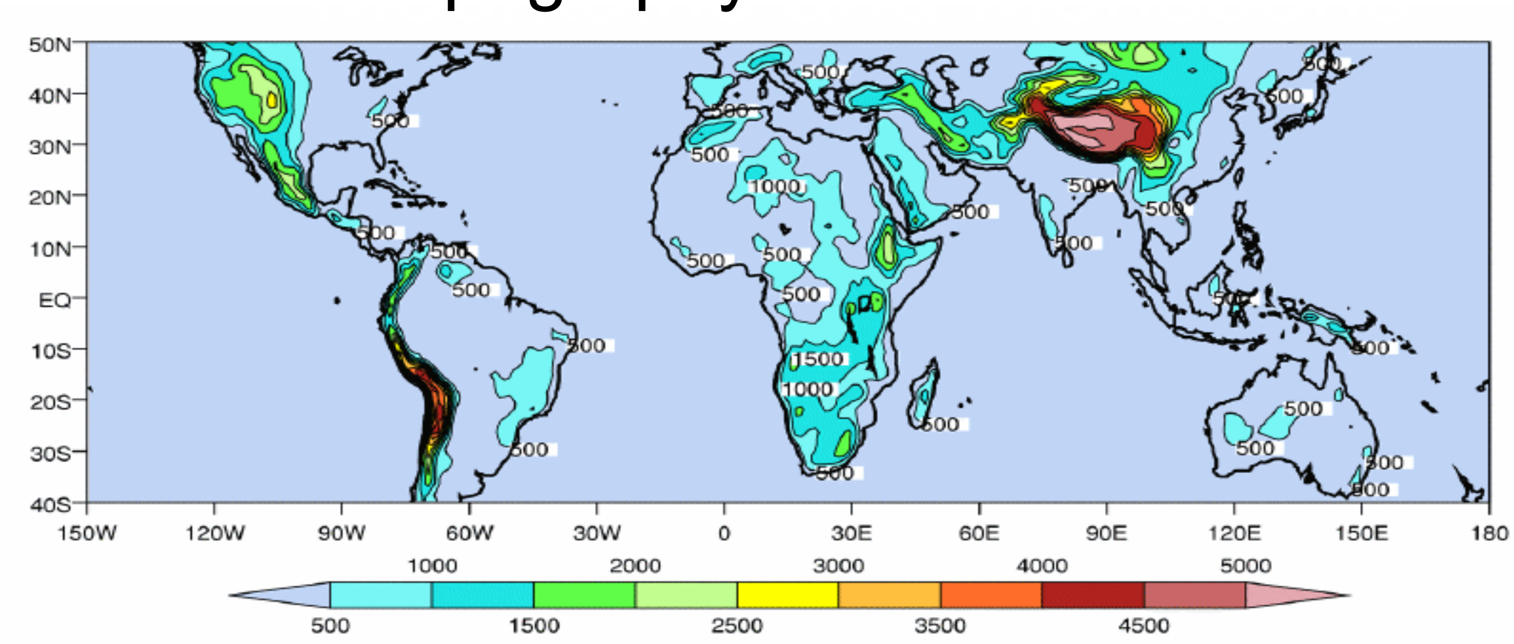
(Fasullo and Webster (2002)

and also ducted water vapor from one hemisphere to the other

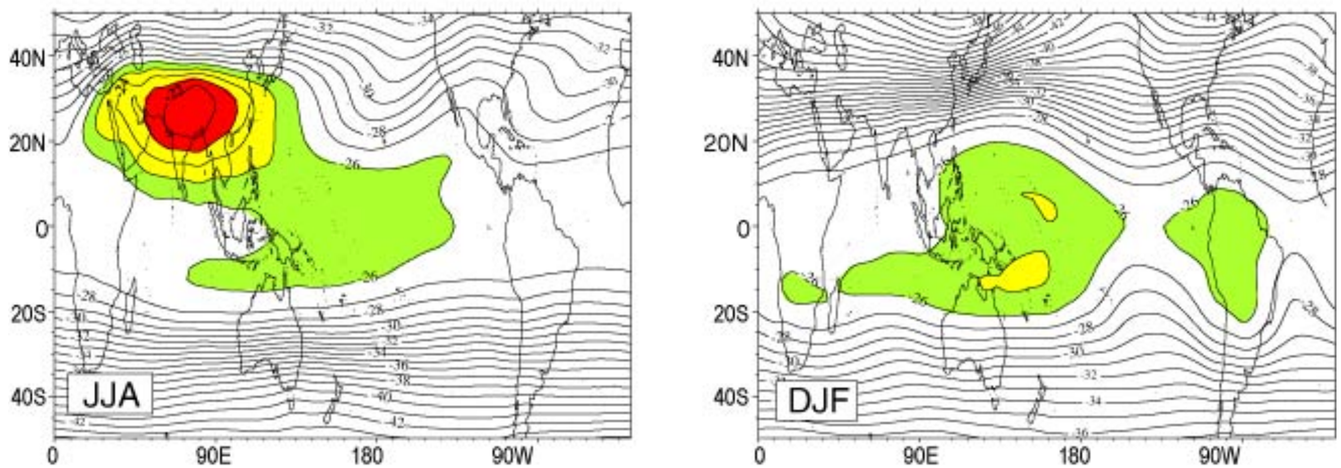


Impact of East African highlands

Topography and the Monsoon

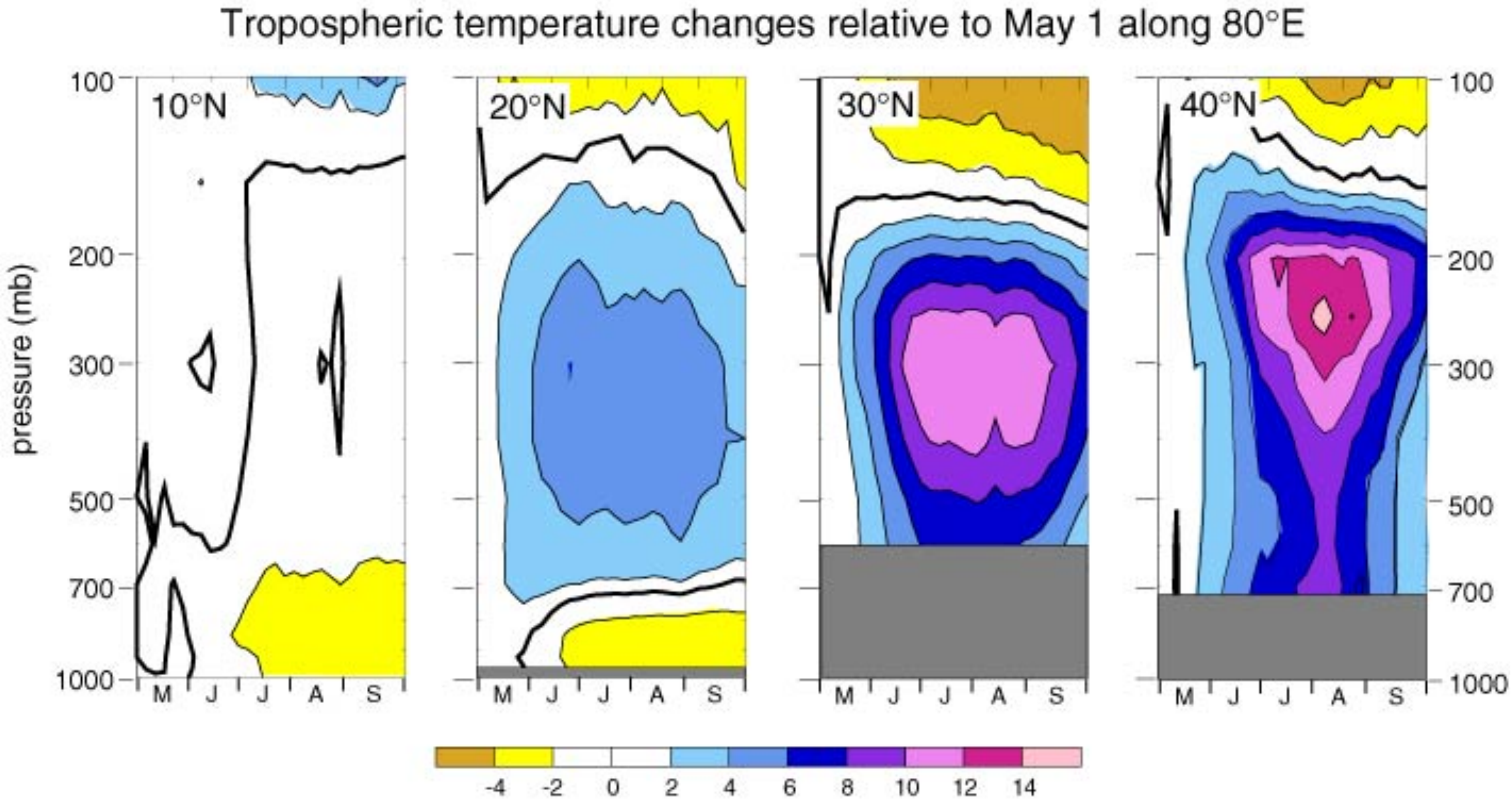


Mean Upper-Tropospheric Temperature: 200-500 mb



Upper troposopheric heat sources

Changes in Tropospheric Temperature in Monsoon Region

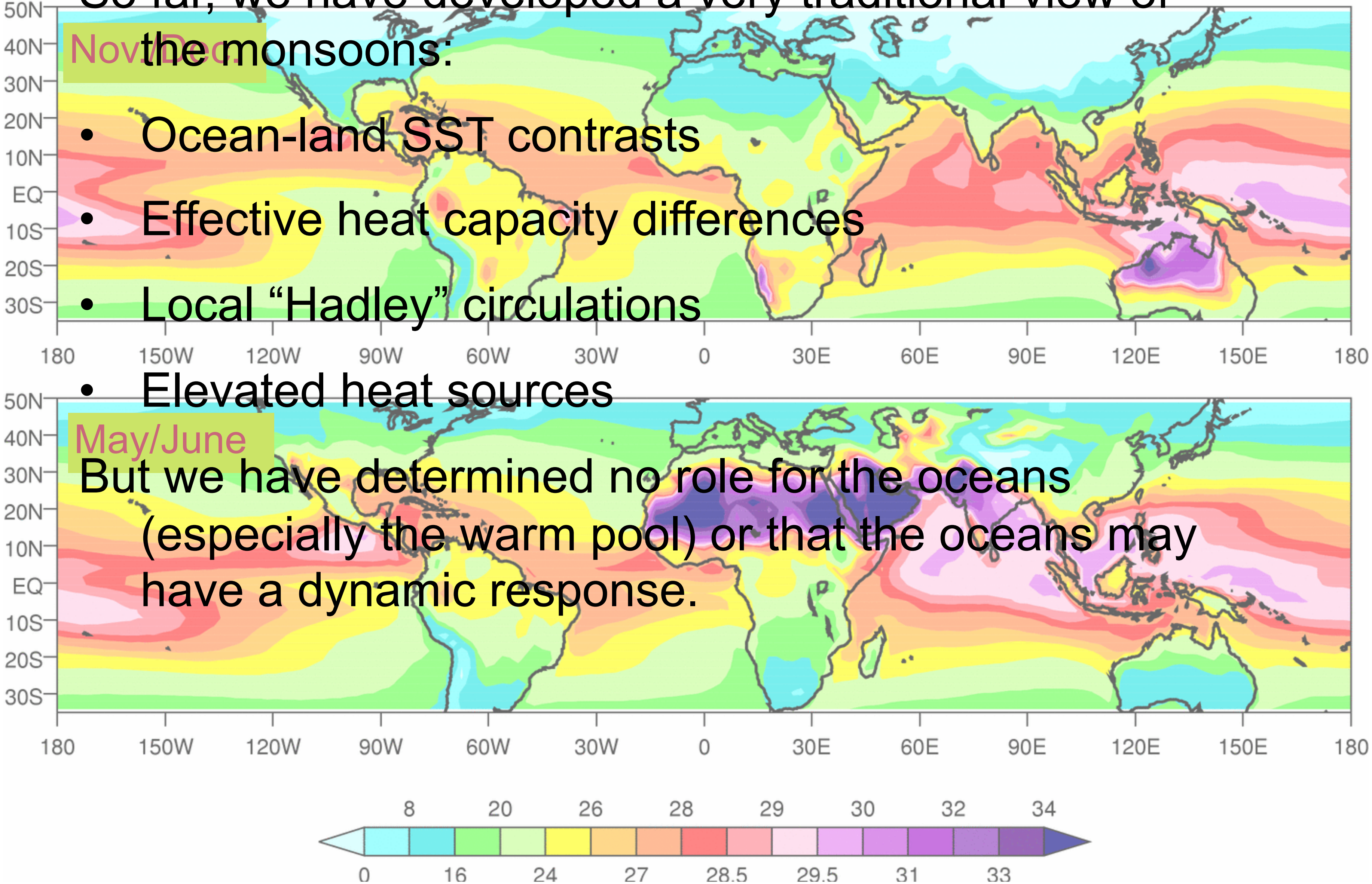


Temperature changes much larger over Himalayas than elsewhere.

So far, we have developed a very traditional view of the monsoons:

- Ocean-land SST contrasts
- Effective heat capacity differences
- Local “Hadley” circulations
- Elevated heat sources

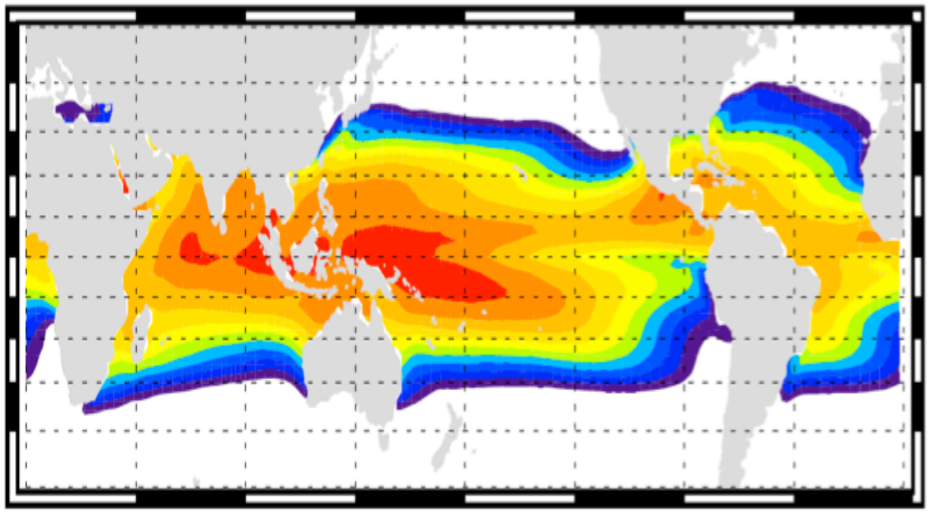
But we have determined no role for the oceans (especially the warm pool) or that the oceans may have a dynamic response.



Outline

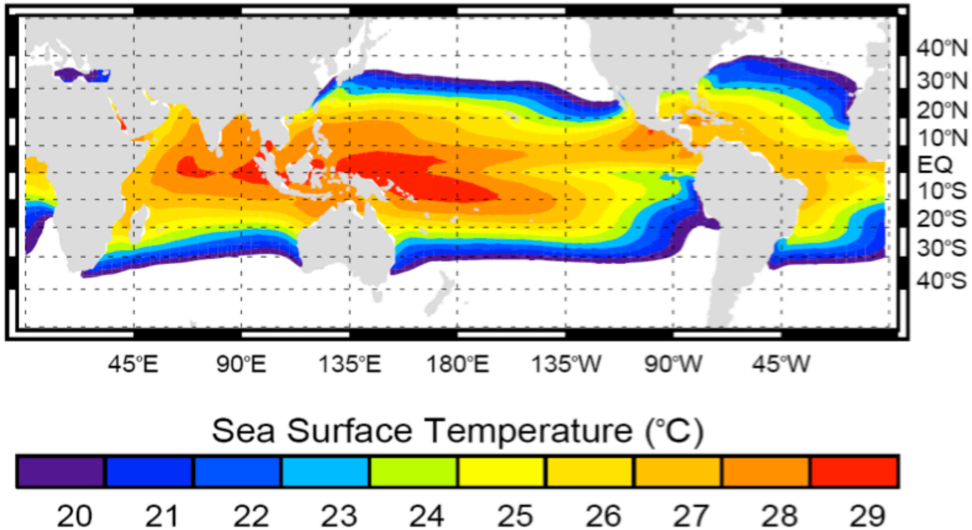
- Introduction (importance of the W.P.)
- Long-term Tropical Ocean Warm Pool (T.O.W.P.) Variability (tendencies during the 20^{th} and 21^{st} centuries)
- A fundamentally different concept: The Dynamic Warm Pool (D.W.P)
- Variability of the D.W.P. during the 20th and 21st centuries
- Is there physical support for the observed variability?

- Some Implications (Monsoons and Low-Latitude Phenomena):
  - Tropical Cyclones
  - South-east Asian Monsoon
  - Ocean-Land Heating Contrast (Global Tropical Monsoon?)



TROPICAL OCEAN WARM POOL

NOAA Extended Reconstructed Product (1979-2001)



Traditional Definition:
The TOWP corresponds to the area of the ocean where SSTs>28°C

In-Situ (Regional) Effects ⟷ Global Impacts

Link between areas of deep convection and tropical cyclone formation to areas of elevated SSTs (e.g. Graham and Barnett 1987, Palmen 1948, Gray 1968)

Tropical cyclogenesis generally occurs at SST>26.5ºC

Convection is rarely observed where SST < 26°C and its frequency increases sharply around 26.5°C to 28°C.

<u>Is there any fundamental physics behind these thresholds?</u>

The TOWP modulates global climate variability as well as teleconnections emanating from the tropics

Modulation of the Hadley and Walker Cells

Modulation of Monsoon Circulation

Modulation of ENSO and releted teleconnections

Underlying Process?

The TOWP define the location and magnitude of the “boiler box” of the heat engine of the planet (e.g. Pierrehumbert 1995).

Residual Estimation of Heating

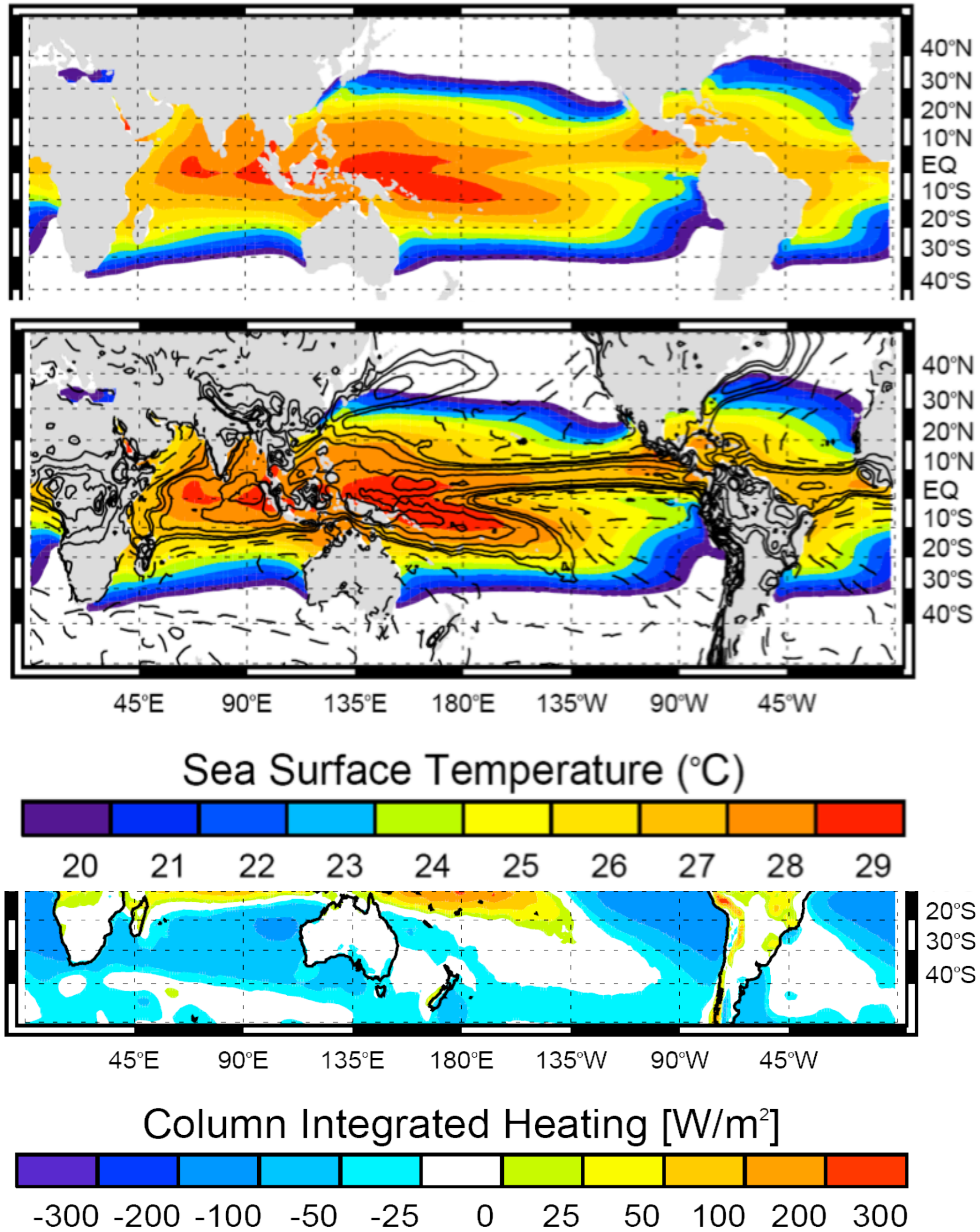
$$Q = \frac{\Delta T}{\Delta t} + \overline{\mathbf{v}} \cdot \nabla \overline{T} + \boxed{(p/p_o)^{(\mathbf{R}/\mathbf{C}_p)} \overline{\omega} \frac{\partial \overline{\Theta}}{\partial p}}$$

$$+ (p/p_o)^{(\mathbf{R}/\mathbf{C}_p)} \left[\nabla \cdot \overline{\mathbf{v}'\Theta'} + \frac{\partial (\overline{\omega'\Theta'})}{\partial p} \right].$$

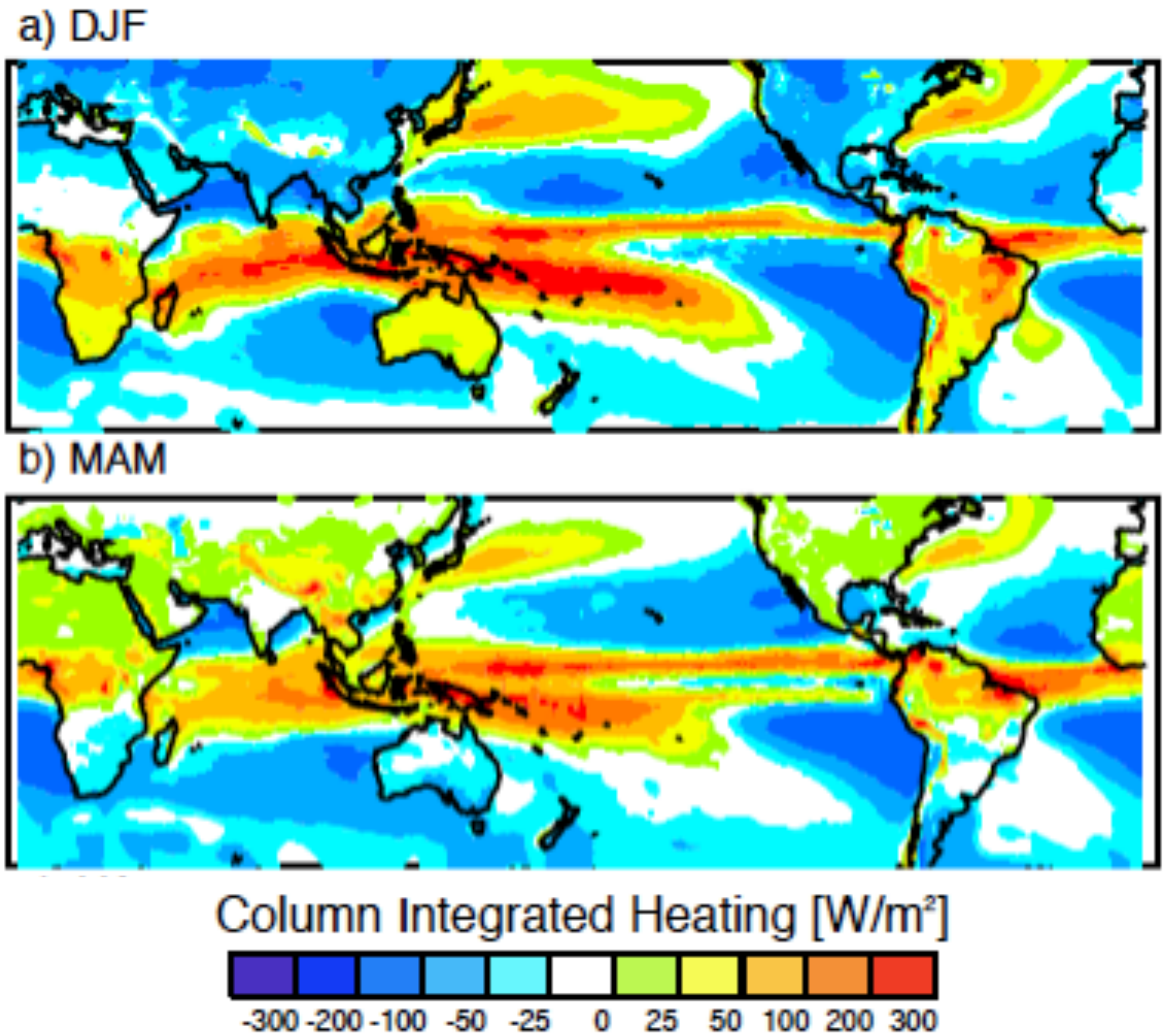
Goal:

“Unravel mechanisms causing variations of the global monsoon system and low-latitude processes”

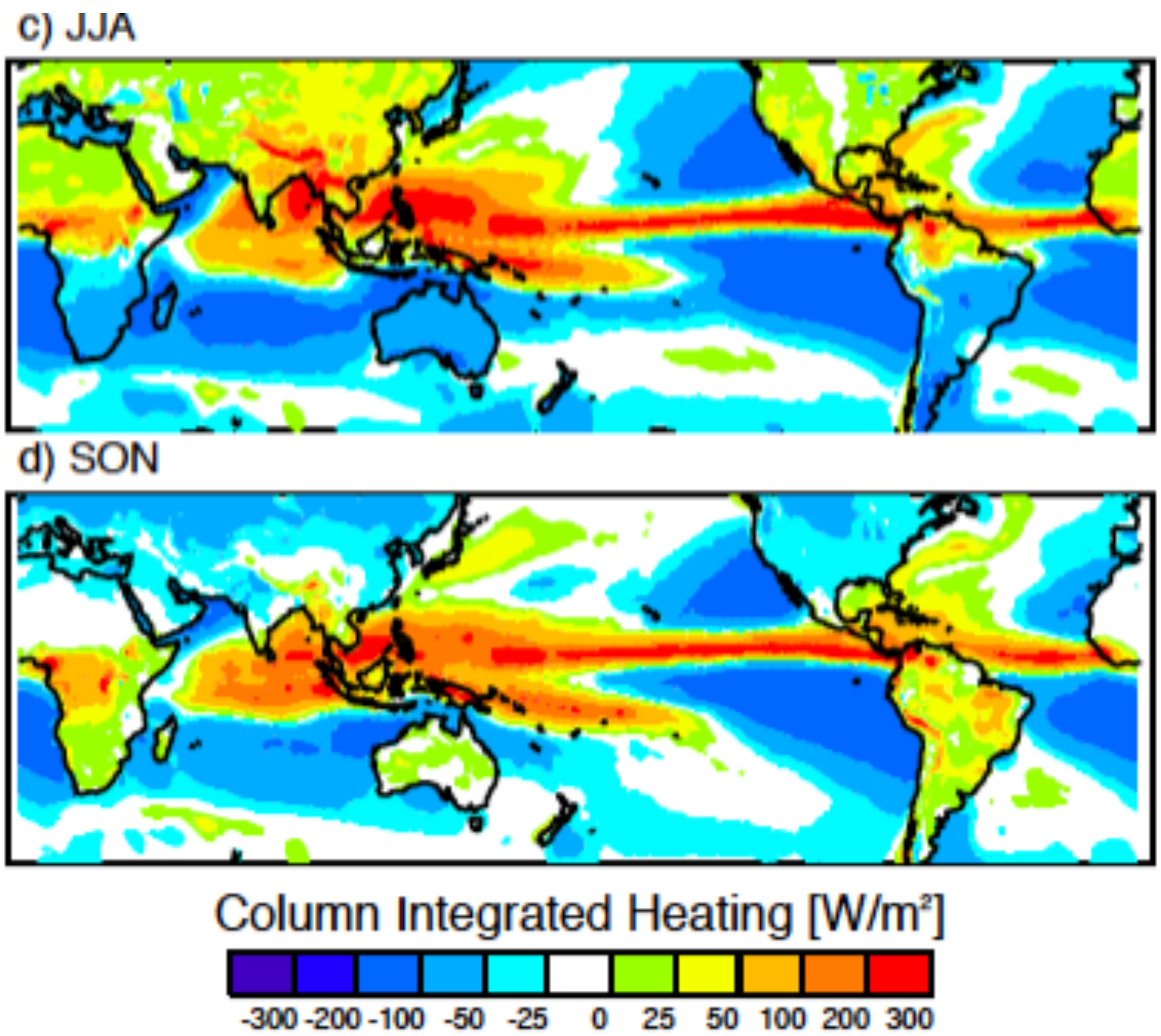
NOAA Extended Reconstructed Product (1979-2001)



ECMWF Atlas (1979-2001)



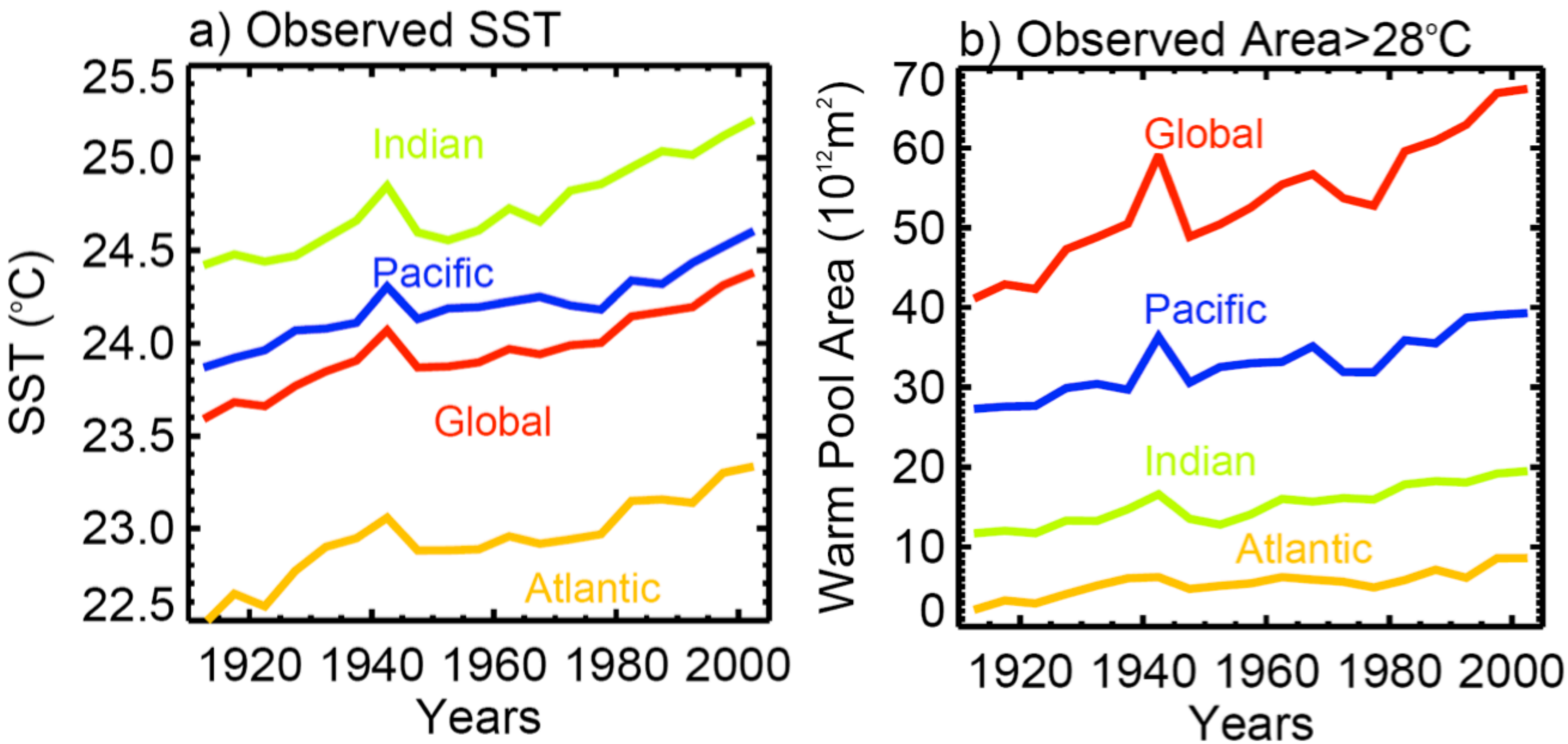
Column integrated heating also undergoes an annual cycle with the positive regions following the SST maxima and surrounded by pools of cooling



Column integrated heating also undergoes an annual cycle with the positive regions following the SST maxima and surrounded by pools of cooling

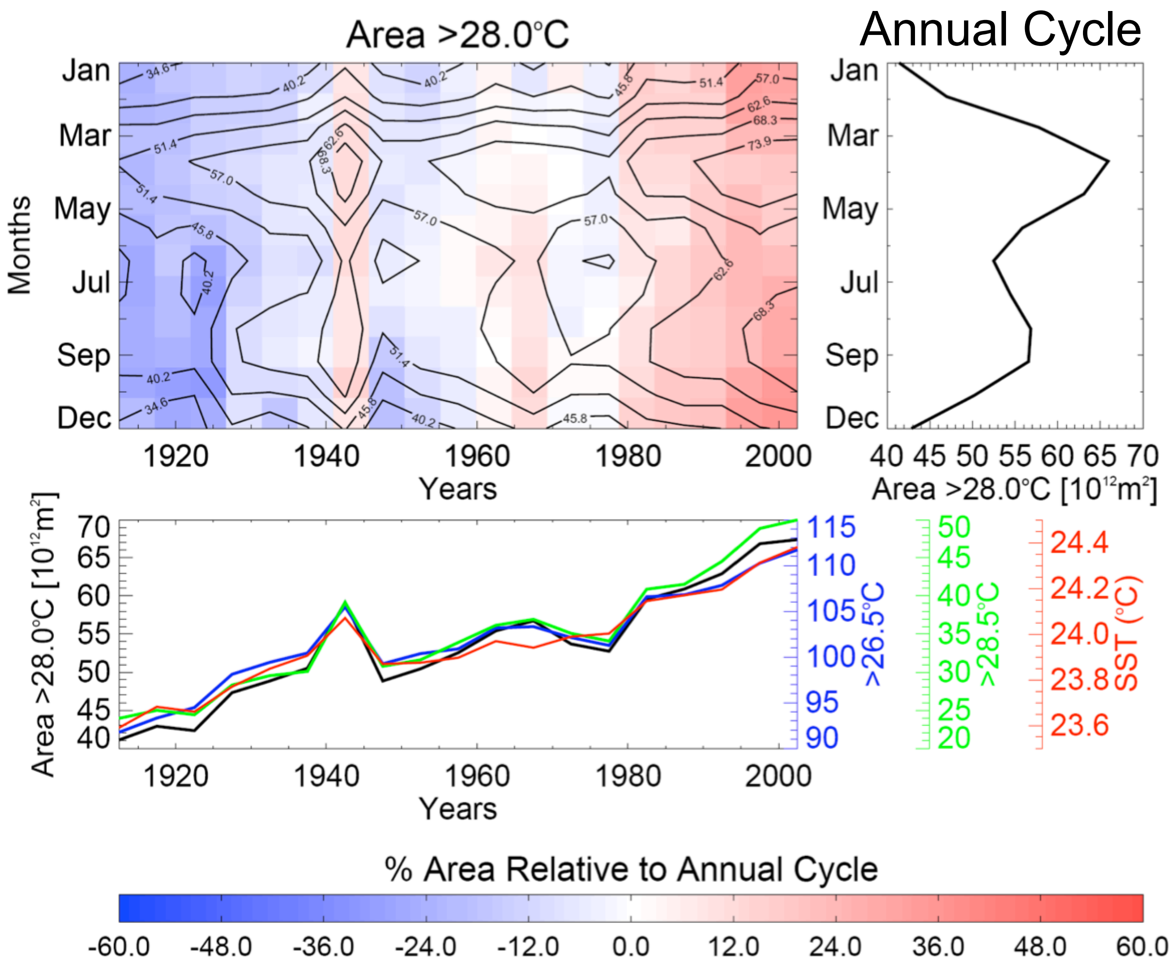
Warm Pool During the 20th Century

Area of the annually-averaged SST>28°C for the entire tropics as well as for the Pacific, Indian and Atlantic Ocean basins



There is a <u>0.8°C</u> increase of tropical SST since 1910 is accompanied by a <u>70%</u> expansion of the area of SST>28°C.

Warm Pool During the 20th Century

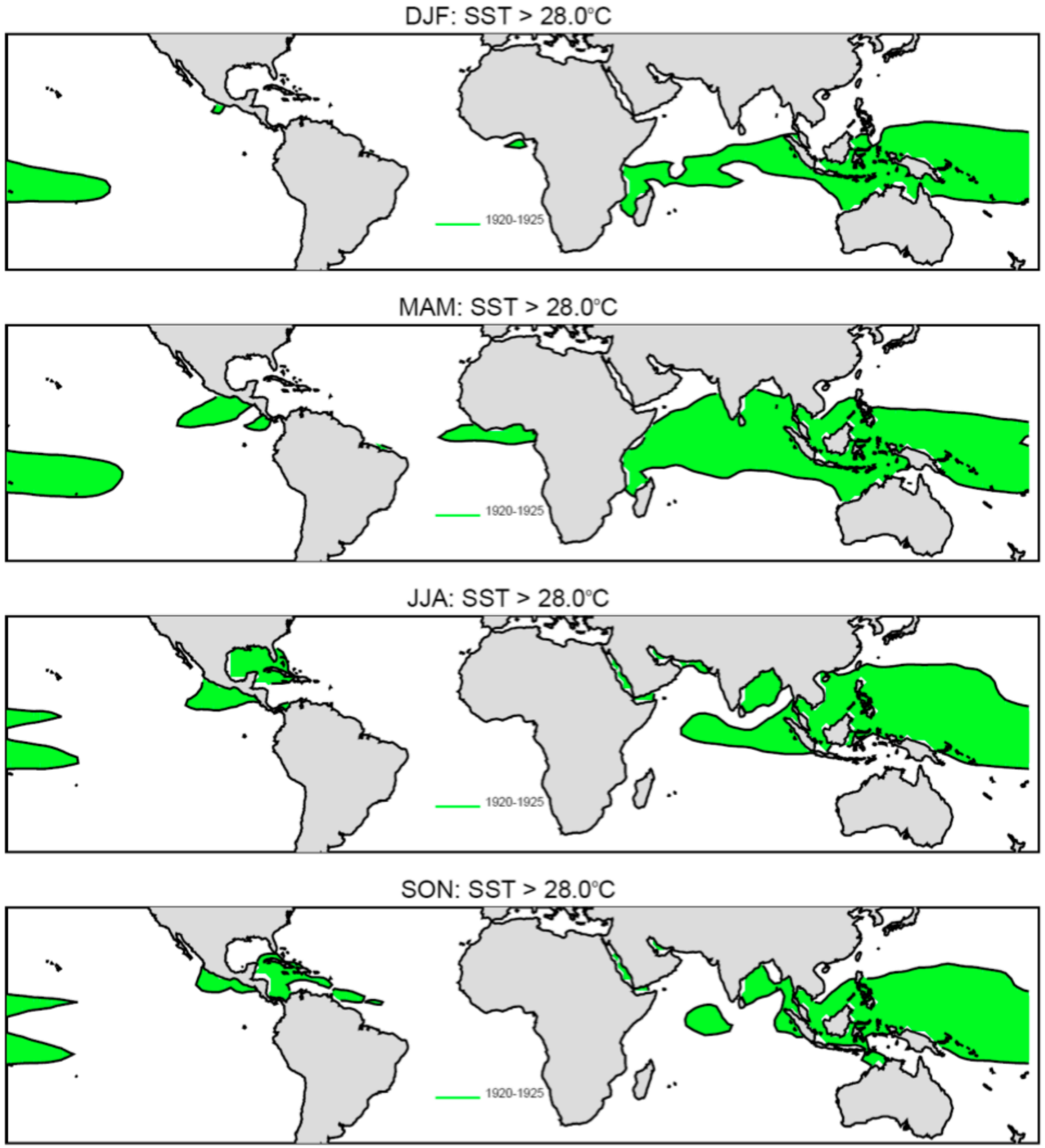


The annual cycle of the area of SST>28°C shows two peaks after the equinoxes with the maximum in April (65 10^{12}m^2) and a secondary peak in October (58 10^{12}m^2).

The increase in area is spread uniformly across the annual cycle.

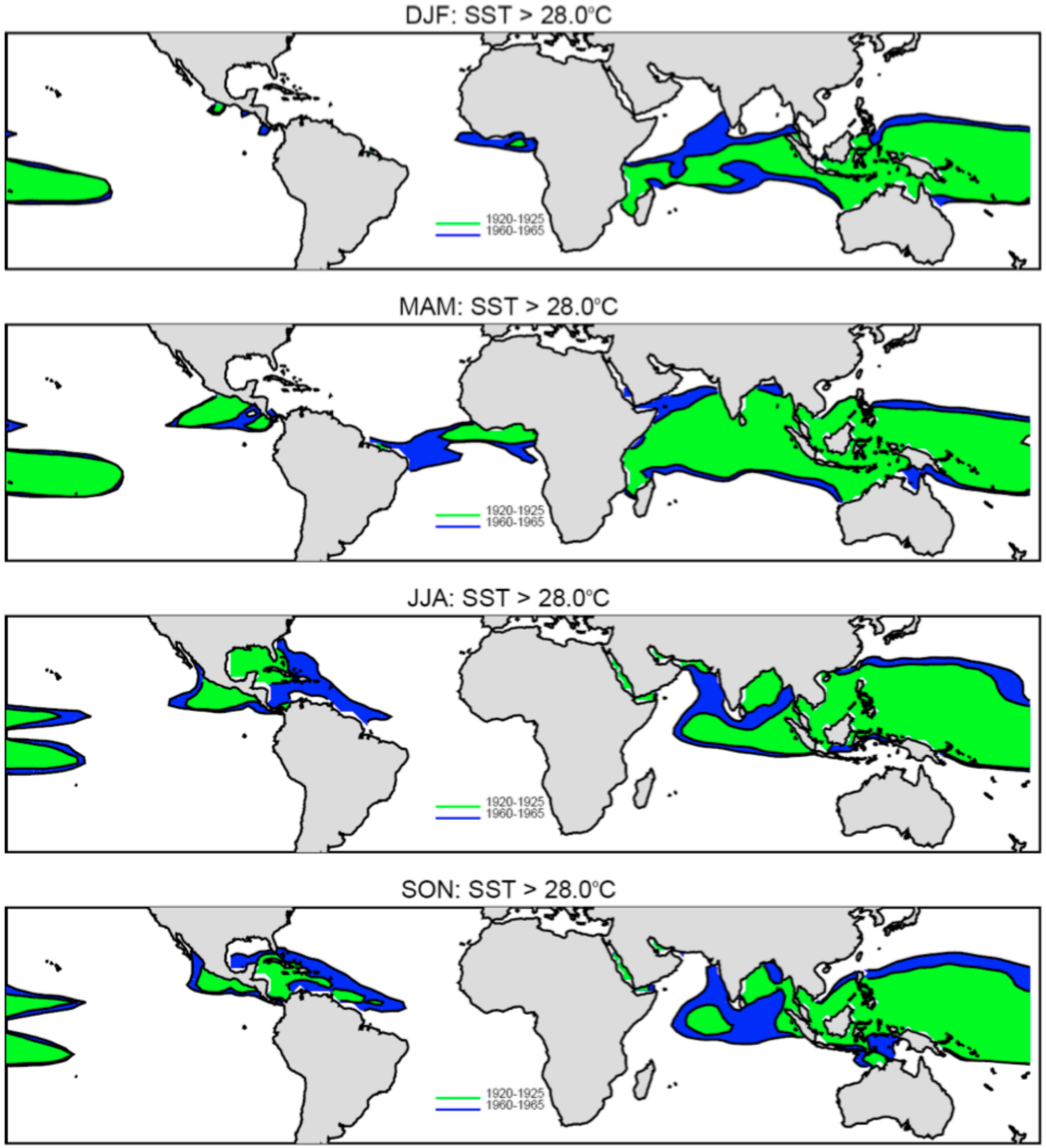
EVOLUTION OF THE SST WARM POOL (SST>28C) 20^{TH} CENTURY

1920-1925

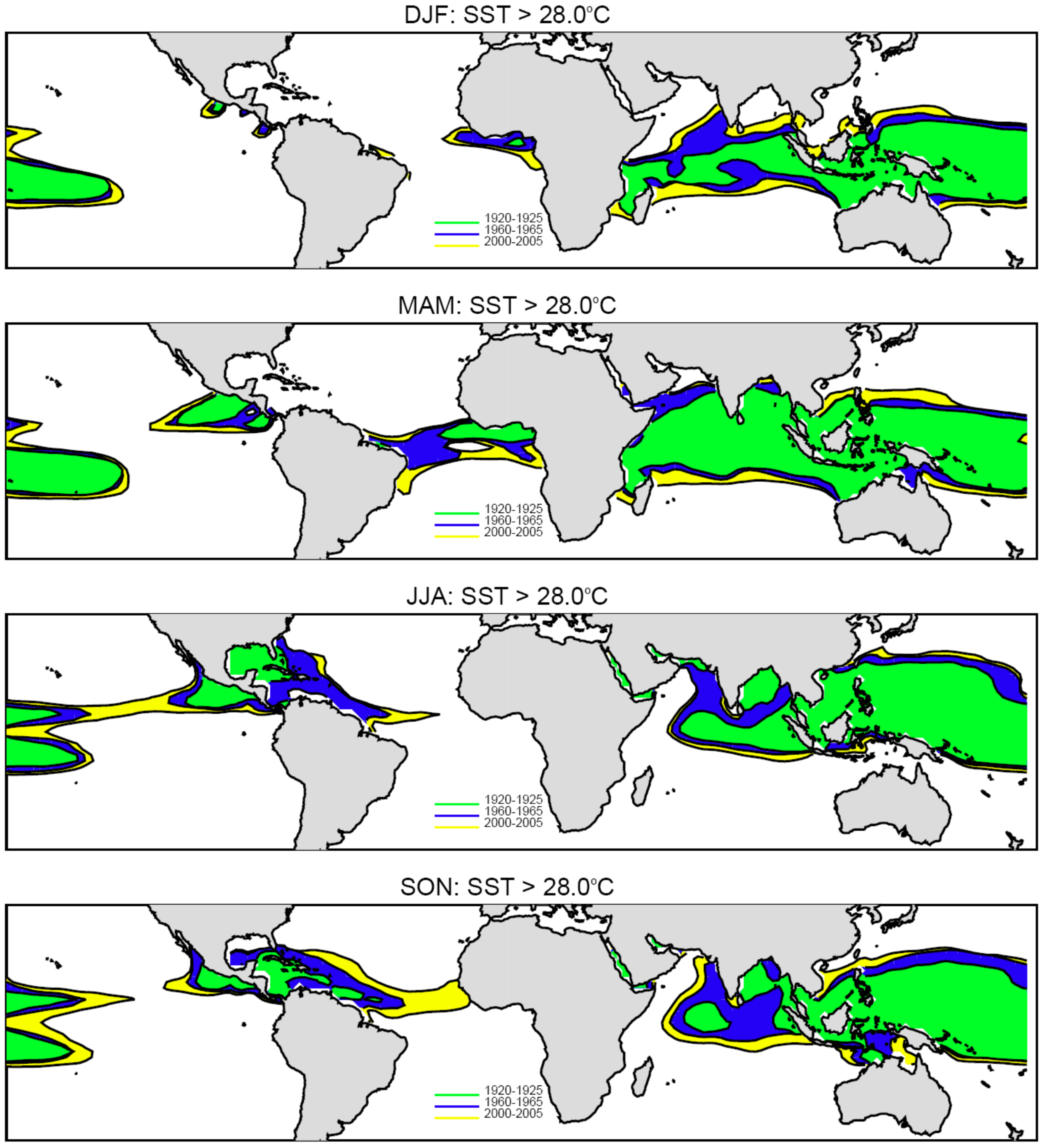


EVOLUTION OF THE SST WARM POOL (SST>28C) 20TH CENTURY

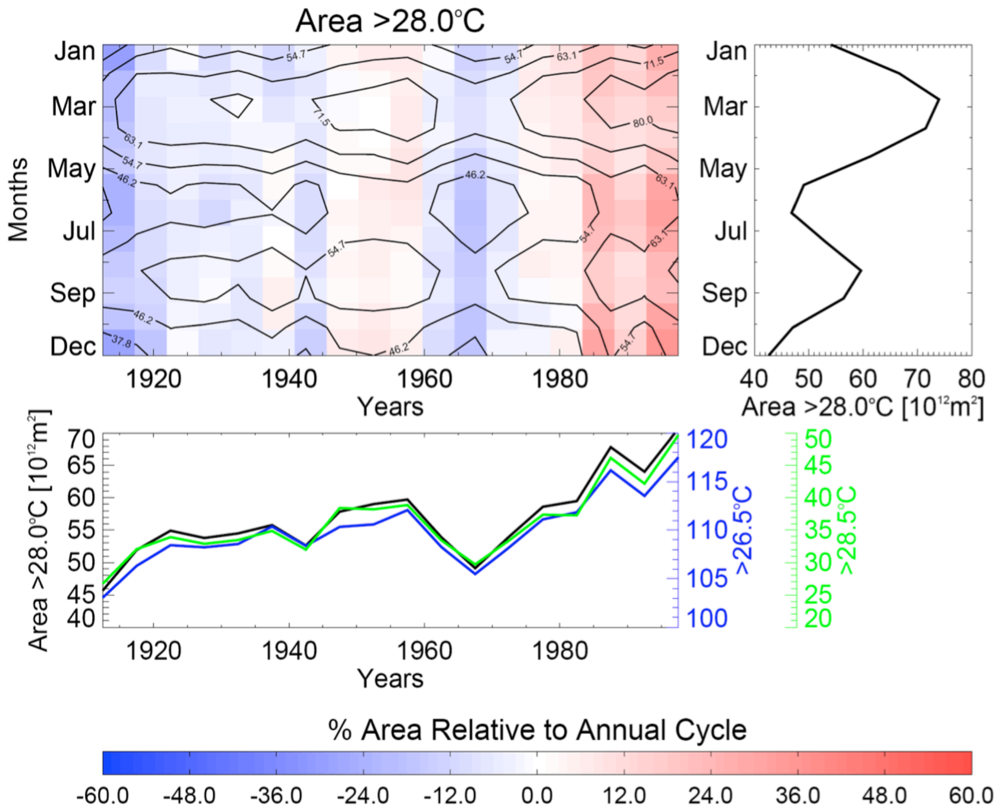
1920-1925,
1960-1965

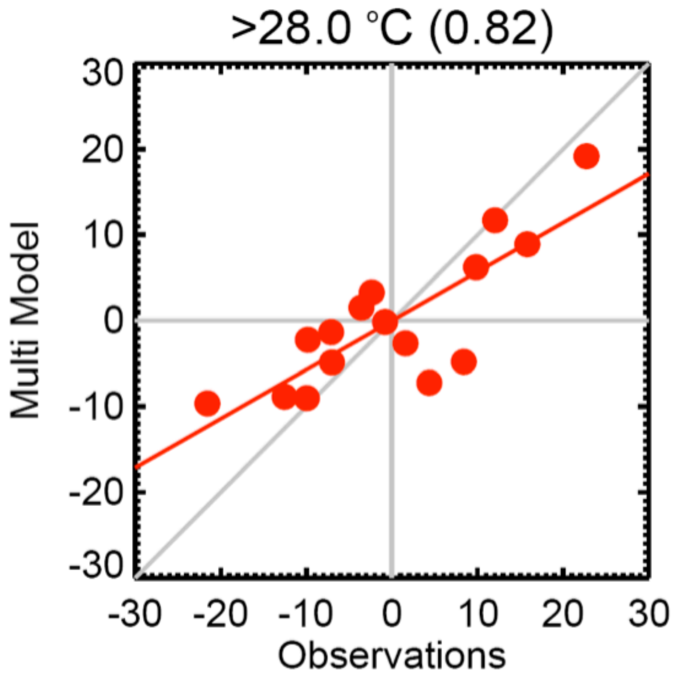


1920-1925,
1960-1965,
2000-2005



CMIP3 Multi-Model Dataset



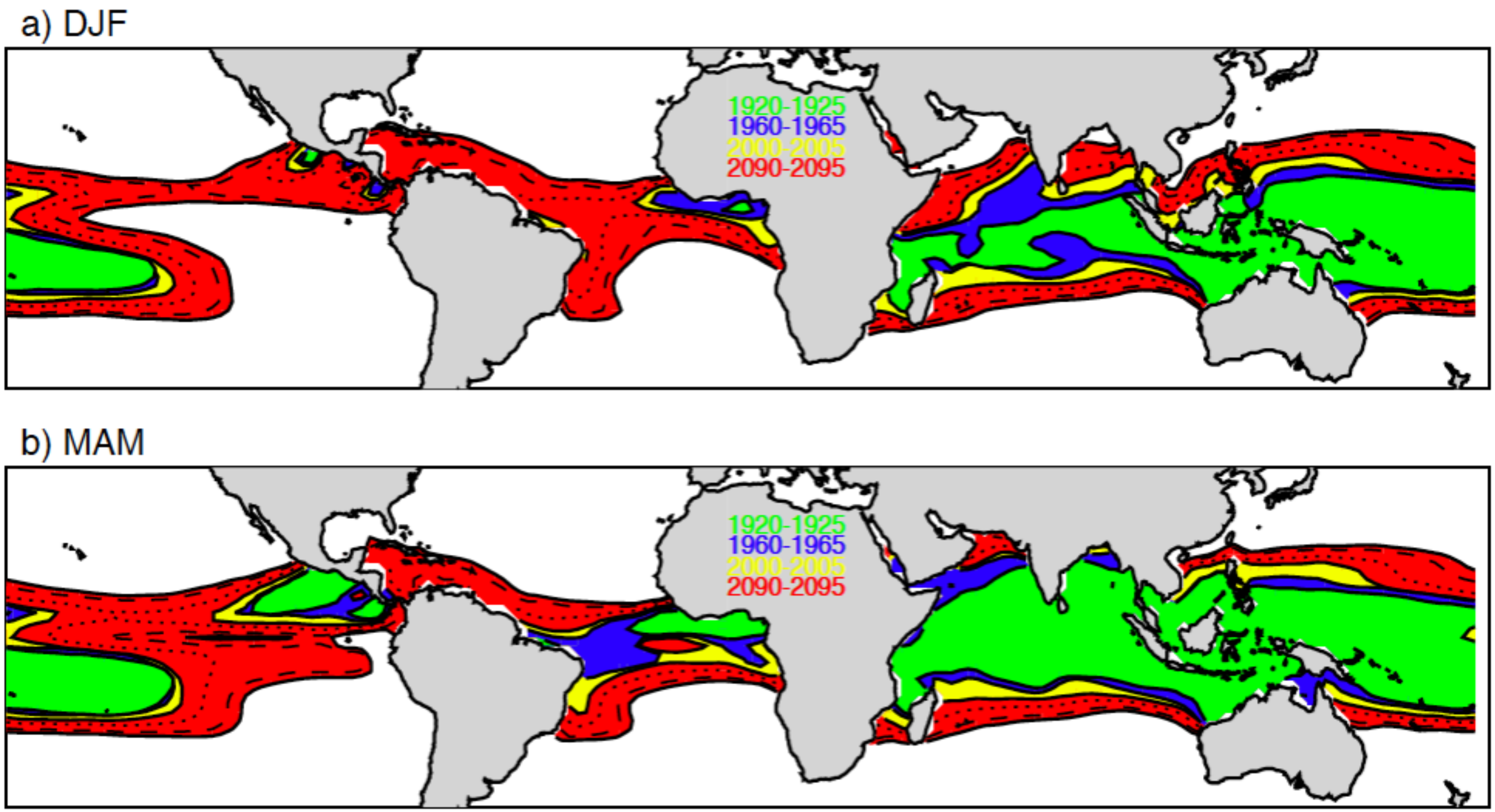


- Changes in area between the observed warm pool and the CMIP3 20th century run are very similar

- The relationships are very strong but show a model bias that slightly underestimates the warm pool area.

Reference for CMIP3 dataset: Meehl et al 2007

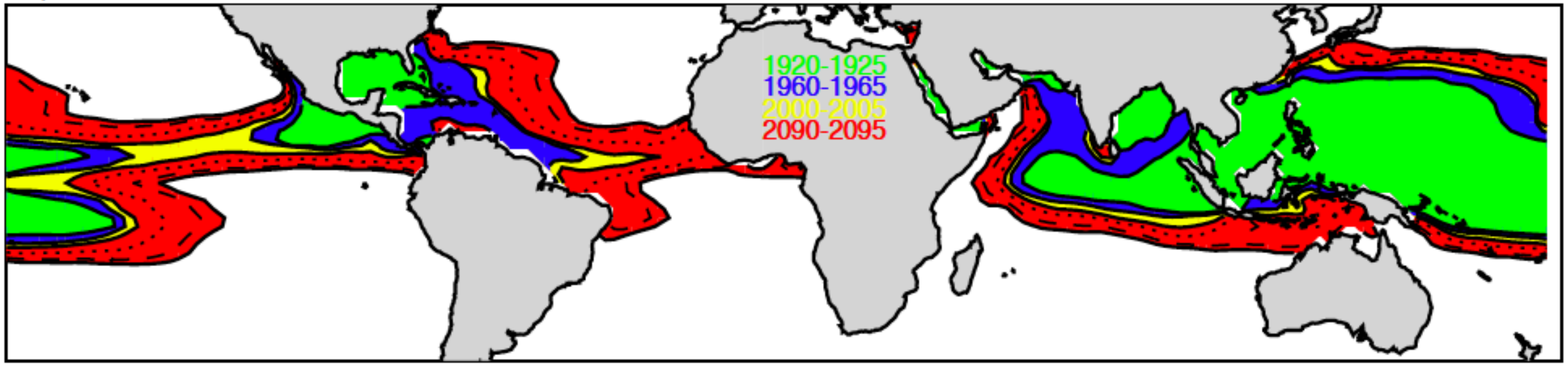
Seasonal cycle of SSTs (20th century observed) 21st century modeled



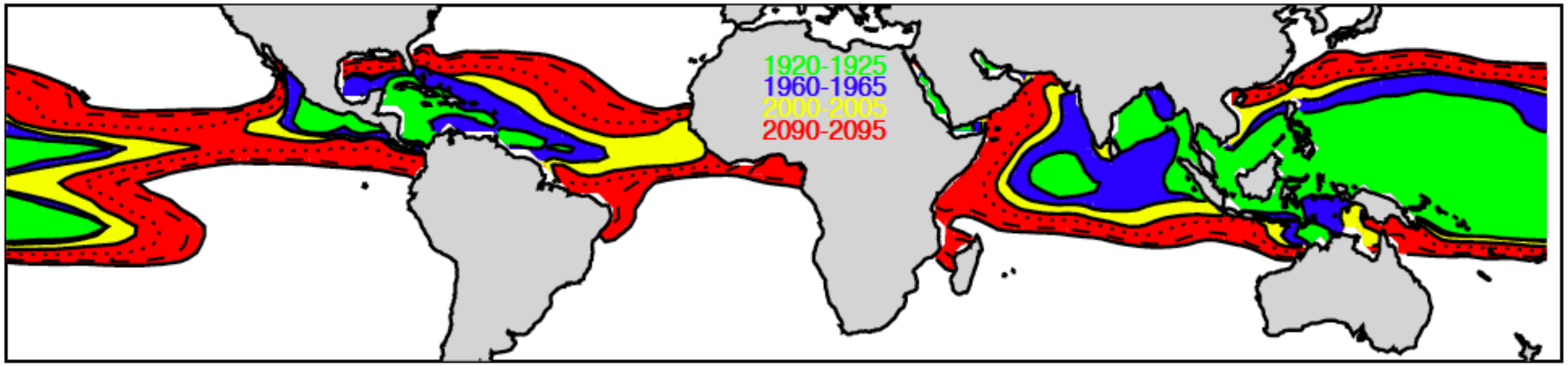
Most of the tropics are expected to have SST> 28C by end of 21st century

Seasonal cycle of SSTs (20th century observed) 21st century modeled

c) JJA

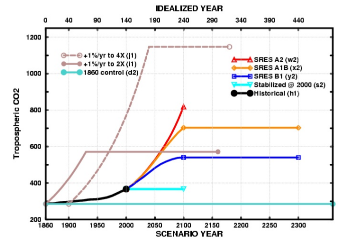


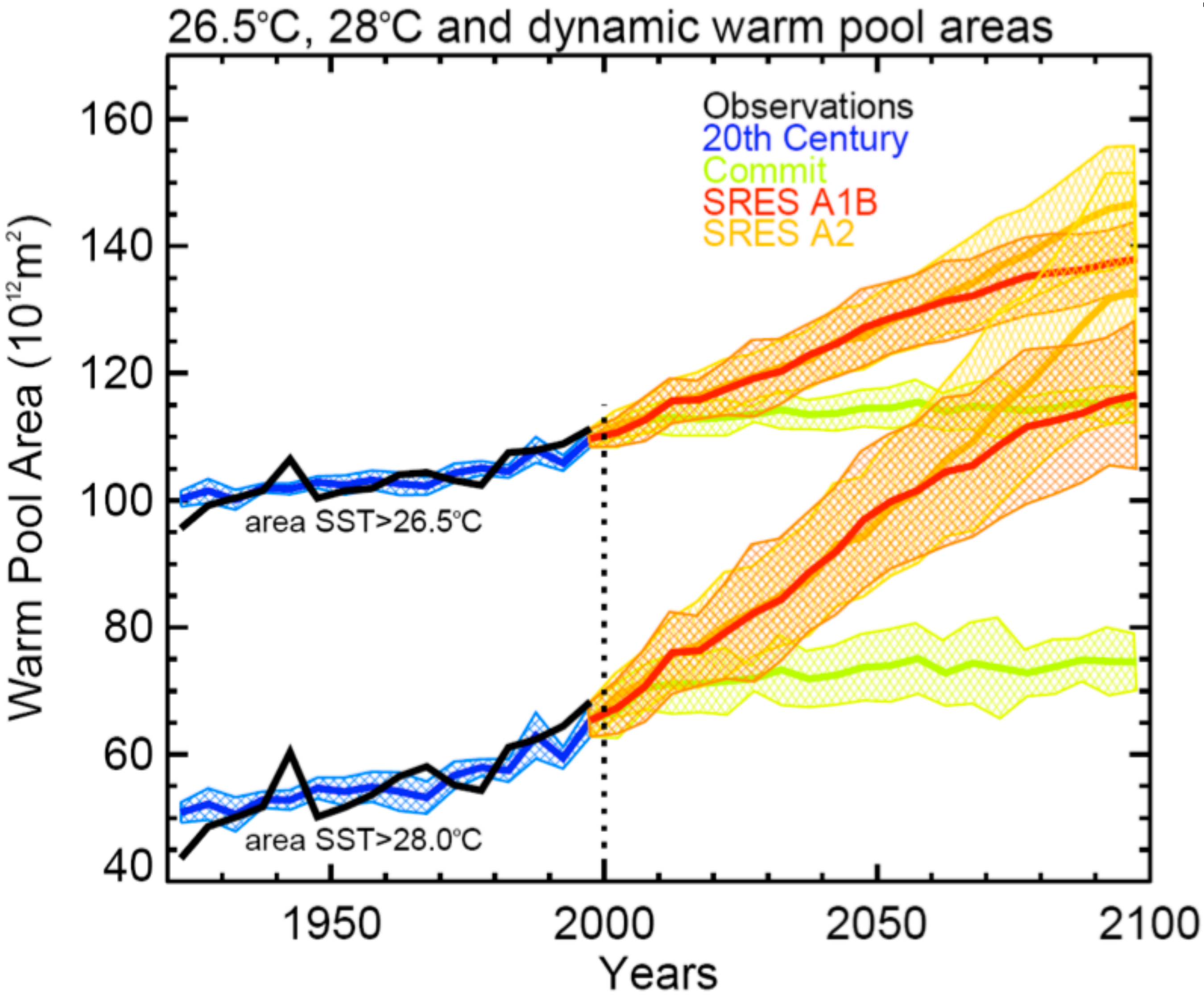
d) SON



Most likely, the increase in SST is due to increased (and expected) increases in green house gases.

Changes in the Tropical Ocean Warm Pool

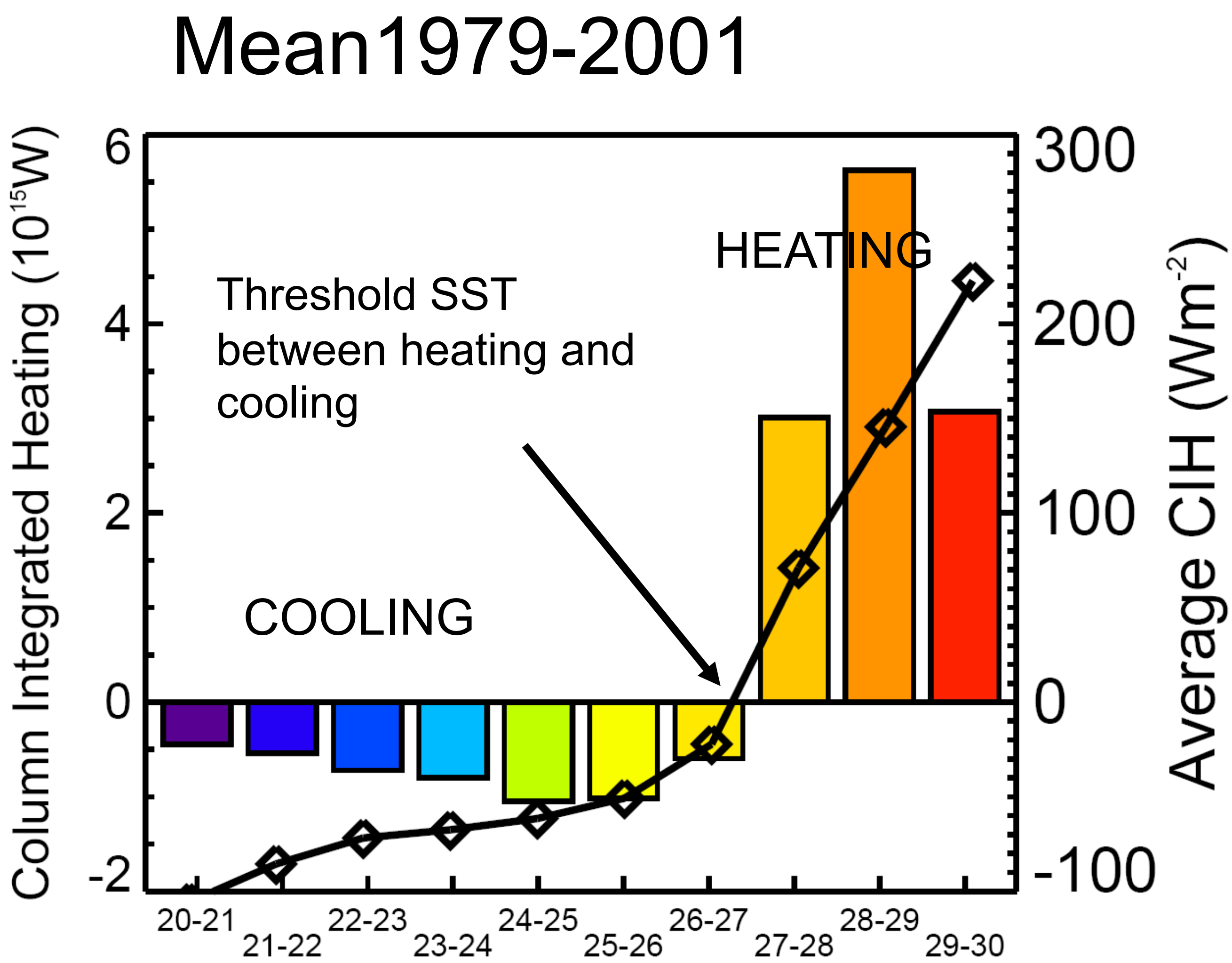




Different models show a large increase of TOWP area associated with CO_2 emissions

How does the Column Integrated Heating (CIH) Distribution change with increasing SST?

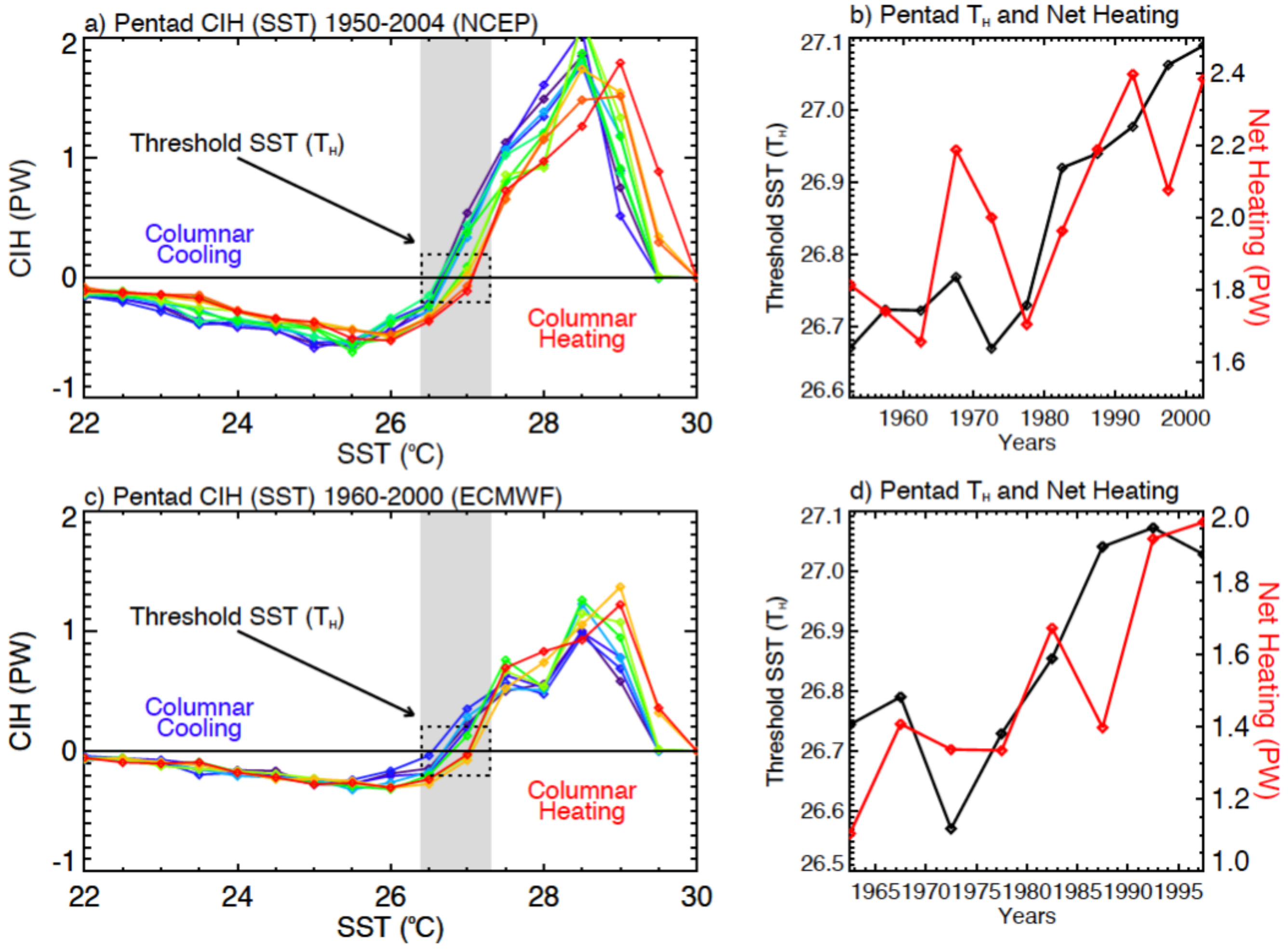
?



OBSERVATIONS: threshold of heating increases with time in the context of a warming world!!

NCEP

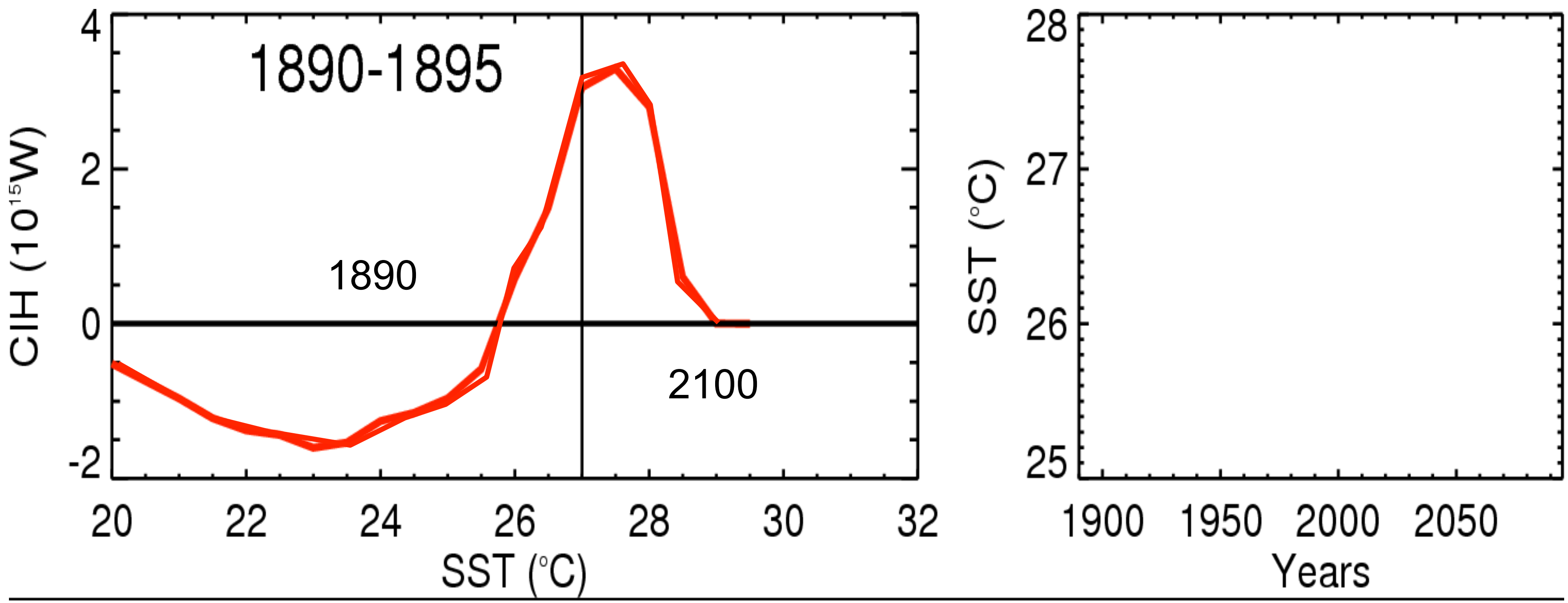
ERA-40



As SST increases, the threshold heating cooling moves to warmer SST

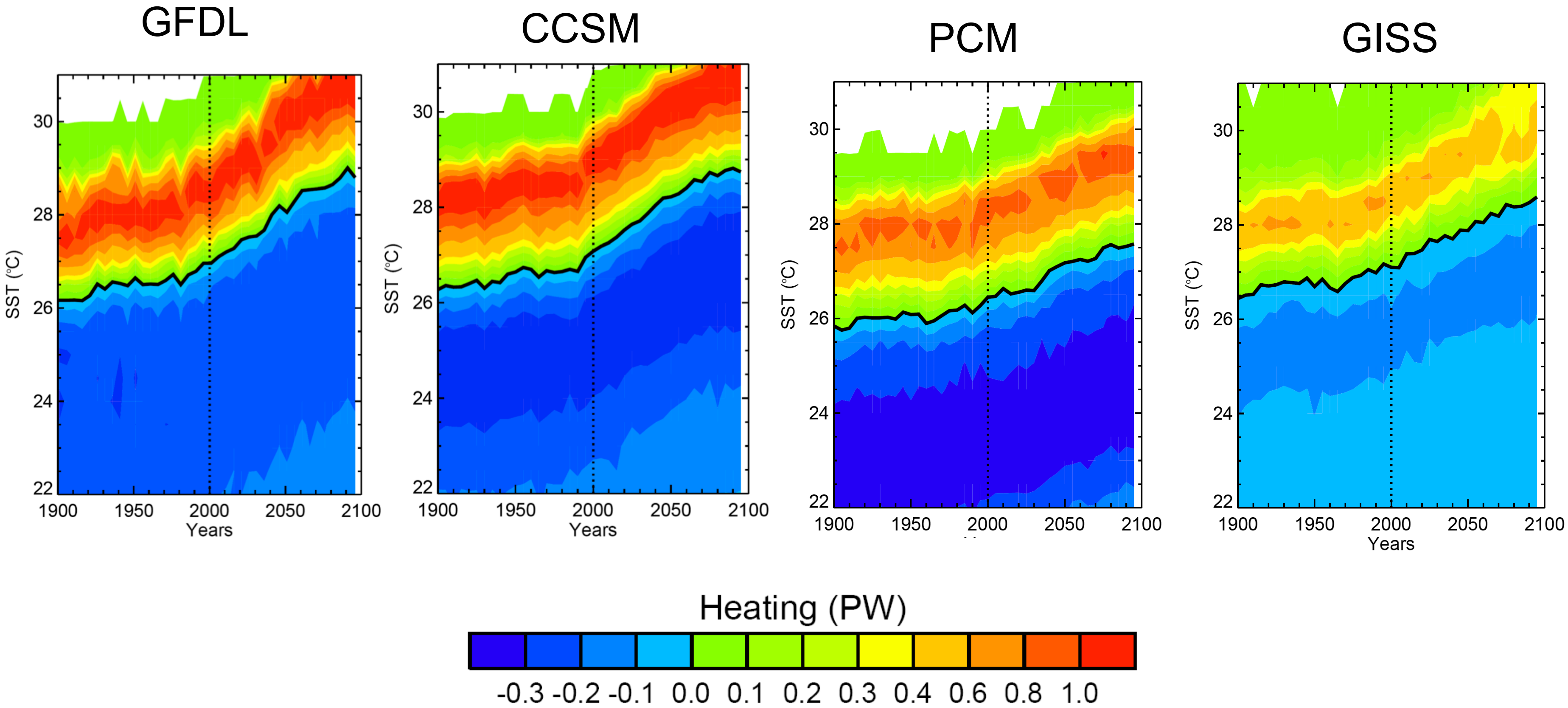
MODELS: threshold of heating increases with time in the context of a warming world!!

CMIP-3 (NCAR: CCSM)



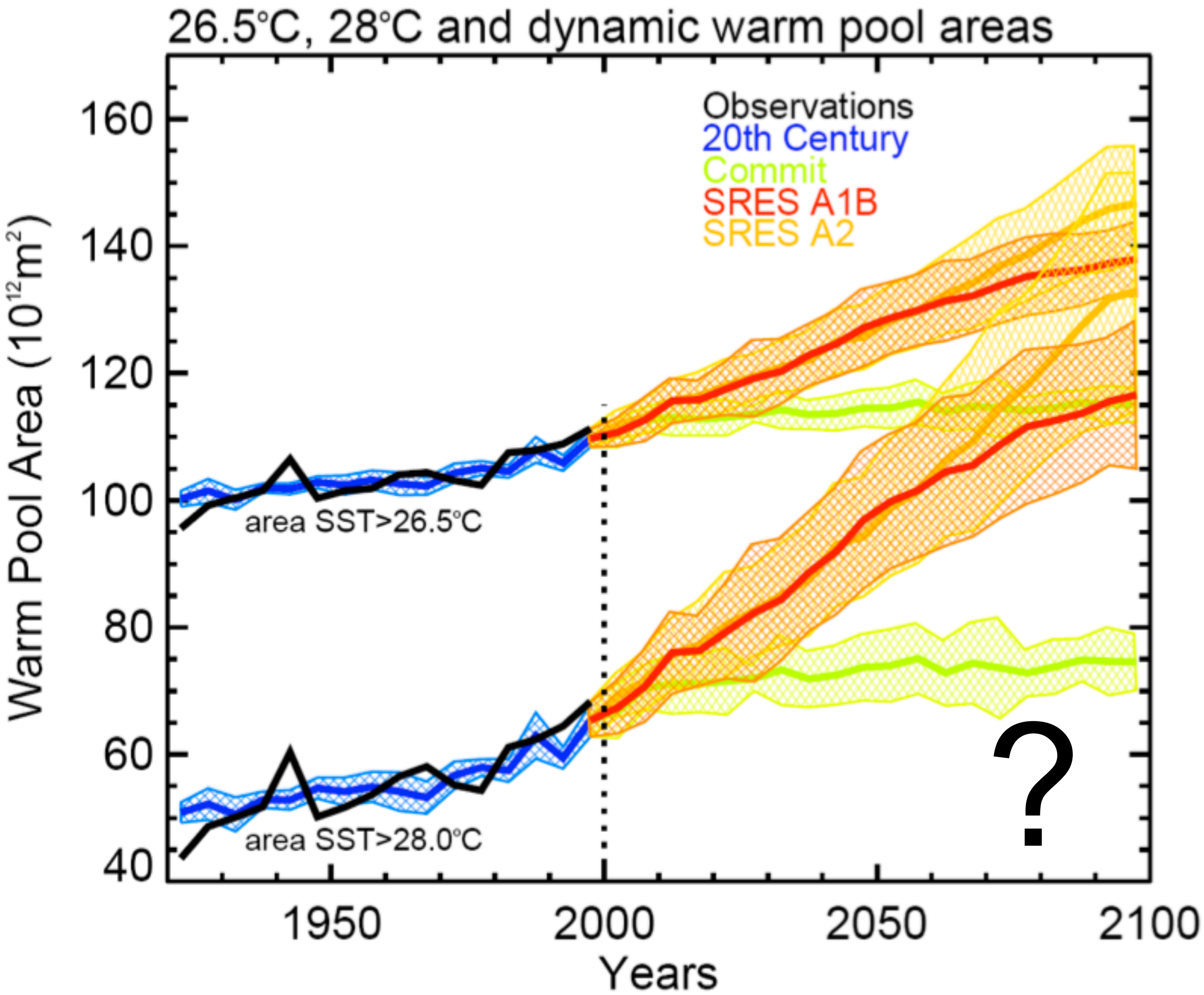
Climate models also show a shift to higher threshold temperatures

Warm Pool and Diabatic Heating:
Different Models Suggest a Similar Outcome



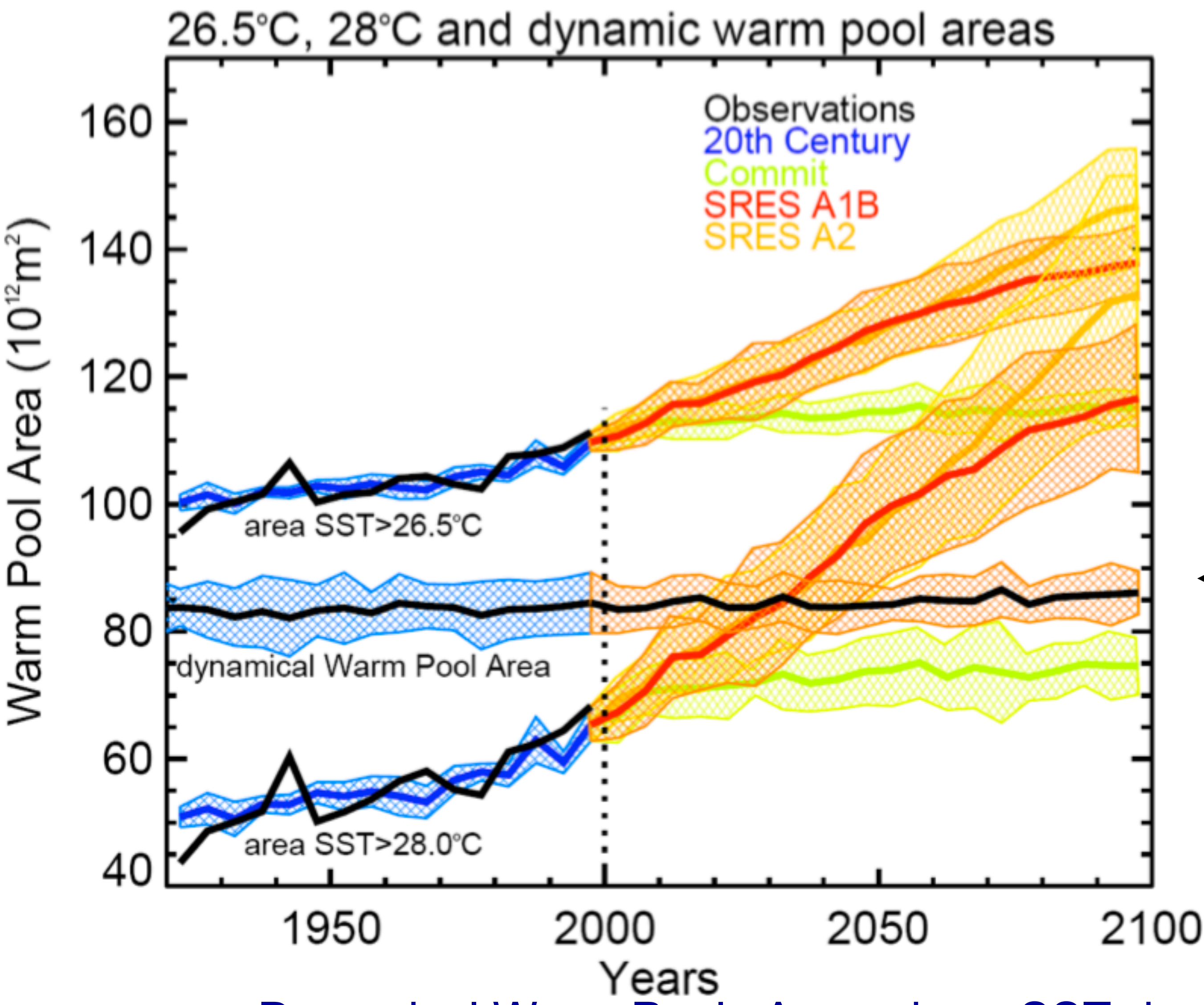
There is a need for a climatological definition of the Warm Pool:
The TWP should be defined as the area where SSTs is greater than the CIH threshold (Dynamic Warm Pool).

Warm Pool Area: New Definition



Dynamical Warm Pool: Area where SSTs is greater than the CIH threshold.

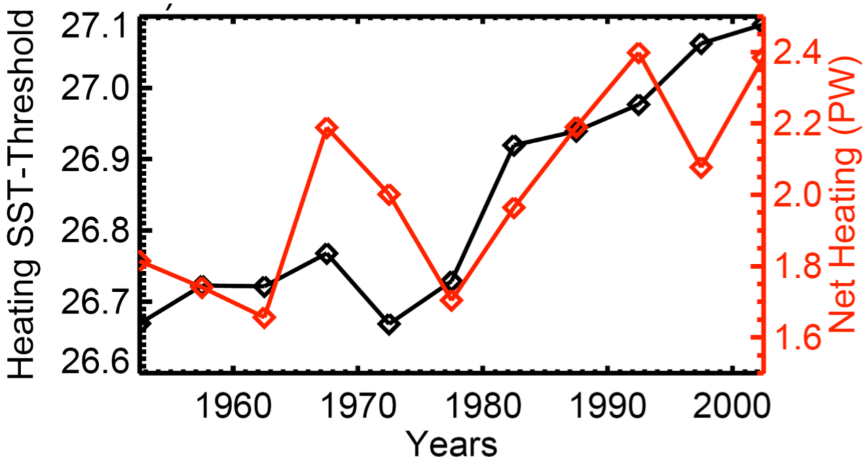
Warm Pool Area: New Definition

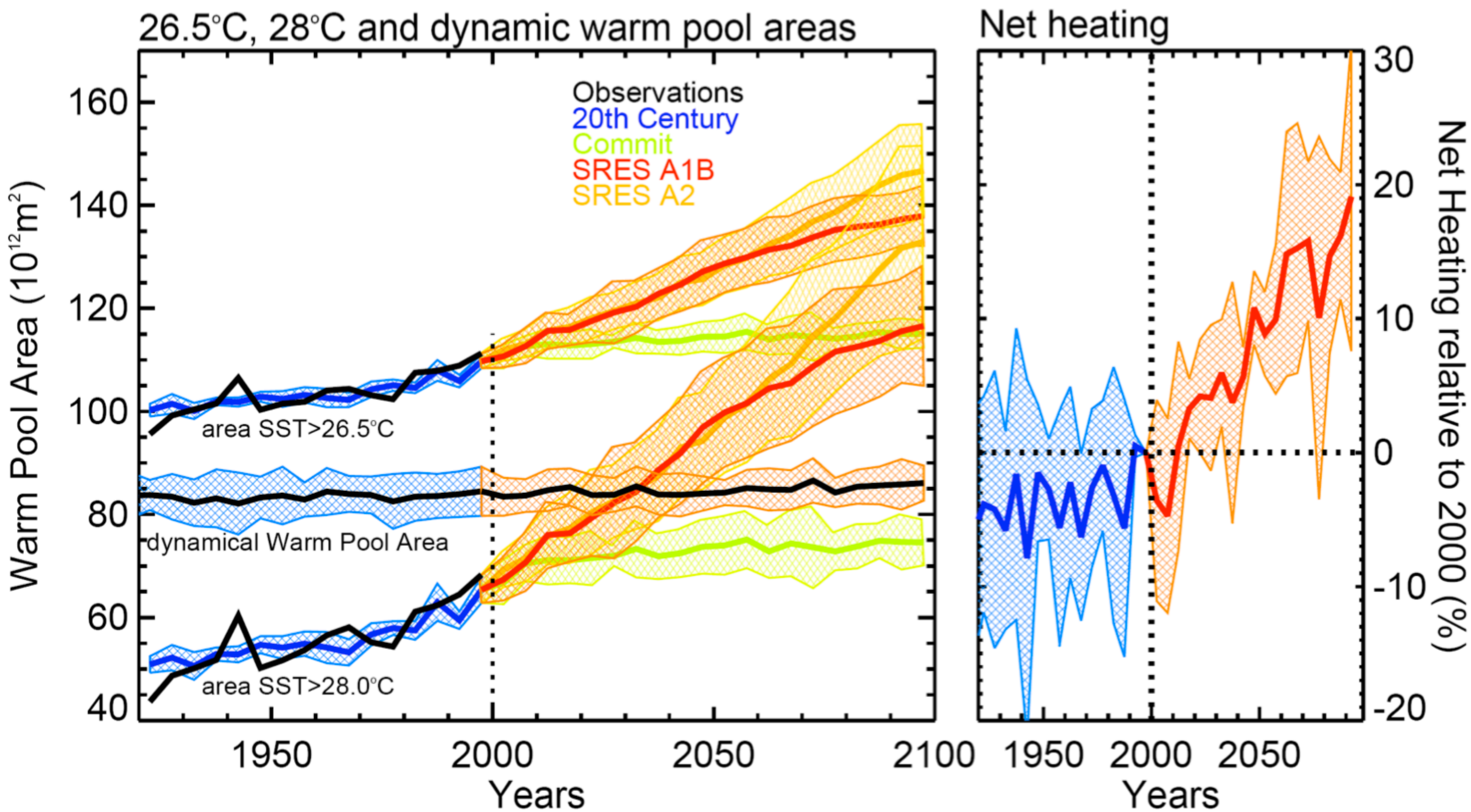


DWP area remains constant!

Dynamical Warm Pool: Area where SSTs is greater than the CIH threshold.

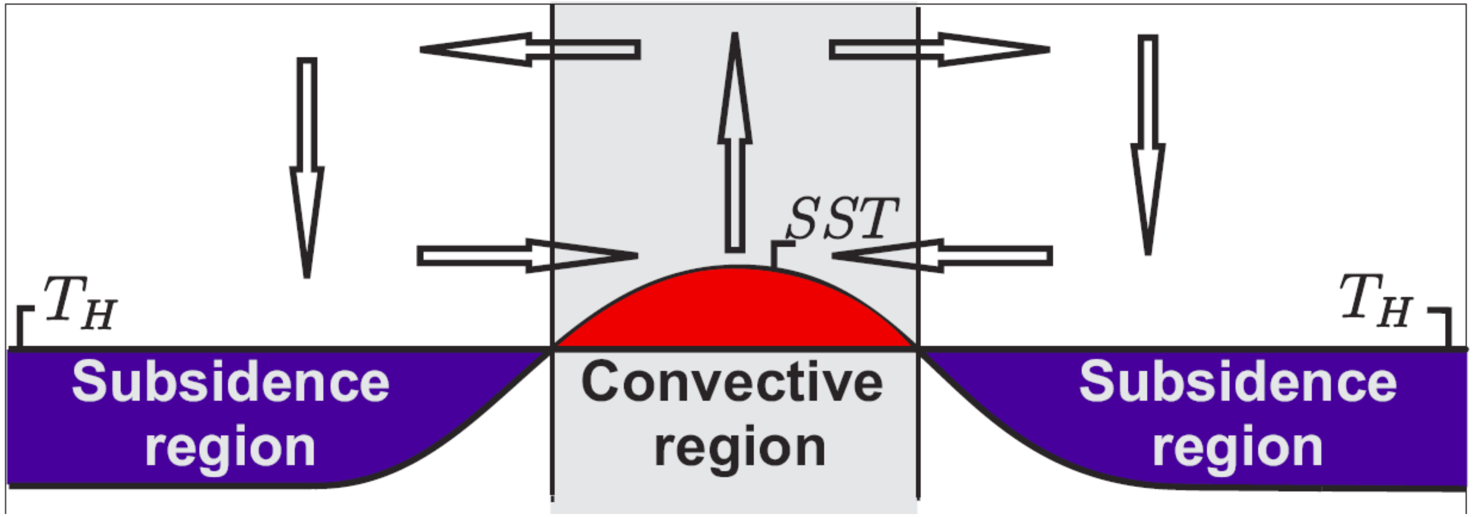
As SST increases, area of heating stays the same but the integrated heating within the dynamic warm pool increases.





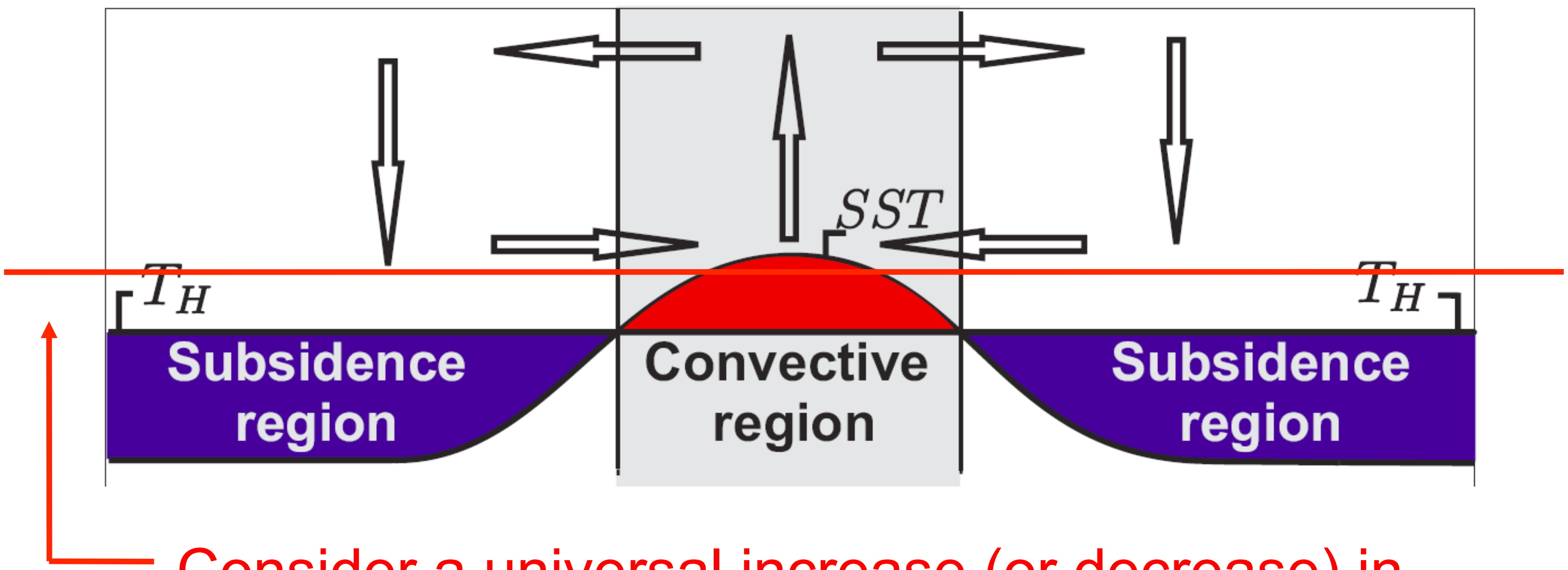
Constancy of the area of convection is critically important to understanding past, current and future climates

a) Schematic of dynamic warm pool with increasing SST



- Area of convection is dominated by latent heat release.
- Area of no convection is subsident and dominated by radiation to space

If area of convection remains constant, increase in convective heating must be balanced by radiative cooling increase as SST increases.



Consider a universal increase (or decrease) in SST that might accompany global warming or during the LGM

What happens to the convective heating and the radiative cooling?

We have simple basic laws that help

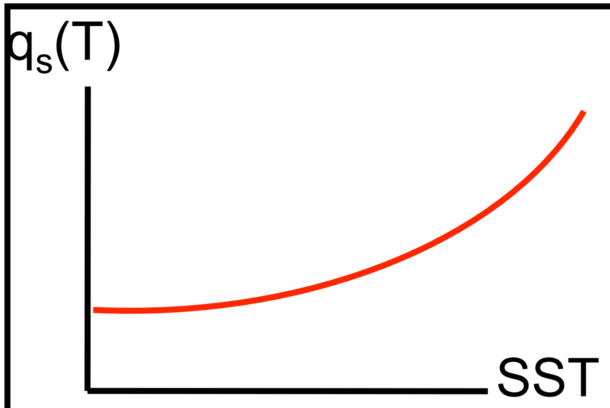
Atmospheric Heating and Cooling

To first approximation, latent heating is given by:

$$LE = \rho_a L C_{DE} U q_s^* \left((1 - RH) + RH \frac{L}{R_v T^2} (T - T_a) \right)$$

and the changes in LE with respect to temperature is:

$$\boxed{\frac{\partial LE}{\partial T} \approx LE \frac{L}{R_v T^2}}$$



Saturated vapor pressure increases exponentially with temperature

Radiative cooling to space goes as:

$$F_{net} = \varepsilon \sigma T^4$$

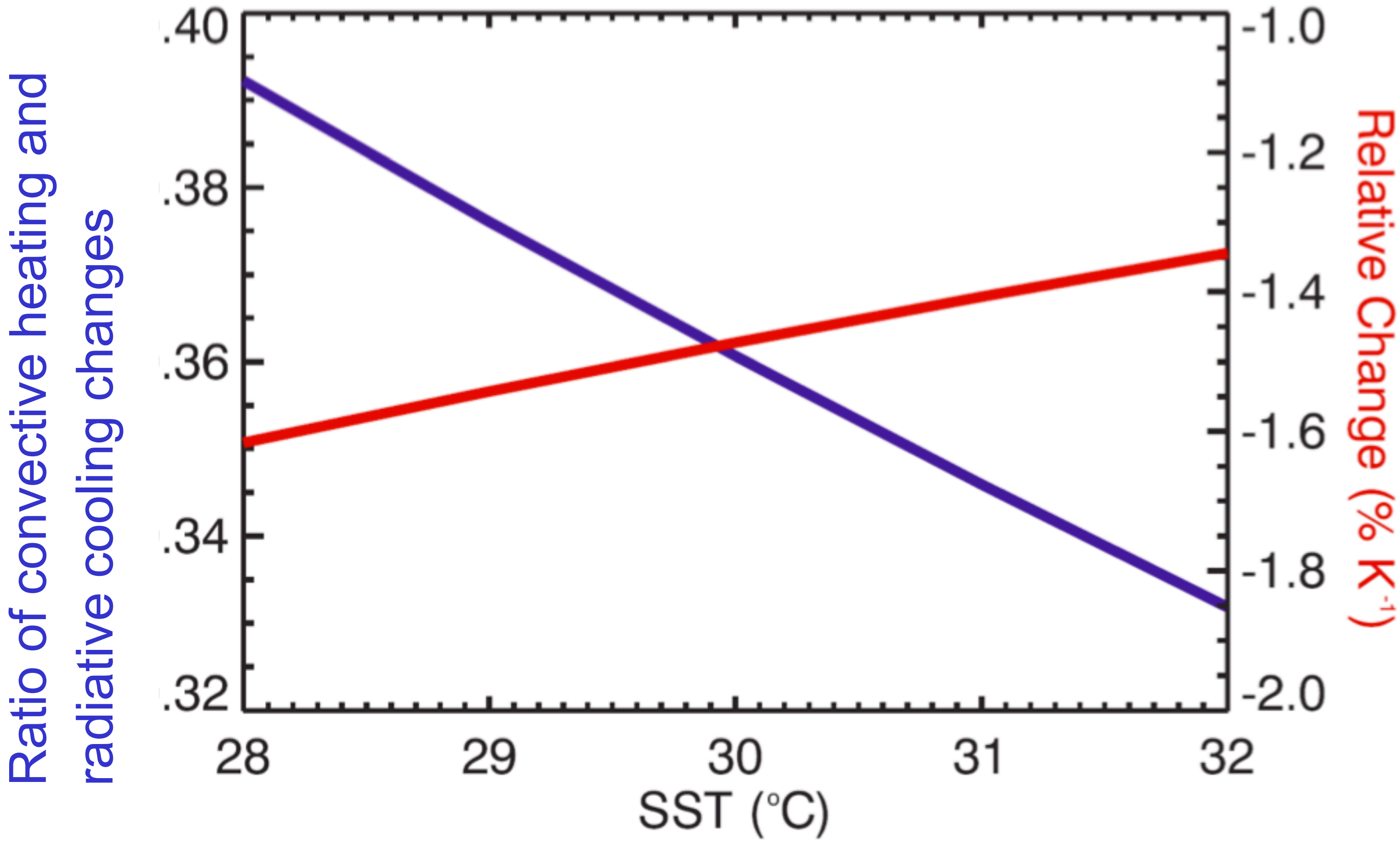
and the changes relative to temperature:

$$\boxed{\partial F_{net} / \partial T \approx 4 \varepsilon \sigma T^3}$$

The ratio of:

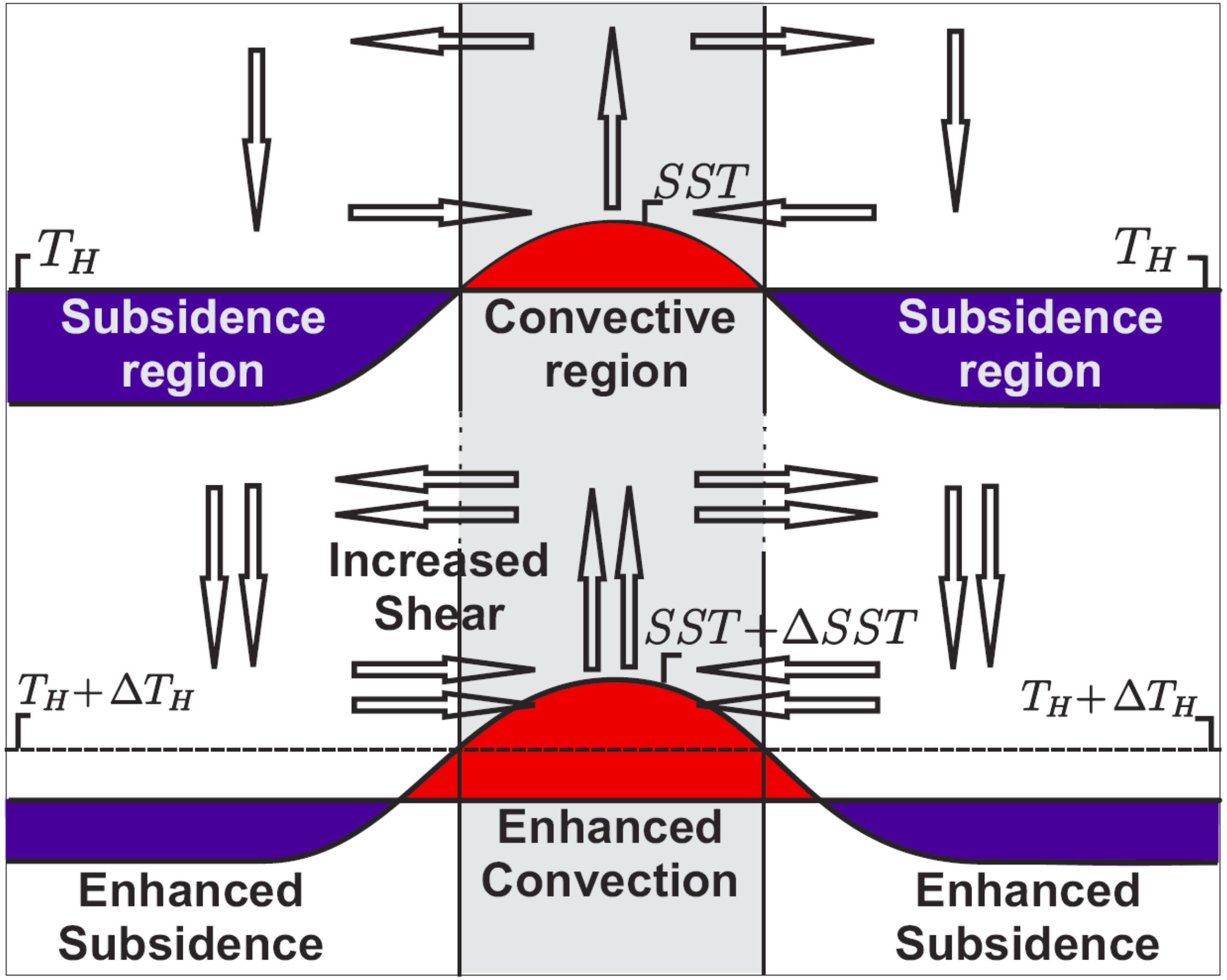
$$\partial F_{net} / \partial T \quad \text{and} \quad \partial LE / \partial T$$

tells us all we want to know



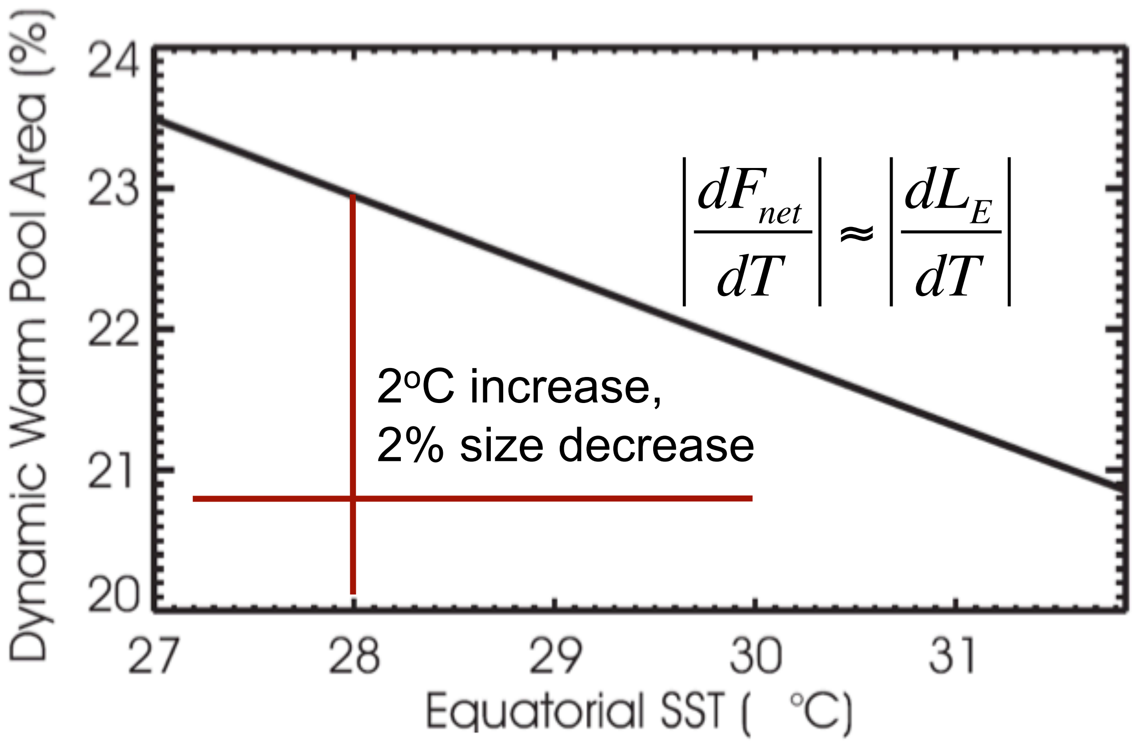
For the current range of temperatures, from the LGM through 21st century, the % change of area of convection is extremely small: essentially constant!

Prediction by ratio of heating cooling matches observations:
Ratio = 0.35-0.4. Descent (cool) area is thus roughly 2.5 times size of a ascending (hot) area as per observations.

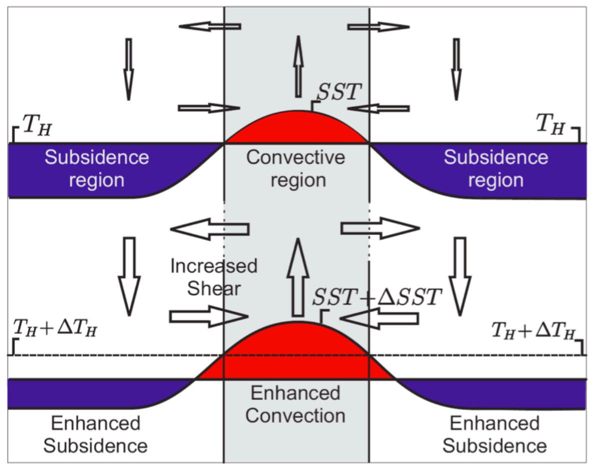


But, as vertical velocity a to heating (cooling) and as the convective heating increases in magnitude with rising SST, the mass flux in and out of the convective area must also increase

Two-box model: Basic Physics



Schematic of dynamic warm pool with increasing SST



$$A_W + A_C = 1$$

$$A_W w_w = A_C w_c$$

$$w_w \propto F_w, \quad w_c \propto F_c$$

$$A_W F_w = A_C F_c$$

$$\frac{d}{dT}\left(A_W F_w = A_C F_c\right)$$

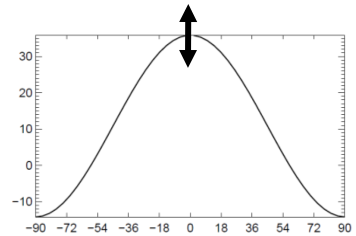
and if $\left|\frac{dF_{net}}{dT}\right| \approx \left|\frac{dL_E}{dT}\right|$

Then A_W/A_C almost constant!

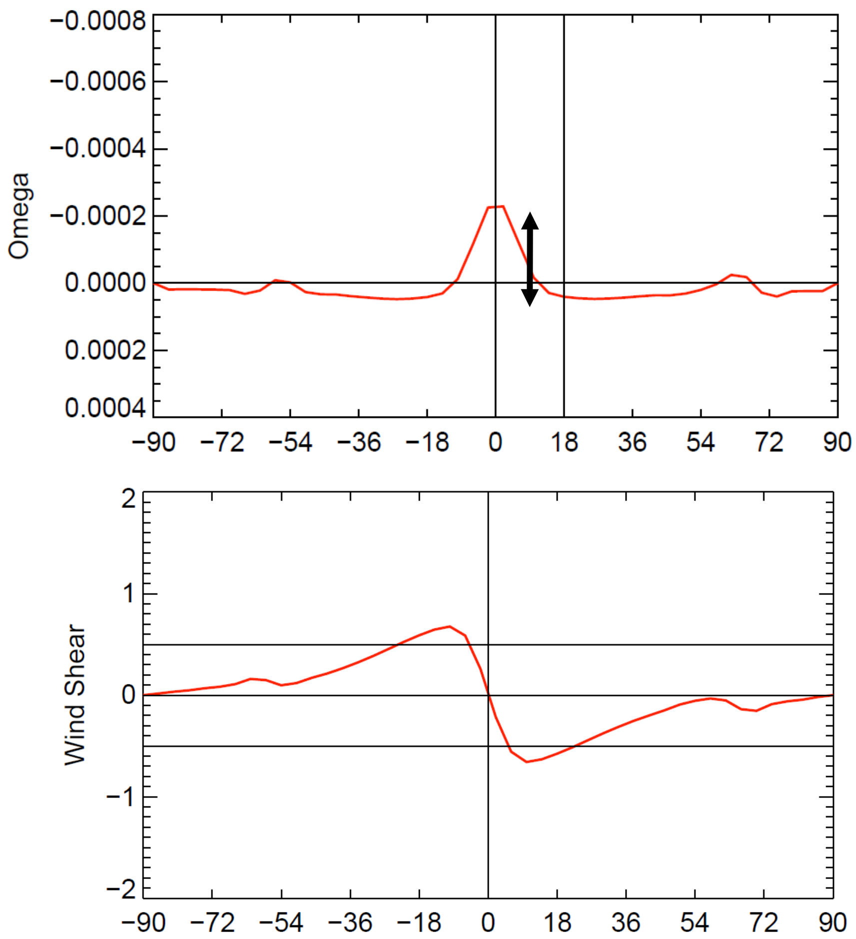
Multi-layer aqua-planet with set SST run to equilibrium.
SST incremented for each run

Zonally symmetric, two level, non-linear coupled model representing an aqua-planet with full hydrologic cycle.

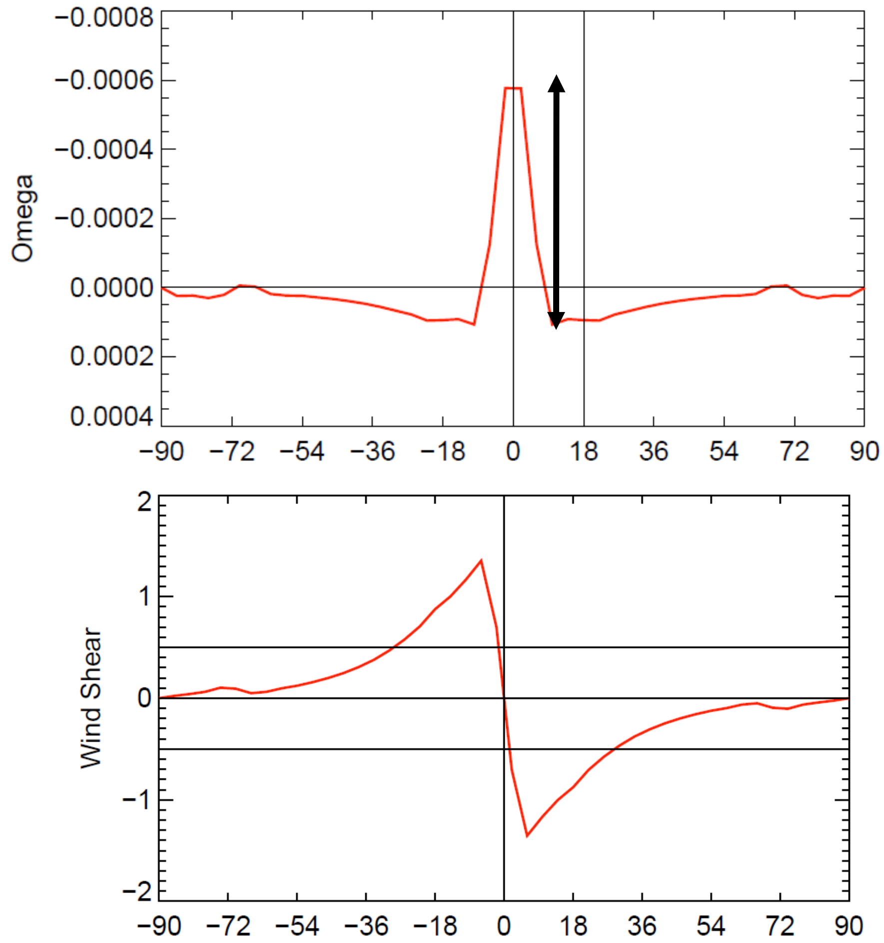
SST



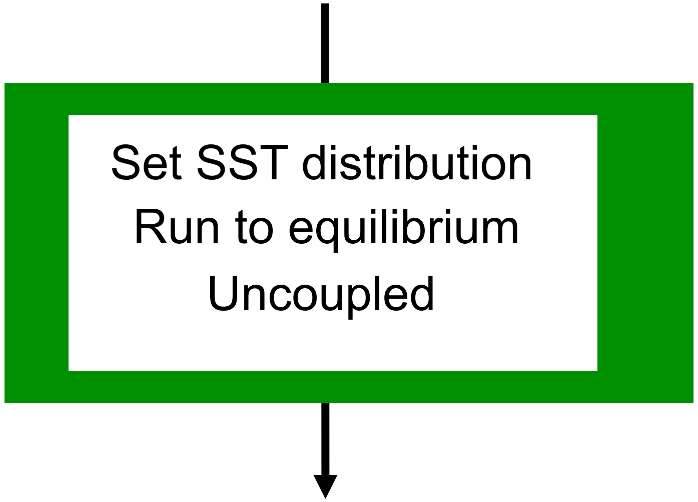
27 C



37 C

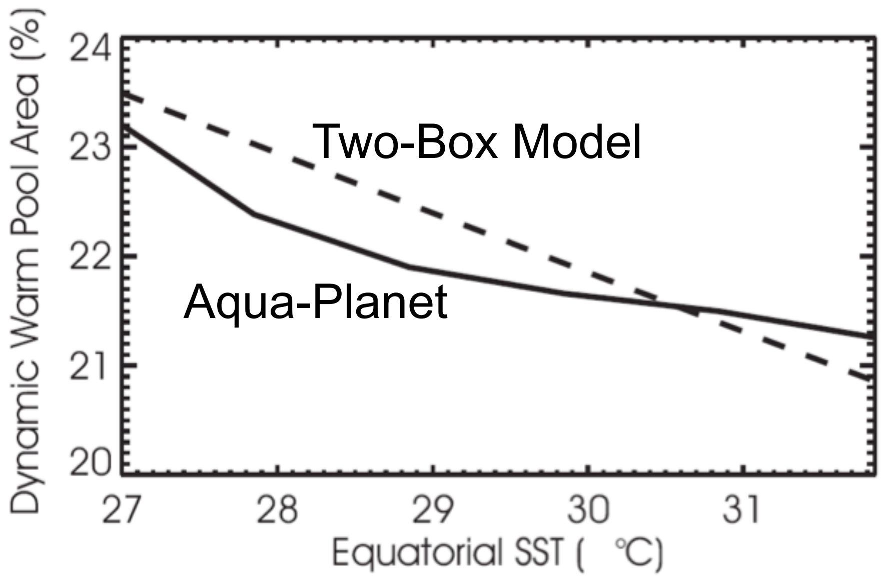


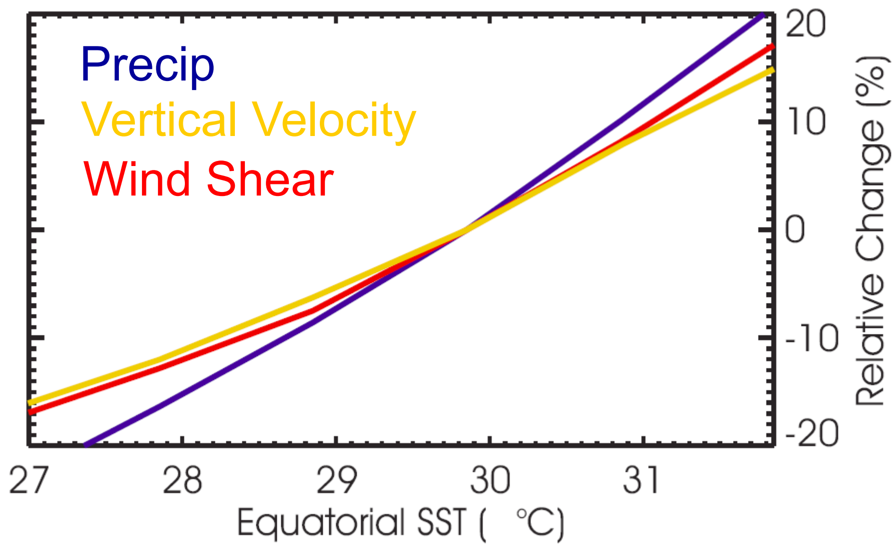
Multi-layer aqua-planet with set SST run to equilibrium.
SST incremented for each run

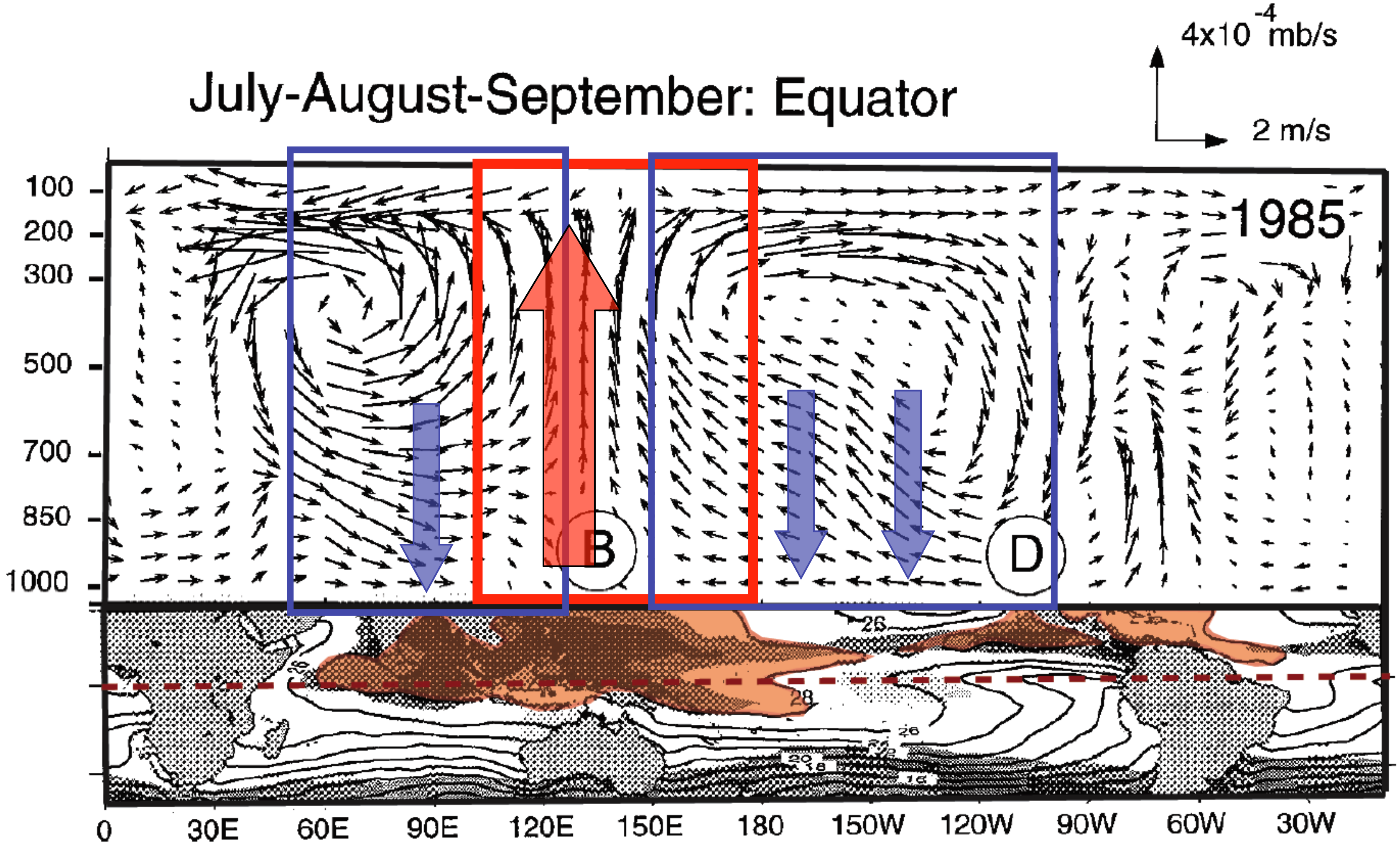


Zonally symmetric, two level, non-linear coupled model representing an aqua-planet with full hydrologic cycle.

- Results very similar to 2 box model.
- Note changes in precipitation, shear and vertical velocity







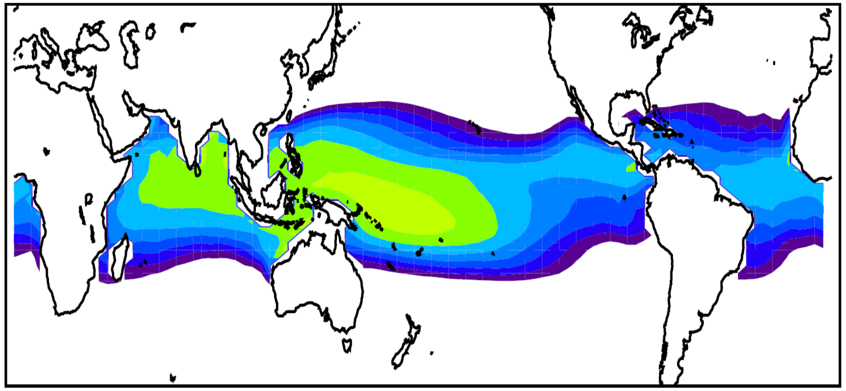
Expect a constancy of areas of rising motion/sinking motion, irrespective of background SST value

Do these rules hold for Past Climates

LGM vs Pre-Industrial SST

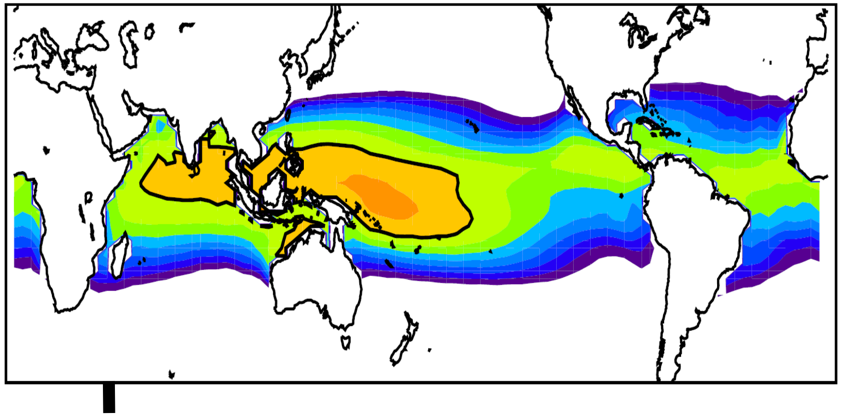
Simulated Last Glacial Maximum (LGM) SST (same models)

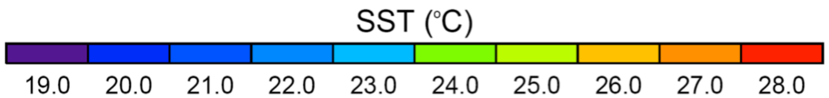
21 ka ago Insolation and Ice sheet reconstruction, CO_2=200 ppm



Simulated Pre-industrial SST

Present Insolation, CO_2=280 ppm





* What was the convective activity during the LGM?

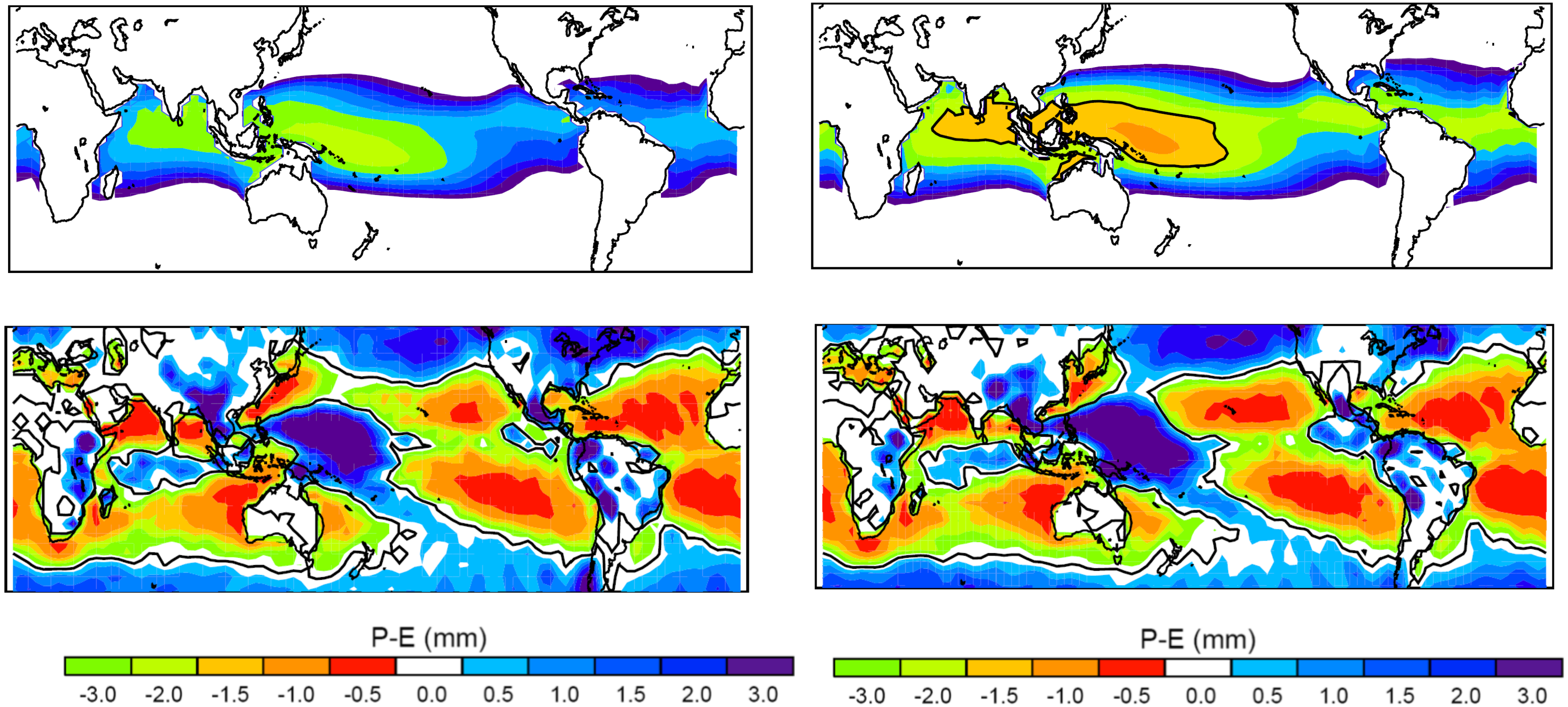
* What was the Tropical Cyclone activity?

PMIP: Paleoclimate Modelling Intercomparison Project

Precipitation-Evaporation (proxy for convectively integrated heating)

Simulated Last Glacial Maximum SST

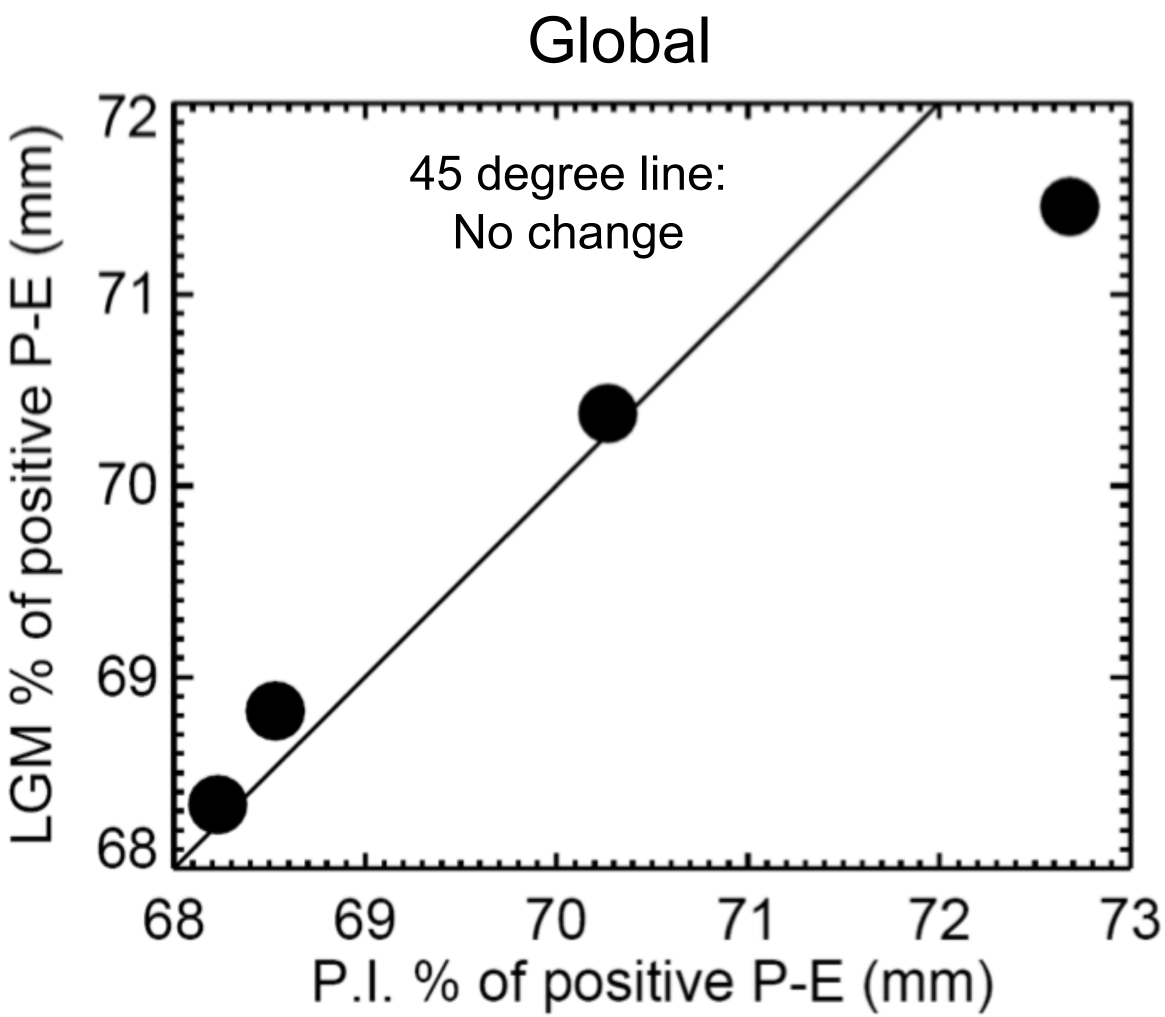
Simulated Pre-industrial SST



The area (size and distribution) of the DWP changes very little!

From LGM to Pre-industrial period: Summary

Each black circle represents a model

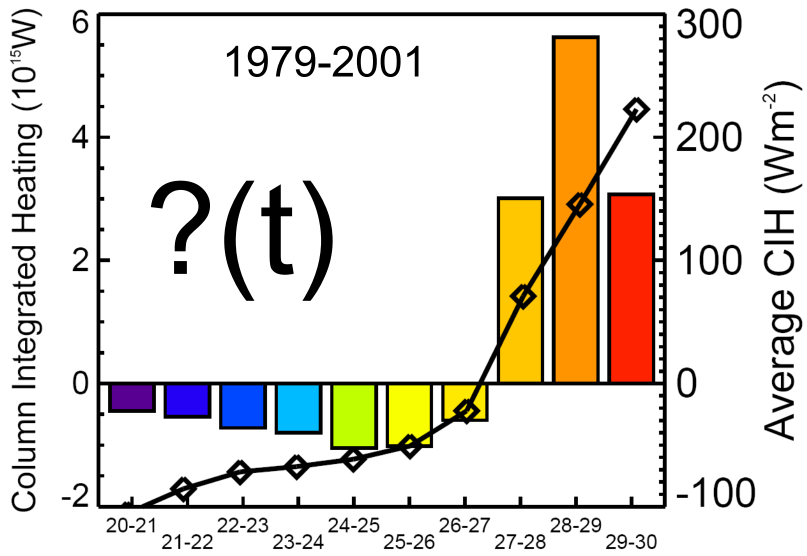


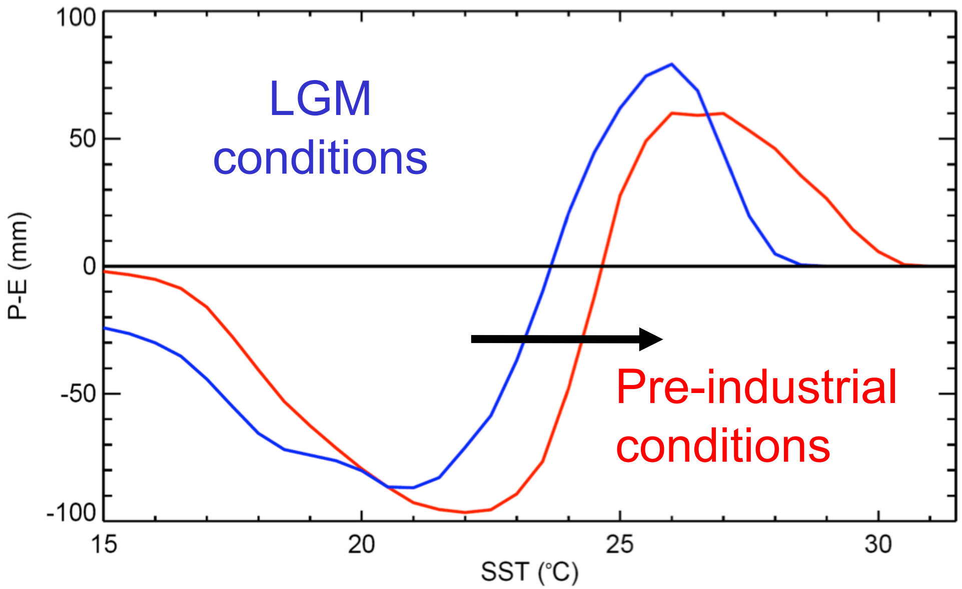
The area of the DWP changes very little!

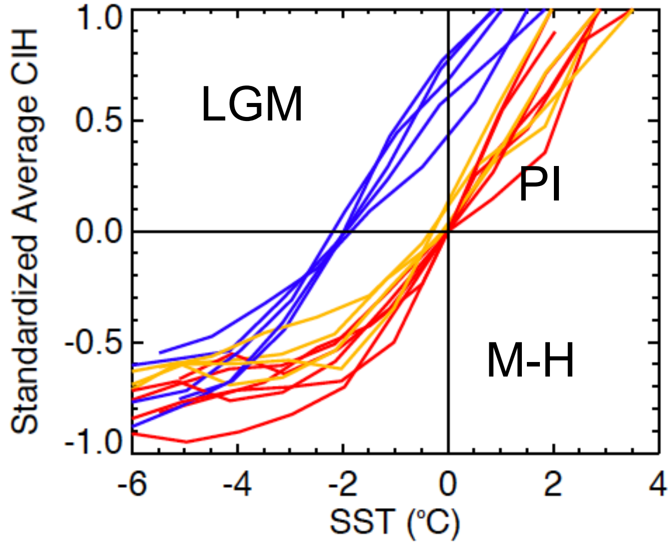
Warm Pool and P-E

Distribution of P-E is closely related to CIH

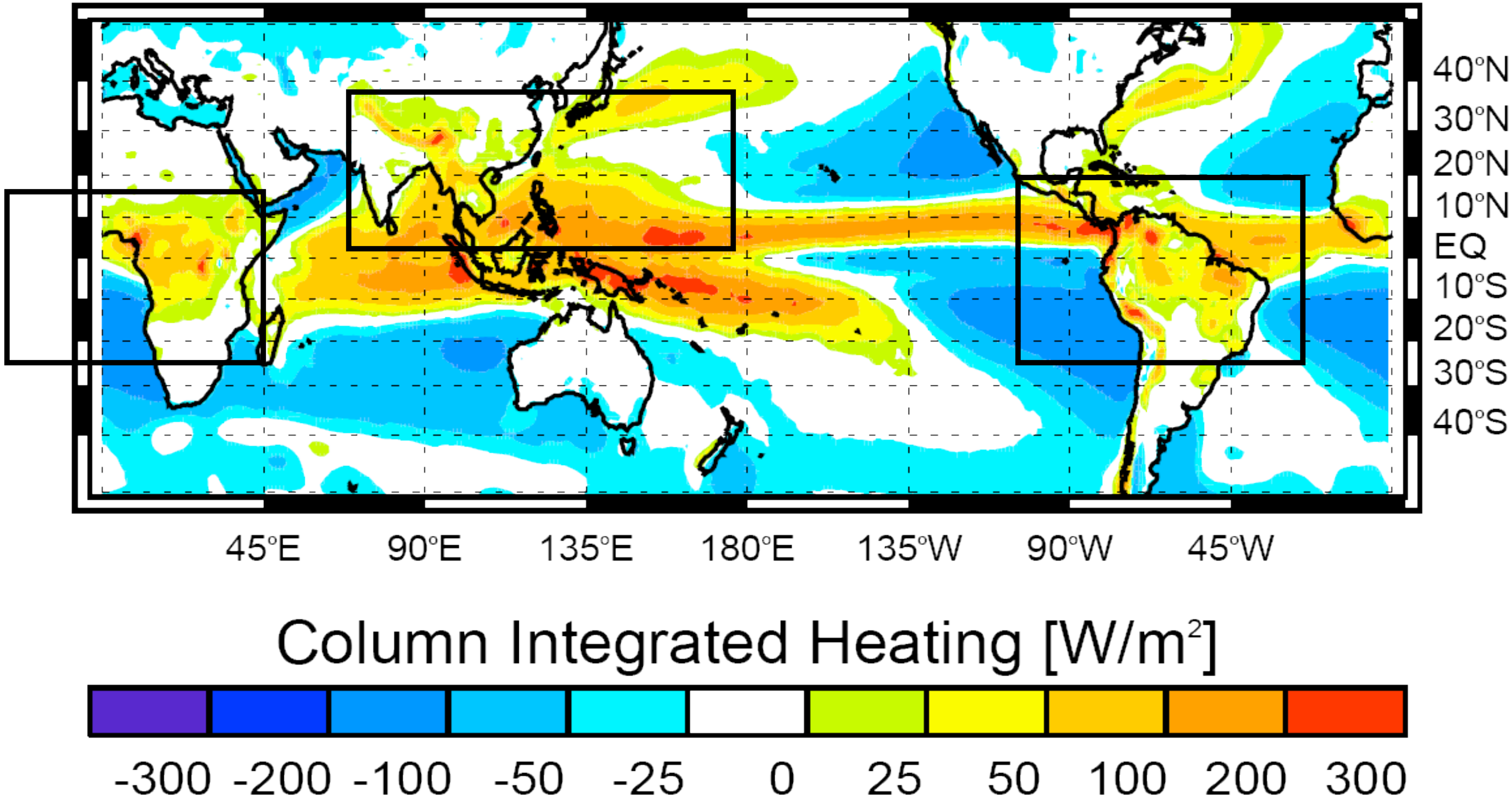
PMIP3 Models:
Multi-Model Ensemble
(4 models)







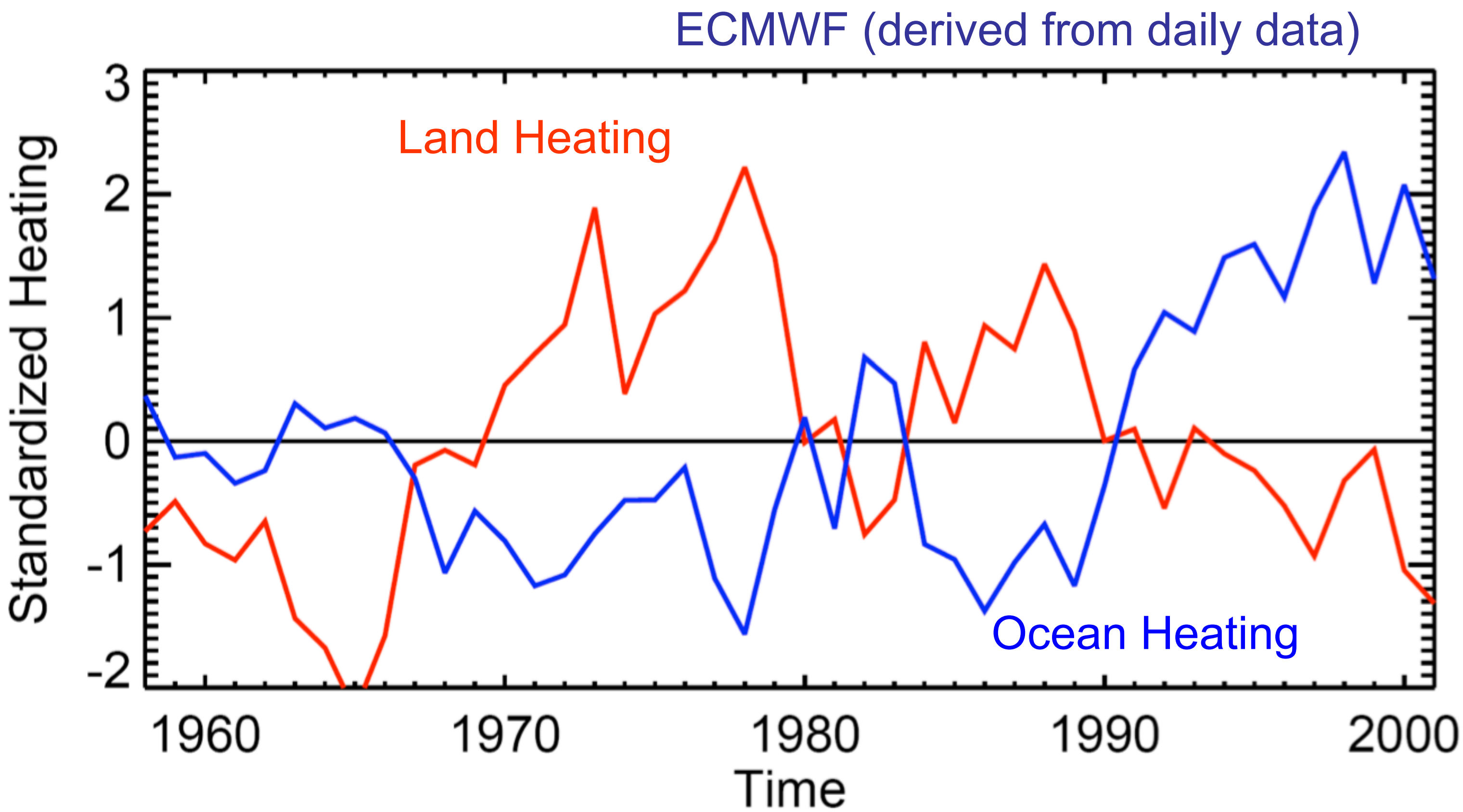
But what about the column integrated heating over land?



Does this change with time?

Ocean-Land Heating Contrast (Global Tropical Monsoon?)

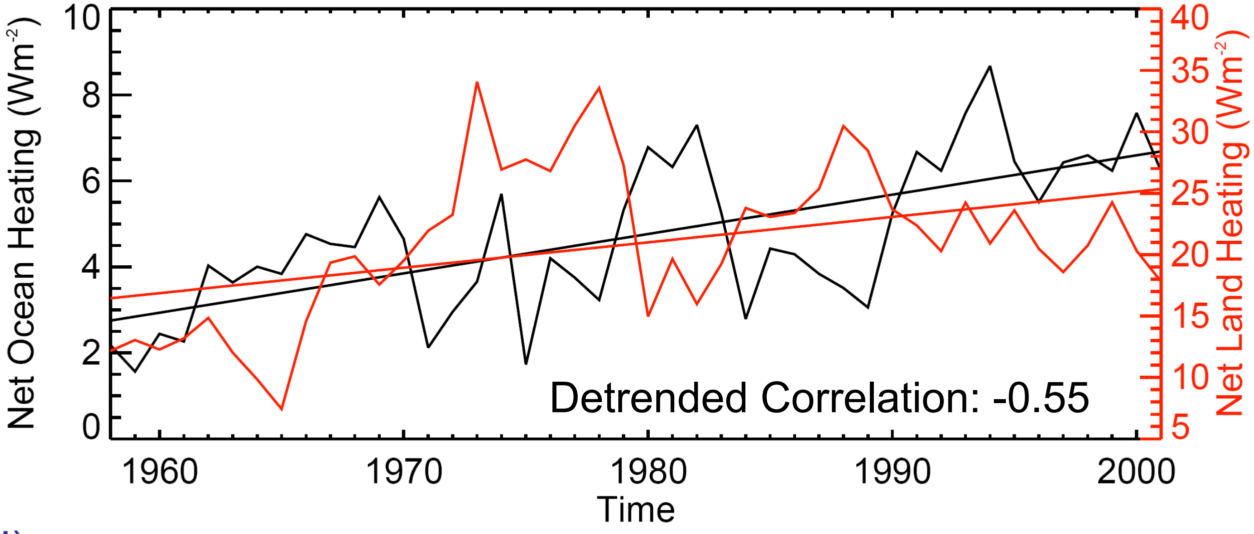
★Standardized Average Heating between 20°S and 20°N



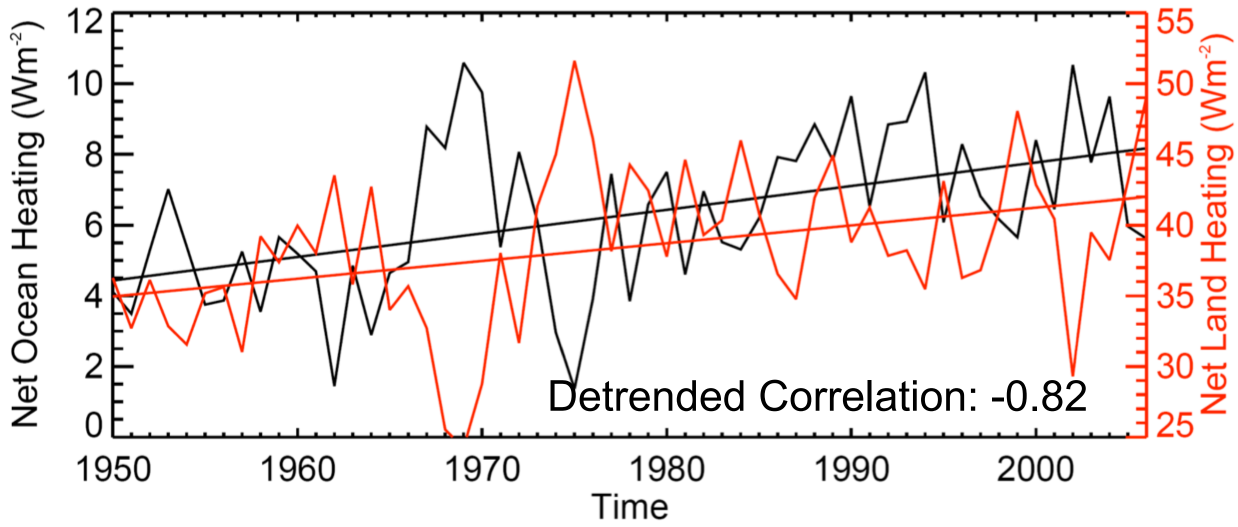
Correlation: -0.6

Data courtesy of S. Nigam

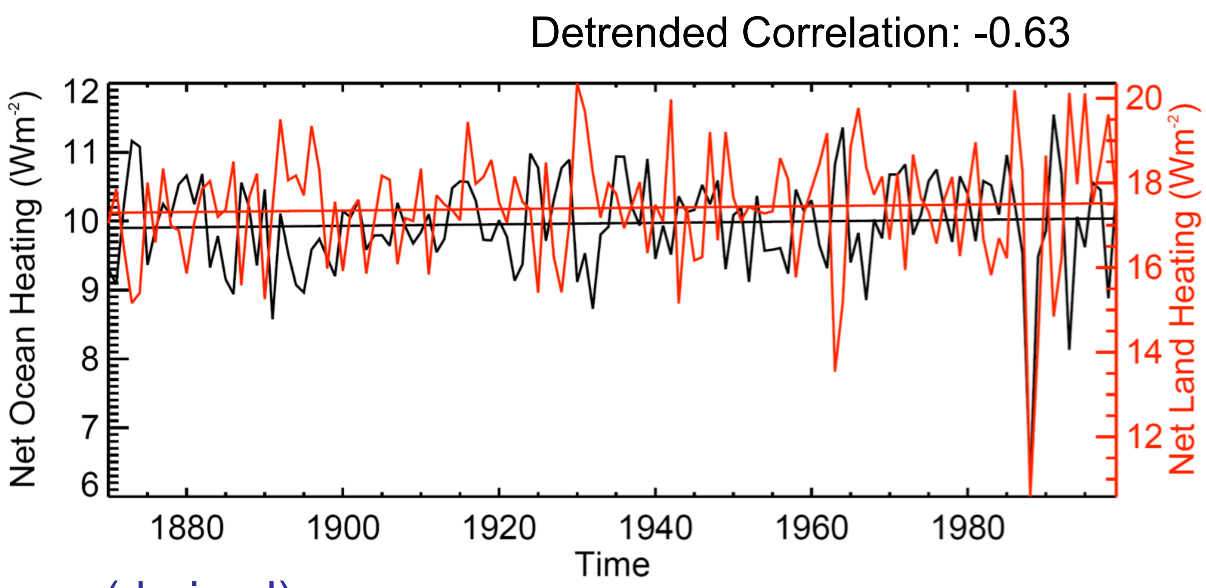
ECMWF (derived from monthly data)



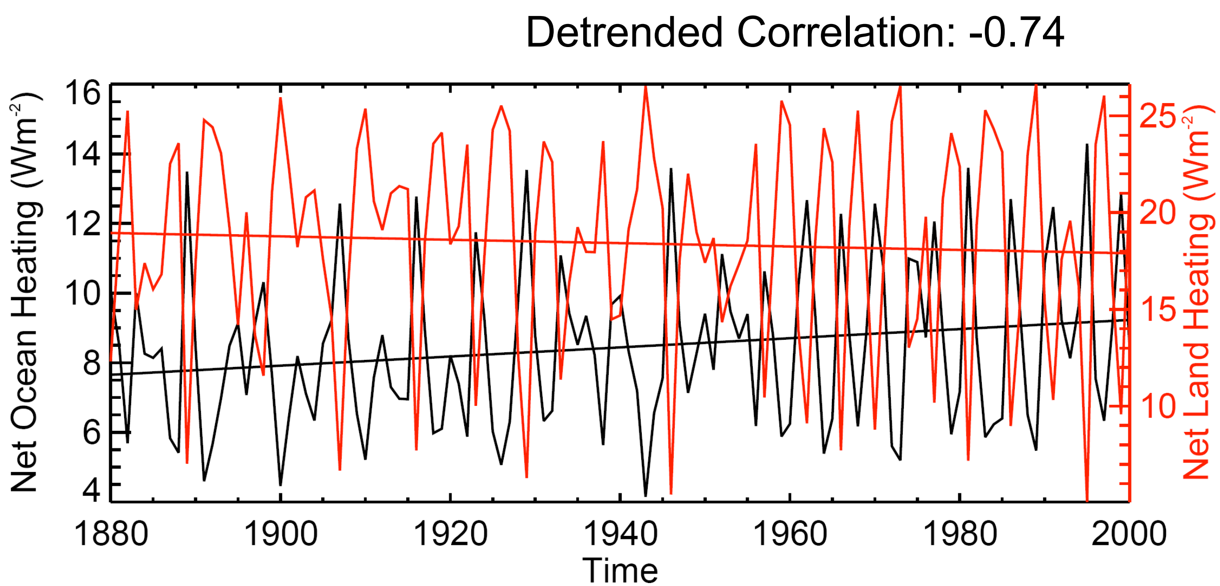
NCEP (derived)



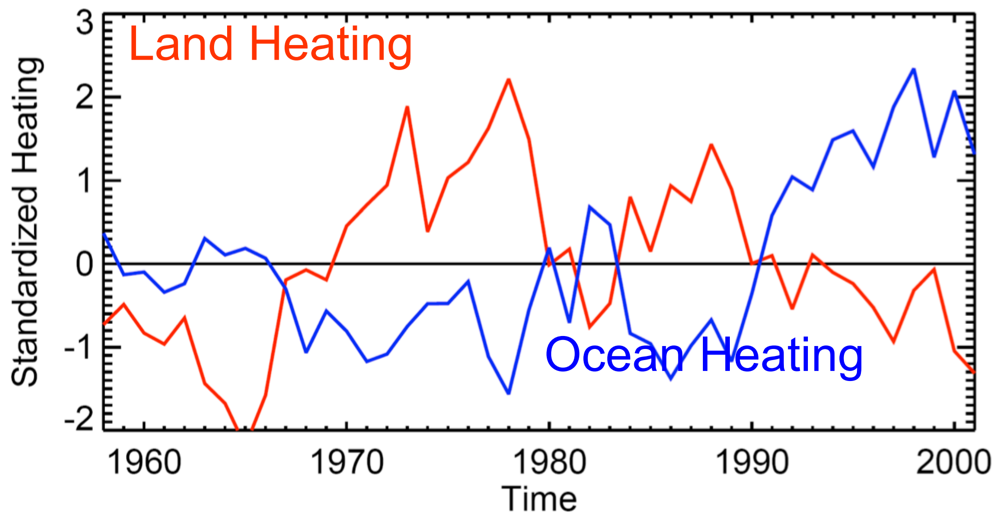
CCSM3 20th Century run (derived)

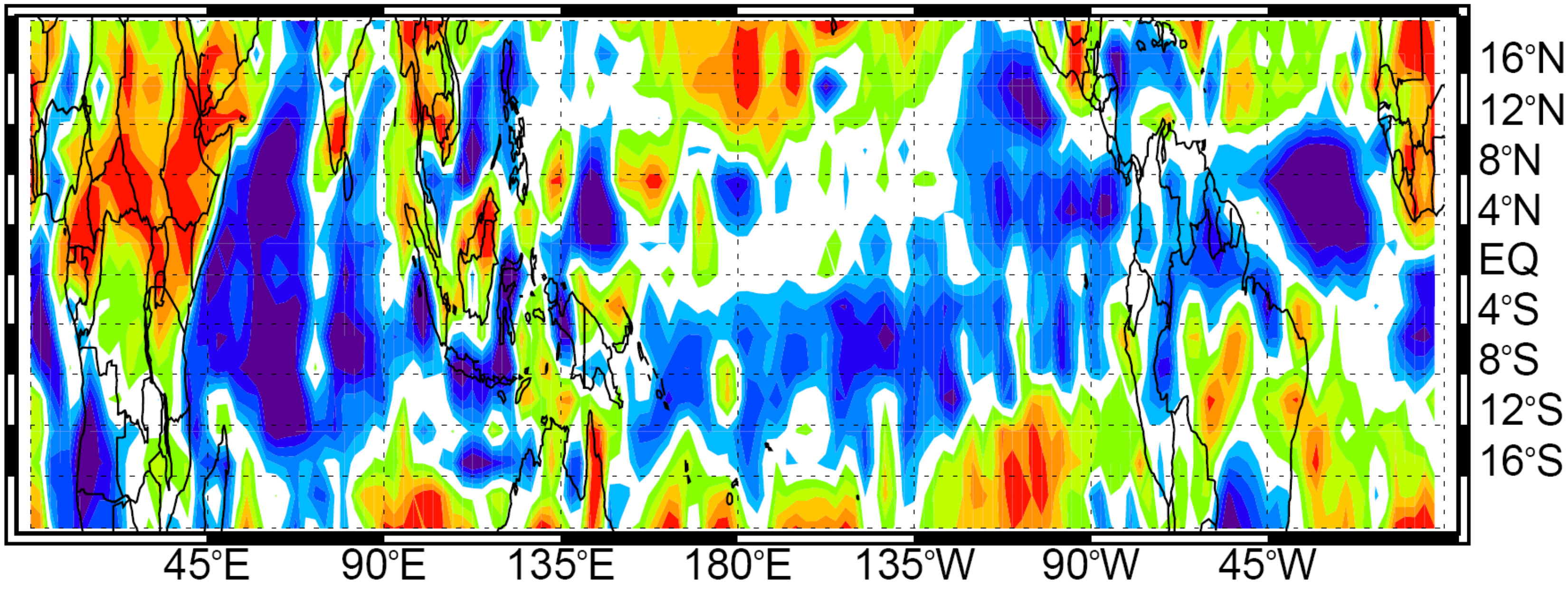


GFDL 20th Century run (derived)

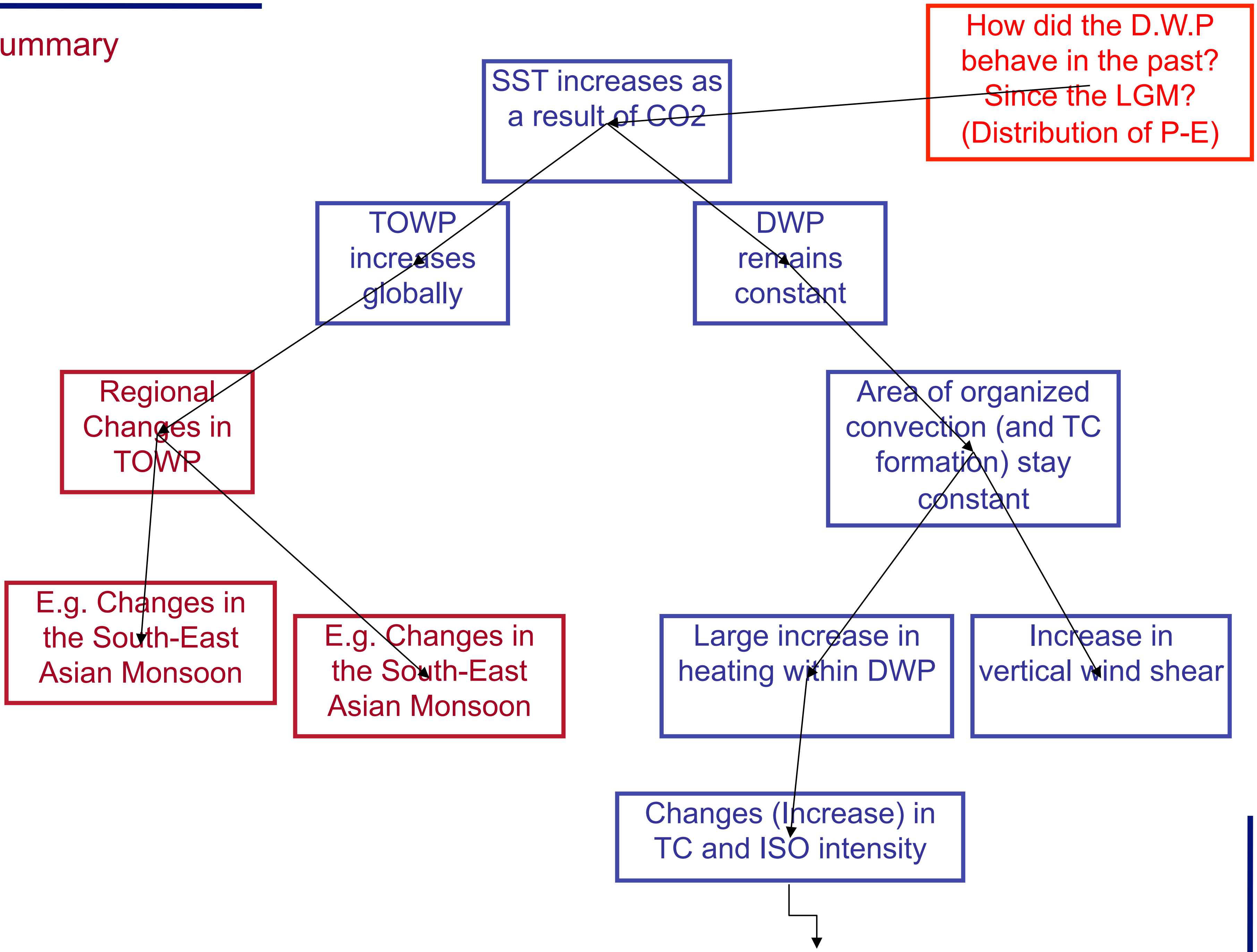


Ocean-Land Heating Contrast





Summary


How did the D.W.P behave in the past? Since the LGM? (Distribution of P-E)
SST increases as a result of CO2
TOWP increases globally
DWP remains constant
Regional Changes in TOWP
Area of organized convection (and TC formation) stay constant
E.g. Changes in the South-East Asian Monsoon
E.g. Changes in the South-East Asian Monsoon
Large increase in heating within DWP
Increase in vertical wind shear
Changes (Increase) in TC and ISO intensity

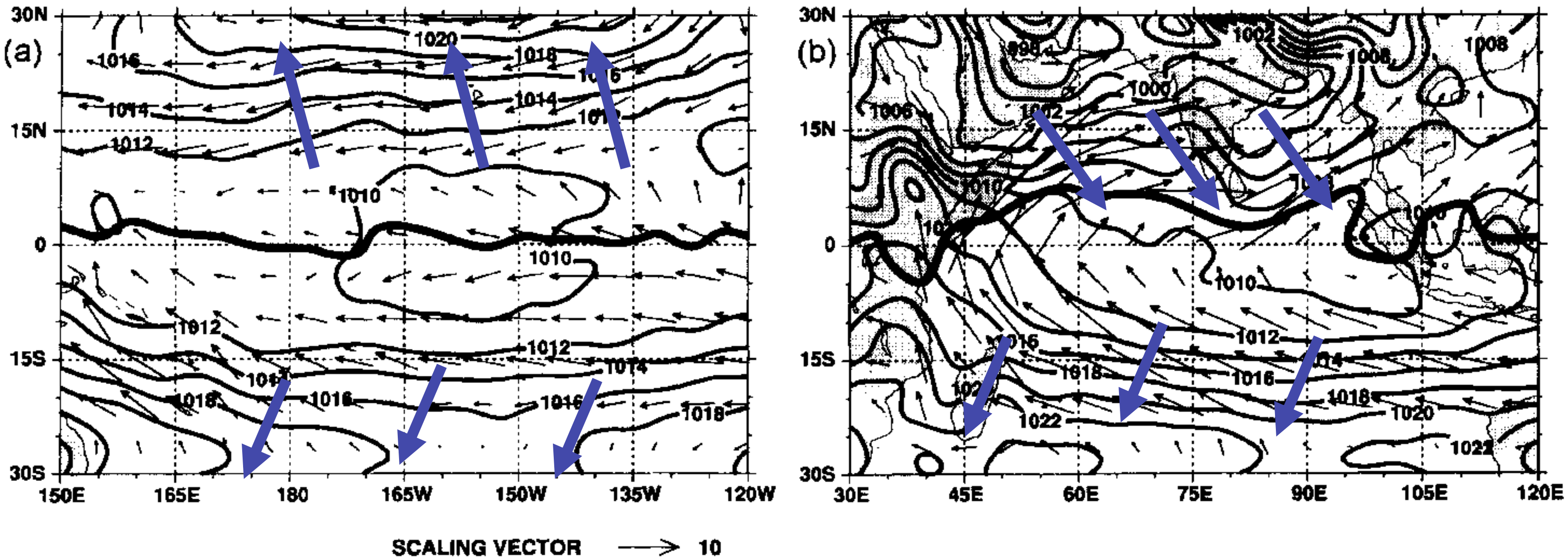
Monsoon Heat Budget

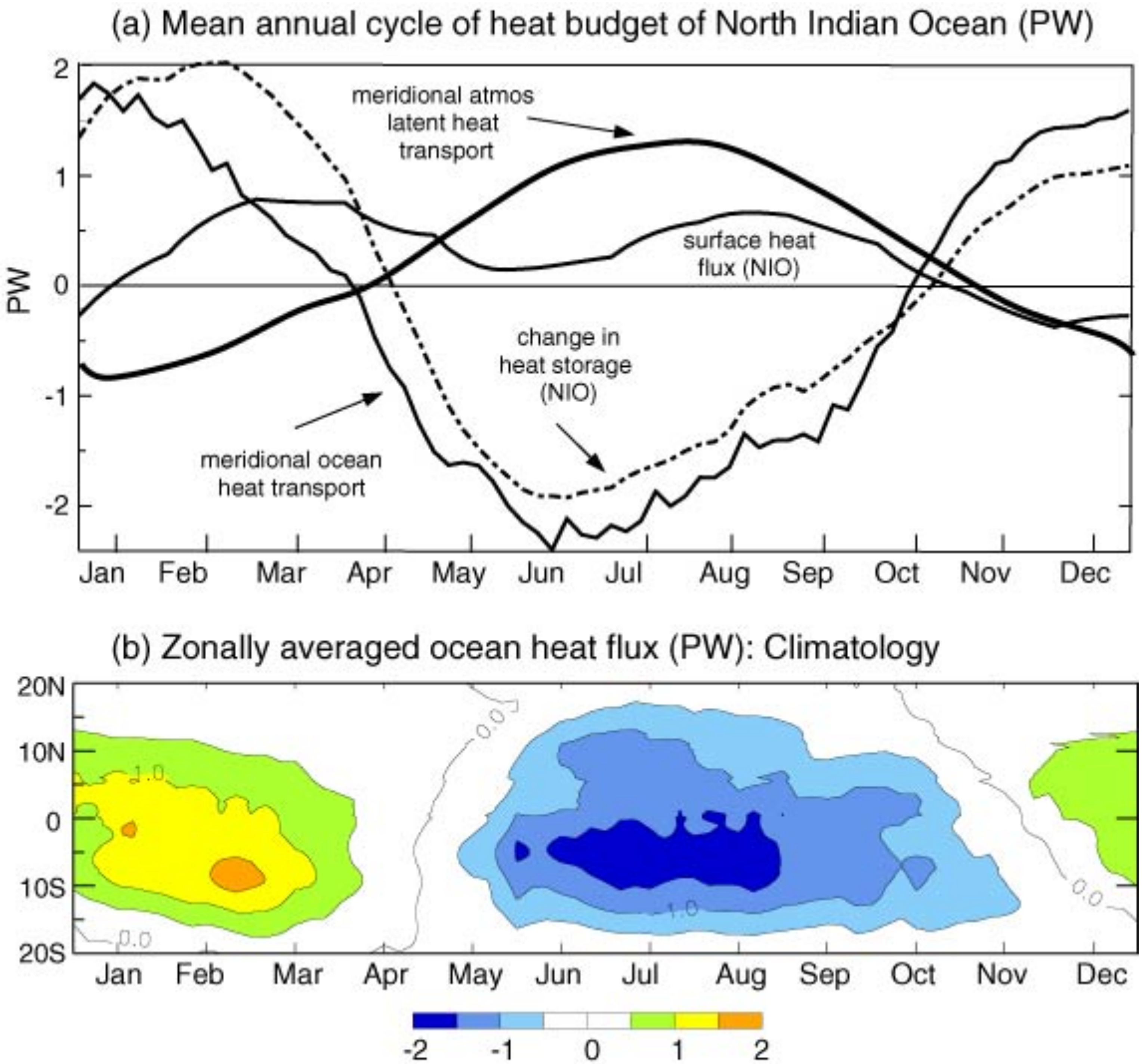
- Hastenrath & Greischer (1987) showed that the monsoon heat budget was almost closed.
- Latent & sensible heat transport by the atmosphere was essentially balanced by ocean heat transport
- Atmospheric & oceanic heat transports were in the opposite direction
- They did not attribute negative feedbacks to these near equal and opposite heat transports

Heat transport accomplished by Ekman drift:

- To the right of surface wind in NH
- To the left of surface wind in SH

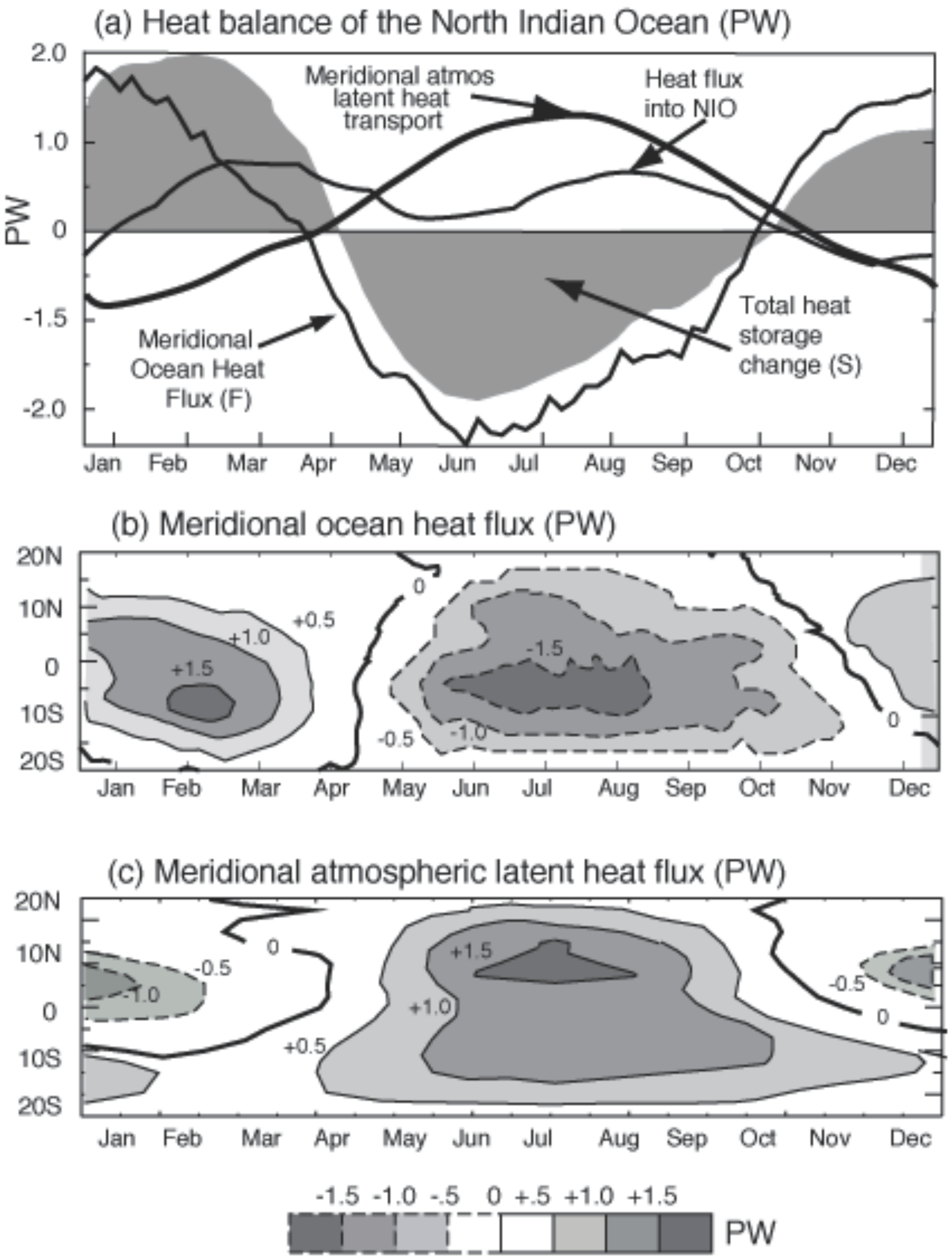
Trade wind regime | Summer monsoon regime





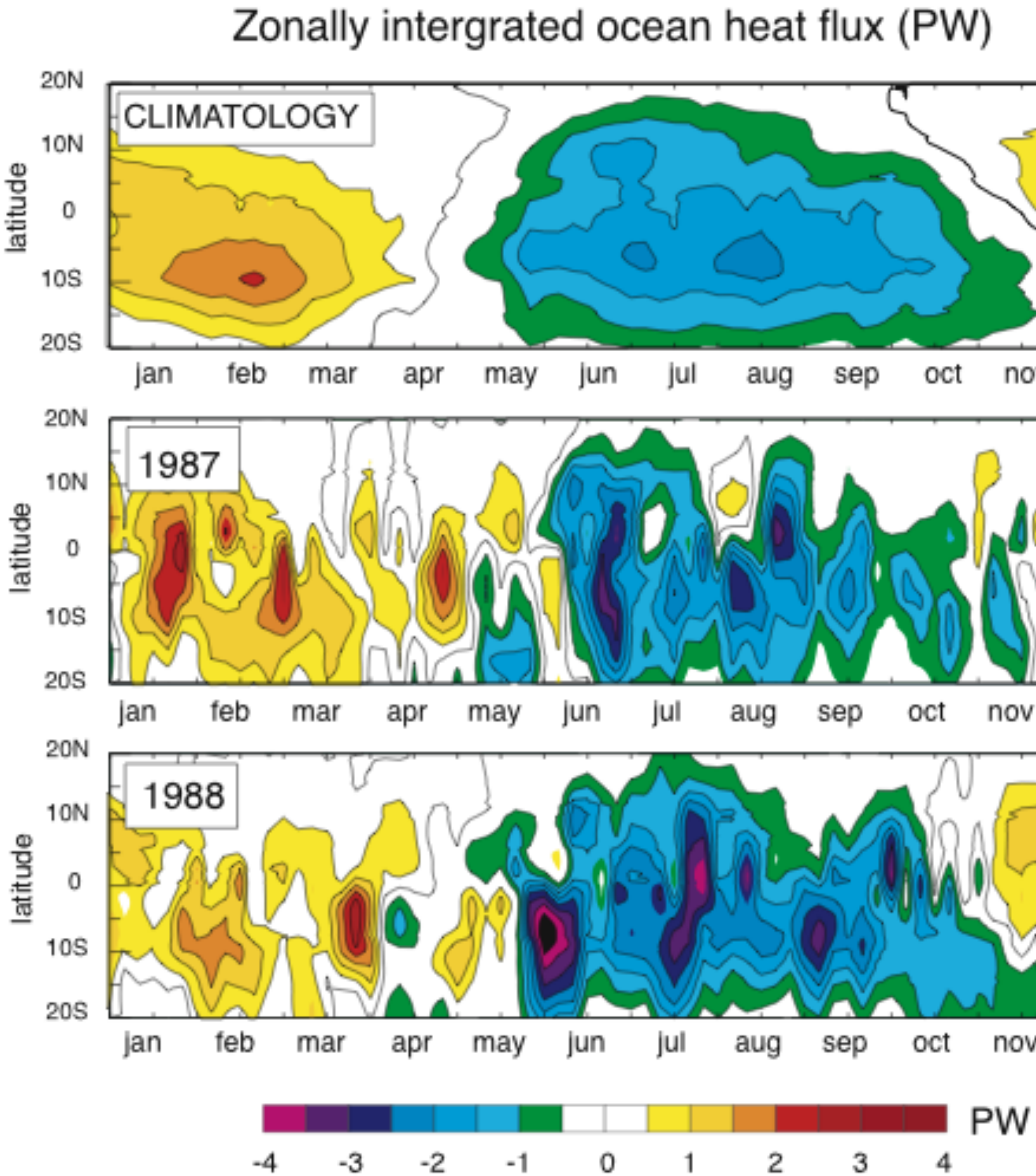
(a) Mean annual cycle of heat budget of North Indian Ocean (PW)
PW
2
1
0
-1
-2
meridional atmos latent heat transport
surface heat flux (NIO)
change in heat storage (NIO)
meridional ocean heat transport
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
(b) Zonally averaged ocean heat flux (PW): Climatology
20N
10N
0
10S
20S
1.0
0.0
-1.0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
-2
-1
0
1
2

Annual Cycle of North Indian Ocean and Latent Heat Flux

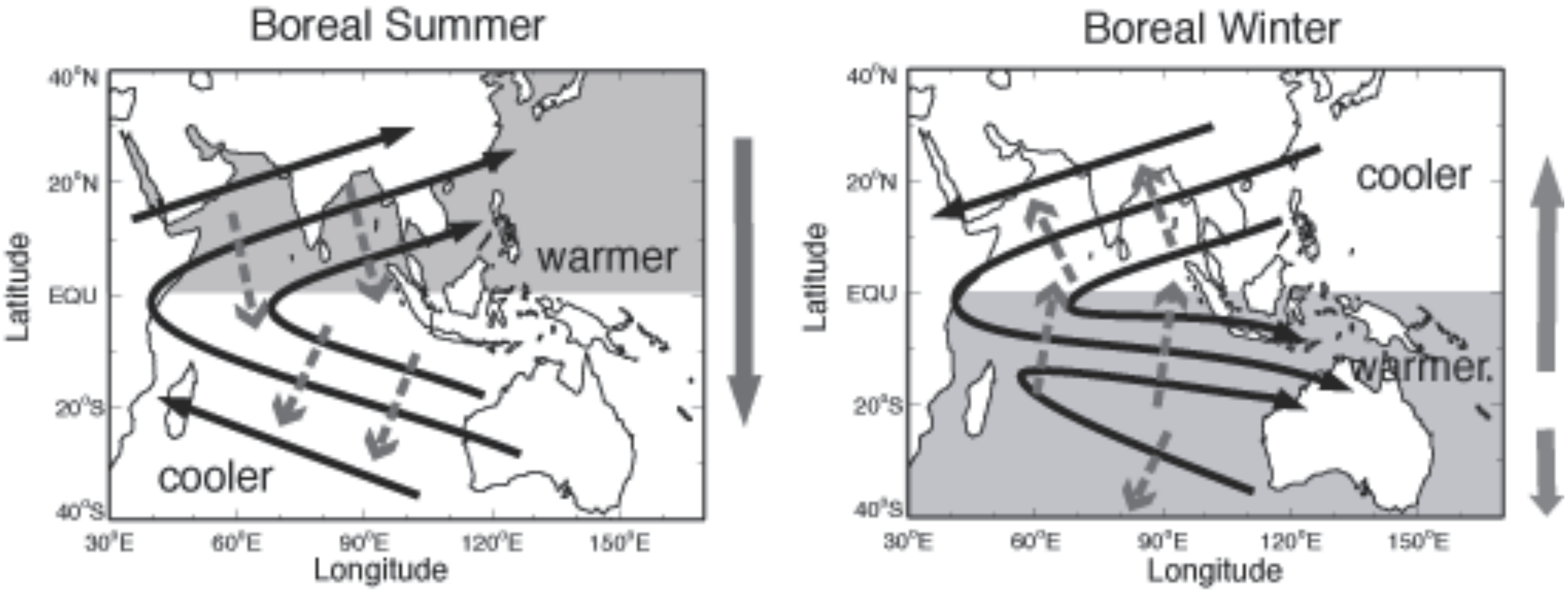


The coupled ocean-atmosphere monsoon system is almost in balance as pointed out first by Hastenrath & Greischer (1987).

This is an important observation and verified by both observations (H&G) and model results (here) and points to fundamental physics of monsoon maintenance and regulation

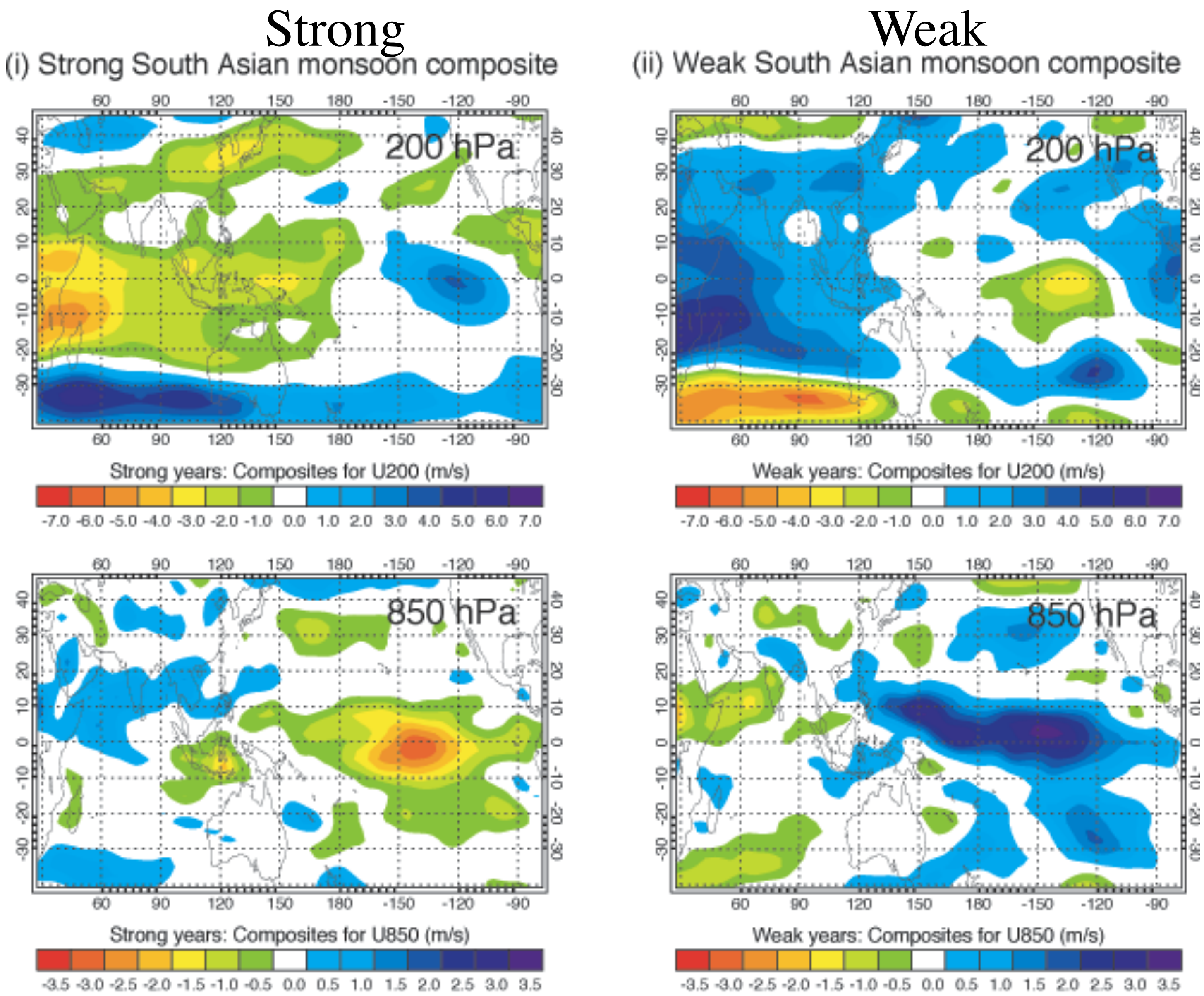

Zonally intergrated ocean heat flux (PW)
CLIMATOLOGY
1987
1988
20N
10N
0
10S
20S
latitude
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
PW
-4
-3
-2
-1
0
1
2
3
4

Wind driven heat flux in the ocean is contrary to the flux of heat in the atmosphere thus cooling the spring and summer hemispheres and warming the fall and winter hemispheres



Impact is to modulate the amplitude of the annual cycle through SST and mixed layer Property control

South Asian Monsoon



North Australian Monsoon

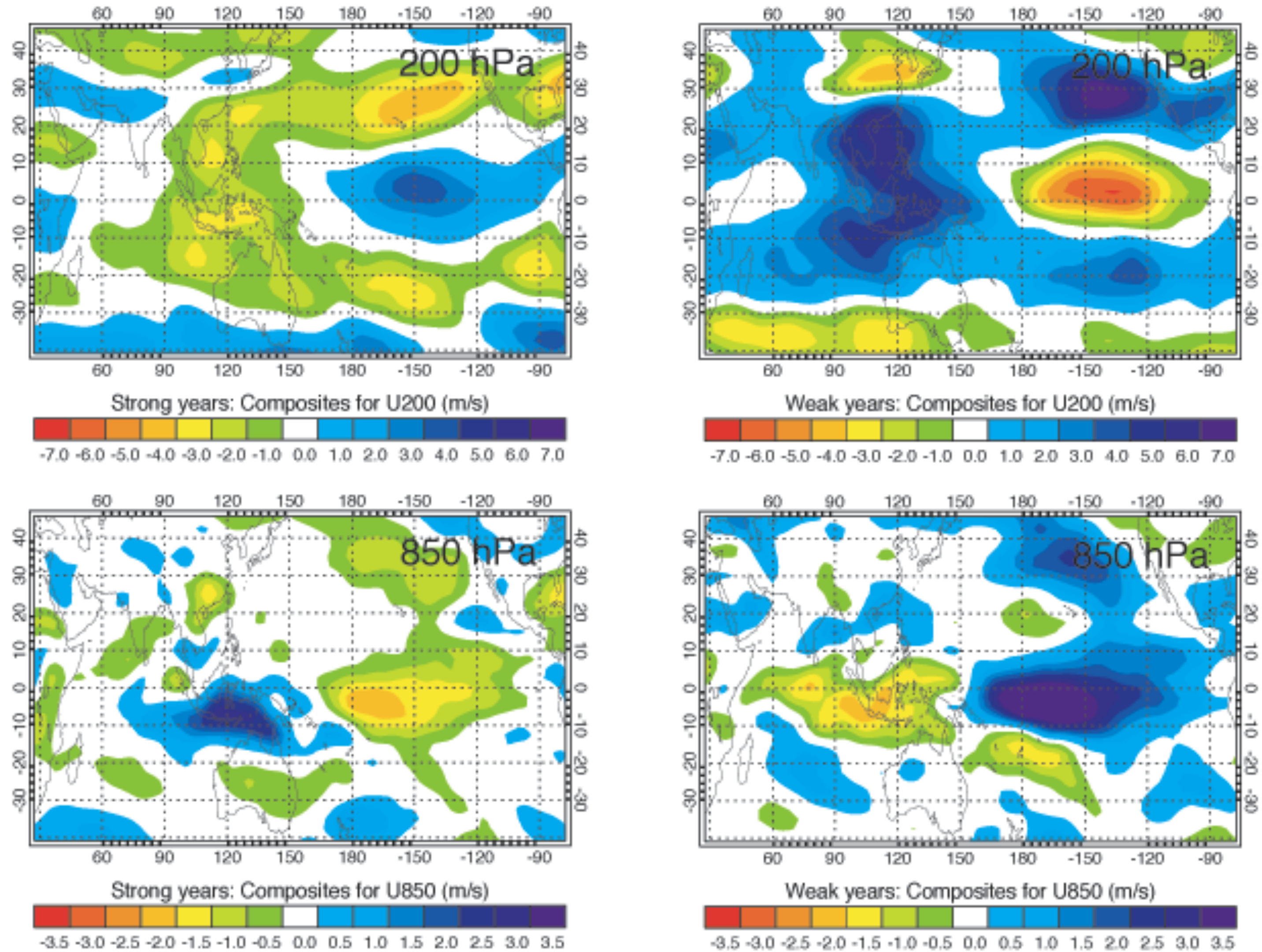
Strong

Weak

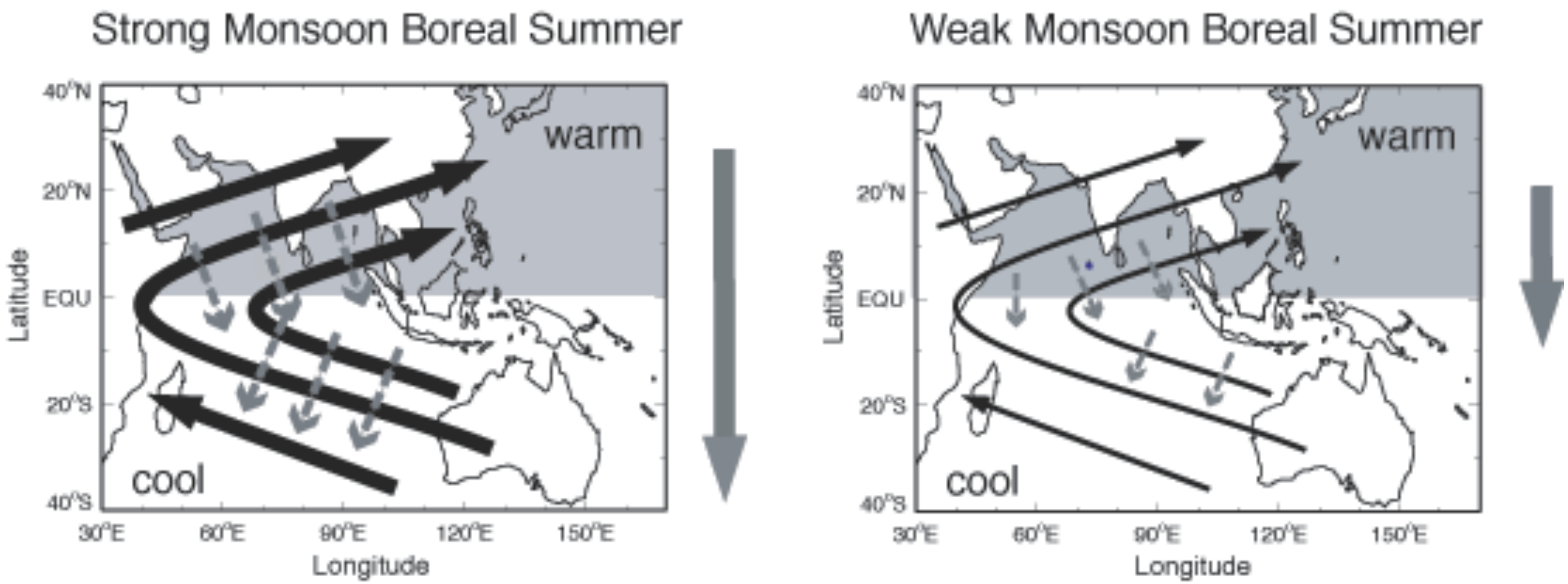
FIGURE 4c

(i) Strong N. Ausralian monsoon composite

(ii) Weak N. Australian monsoon composite



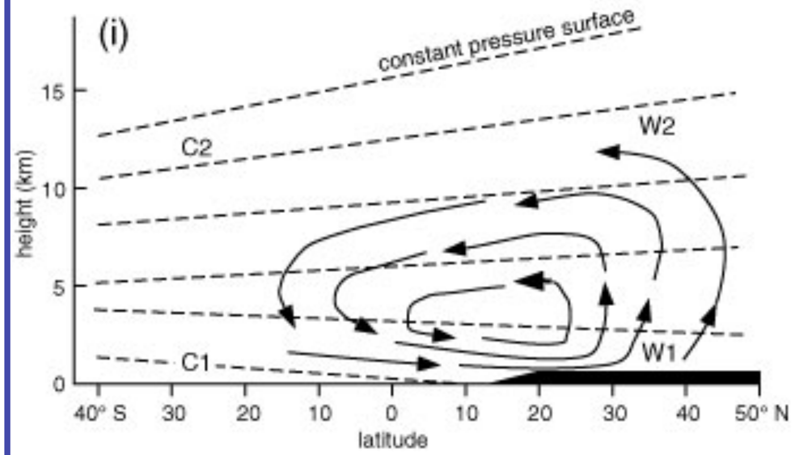
Regulation of interannual variability of the monsoon. Strong and weak monsoons change heat balance to provide an anomaly of the opposite sign the following year



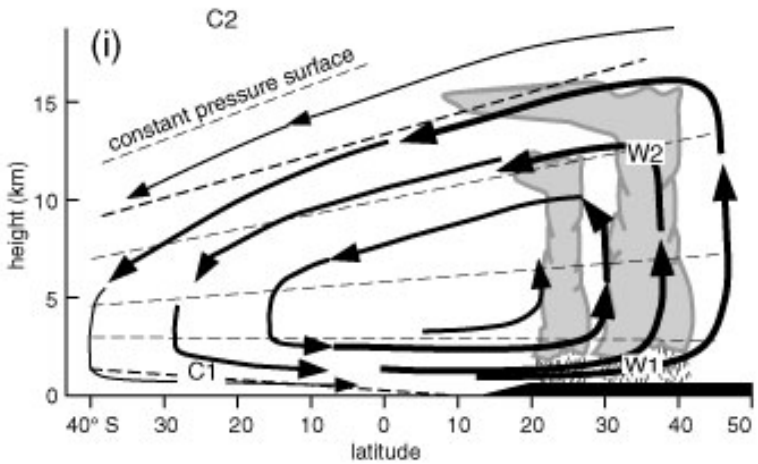
This adds a dynamic component to Meehl bienniality theory

Ocean transport and monsoon strength

weak monsoon



strong monsoon



weak southward
ocean heat transport

strong southward
heat transport

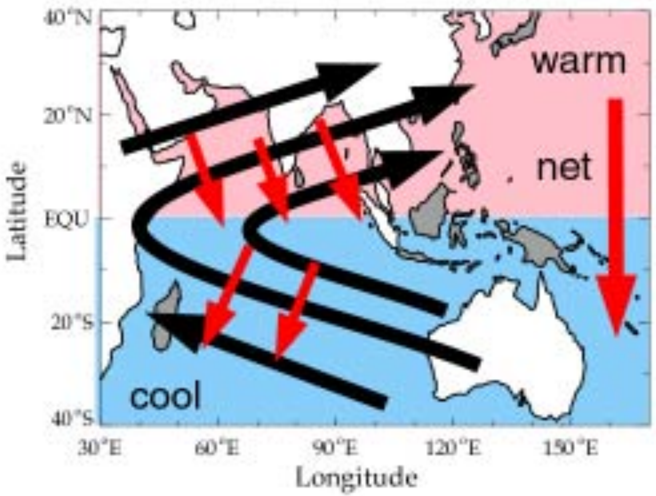
anom warms NIO

anom cools NIO

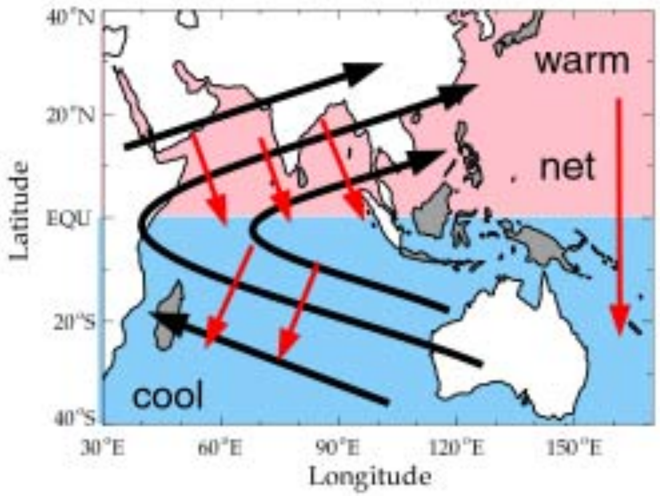
temperature log(pressure) temperature log(pressure)

MODULATION OF INTERANNUAL VARIABILITY IN THE MONSOON

STRONG MONSOON



WEAK MONSOON



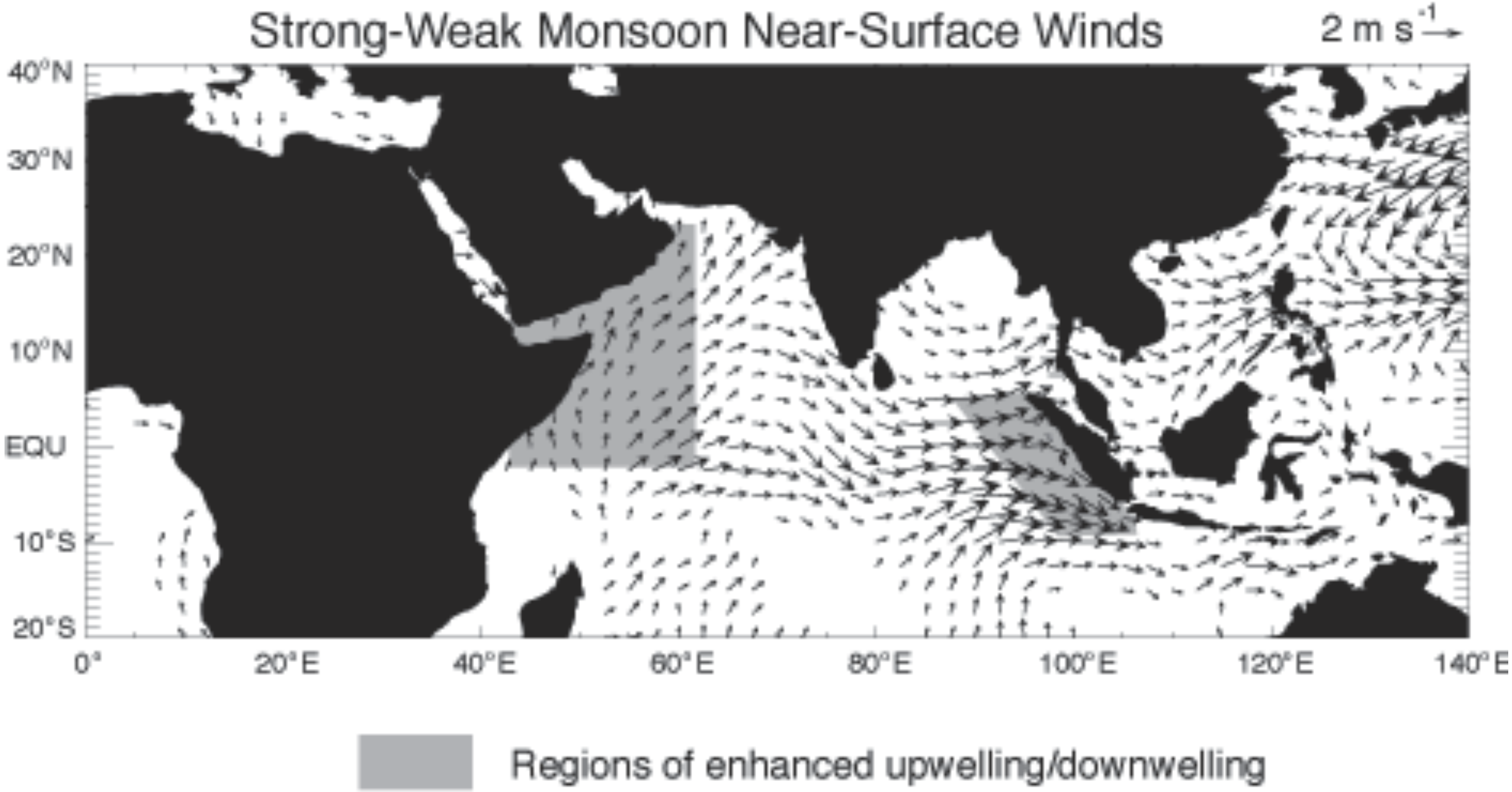
Strong monsoon:
- strong winds
- strong Ekman transport
- large southward transport
- cool North Indian Ocean

Weak monsoon:
- weak winds
- weak Ekman transport
- weak southward transport
- warm Northern Indian Ocean

Tendency to produce anomaous monsoon of opposite sign the following year.

Bienniality produced into monsoon system

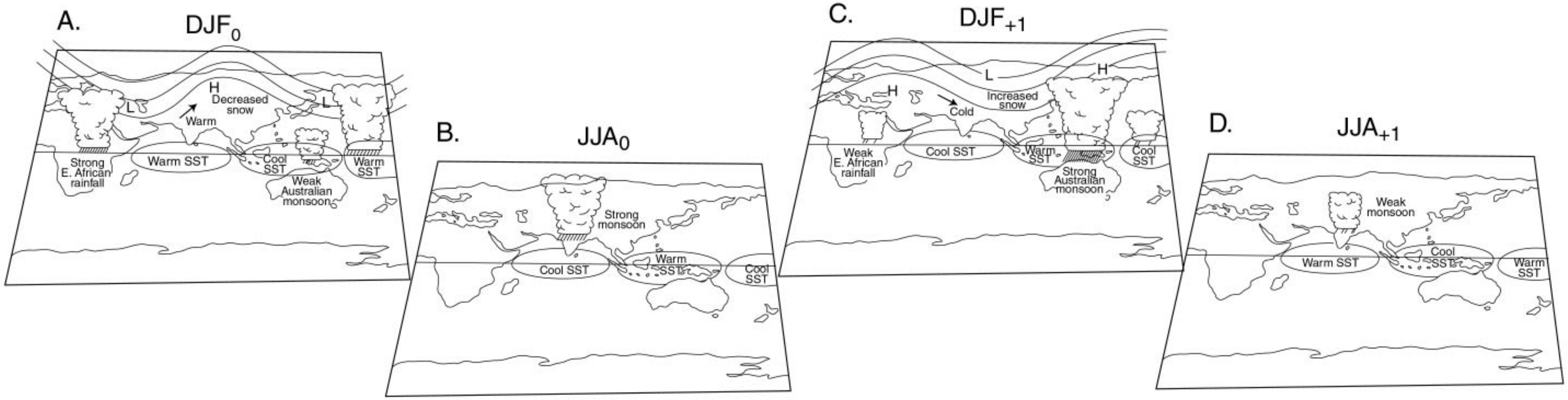
Differences in the low level winds between strong and weak monsoons



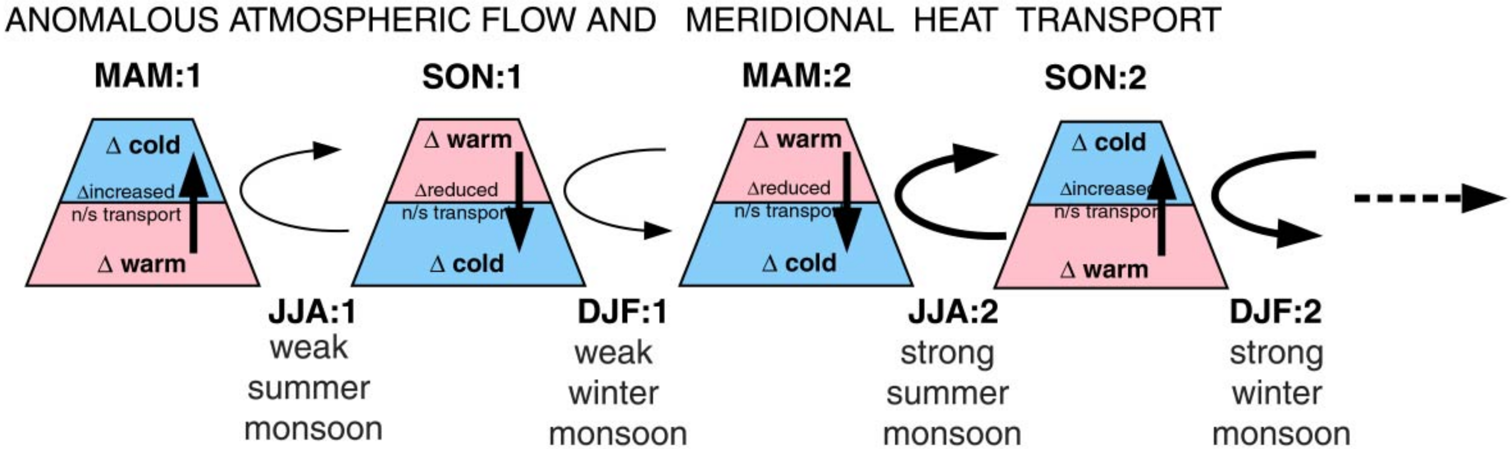
Note that a strong monsoon enhances upwelling in EIO, decreases WIO
……………weak………………………………………WIO,…………EIO

Residual effects and oceanic memory

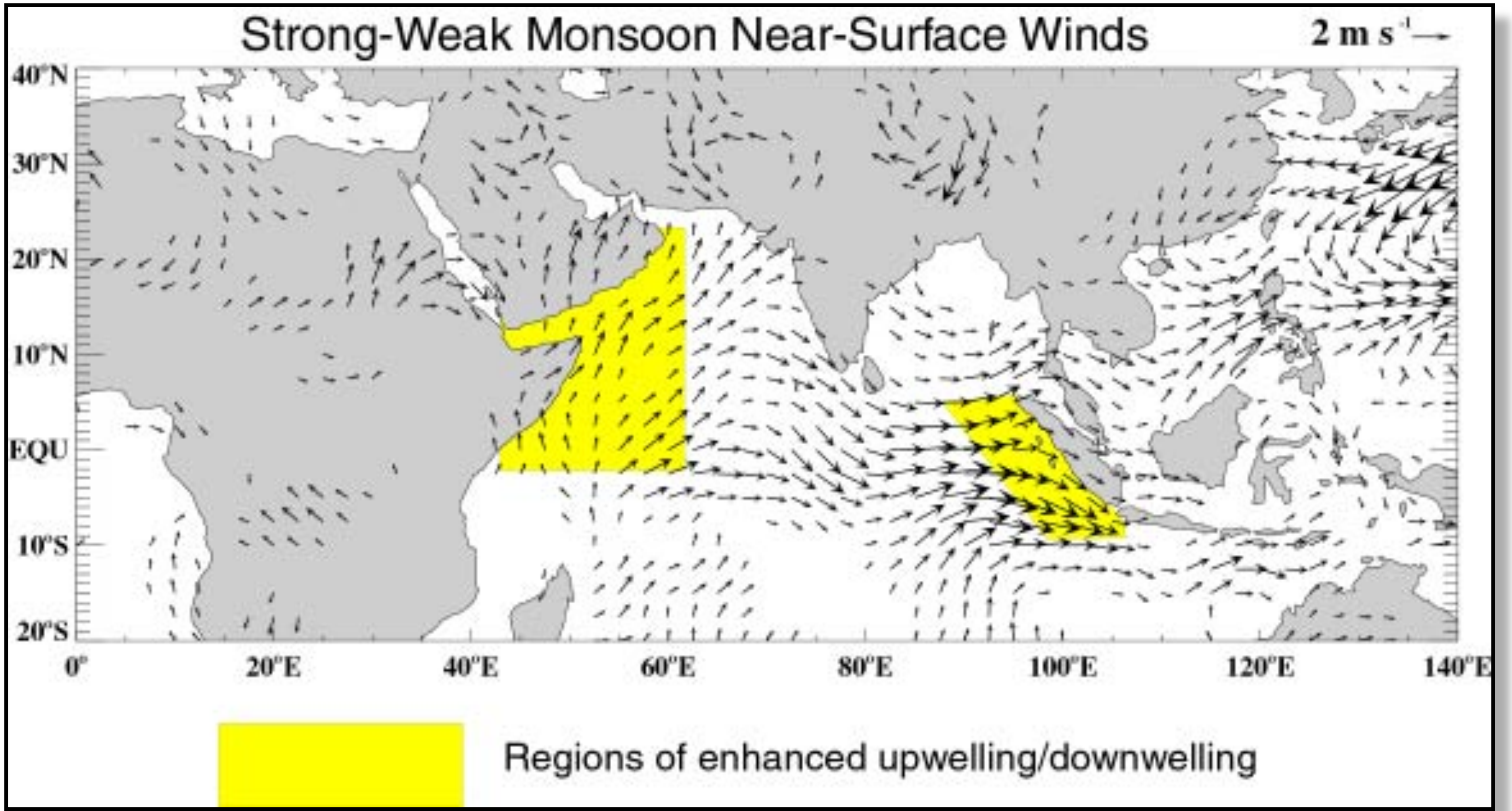
The enhanced or reduced ocean heat transport has an impact on subsequent monsoon years. Meehl (1994, 1997) noted that there existed a biennial oscillation in the monsoon (i.e., strong years followed by weak years). Although he did not identify the monsoon strength-dynamic ocean heat transport negative feedback, he related properly the relationship between SST variability and monsoon strength.



We can redraw Meehl's schematic but incorporating the wind driven dynamic transports of heat.



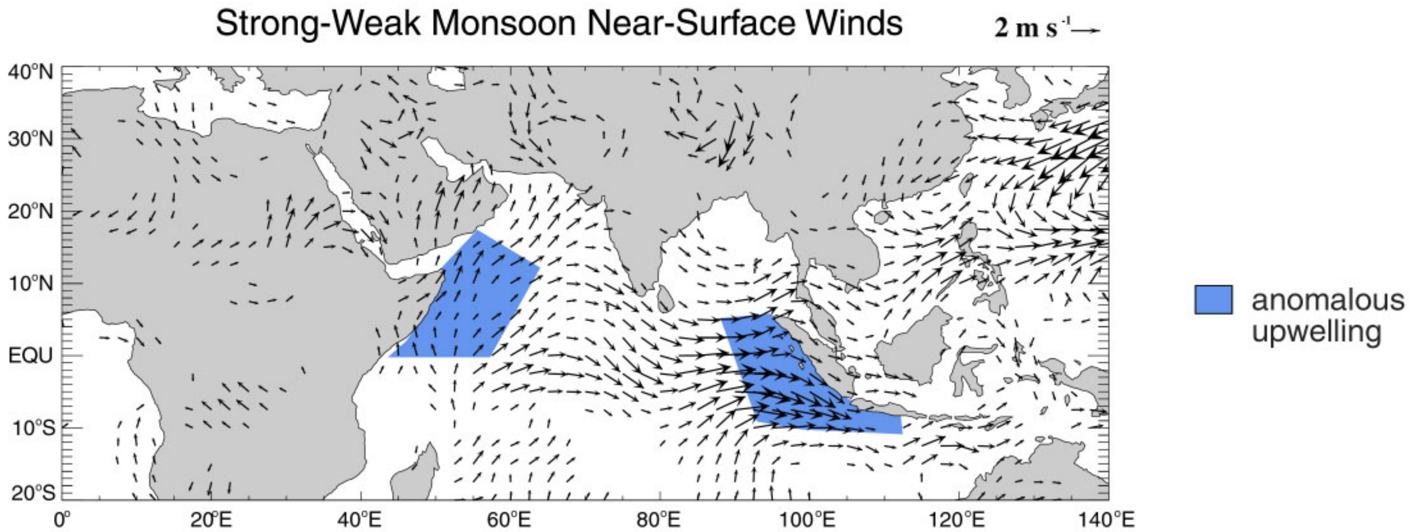
Impact of anomalous monsoon seasons



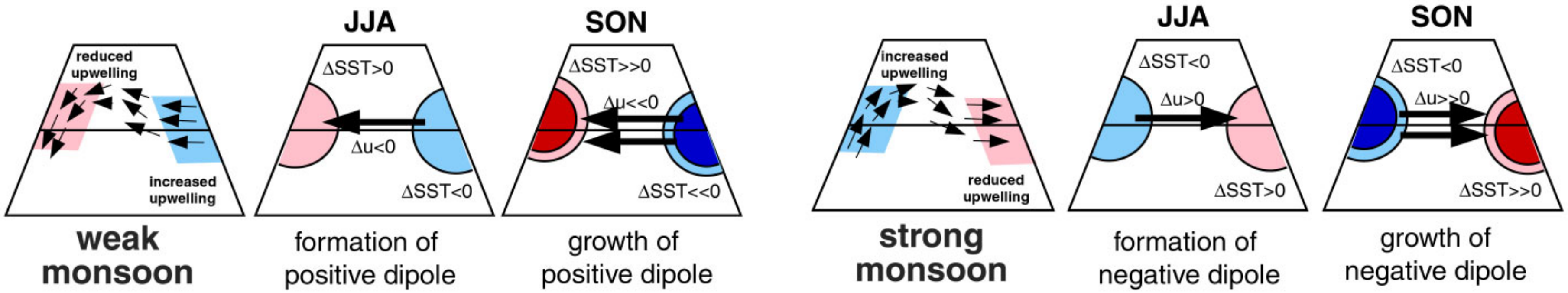
Strong and weak monsoons invoke different upwelling effects creating SST gradients. Then …….

The IOZM and the anomalous monsoon

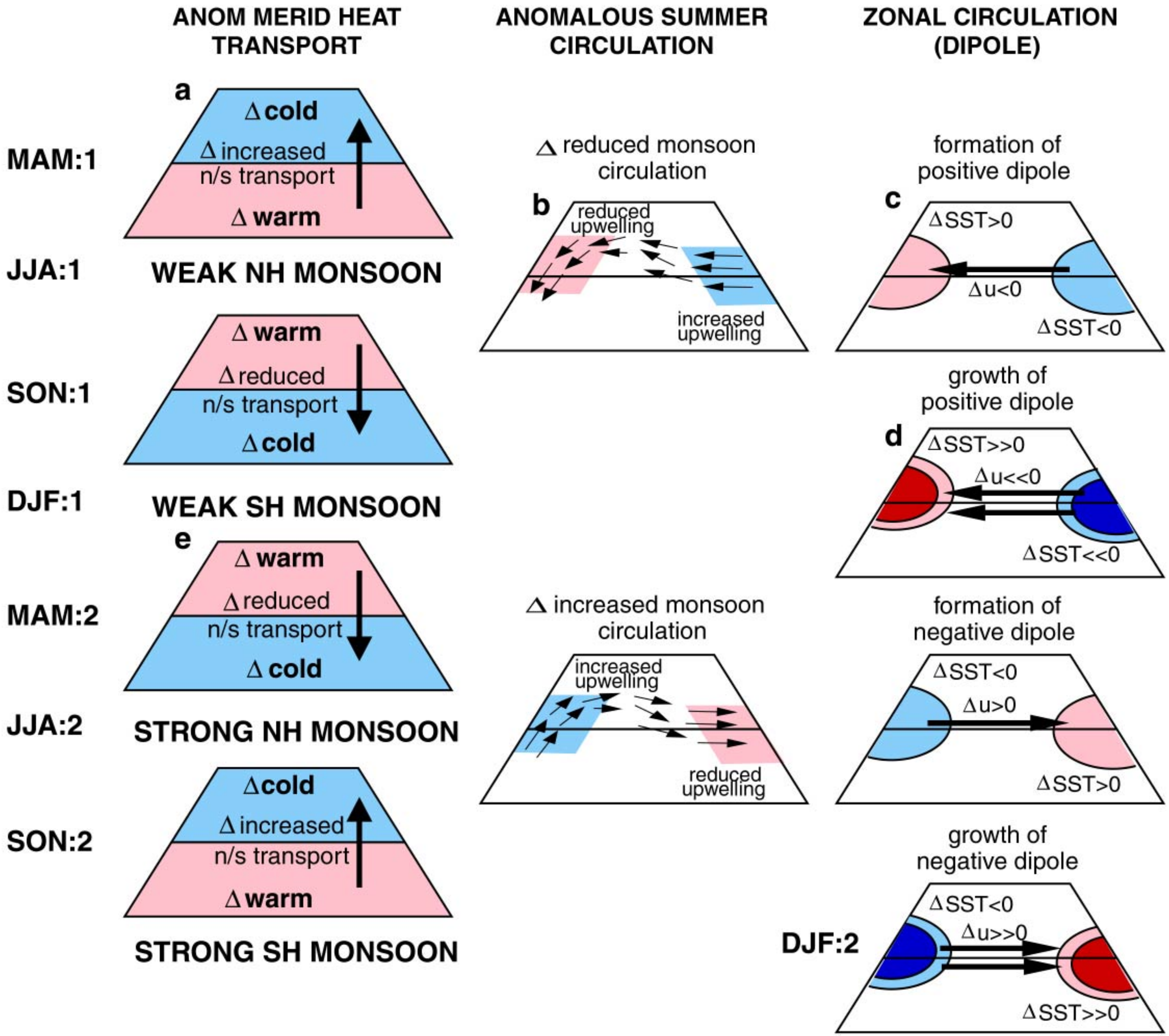
- A critical clue to the formation of the IOZM is its phase-locking with the annual cycle.
- The IOZM forms at a time of maximum anomalous upwelling associated with the anomalously strong or weak monsoon & when the zonal SST gradient is flattest. Anomalous monsoon winds produce enhanced or reduced upwelling regions.



- We can now relate the formation of the IOZM with the anomalous summer monsoon:



COMPOSITE MONSOON REGULATION SYSTEM



MONSOON AND OCEAN DYNAMICS

- The South Asian monsoon is a strongly coupled ocean atmosphere system
- The negative feedback between latent heat release and ocean heat transport regulates the monsoon into rather narrow bounds, limits interannual variability
- How this regulating system impacts the other monsoons (e.g., east Asia) requires investigation