El Nino and global warming:

a long-term perspective

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and

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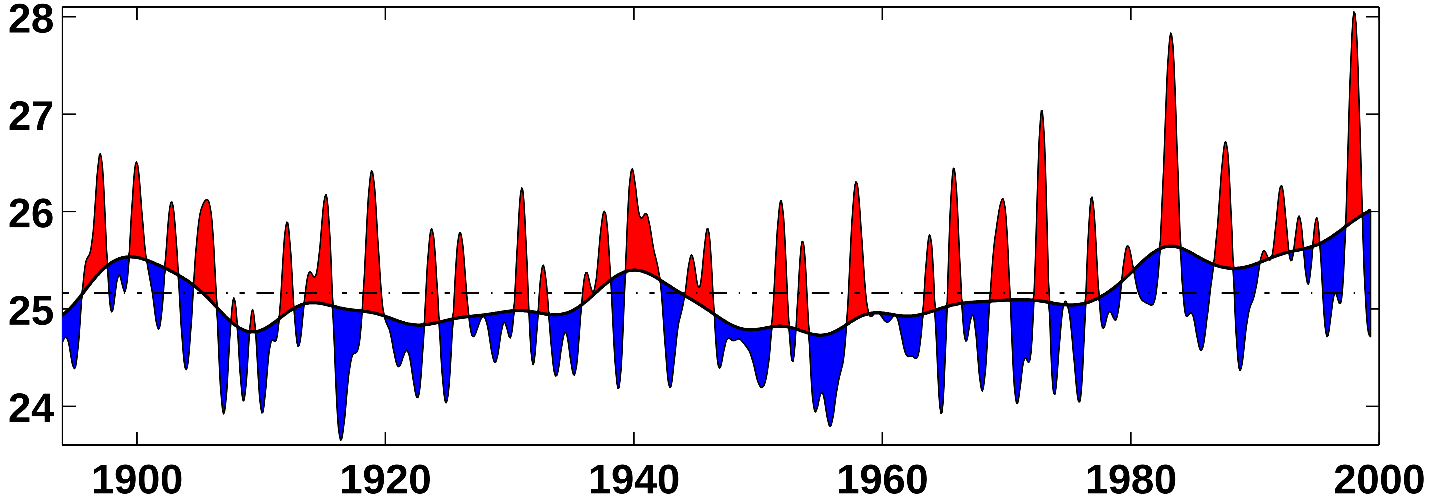
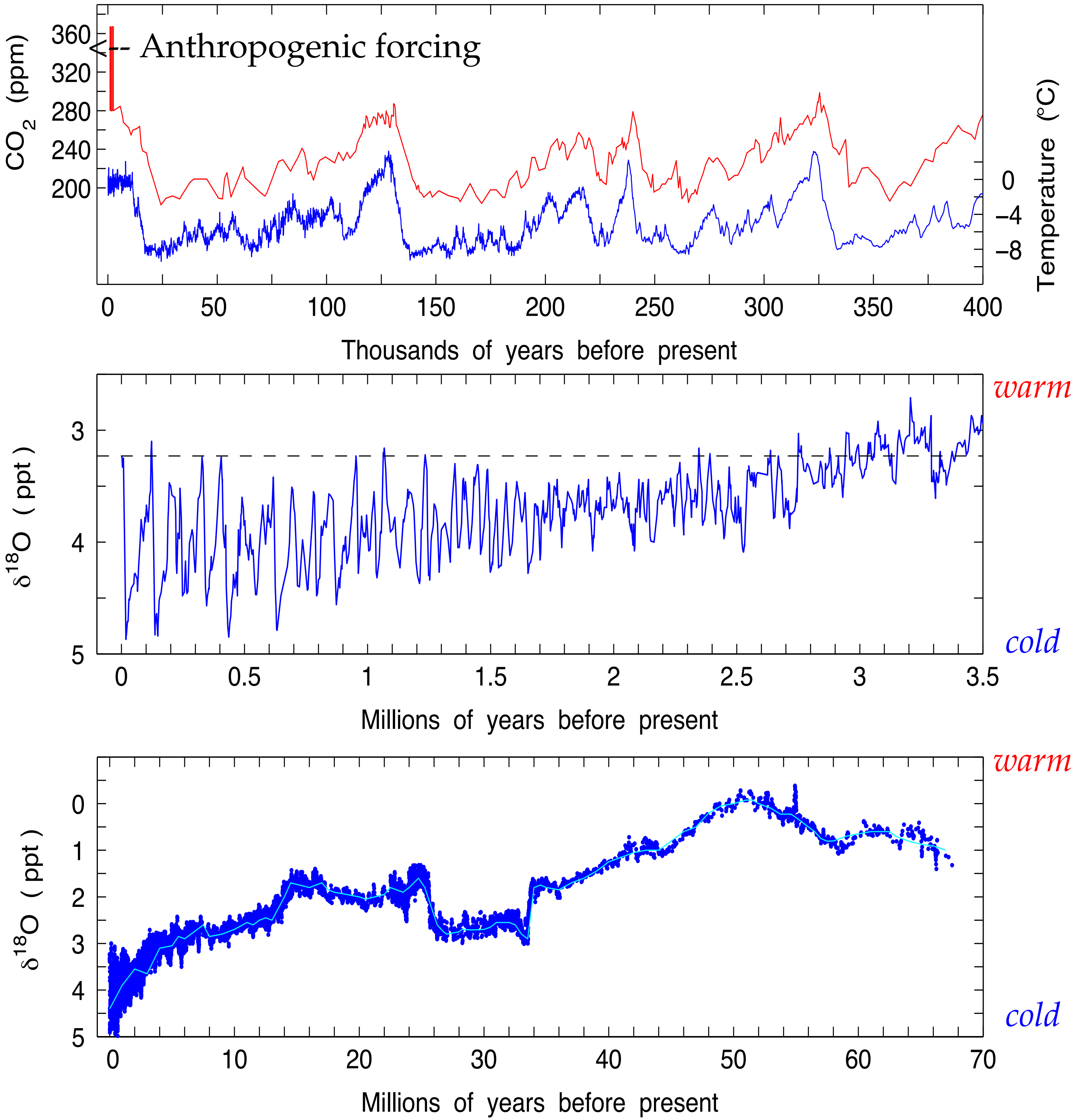
Thanks to:

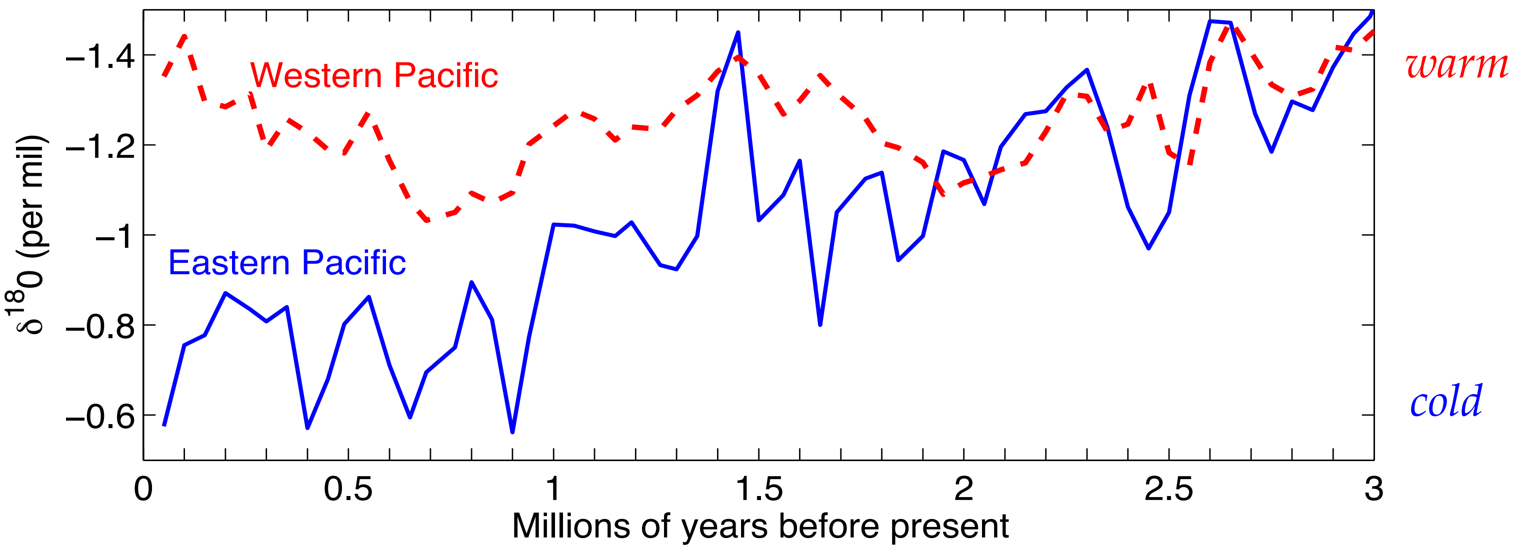
Ron Pacanowski
George Philander
Giulio Boccaletti

SST in the Eastern equatorial Pacific



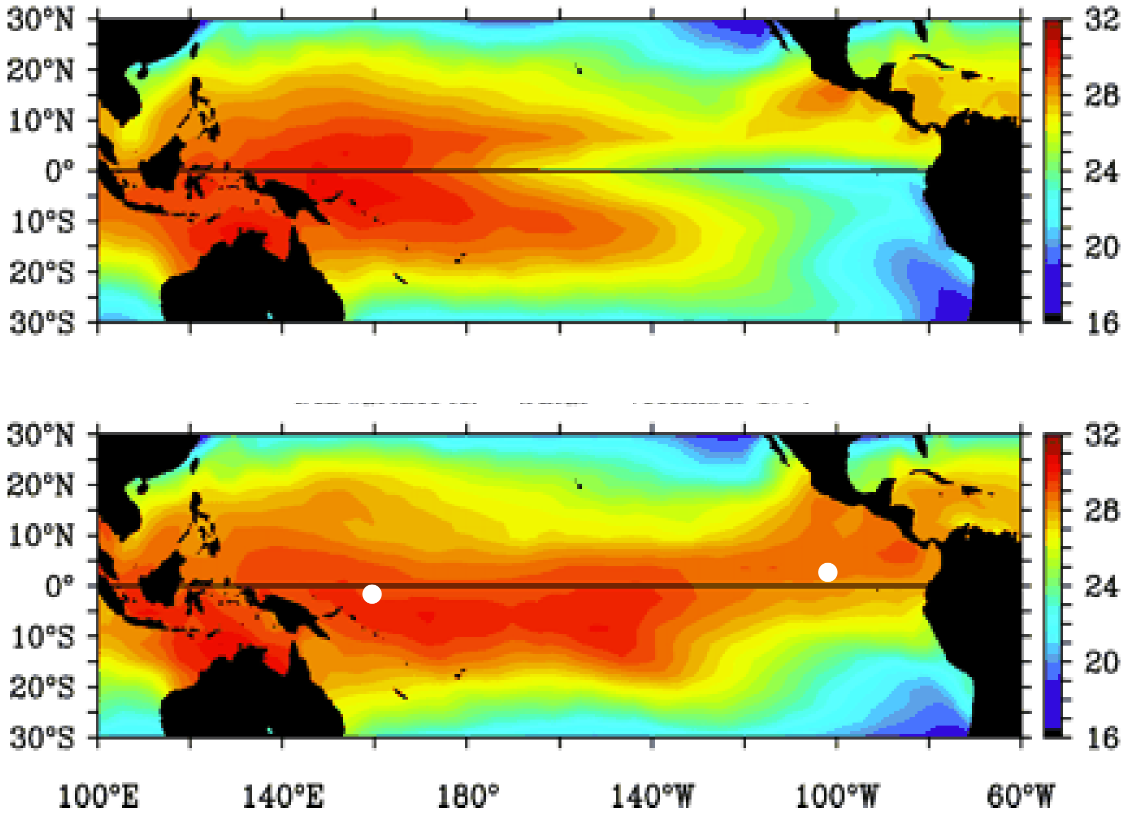


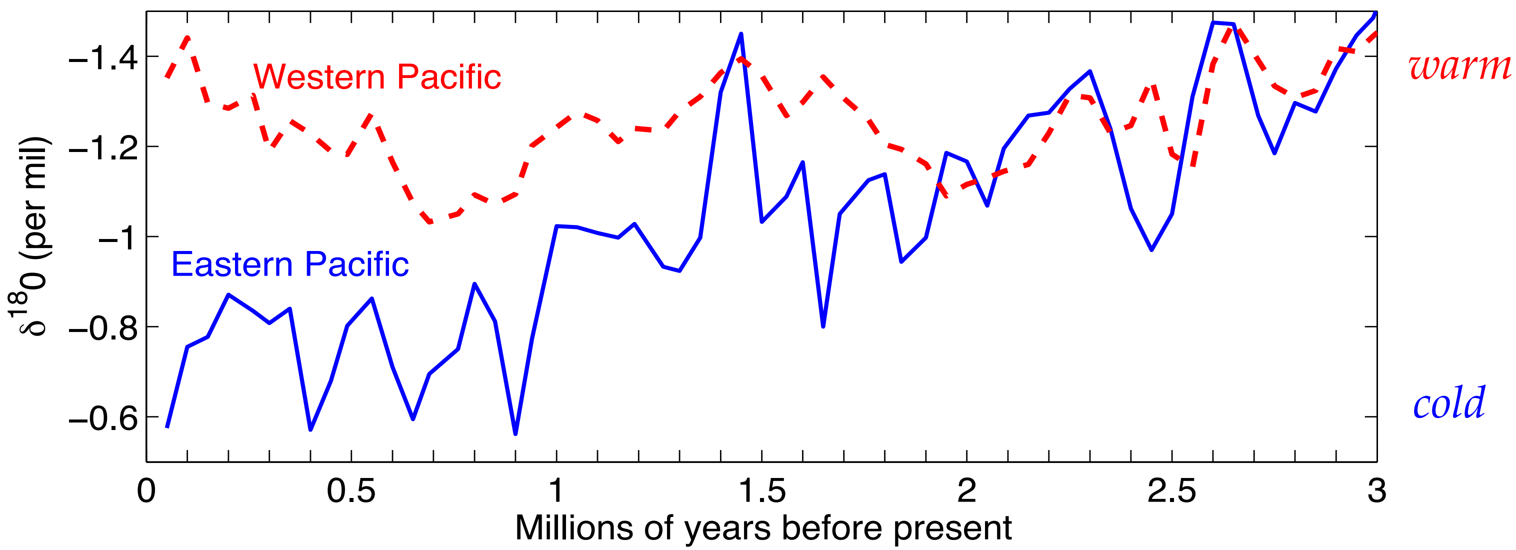
<-- Anthropogenic forcing
CO2 (ppm)
360
320
280
240
200
Temperature (°C)
0
−4
−8
0
50
100
150
200
250
300
350
400
Thousands of years before present
warm
cold
δ18O (ppt)
3
4
5
0
0.5
1
1.5
2
2.5
3
3.5
Millions of years before present
warm
cold
δ18O (ppt)
0
1
2
3
4
5
0
10
20
30
40
50
60
70
Millions of years before present



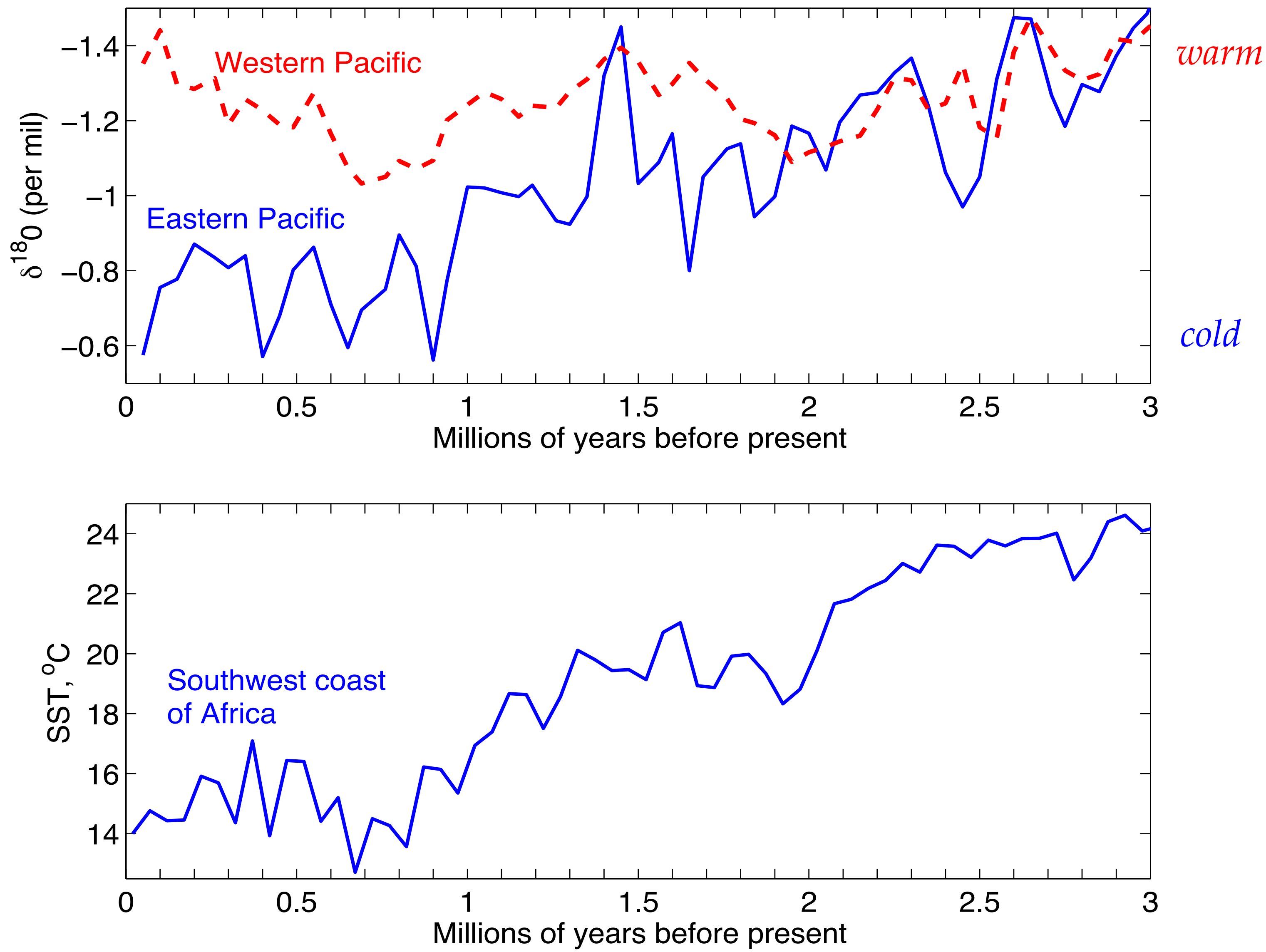
(after Ravelo et al 2001, also Molnar and Cane 2002)

La Niña versus El Niño





(after Ravelo et al 2001, also Molnar and Cane 2002)



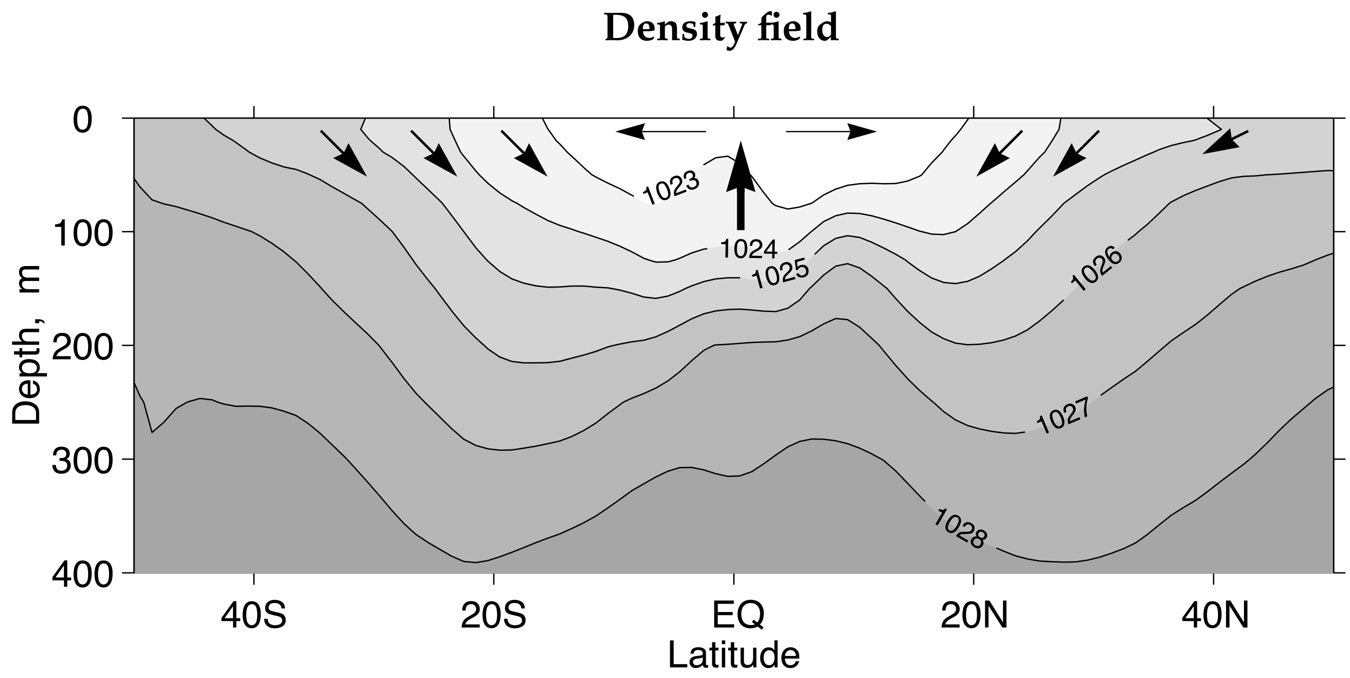
Similar results are also obtained for the SST off the coast of California (Ravelo et al 2001)

Question:

Could global warming eventually result in a permanent El Niño similar to the situation some 3 million years ago?

Sub-Questions:

How would a warming of high latitudes affect the tropics (in the Pacific)?
How would a freshening of surface waters in high latitudes affect the tropics (in the Pacific)?

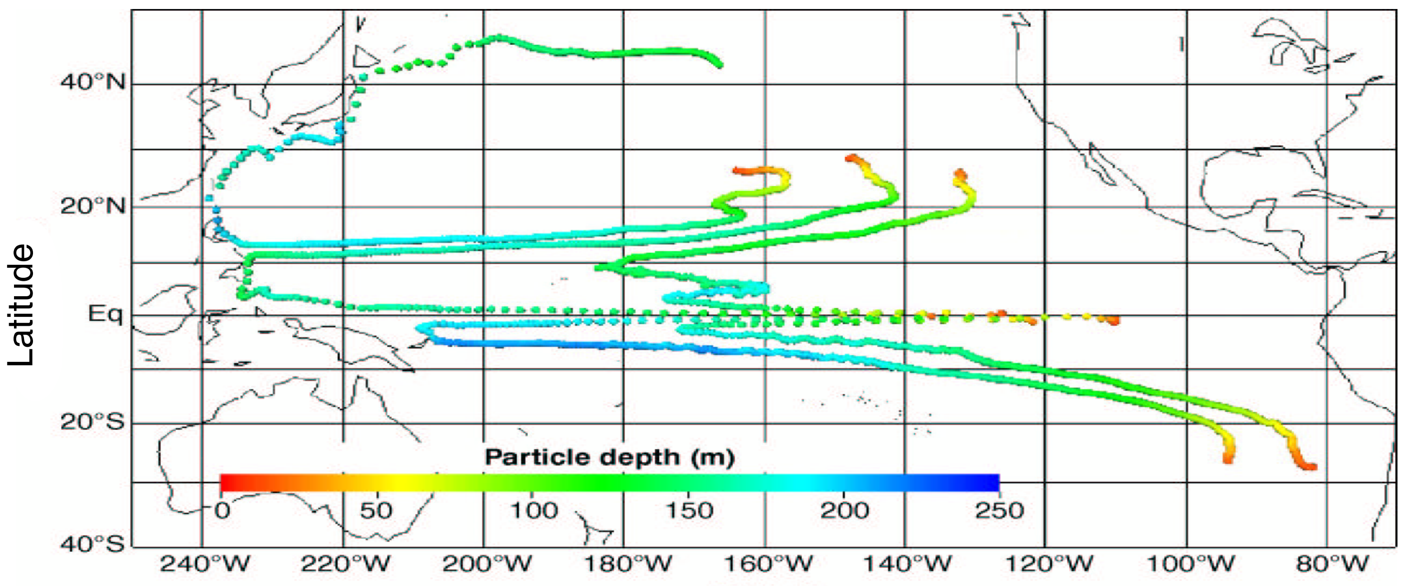


A schematic picture of the thermocline "ventilation"
After subduction the water parcels travel along
the density surfaces towards the equator

Two controlling factors:

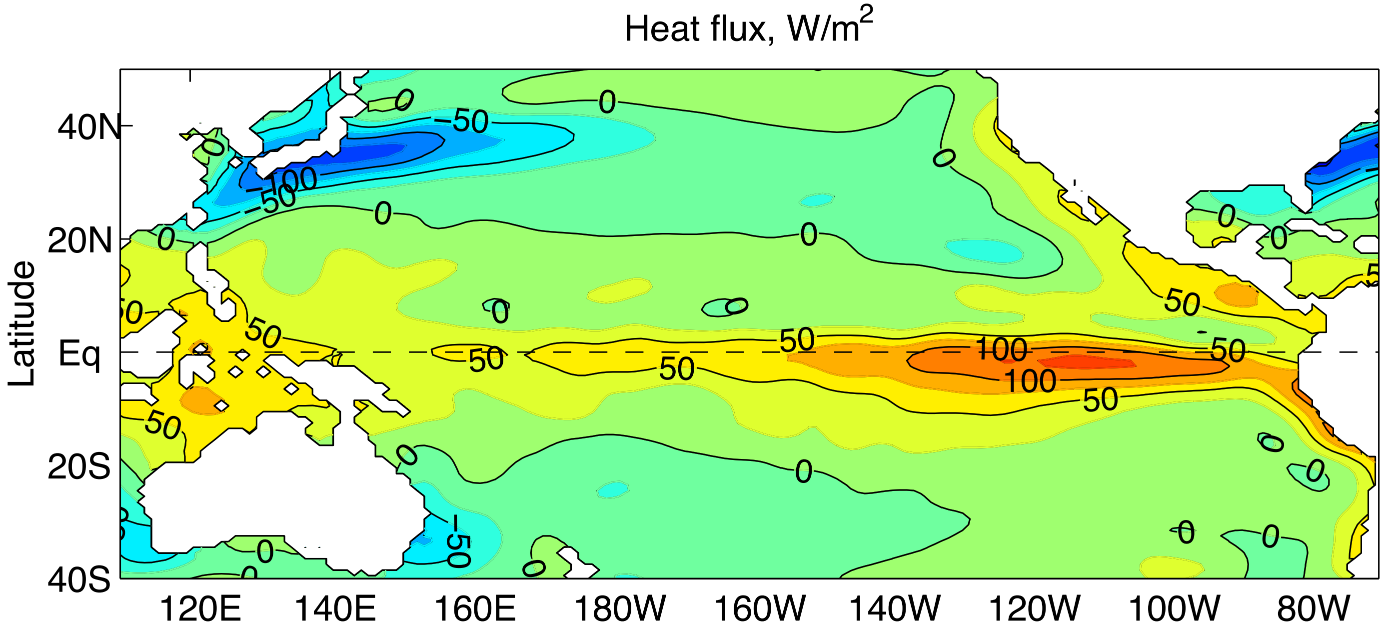
$\Delta\rho = \alpha\Delta T - \beta\Delta S$ - the meridional density gradient and
τ - the wind stress

A



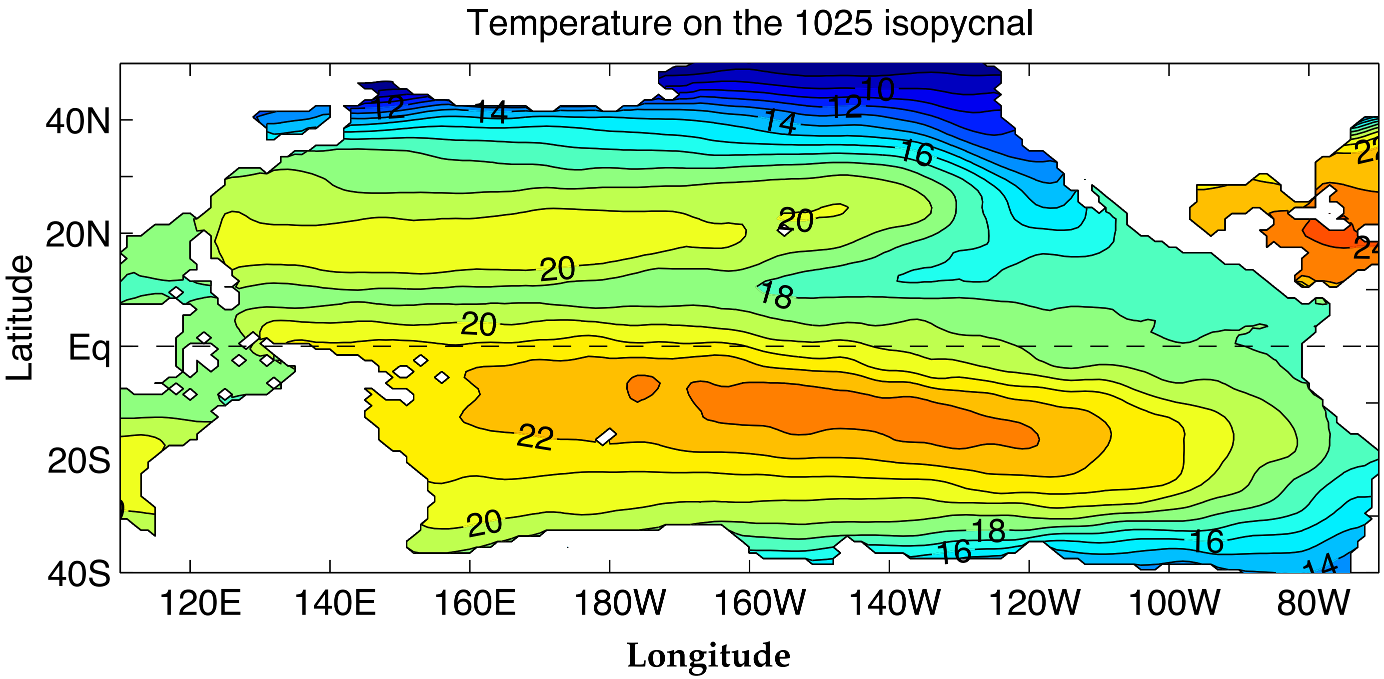
Latitude
40°N
20°N
Eq
20°S
40°S
Particle depth (m)
0
50
100
150
200
250
240°W
220°W
200°W
180°W
160°W
140°W
120°W
100°W
80°W

B

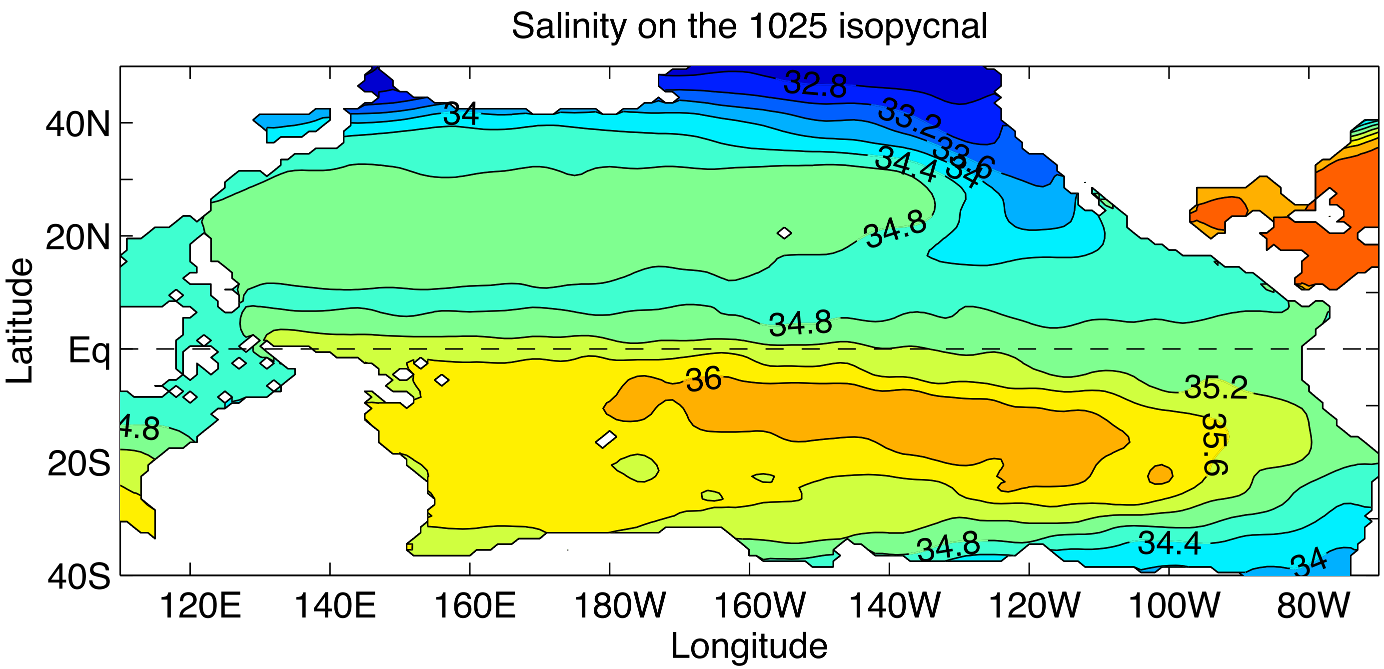


Heat flux, W/m^2
Latitude
40N
20N
Eq
20S
40S
120E
140E
160E
180W
160W
140W
120W
100W
80W

A


Temperature on the 1025 isopycnal
40N
20N
Eq
20S
40S
Latitude
120E
140E
160E
180W
160W
140W
120W
100W
80W
Longitude
10
12
14
16
18
20
22
16

B


Salinity on the 1025 isopycnal
40N
20N
Eq
20S
40S
Latitude
120E
140E
160E
180W
160W
140W
120W
100W
80W
Longitude
32.8
33.2
33.6
34
34.4
34.8
35.2
35.6
36

$$\Delta\rho = \alpha\Delta T - \beta\Delta S$$

$$R = \frac{\beta\Delta S}{\alpha\Delta T}$$

R **- the horizontal density ratio**

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(1) $R = 0$ **- the world controlled only by temperature;**

(2) $R = 1$ **- the world with no meridional density difference** (i.e. $\Delta\rho$=**0)**

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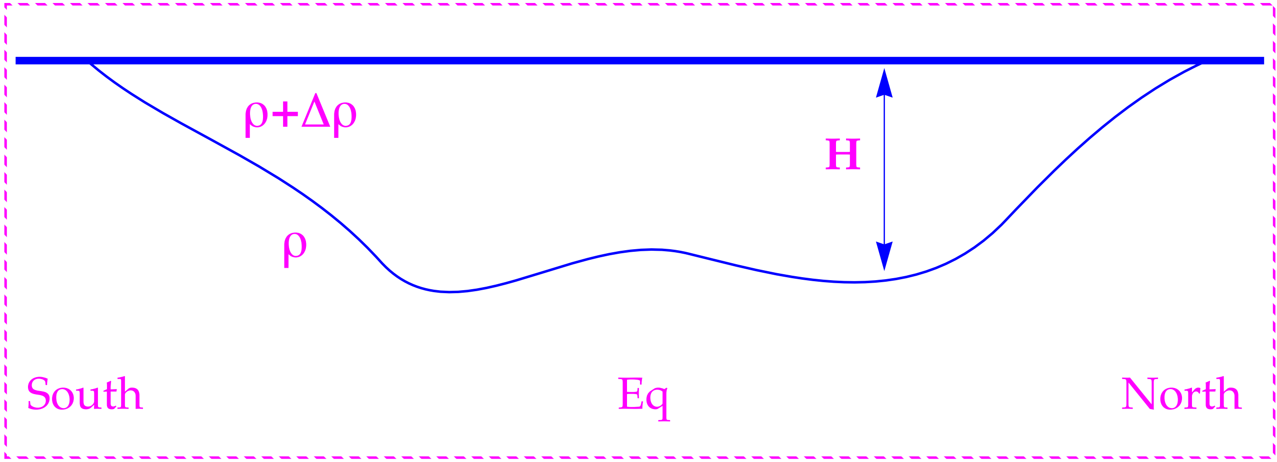
(3) $R \approx 0.5$ **- the world of today**

The ventilated thermocline



Luyten, Pedlosky, Stommel 1983
Huang 1988

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the characteristic thermocline depth

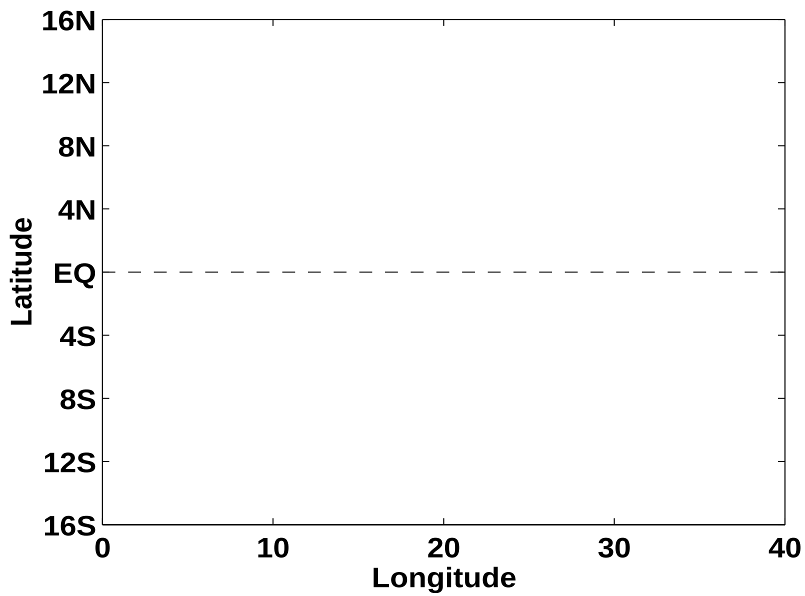
$$H \sim (\tau/\Delta\rho)^{1/2}$$

The small-basin model (GFDL MOM4):

$1/2^o$ horizontal resolution
32 levels in the vertical

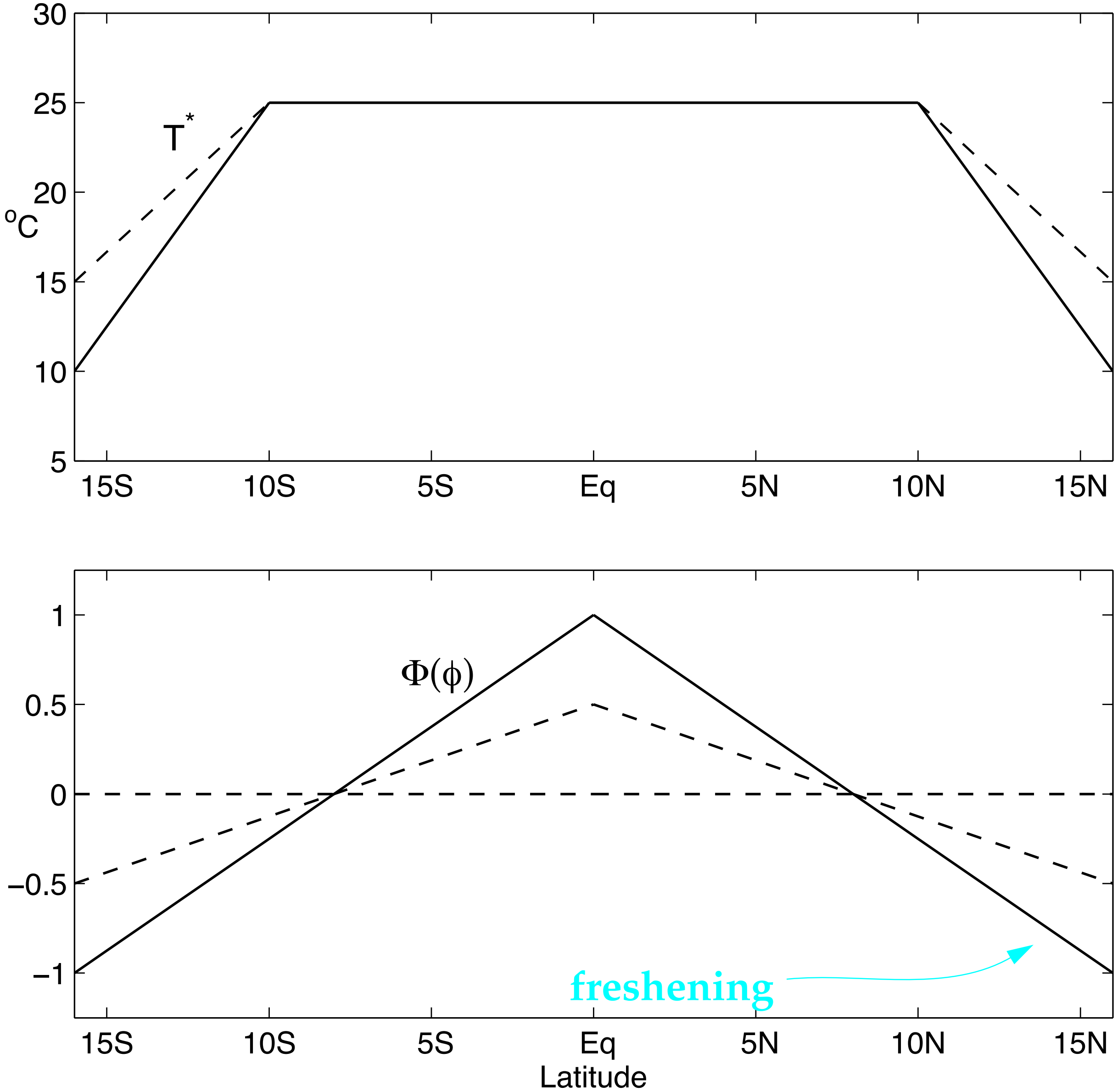
Philander - Pacanowski mixing;
background diffusion K=0.01 cm^2/s

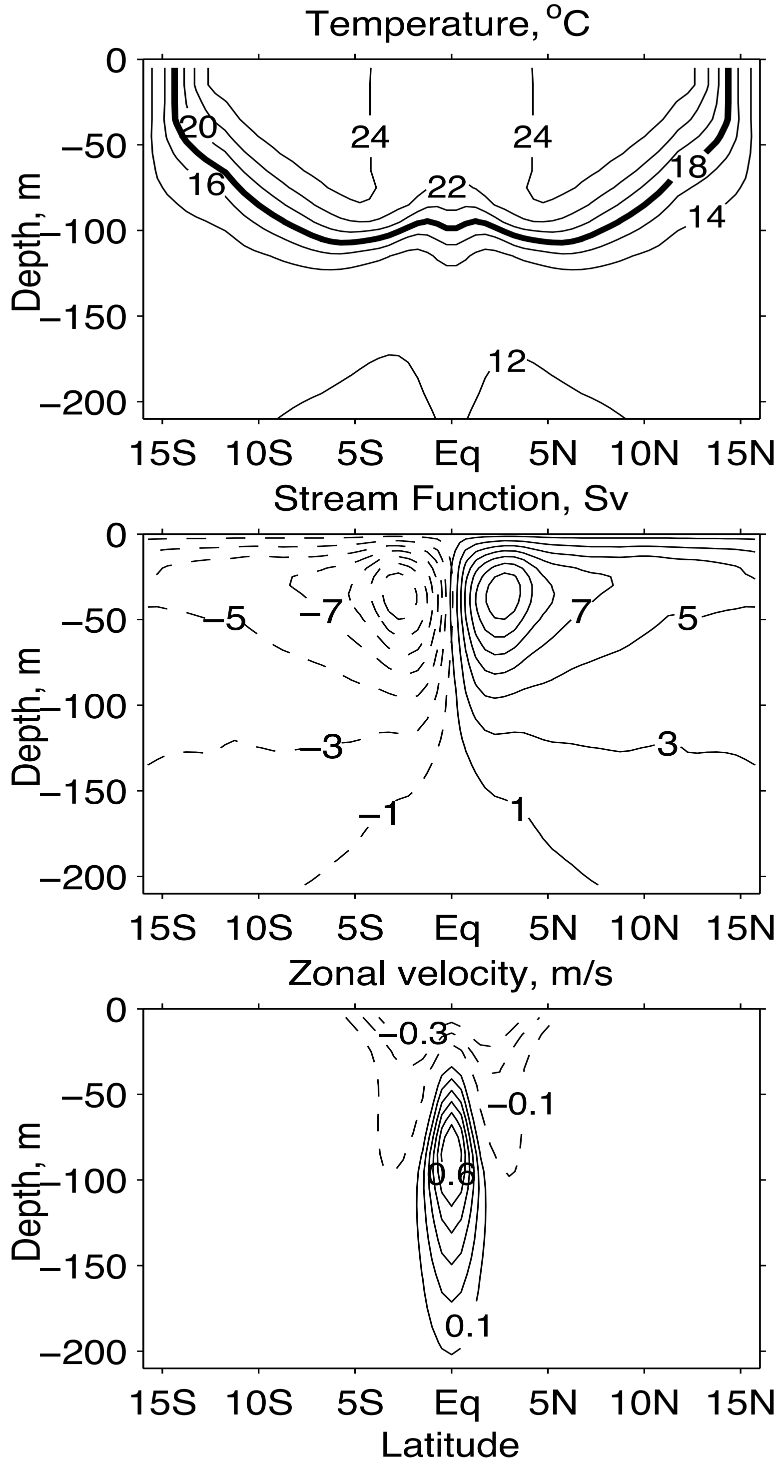
Uniform zonal easterly winds
τ^x=-0.5 dyn/cm^2



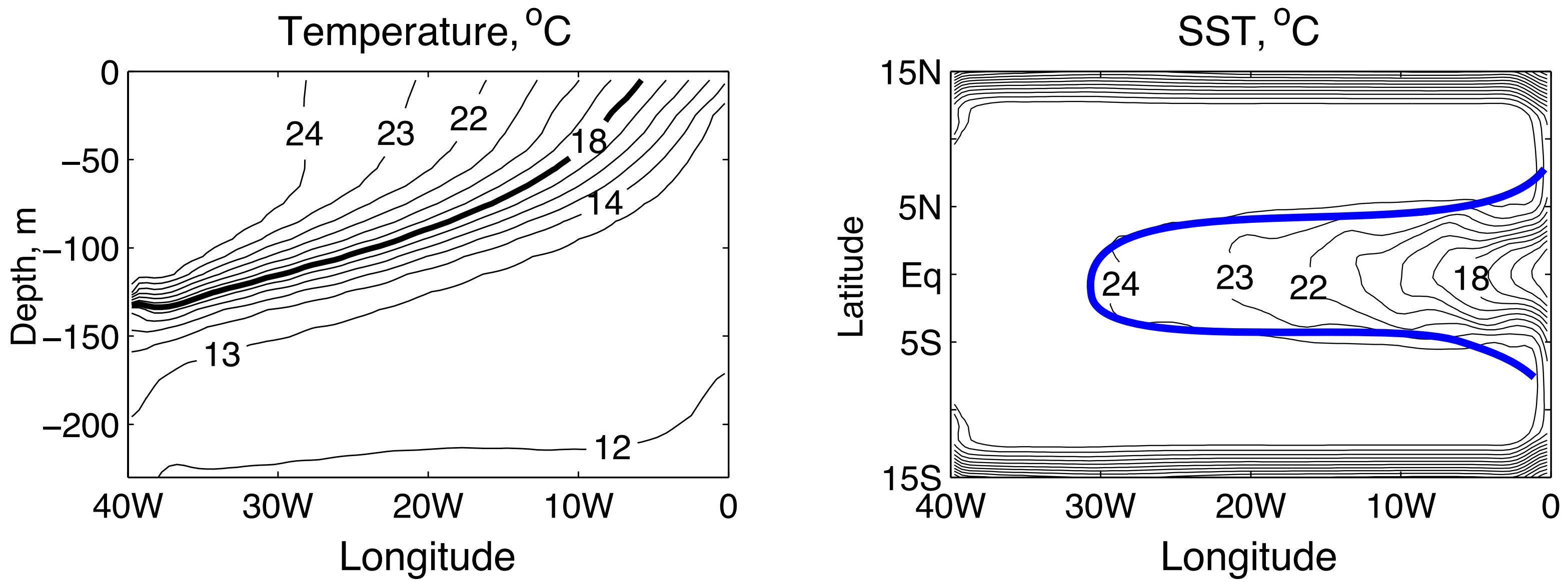
Latitude: 16^oN - 16^oS
Longitude: 0^o- 40^o

B.C.: $$K\frac{\partial T}{\partial Z} = -\gamma_T (T - T^*); \quad K\frac{\partial S}{\partial Z} = \gamma S_0 \Phi(\varphi)$$

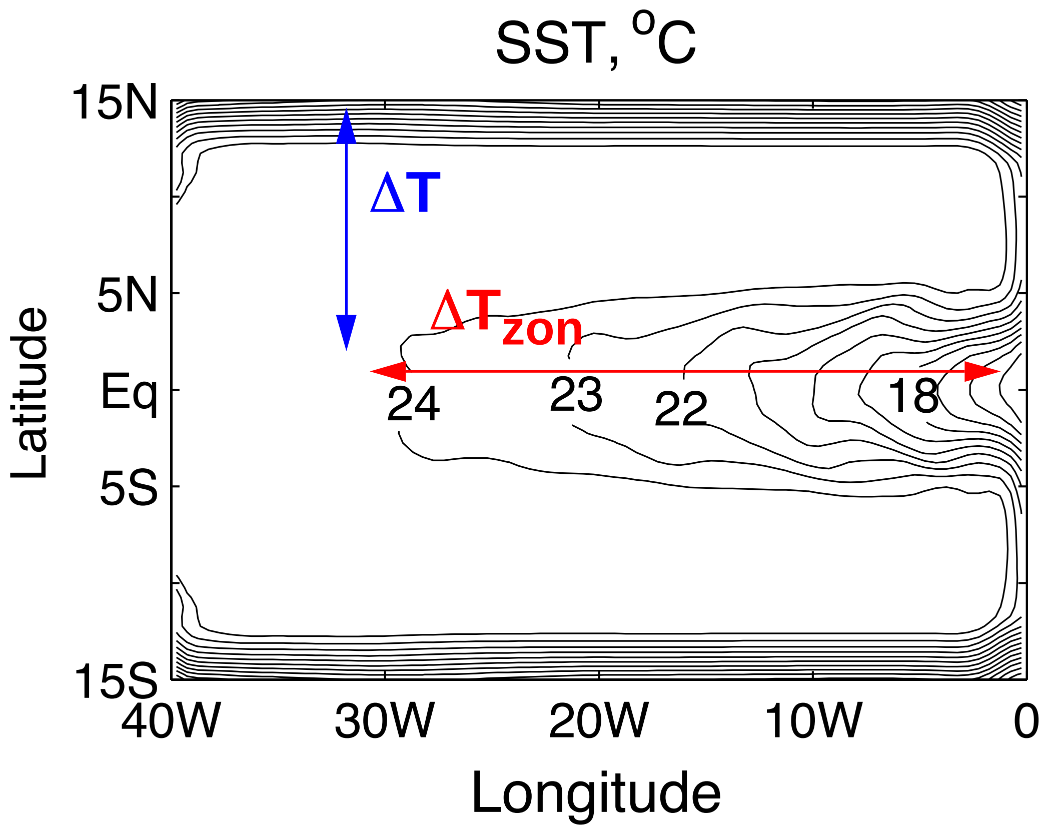




Temperature, °C
24
24
20
22
16
18
14
12
Depth, m
0
−50
−100
−150
−200
15S
10S
5S
Eq
5N
10N
15N
Stream Function, Sv
−7
−5
7
5
−3
3
−1
1
Zonal velocity, m/s
−0.3
−0.1
0.6
0.1
Latitude



Temperature, °C
0
−50
−100
−150
−200
Depth, m
24
23
22
18
14
13
12
40W
30W
20W
10W
0
Longitude
SST, °C
15N
5N
Eq
5S
15S
Latitude
24
23
22
18
40W
30W
20W
10W
0
Longitude

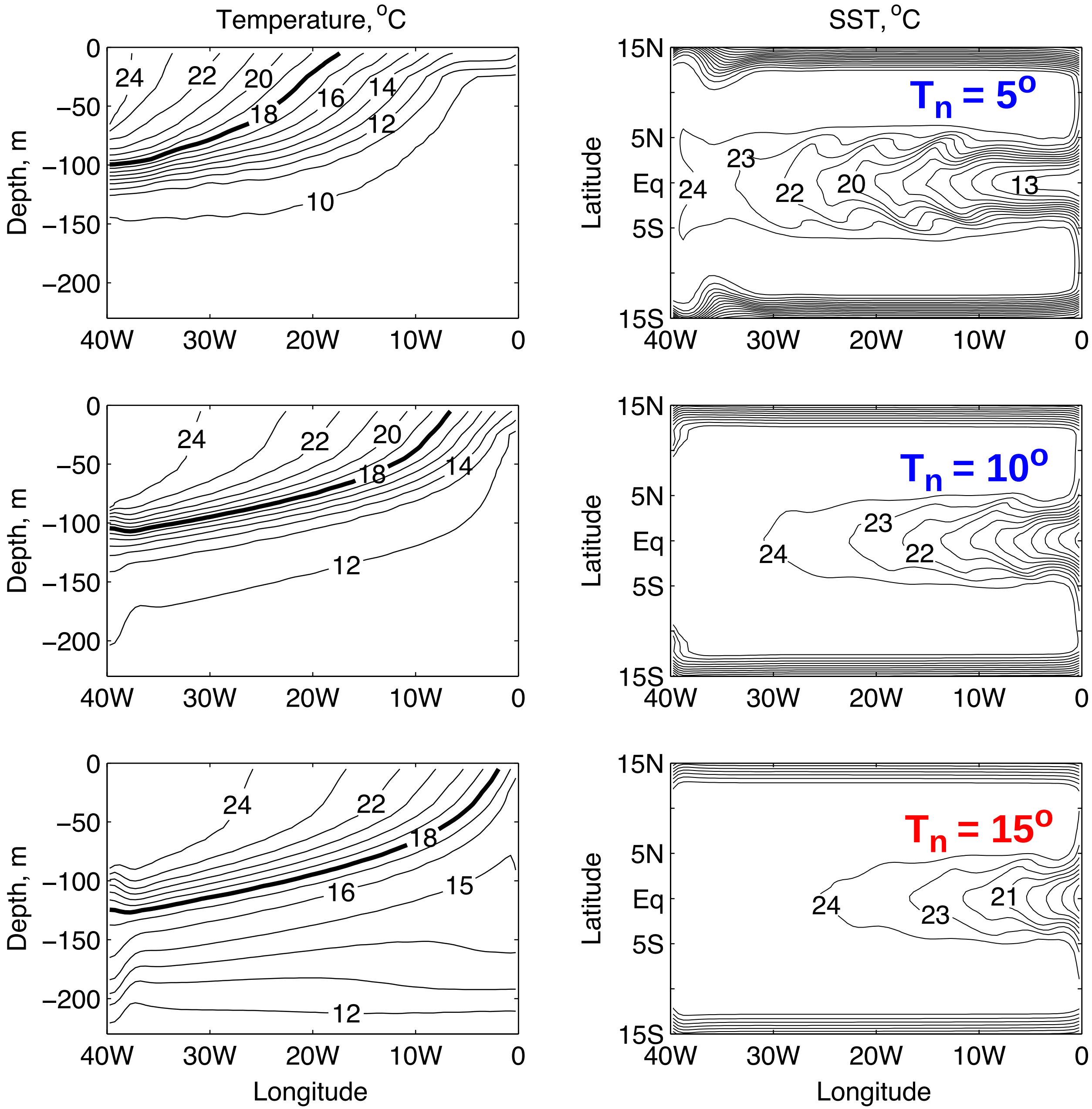


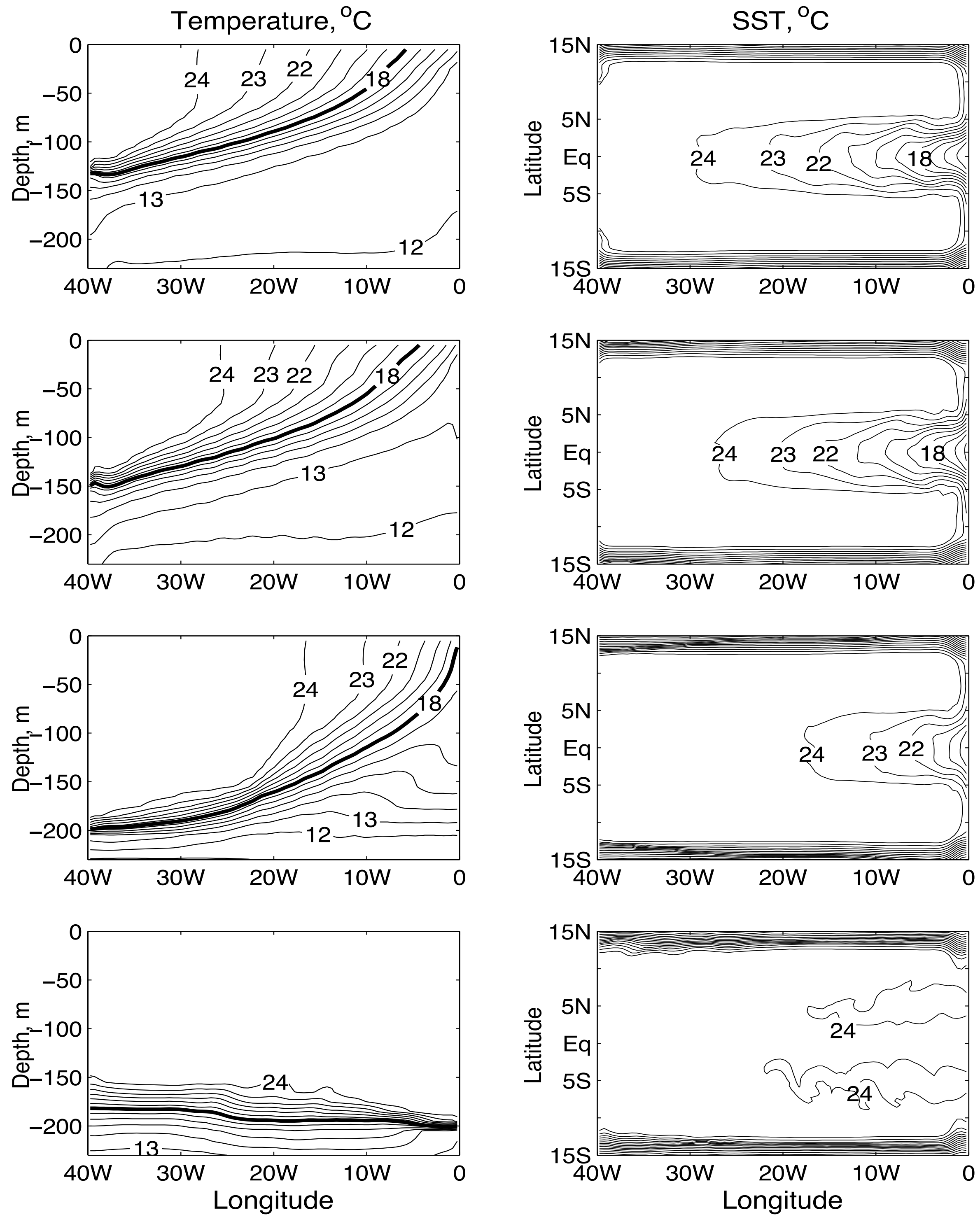
$\Delta T_{zon} \sim \Delta T$

(no salinity)

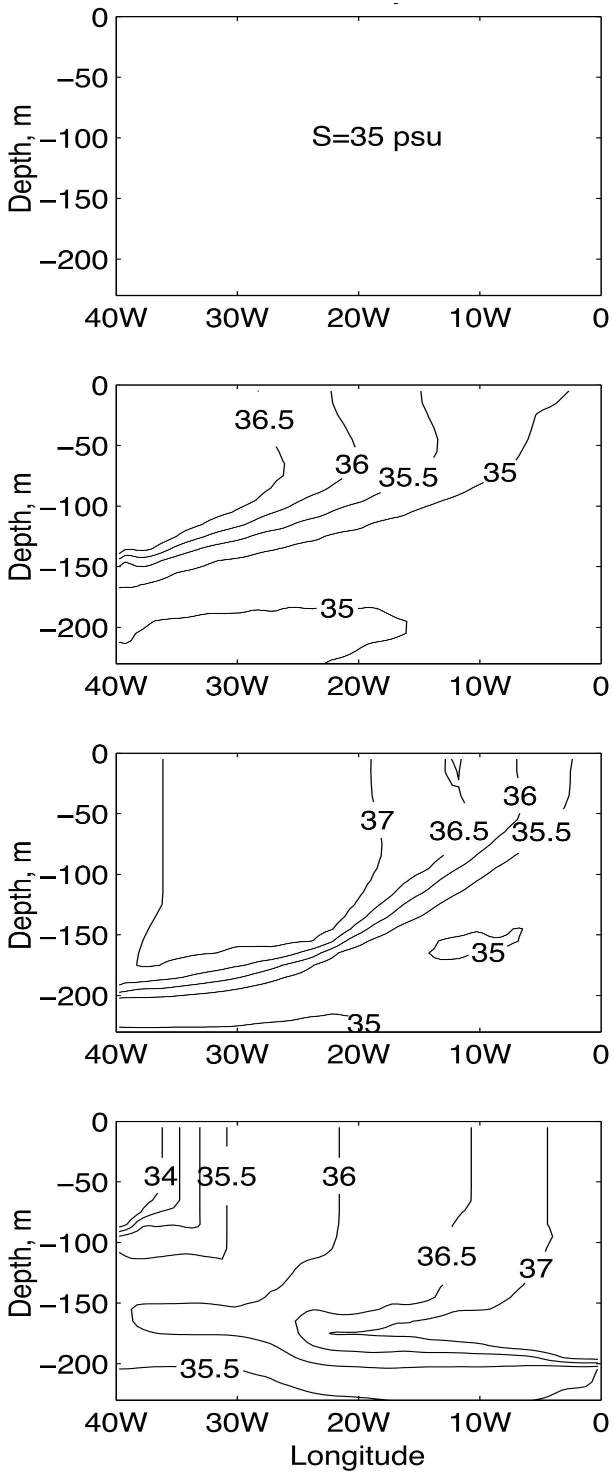
$\Delta T_{zon} \sim \Delta T, \Delta S$

(with salinity)

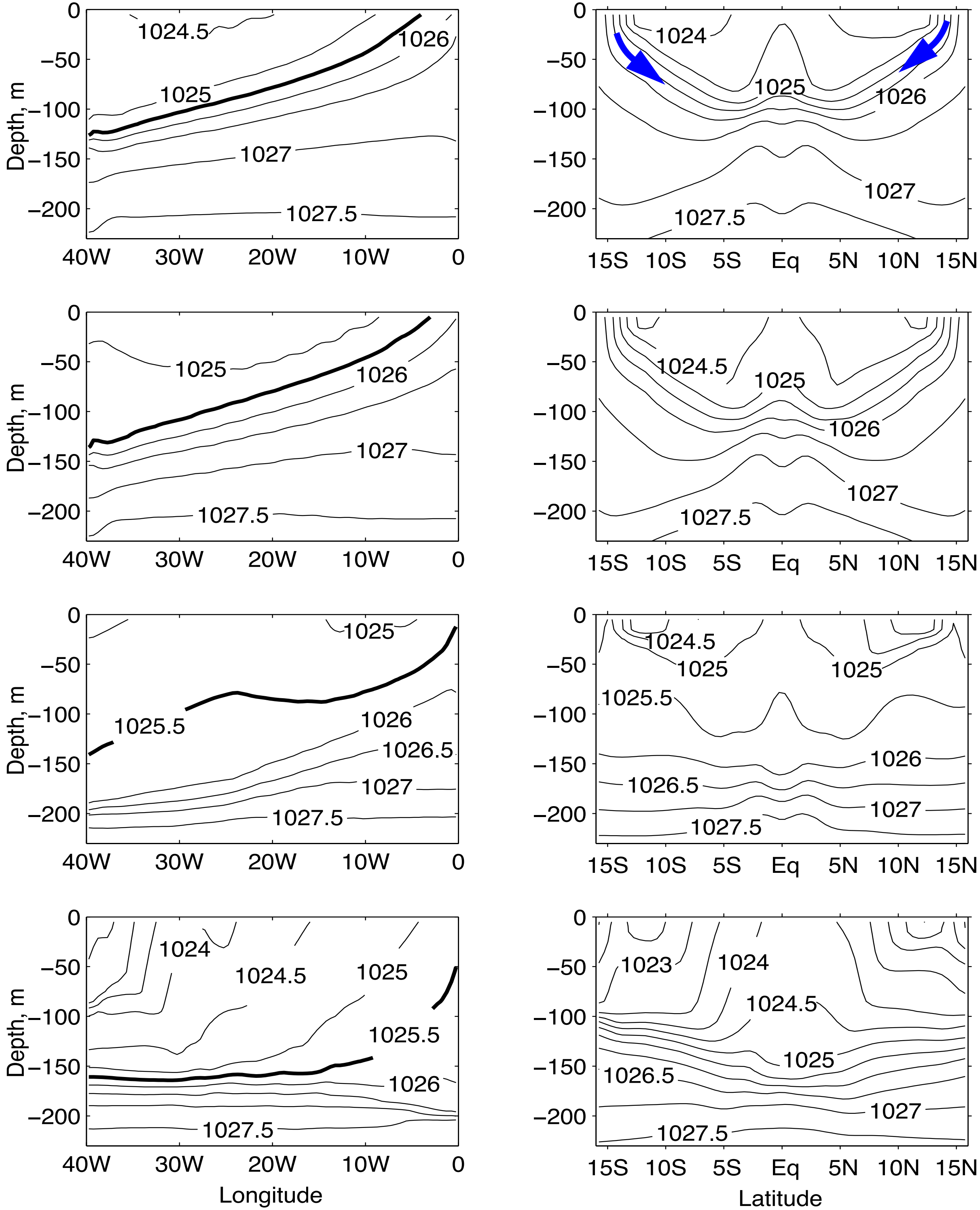

Temperature, ^oC
SST, ^oC
Depth, m
Latitude
Longitude
$T_n = 5^o$
$T_n = 10^o$
$T_n = 15^o$
0
−50
−100
−150
−200
40W
30W
20W
10W
15N
5N
Eq
5S
15S
24
22
20
18
16
14
12
10
23
13
21
15


Temperature, °C
SST, °C
Depth, m
Latitude
Longitude
0
−50
−100
−150
−200
15N
5N
Eq
5S
15S
40W
30W
20W
10W
24
23
22
18
13
12

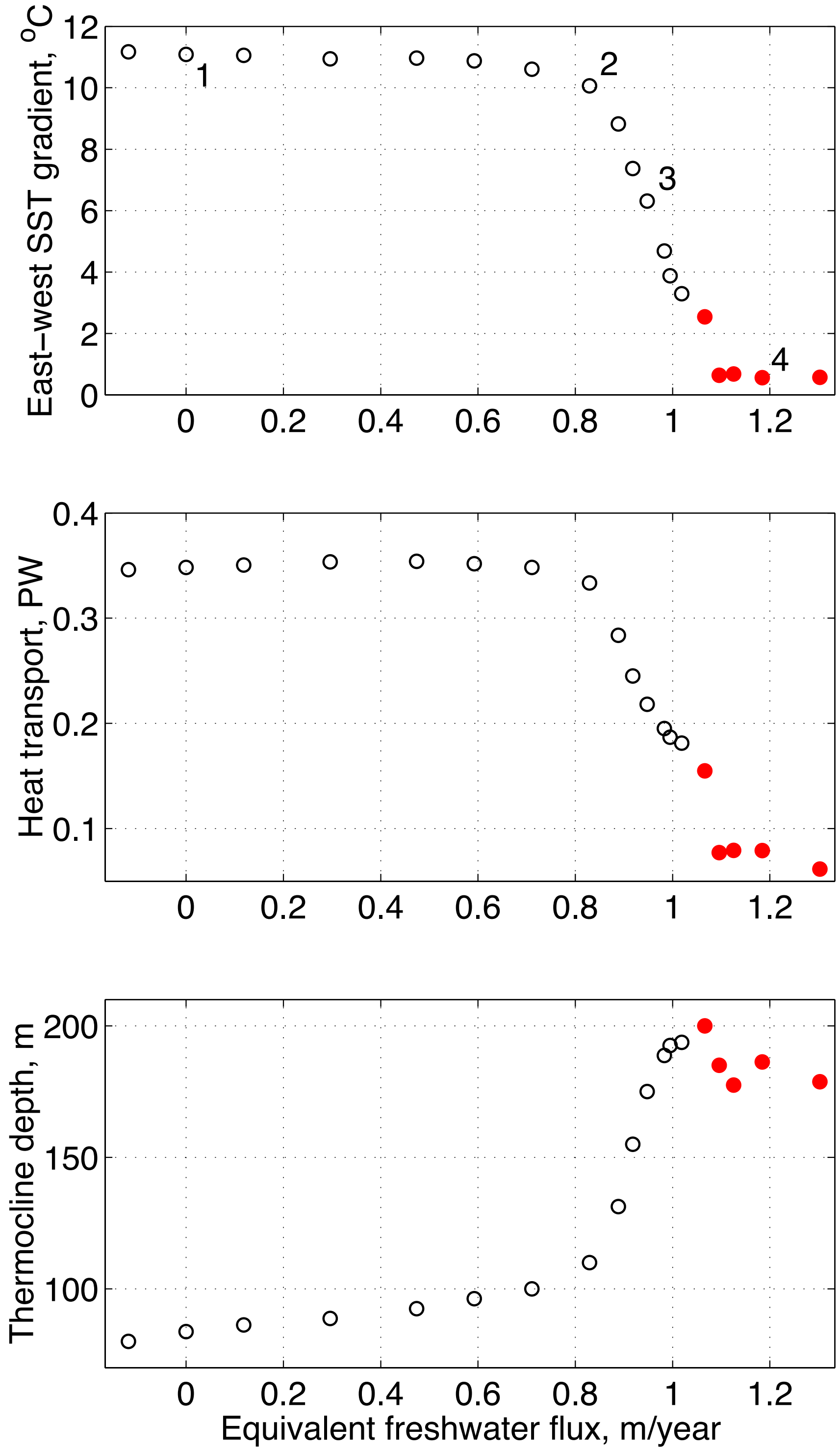
Salinity



Density

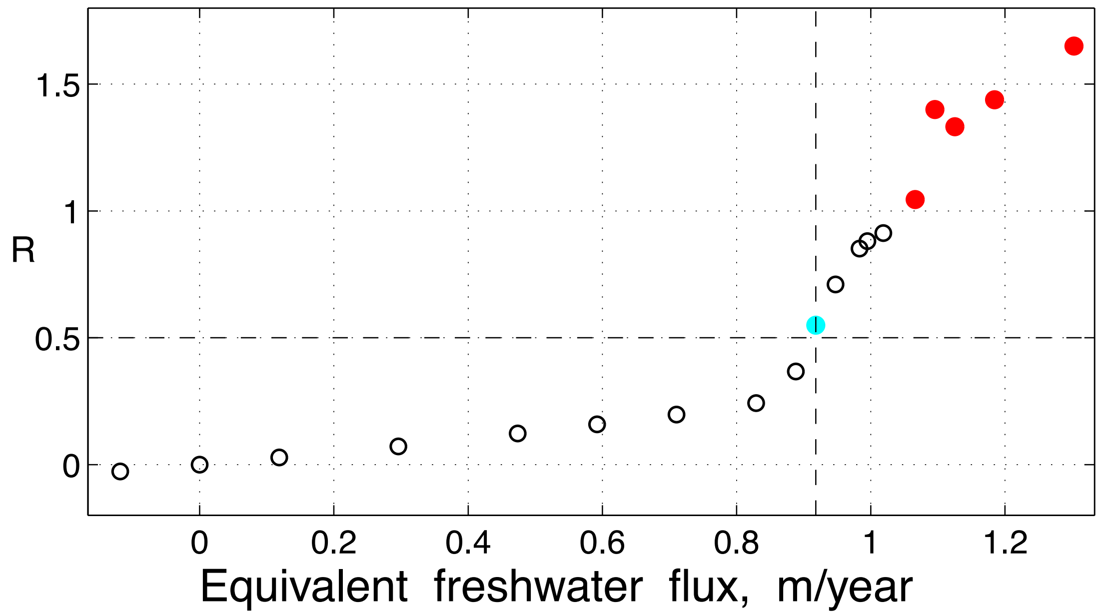


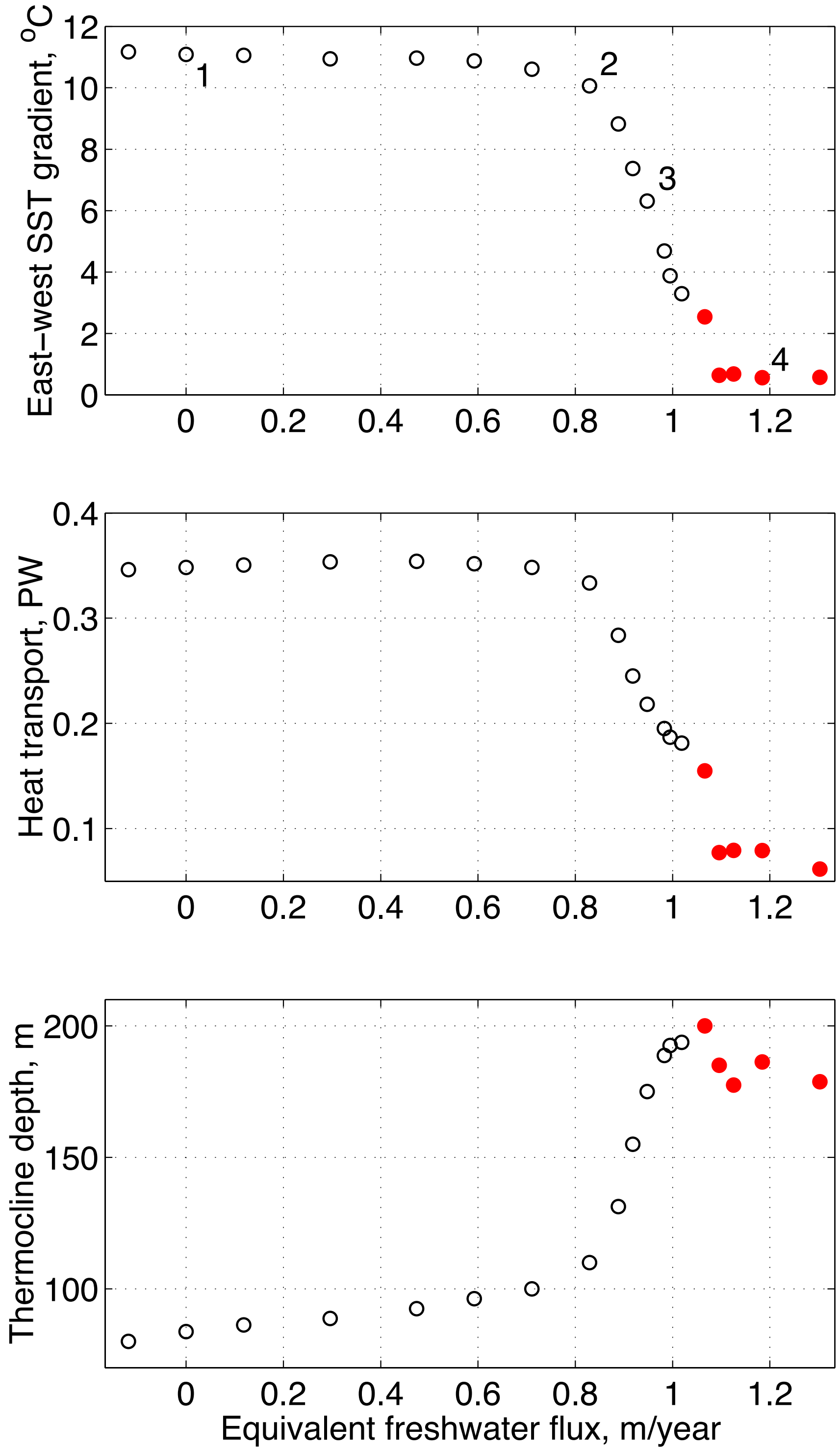
Depth, m
0
−50
−100
−150
−200
40W
30W
20W
10W
0
Longitude
15S
10S
5S
Eq
5N
10N
15N
Latitude
1023
1024
1024.5
1025
1025.5
1026
1026.5
1027
1027.5



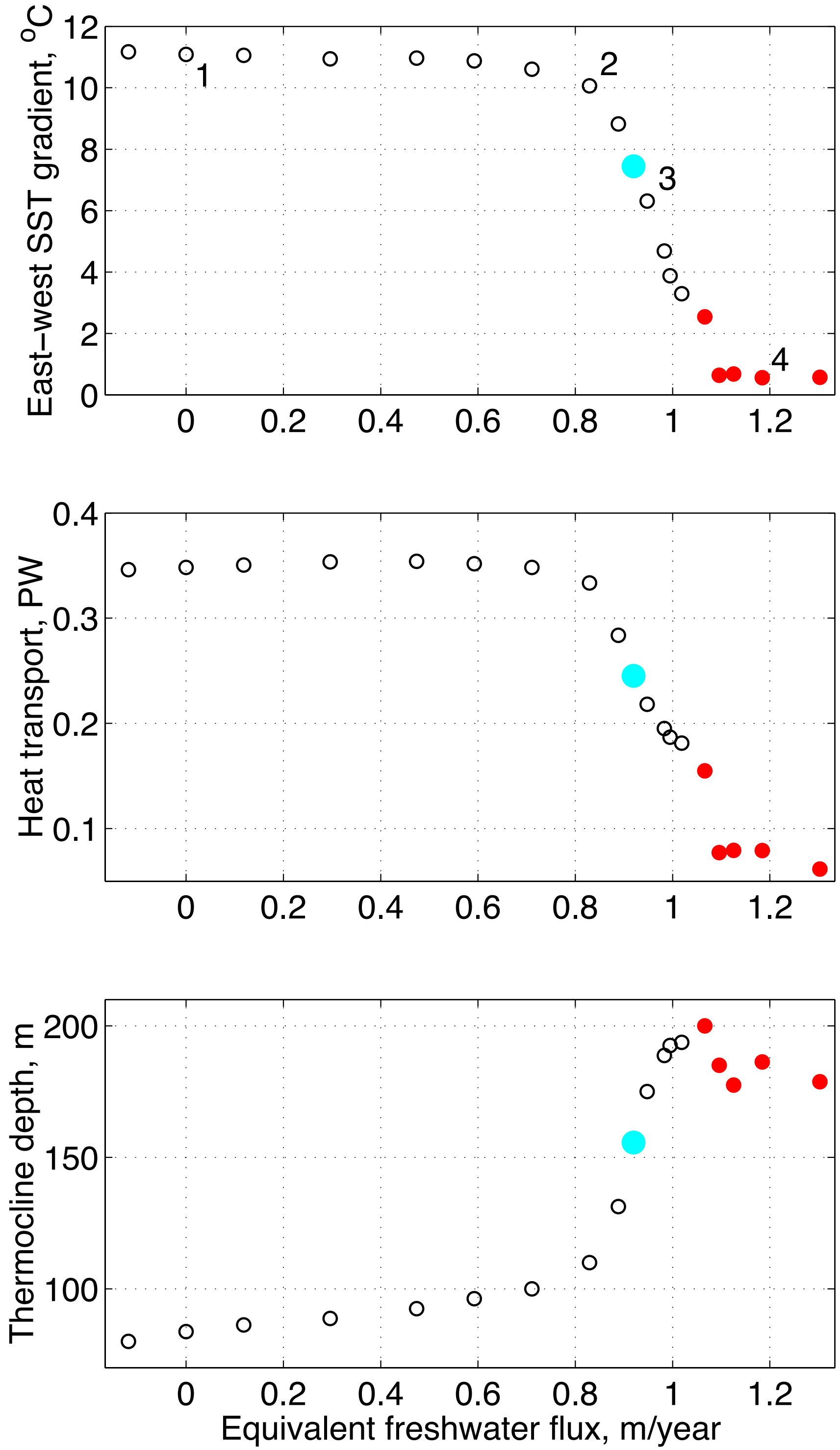
East–west SST gradient, °C
1
2
3
4
Heat transport, PW
Thermocline depth, m
Equivalent freshwater flux, m/year

Horizontal density ratio R



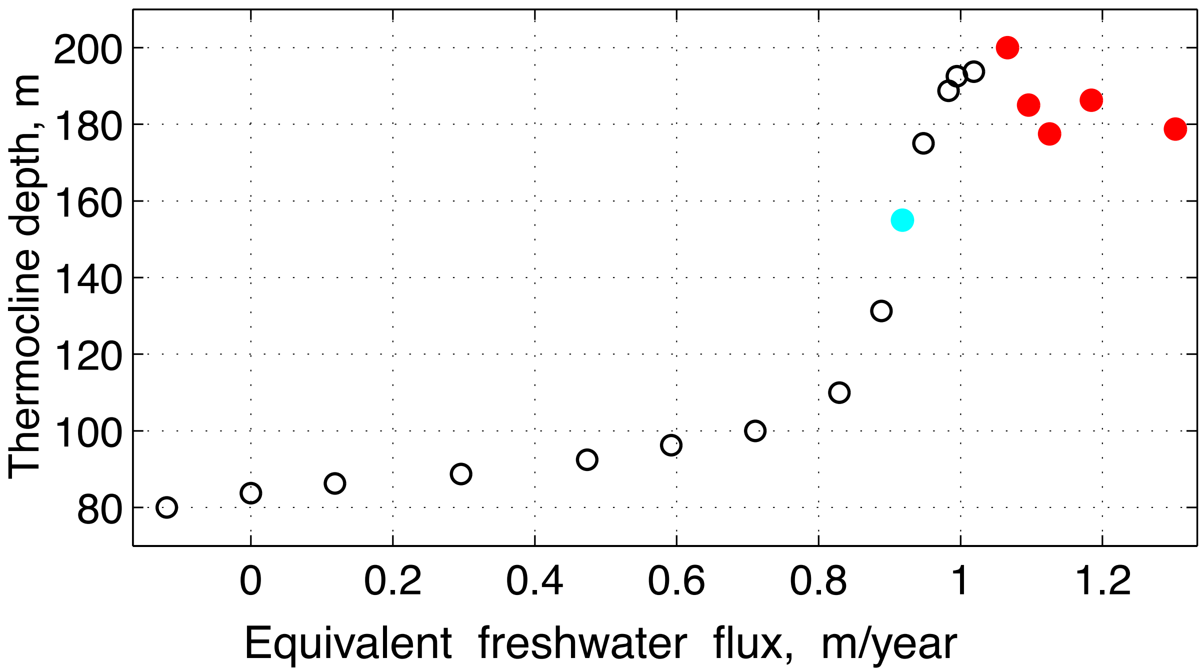


East–west SST gradient, °C
Heat transport, PW
Thermocline depth, m
Equivalent freshwater flux, m/year
1
2
3
4



East–west SST gradient, °C
12
10
8
6
4
2
0
1
2
3
4
0
0.2
0.4
0.6
0.8
1
1.2
Heat transport, PW
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
1.2
Thermocline depth, m
200
150
100
0
0.2
0.4
0.6
0.8
1
1.2
Equivalent freshwater flux, m/year

Themocline depth.



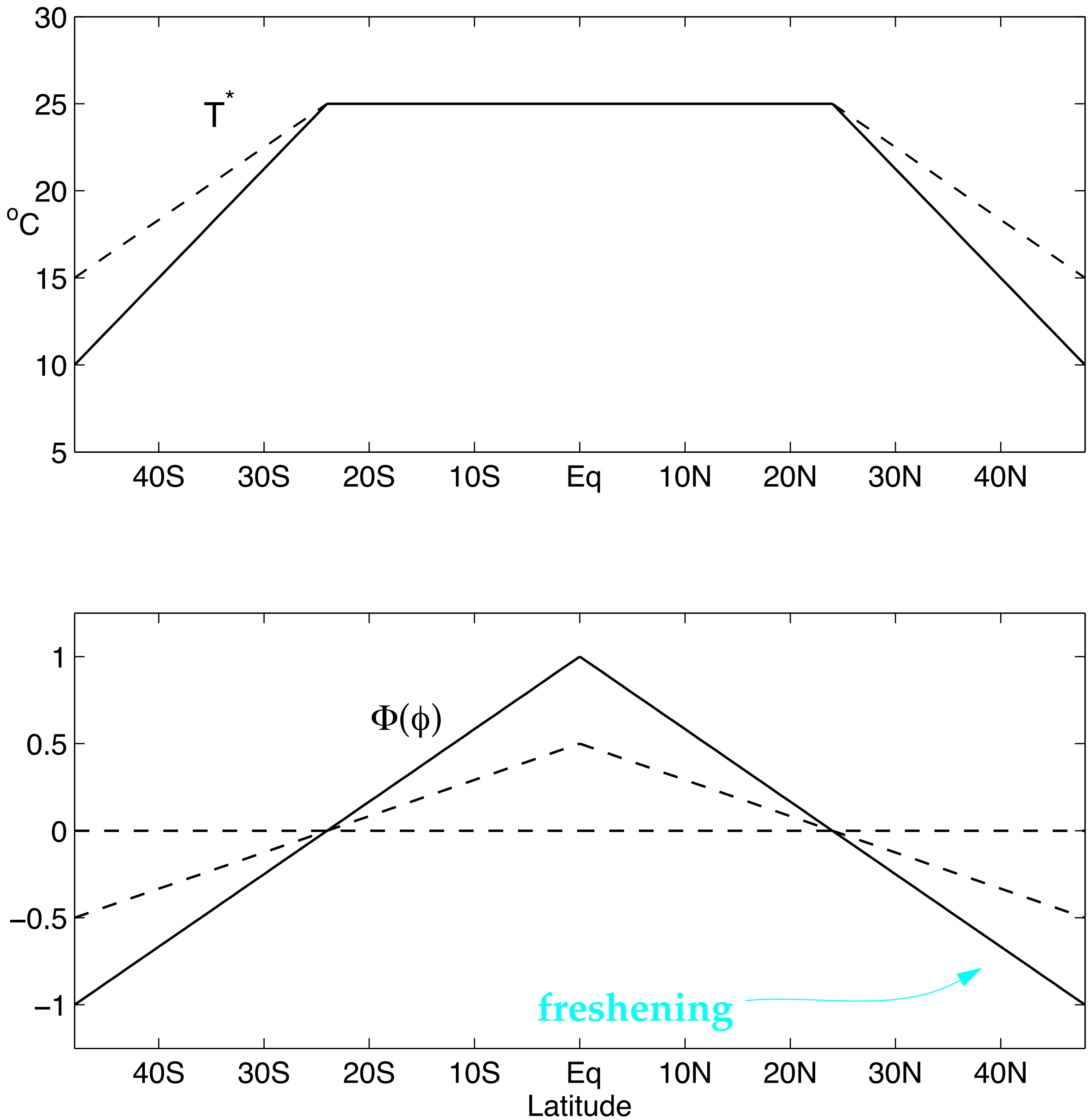
The large-basin model (GFDL MOM4):

$1/2^o$ horizontal resolution
32 levels in the vertical

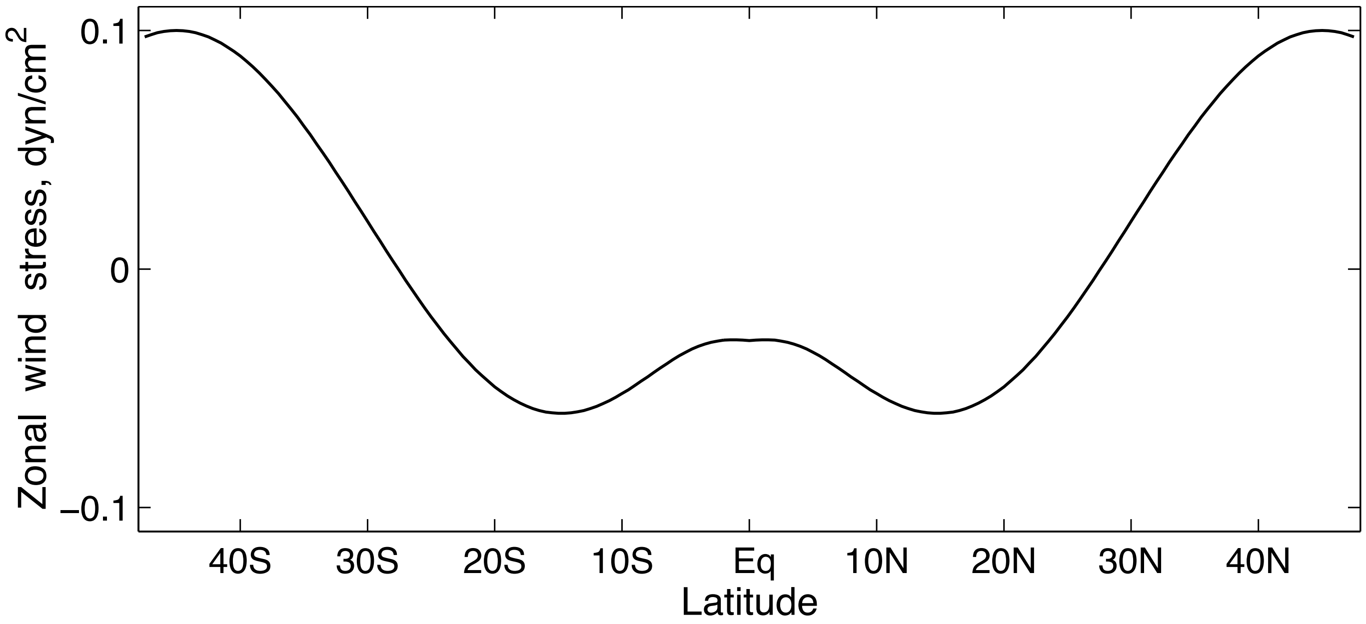
Latitude: 48^oN - 48^oS
Longitude: 120^oE- 280^oE

(almost the size of the Pacific ocean)

B.C. $K\frac{\partial T}{\partial Z} = -\gamma_T(T - T^*)$; $K\frac{\partial S}{\partial Z} = \gamma S_0 \Phi(\varphi)$

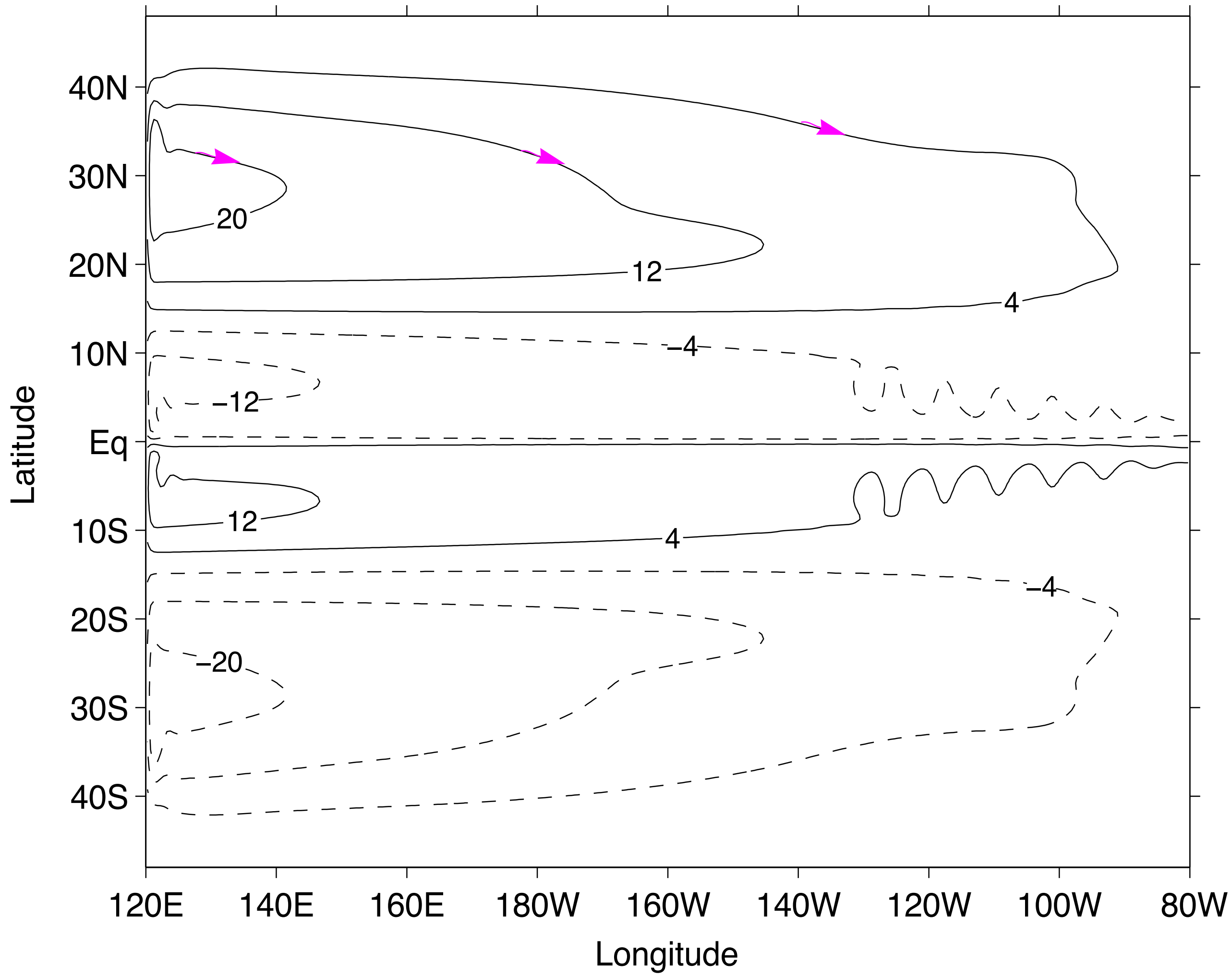


Zonal wind stress, $\tau^{(x)}$

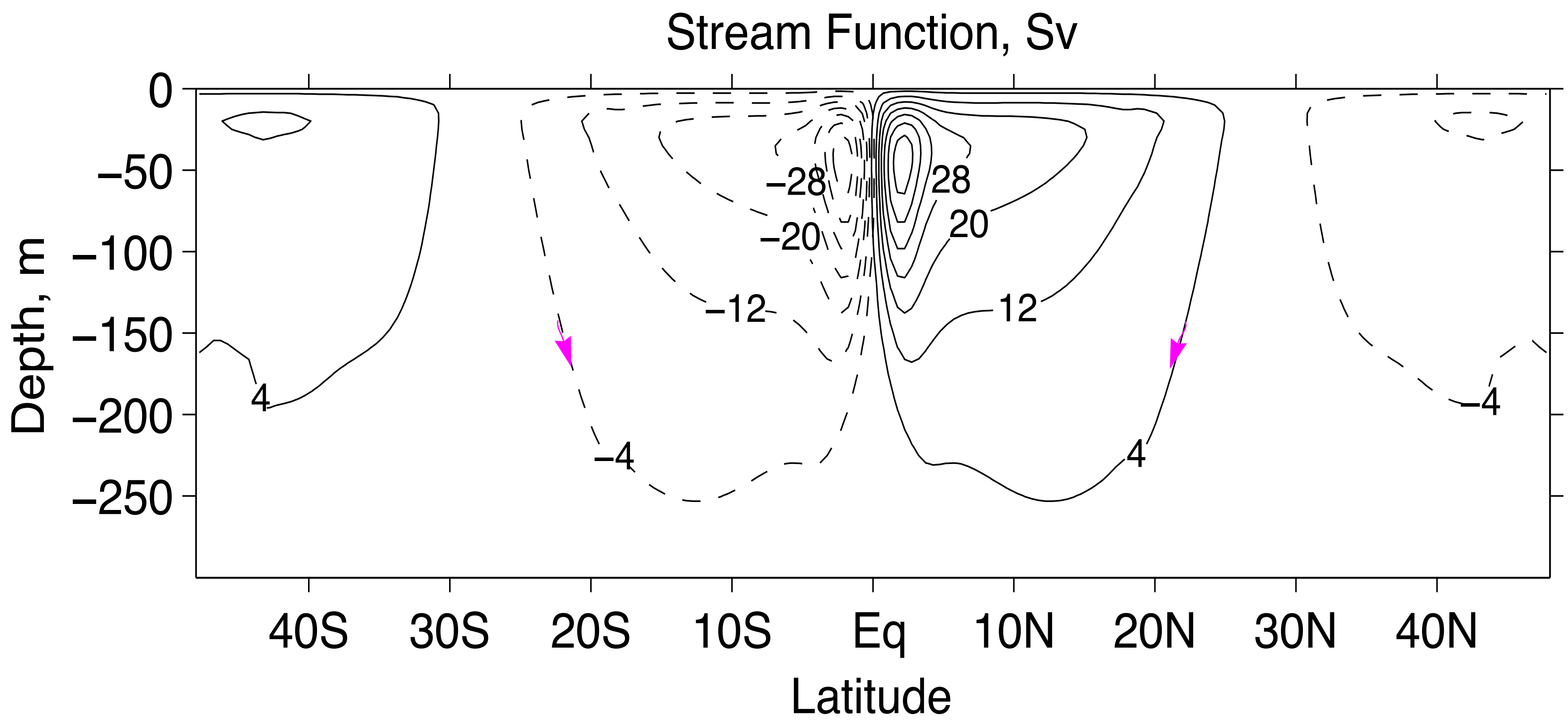


An analytic approximation to the zonally-averaged annual mean winds by Hellerman and Rosenstein, 1983

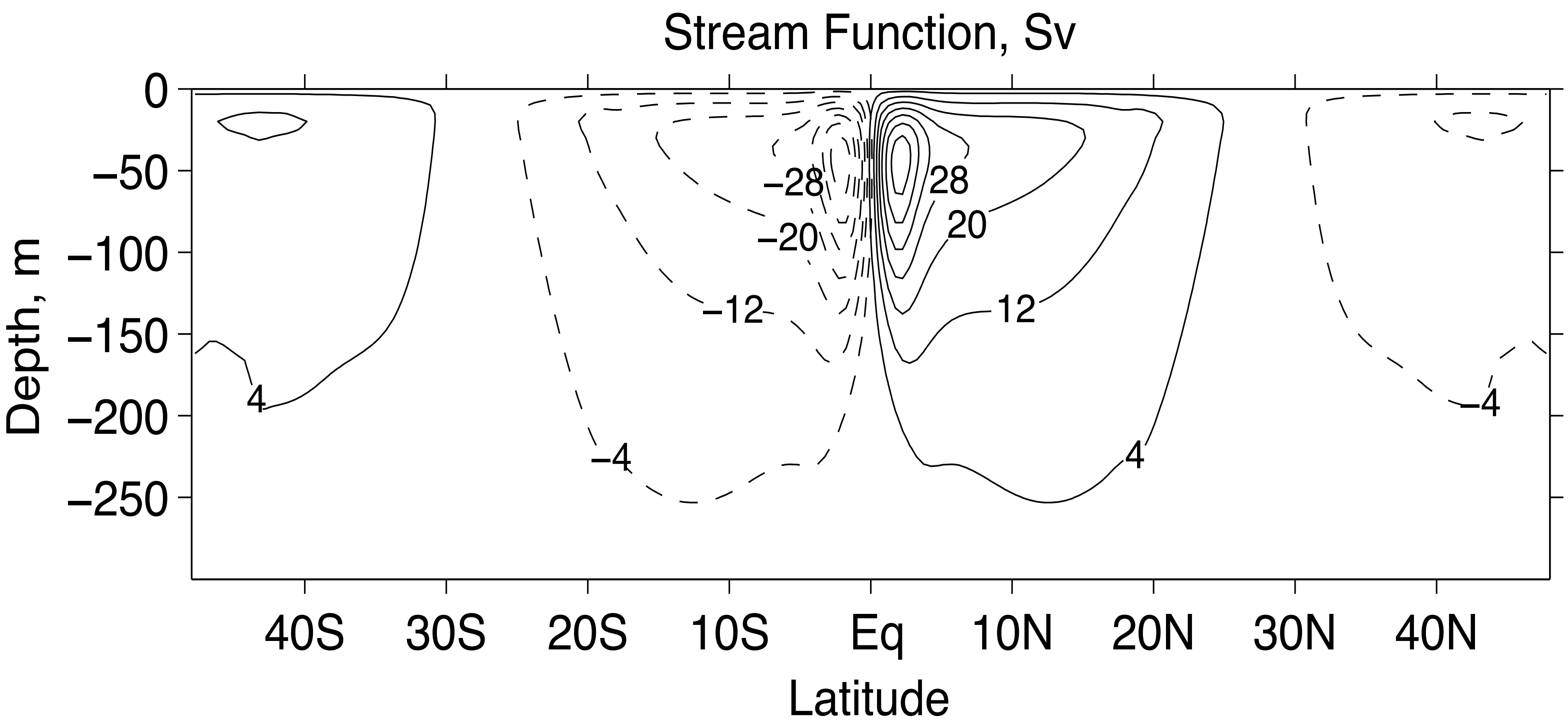
Vertically-integrated Stream Function, Sv

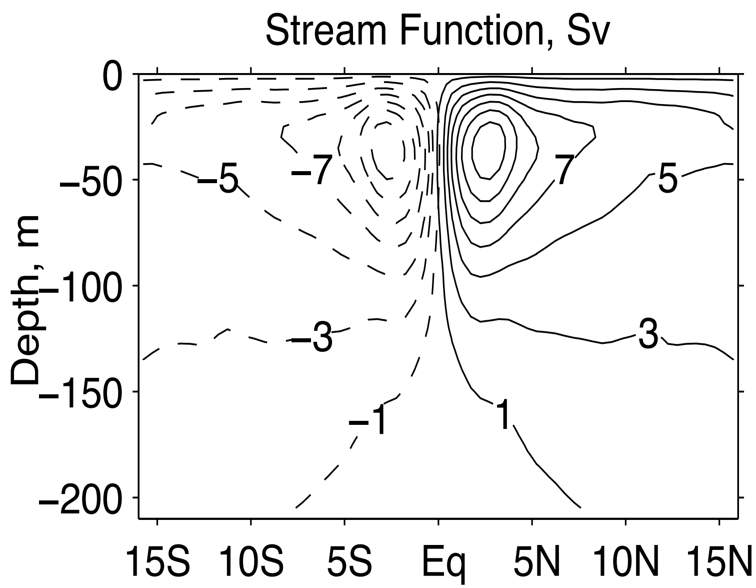


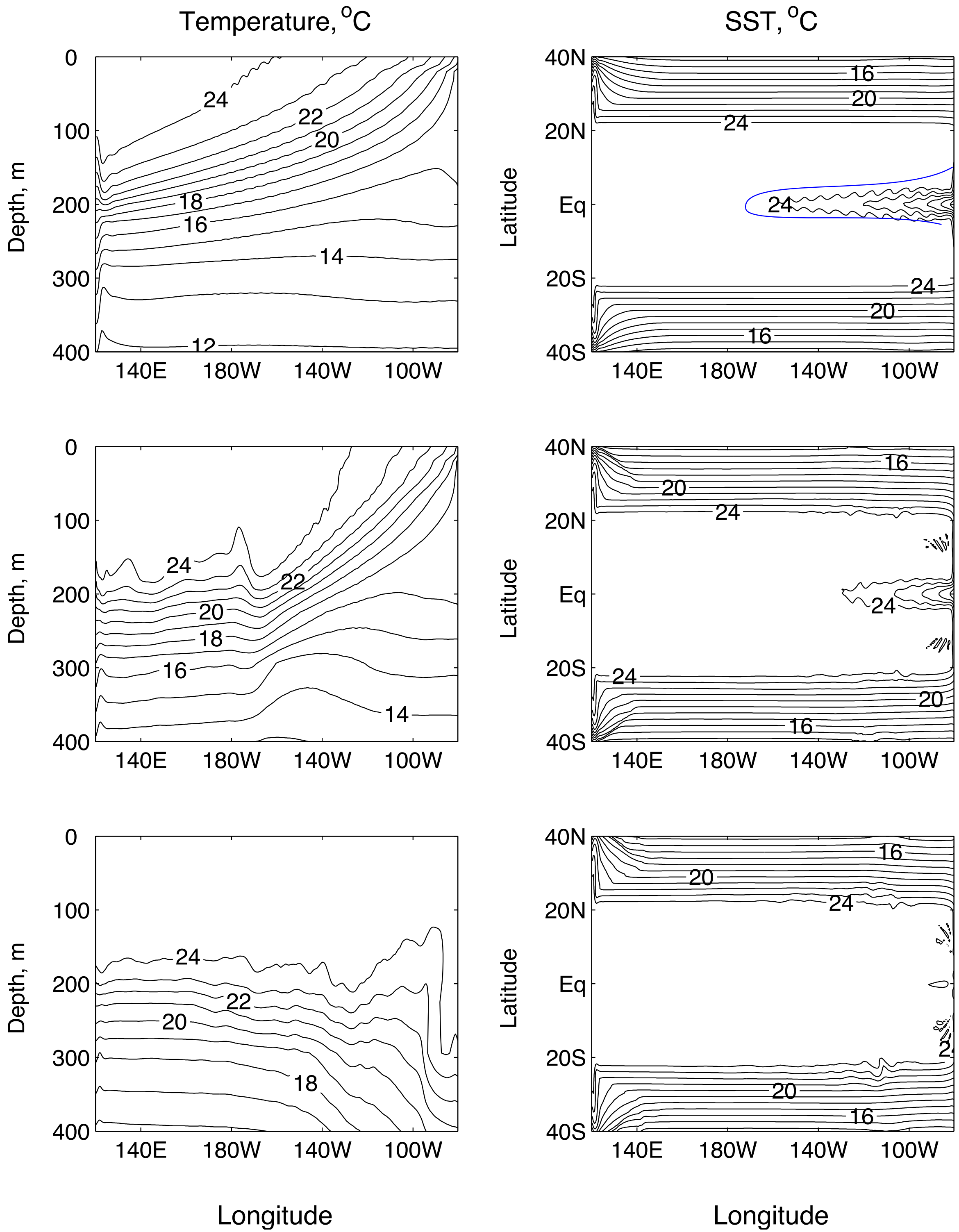
Overturning (zonally-integrated) stream function, Sv

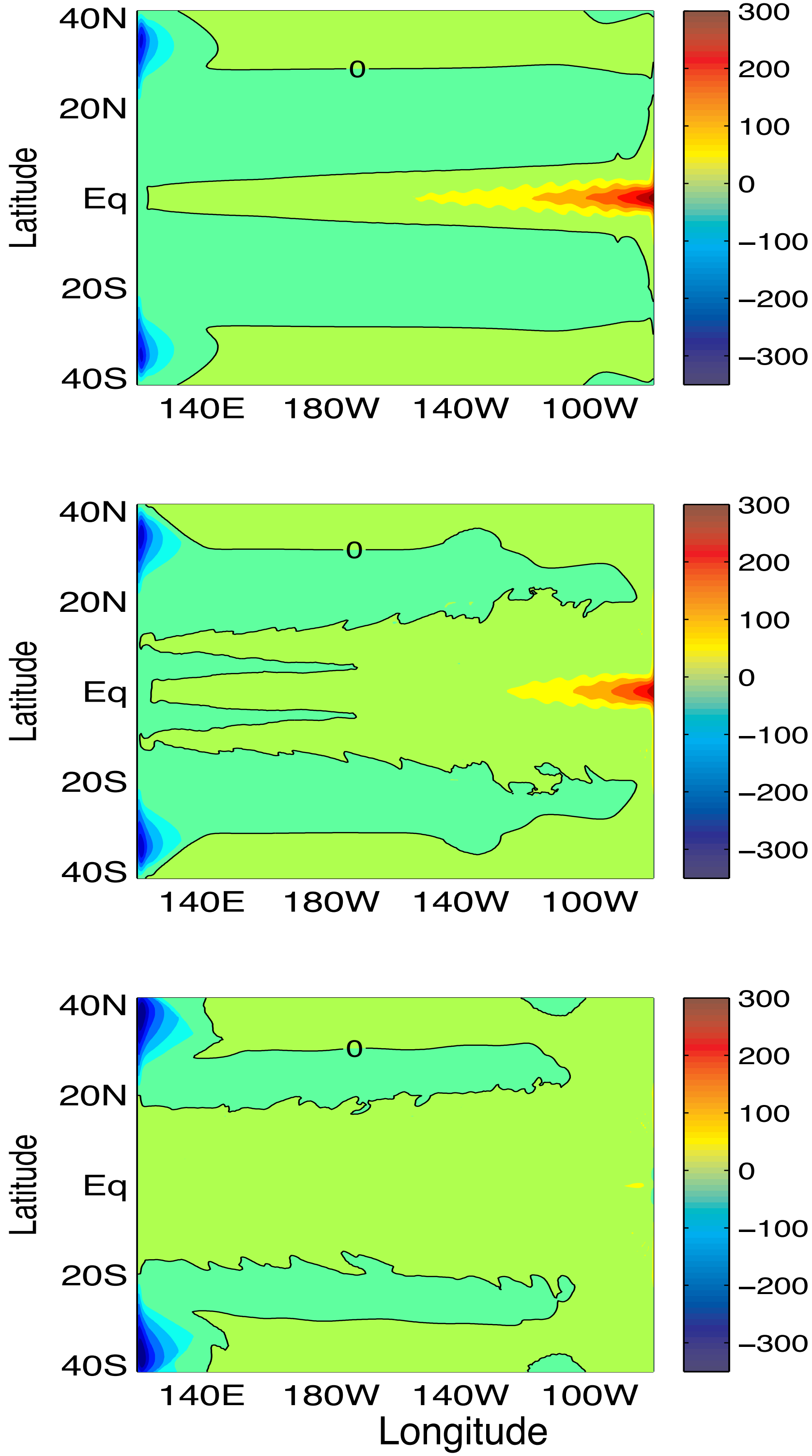


Overturning (zonally-integrated) stream function, Sv

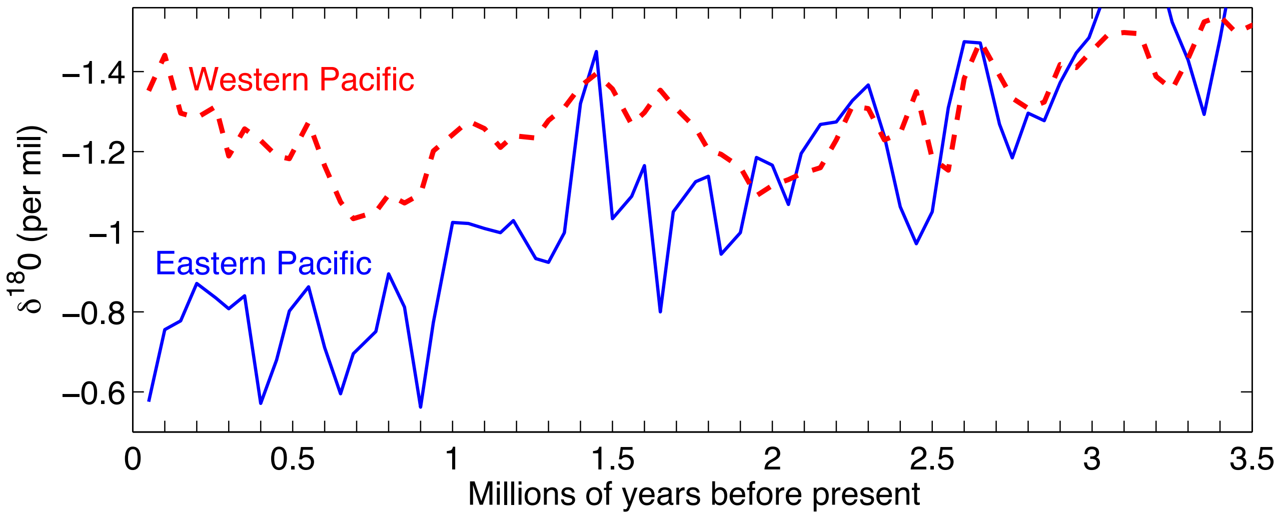




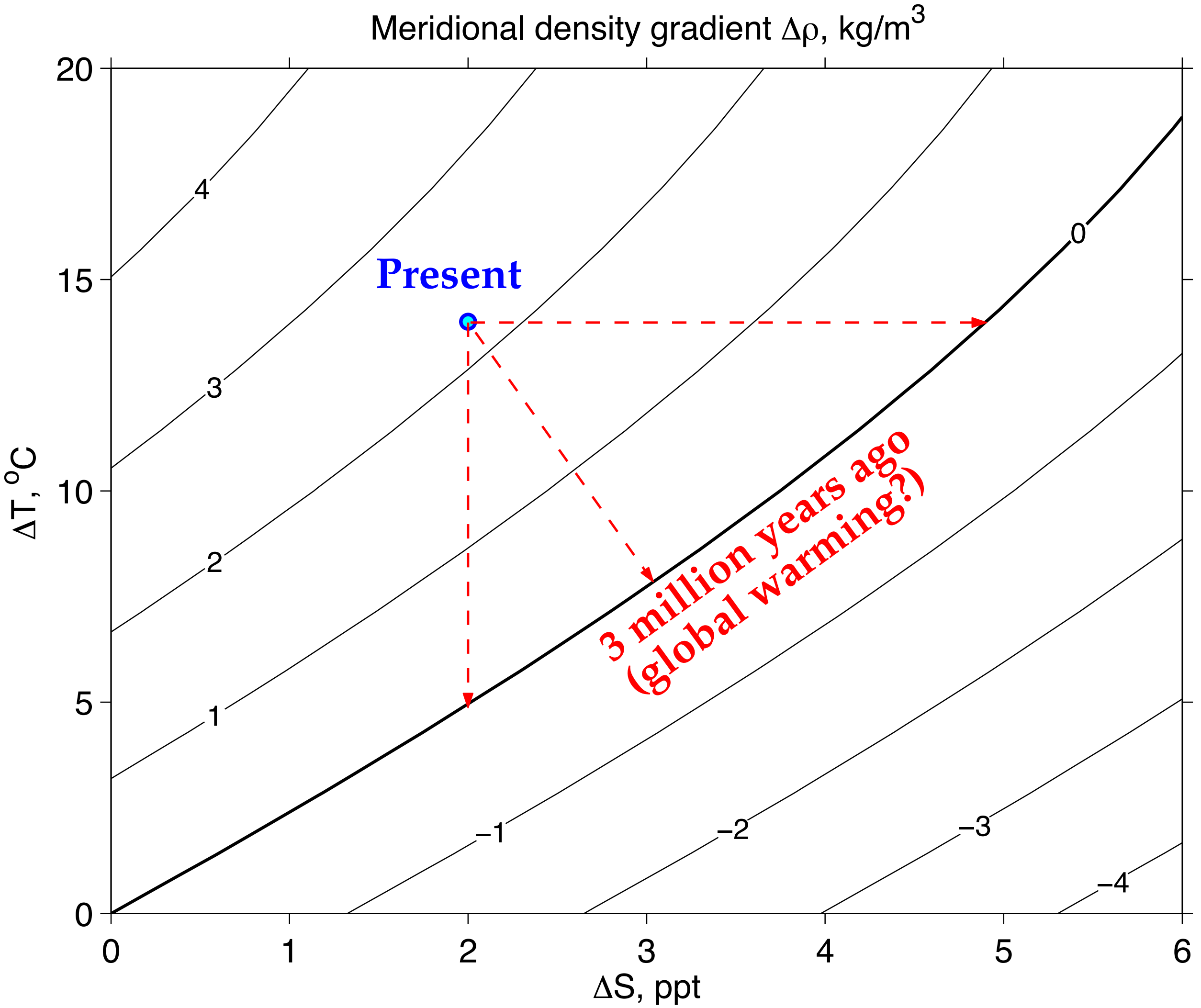

Temperature, ^oC
SST, ^oC
Depth, m
Latitude
Longitude
0
100
200
300
400
40N
20N
Eq
20S
40S
140E
180W
140W
100W
24
22
20
18
16
14
12



Downward Heat Flux

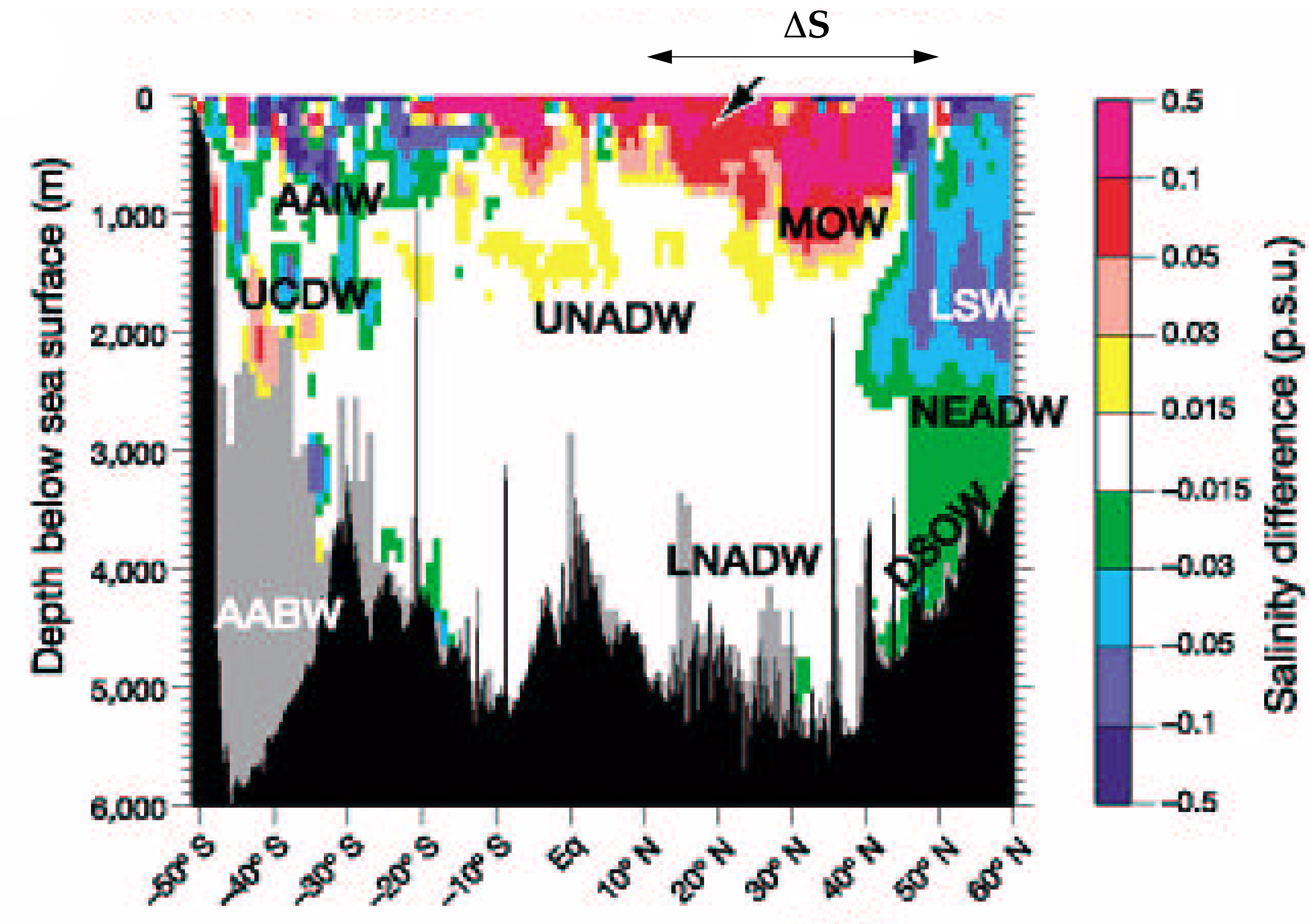


Western Pacific
Eastern Pacific
−1.4
−1.2
−1
−0.8
−0.6
δ18O (per mil)
0
0.5
1
1.5
2
2.5
3
3.5
Millions of years before present



Meridional density gradient Δρ, kg/m3
Present
3 million years ago
(global warming?)
ΔT, oC
ΔS, ppt
4
3
2
1
0
−1
−2
−3
−4
20
15
10
5
0
0
1
2
3
4
5
6

Changes in salinity over half-a-century in the Atlantic ocean

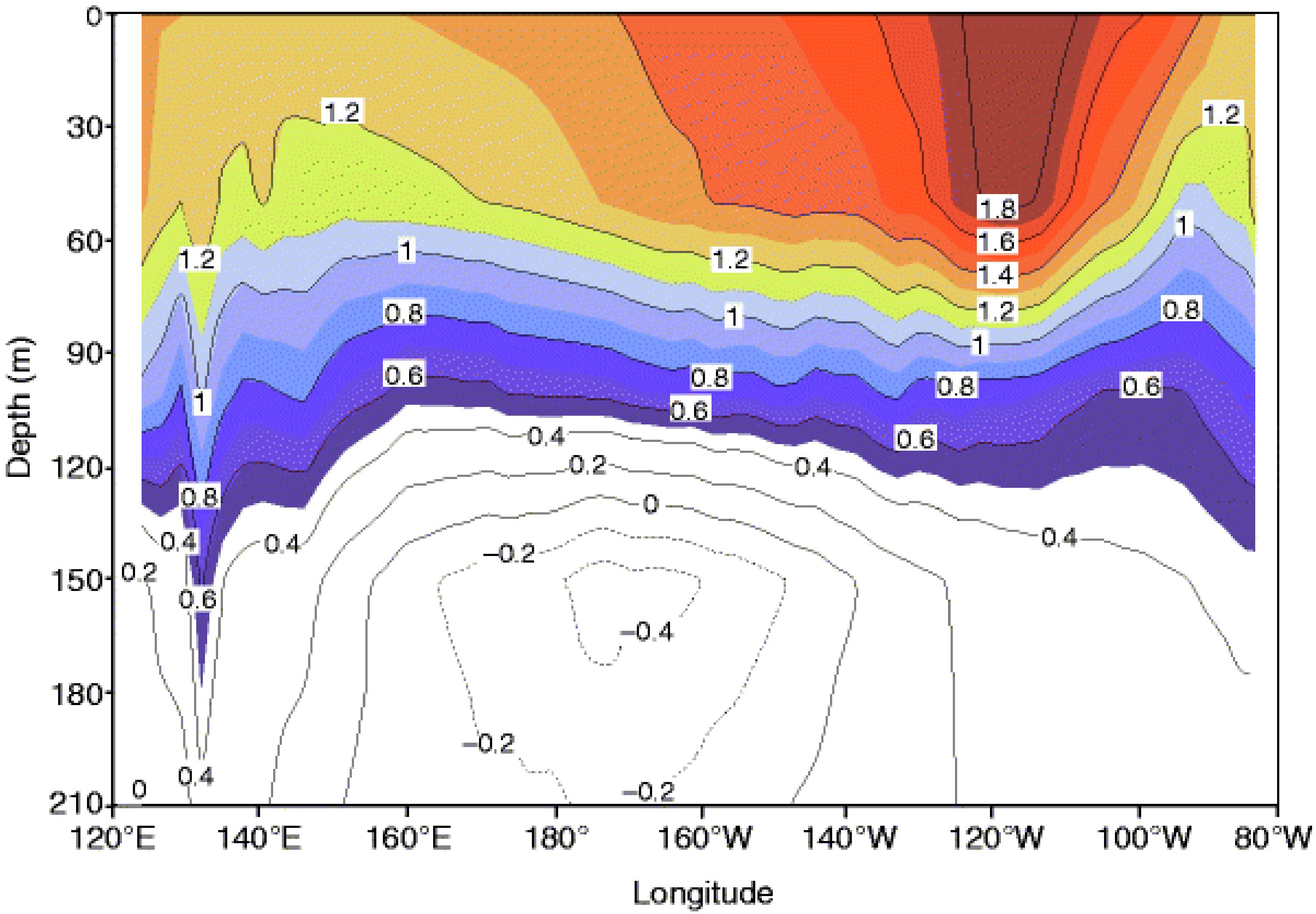


(After Curry et al 2003)

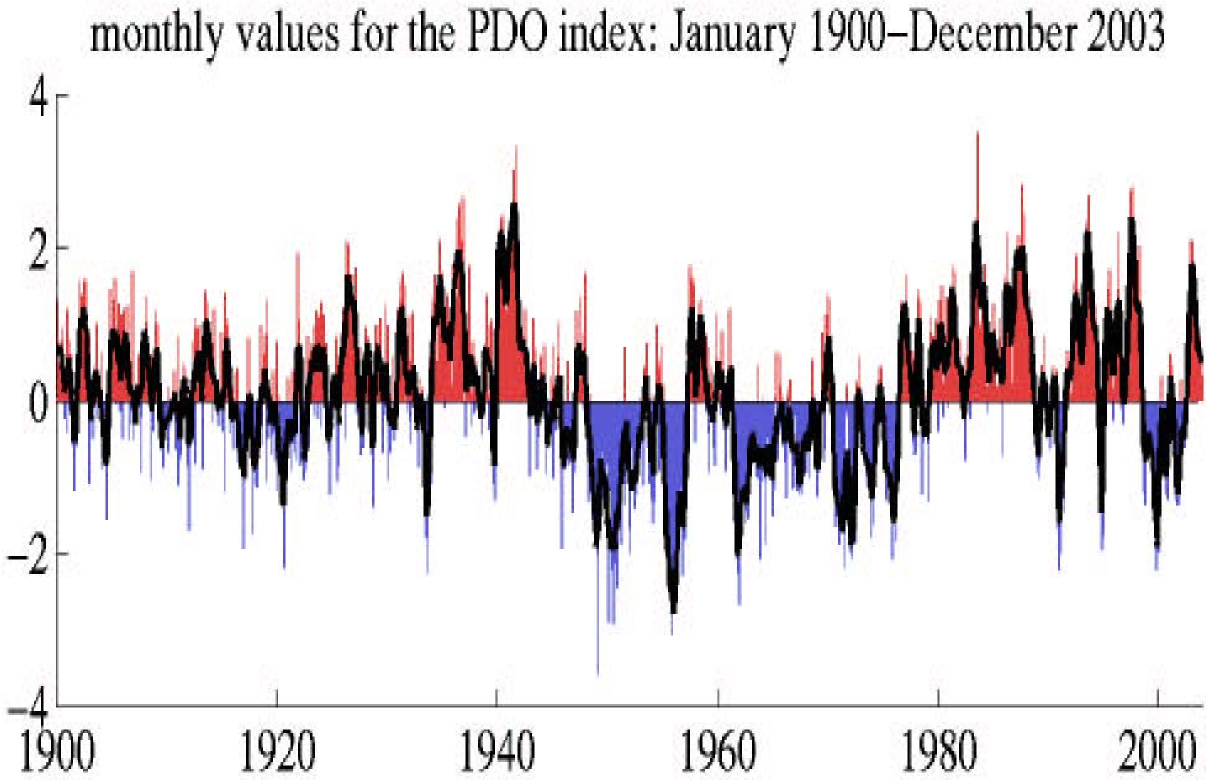
Conclusions

- **The wind-driven circulation, and the ventilated thermocline, appear to be sensitive to changes in surface freshwater fluxes, as well as in the meridional temperature gradient.**

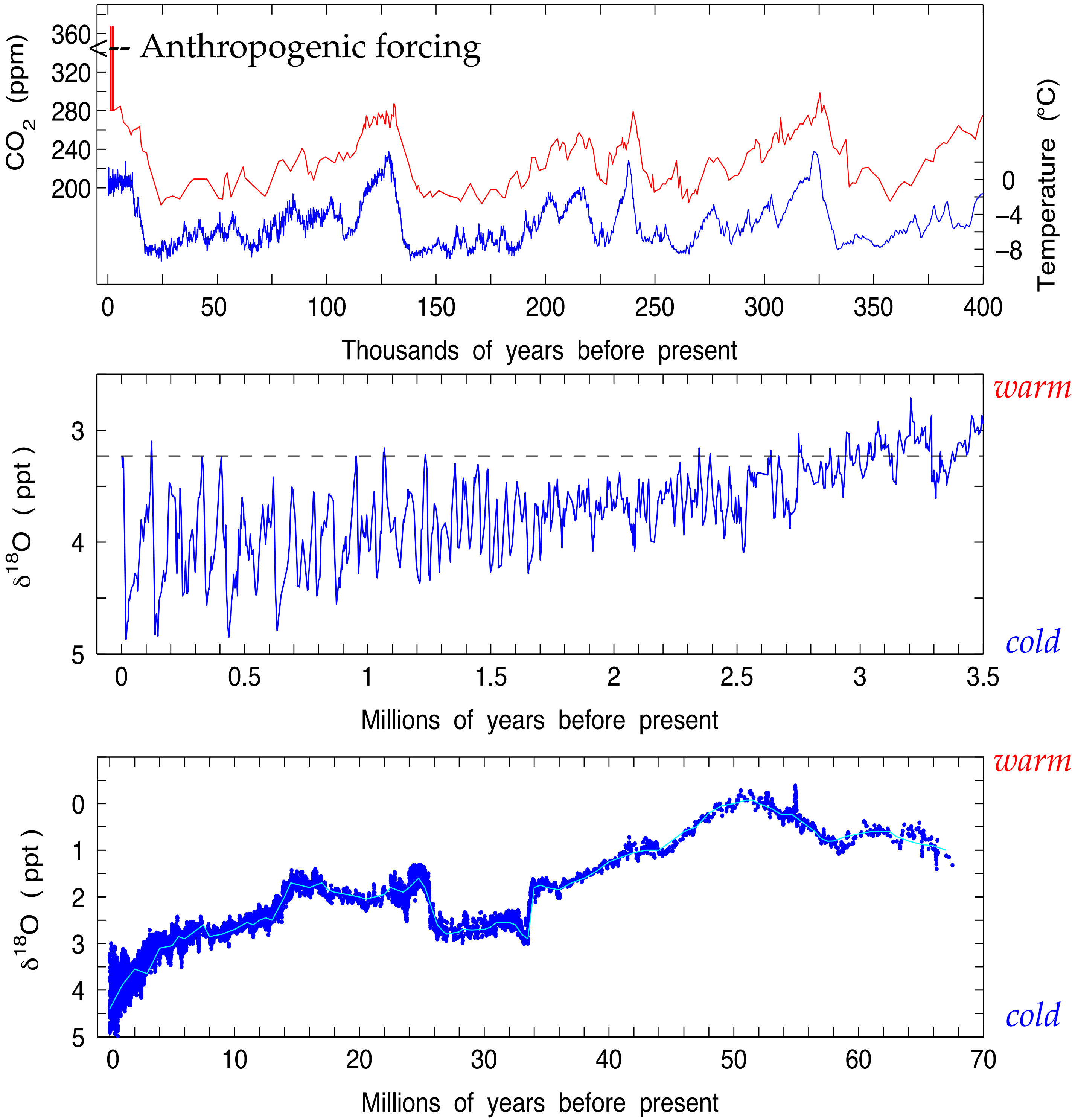
- **The possibility that global warming may lead to permanent El Niño-like conditions (which happened in the past) can not be excluded. It would happen if $R=\alpha\Delta S/\beta\Delta T \rightarrow 1$.**



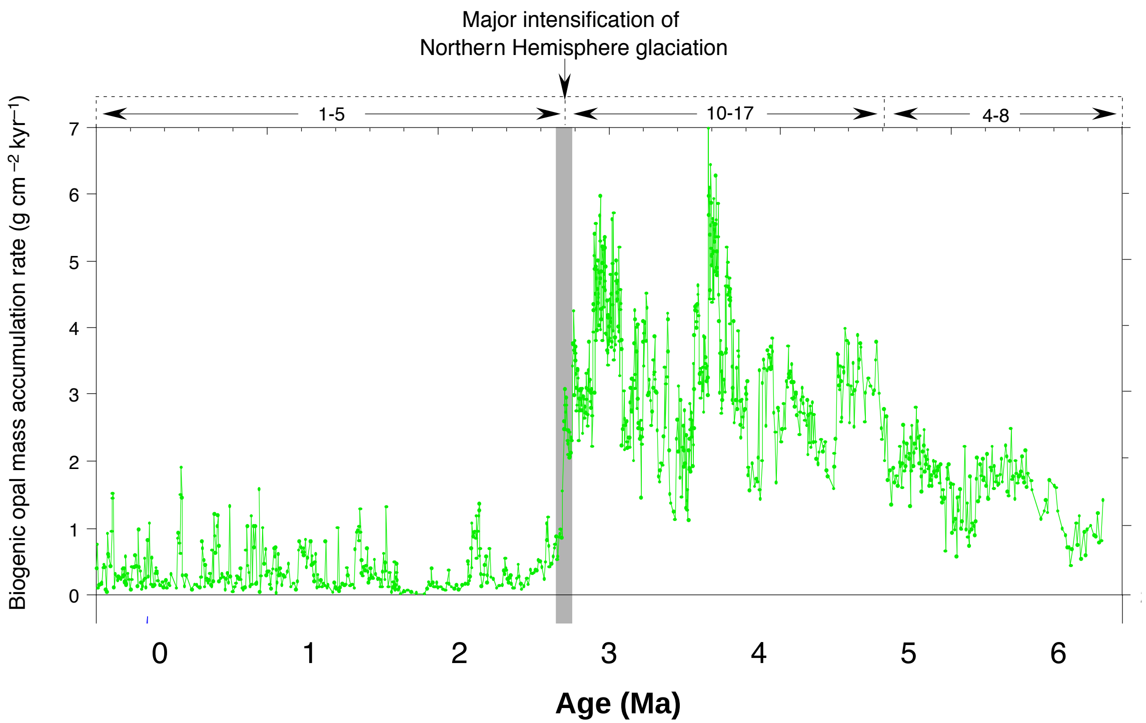
Simulated temperature trends in equatorial waters. The linear trends in the temperatures (˚C rise per 100 years) are derived from a 240-year-long transient greenhouse warming simulation. The trends at the surface resemble the anomalous conditions observed during present-day El Niño. (after TIMMERMANN et al 1999)



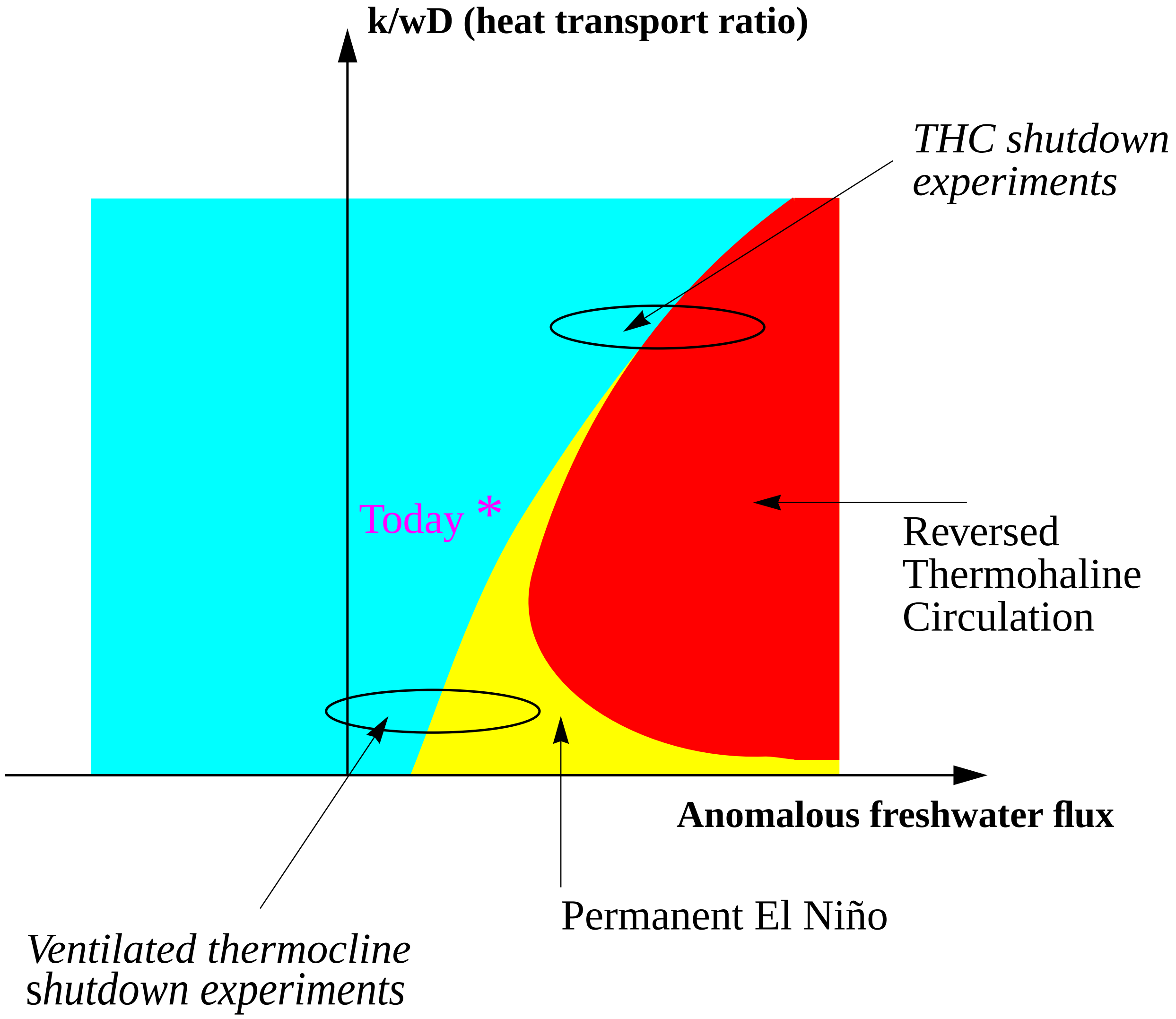
Pacific Decadal Oscillation.



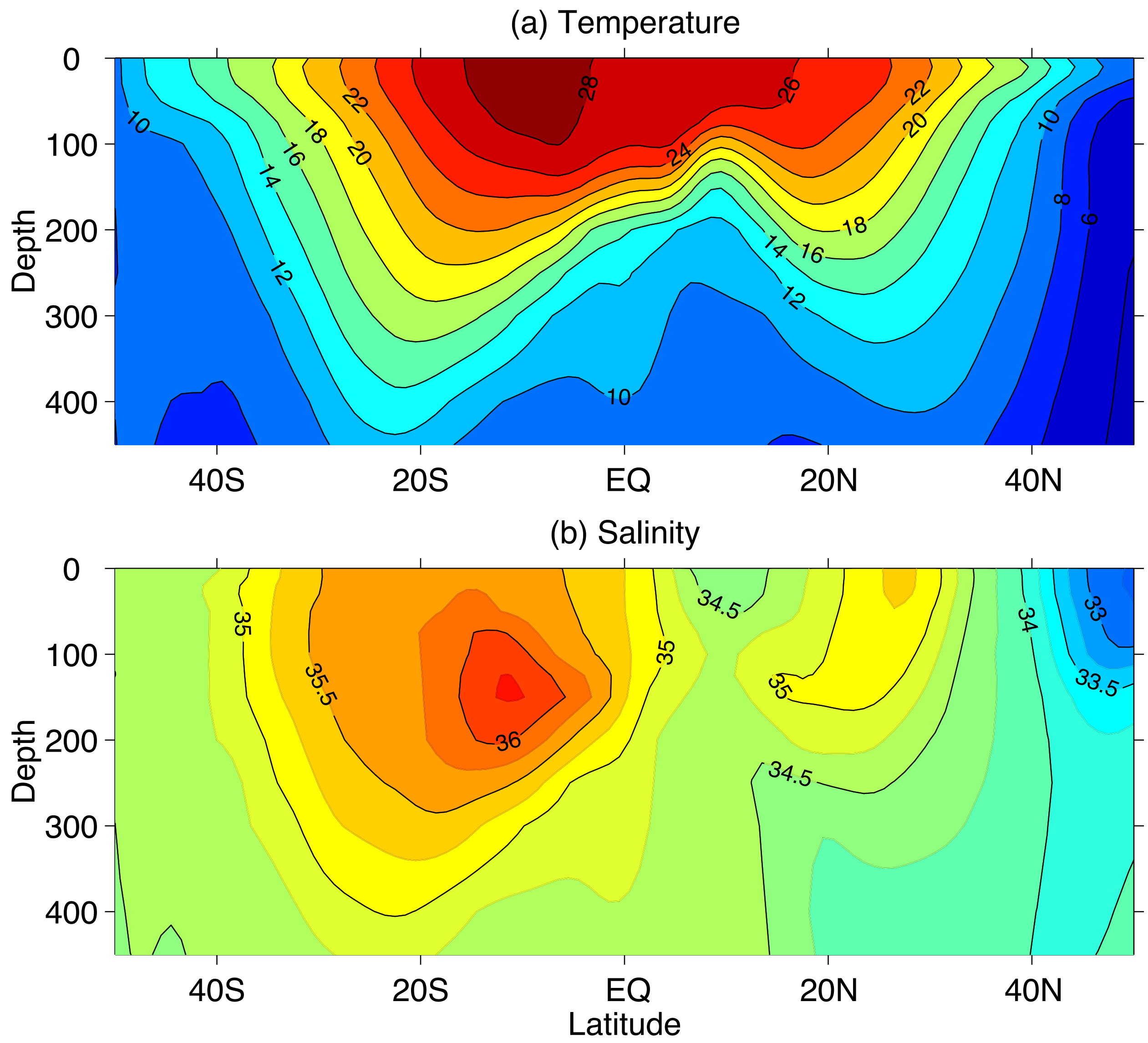
<-- Anthropogenic forcing
CO2 (ppm)
360
320
280
240
200
Temperature (°C)
0
−4
−8
0
50
100
150
200
250
300
350
400
Thousands of years before present
warm
cold
δ18O (ppt)
3
4
5
0
0.5
1
1.5
2
2.5
3
3.5
Millions of years before present
warm
cold
δ18O (ppt)
0
1
2
3
4
5
0
10
20
30
40
50
60
70
Millions of years before present



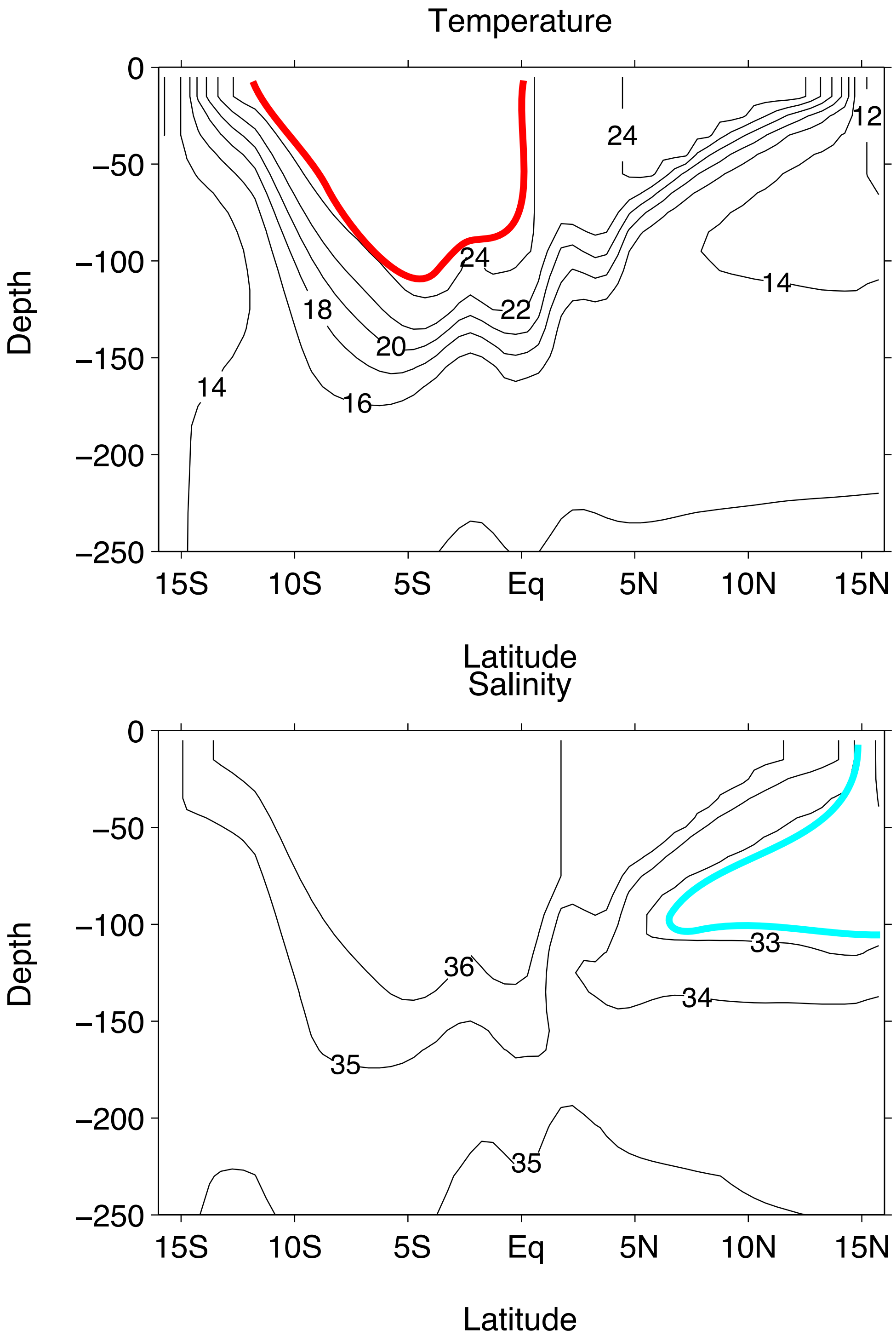
Mass accumulation rates of biogenic opal in the North Pacific.
The change in biological production 2.7 million years ago
may indicate a major shift in ocean stratification.
(after Haug *et al* 1999)



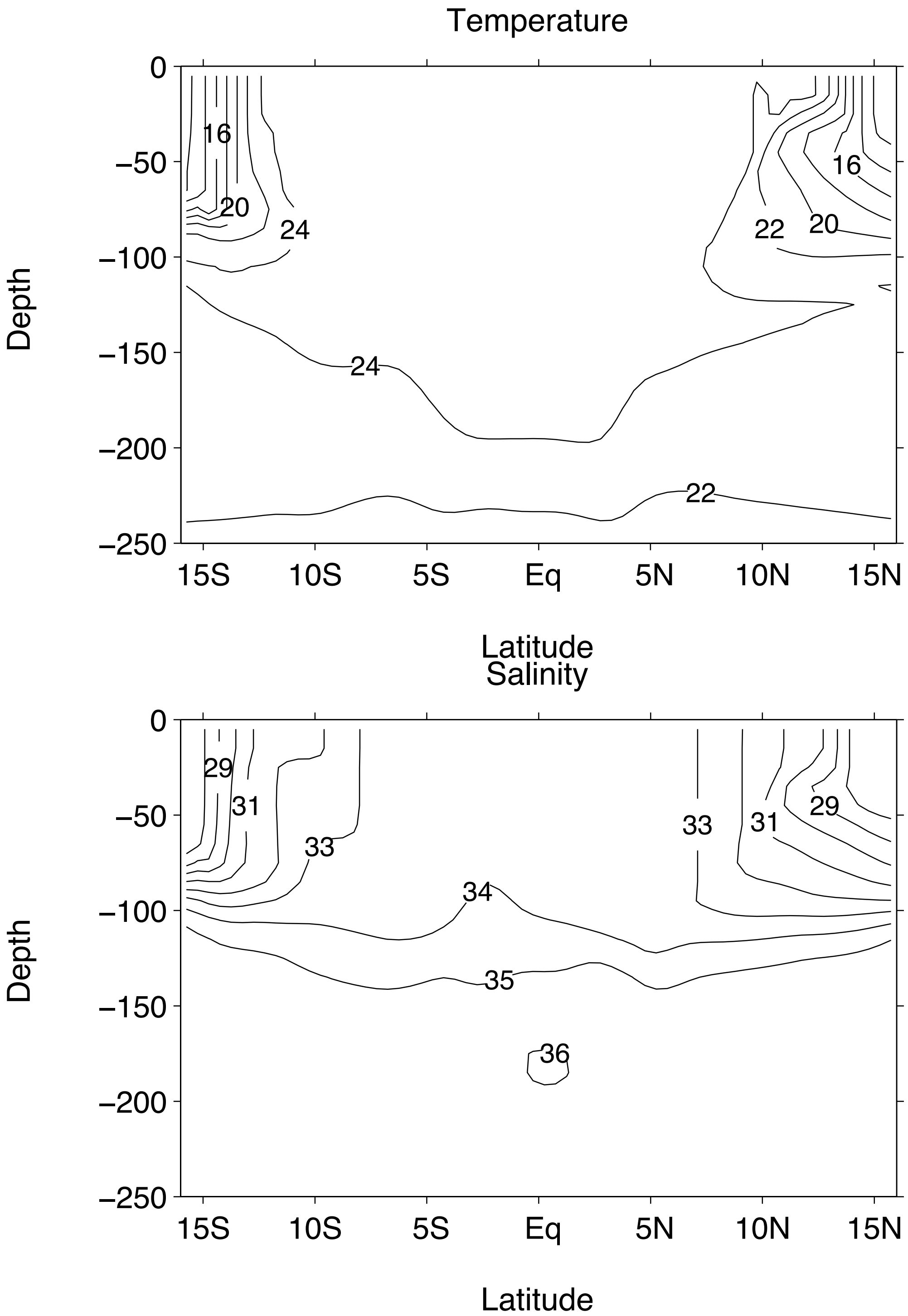
k/wD (heat transport ratio)
THC shutdown
experiments
Today *
Reversed
Thermohaline
Circulation
Anomalous freshwater flux
Permanent El Niño
Ventilated thermocline
shutdown experiments

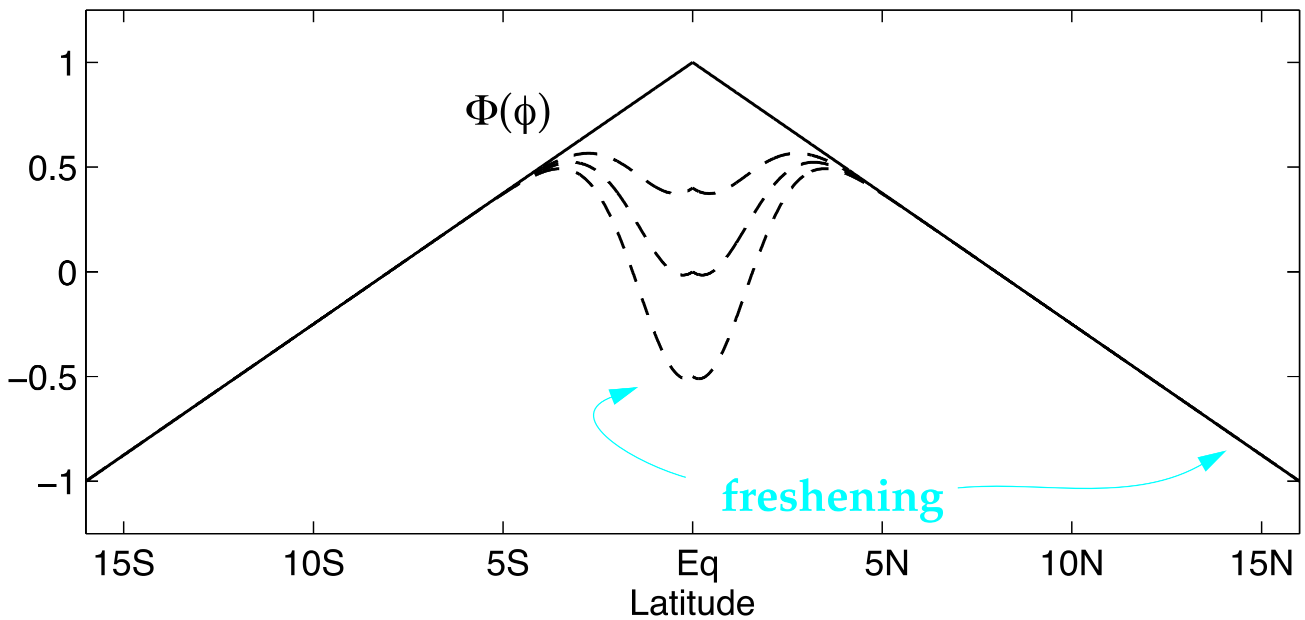


Meridional (a) temperature and (b) salinity variations along 165^0W in the Pacific ocean

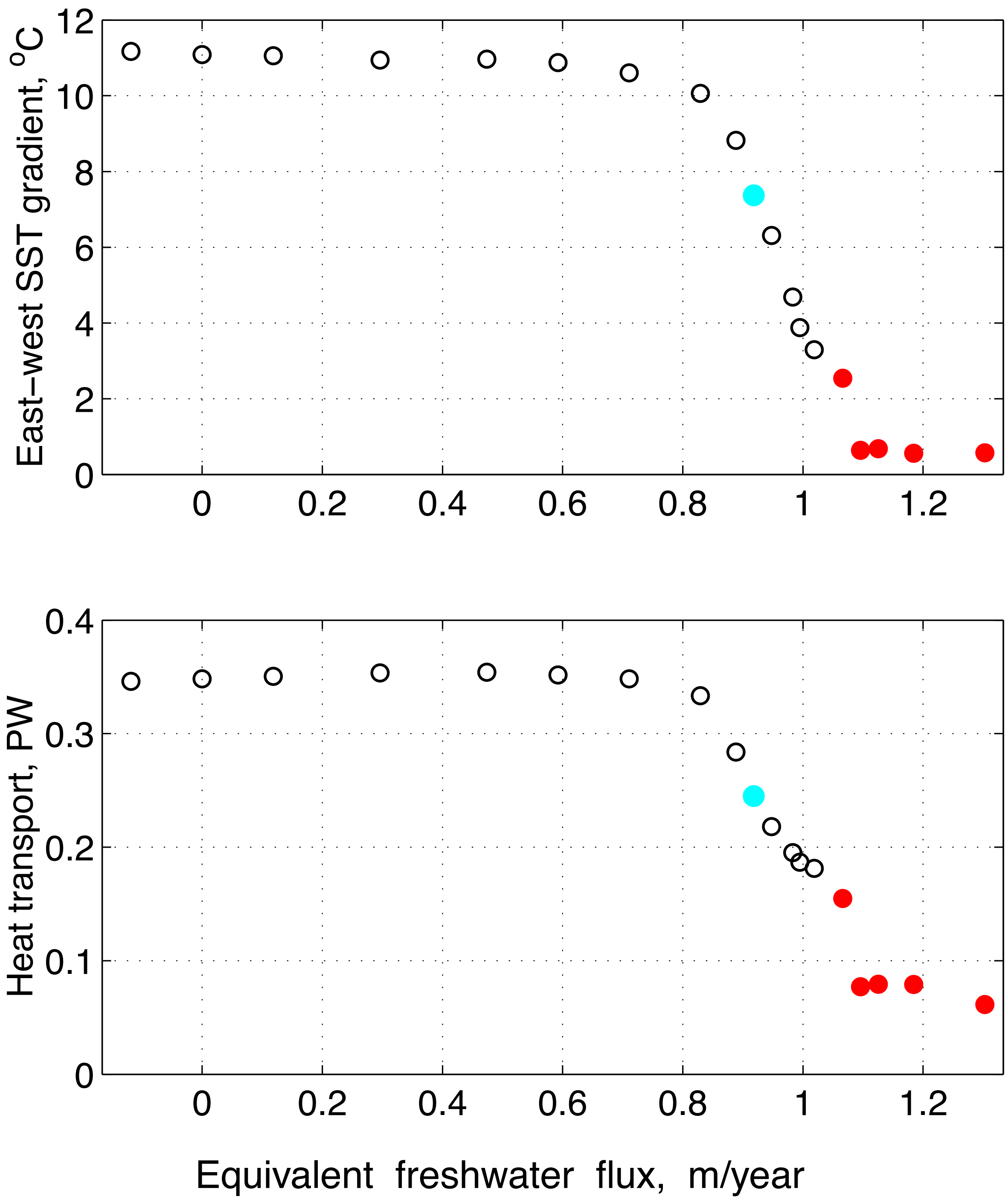


Temperature
0
−50
−100
−150
−200
−250
Depth
24
12
24
14
18
22
20
14
16
15S
10S
5S
Eq
5N
10N
15N
Latitude
Salinity
0
−50
−100
−150
−200
−250
Depth
36
33
34
35
35
15S
10S
5S
Eq
5N
10N
15N
Latitude


Temperature
Depth
Latitude
16
20
24
24
22
16
20
22
0
−50
−100
−150
−200
−250
15S
10S
5S
Eq
5N
10N
15N
Salinity
Depth
Latitude
29
31
33
34
35
36
33
31
29
0
−50
−100
−150
−200
−250
15S
10S
5S
Eq
5N
10N
15N



1
0.5
0
−0.5
−1
Φ(ϕ)
freshening
15S
10S
5S
Eq
5N
10N
15N
Latitude



East–west SST gradient, °C
Heat transport, PW
Equivalent freshwater flux, m/year
0
0.2
0.4
0.6
0.8
1
1.2
0
2
4
6
8
10
12
0.1
0.2
0.3
0.4

Zonal (vertically-integrated) stream function