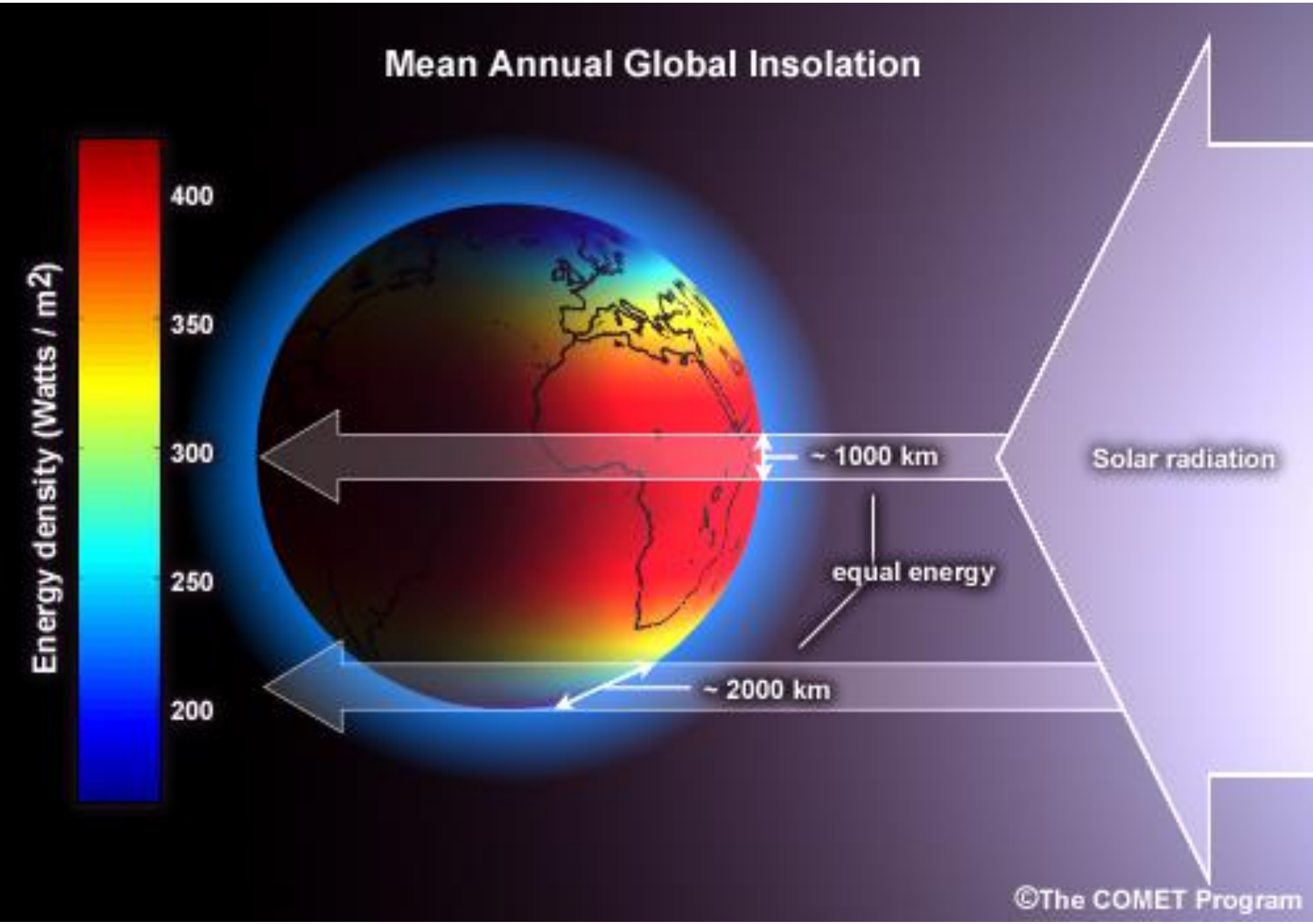
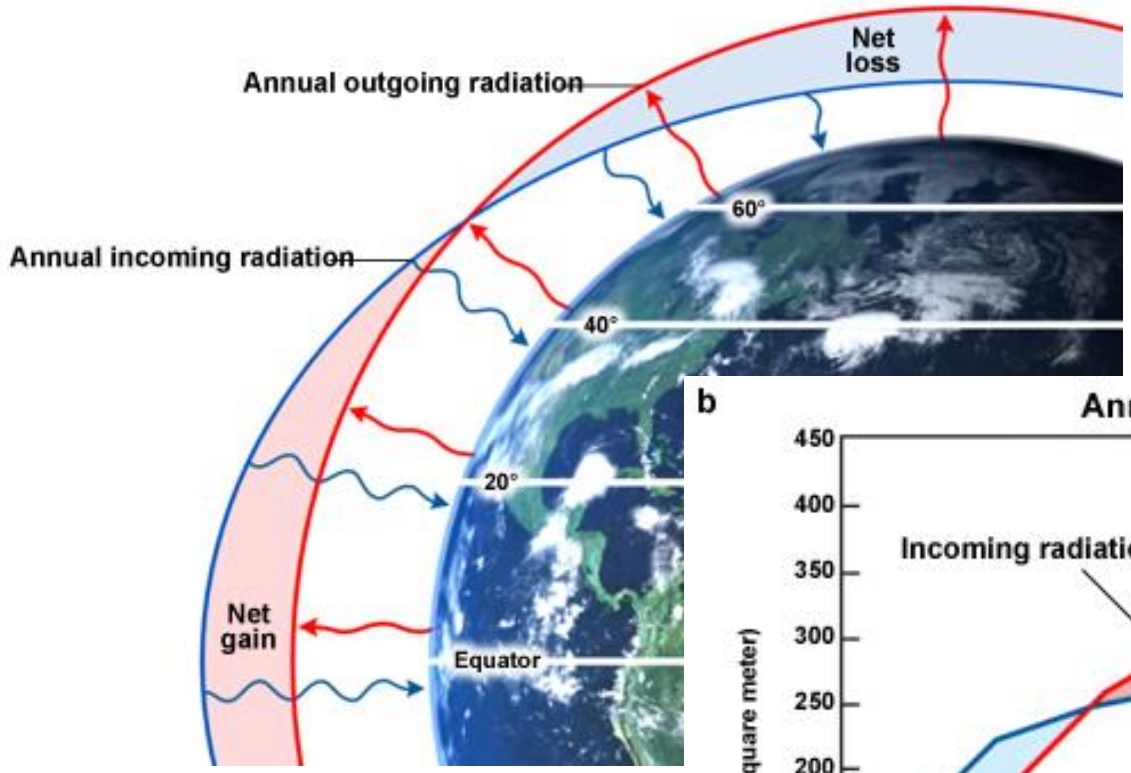
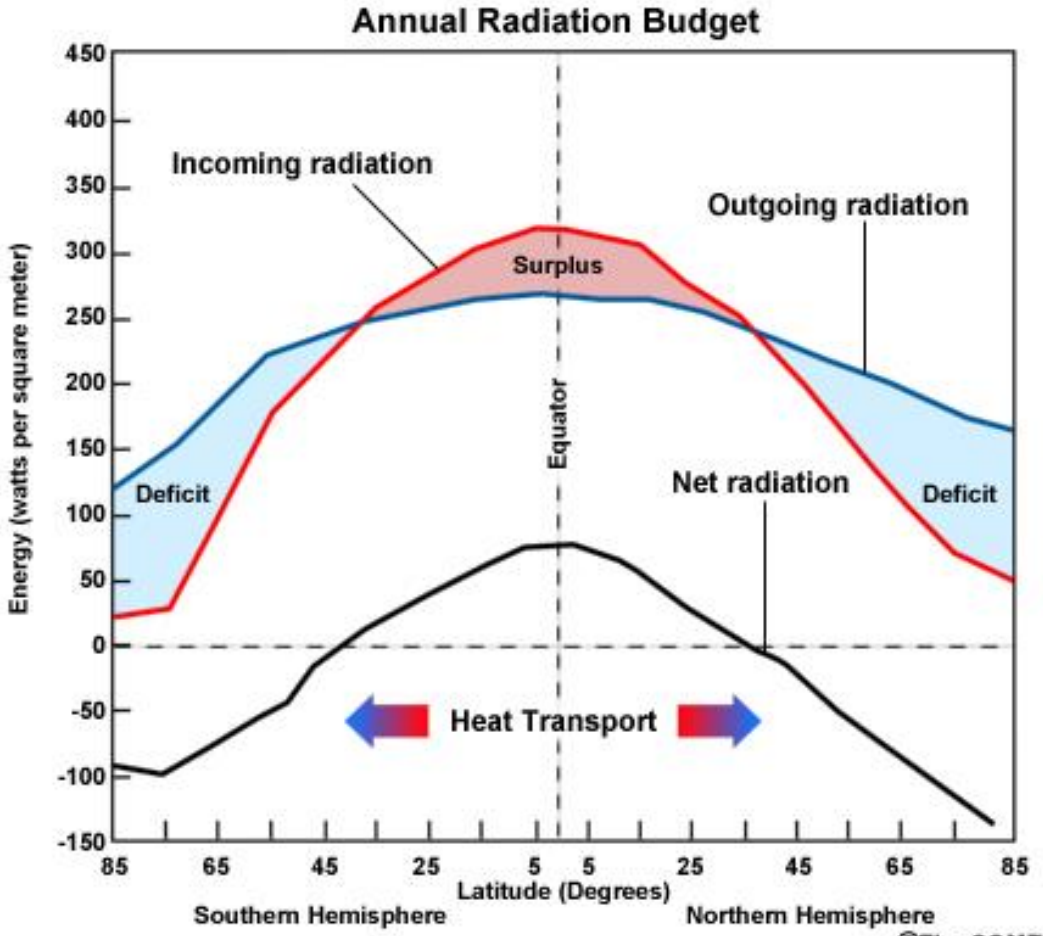
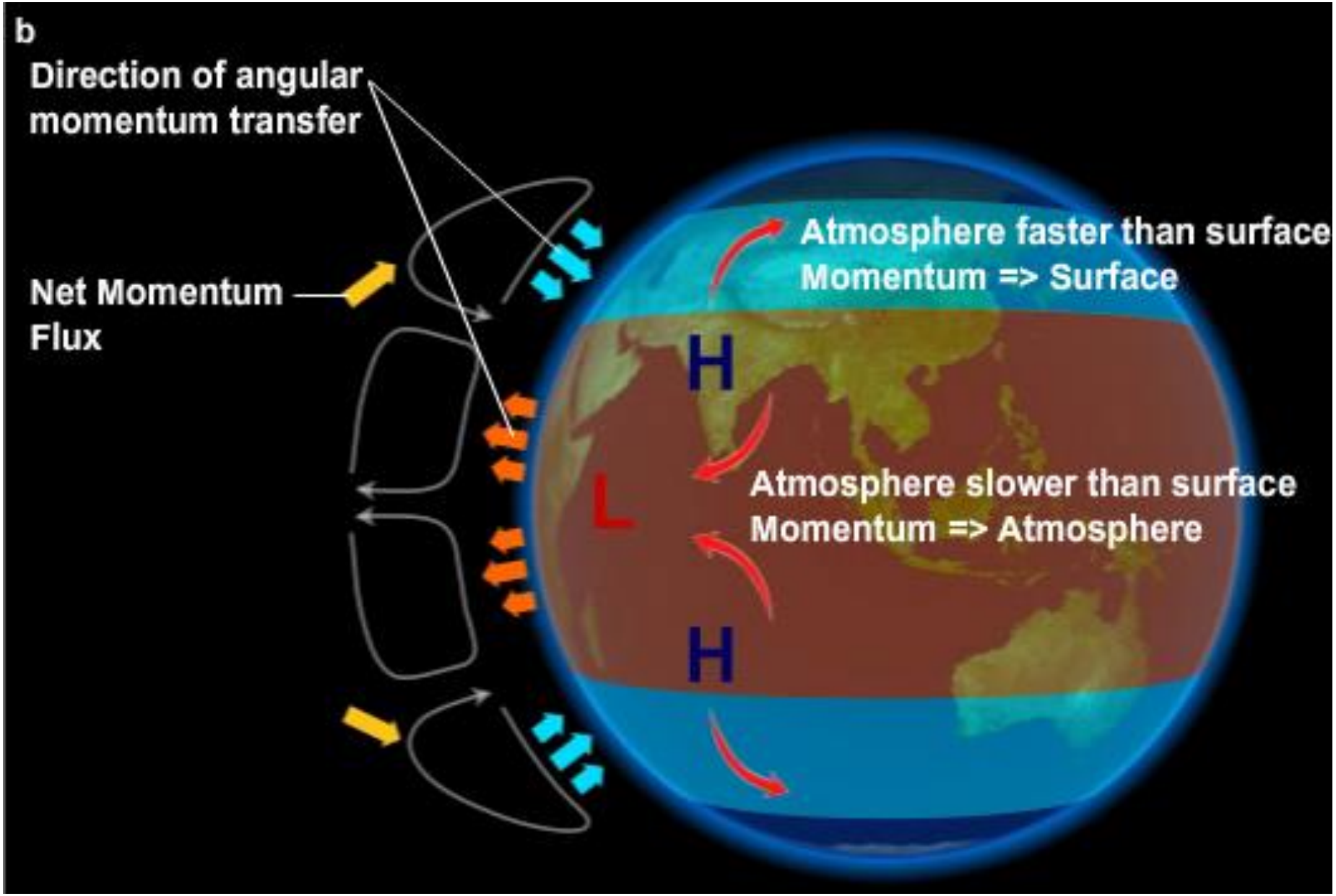

Mean Annual Global Insolation
Energy density (Watts / m2)
400
350
300
250
200
~ 1000 km
Solar radiation
equal energy
~ 2000 km
©The COMET Program

a

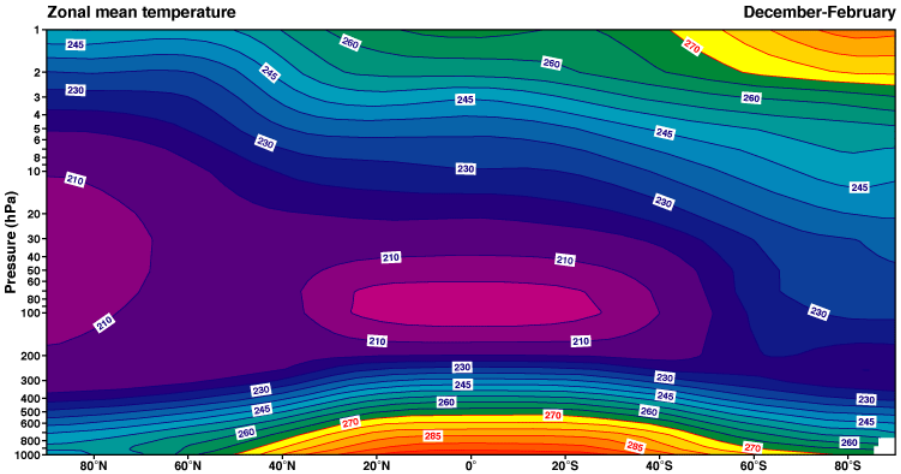


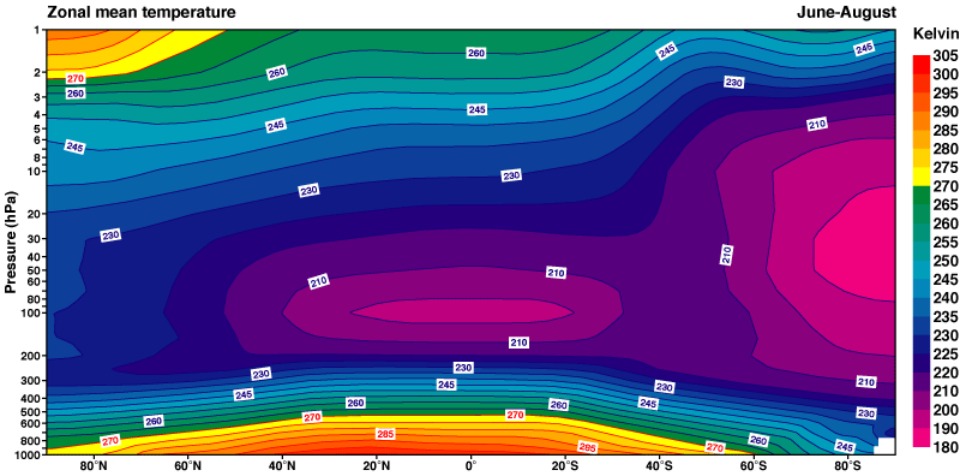
b

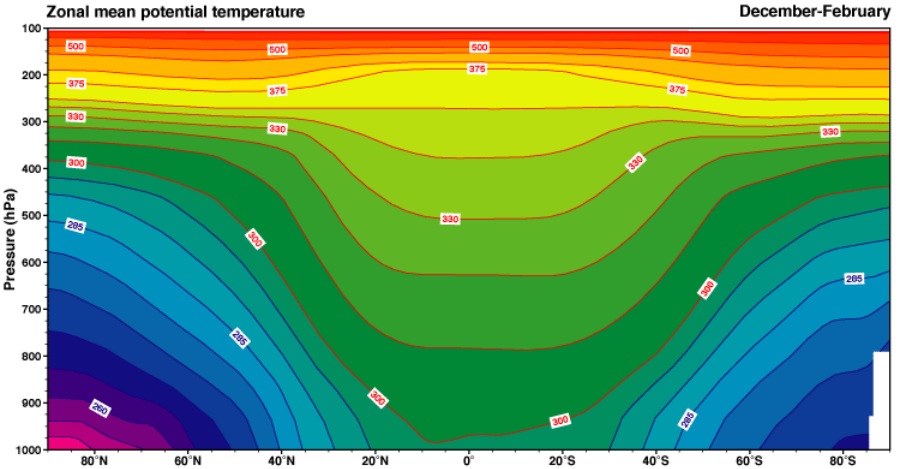


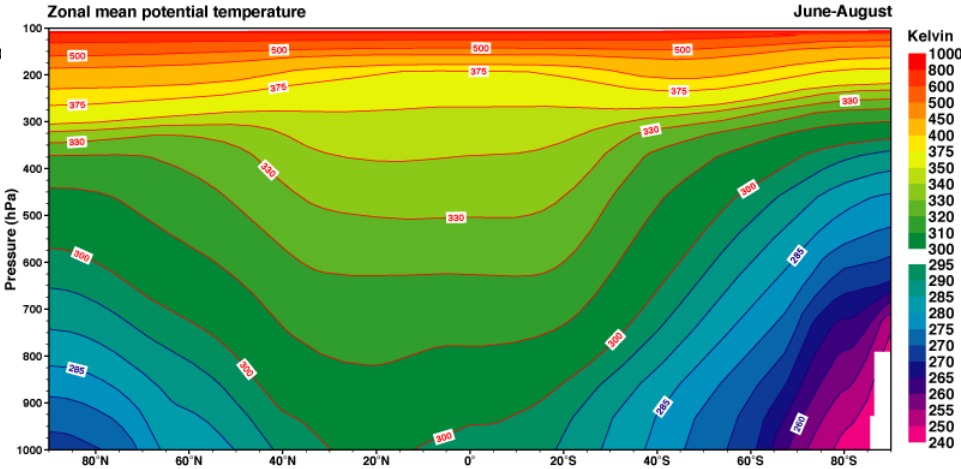

b
Direction of angular momentum transfer
Net Momentum Flux
Atmosphere faster than surface
Momentum => Surface
H
L
Atmosphere slower than surface
Momentum => Atmosphere
H

Temperature and Potential Temperature Structure of the Atmosphere

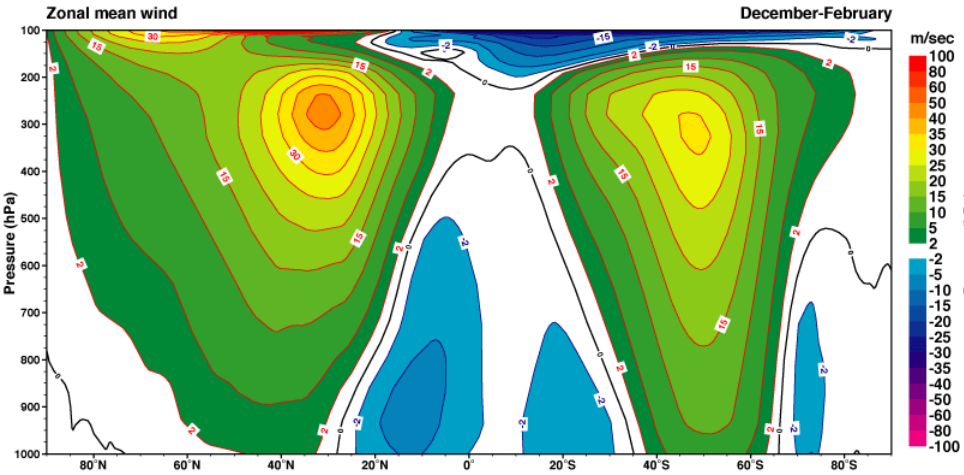


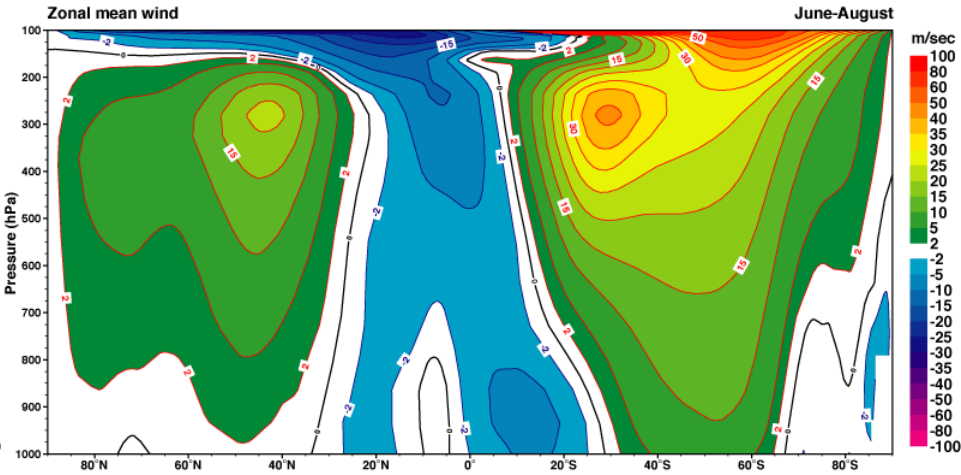


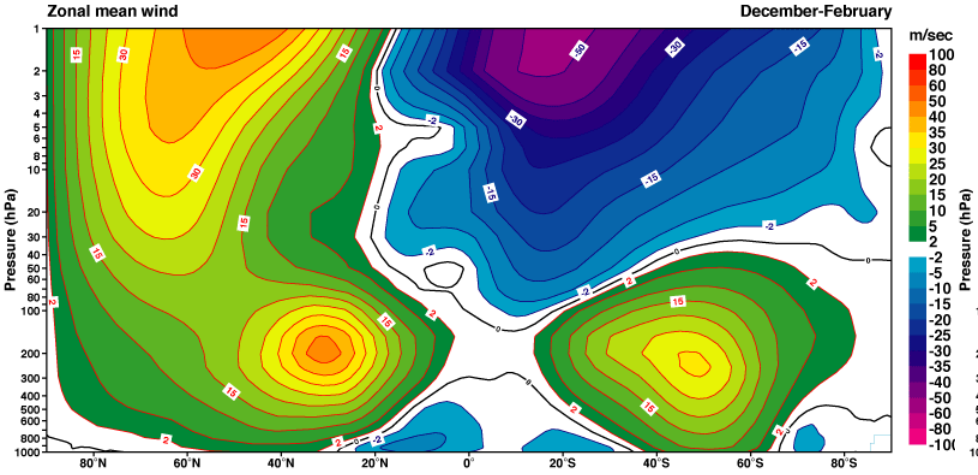


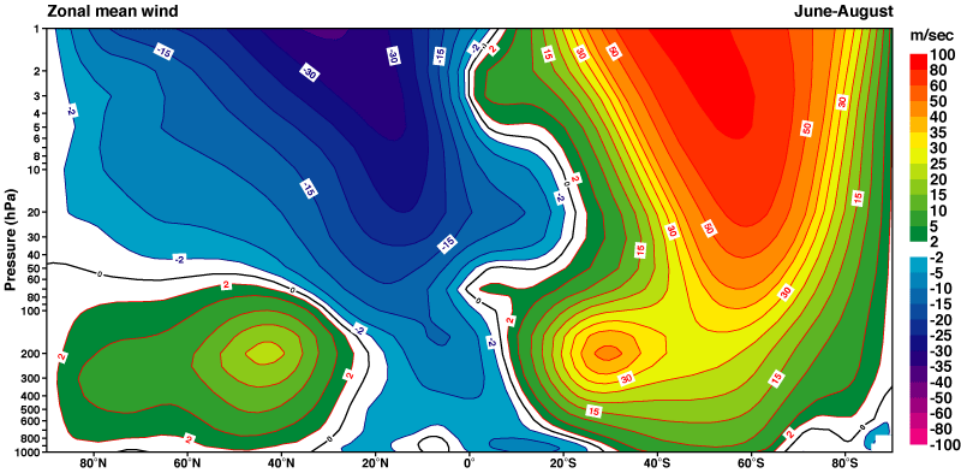


Zonal Wind Sturcture Structure of the Atmosphere



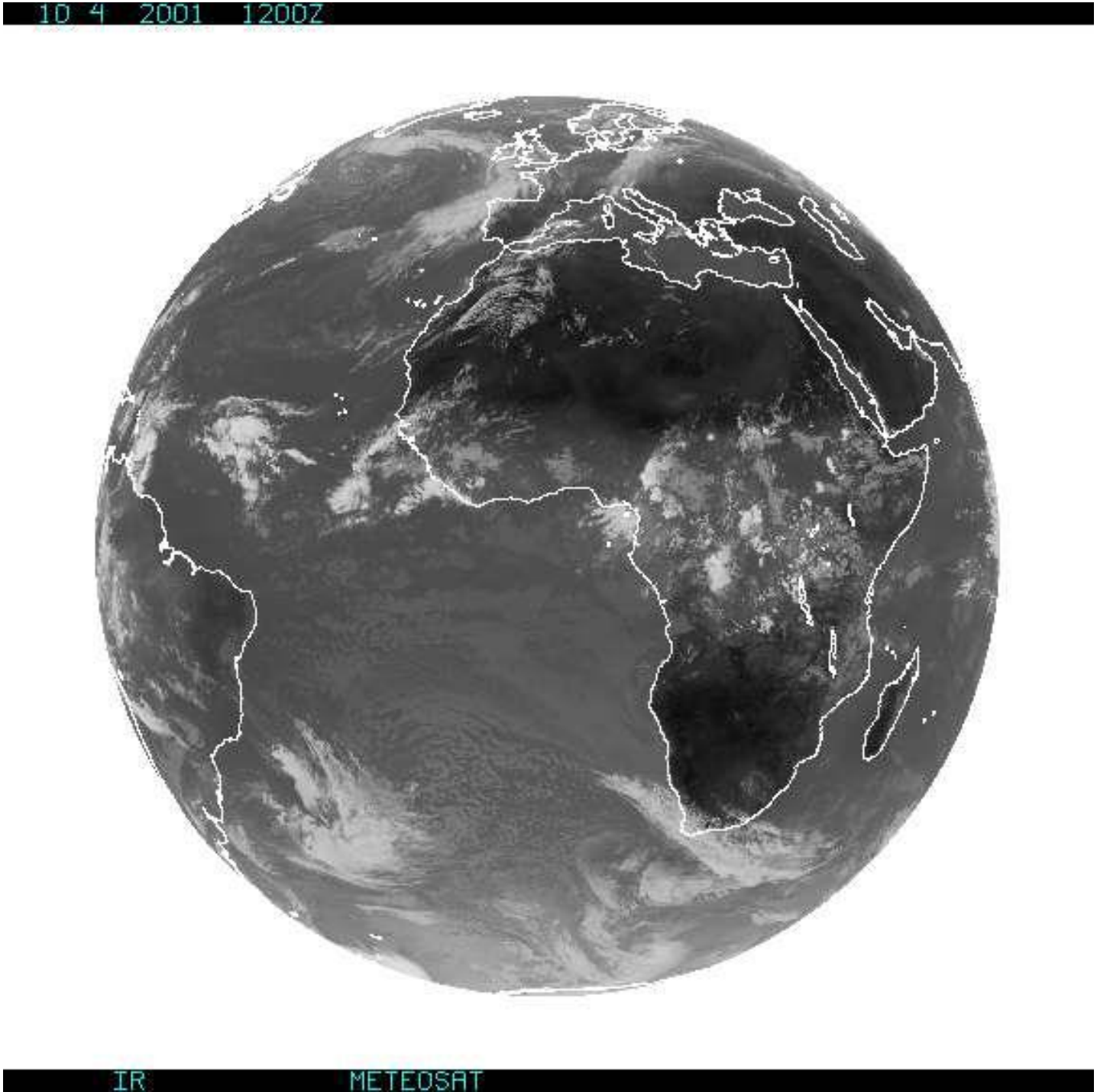


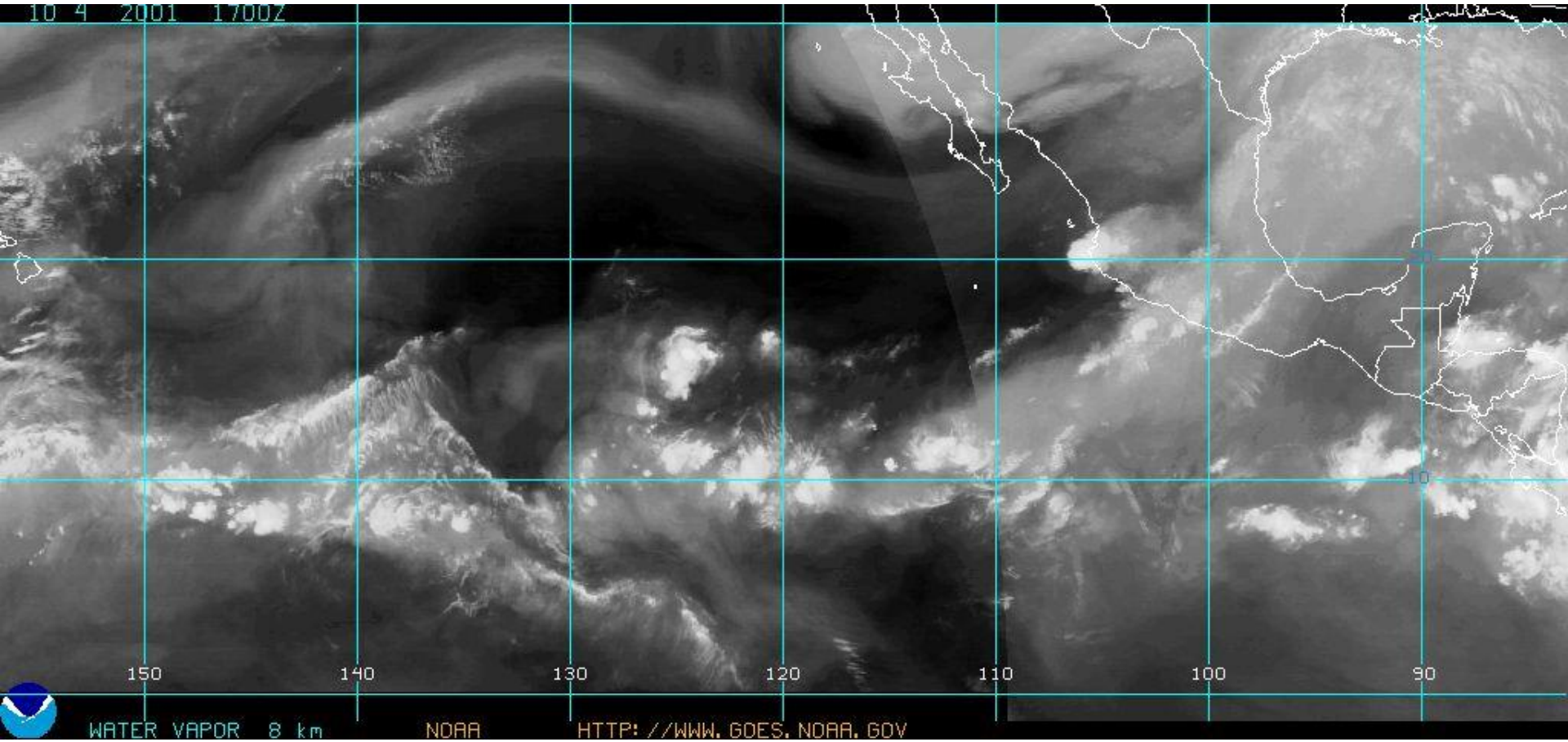




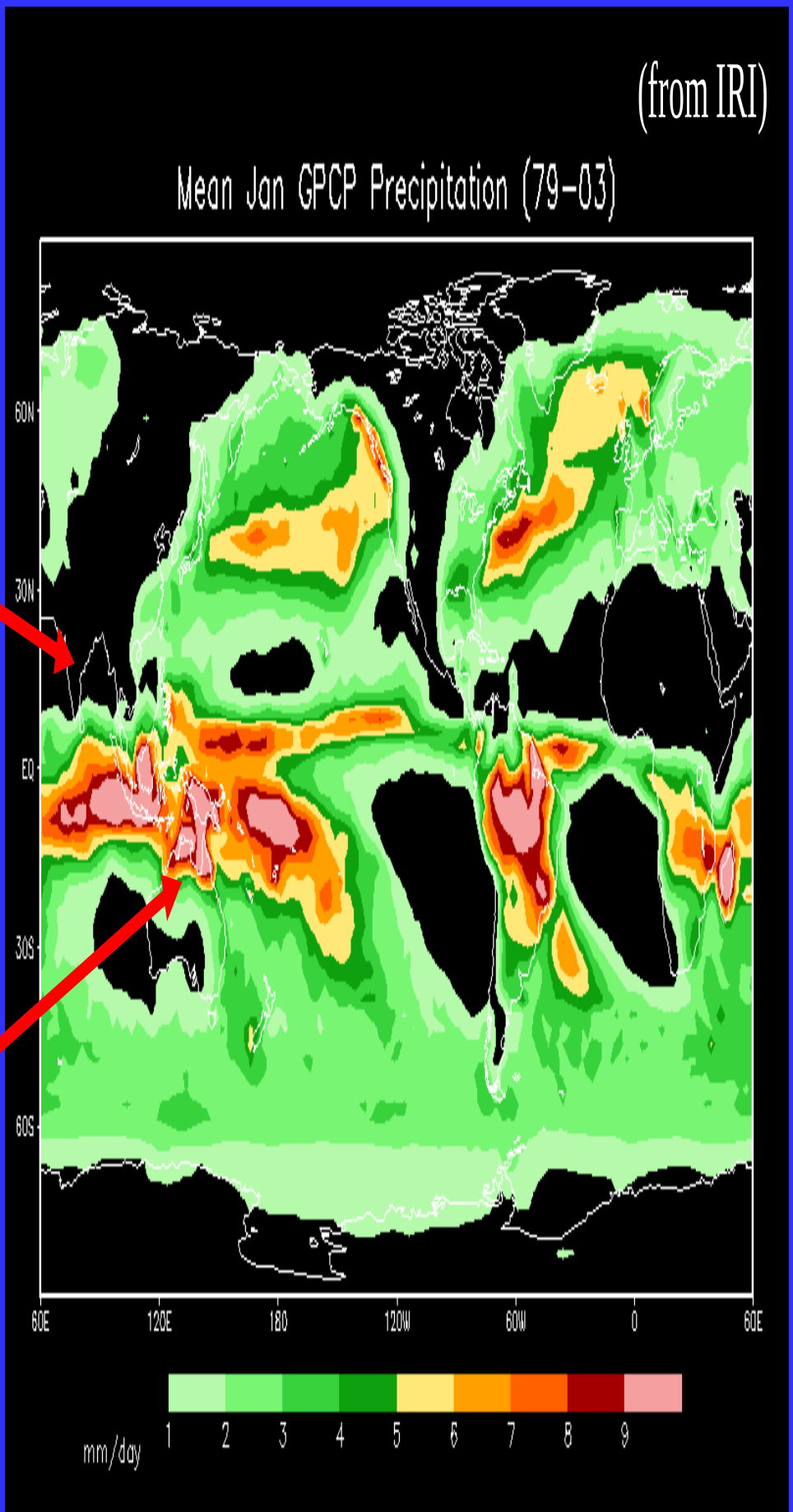
ITCZ Intertropical Convergence Zone

- Latitude of Tropical Precipitation Maximum
- Not Necessarily Latitude of Maximum Rising Motion


10 4 2001 1200Z
IR METEOSAT

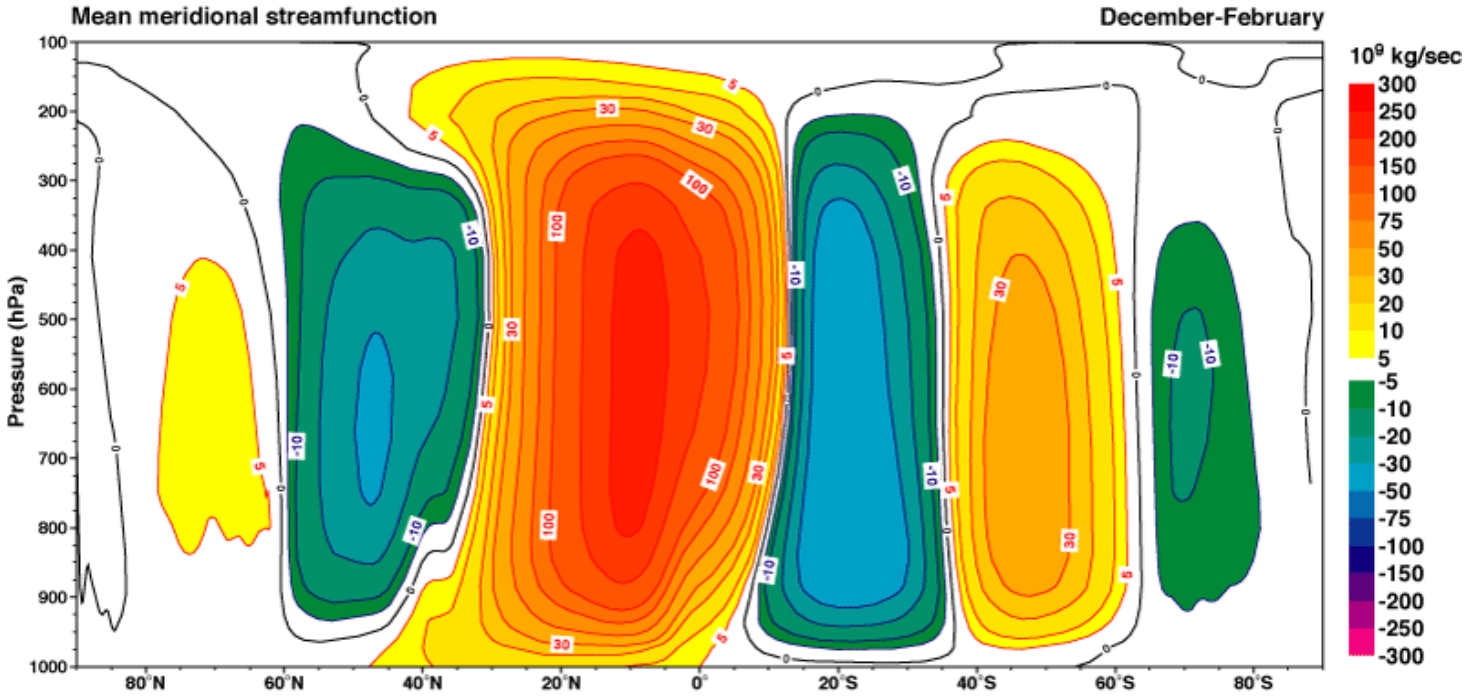

10 4 2001 1700Z
150
140
130
120
110
100
90
10
WATER VAPOR 8 km
NOAA
HTTP://WWW.GOES.NOAA.GOV

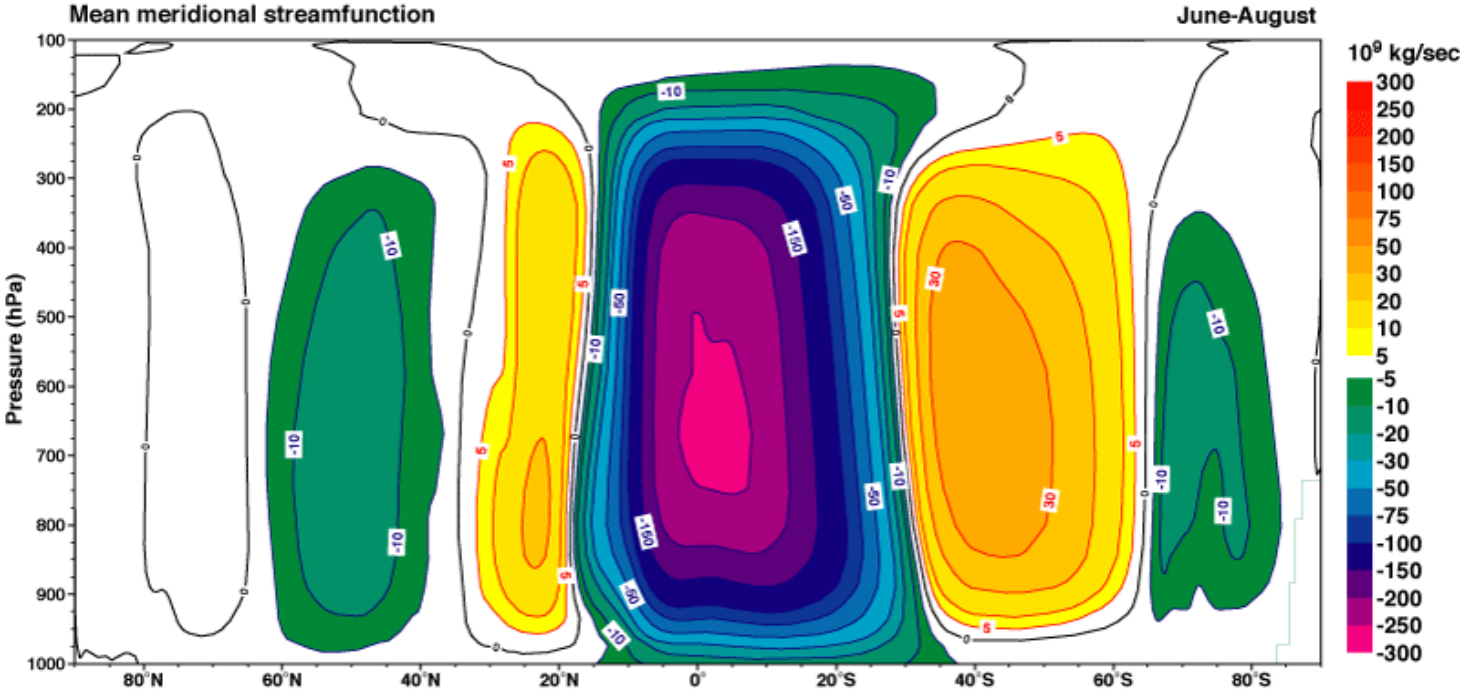
(from IRI)

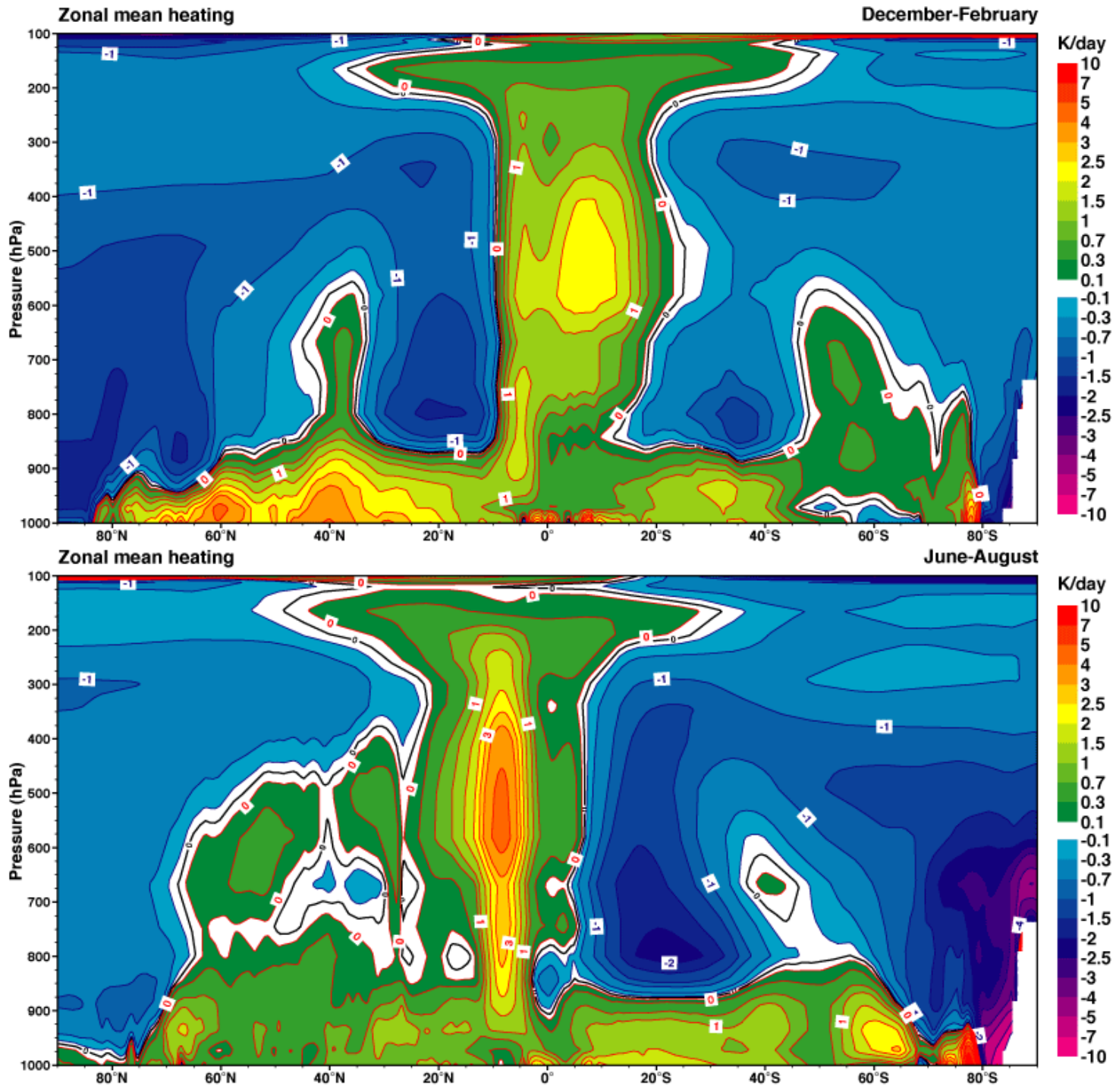


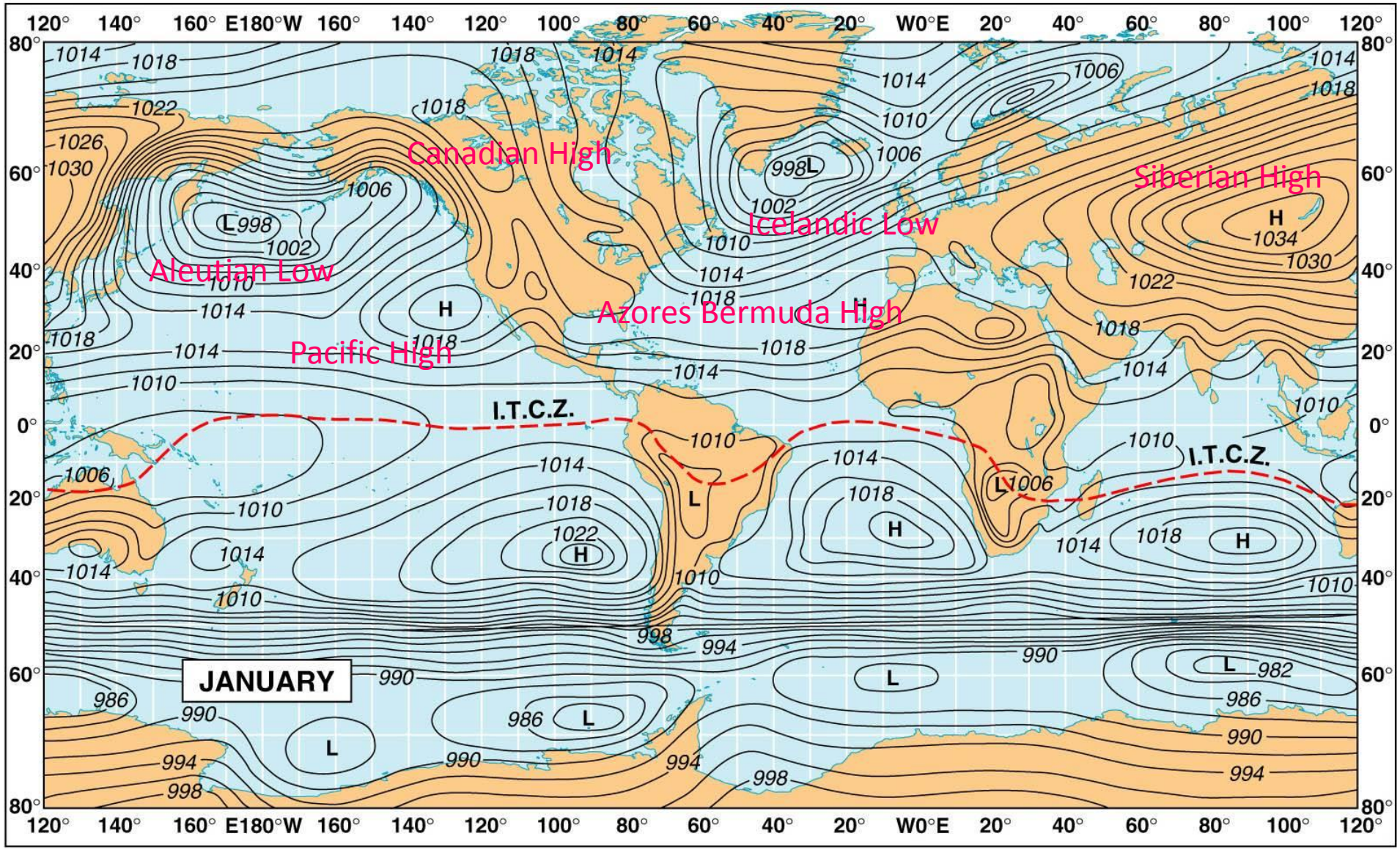
Indian Monsoon

Australian Monsoon

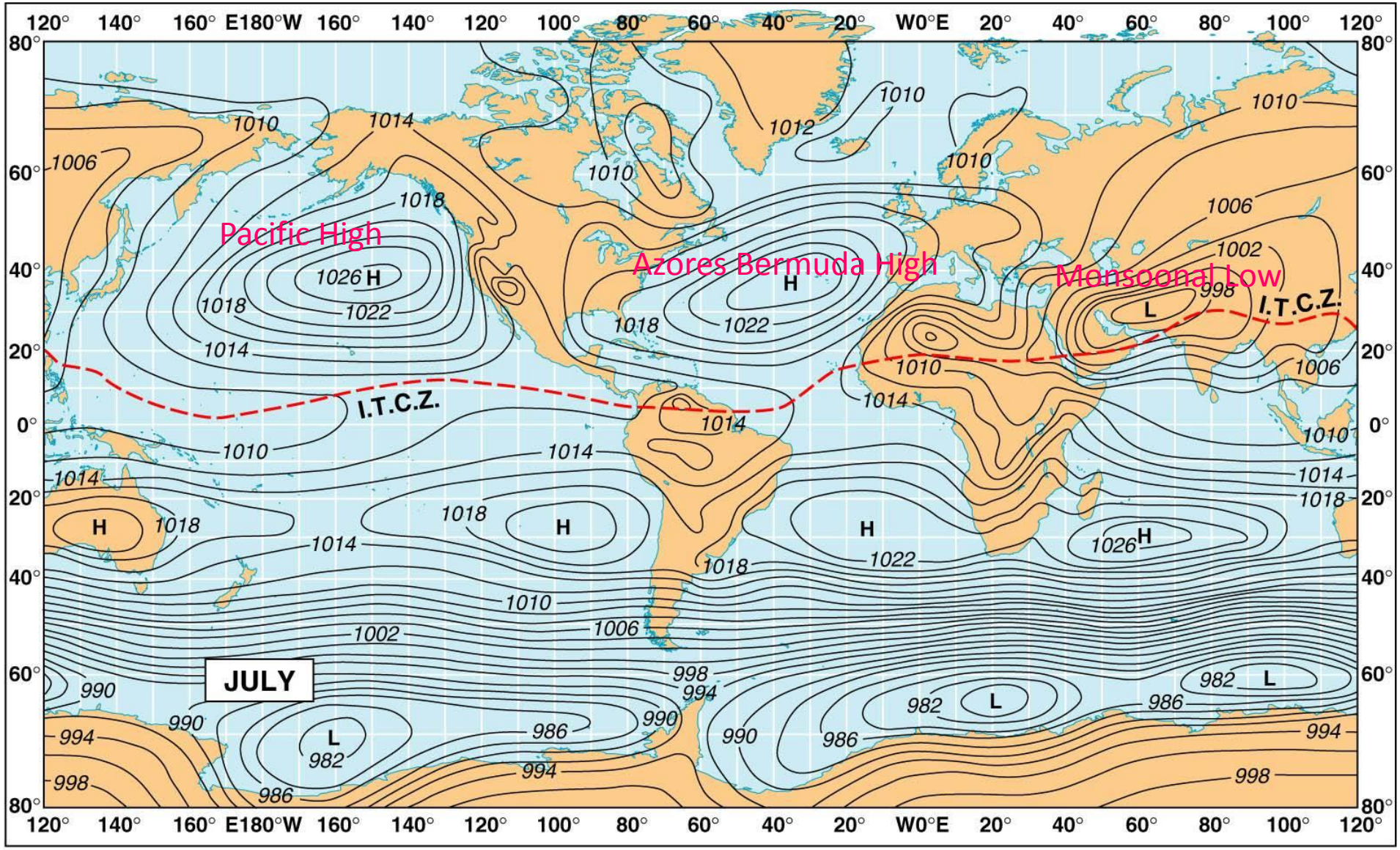

Mean meridional streamfunction
December-February
Pressure (hPa)
100
200
300
400
500
600
700
800
900
1000
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
10⁹ kg/sec
300
250
200
150
100
75
50
30
20
10
5
-5
-10
-20
-30
-50
-75
-100
-150
-200
-250
-300


Mean meridional streamfunction
June-August
Pressure (hPa)
100
200
300
400
500
600
700
800
900
1000
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
10⁹ kg/sec
300
250
200
150
100
75
50
30
20
10
5
-5
-10
-20
-30
-50
-75
-100
-150
-200
-250
-300


Zonal mean heating
December-February
K/day
10
7
5
4
3
2.5
2
1.5
1
0.7
0.3
0.1
-0.1
-0.3
-0.7
-1
-1.5
-2
-2.5
-3
-4
-5
-7
-10
Pressure (hPa)
100
200
300
400
500
600
700
800
900
1000
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
Zonal mean heating
June-August
K/day
Pressure (hPa)

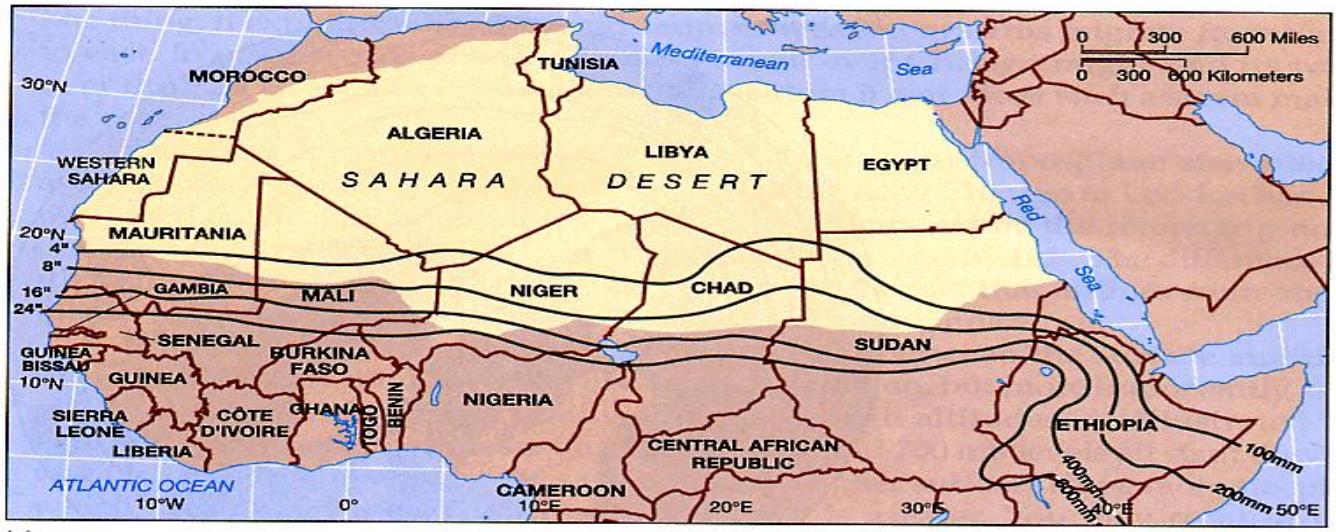

Canadian High
Siberian High
Icelandic Low
Aleutian Low
Azores Bermuda High
Pacific High
I.T.C.Z.
I.T.C.Z.
JANUARY

(a)

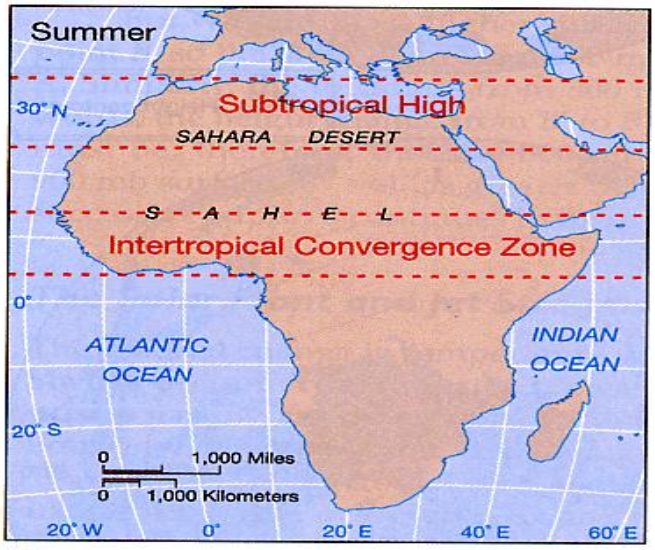

120° 140° 160° E180°W 160° 140° 120° 100° 80° 60° 40° 20° W0°E 20° 40° 60° 80° 100° 120°
80° 60° 40° 20° 0° 20° 40° 60° 80°
Pacific High
Azores Bermuda High
Monsoonal Low
I.T.C.Z.
I.T.C.Z.
JULY
H
L
1026 H
1022
1018
1014
1010
1006
1002
998
994
990
986
982

(b)

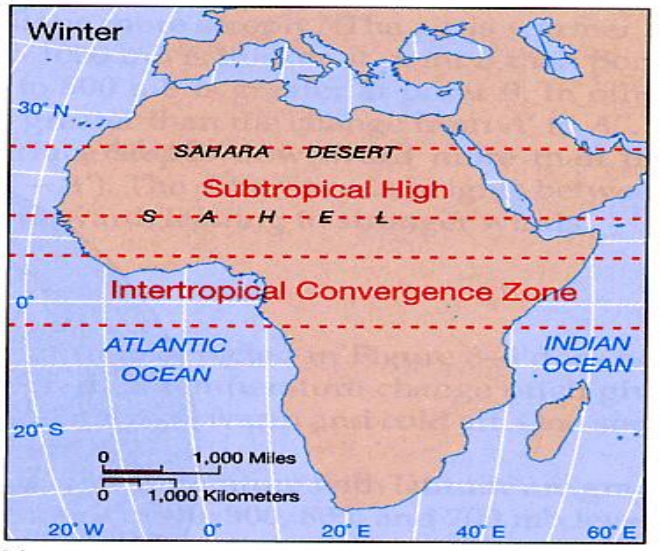
Sinking Branches and Deserts



(a)

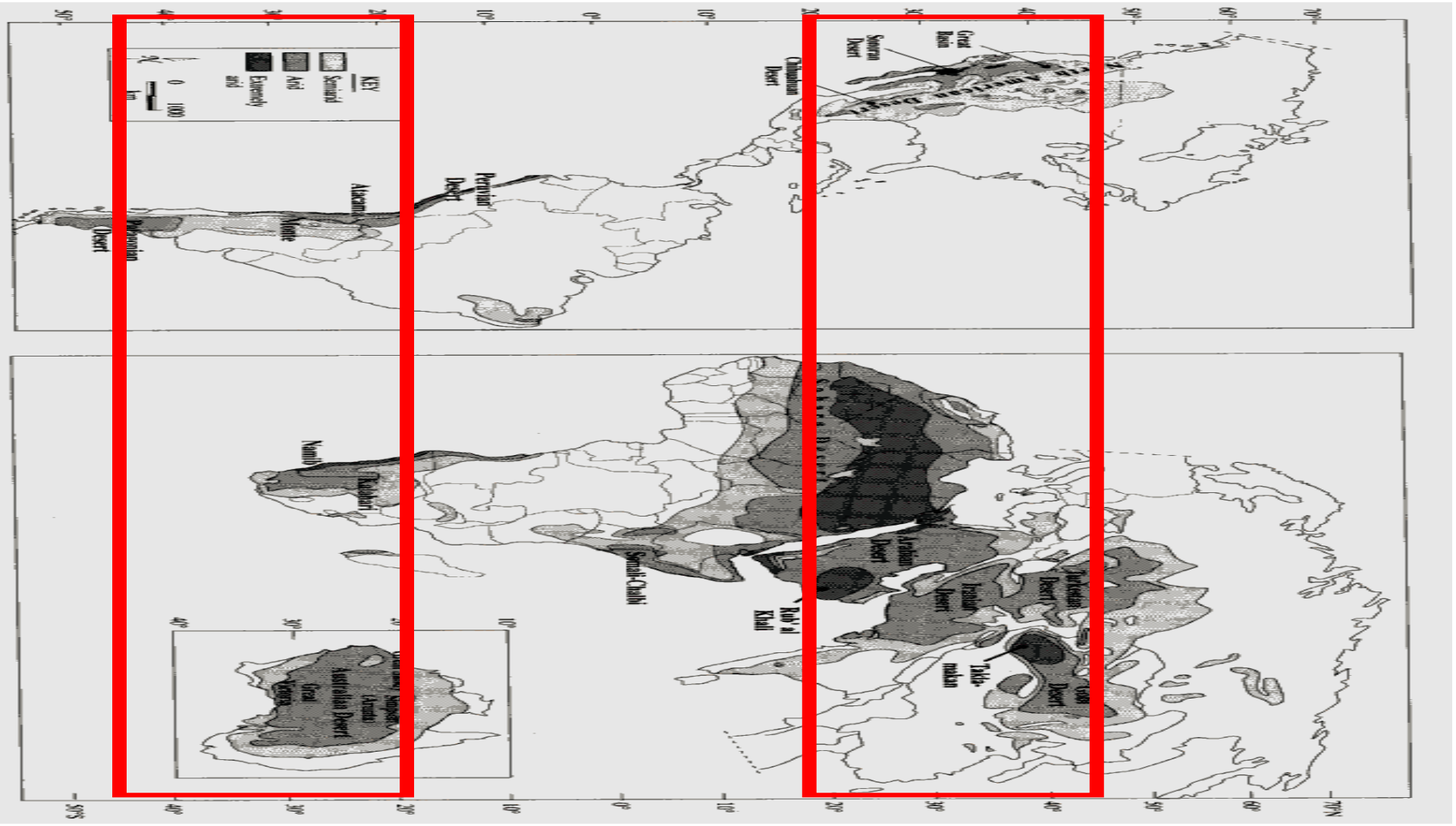


(b)

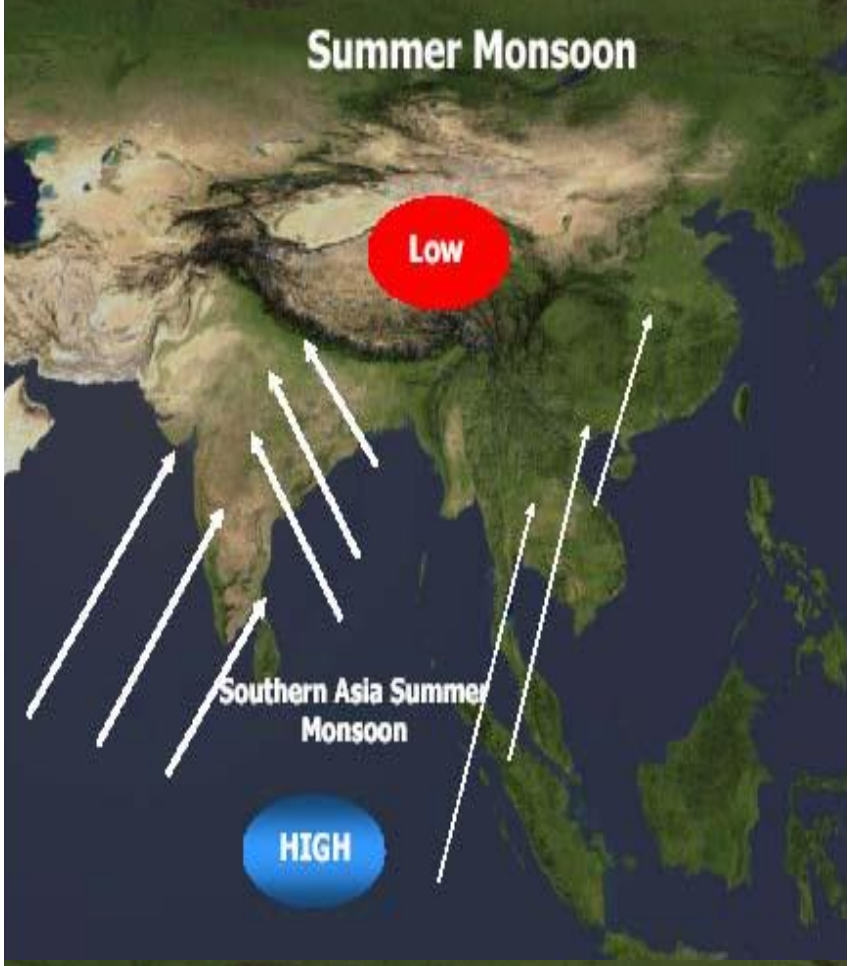


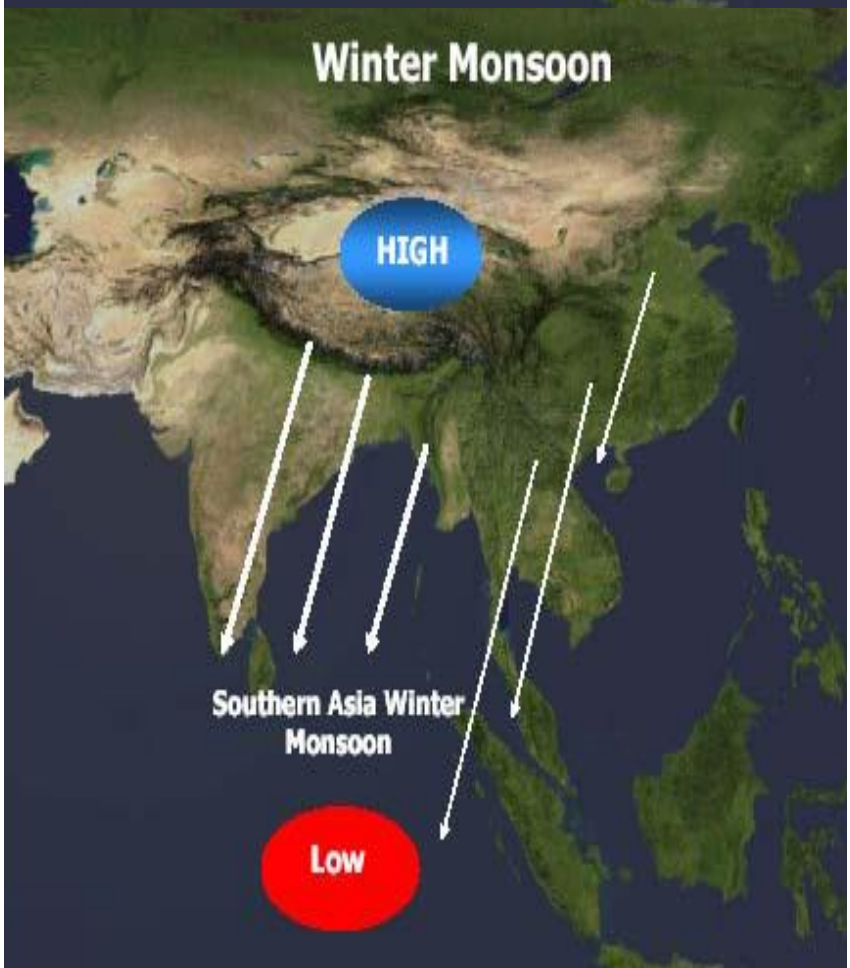
(c)

Global Deserts



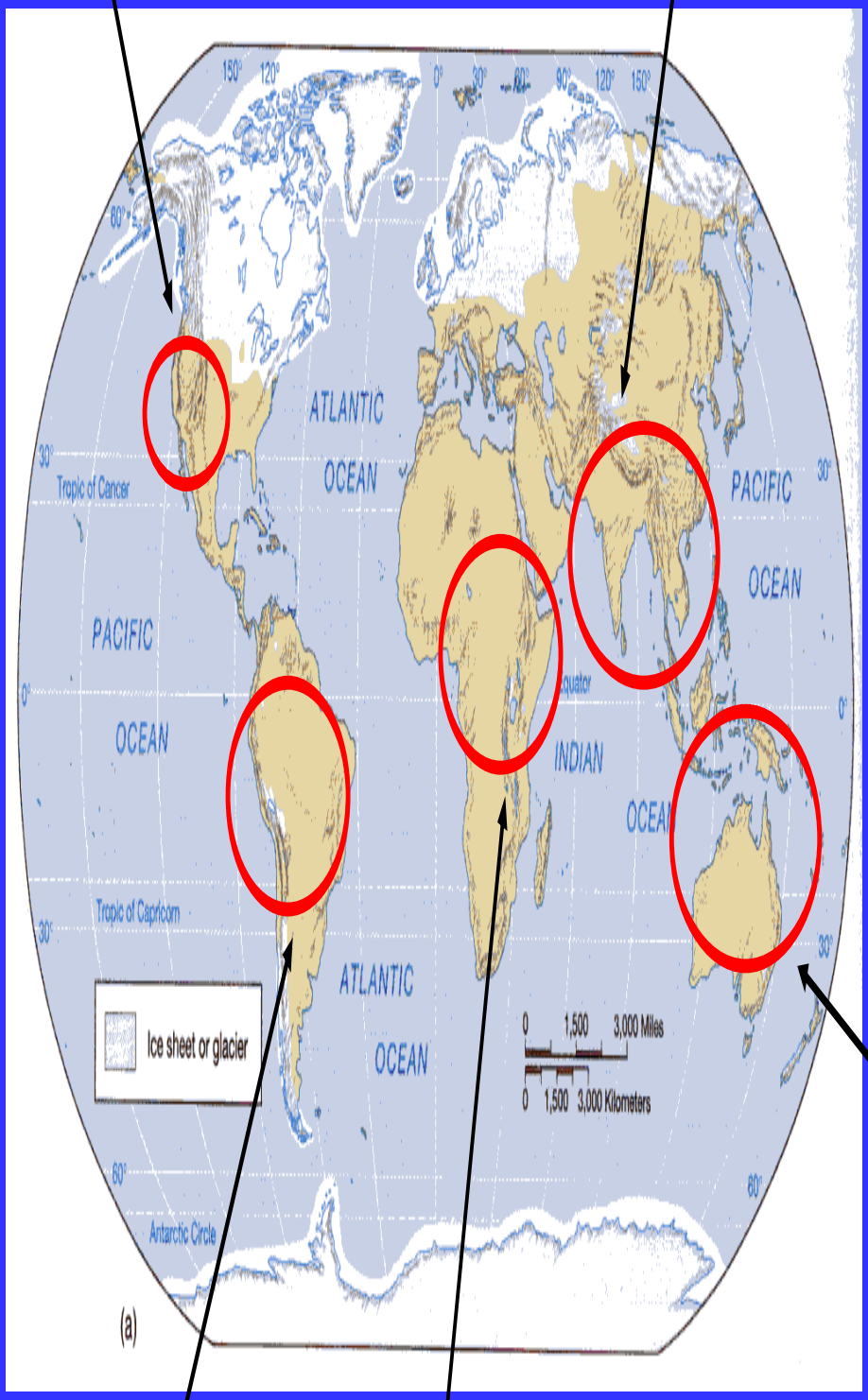
Monsoons


Summer Monsoon
Low
Southern Asia Summer Monsoon
HIGH


Winter Monsoon
HIGH
Southern Asia Winter Monsoon
Low

North America Monsoon

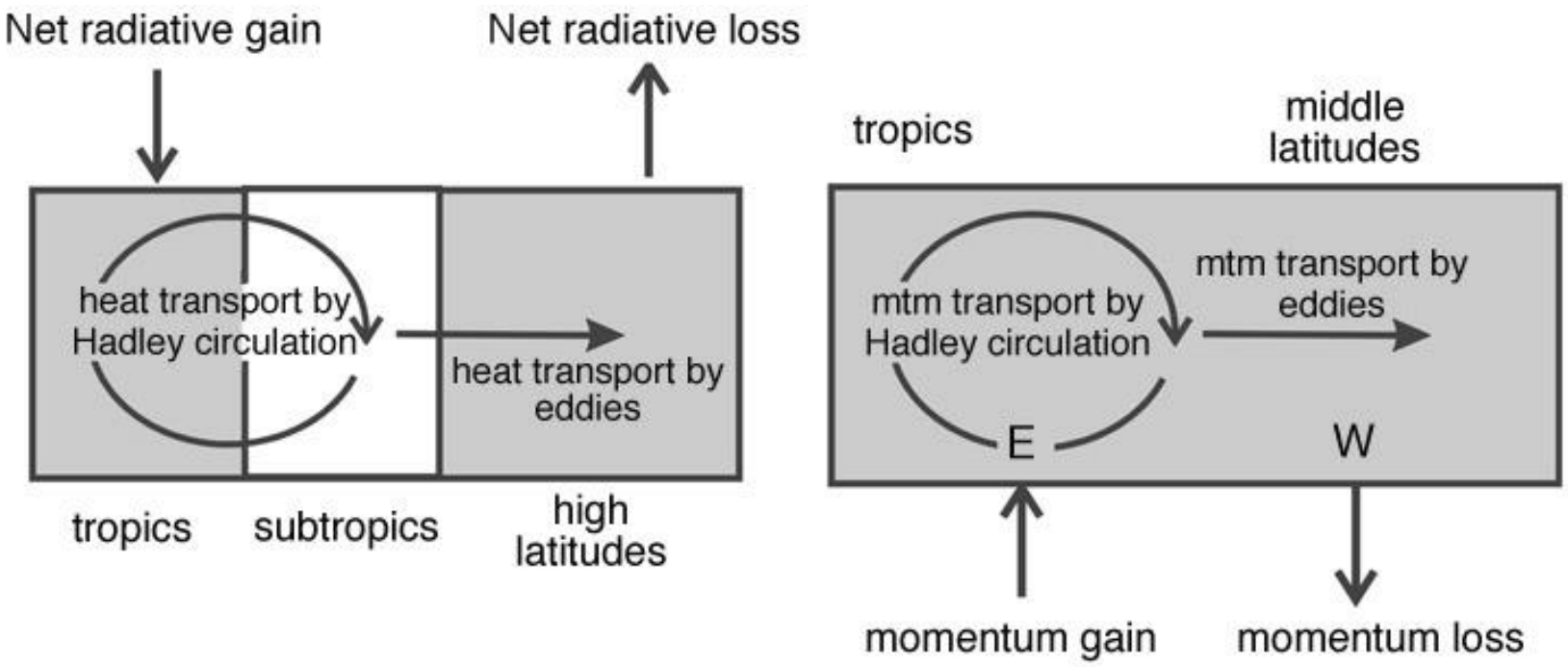
Asian Monsoon



Australian Monsoon

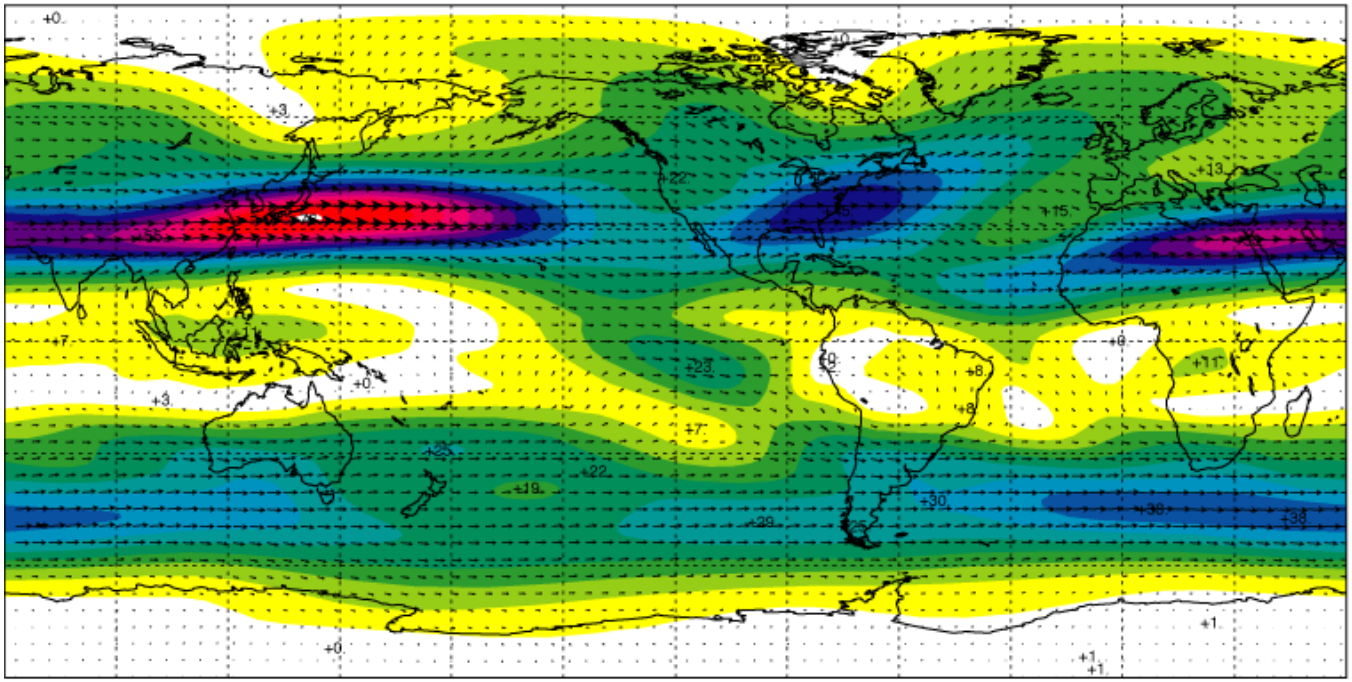
South America Monsoon

Africa Monsoon


Net radiative gain
Net radiative loss
heat transport by
Hadley circulation
heat transport by
eddies
tropics
subtropics
high
latitudes
tropics
middle
latitudes
mtm transport by
Hadley circulation
mtm transport by
eddies
E
W
momentum gain
momentum loss

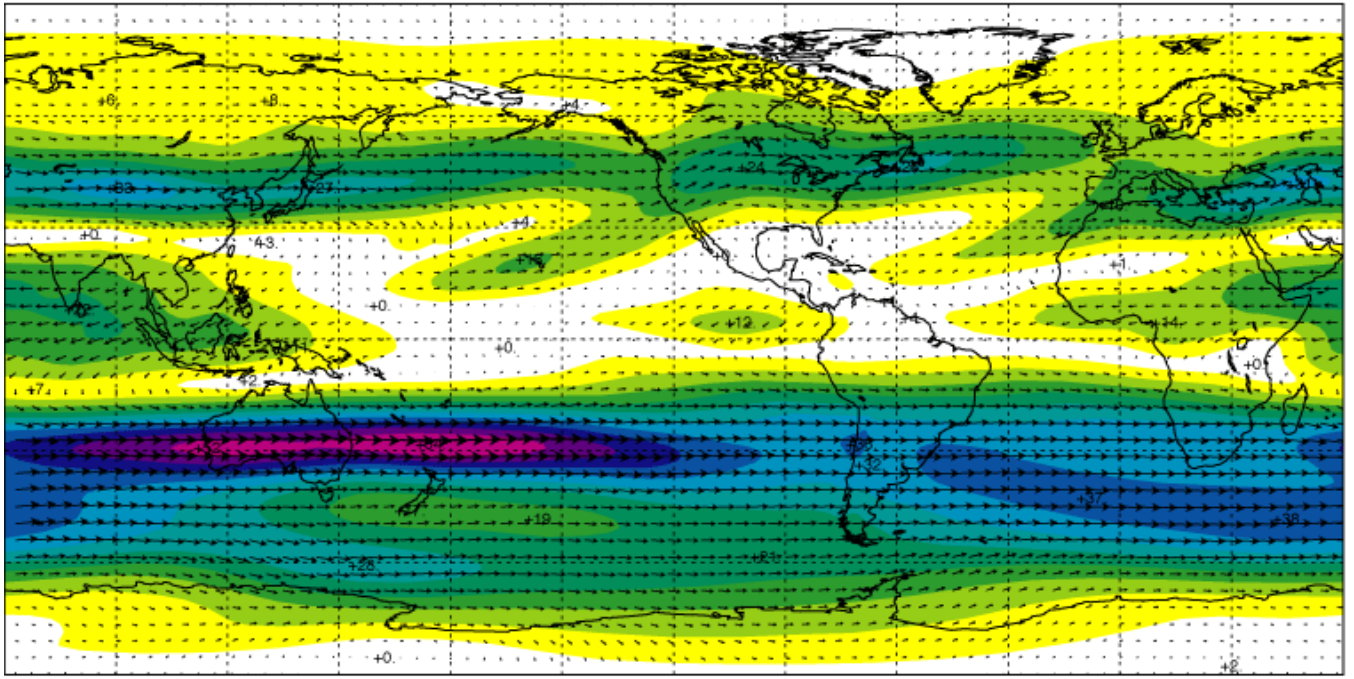
Wind vector and isotachs at 200 hPa

December-February



Wind vector and isotachs at 200 hPa

June-August



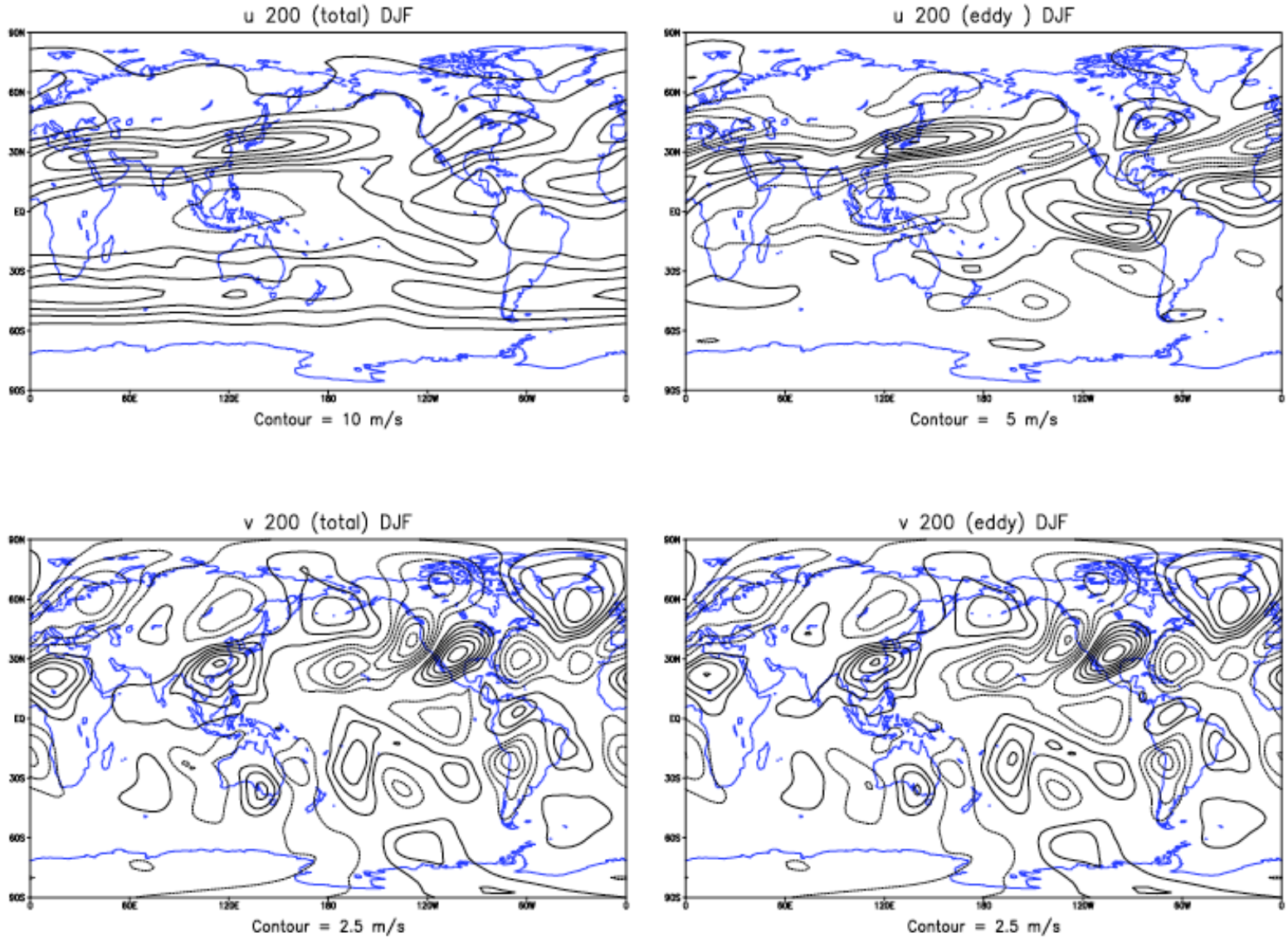


Figure 1: **DJF 200 hPa u and v wind, total and eddy.**

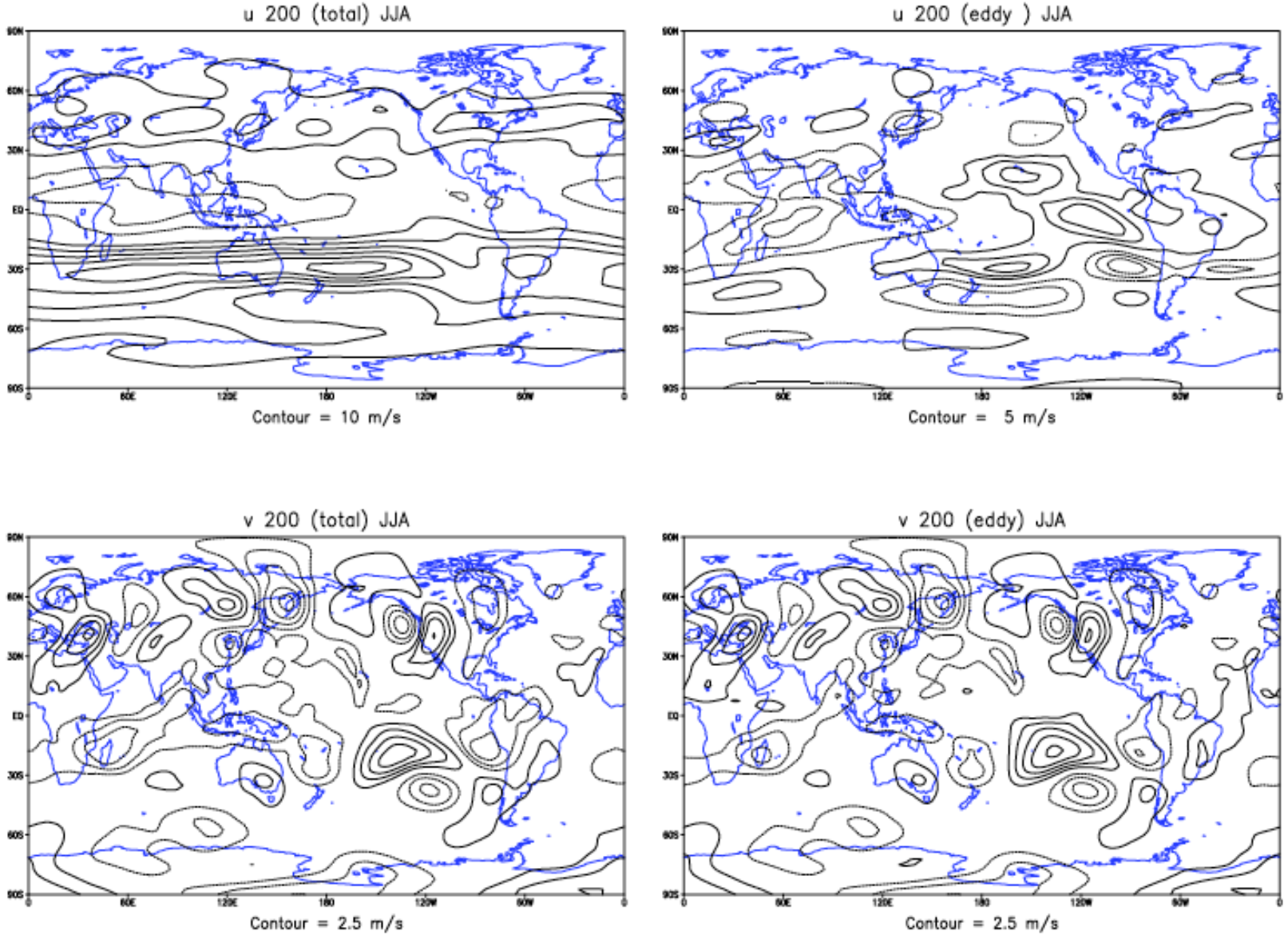


Figure 2: **JJA 200 hPa u and v wind, total and eddy.**

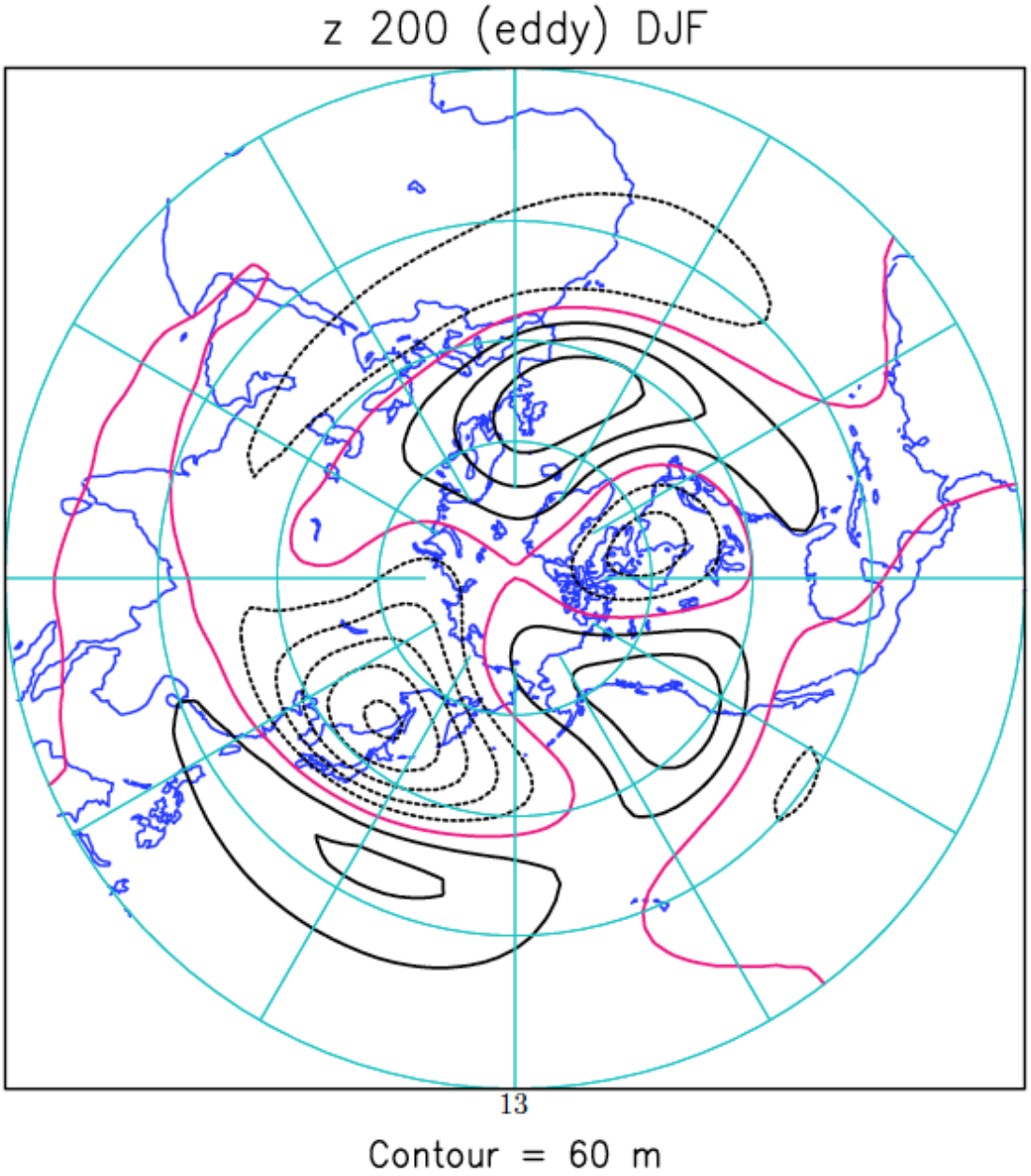


Figure 3: **DJF 200 hPa Z eddy.**

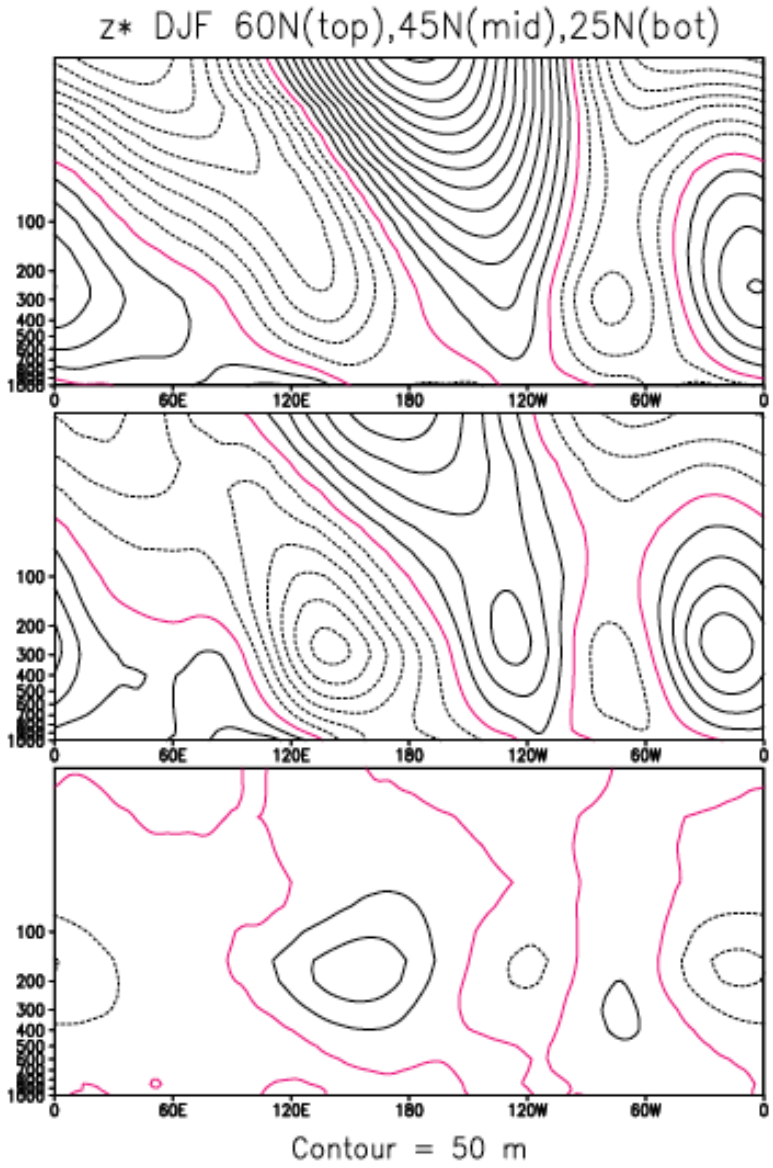


Figure 4: **Longitude/Pressure sections of DJF Z* at 60N (top), 45N(mid), and 25N(lower) .**

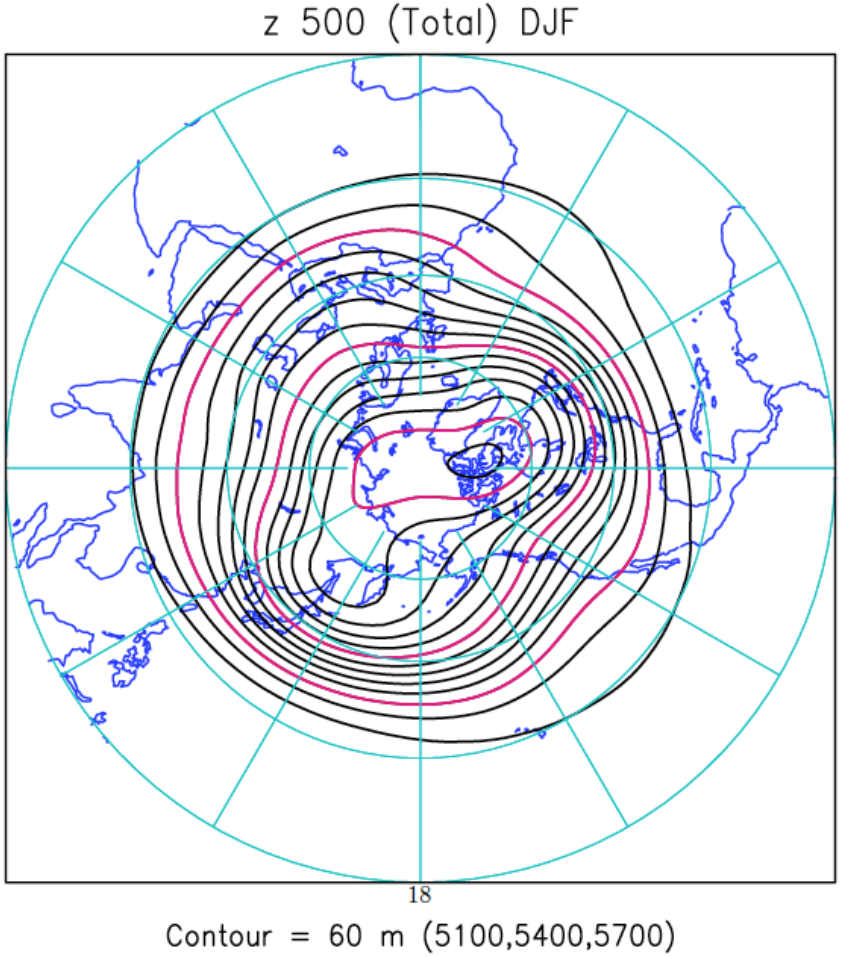


Figure 6: **DJF 500 hPa Z NH.**

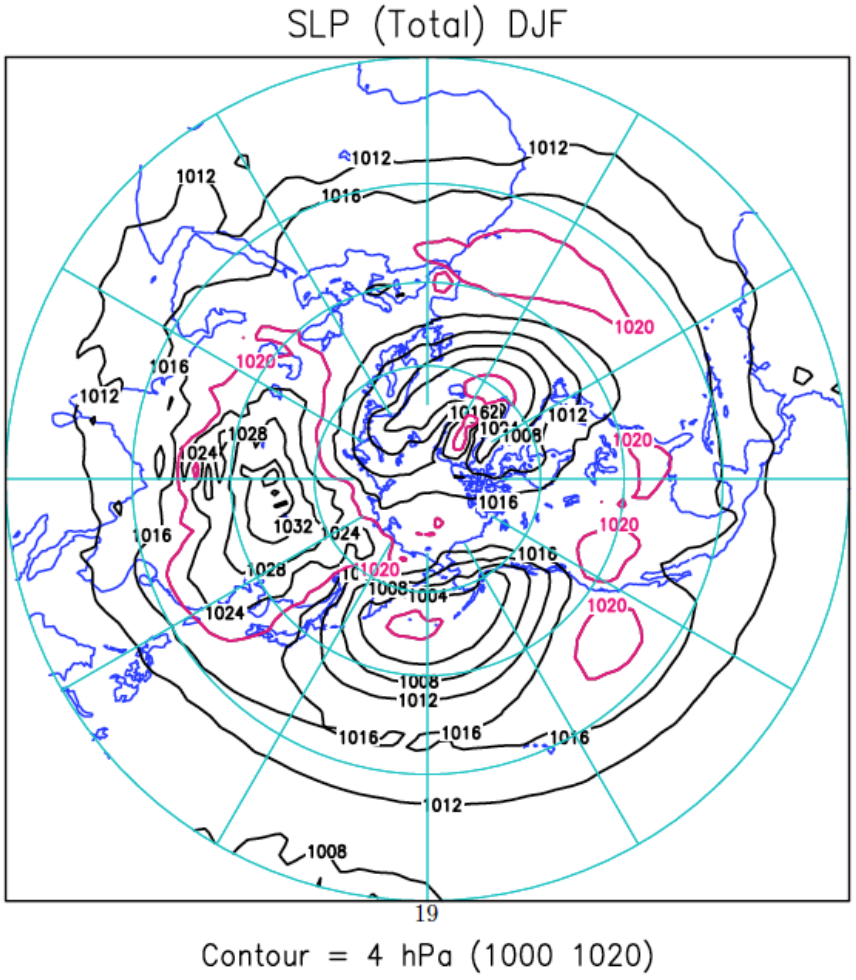
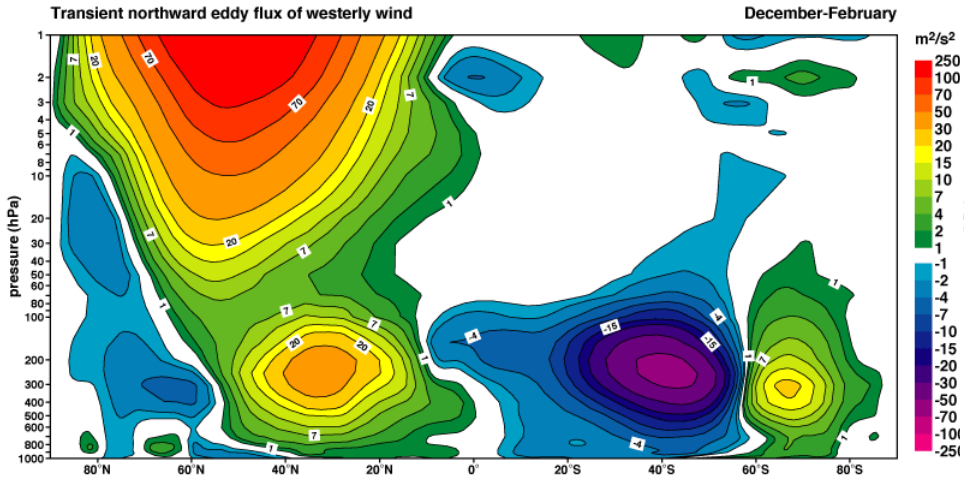
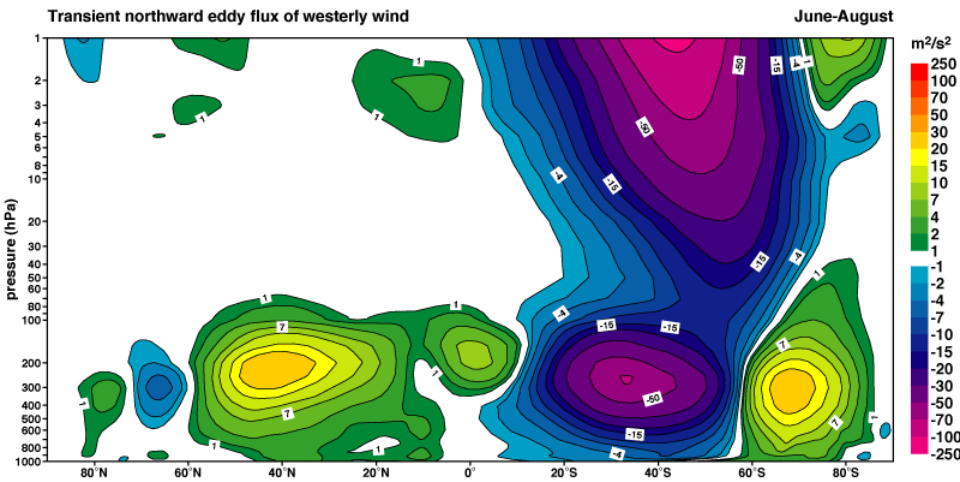
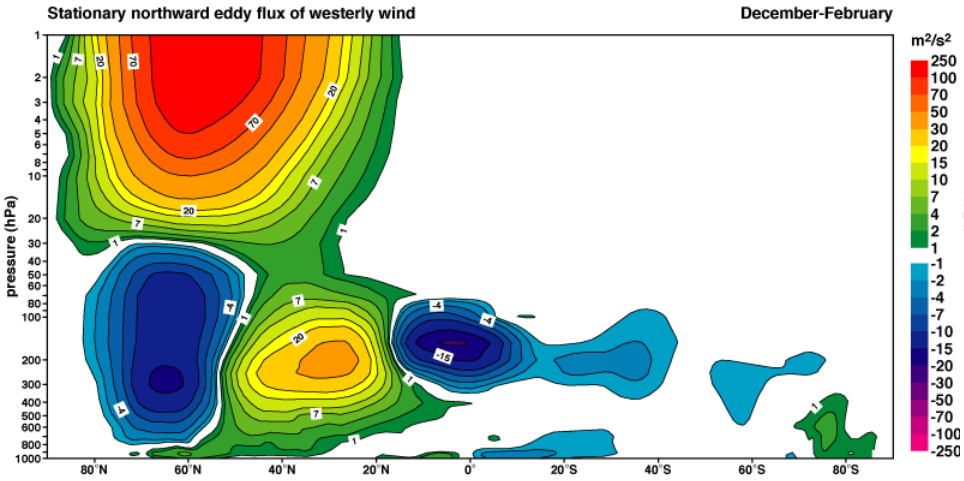


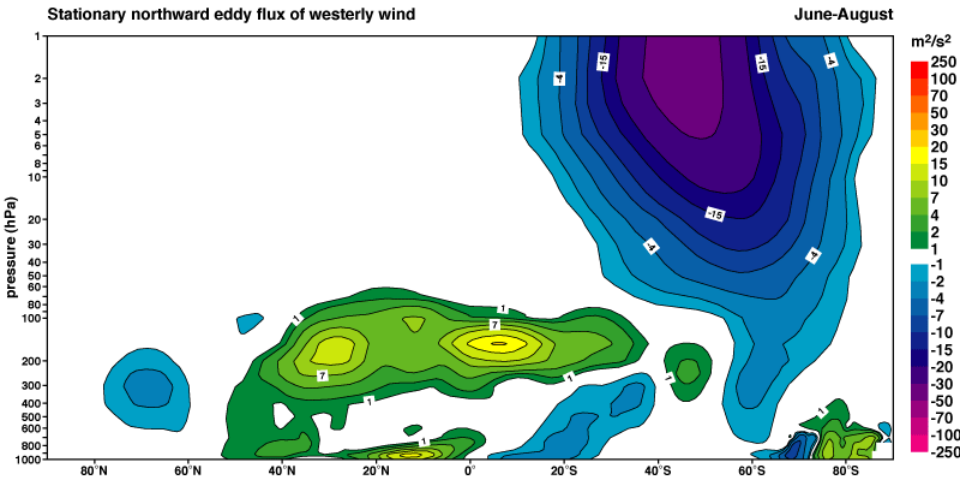
Figure 7: **DJF SLP NH.**

Transient and Stationary Eddy Flux of Westerly Momentum

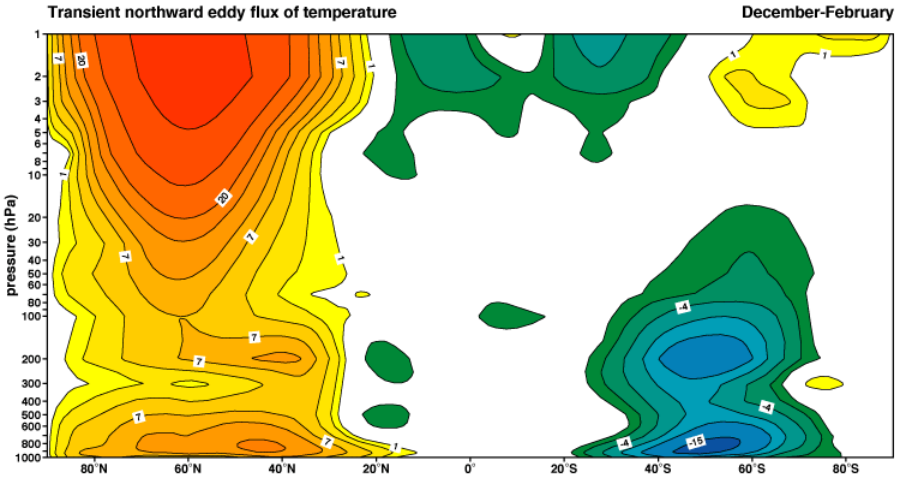


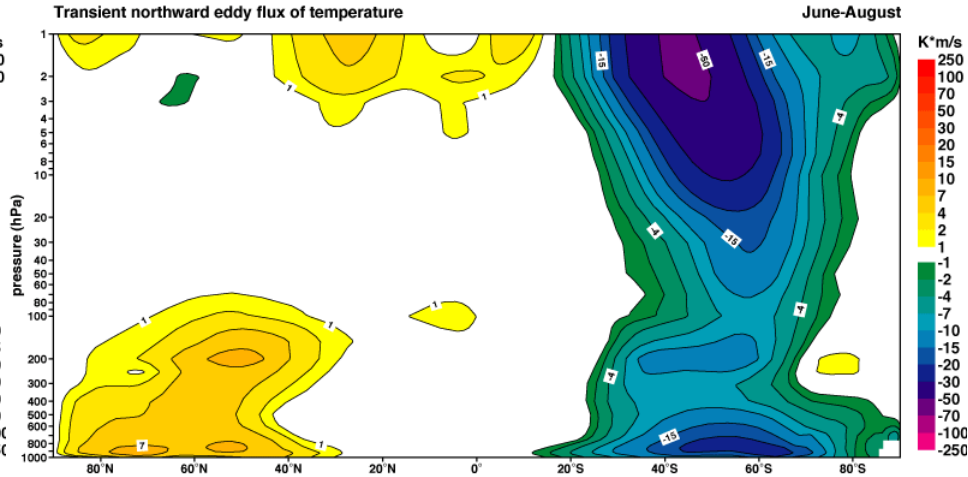


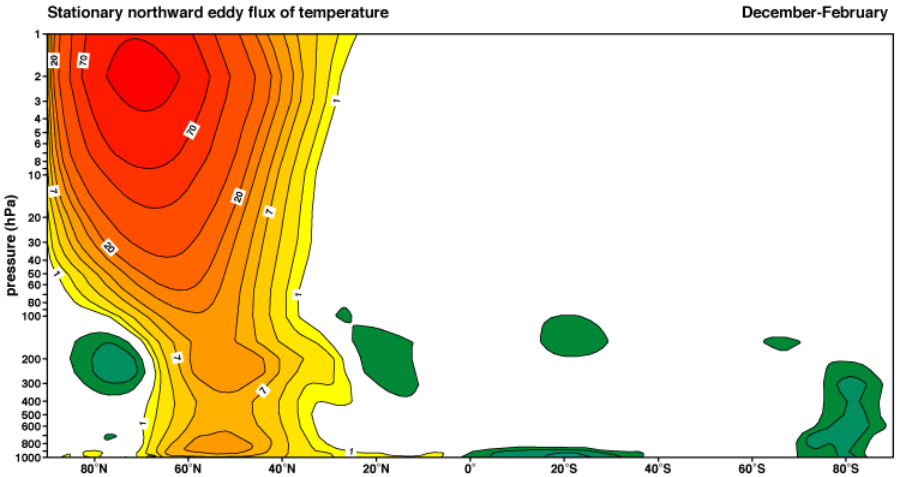


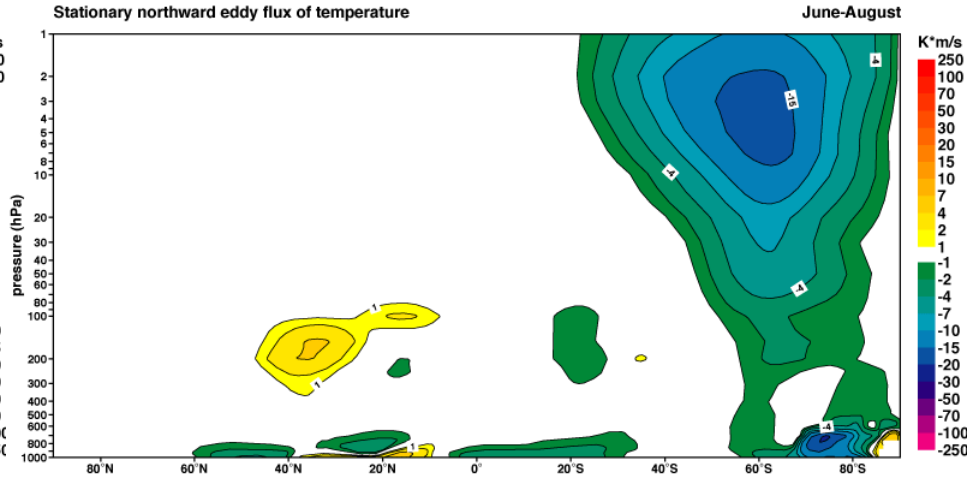


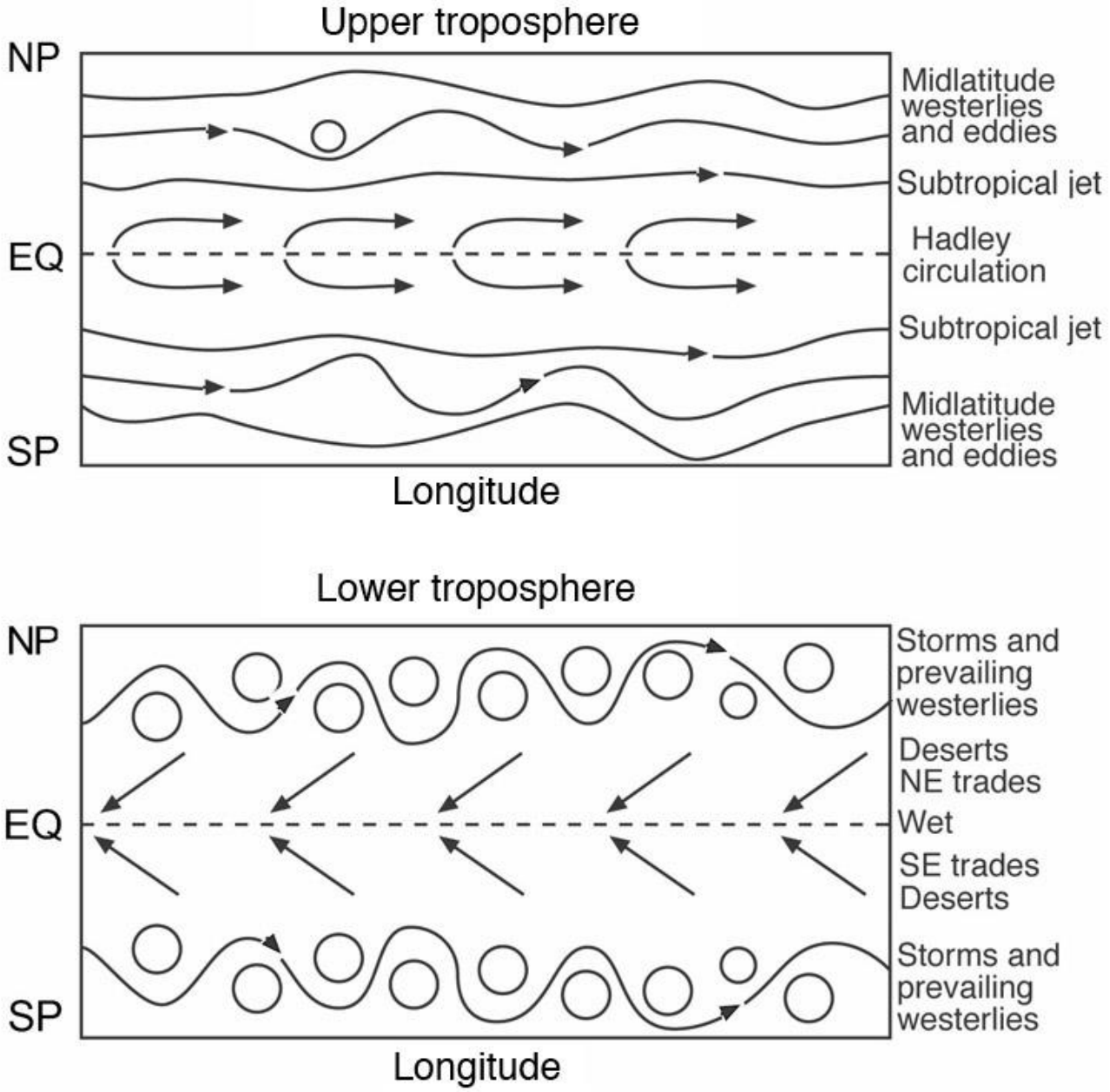
Transient and Stationary Eddy Flux of Temperature

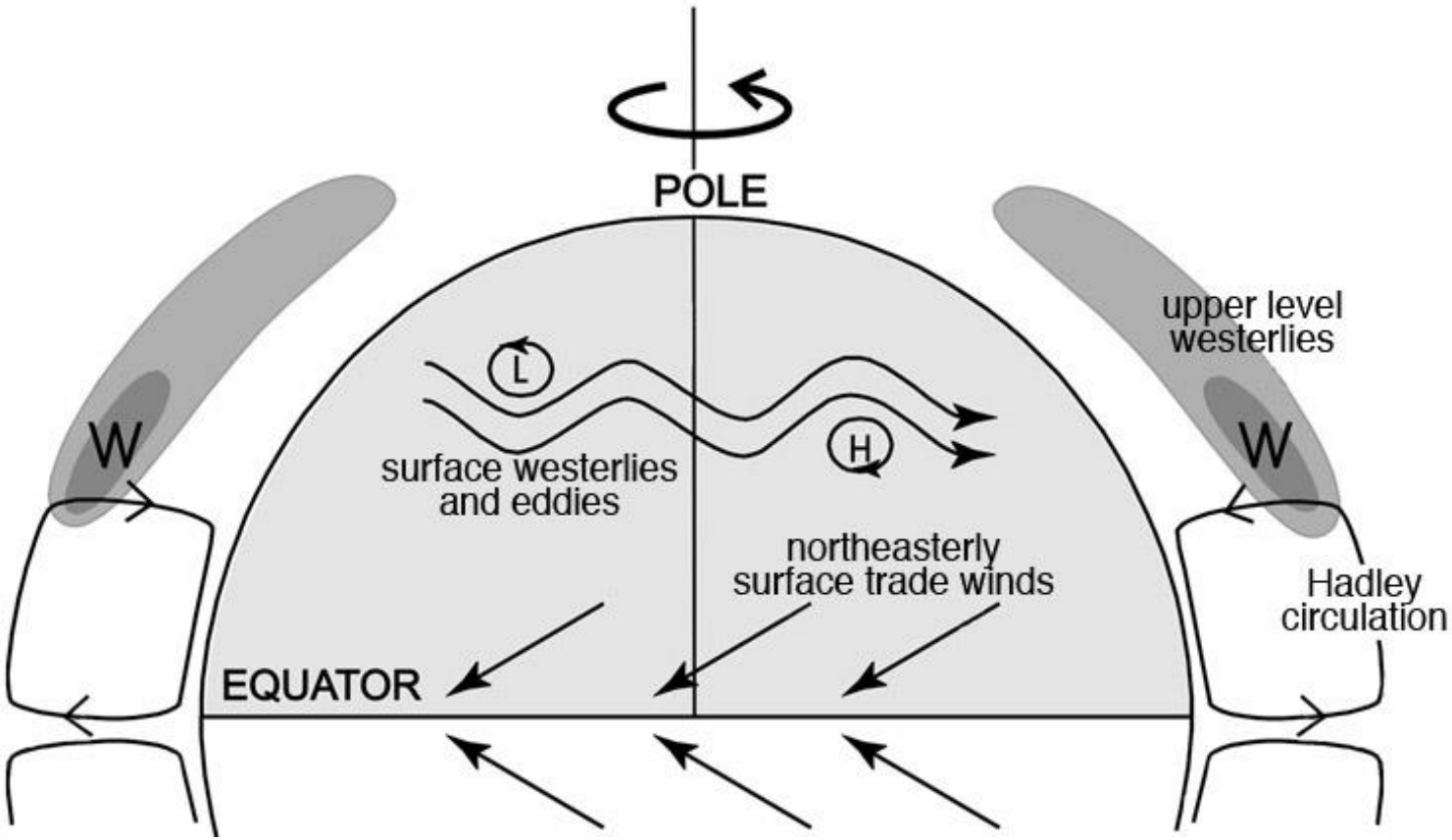


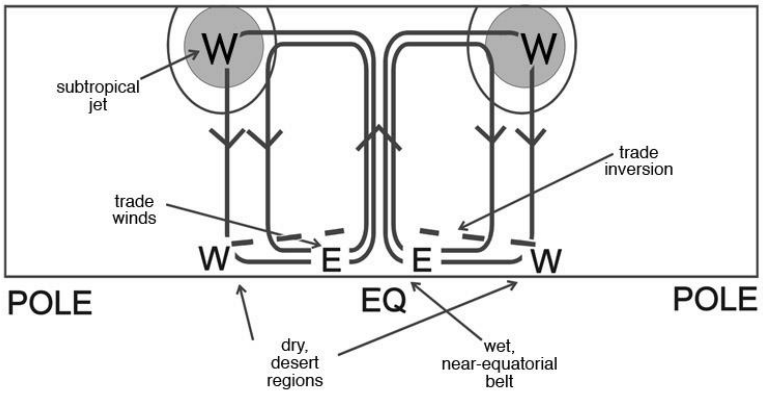


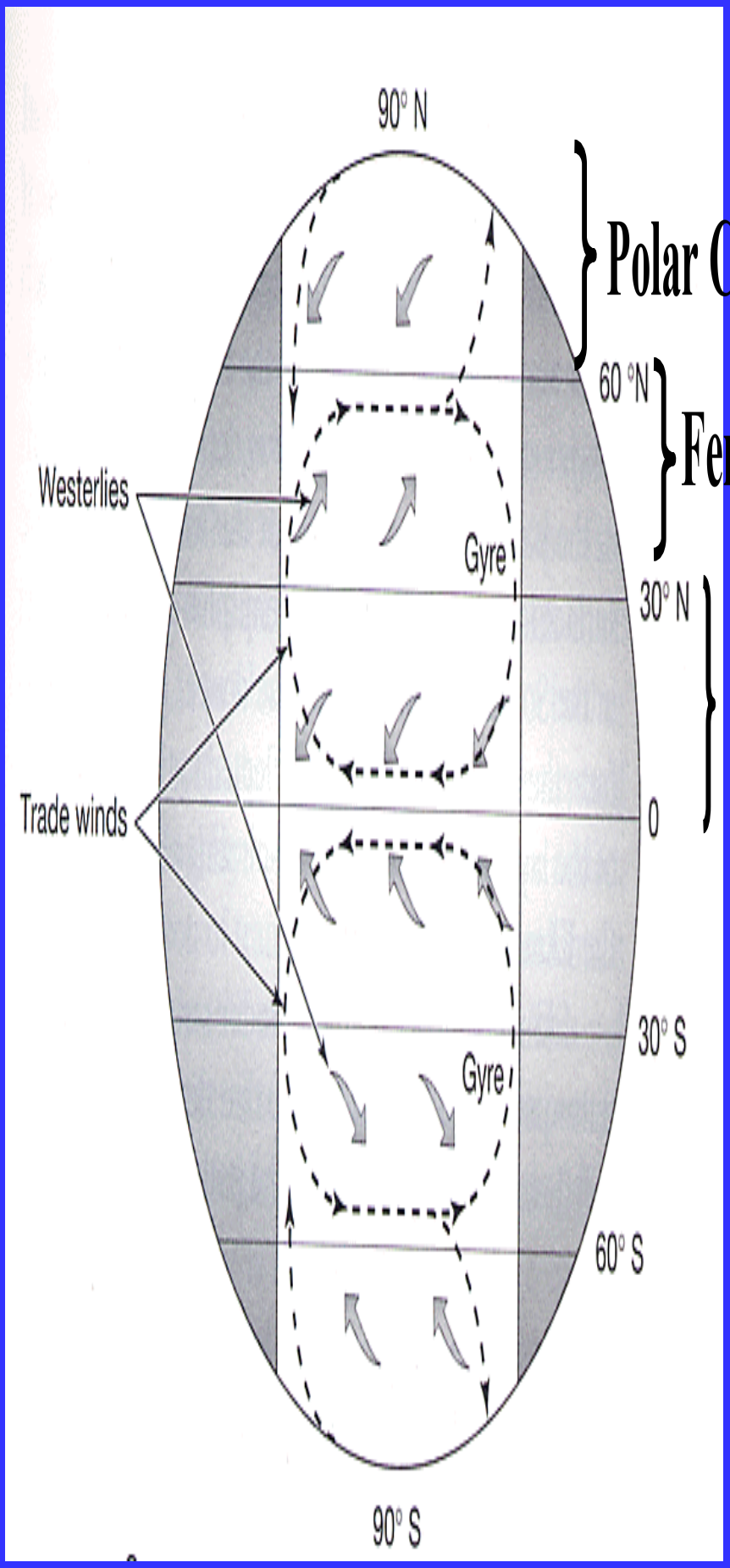




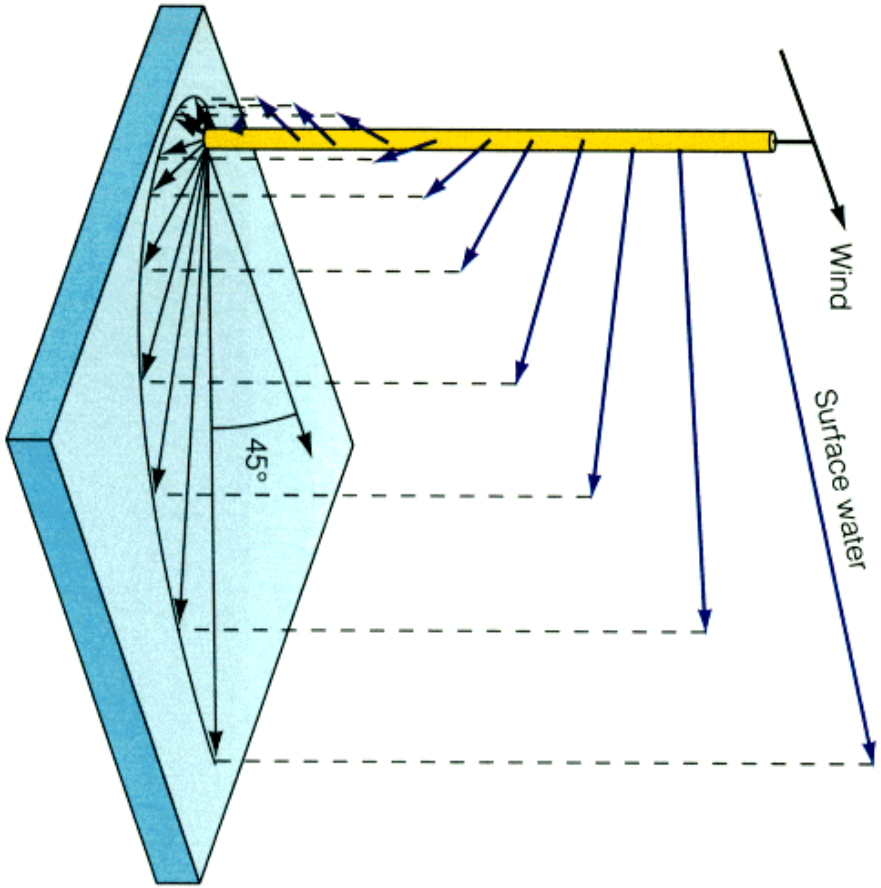

Upper troposphere
NP
EQ
SP
Midlatitude westerlies and eddies
Subtropical jet
Hadley circulation
Subtropical jet
Midlatitude westerlies and eddies
Longitude
Lower troposphere
NP
EQ
SP
Storms and prevailing westerlies
Deserts
NE trades
Wet
SE trades
Deserts
Storms and prevailing westerlies
Longitude

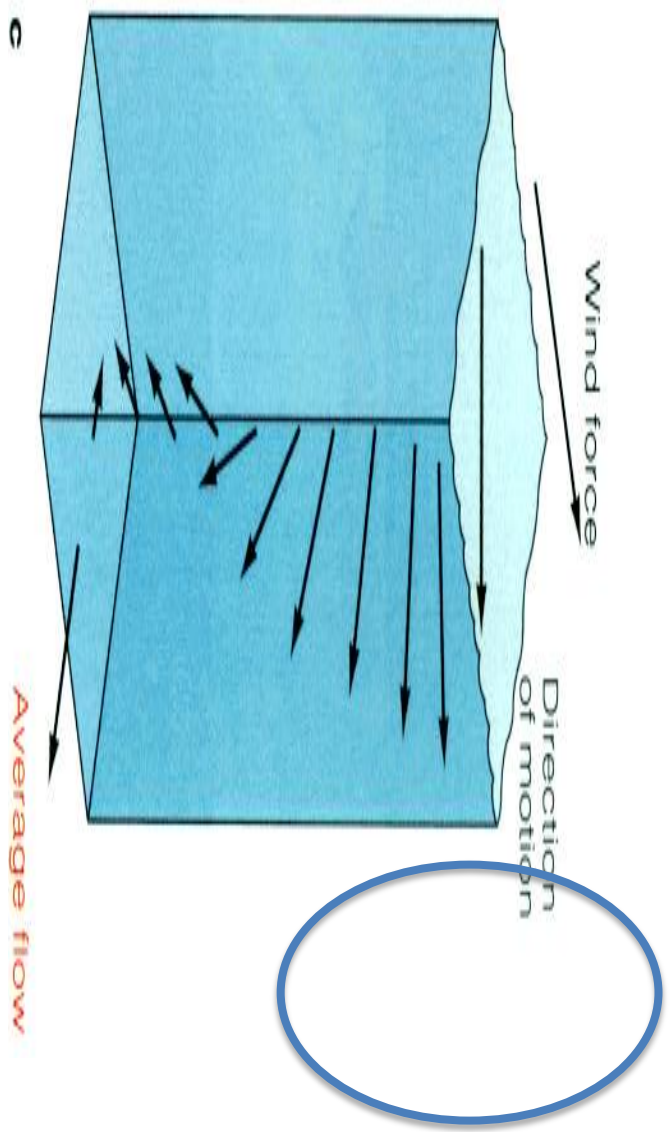

POLE
upper level
westerlies
W
W
L
H
surface westerlies
and eddies
northeasterly
surface trade winds
Hadley
circulation
EQUATOR

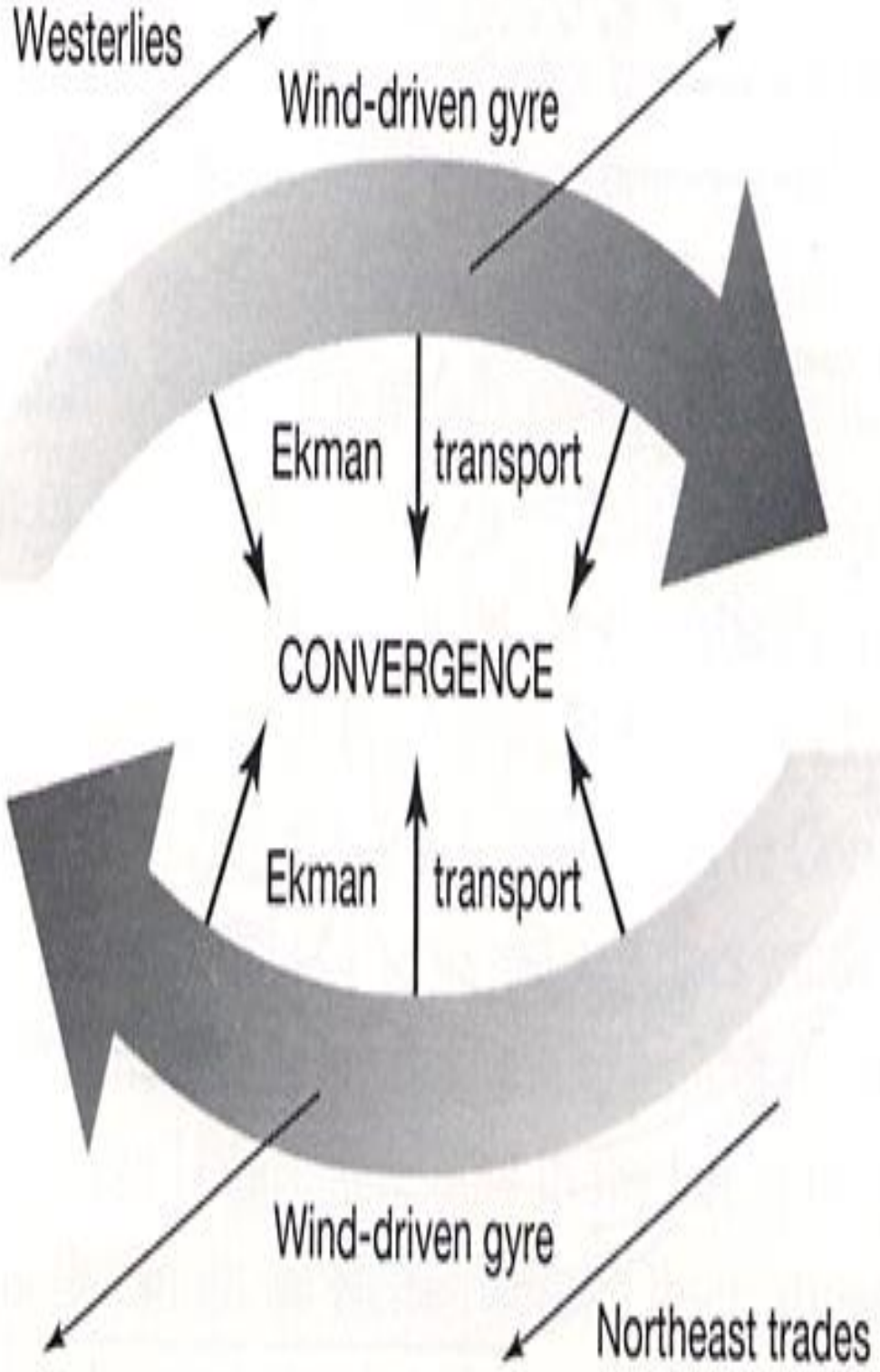

W
W
subtropical
jet
trade
inversion
trade
winds
W
E
E
W
POLE
EQ
POLE
dry,
desert
regions
wet,
near-equatorial
belt


90° N
Polar Cell
60 °N
Ferrel Cell
Westerlies
Gyre
30° N
Hadley Cell
Trade winds
0
30° S
Gyre
60° S
90° S

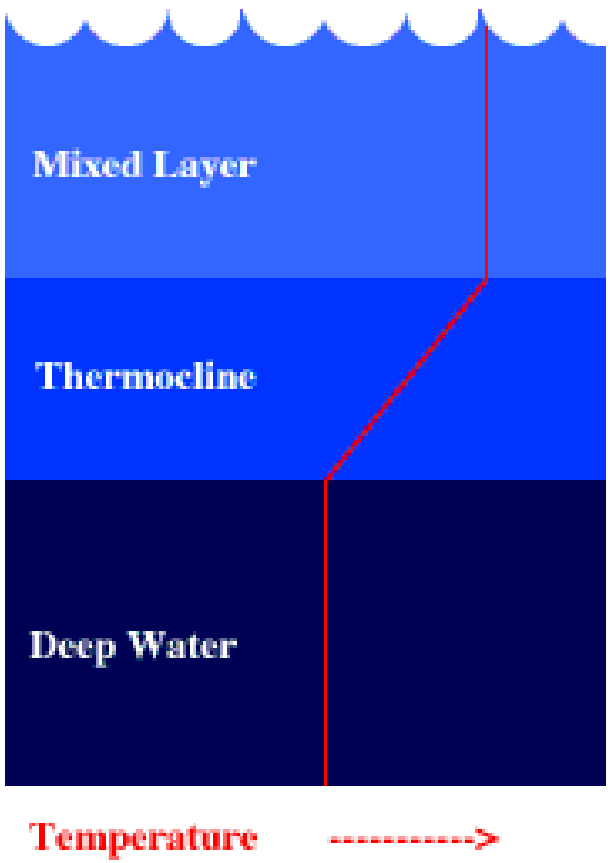
Ekman Spiral: Friction+Coriolis



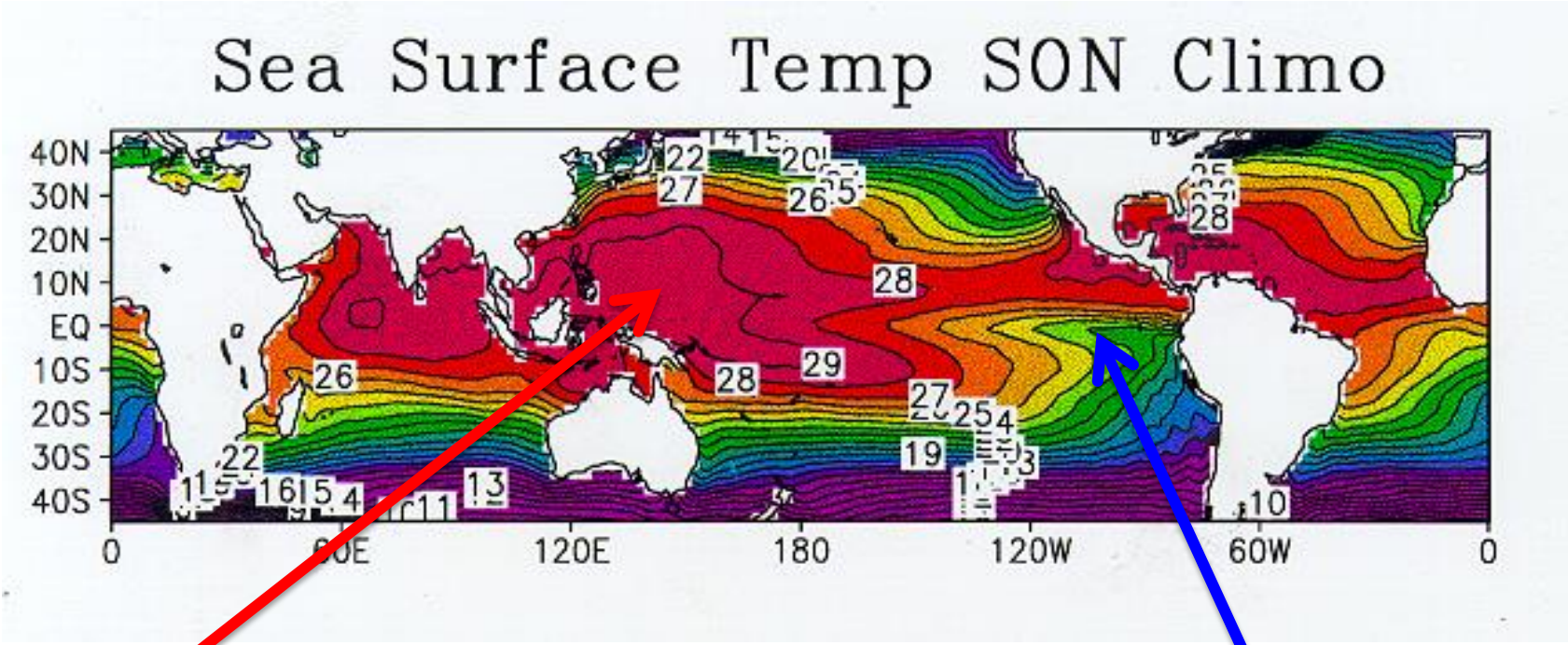



Westerlies
Wind-driven gyre
Ekman transport
CONVERGENCE
Ekman transport
Wind-driven gyre
Northeast trades

Ocean Mixed-Layer



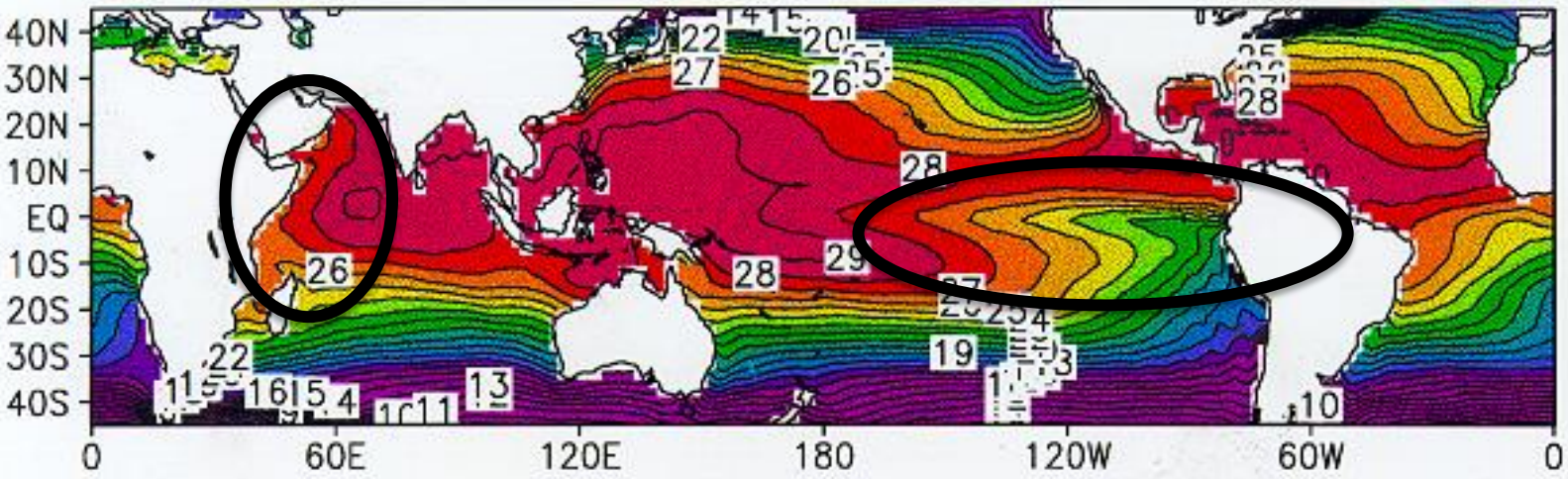
September-October-November
Sea Surface Temperature Climatology



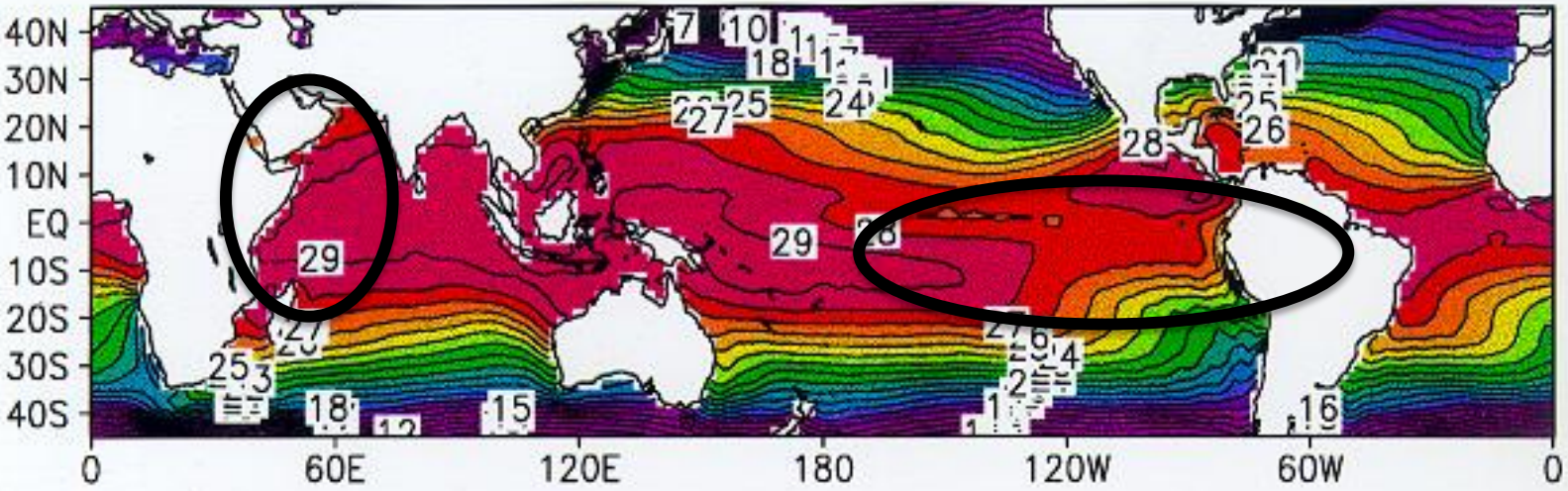
Warm Pool

Cold Tongue

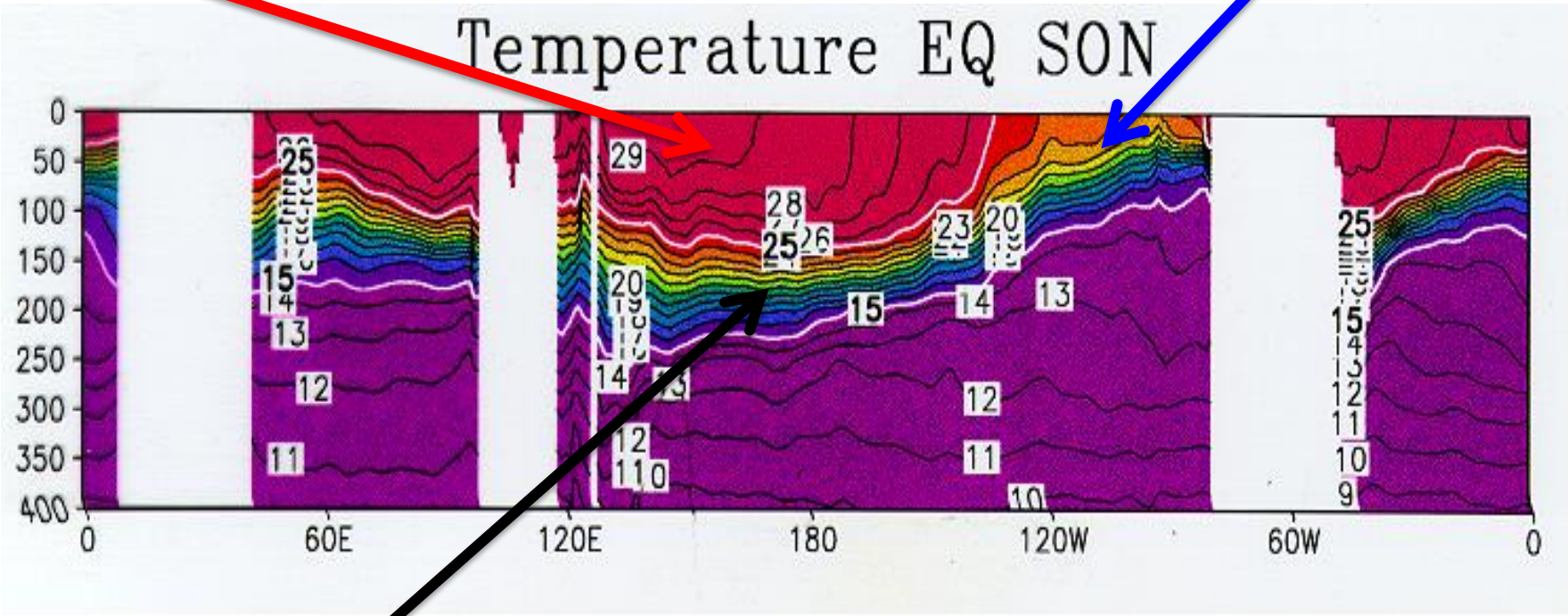
Sea Surface Temp SON Climo

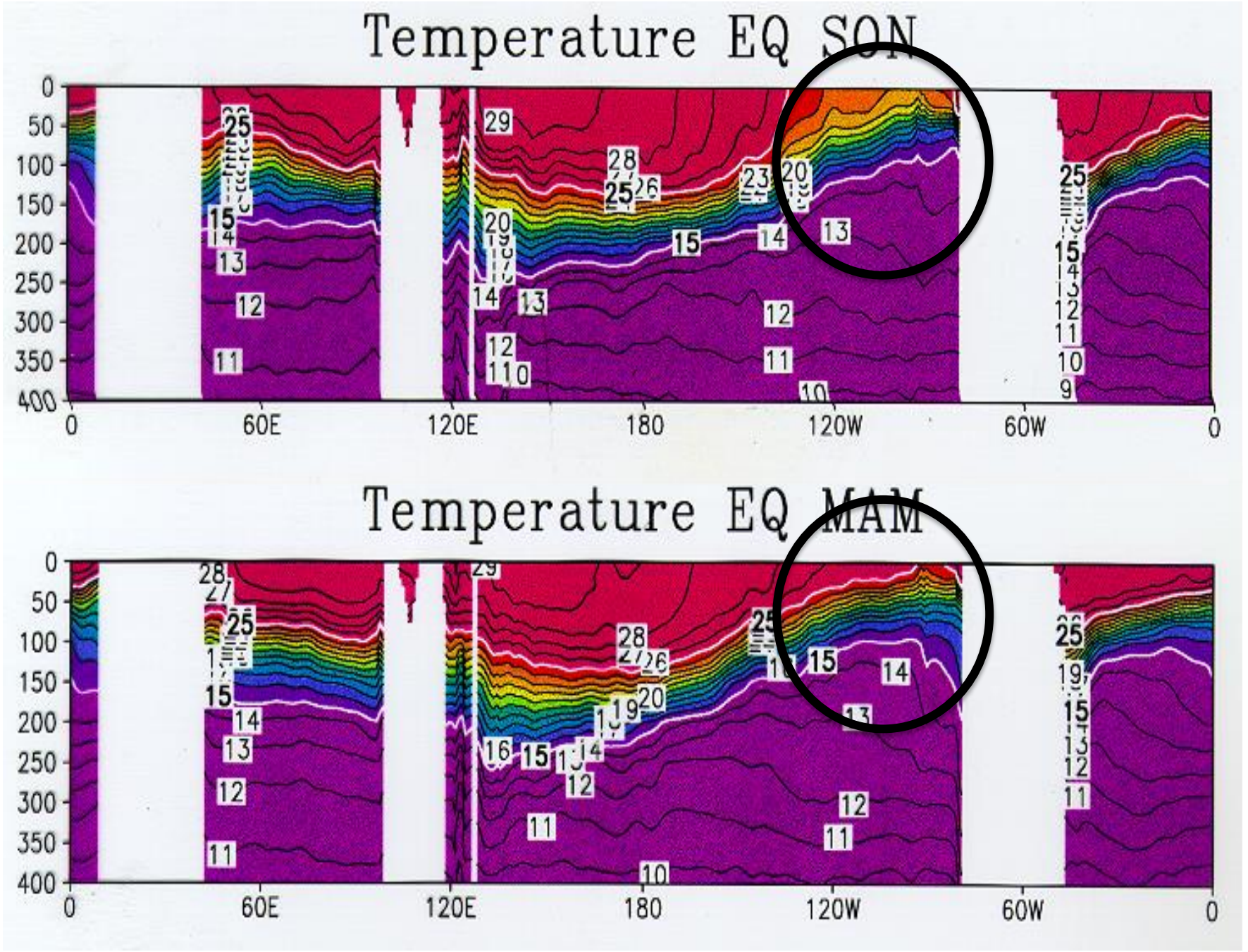


Sea Surface Temp MAM Climo

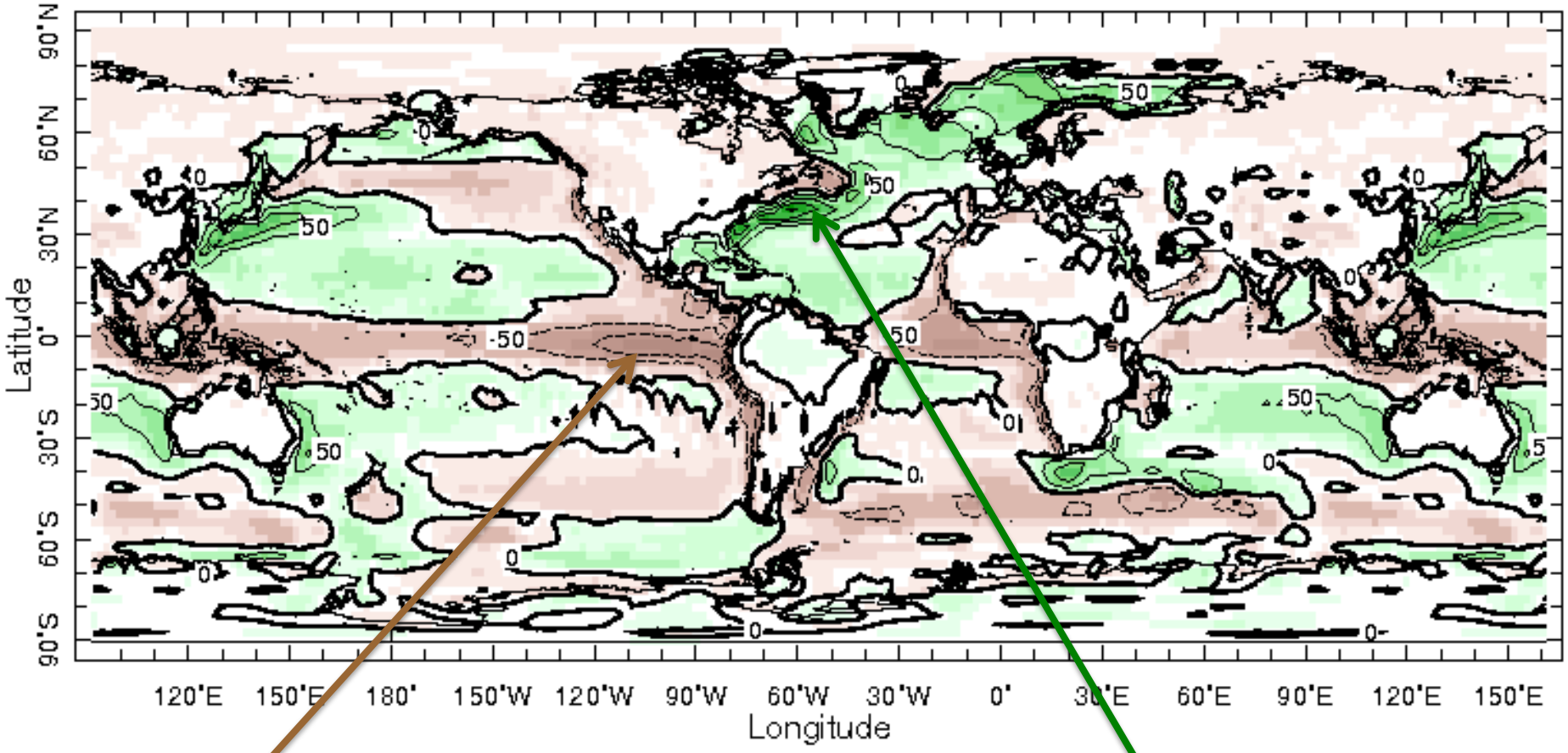


September-October-November
Equatorial Temperature Climatology




Temperature EQ SON
0
50
100
150
200
250
300
350
400
0
60E
120E
180
120W
60W
0
Temperature EQ MAM
0
50
100
150
200
250
300
350
400
0
60E
120E
180
120W
60W
0

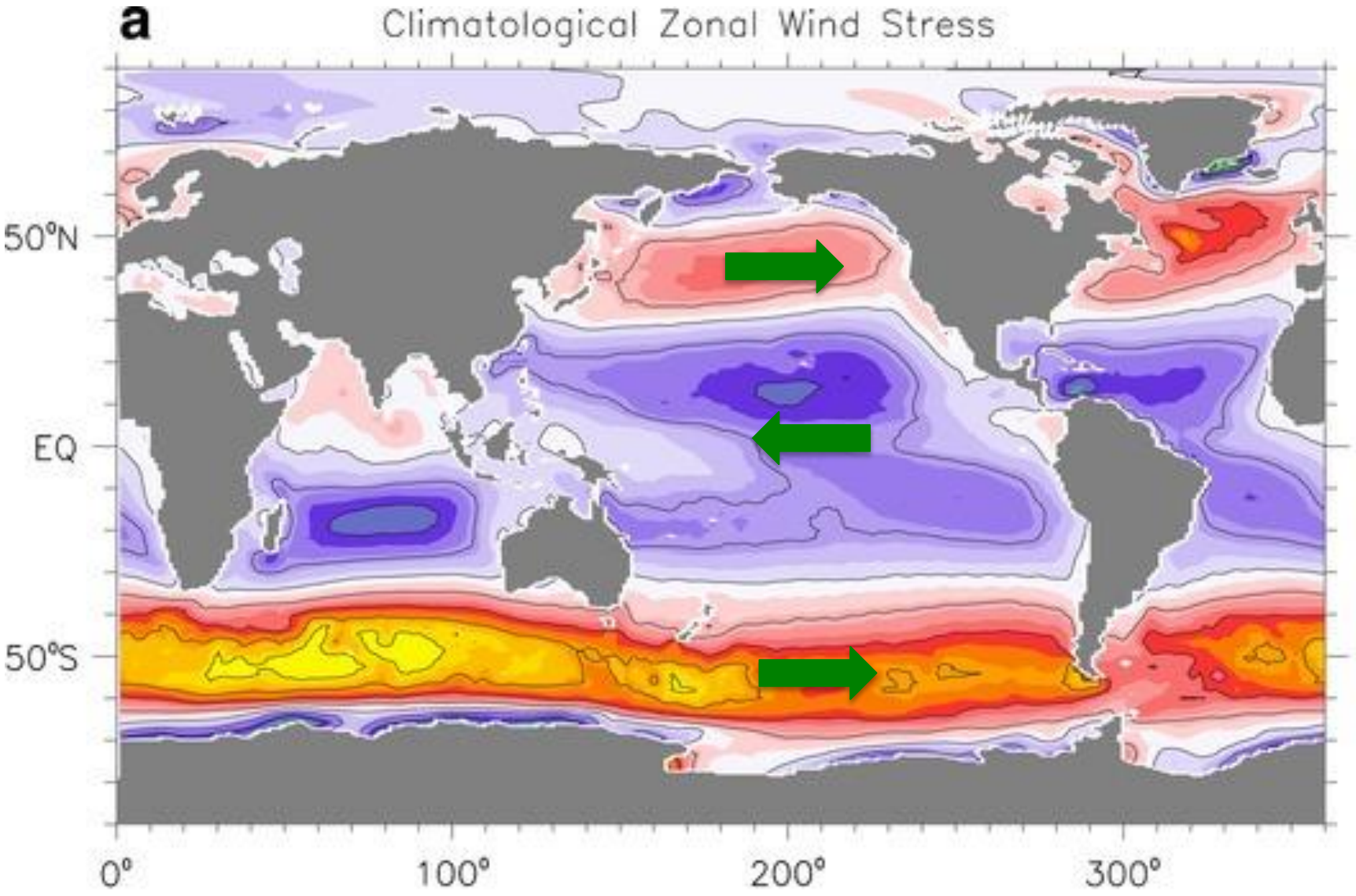
Air-Sea Heat Flux



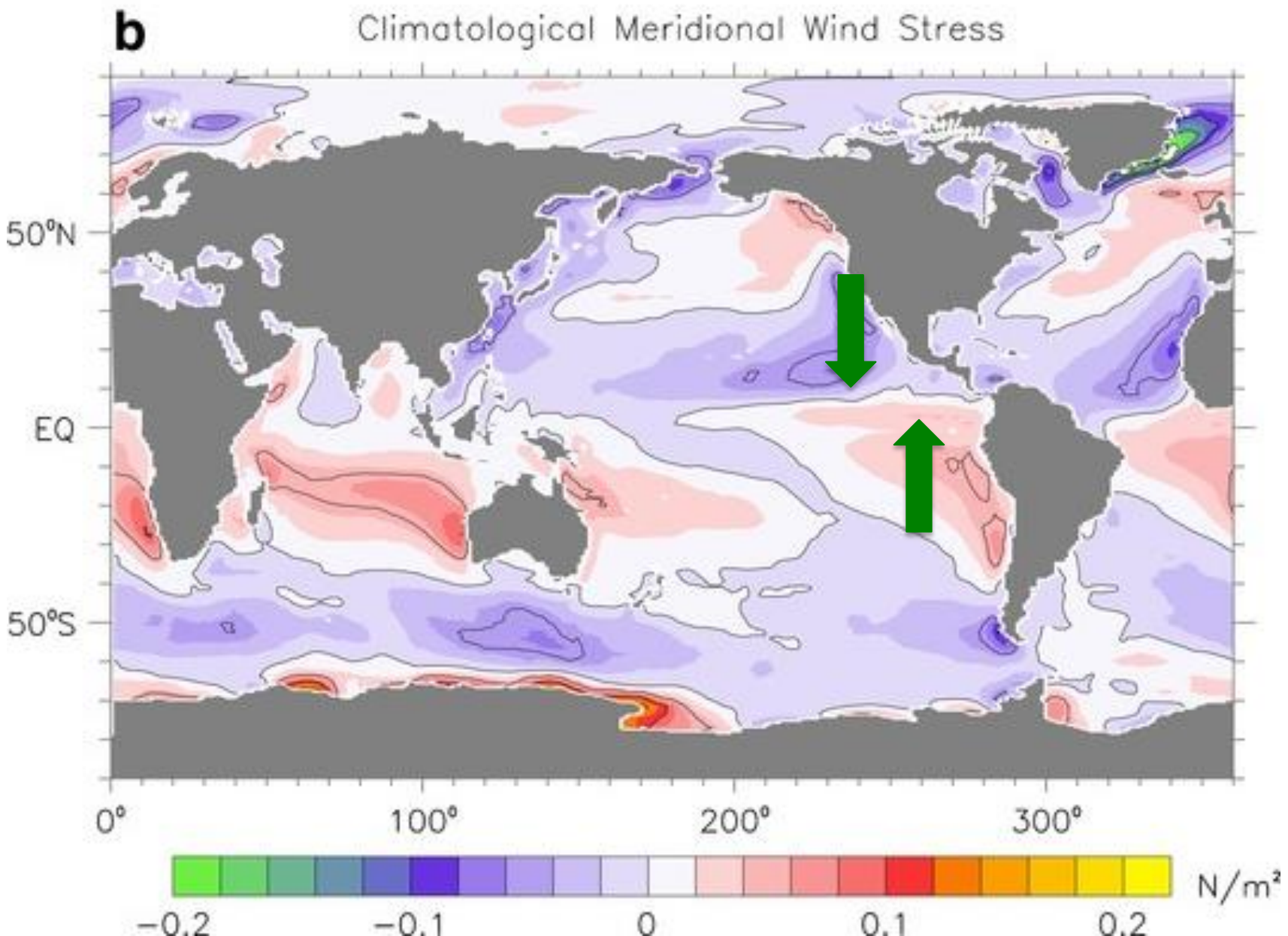
Heat Flux INTO the Ocean

Heat Flux OUT OF the Ocean

Zonal Momentum Flux (Wind Stress)



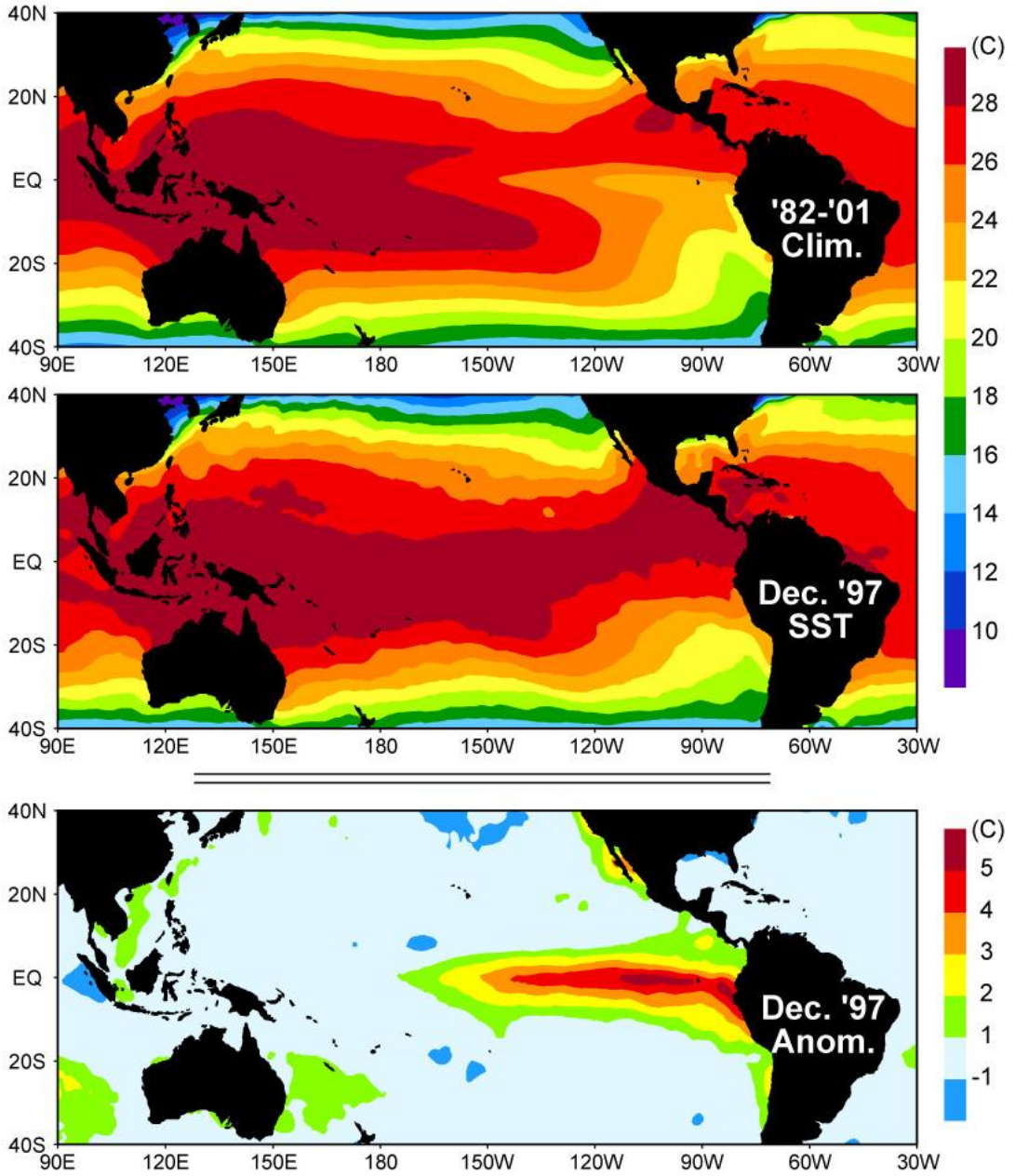
Meridional Momentum Flux

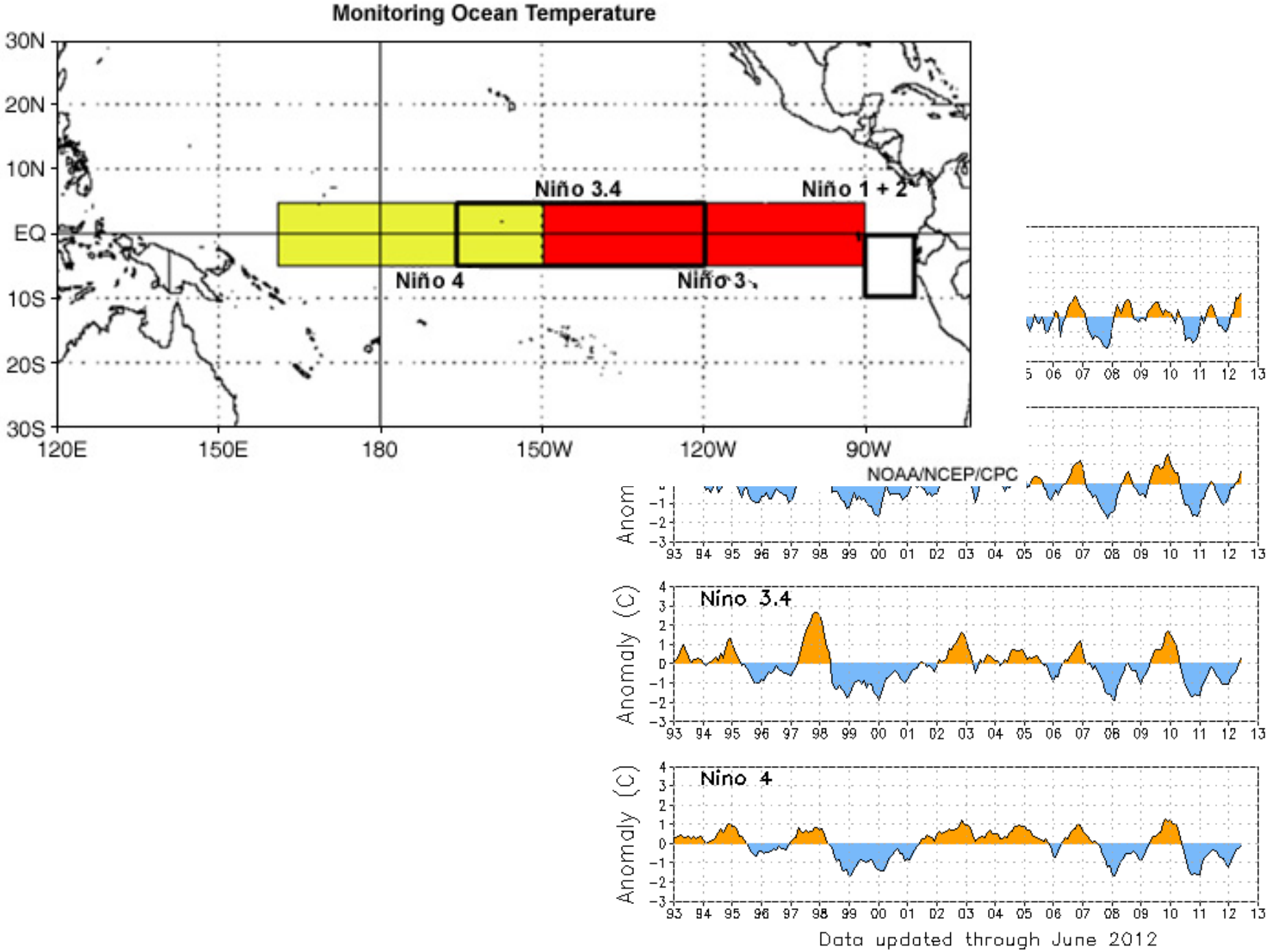


December 1982-2001
SST Climatology

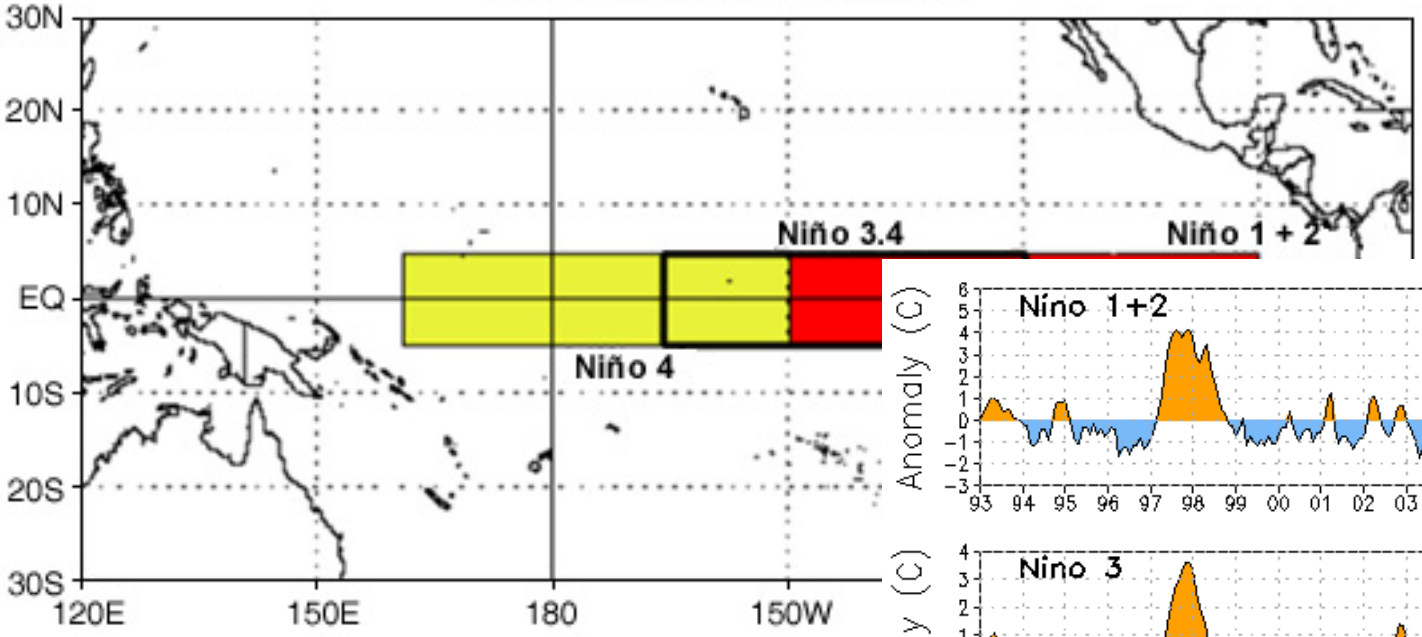
December 1997
Total SST

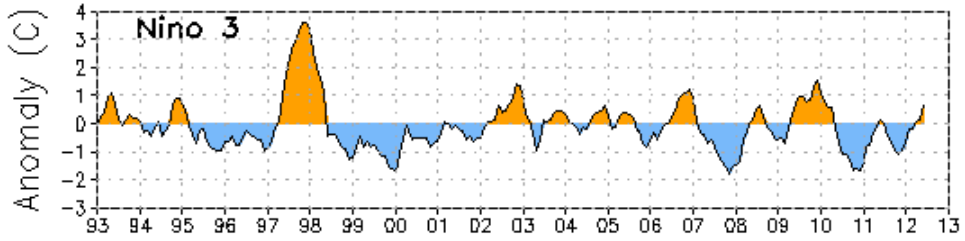
December 1997
SST Anomaly

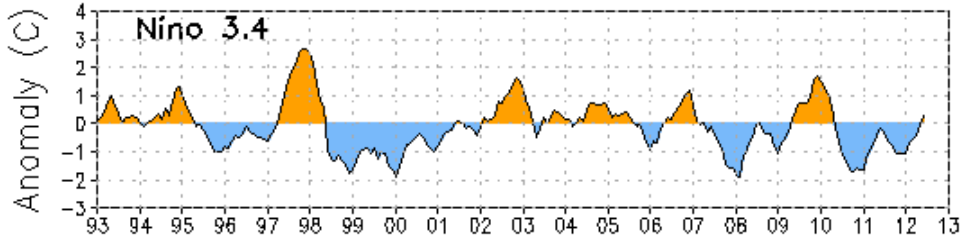


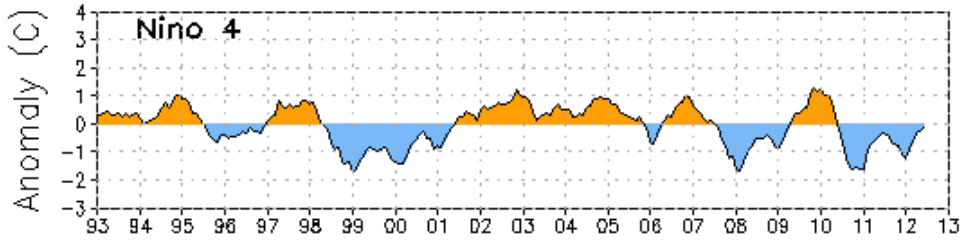

Monitoring Ocean Temperature
30N
20N
10N
EQ
10S
20S
30S
120E
150E
180
150W
120W
90W
Niño 3.4
Niño 1 + 2
Niño 4
Niño 3
NOAA/NCEP/CPC
Anom
Nino 3.4
Anomaly (C)
Nino 4
Anomaly (C)
93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13
Data updated through June 2012

Monitoring Ocean Temperature

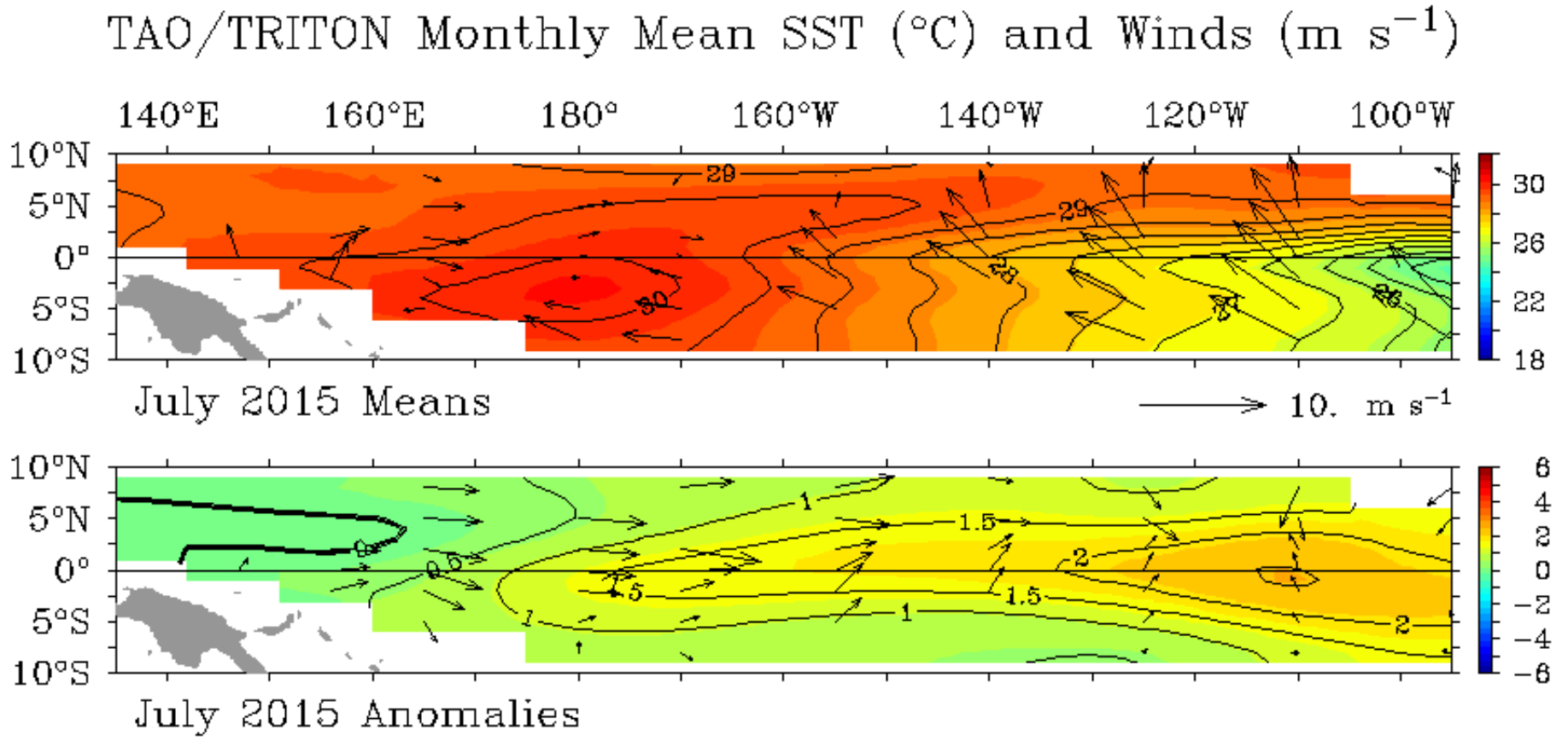


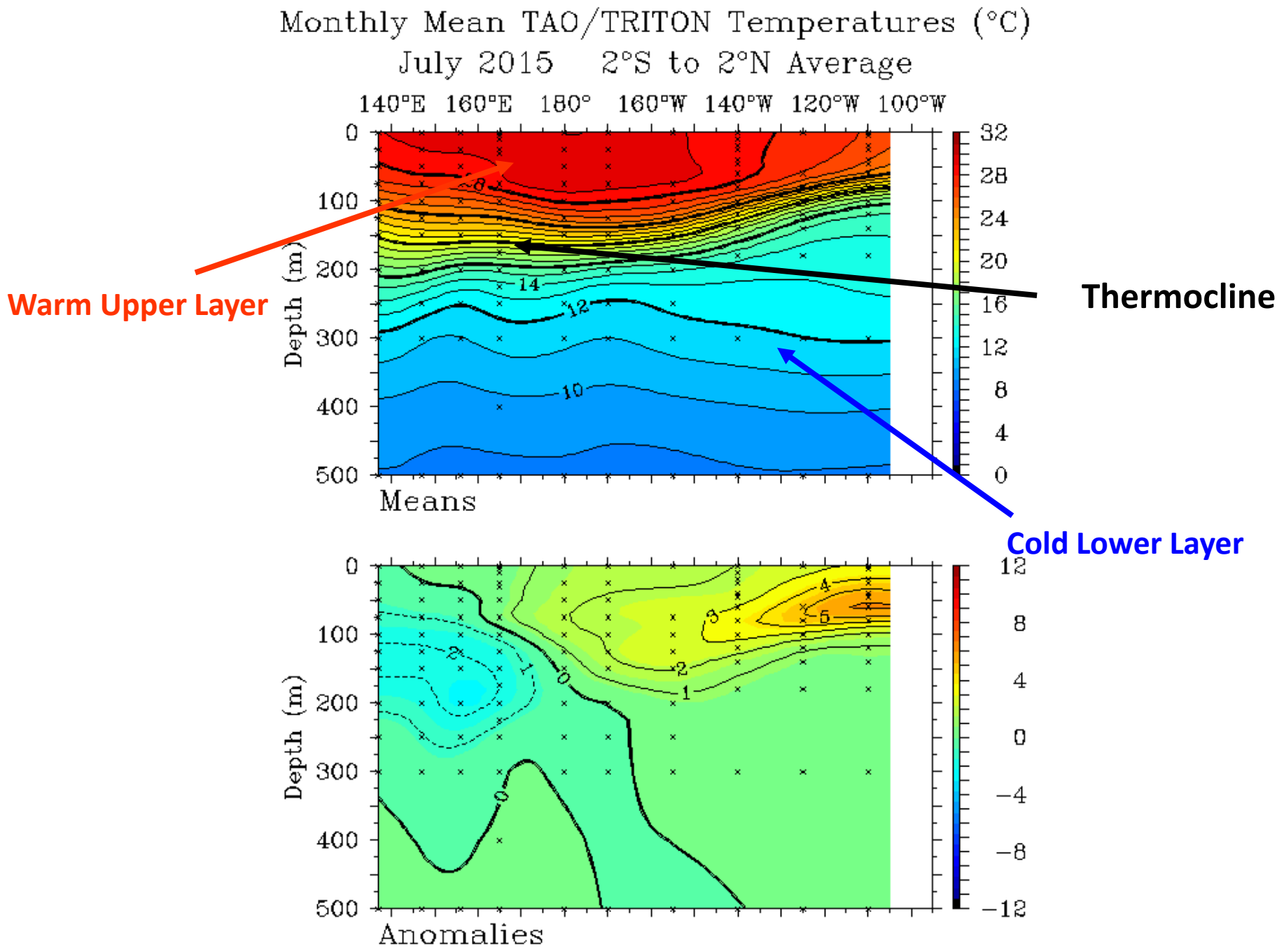




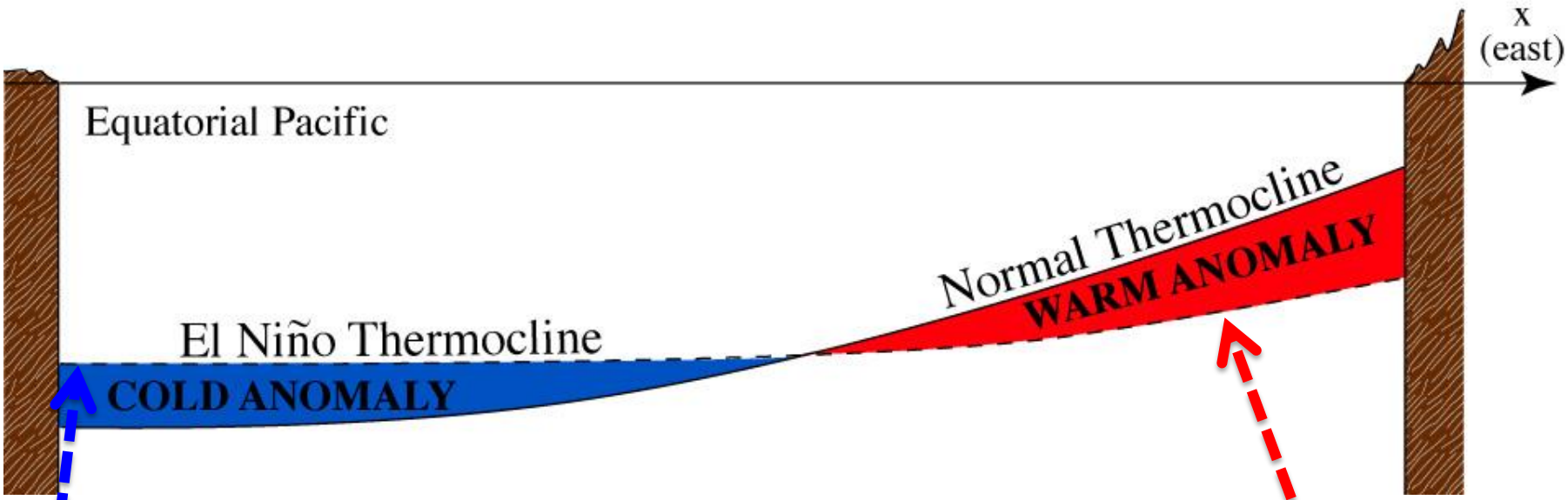


Data updated through June 2012


TAO/TRITON Monthly Mean SST (°C) and Winds (m s−1)
140°E
160°E
180°
160°W
140°W
120°W
100°W
10°N
5°N
0°
5°S
10°S
29
30
July 2015 Means
10. m s−1
1
1.5
2
0.5
July 2015 Anomalies
TAO Project Office/PMEL/NOAA
Aug 24 2015


Monthly Mean TAO/TRITON Temperatures (°C)
July 2015 2°S to 2°N Average
140°E 160°E 180° 160°W 140°W 120°W 100°W
Depth (m)
Means
Anomalies
TAO Project Office/PMEL/NOAA
Aug 23 2015
Warm Upper Layer
Thermocline
Cold Lower Layer

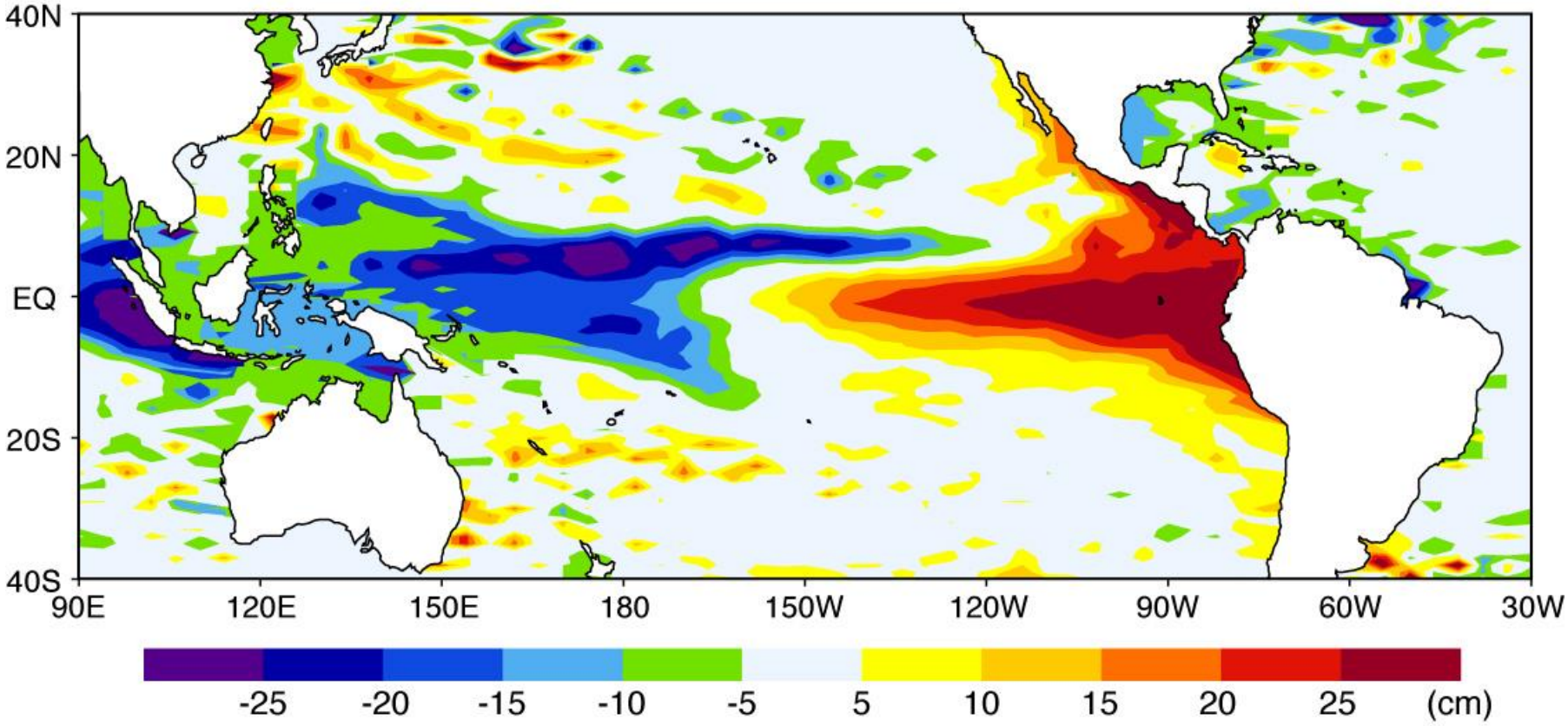
El Nino vs. Normal Thermocline Depth

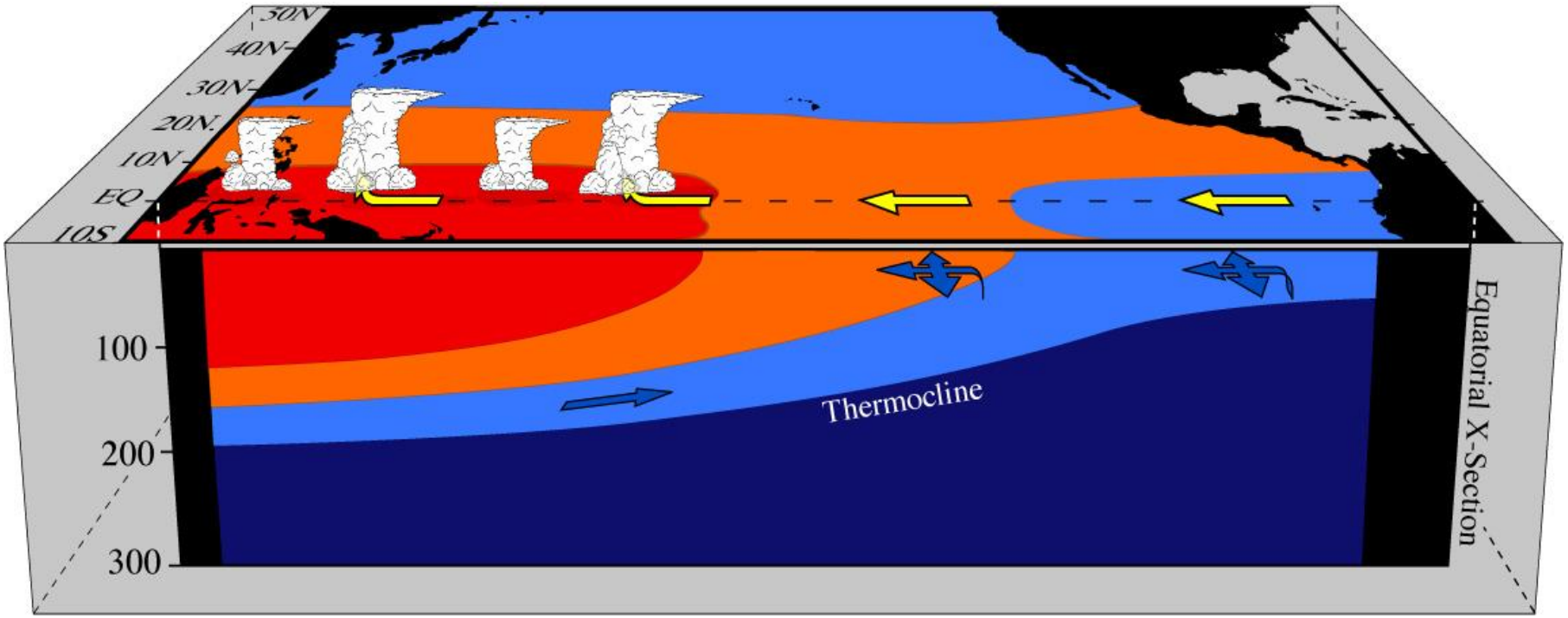


Thermocline is Shallower than Normal
Negative Depth Anomaly

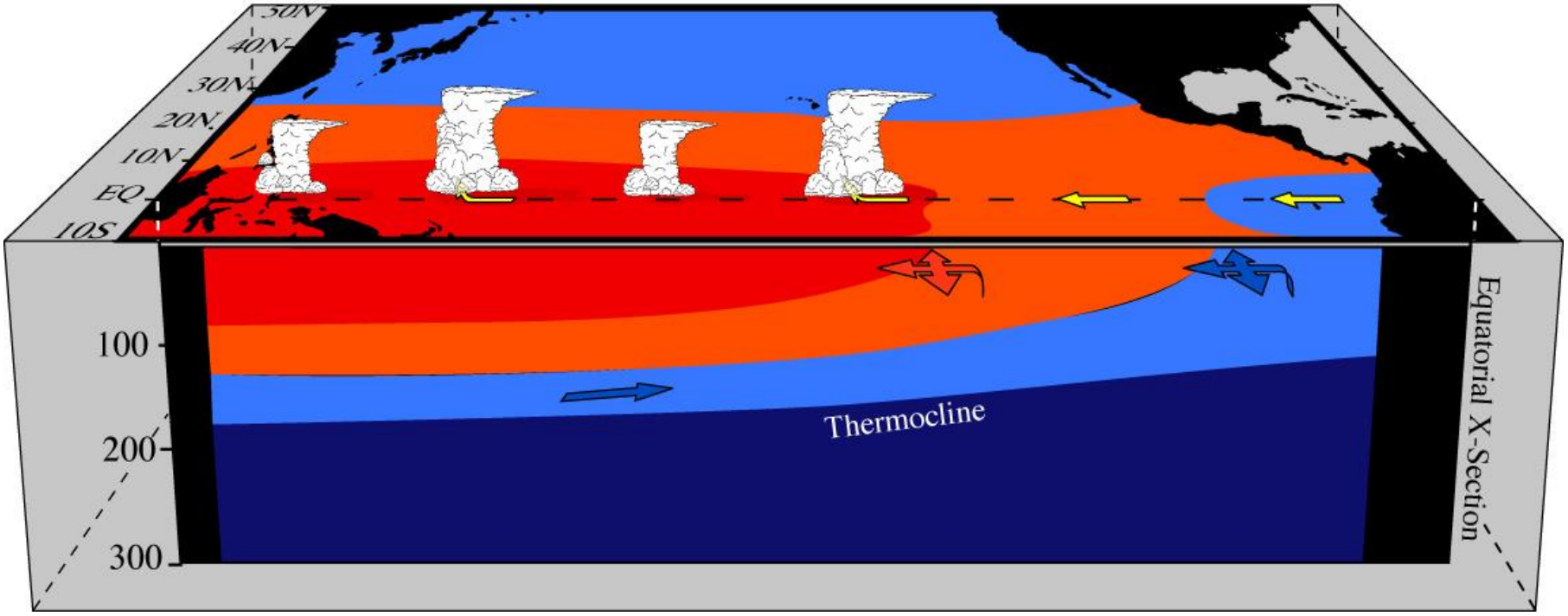
Thermocline is Deeper than Normal
Positive Depth Anomaly

December 1997 (El Nino) Thermocline Depth Anomalies)

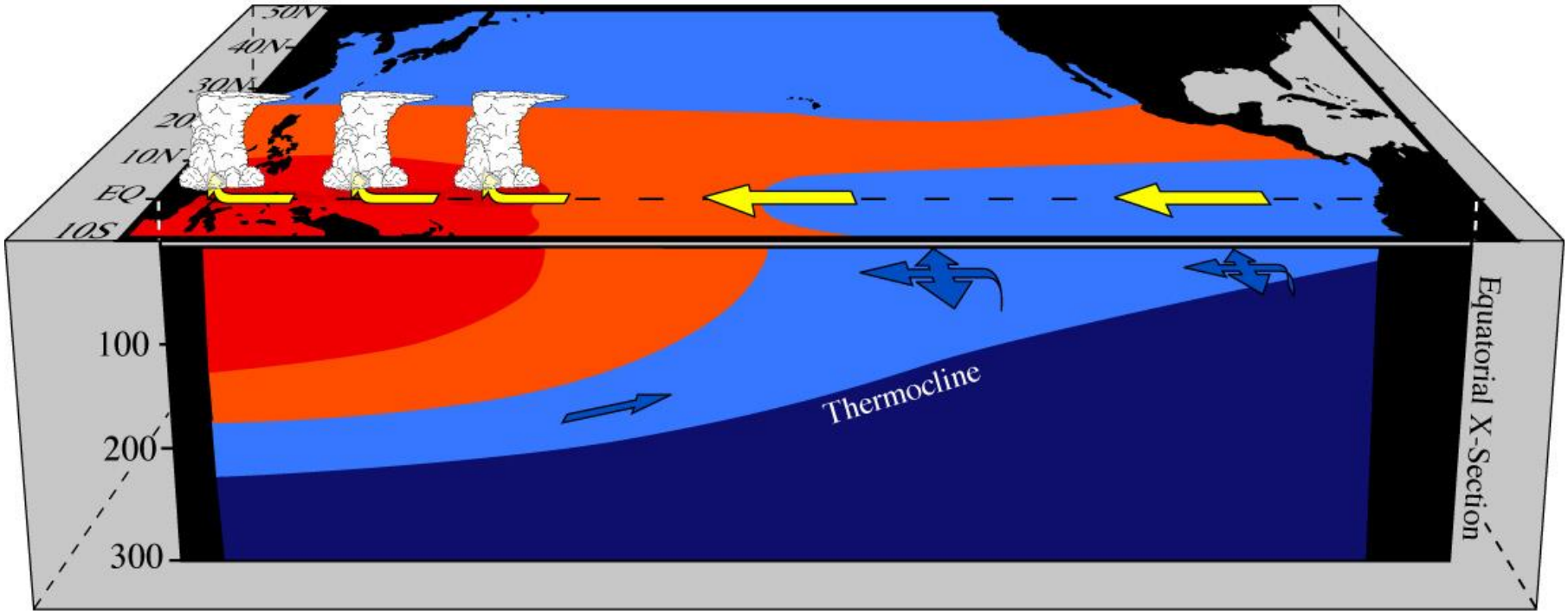




Normal Conditions in the Tropical Pacific

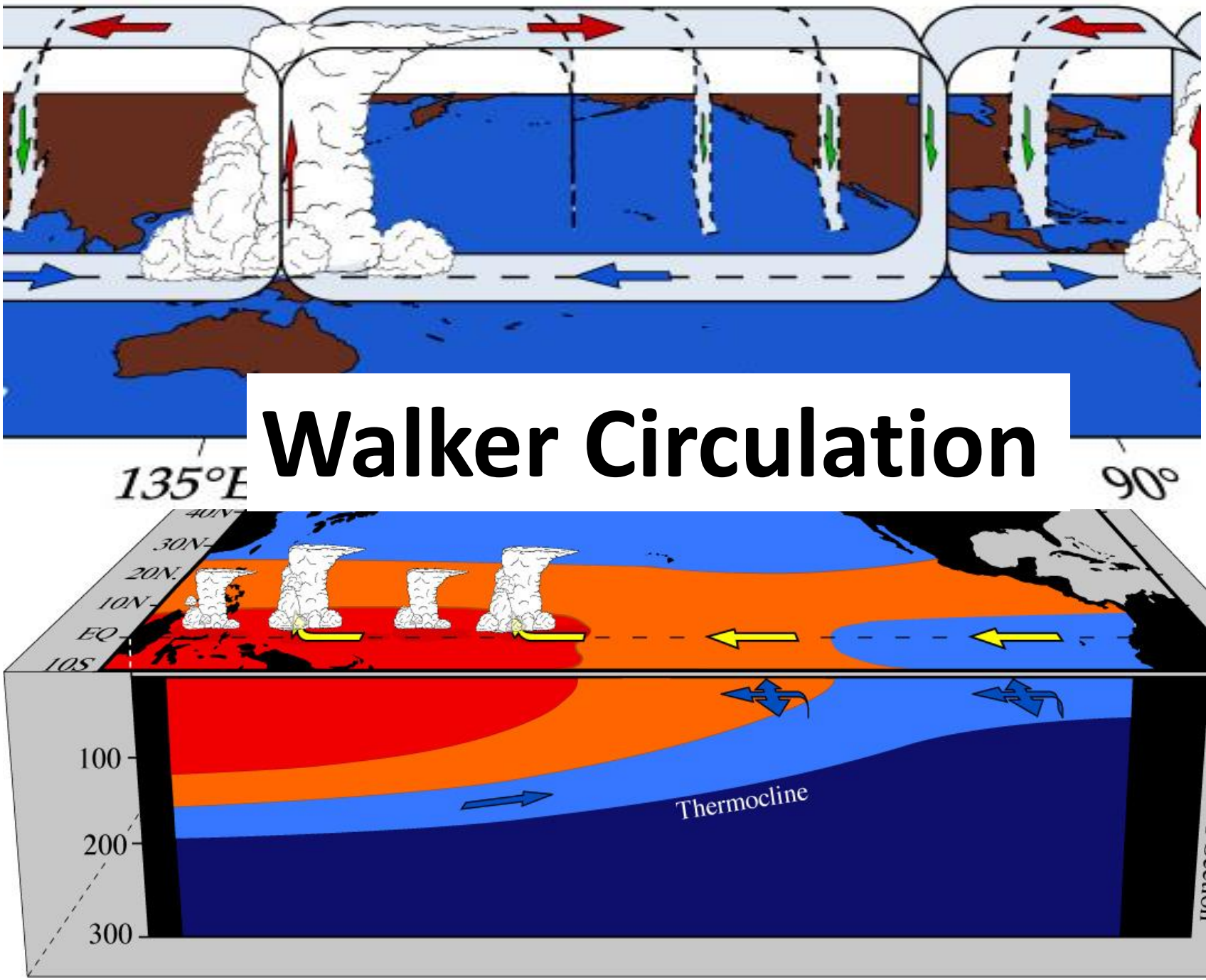


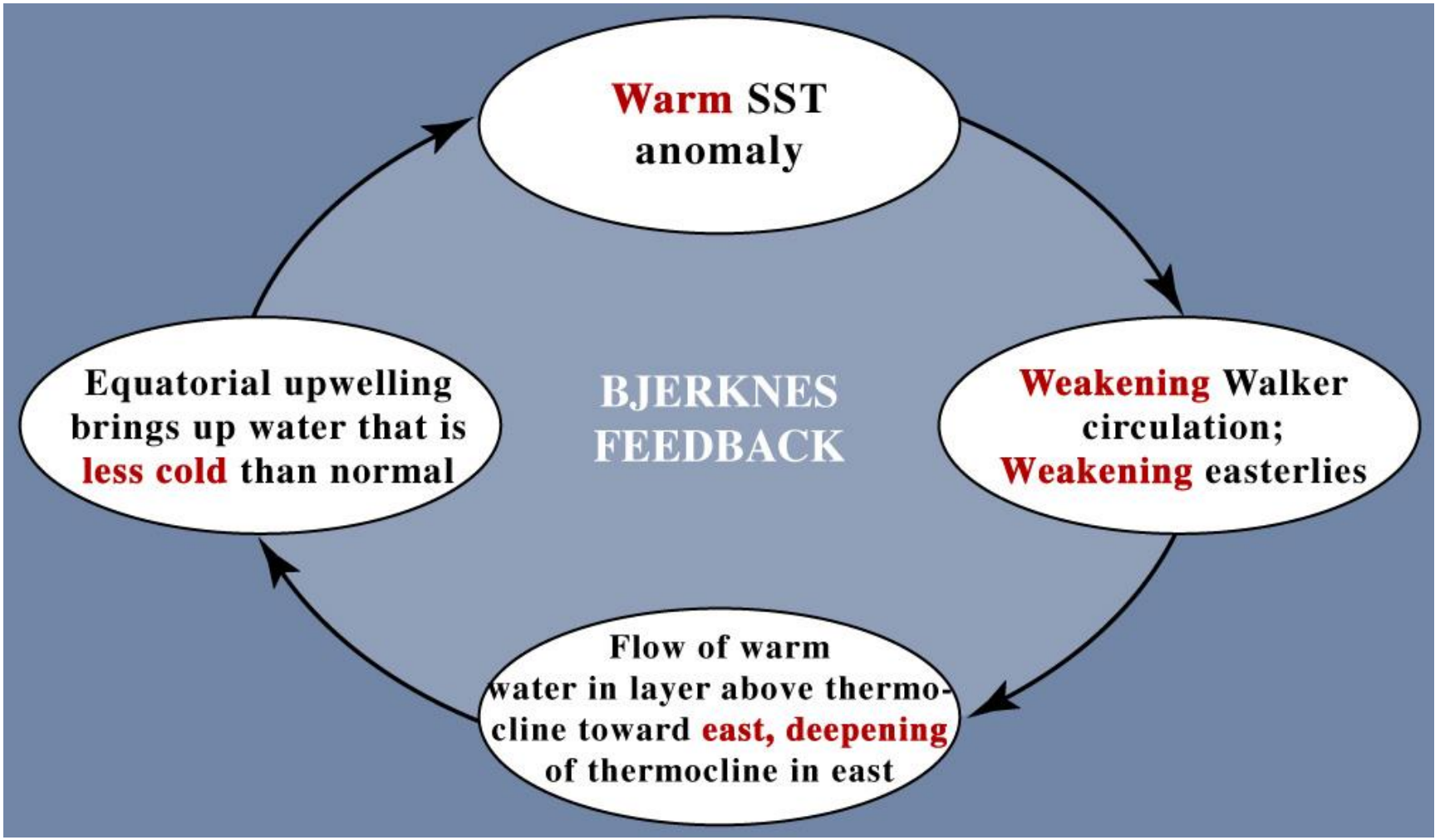
Warm (El Nino) Conditions in the Tropical Pacific

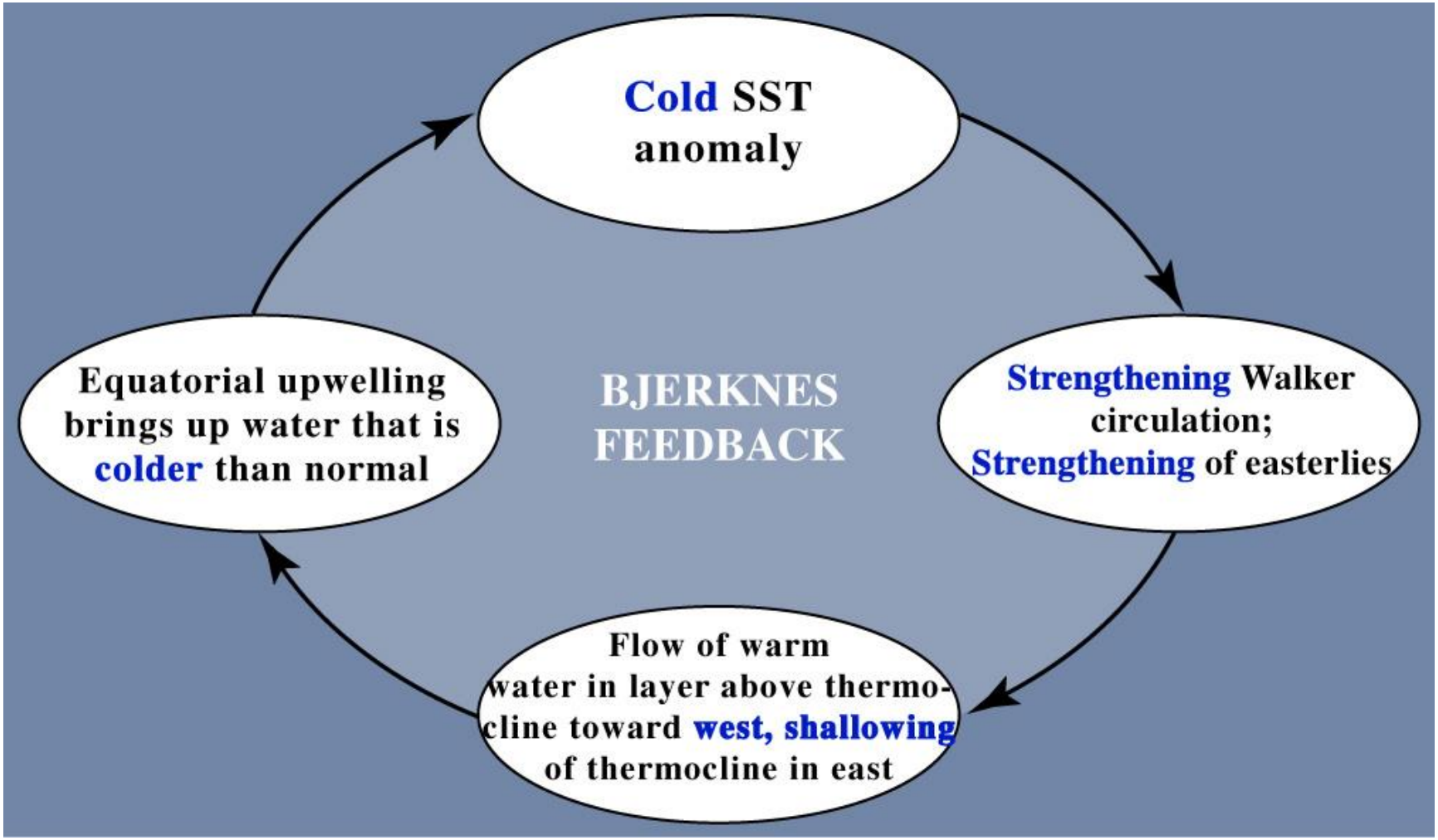


Cold (La Nina) Conditions in the Tropical Pacific

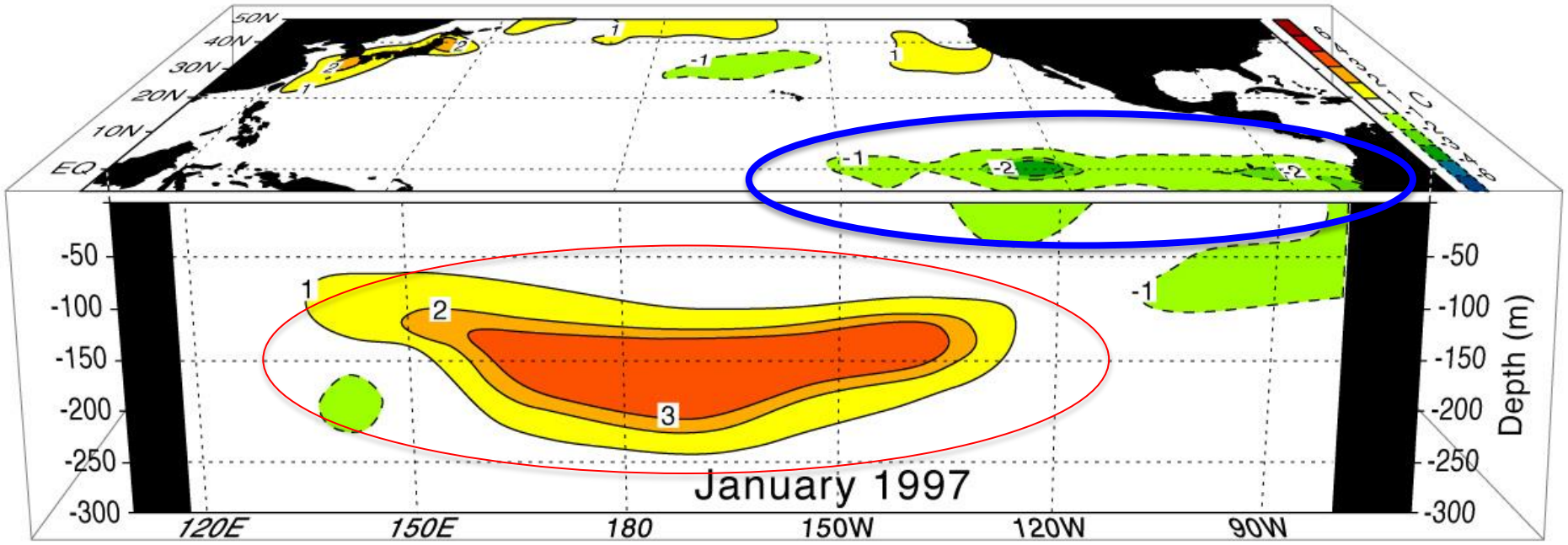
Walker Circulation



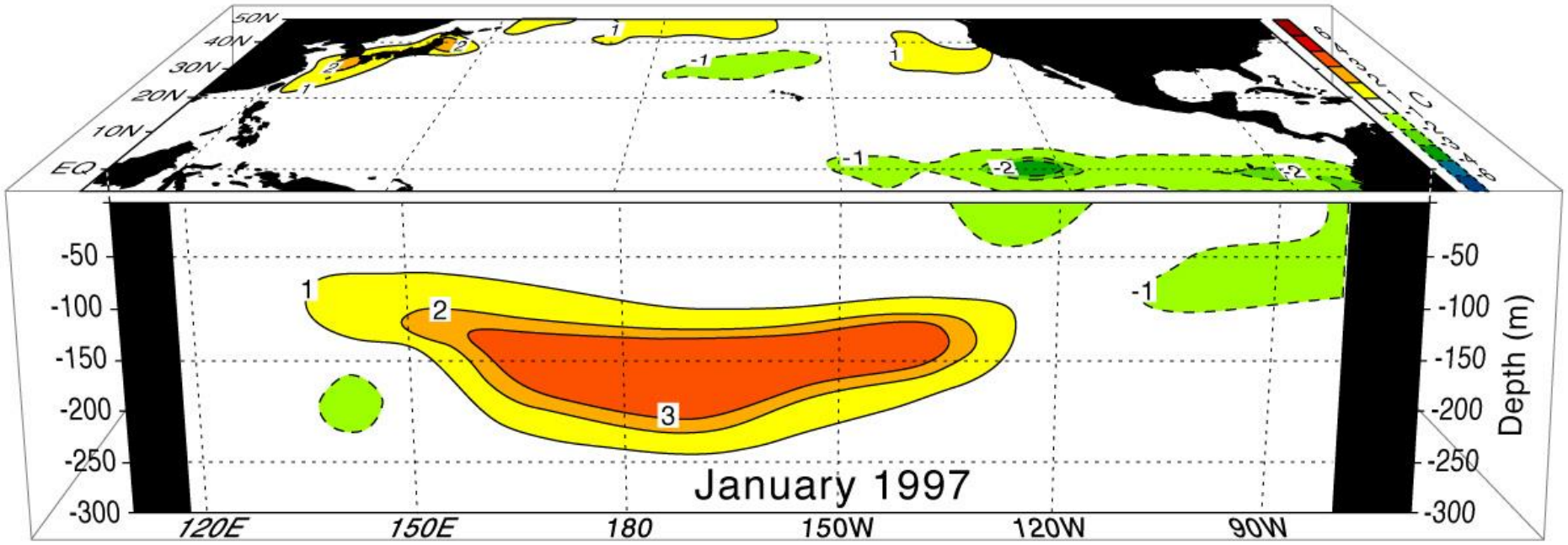

Warm SST anomaly
Weakening Walker circulation; Weakening easterlies
Flow of warm water in layer above thermo-cline toward east, deepening of thermocline in east
Equatorial upwelling brings up water that is less cold than normal
BJERKNES FEEDBACK

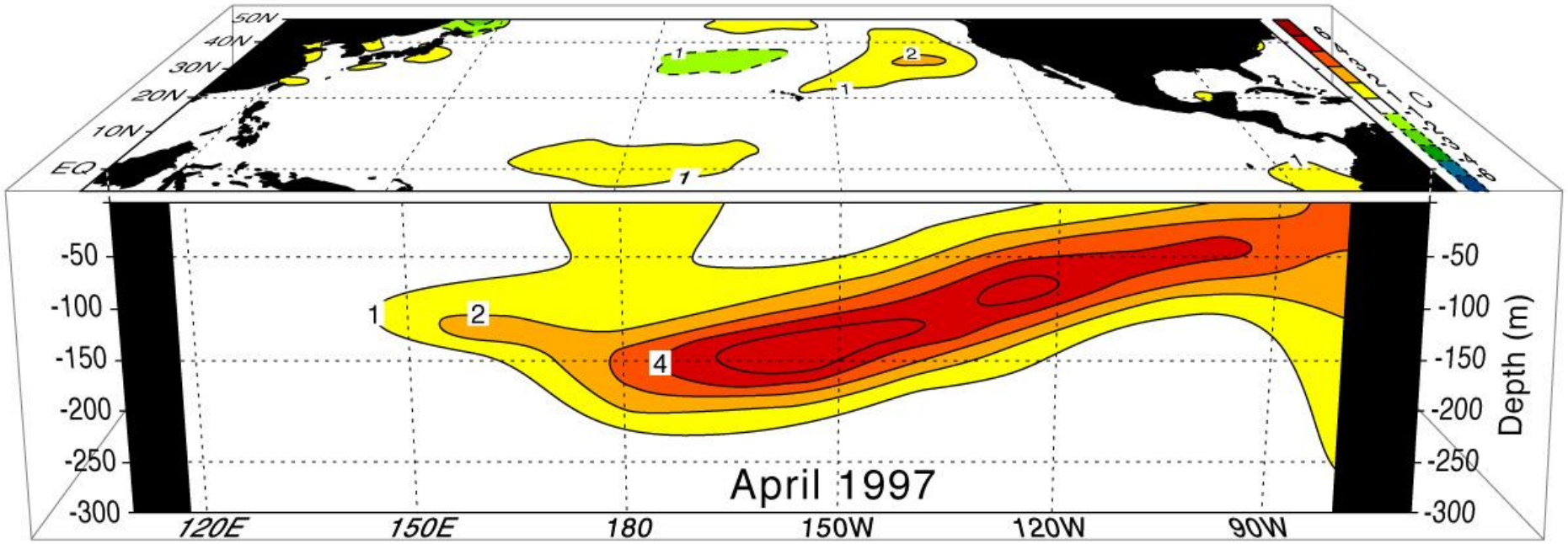

Cold SST anomaly
Strengthening Walker circulation; Strengthening of easterlies
Flow of warm water in layer above thermo-cline toward west, shallowing of thermocline in east
Equatorial upwelling brings up water that is colder than normal
BJERKNES FEEDBACK

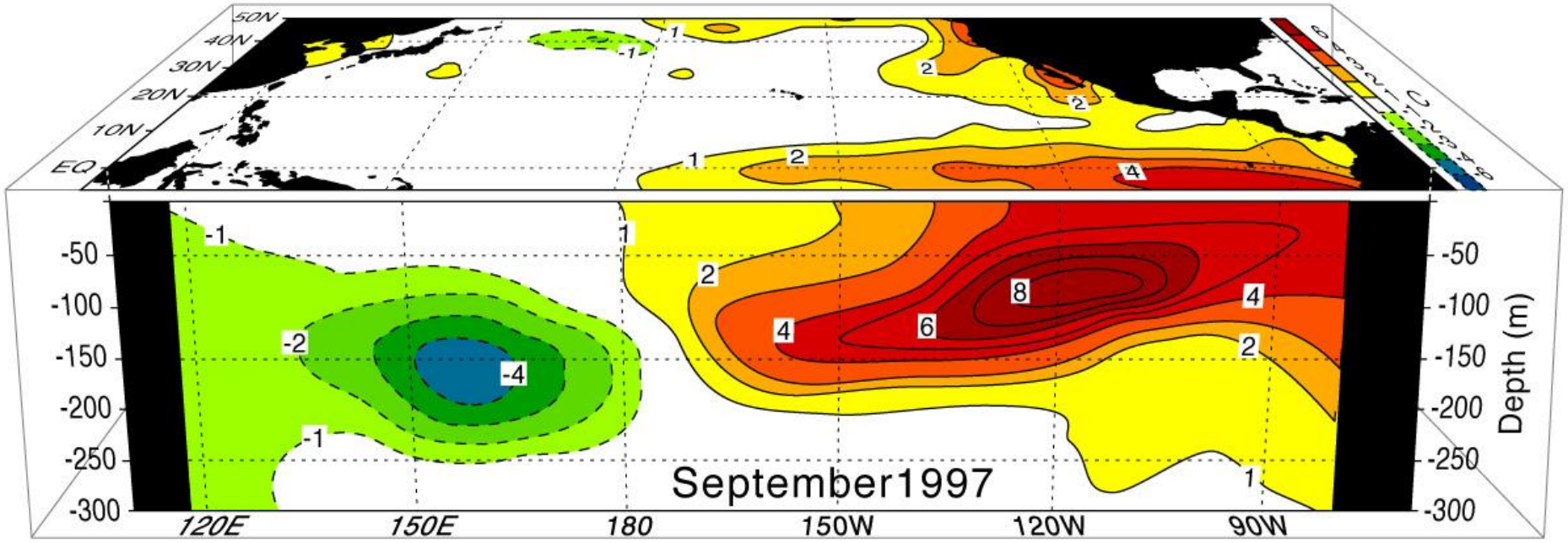
Evolution of the 1997-98 ENSO Event



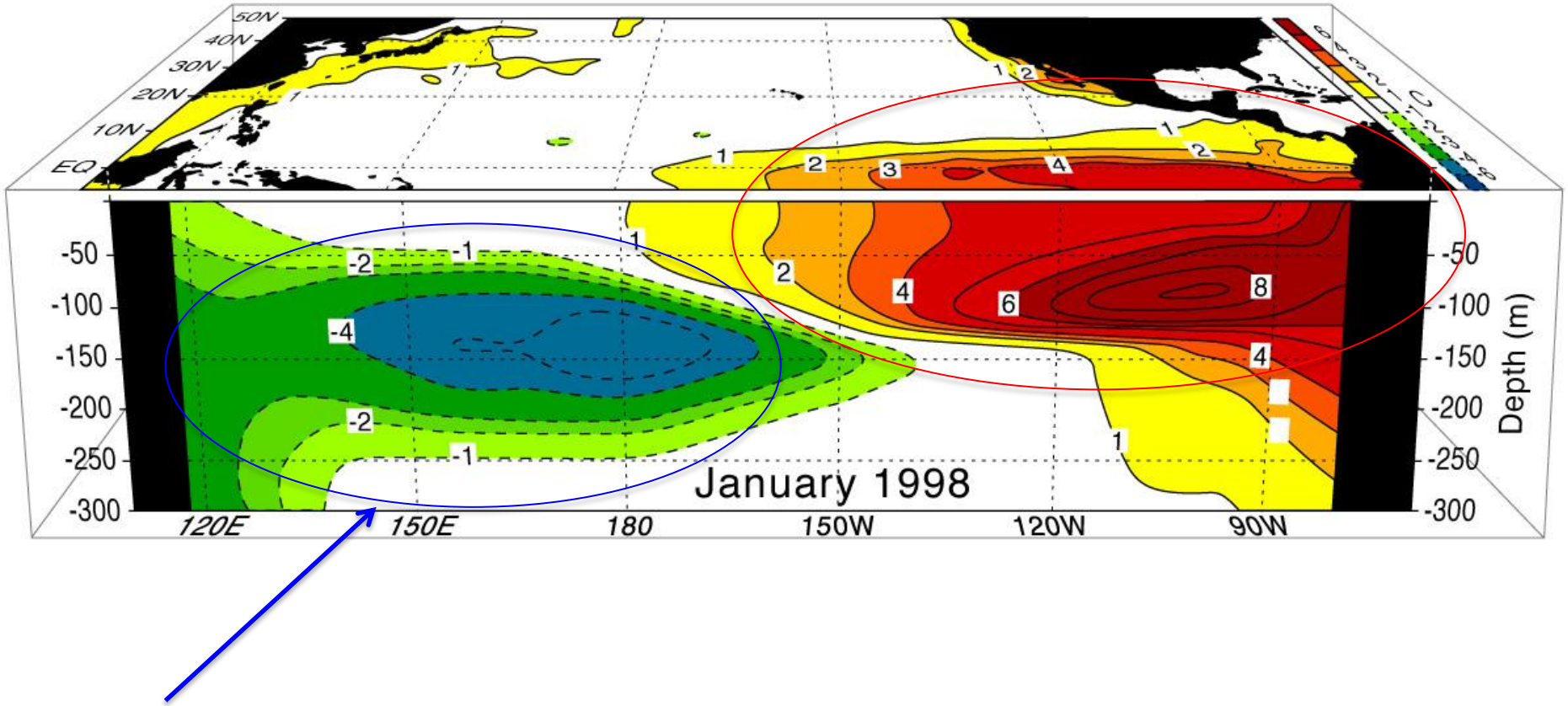
Warm Sub-Surface Temperature (Deeper Thermocline) Anomaly is the Precursor of the Coming Warm Event – Why We Can Predict


50N
40N
30N
20N
10N
EQ
-50
-100
-150
-200
-250
-300
120E
150E
180
150W
120W
90W
Depth (m)
January 1997

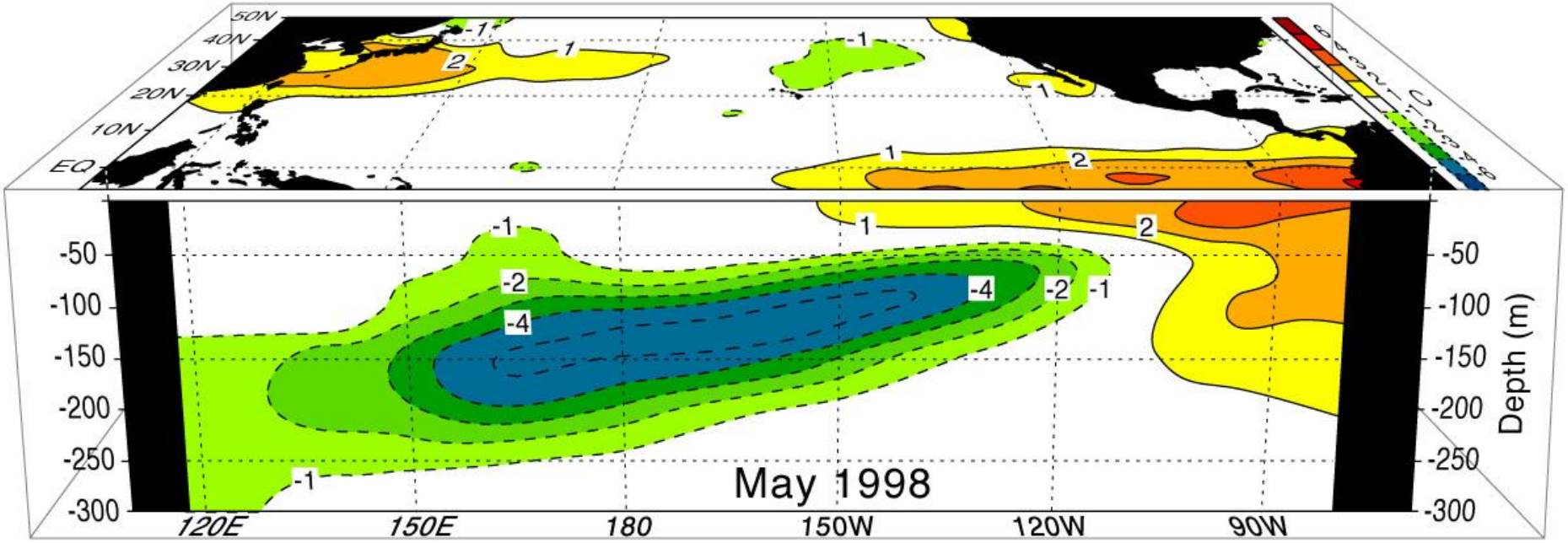

50N
40N
30N
20N
10N
EQ
1
2
1
1
1
-50
-100
-150
-200
-250
-300
1
2
4
April 1997
120E
150E
180
150W
120W
90W
Depth (m)

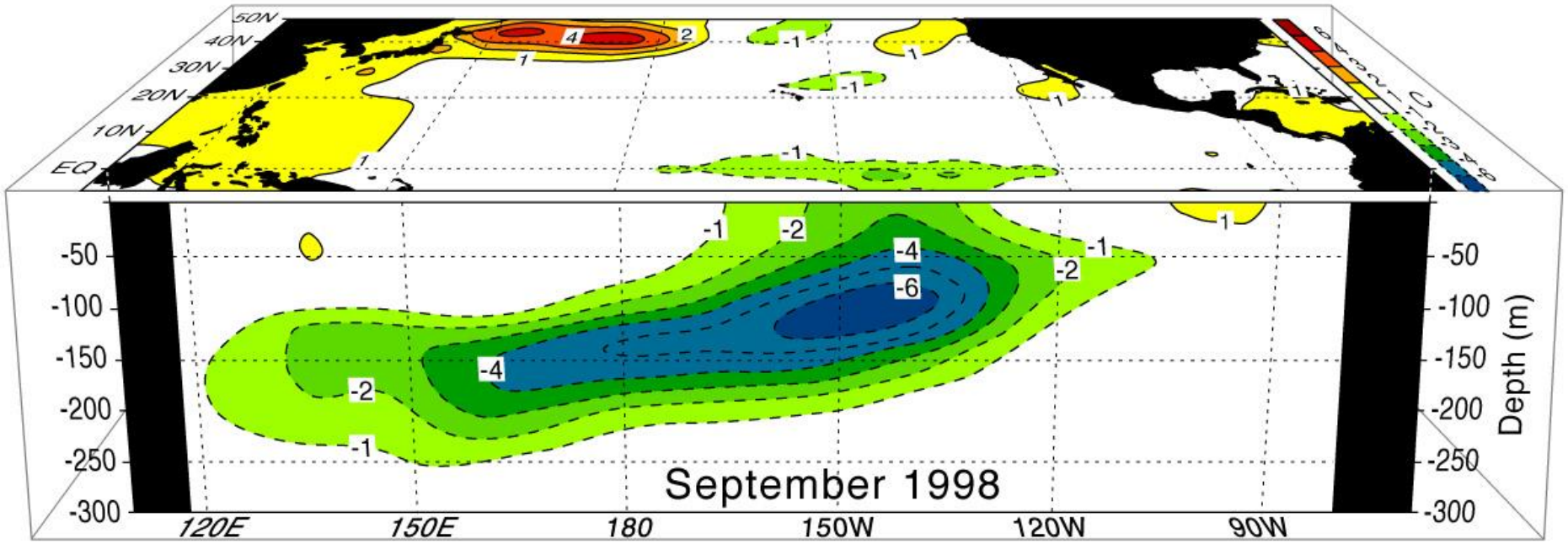

50N
40N
30N
20N
10N
EQ
-1
1
2
4
-50
-100
-150
-200
-250
-300
-2
-4
6
8
September1997
120E
150E
180
150W
120W
90W
Depth (m)

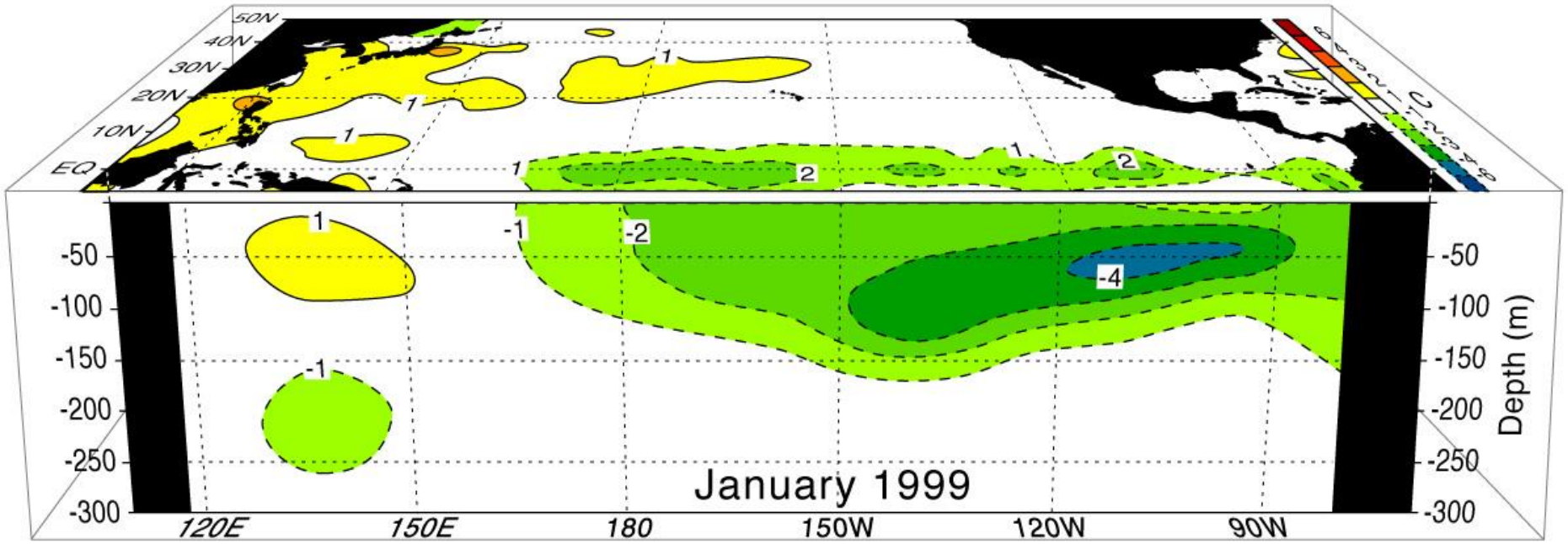
Mature Warm Event

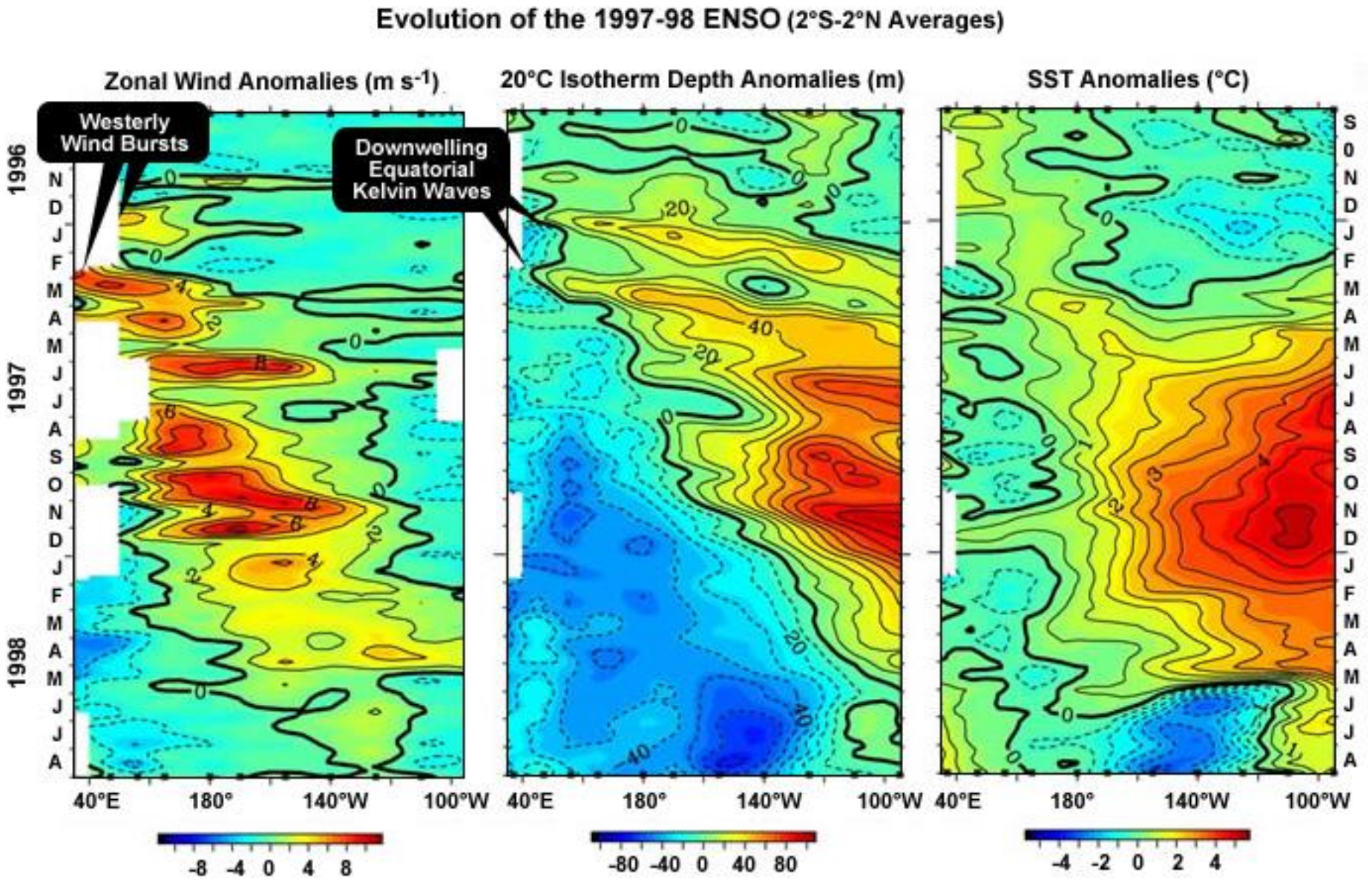


The Precursor of the Coming Cold Event


50N
40N
30N
20N
10N
EQ
-1
1
2
-1
1
1
2
-50
-100
-150
-200
-250
-300
-1
-2
-4
1
2
-4
-2
-1
-1
Depth (m)
May 1998
120E
150E
180
150W
120W
90W

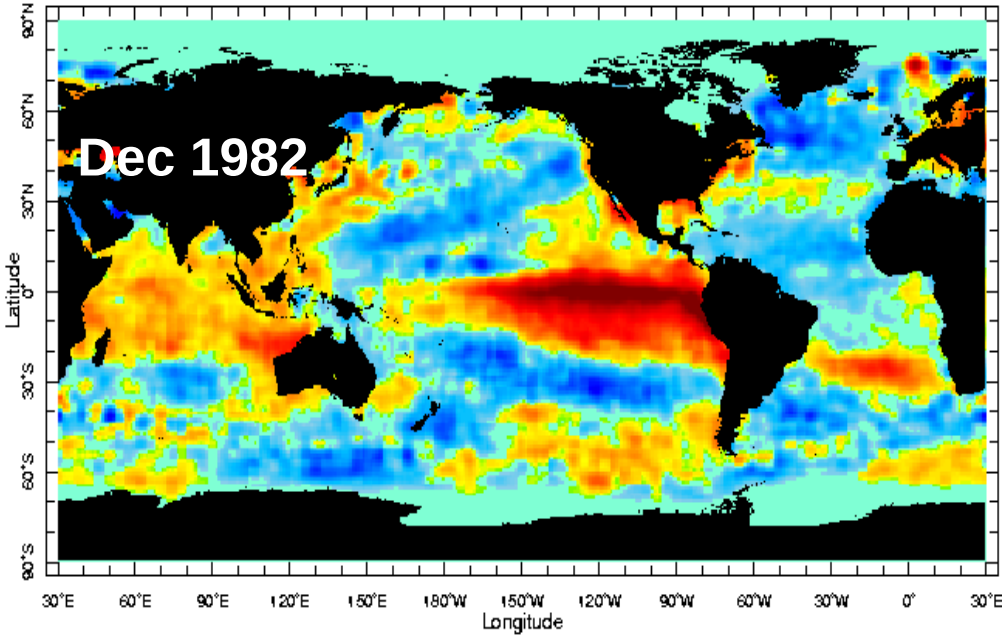

50N
40N
30N
20N
10N
EQ
120E
150E
180
150W
120W
90W
-50
-100
-150
-200
-250
-300
Depth (m)
September 1998

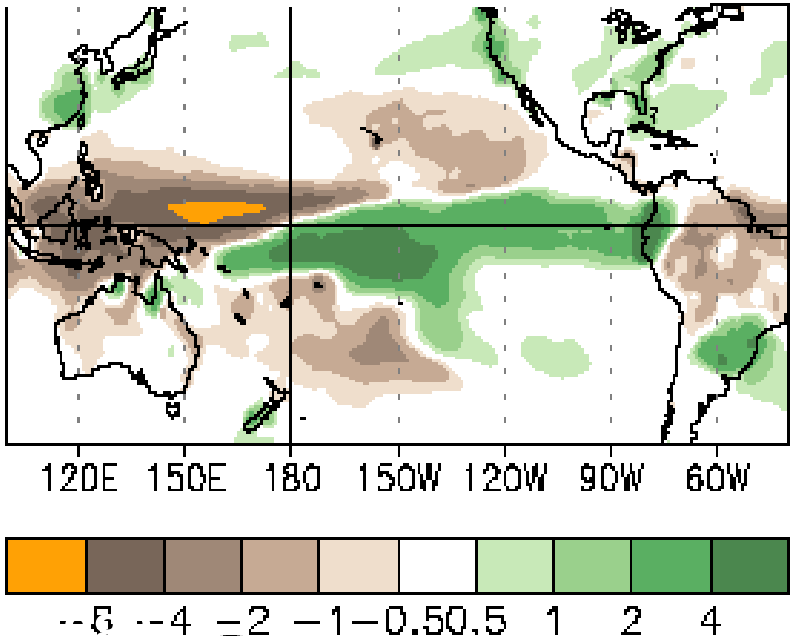

50N
40N
30N
20N
10N
EQ
120E
150E
180
150W
120W
90W
-50
-100
-150
-200
-250
-300
Depth (m)
January 1999

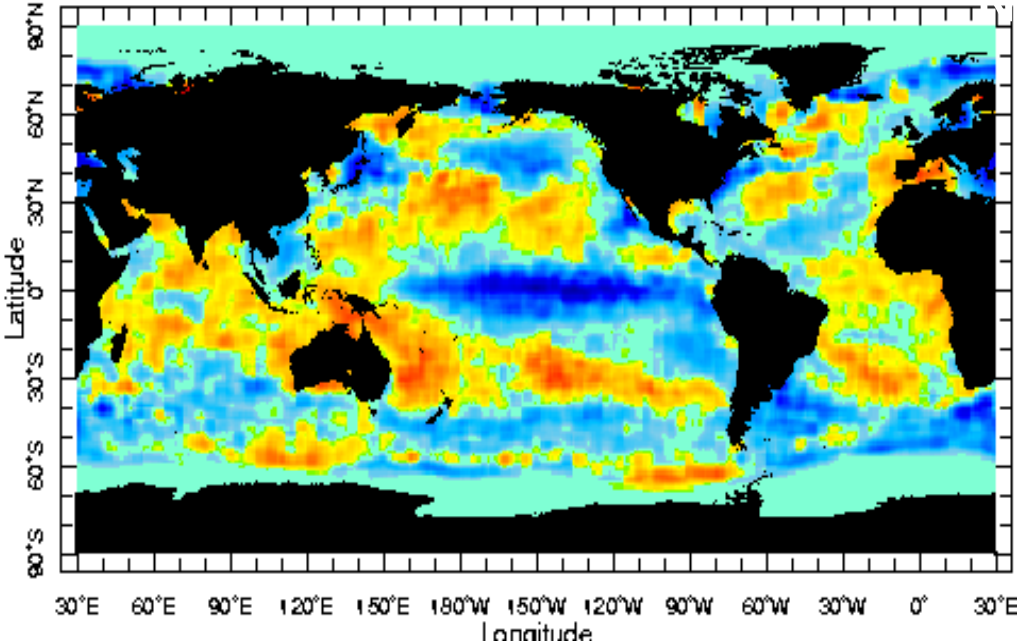

Evolution of the 1997-98 ENSO (2°S-2°N Averages)
Zonal Wind Anomalies (m s-1)
20°C Isotherm Depth Anomalies (m)
SST Anomalies (°C)
Westerly Wind Bursts
Downwelling Equatorial Kelvin Waves
1996
1997
1998
N D J F M A M J J A S O N D J F M A M J J A
S O N D J F M A M J J A S O N D J F M A M J J A
40°E
180°
140°W
100°W
-8 -4 0 4 8
-80 -40 0 40 80
-4 -2 0 2 4
NOAA / PMEL

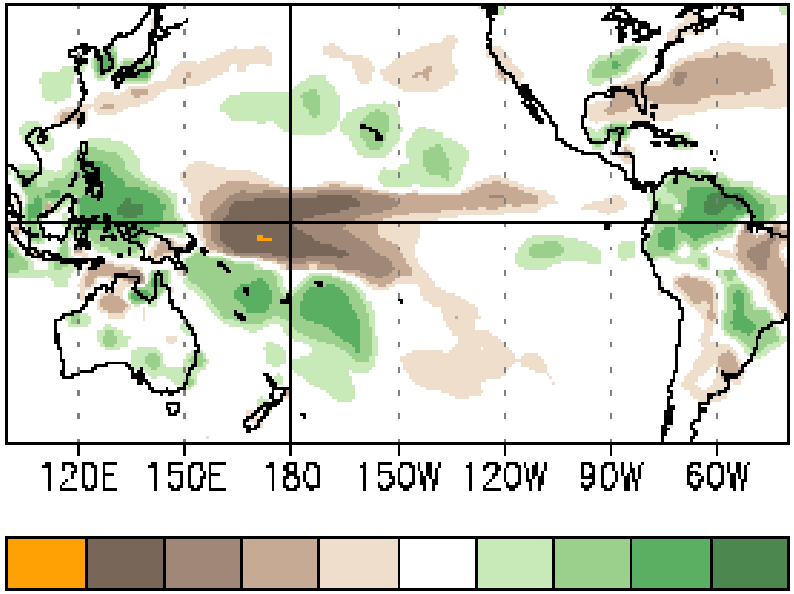
Teleconnections

SST ⇒ Rainfall







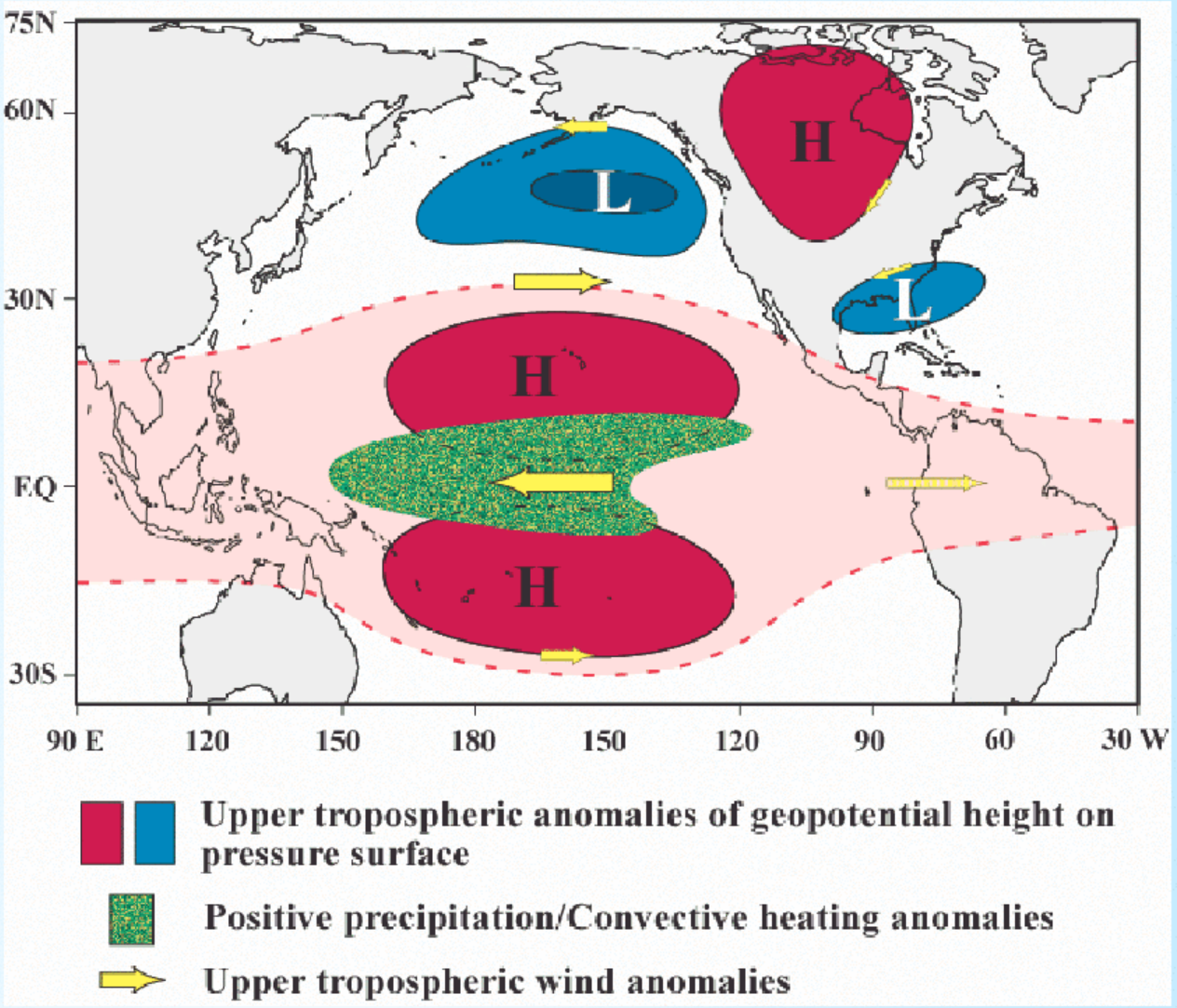


Pacific - North American sector Response to El Niño

La Niña: opposite sign to a first approximation
(but weaker, esp. over N. America)

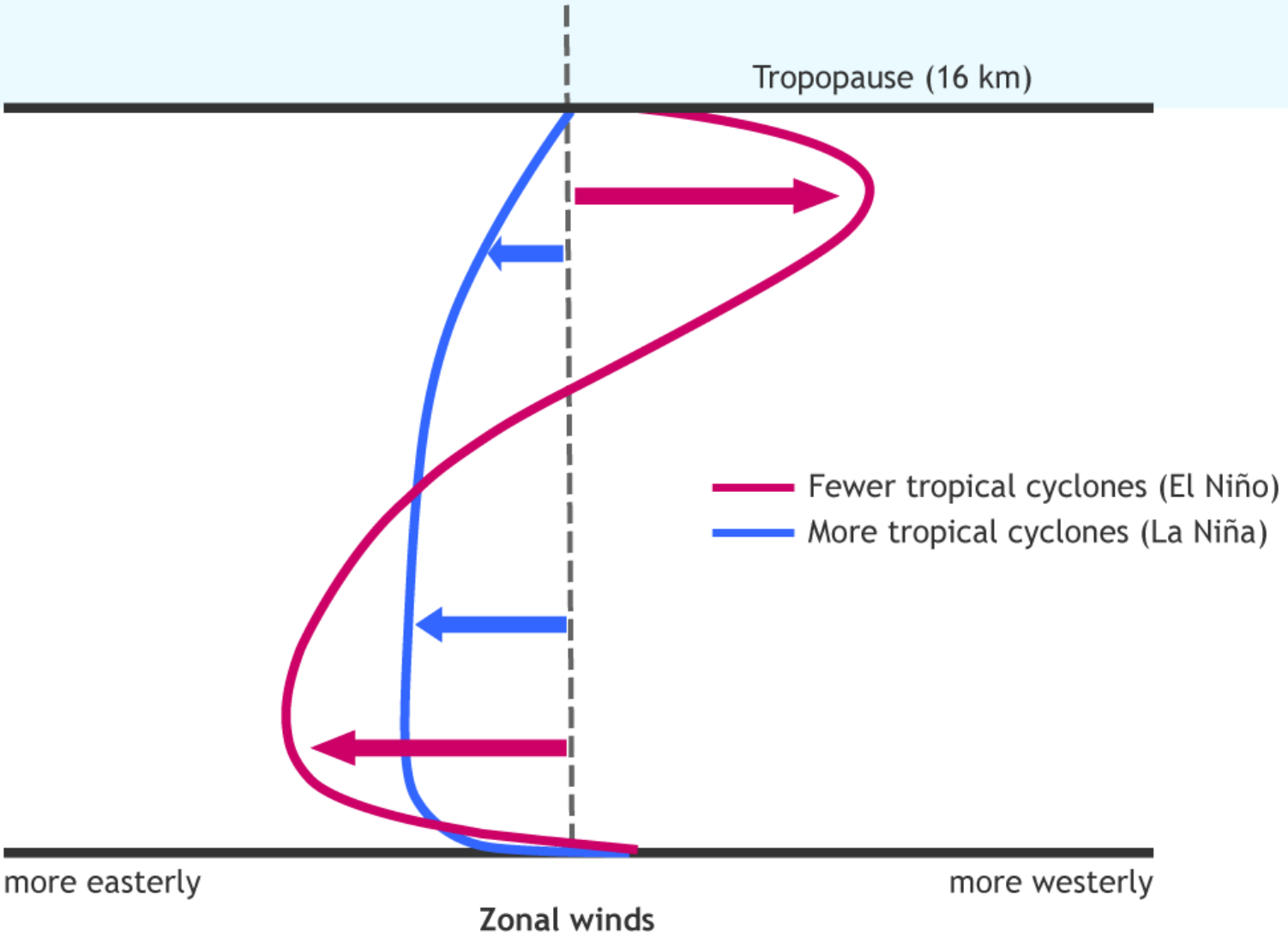
Mid-latitude response:
barotropic, same sign through depth of troposphere

Tropical response:
baroclinic, opposite sign at low levels



Refs: J.M. Wallace et al 1998,
K. Trenberth et al 1998

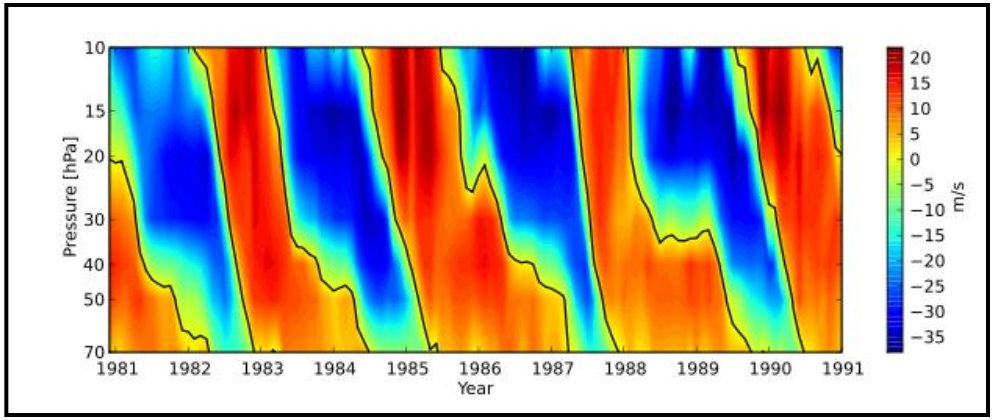
Vertical wind profile in the western tropical Atlantic



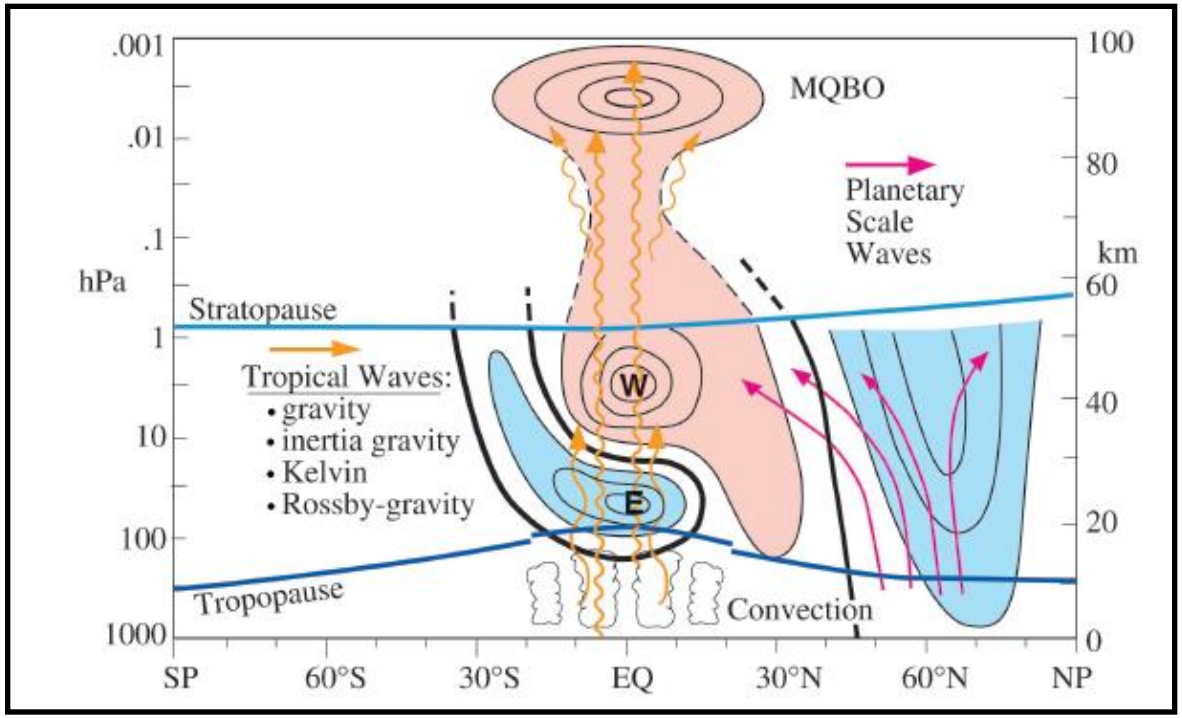
NOAA.gov

Quai-Biennial Oscillation

Quasi-biennial Oscillation (QBO)



Time–height plot of equatorial zonal wind (*u*) in m/s between about 20 and 35 km altitude above sea level over a ten-year period. Positive values denote westerly winds and the contour line is at 0 m/s.

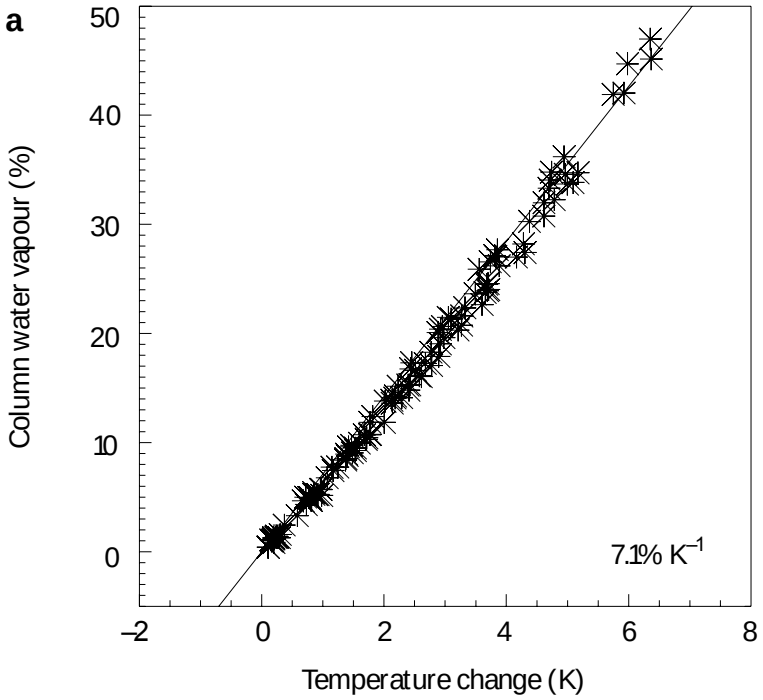


After Holton et al

Climate Change

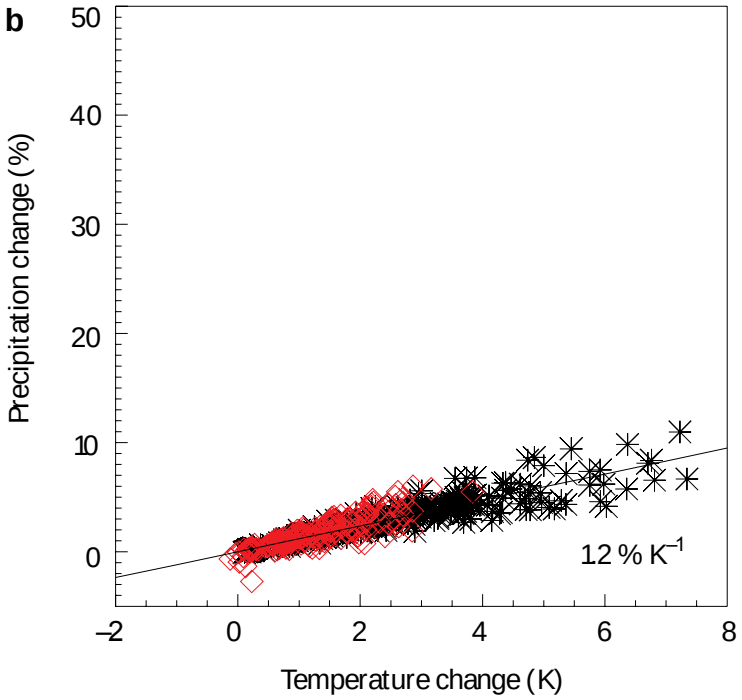
Global Changes with Warming

Increase in Water Vapor

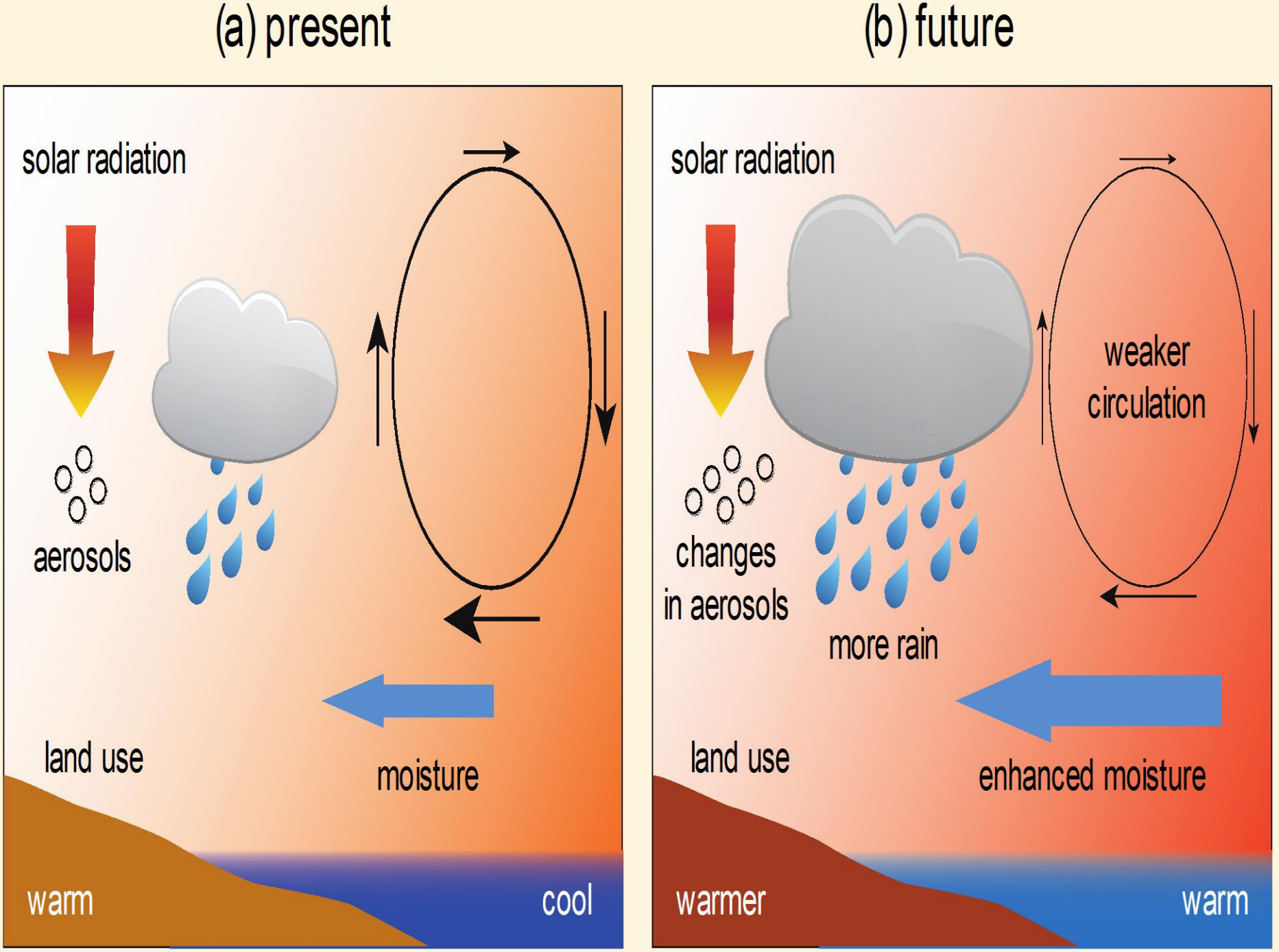


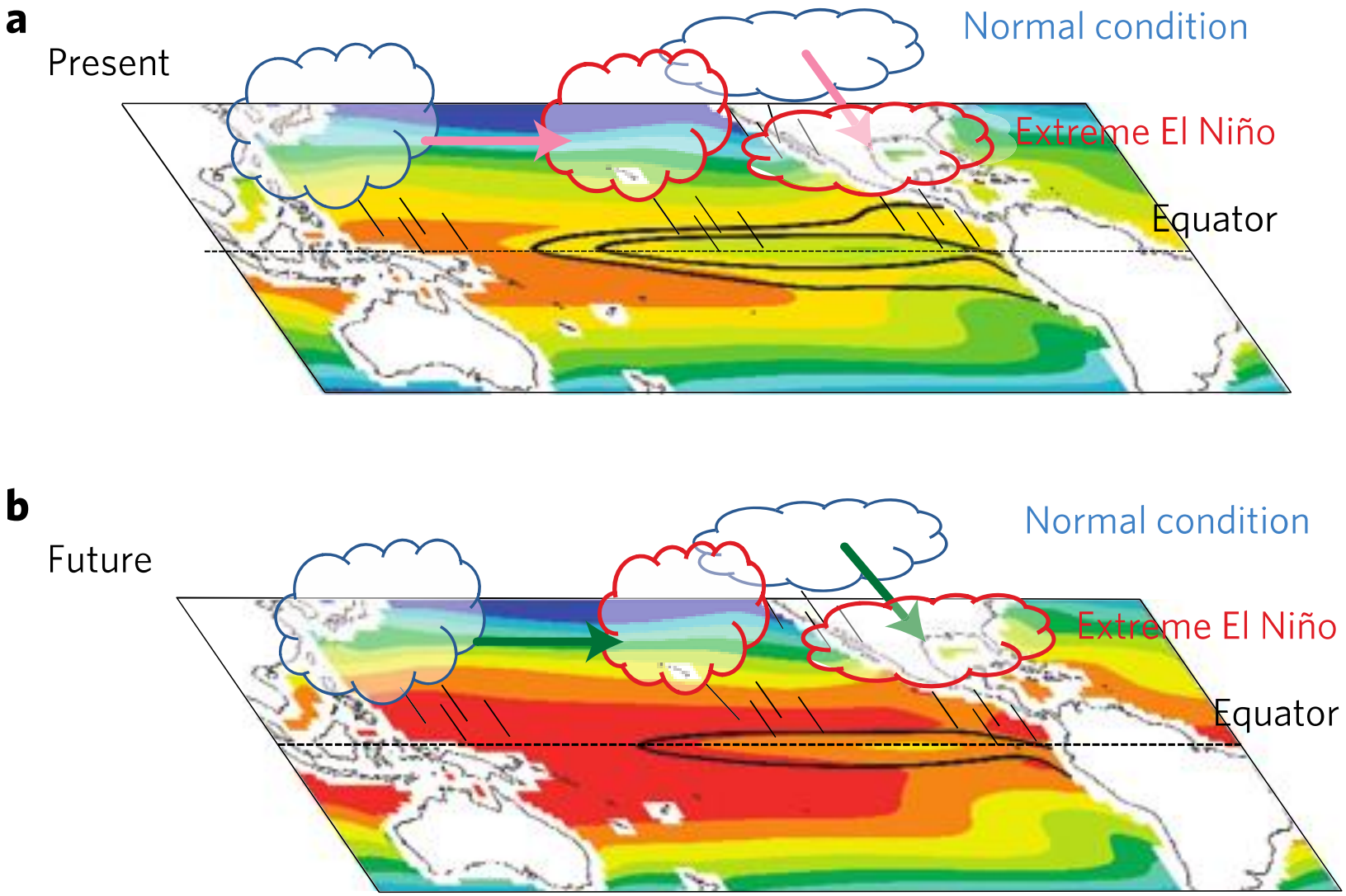
Expected From Clausius-Clapeyron

Changes in Precipitation



Smaller than Expected -> Decrease in Overturning Circulation


(a) present
solar radiation
aerosols
land use
moisture
warm
cool
(b) future
solar radiation
weaker
circulation
changes
in aerosols
more rain
land use
enhanced moisture
warmer
warm


a
Present
Normal condition
Extreme El Niño
Equator
b
Future
Normal condition
Extreme El Niño
Equator