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IAEA International Atomic Energy Agency

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Conference on Milankovitch cycles over the past 5 million years

22 - 24 March 2007

Tropical aspects of Milankovitch Cycles

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Tropical aspects of Milankovitch cycles.

(theory)

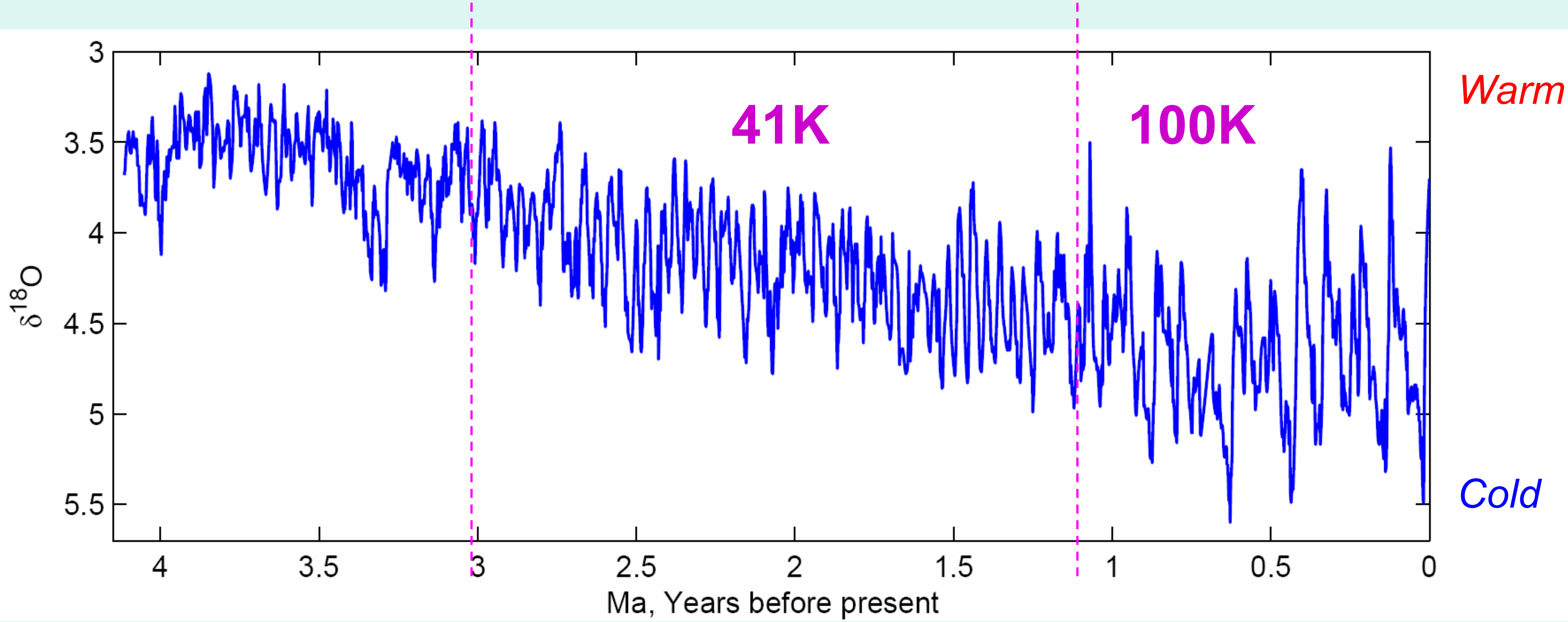
Alexey Fedorov (Yale University)

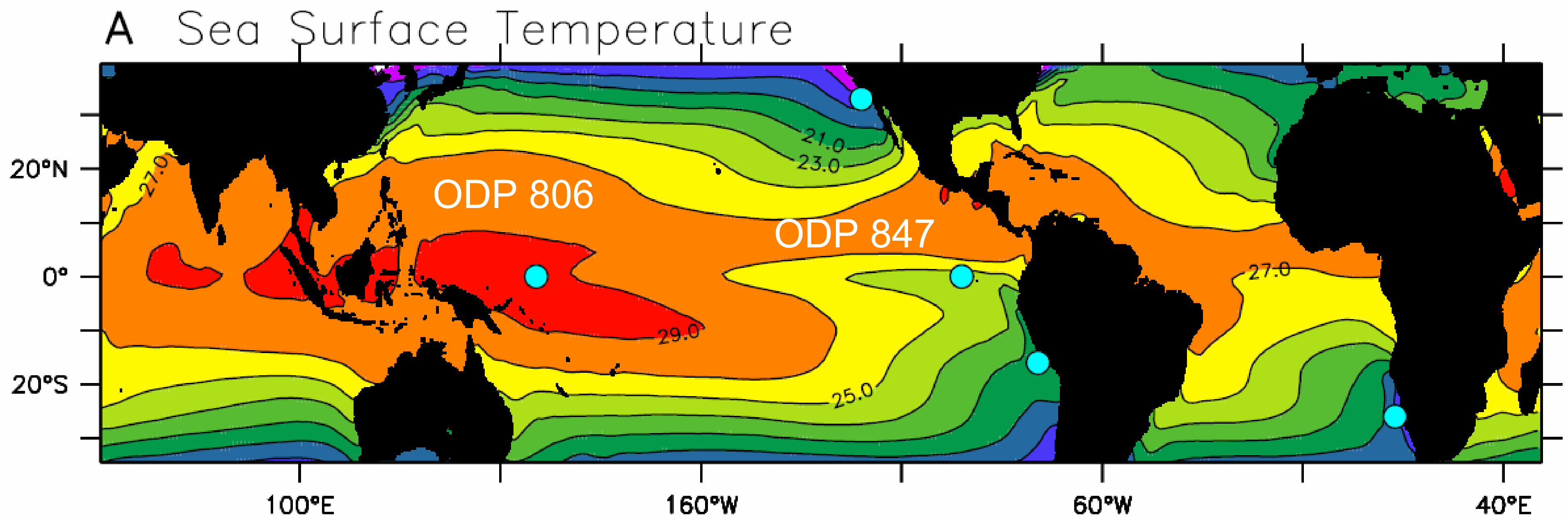
Thanks to: Marcelo Barreiro, Giulio Boccaletti, Ron Pacanowski

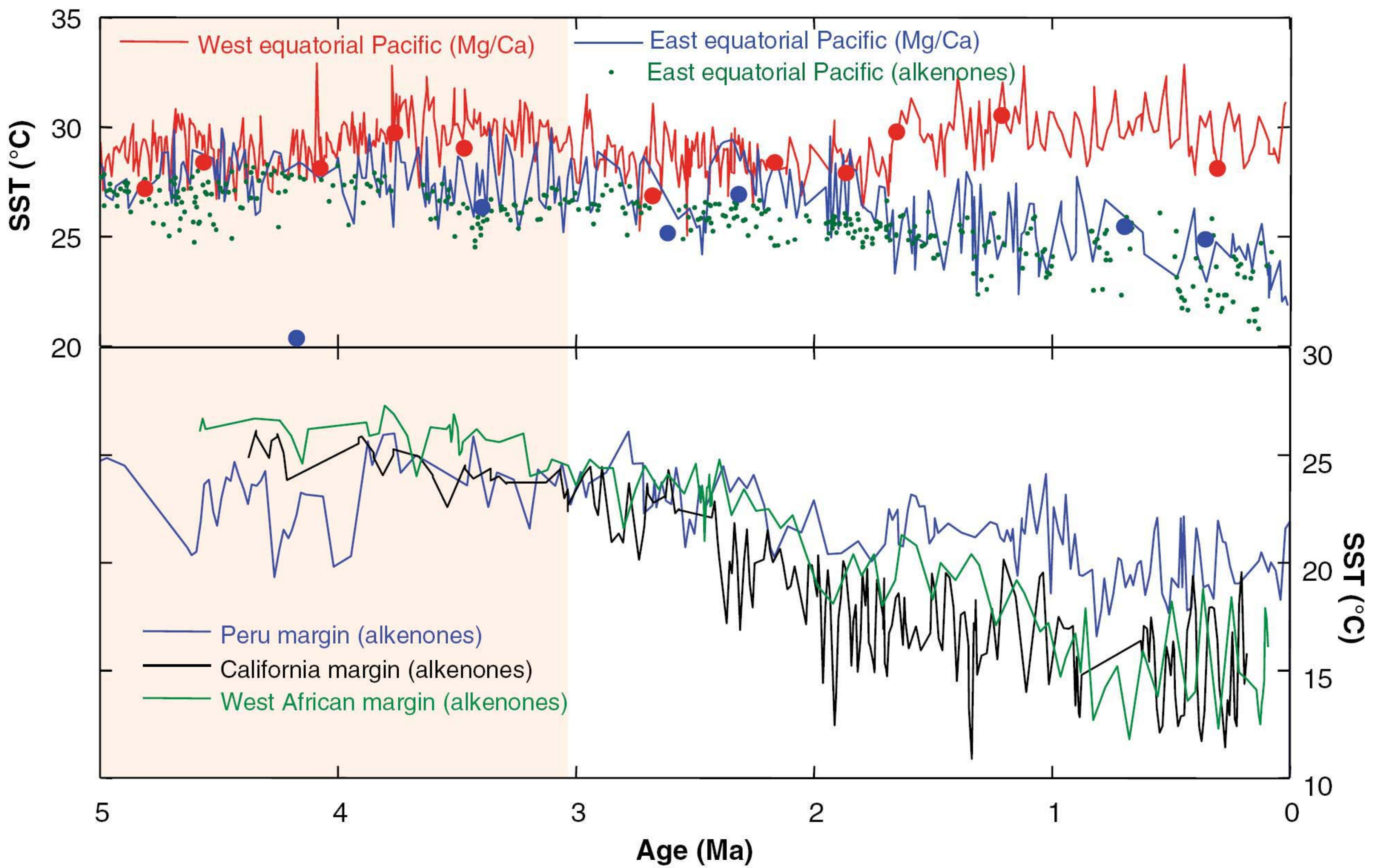
George Philander, Christina Ravelo, Peter deMenocal

March 2007

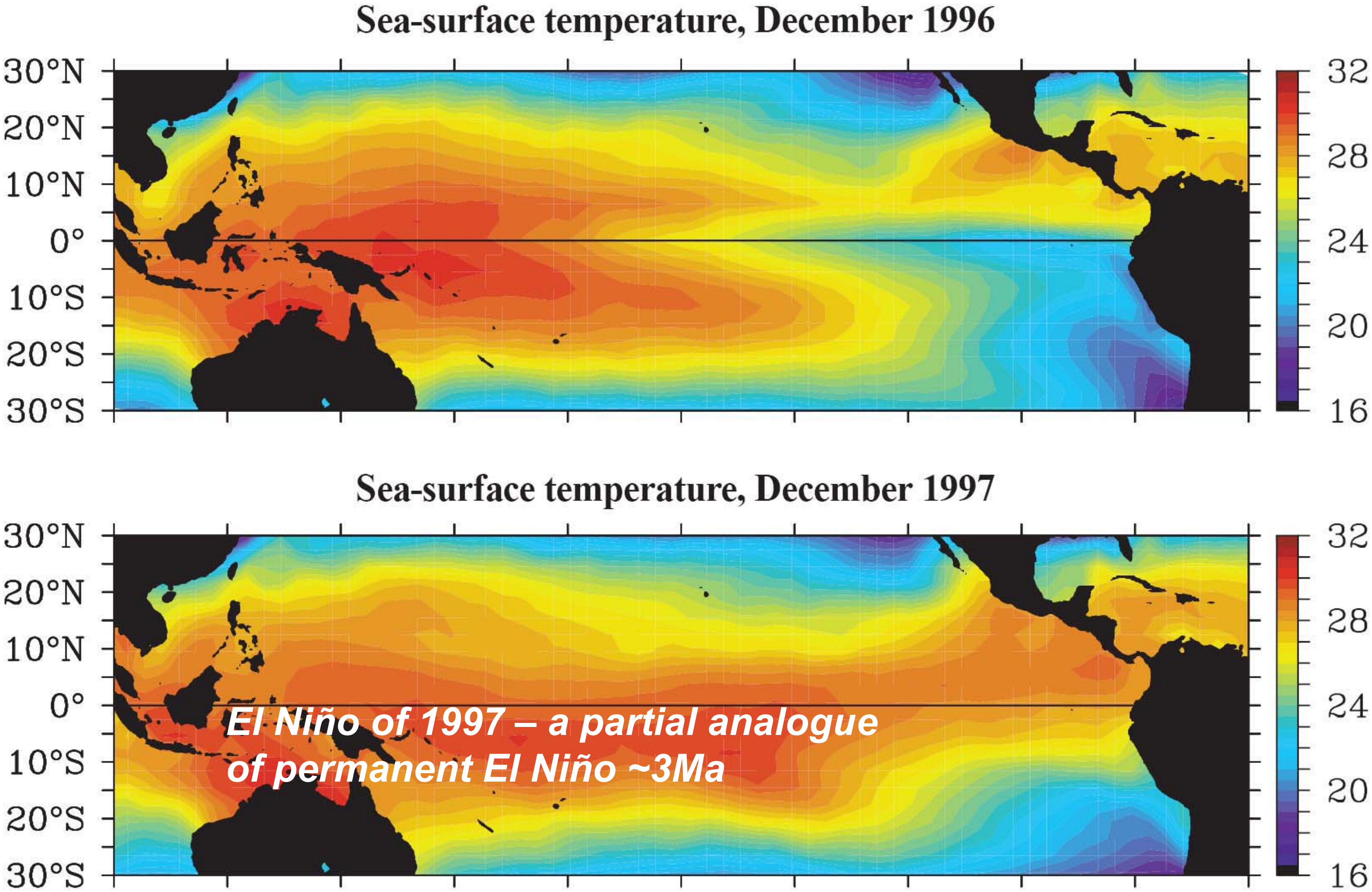
High latitudes: Glacial cycles as reflected in benthic $\delta^{18}O$




A Sea Surface Temperature
ODP 806
ODP 847
27.0
21.0
23.0
29.0
25.0
27.0
20°N
0°
20°S
100°E
160°W
60°W
40°E



Fedorov, Dekens, McCarthy, Ravelo, Barreiro, deMenocal, Pacanowski, Philander, Science 2006



After McPhaden 1999

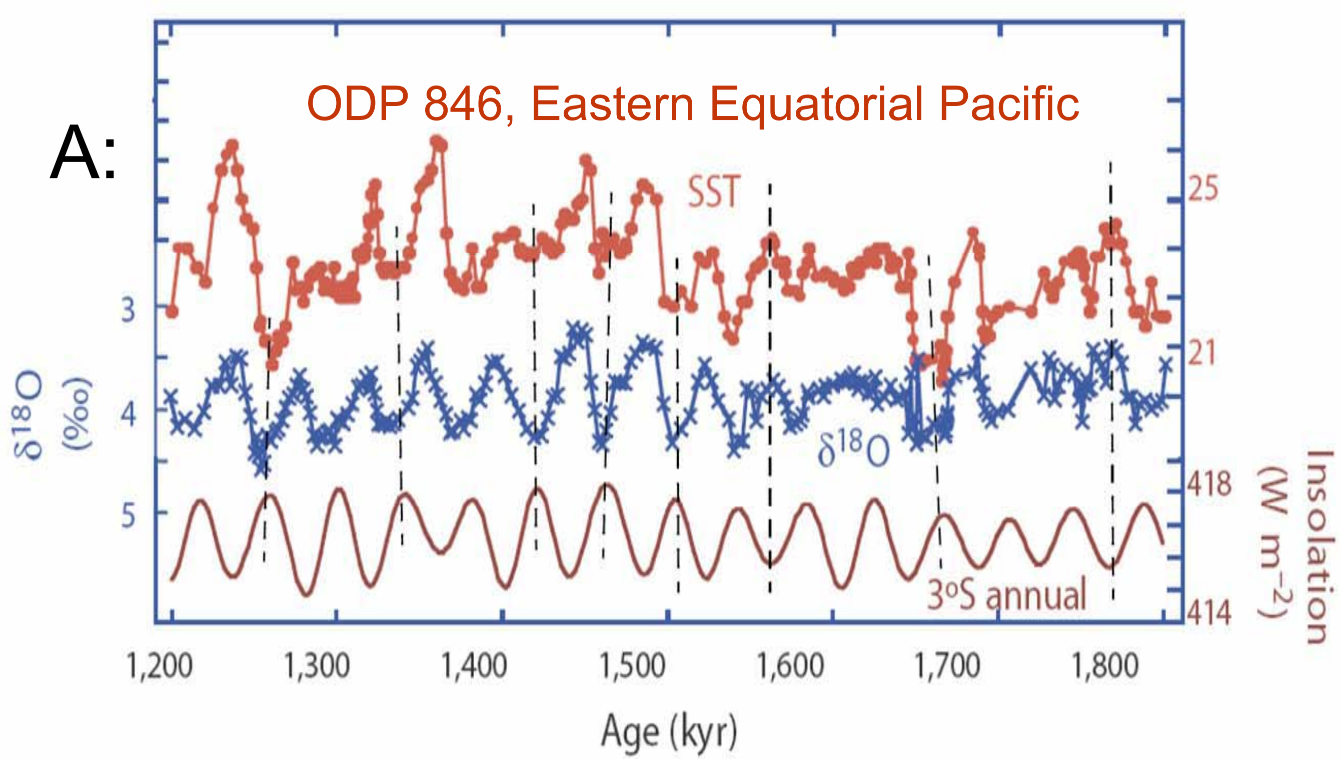
1. Meridional temperature gradients ΔT between the equator and the subtropics (0^o-30^oN/S):

The early Pliocene: ΔT~2^oC (proxy data)

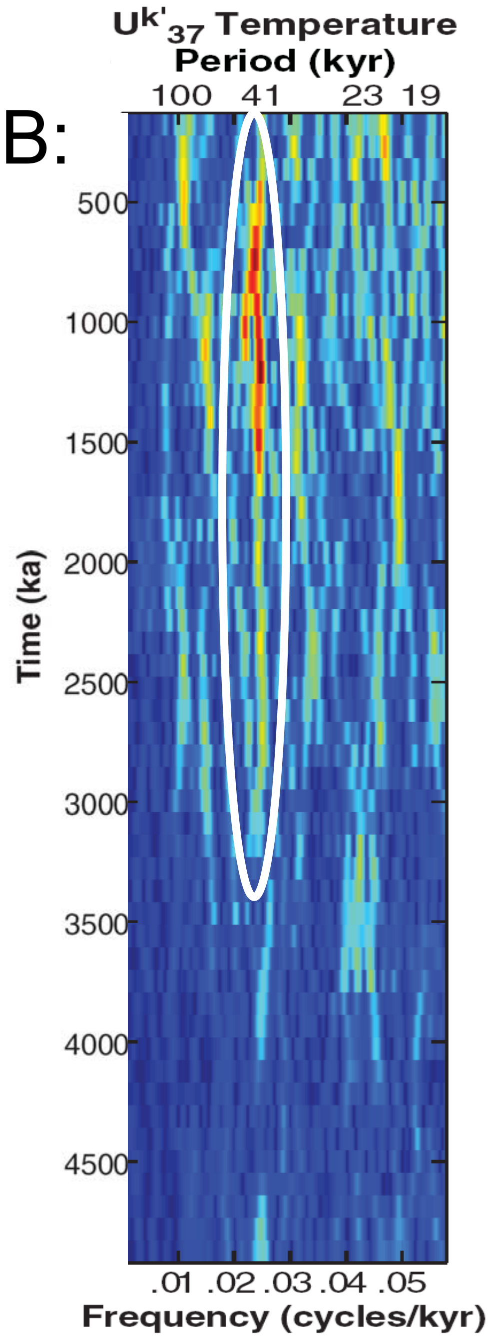
Present: ΔT~9^oC (observations)

2. The 41K obliquity signal is dominating in these upwelling regions

A:



B:



A: SST, $\delta^{18}O$, and local insolation in the eastern equatorial Pacific 1.2 - 1.8 Ma years ago and

B: Power spectrum of SSTs over the last 5Ma years (Liu and Herbert 2004, Lawrence et al 2006).

Tropics: Strong obliquity component (41K) is anti-phased with local insolation; in phase with high-latitude insolation.
More sunlight locally corresponds to colder temperatures

Questions:

- *How was permanent El Niño maintained? Why did it end ~3Ma ago? Did the termination of permanent El Niño conditions contribute to the onset of the Ice Ages?*

- *Obliquity signal (41K) dominates SST in the eastern equatorial Pacific (and in the tropical Atlantic 2-3Ma ago) and in the coastal upwelling regions. SST variations are in phase with high-latitude insolation (more sunlight locally corresponds to colder temperatures). Are the tropics connected to high latitudes through ocean circulation?*

- *Could tropical processes contribute to the shift from 41K to 100K world around 1Ma?*

Mechanisms for a permanent El Niño:

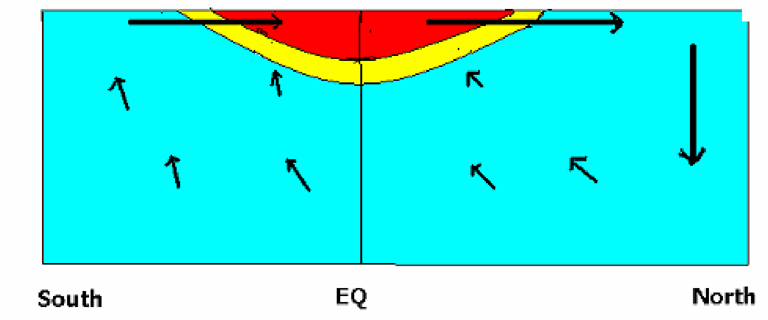
From the point of the view of the ocean, such radical changes in the equatorial and coastal upwelling regions can be explained by a significantly deeper ocean thermocline before ~3Ma than at present.

What do we know about ocean processes, ocean thermal structure and circulation that could explain a deepening of the tropical thermocline during the early Pliocene?

The Oceanic Circulation has two components:

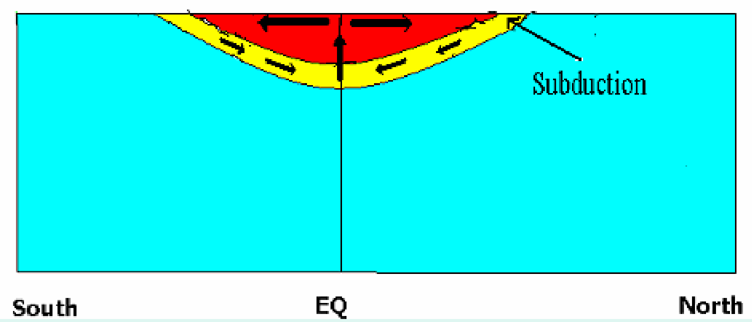
A. The <u>deep</u>, slow, thermohaline circulation THC:

involves the sinking of cold saline water in high latitudes, and "broad" upwelling.



B. The <u>shallow</u>, fast wind-driven circulation of the Ventilated Thermocline:

involves equatorial upwelling, poleward Ekman flow, western boundary currents, and subtropical subduction.



Both types of circulation transport heat poleward, contribute to the balanced heat budget, and can affect climate. In a given ocean model, changing ocean mixing changes the relative importance of the two

Both components of the circulation, and hence their meridonal heat transport, depend on meridional density gradient $\Delta\rho$ and therefore on temperature ΔT, and salinity ΔS gradients:

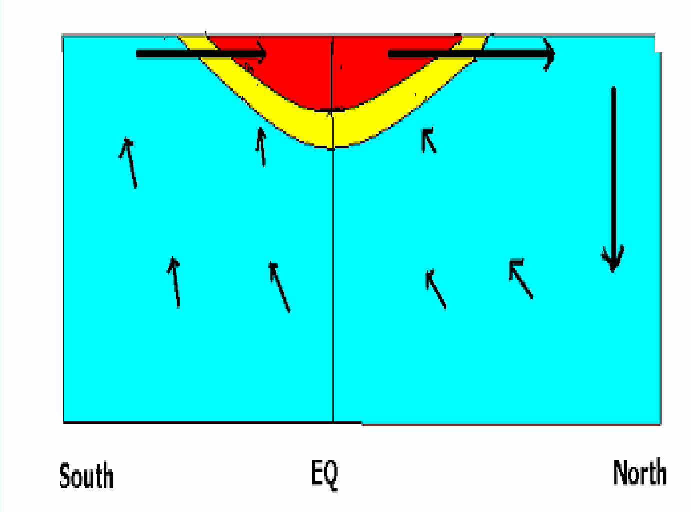
$$\boxed{\Delta\rho = \alpha\Delta T - \beta\Delta S}$$

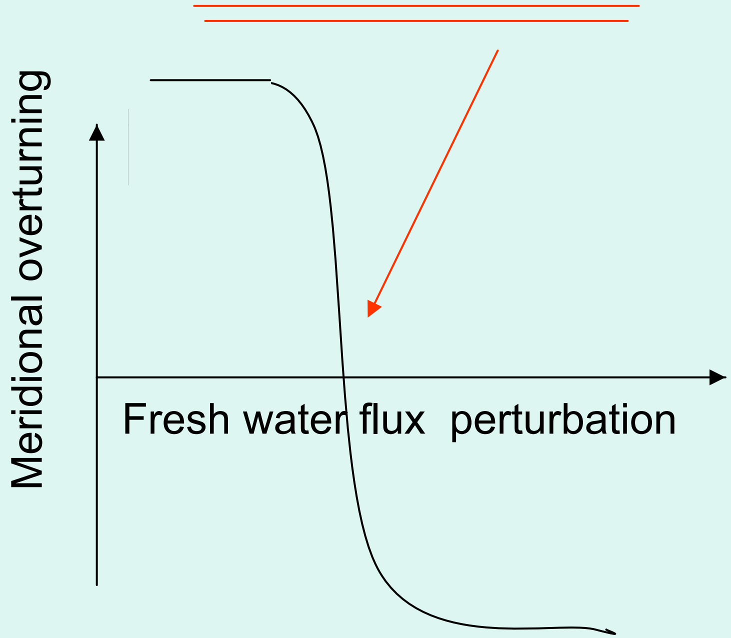
In high latitudes, a freshening of surface water can negate the low temperatures, and can potentially cause surface densities to be the same in low and high latitudes.

This introduces a SINGULARITY when $\Delta\rho \to 0$

$\Delta\rho \sim 0$ is a singularity !

Thermohaline Circulation:

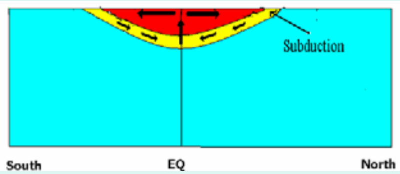


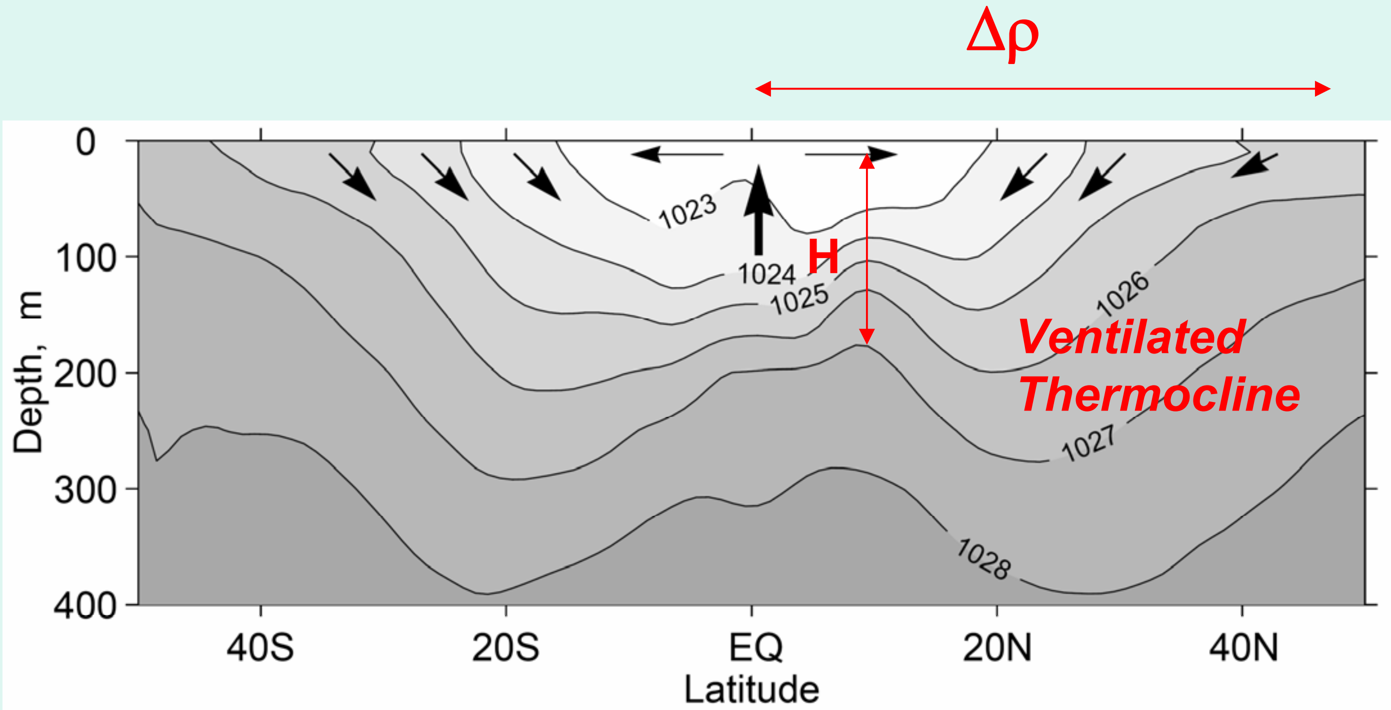


For the Thermohaline Circulation, when $\Delta\rho \sim 0$, the overturning collapses (Vol.Transport $\sim\Delta\rho^{1/3}$; $H\sim\Delta\rho^{-1/3}$) "The Shut-down" of the thermohaline circulation.

Thermocline "ventilation" in the Pacific. After subduction water parcels travel along the density surfaces towards the equator

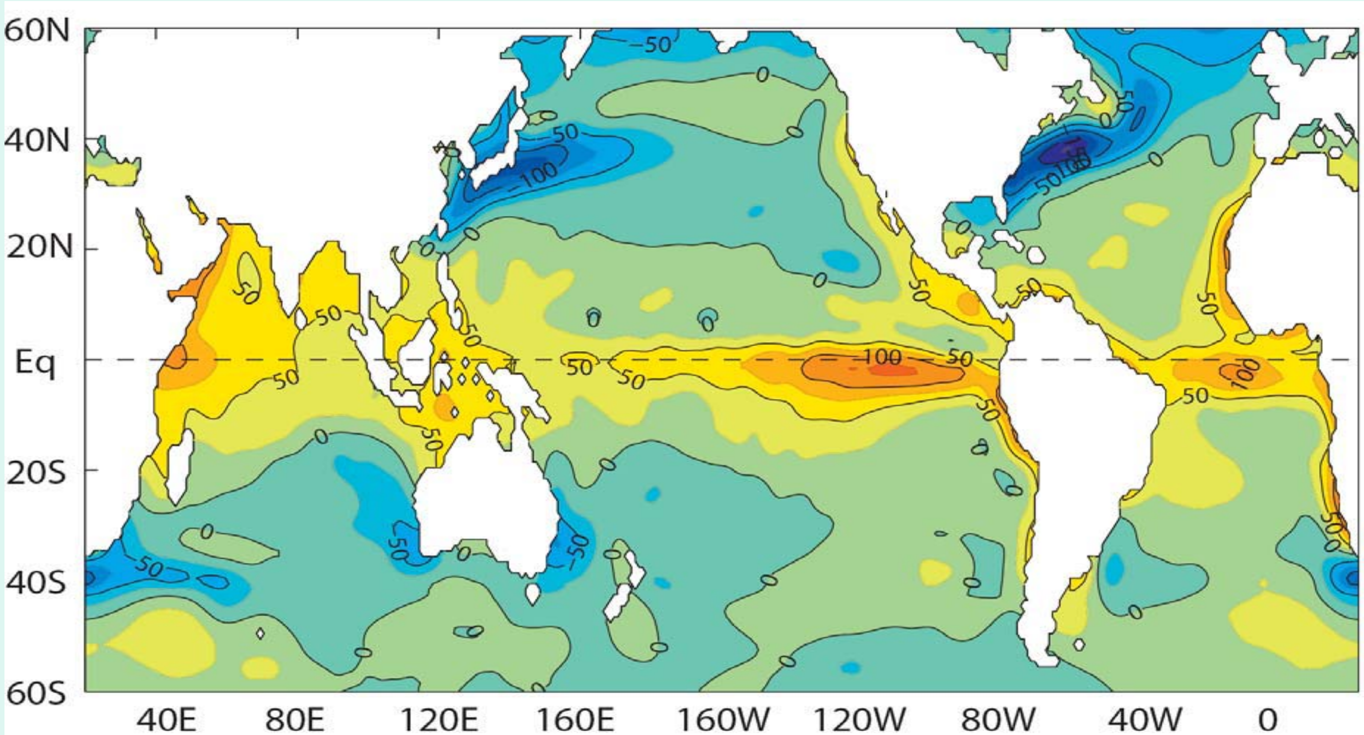
Wind-driven Circulation:





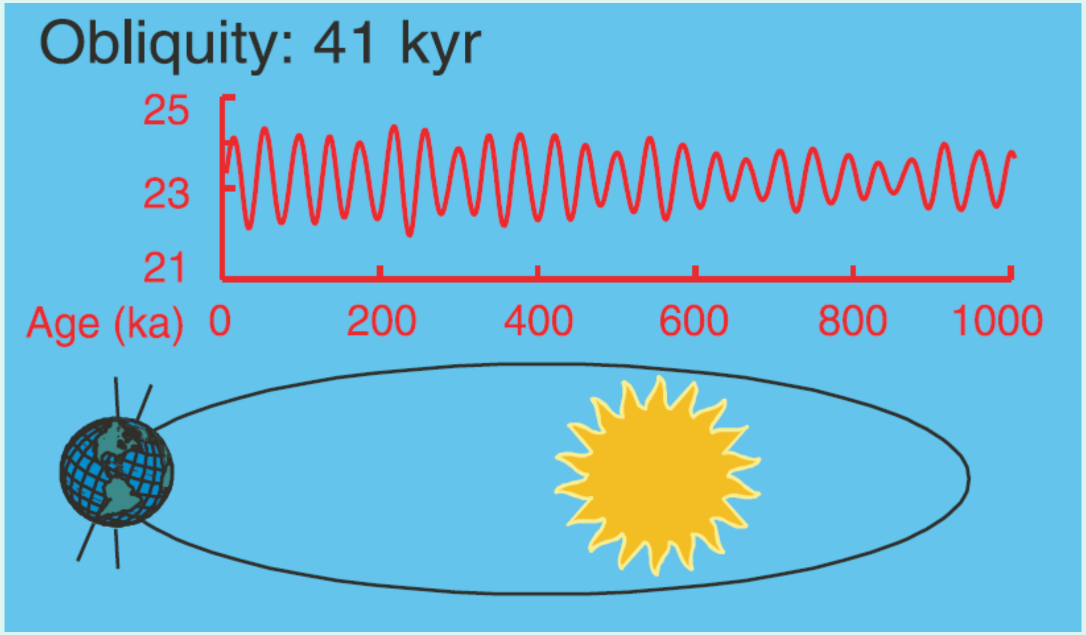
For the Wind-Driven Circulation, when $\Delta\rho \sim 0$, the depth of the ventilated themocline H becomes very large: $H \sim (1/\Delta\rho)^{1/2}$

Downward heat fluxes into the ocean



1. ***Both THC and the wind-driven circulation contribute to the heat transport.***
2. ***The ocean gains heat mainly in the wind-driven upwelling regions. Apparently, during permanent El Niño this was not the case.***
3. ***In a steady state the heat loss and heat gain should be balanced***
4. ***Deepening the thermocline in the eastern equatorial Pacific decreases the ocean uptake of heat.***

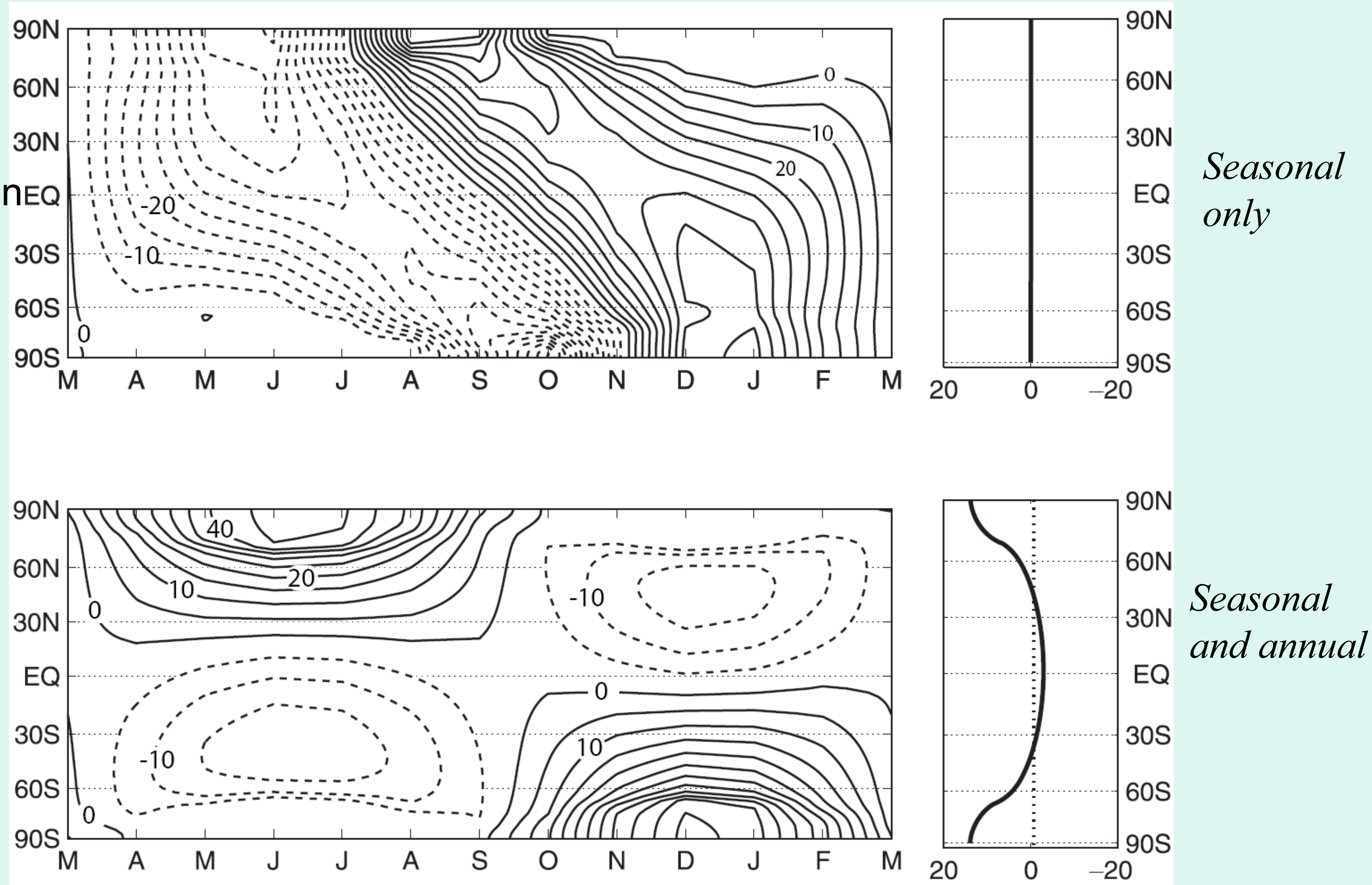
How is this related to variations in obliquity forcing?



Seasonal and Annual Orbital Insolation Forcing (W/m^2)

Precession Forcing

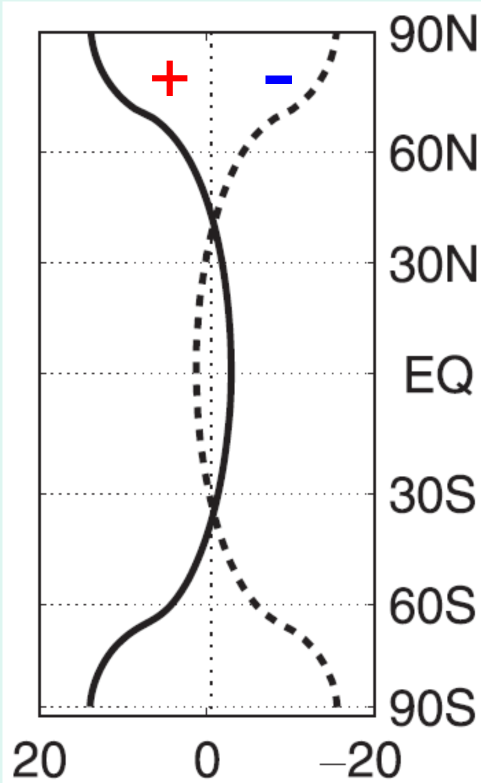
Obliquity Forcing



Changes in the incident sunlight . Top: when perihelion shifts from its current date (in January) to six months later. Bottom: when obliquity changes from 22 to 24 degrees. Left-side: The time integral over one year.

High obliquity induces anomalous heating of high latitudes (+)
Low obliquity induces anomalous cooling of high latitudes (-)

The half-period of these changes is ~20,500 years



Ocean response in the tropics to a periodic forcing in high latitudes increases with increasing period. The ocean works as a low-pass filter.

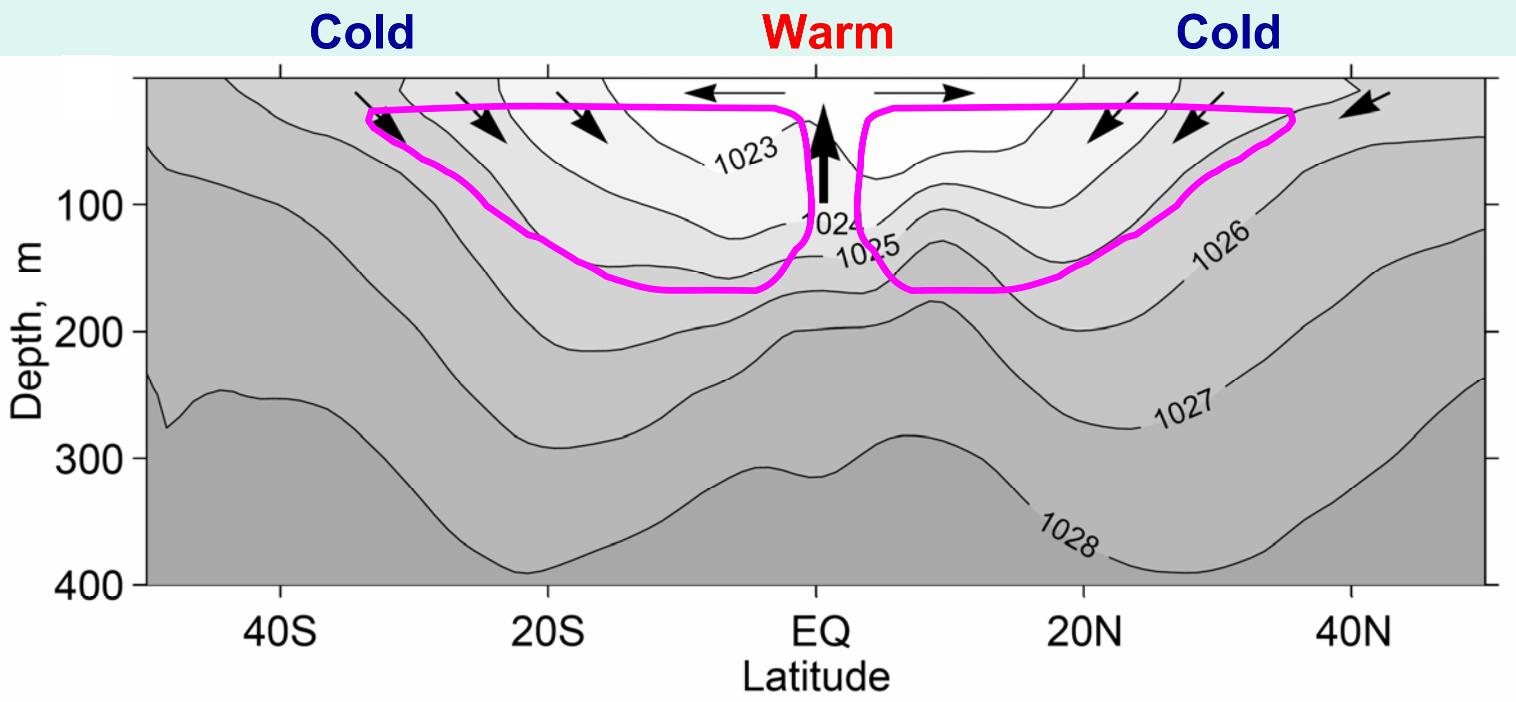
Calculations with idealized GCMs for the Pacific. (trying to reproduce a permanent El Niño and the forced ocean response to insolation variations due to obliquity)

Imposing anomalous surface heating/cooling or freshwater forcing in high latitudes (changing $\Delta\rho$)

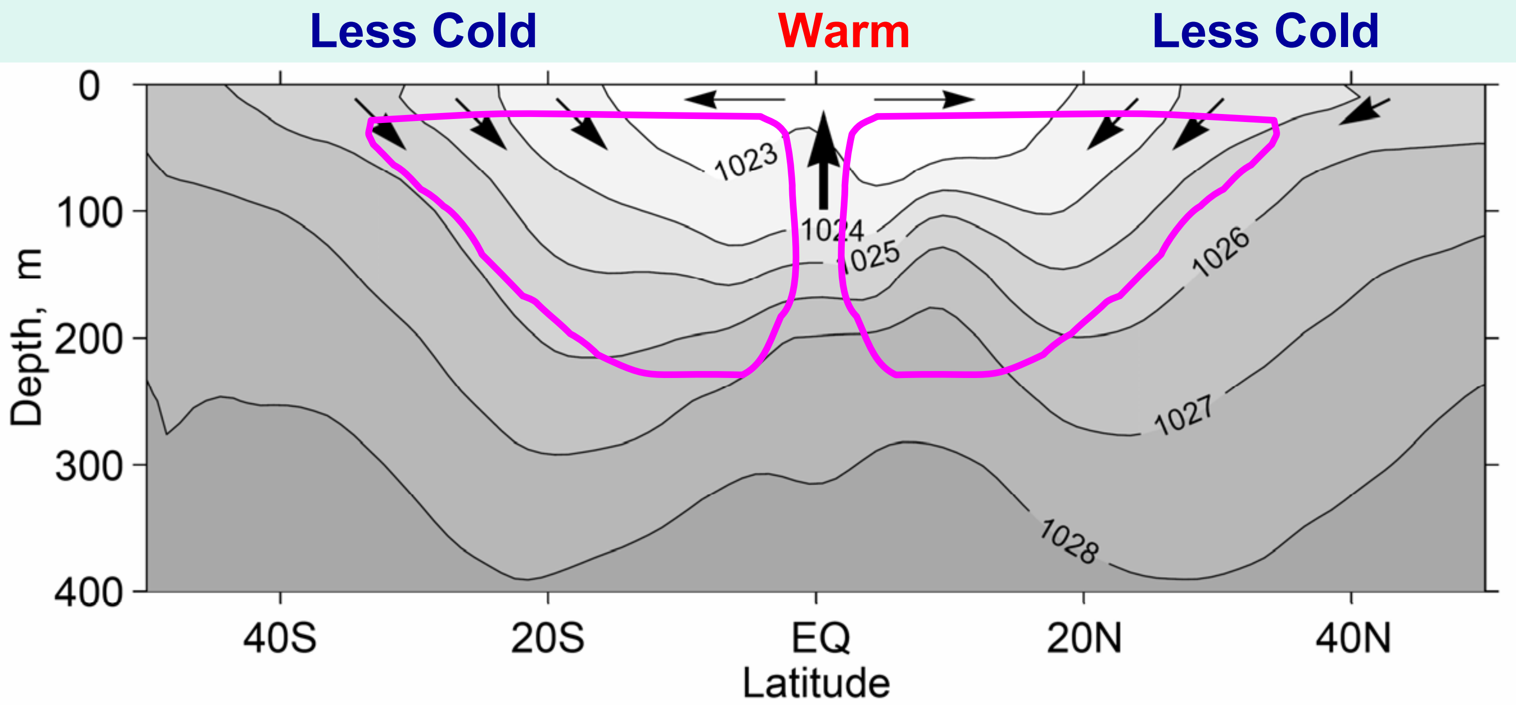
No active THC (Pacific)

Pacific-size basin, realistic winds, mixed surface boundary conditions, high resolution, small mixing

Mechanisms of thermocline deepening:

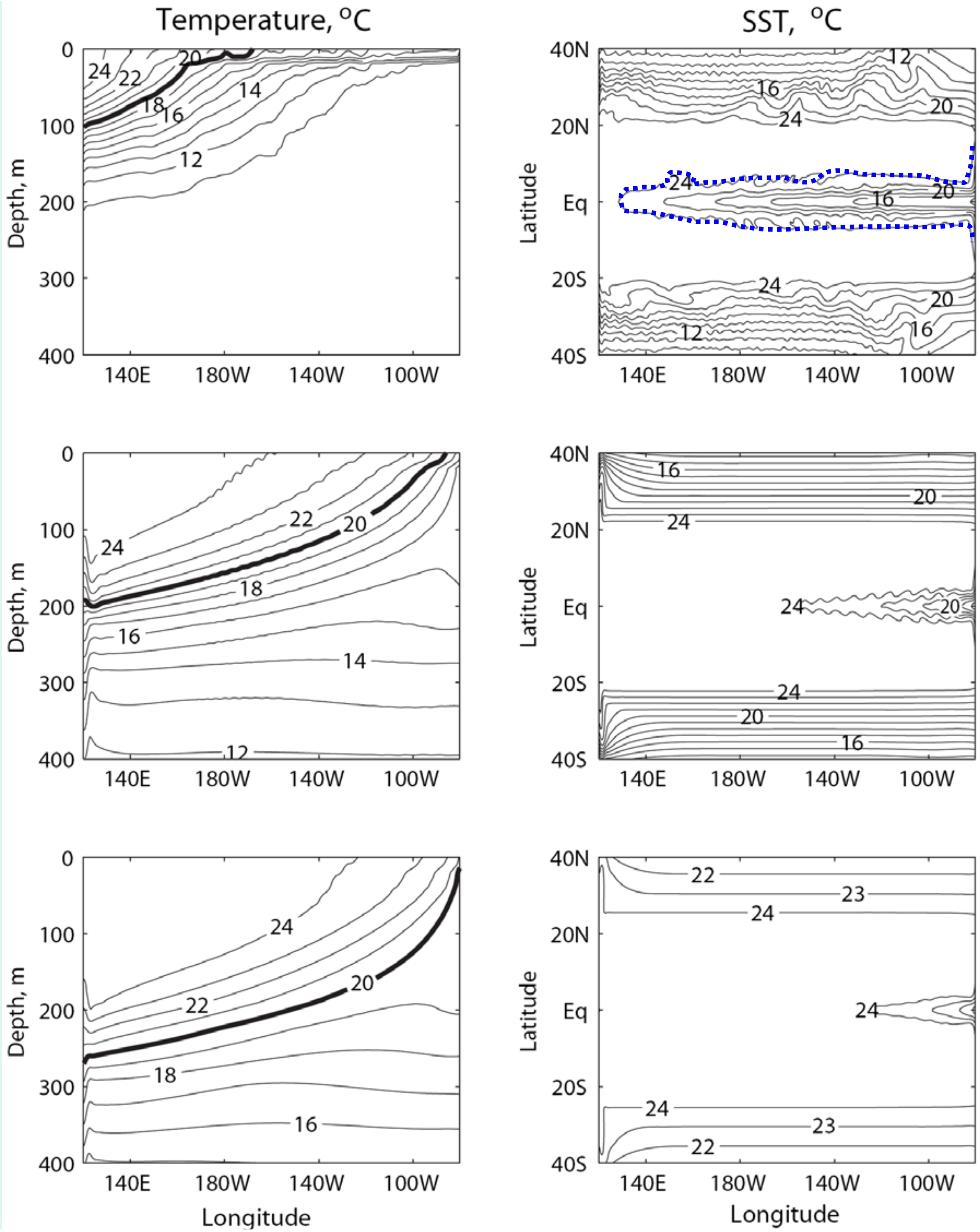


Imposing anomalous heating of high latitudes



Changes in the ocean thermal structure along the equator and in the tropical SST

when anomalous heating/cooling is applied in the high-latitude Pacific.



T*=5°C

Colder high latitudes

T*=10°C

Standard case

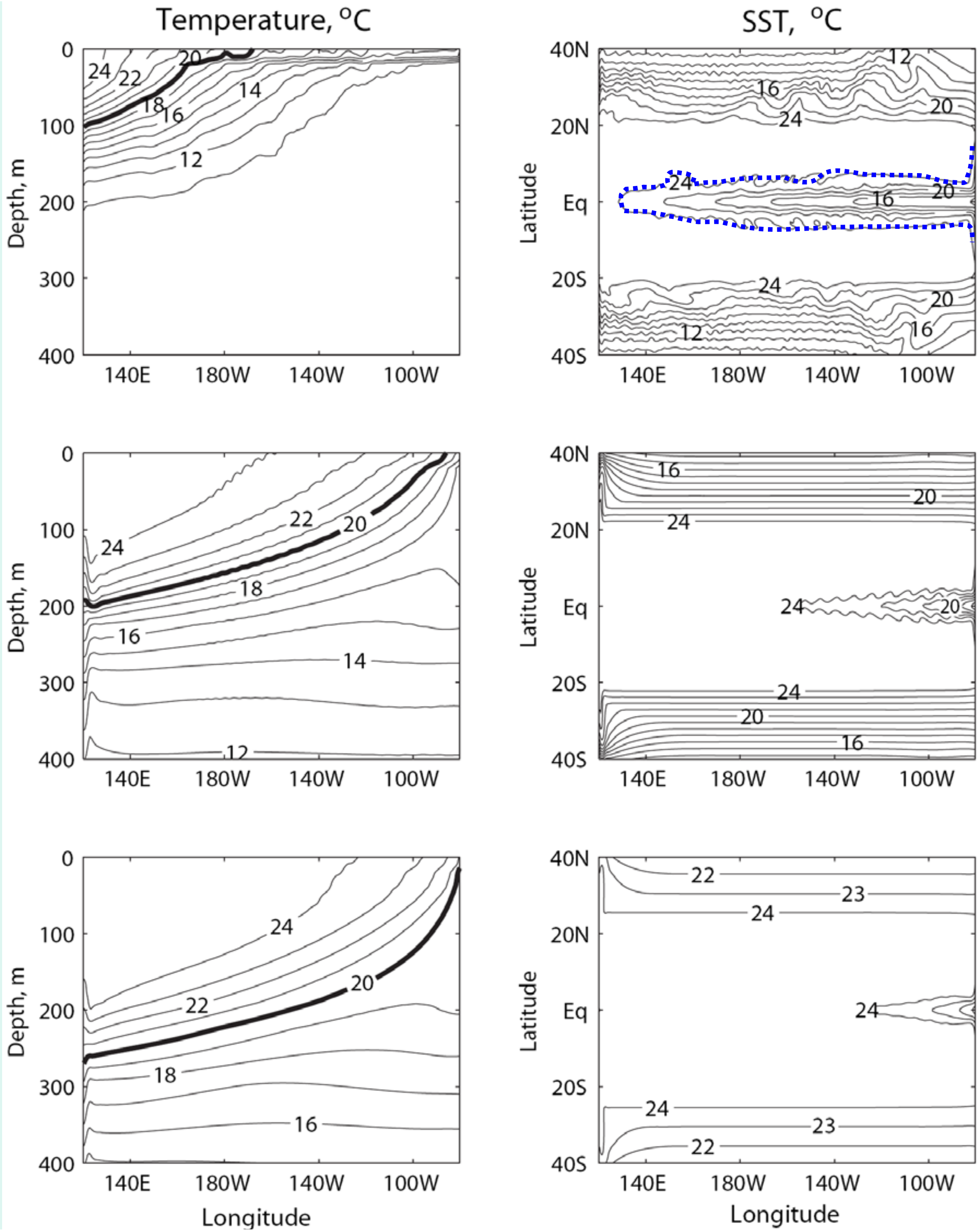
T*=15°C

Warmer high latitude

Temp in high latitudes

Changes in the ocean thermal structure along the equator and in the tropical SST

when anomalous heating/cooling is applied in the high-latitude Pacific.



T*=5°C

Low obliquity

T*=10°C

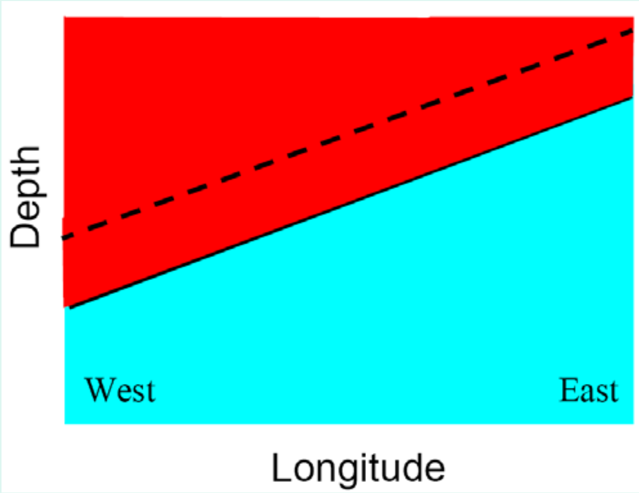
Standard case

T*=15°C

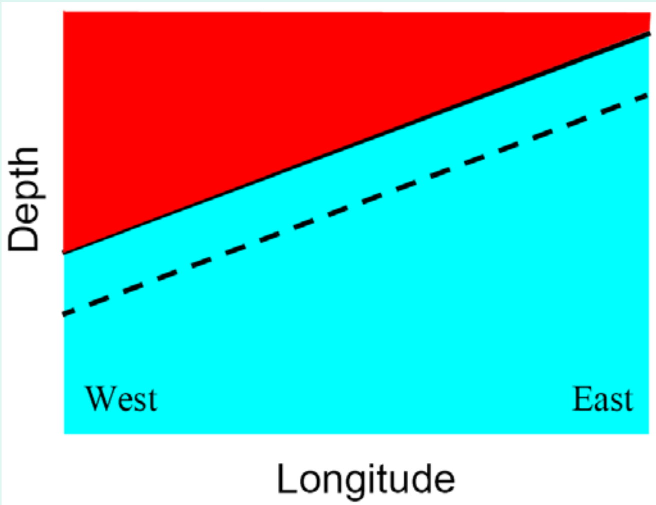
High obliquity

Temp in high latitudes

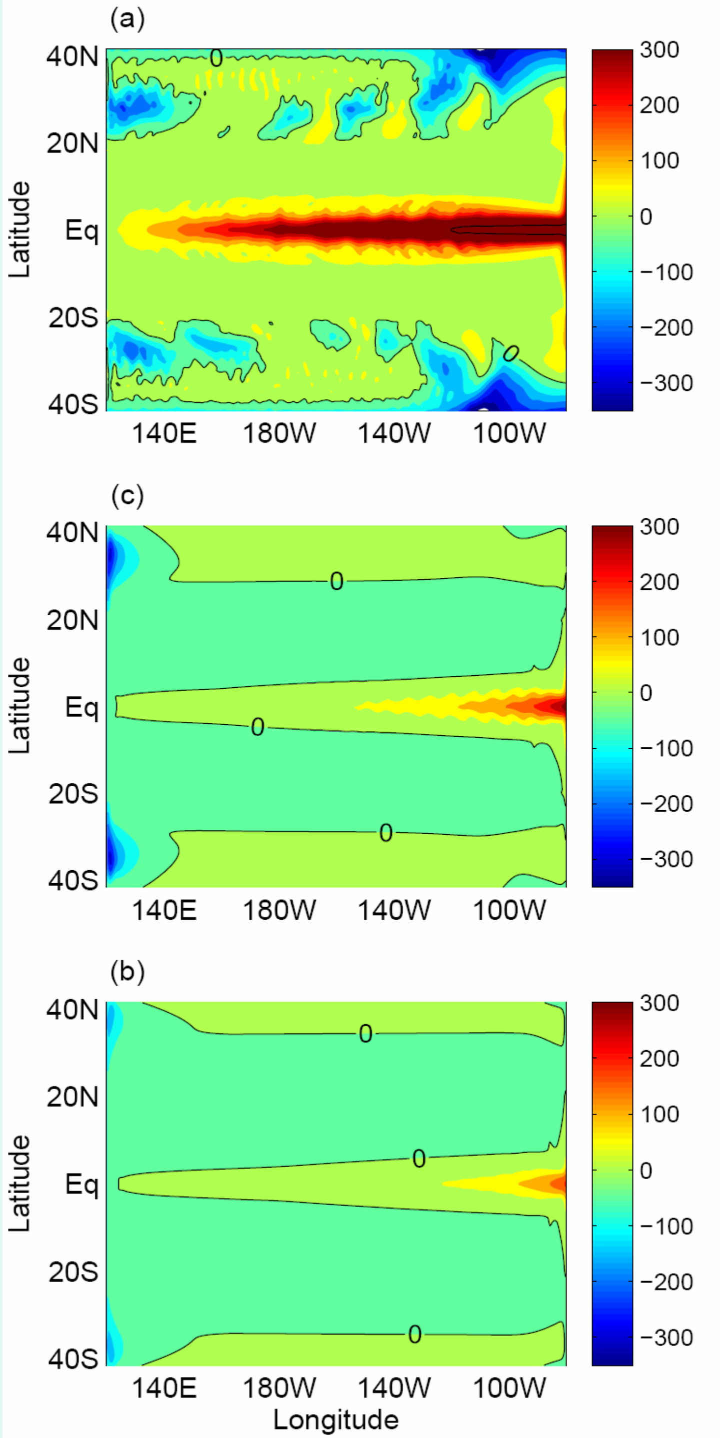
High obliquity -> anomalous heating of high latitudes-> reduced poleward heat transport + deeper thermocline + warmer water in the upwelling regions:

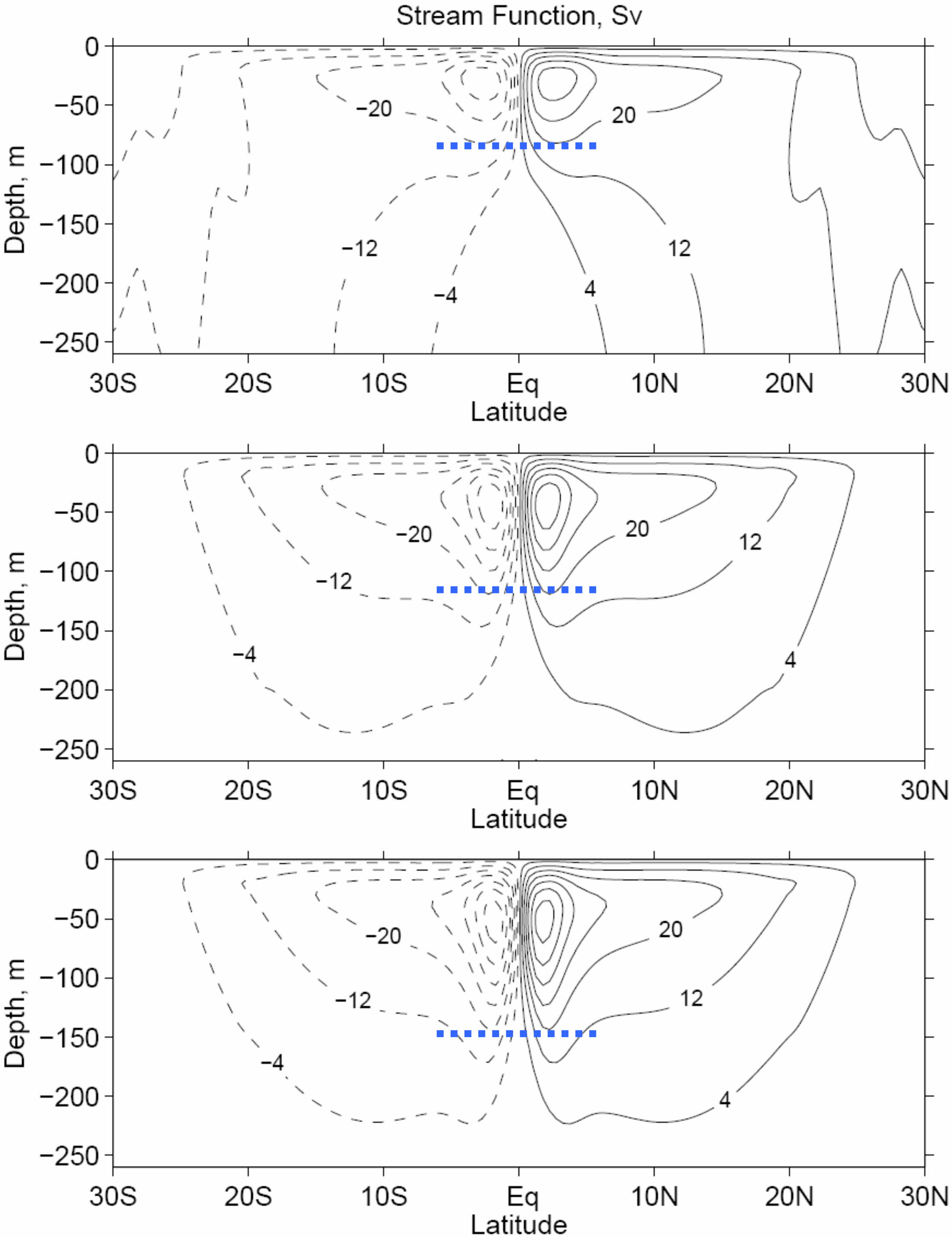


Low obliquity -> anomalous cooling of high latitudes -> increased poleward heat transport + shallow thermocline + colder water in the upwelling regions:



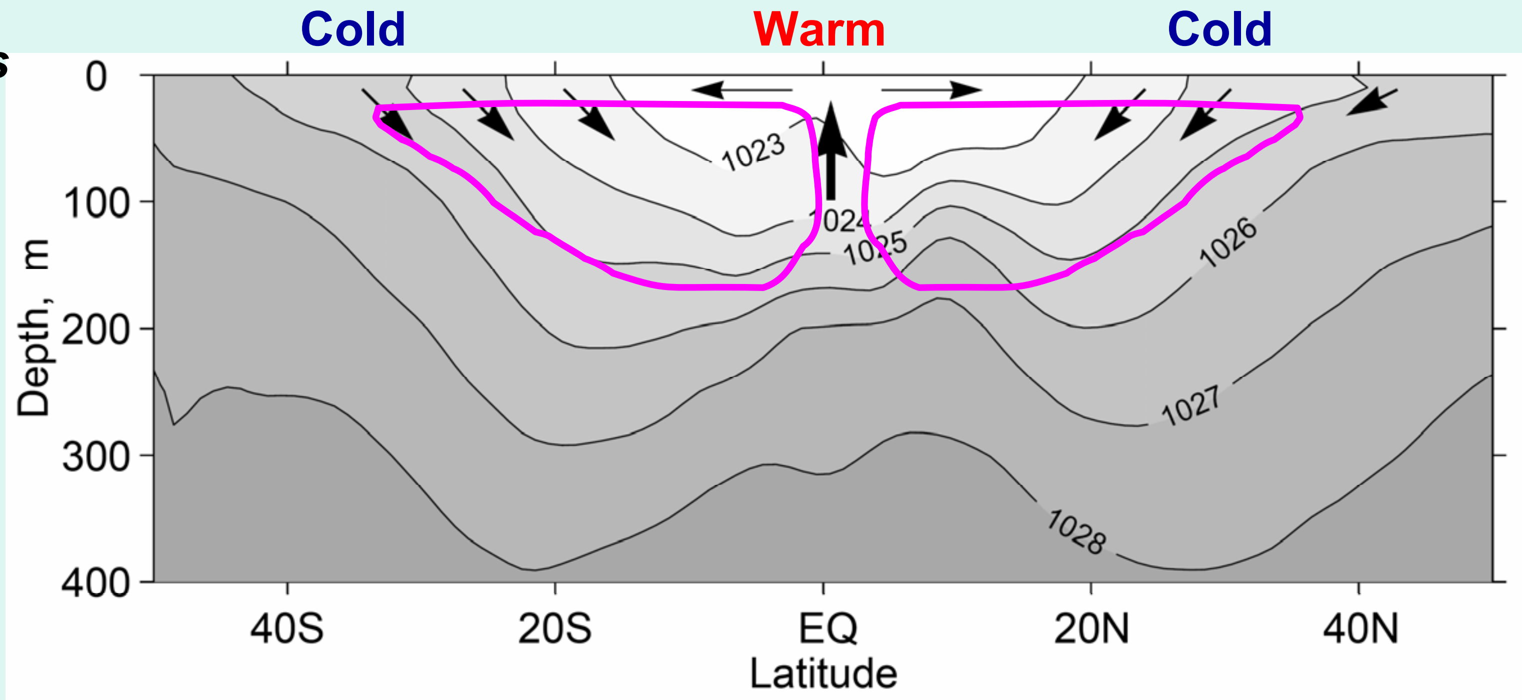
Net downward heat fluxes into the ocean



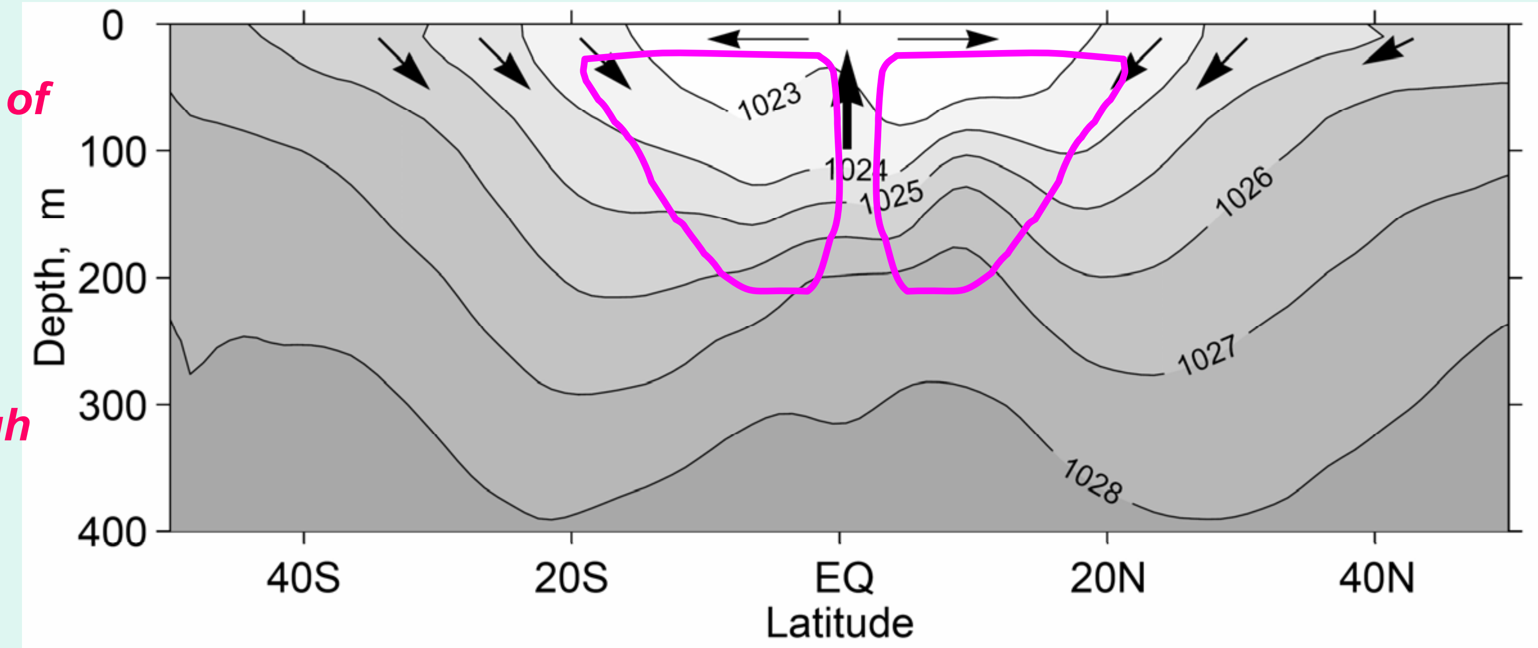


Stream Function, Sv
Depth, m
Latitude
0
−50
−100
−150
−200
−250
30S
20S
10S
Eq
10N
20N
30N
−20
20
−12
12
−4
4

Mechanisms of thermocline deepening:



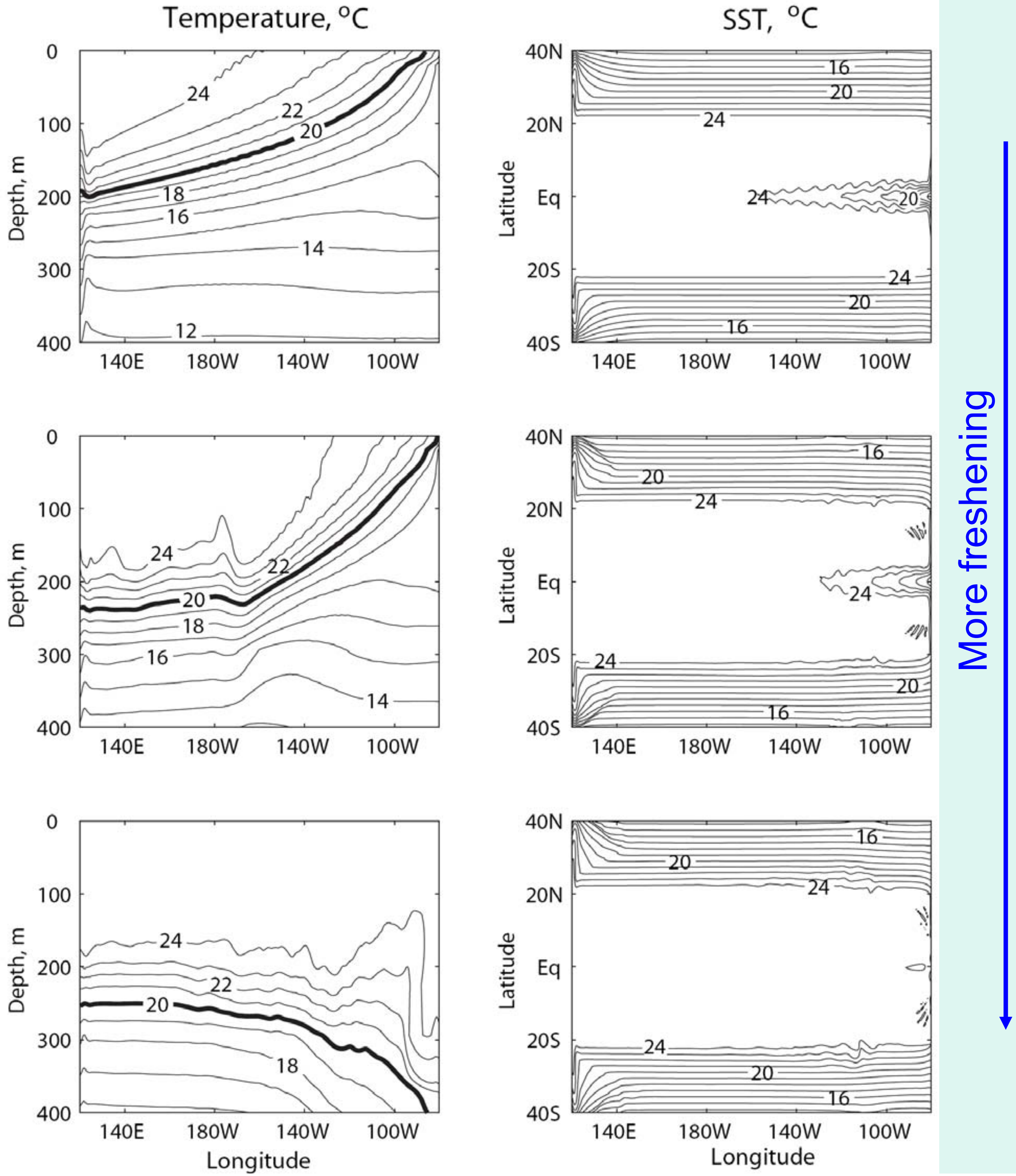
Contraction of the shallow subtropical cell, e.g. imposing freshwater fluxes in high latitudes



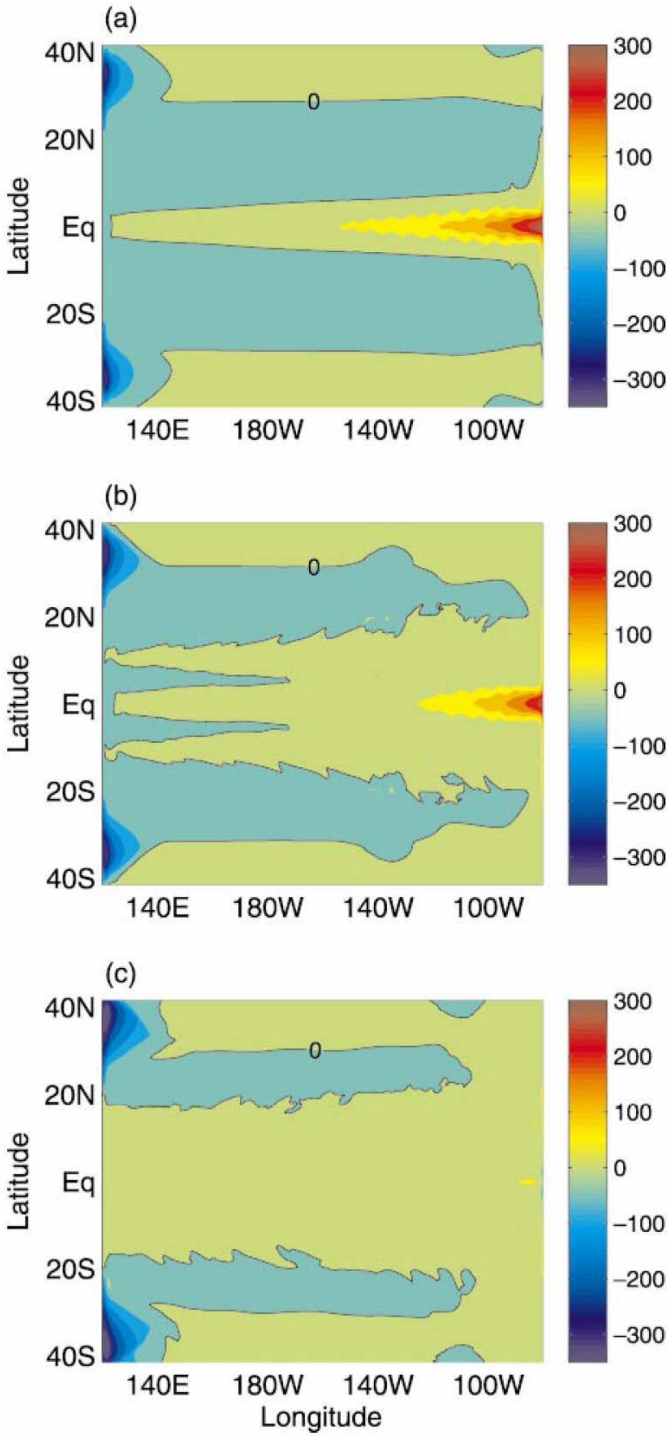
Changes in the ocean thermal structure along the equator and tropical SST

when surface freshening is applied in high latitudes (Pacific).

After Fedorov *et al* 2004



Changes in surface heat fluxes, W/m²



More freshening

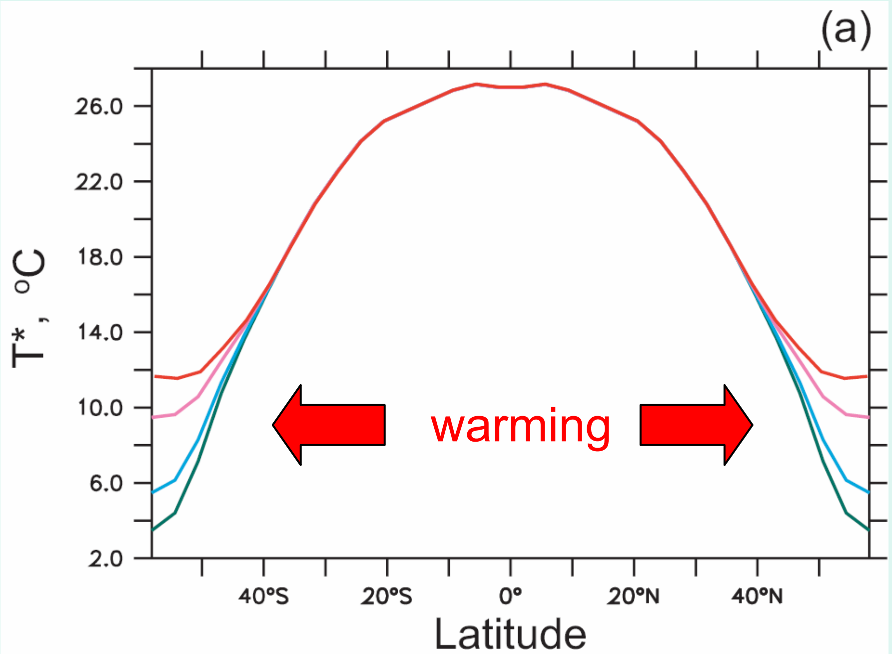
Calculations with idealized GCMs for the Atlantic:

Imposing anomalous surface heat fluxes or freshwater forcing in high latitudes (changing $\Delta\rho$) !

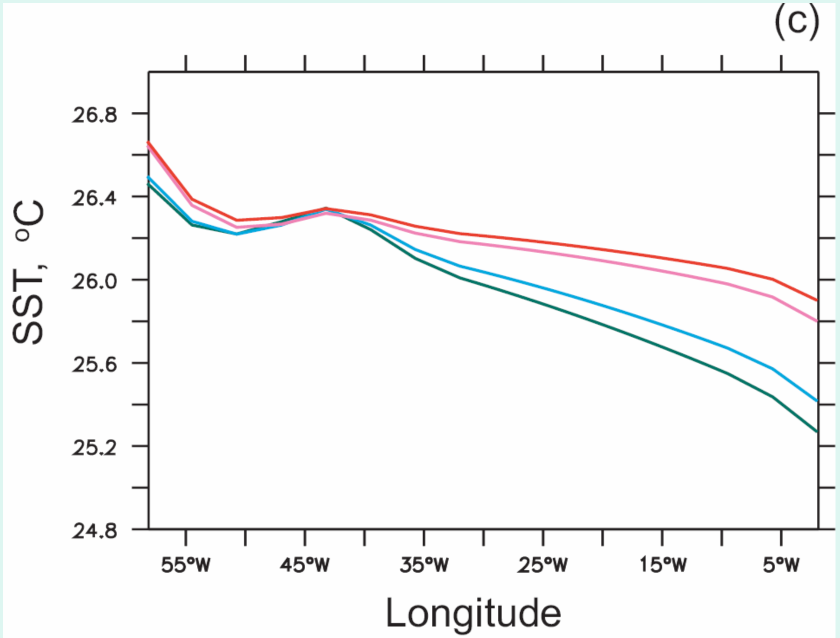
Both the thermohaline (THC) and wind-driven circulations are affected

Atlantic-size closed basin, realistic winds, mixed surface boundary conditions.

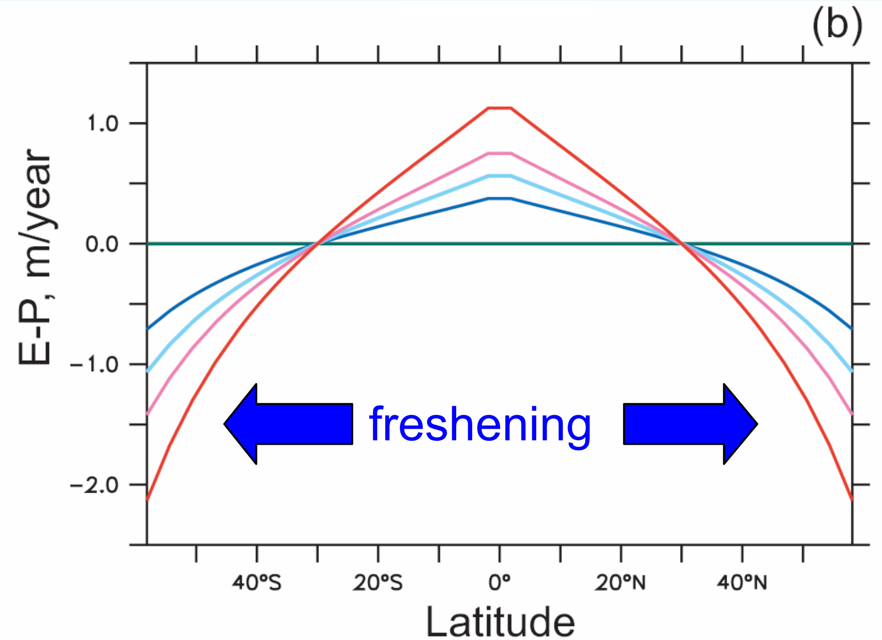
Forcing: (a) T*



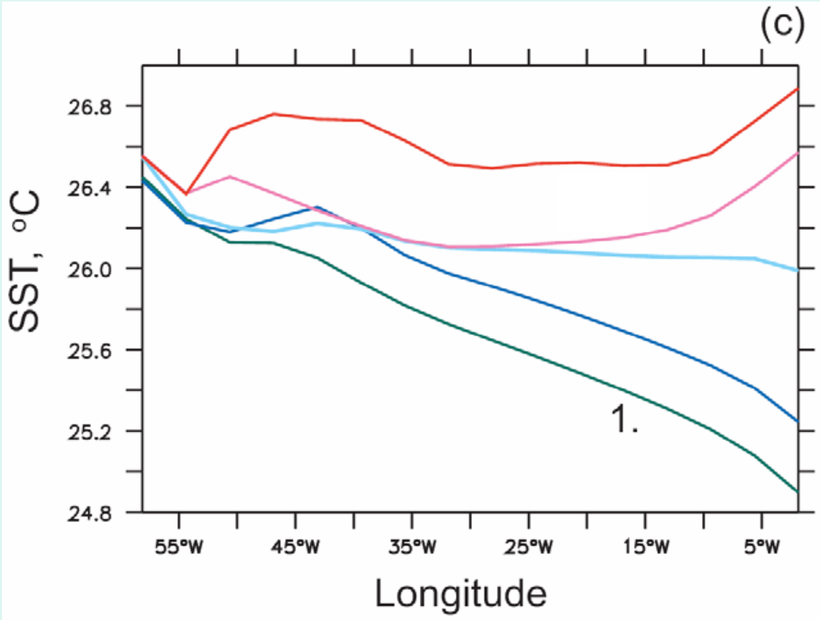
Results: (c) SST along the equator

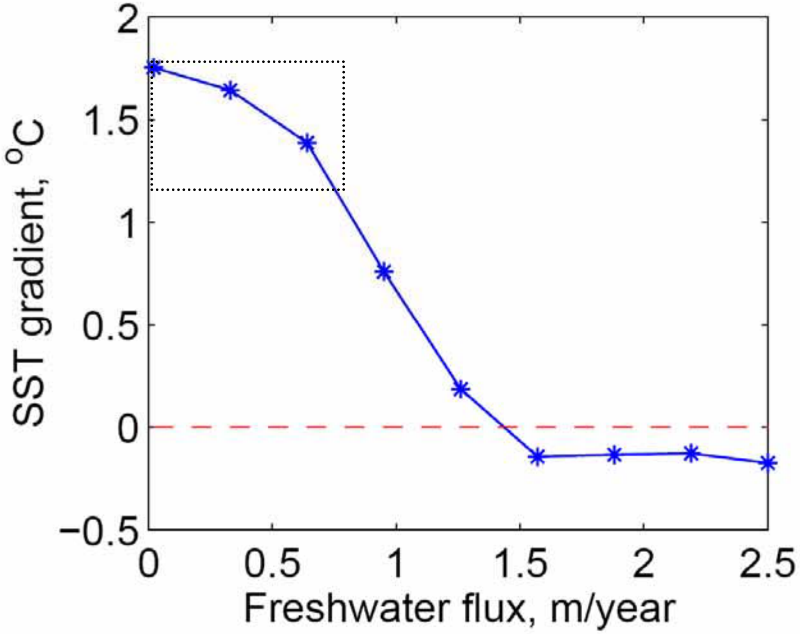


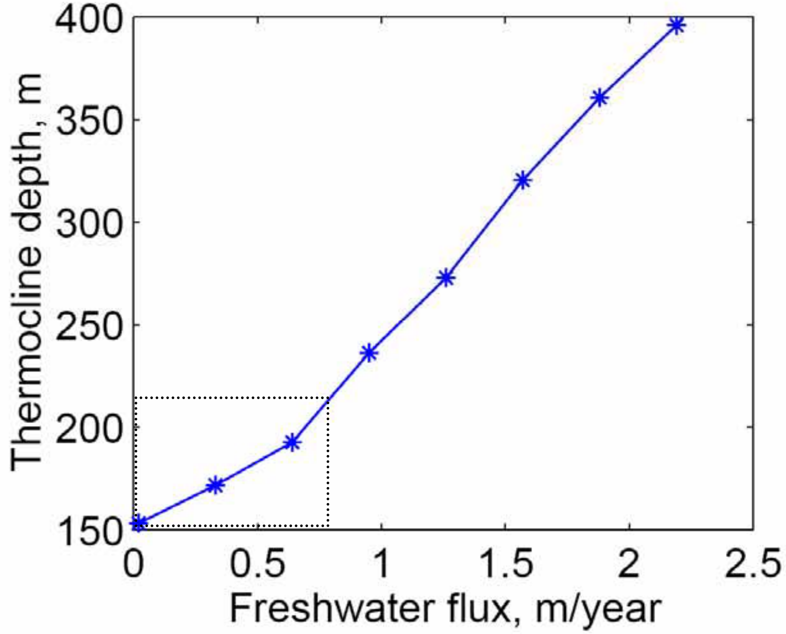
Forcing: (a) T*; (b) E-P (m/year)

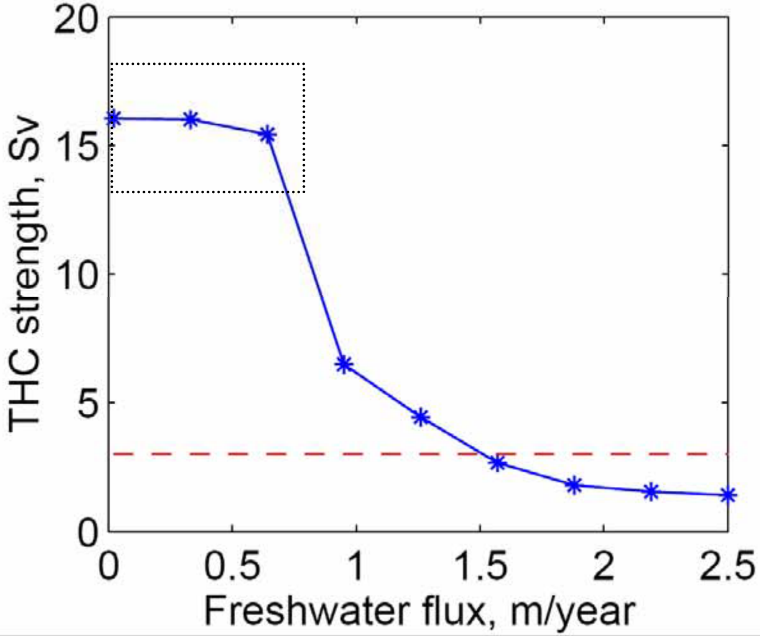


Results: SST along the equator









Forcing: freshwater fluxes in high latitudes

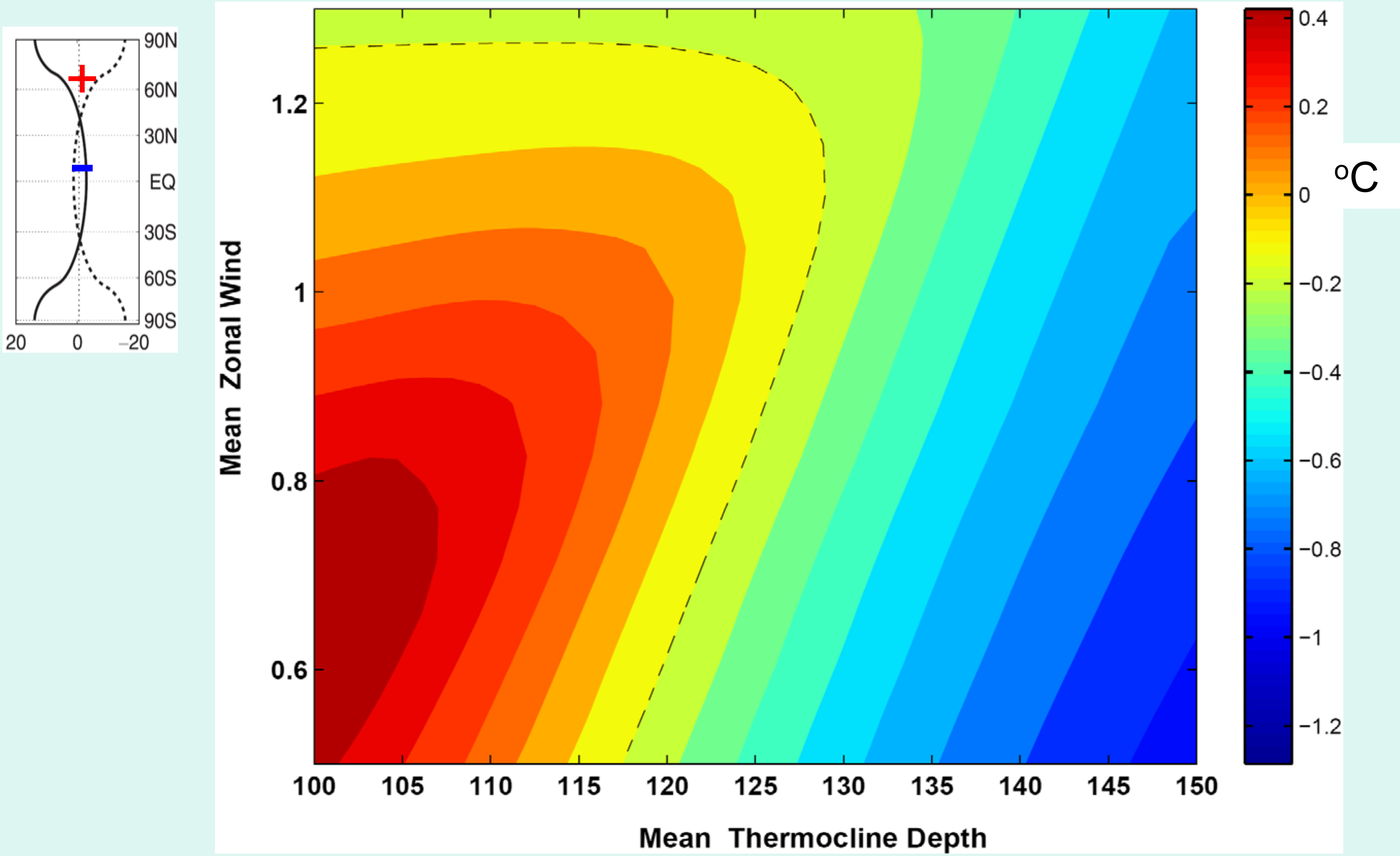
Relevant tropical ocean-atmosphere interactions and tropical feedbacks:

1) Dynamical thermostat

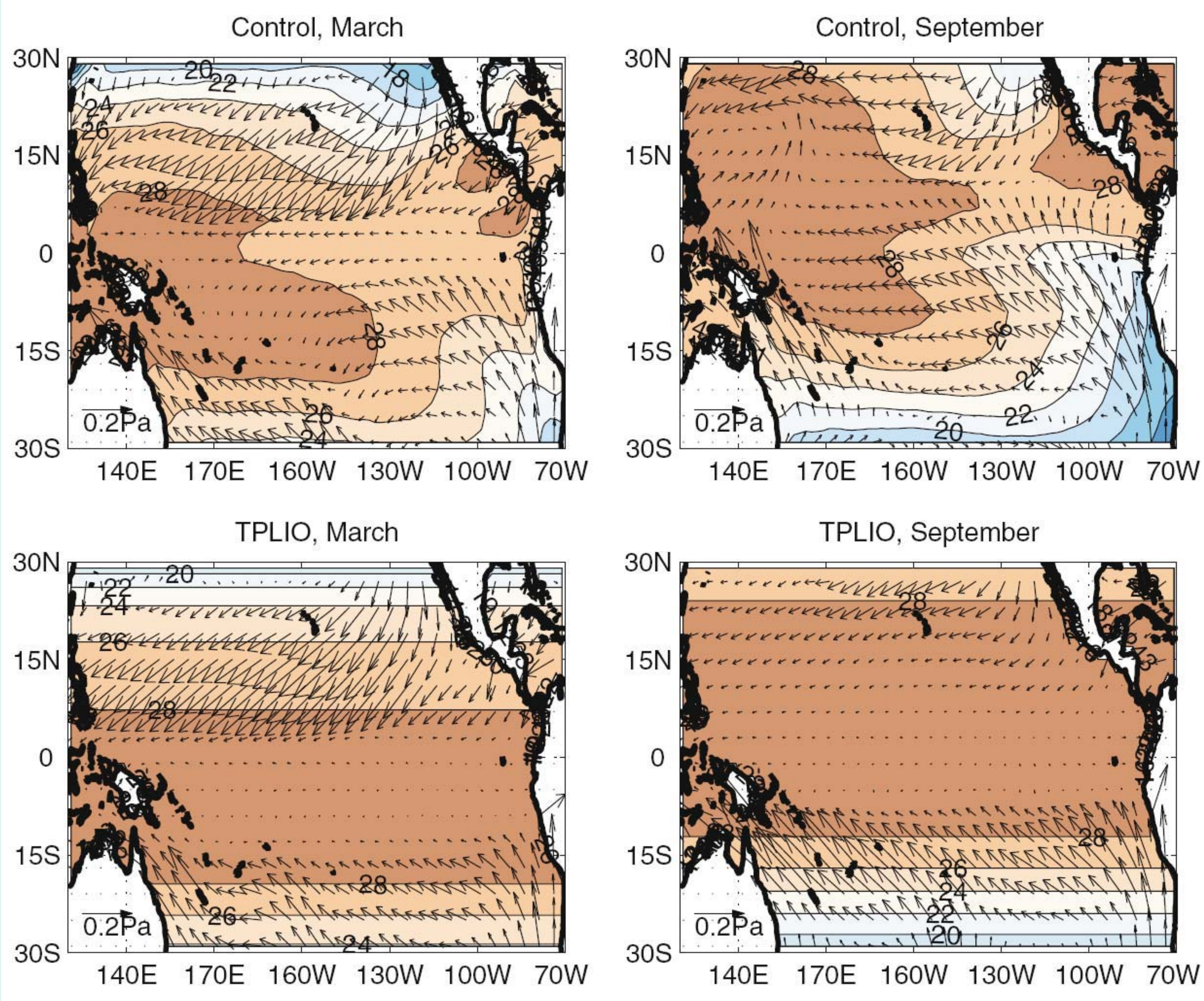
2) Water vapor feedback

3) Low stratus cloud feedback

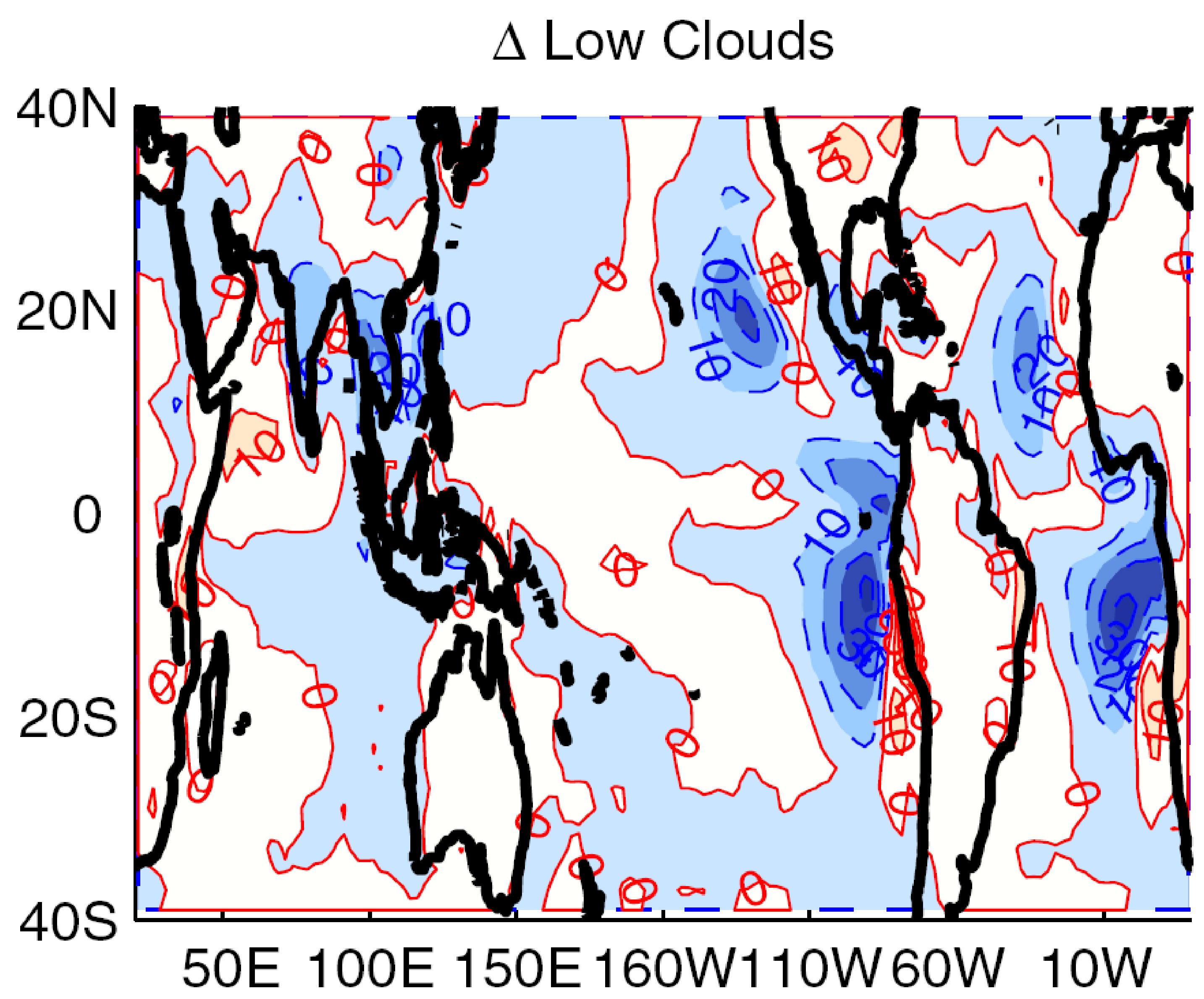
4) Atmospheric teleconnections to high latitudes



*Temperature change in the eastern equatorial Pacific when a uniform **NEGATIVE** heat flux (-10W/m^2) is applied over the tropics in an intermediate coupled model (the idea is similar to the dynamical thermostat of Cane et al 1997).*

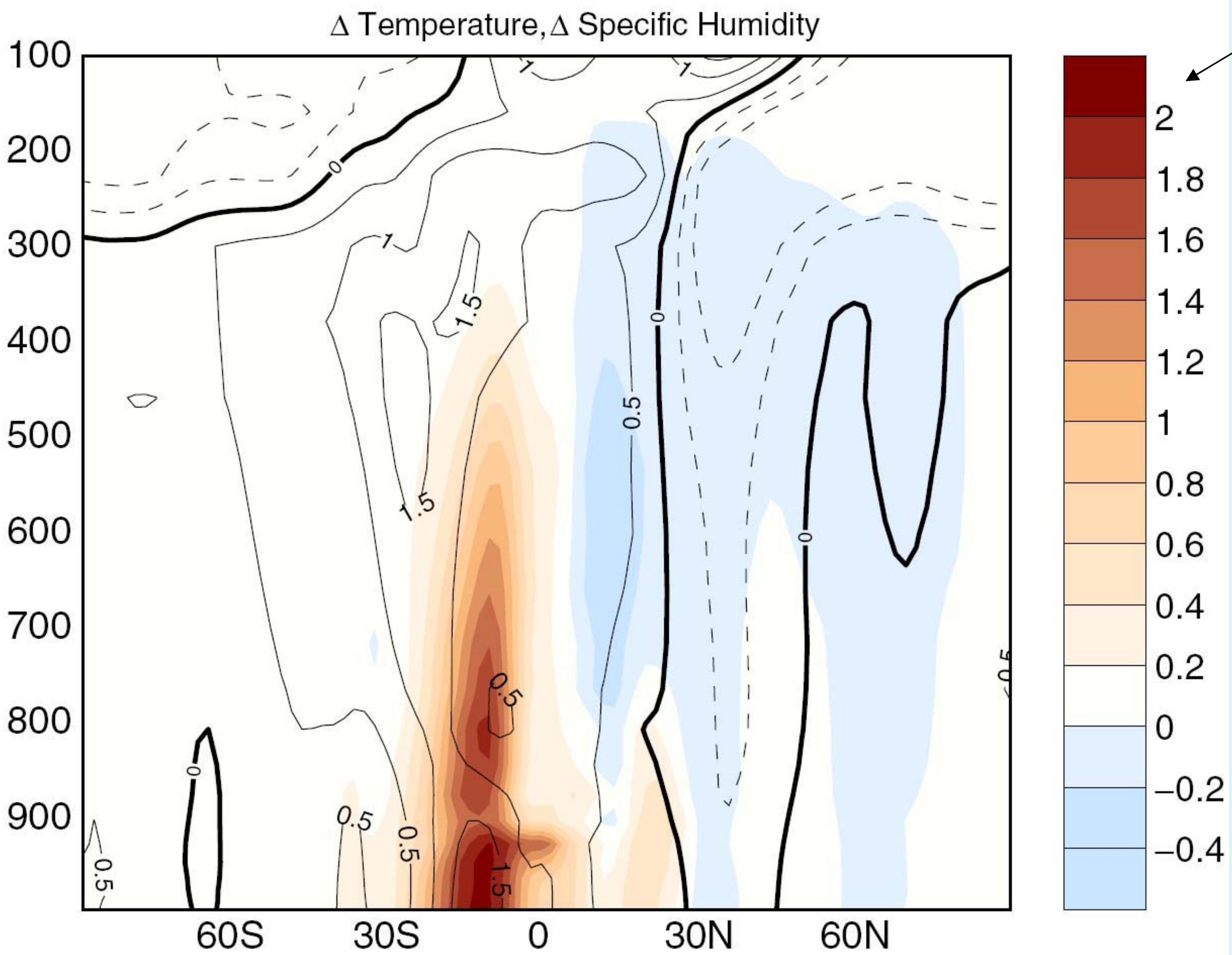


Calculations with an atmospheric GCM forced by zonally uniform SSTs, Barreiro, Pacanowski, Philander and Fedorov 2006



Going back to the warm world!

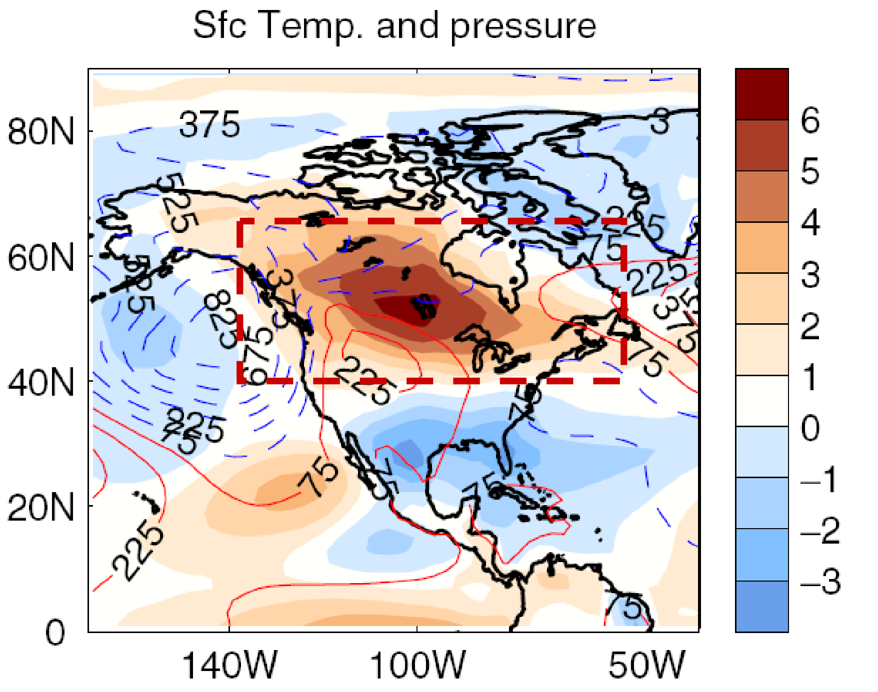
Reduction in the amount of low stratus cloud cover (in %)
in the "warm world" compared to the present climate

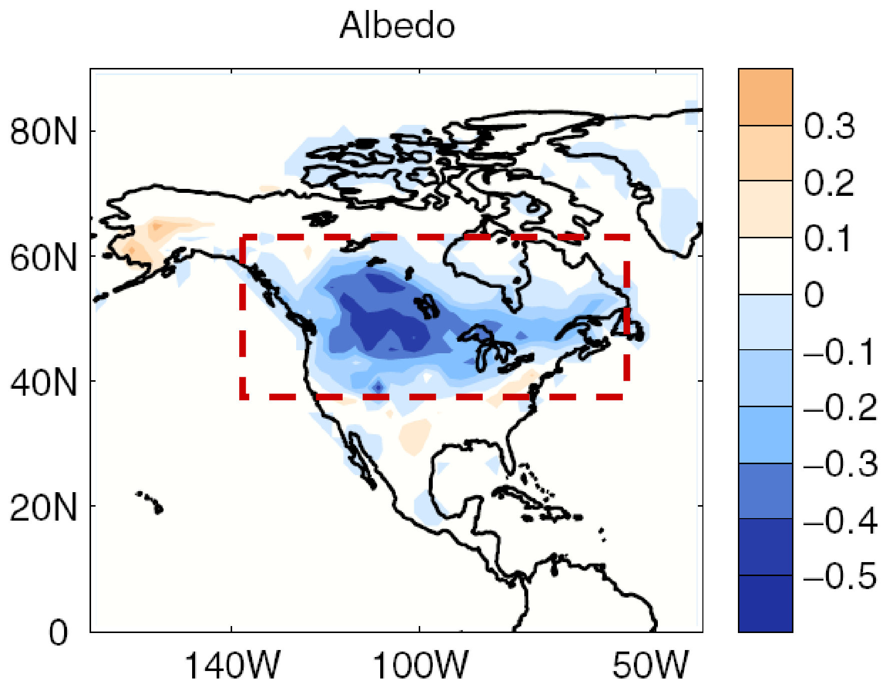


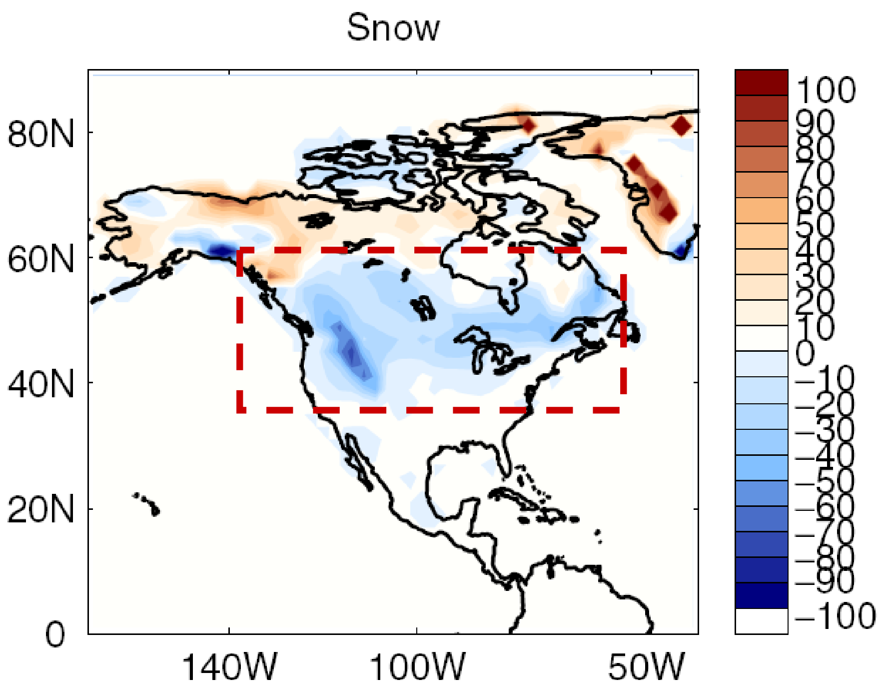
Specific humidity change

Going back to the warm world!

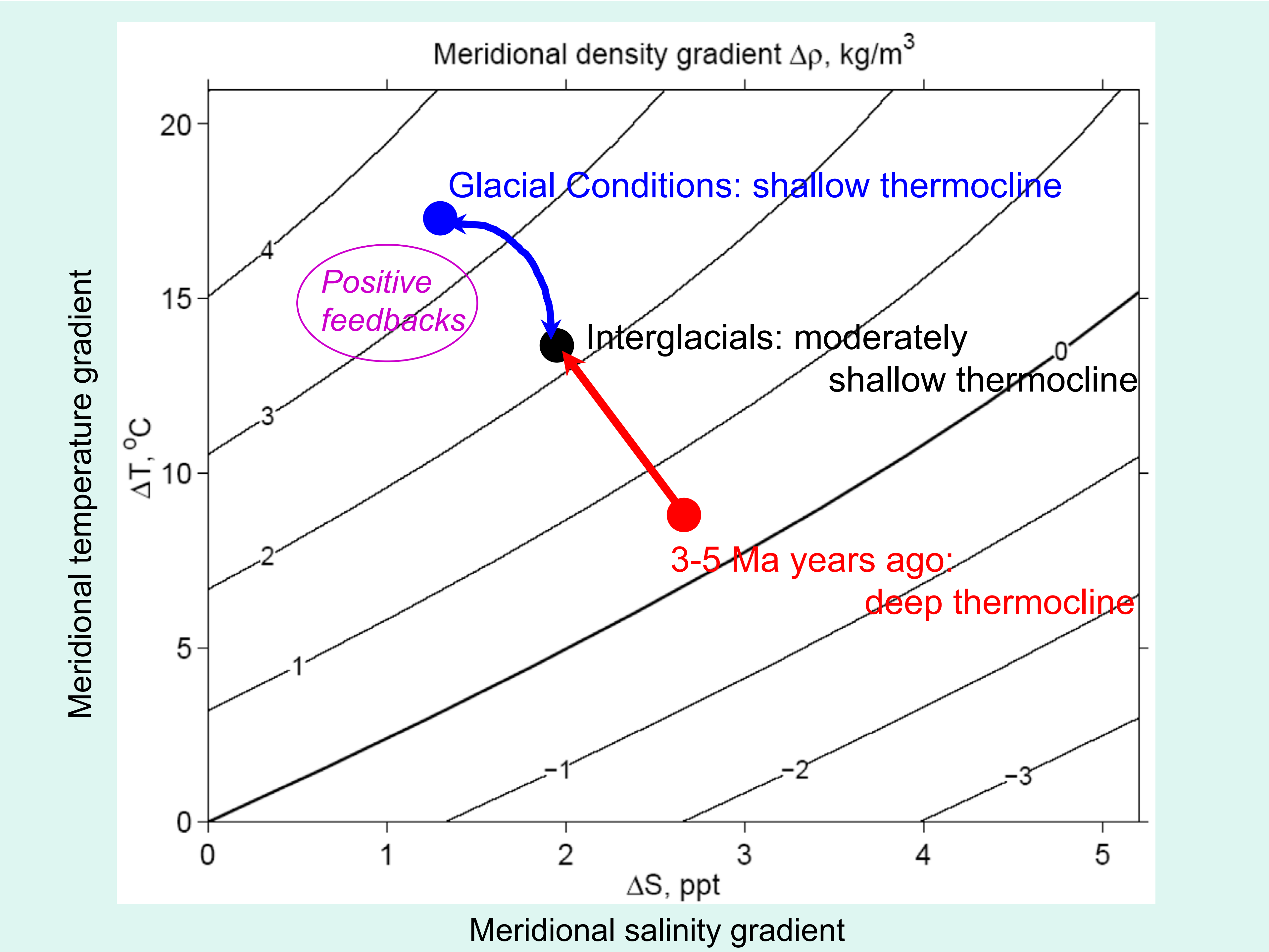
***Increase in the net amount of water vapor** in the "warm world" (specific humidity change, in 10^{-3} g/kg, color shading)*







Changes in surface air temperature, snow cover and albedo in the "warm world" as compared to the present climate (DJF)



Meridional density gradient Δρ, kg/m3
Glacial Conditions: shallow thermocline
Positive feedbacks
Interglacials: moderately shallow thermocline
3-5 Ma years ago: deep thermocline
ΔT, °C
ΔS, ppt
Meridional temperature gradient
Meridional salinity gradient
4
3
2
1
0
−1
−2
−3
0
5
10
15
20
0
1
2
3
4
5

Summary

•As the high latitude surface water warms or freshen, the meridional density gradient and poleward heat transport decrease. One of the consequences is a deepening of the tropical thermocline.

•Obliquity variations have a similar effect, leading to a deepening (high obliquity) or shoaling (low obliquity) of the tropical thermocline.

• Positive feedbacks can amplify climatic impacts of these tropical changes

•A reduction of the meridional density gradient beyond some critical value can lead to the collapse of the equatorial thermocline and a permanent El Niño.