11 July 2011, ICTP

Introduction to Physical Climate Systems

Jagadish Shukla

University Professor, George Mason University (GMU)

President, Institute of Global Environment and Society (IGES)

Outline

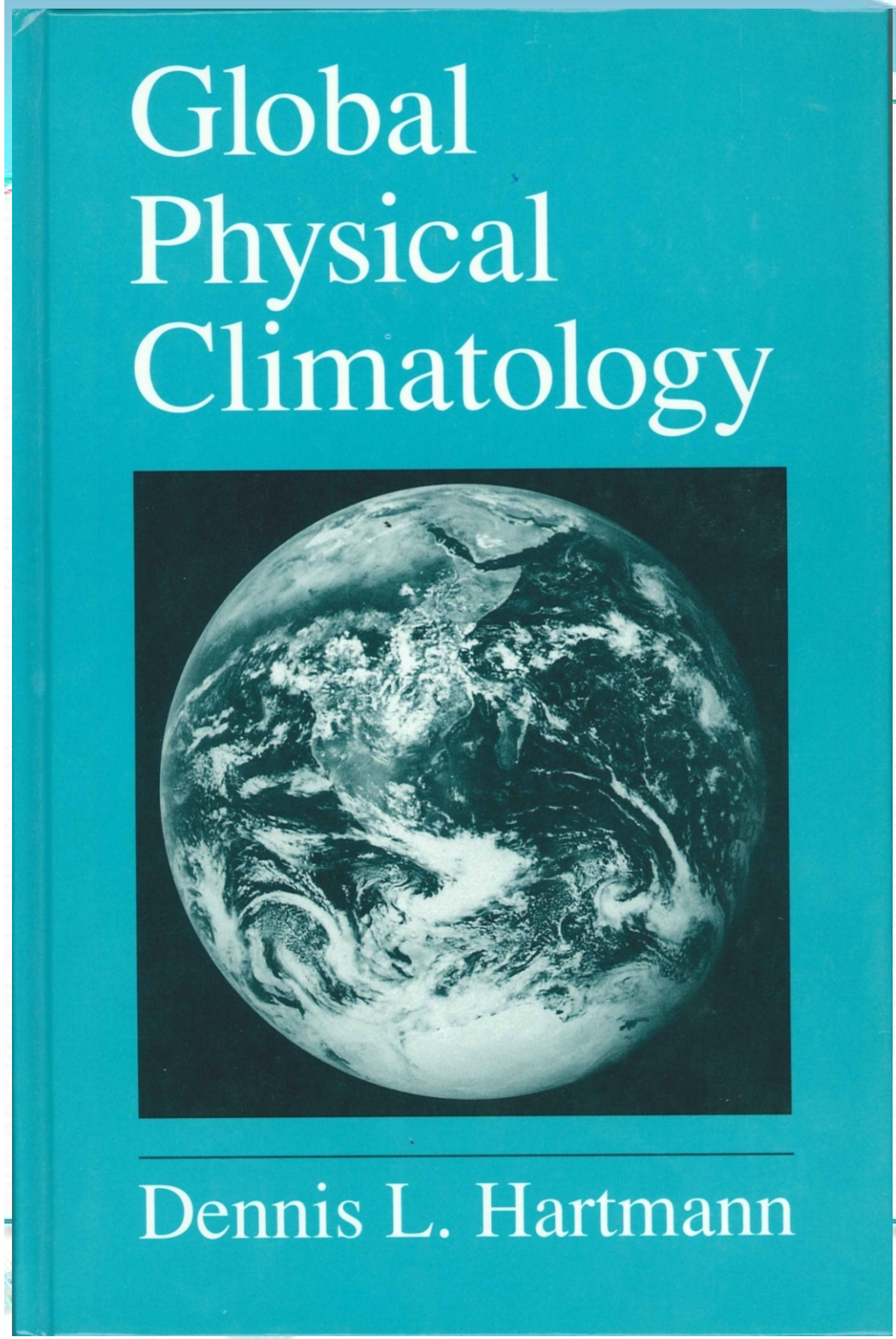
- The Earth's Climate – an overview
- Weather and Climate for Poets
- Observed Mean Climate of the Earth
- Selected Examples of Climate Variability
- Mechanisms of Climate Variability
- Predictability of Weather and Climate (?)
- Climate Change (?)
- Overview of the Workshop

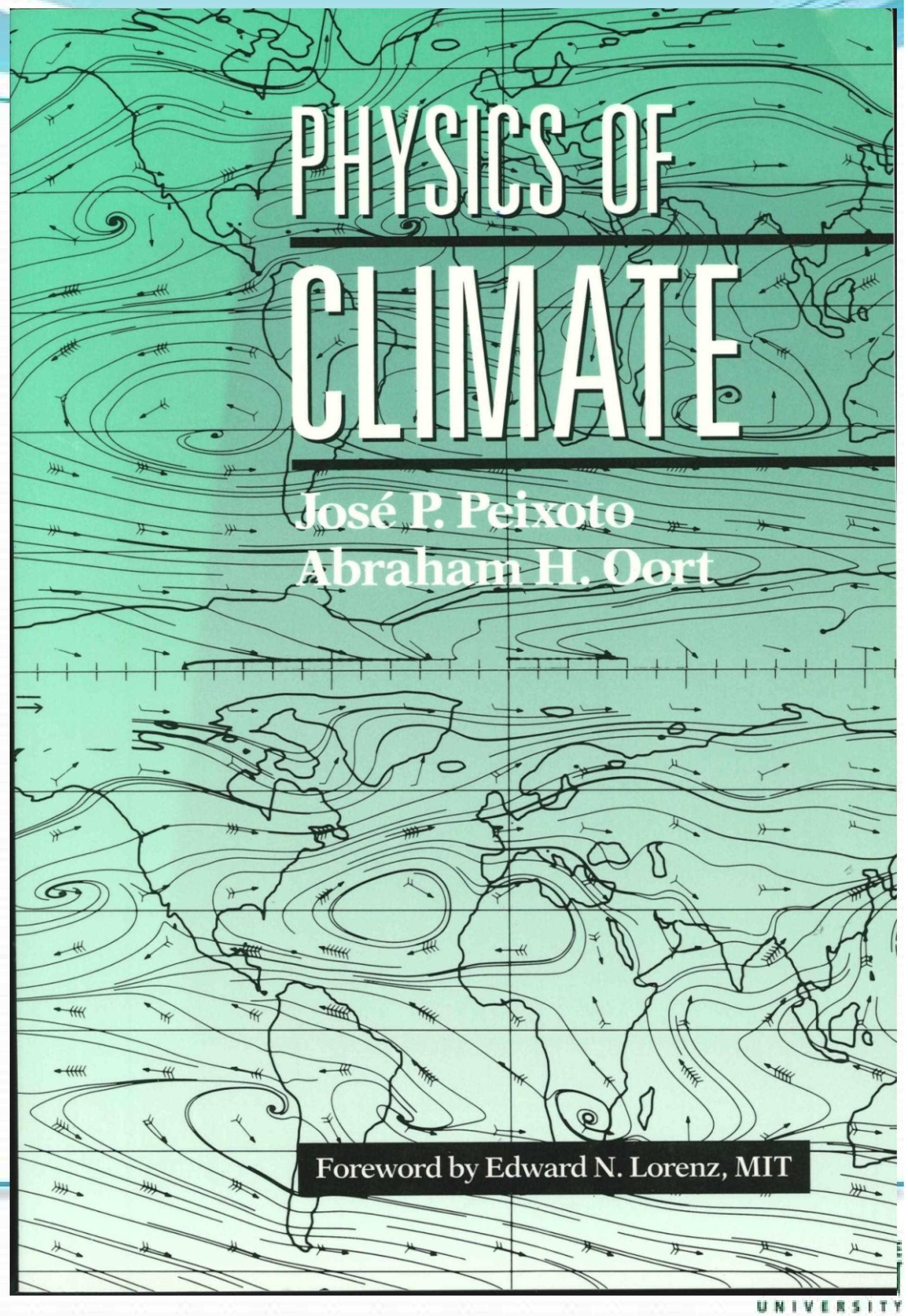
The Earth's Climate

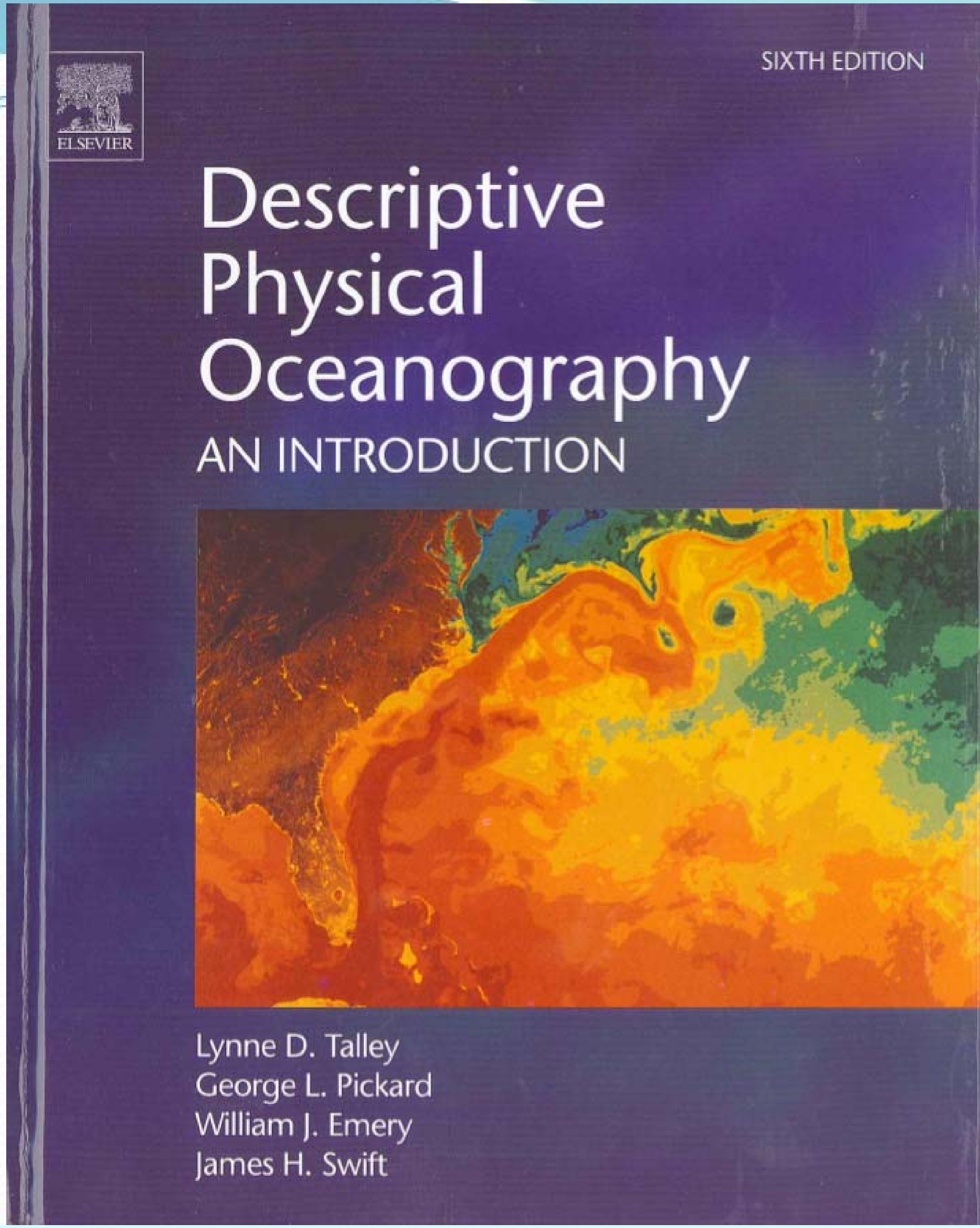
- **Physics, Chemistry, and Biology of: Ocean, Atmosphere, Biosphere, Cryosphere**
- **Dynamics of Atmosphere, Ocean, and Coupled Atmosphere – Ocean System**
- **Energy and Water Balance: Energy Exchanges; Potential and Kinetic Energies of Atmosphere, Ocean; Global Water Cycle**
- **The Mean Climate:**
  - **Annual Mean; Annual Cycle; Diurnal Cycle**
  - **Daily, intraseasonal, seasonal, interannual, decadal, multi-decadal variability**
- **Mechanisms of Climate Variability:**
  - **Atmosphere – Ocean Interactions**
  - **Atmosphere – Land Interactions**
  - **Atmosphere – Ocean – Land – Cryosphere Interaction**
- **Climate Change:**
  - **Natural (Solar, Volcanoes) & Anthropogenic (GHG, Deforestation, Land Use…)**

" I think the causes of the General Trade-Winds have not been fully explained by any of those who have wrote on that subject…." ***(George Hadley, 1735)***

"The (above) opening words of Hadley's classical paper afford an apt description of the state of the same subject today." ***(Edward N. Lorenz, 1967)***


Global
Physical
Climatology
Dennis L. Hartmann


PHYSICS OF
CLIMATE
José P. Peixoto
Abraham H. Oort
Foreword by Edward N. Lorenz, MIT
UNIVERSITY

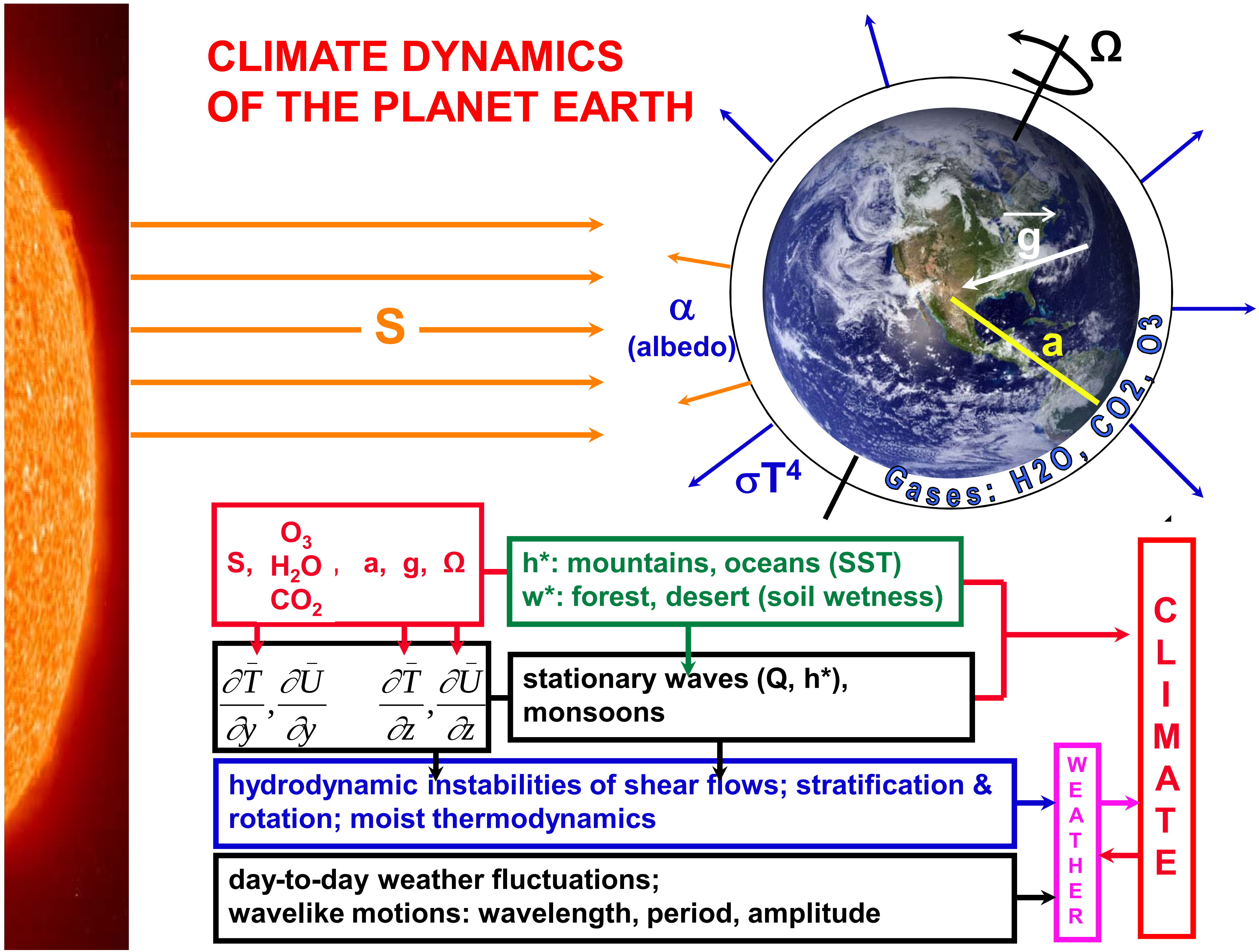

ELSEVIER
SIXTH EDITION
Descriptive
Physical
Oceanography
AN INTRODUCTION
Lynne D. Talley
George L. Pickard
William J. Emery
James H. Swift

The Climate of a Planet Depends On …

1. Energy from the Sun — S

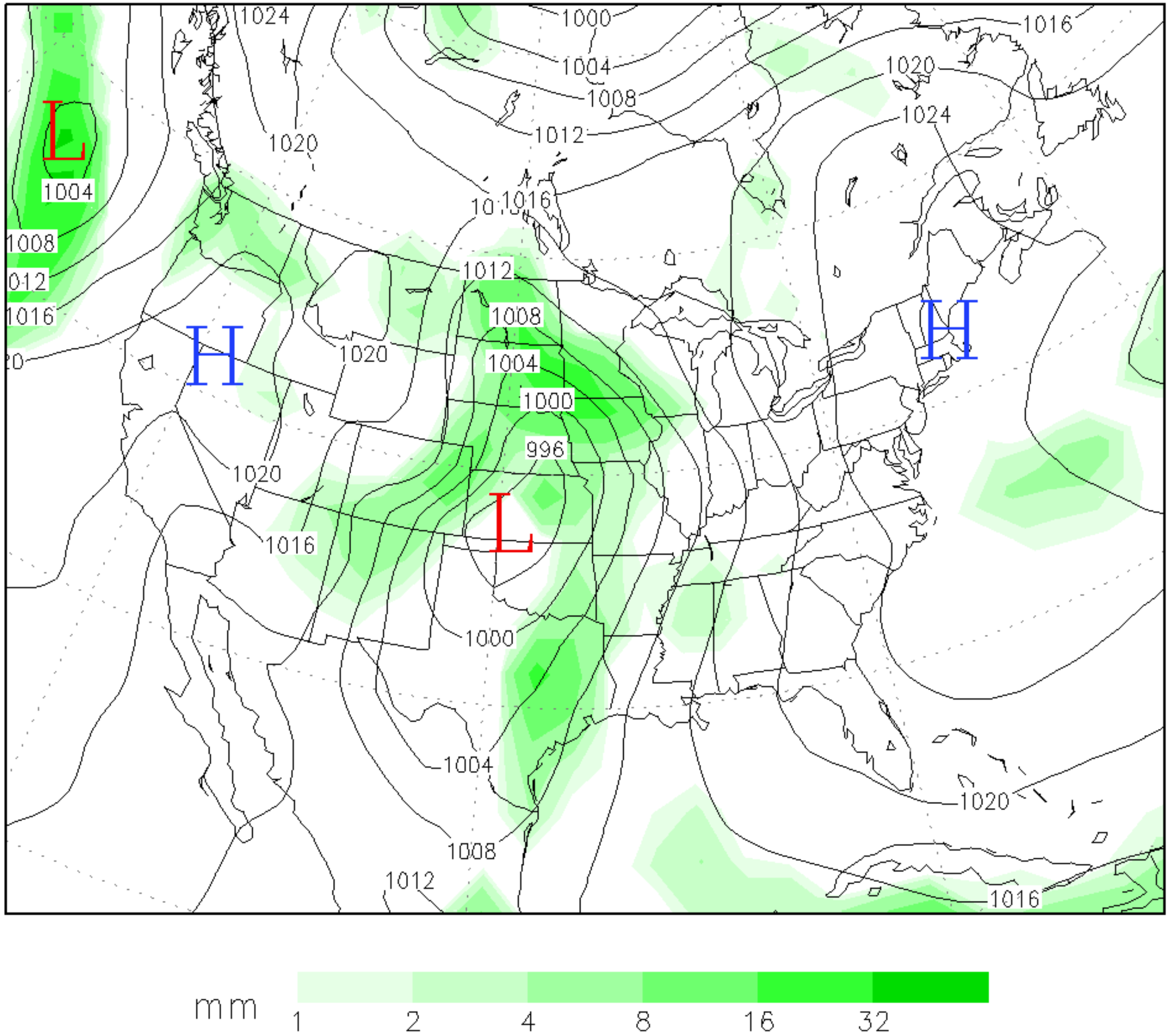
   (energy from the interior)

2. Planetary Albedo — α
3. Speed of Planet's Rotation — Ω
4. Mass of the Planet — M
5. Radius of the Planet — a
6. Atmospheric Composition — H_2O, CO_2, O_3, clouds
7. Ocean-Land, Topography — h*
8. Biosphere, Cryosphere — w, α


CLIMATE DYNAMICS
OF THE PLANET EARTH
S
α
(albedo)
σT⁴
g
a
Ω
Gases: H2O, CO2, O3
S, H_2O, O_3, CO_2, a, g, Ω
h*: mountains, oceans (SST)
w*: forest, desert (soil wetness)
$\frac{\partial \bar{T}}{\partial y}, \frac{\partial \bar{U}}{\partial y}$ $\frac{\partial \bar{T}}{\partial z}, \frac{\partial \bar{U}}{\partial z}$
stationary waves (Q, h*),
monsoons
hydrodynamic instabilities of shear flows; stratification &
rotation; moist thermodynamics
day-to-day weather fluctuations;
wavelike motions: wavelength, period, amplitude
WEATHER
CLIMATE

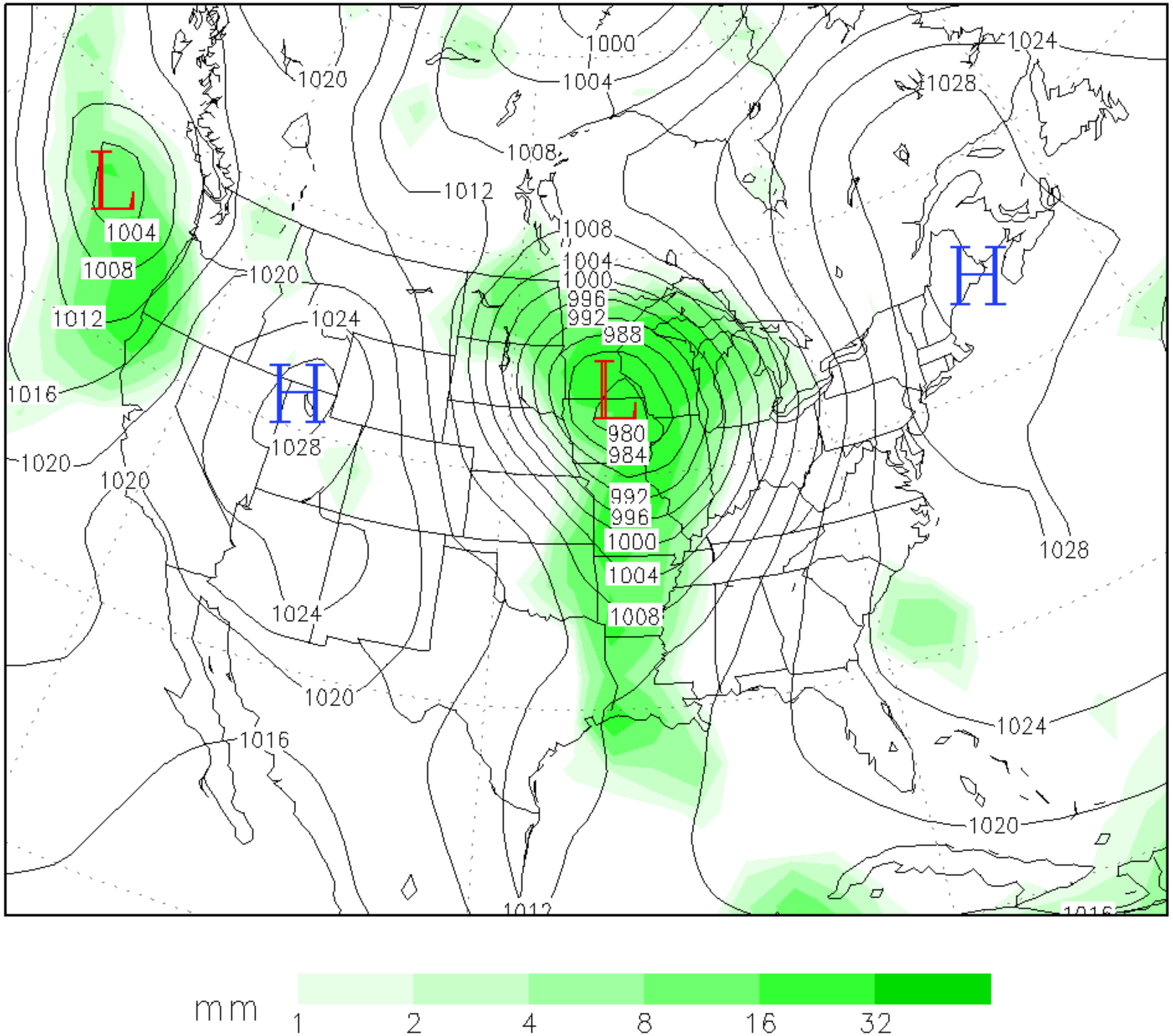
Sea Level Pressure (mb) & Precipitation Rate (mm/12Hr)

00Z Tue 10 Nov 1998



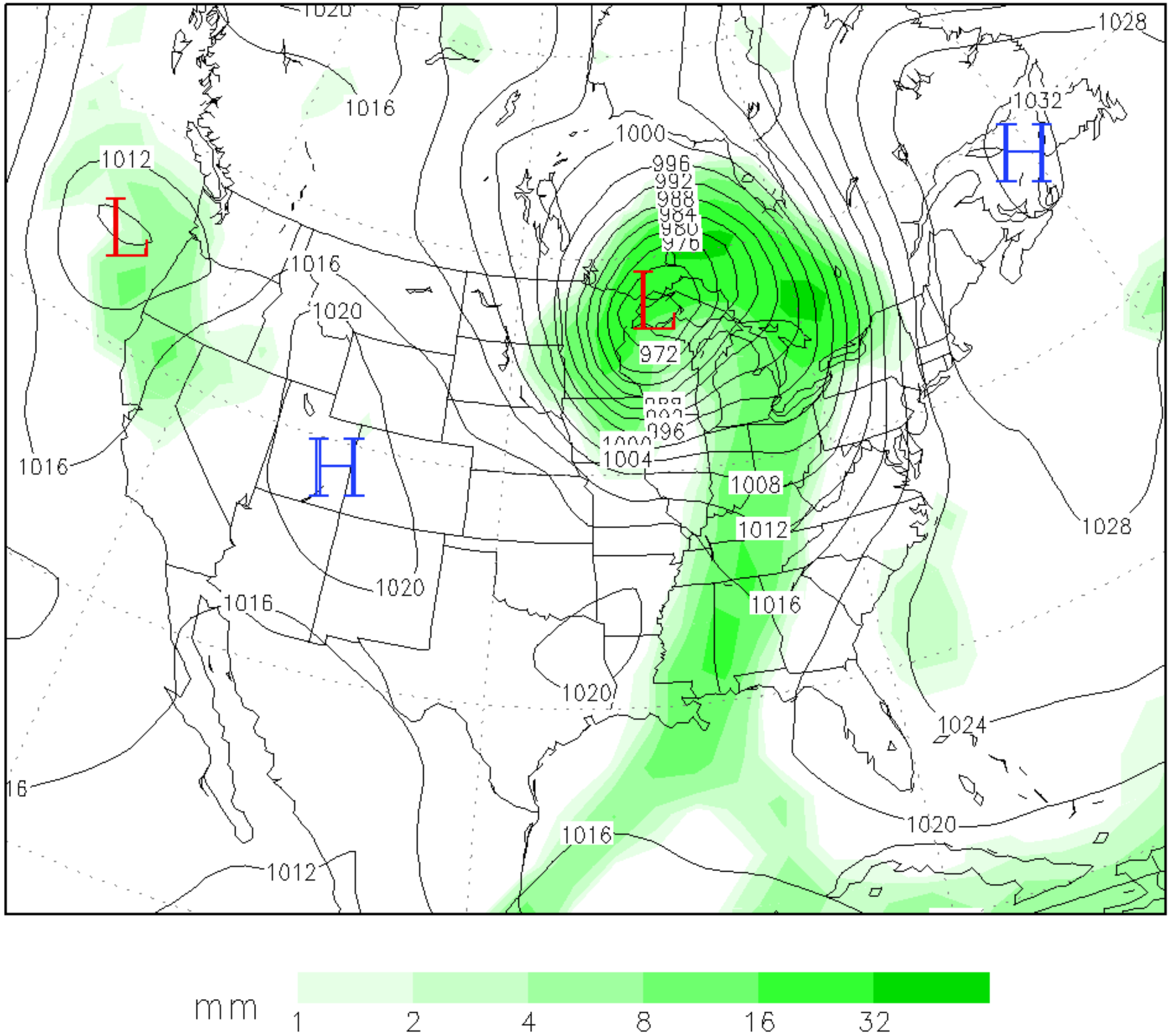
Sea Level Pressure (mb) & Precipitation Rate (mm/12Hr)

12Z Tue 10 Nov 1998

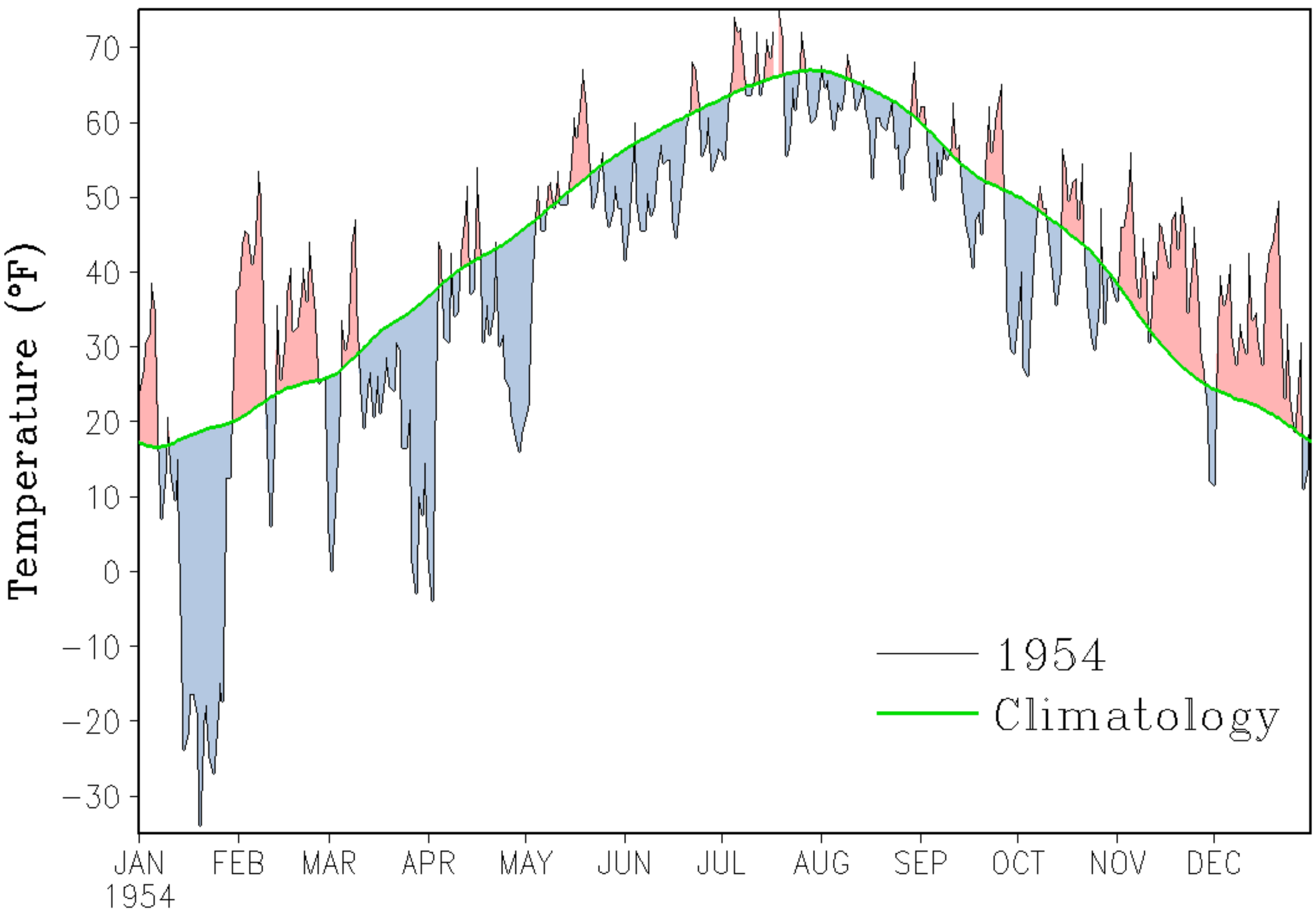


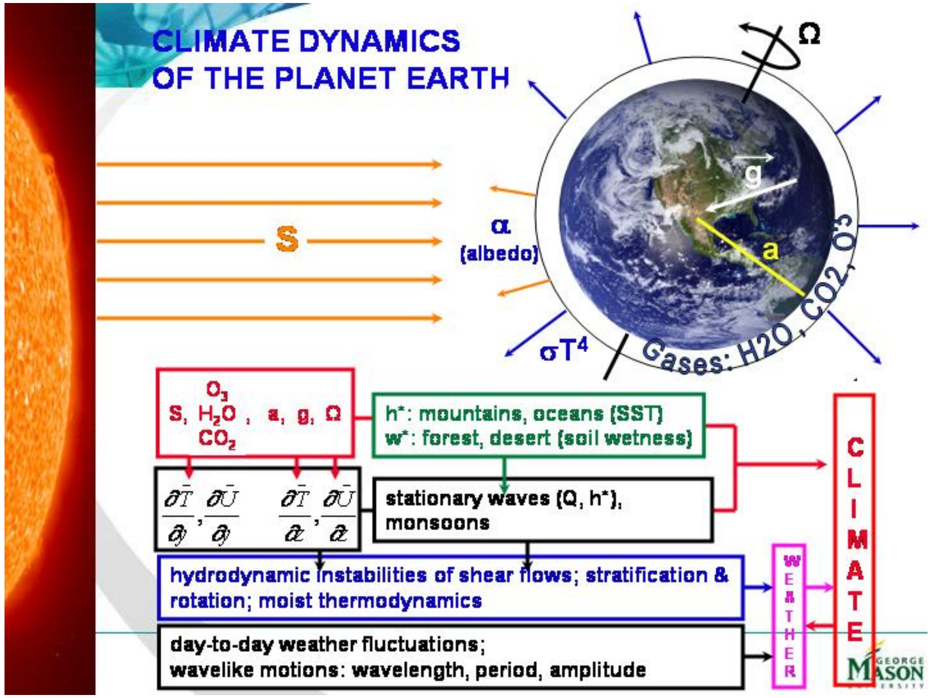
Sea Level Pressure (mb) & Precipitation Rate (mm/12Hr)

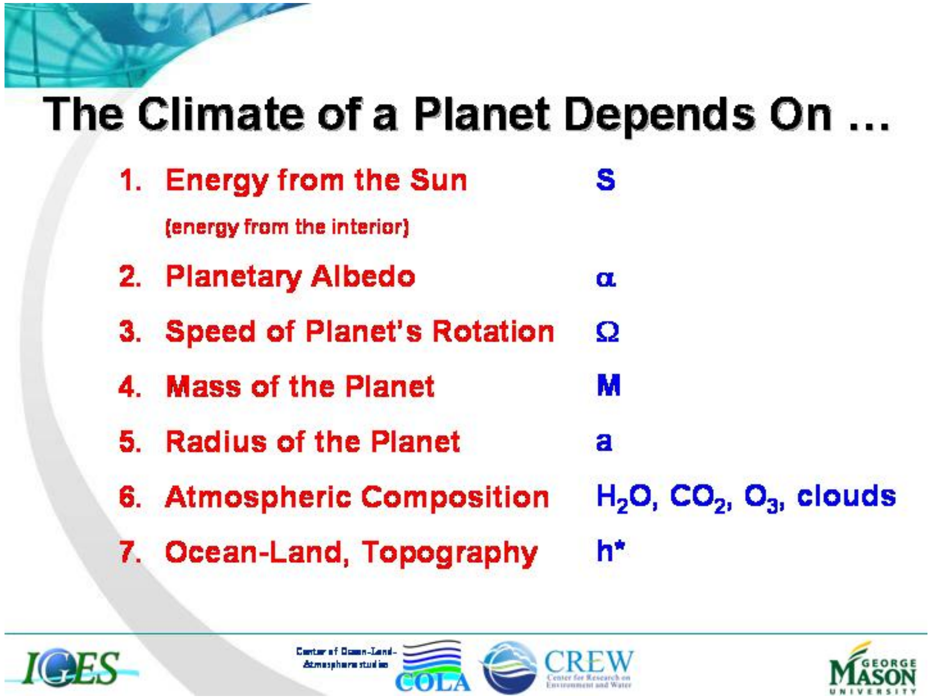
00Z Wed 11 Nov 1998

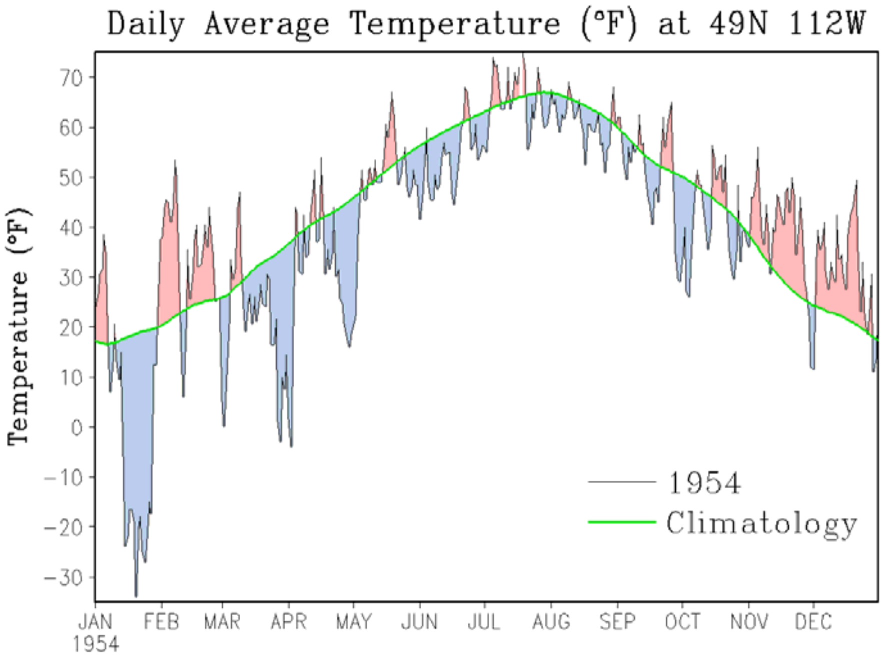


Daily Average Temperature at 49N, 112W



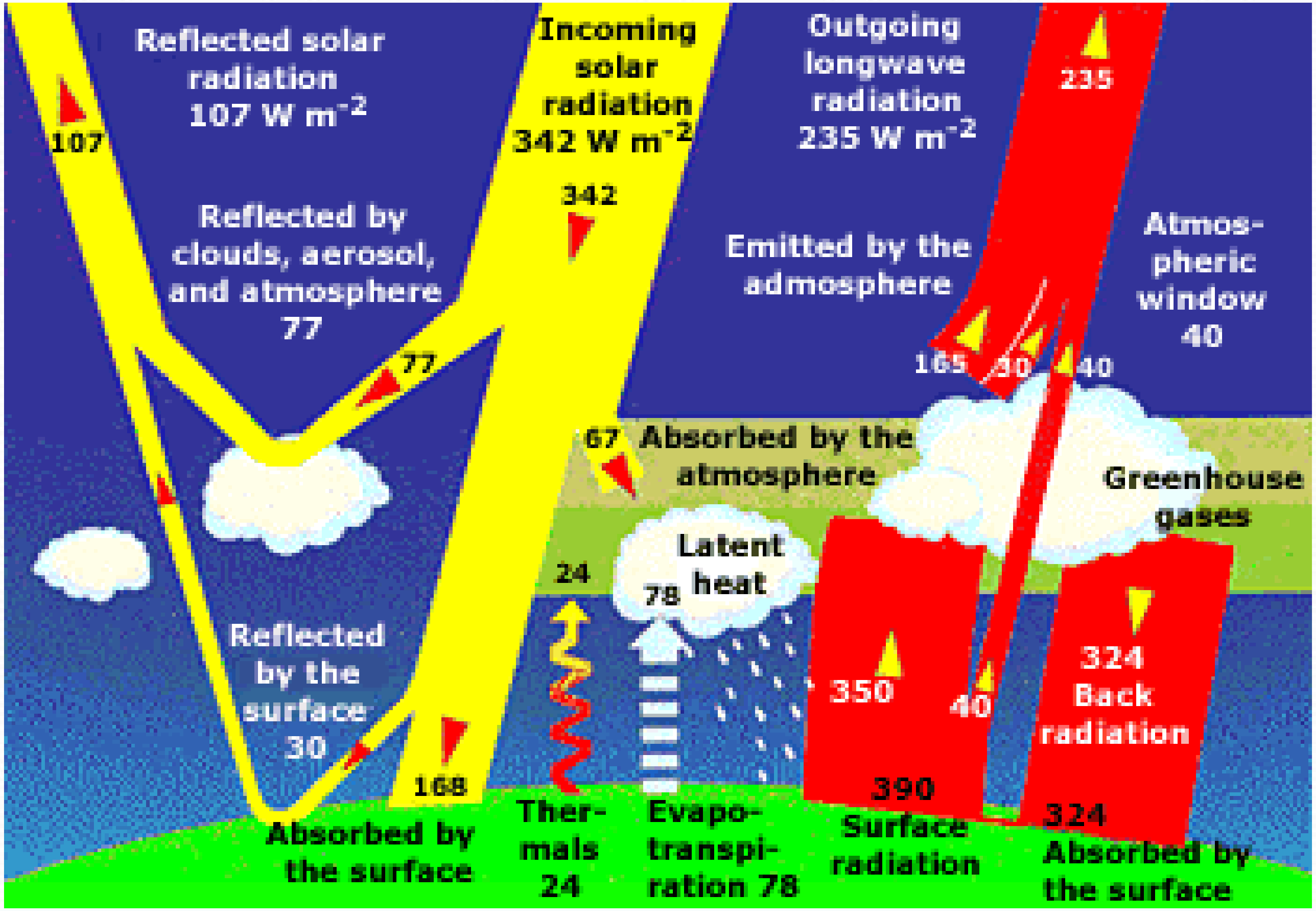

CLIMATE DYNAMICS
OF THE PLANET EARTH
S
α
(albedo)
σT4
Ω
g
a
Gases: H2O, CO2, O3
O3
S, H2O, a, g, Ω
CO2
h*: mountains, oceans (SST)
w*: forest, desert (soil wetness)
stationary waves (Q, h*),
monsoons
hydrodynamic instabilities of shear flows; stratification &
rotation; moist thermodynamics
day-to-day weather fluctuations;
wavelike motions: wavelength, period, amplitude
WEATHER
CLIMATE
GEORGE MASON


The Climate of a Planet Depends On …
1. Energy from the Sun S
(energy from the interior)
2. Planetary Albedo α
3. Speed of Planet's Rotation Ω
4. Mass of the Planet M
5. Radius of the Planet a
6. Atmospheric Composition H2O, CO2, O3, clouds
7. Ocean-Land, Topography h*
IGES
COLA
CREW
GEORGE MASON UNIVERSITY

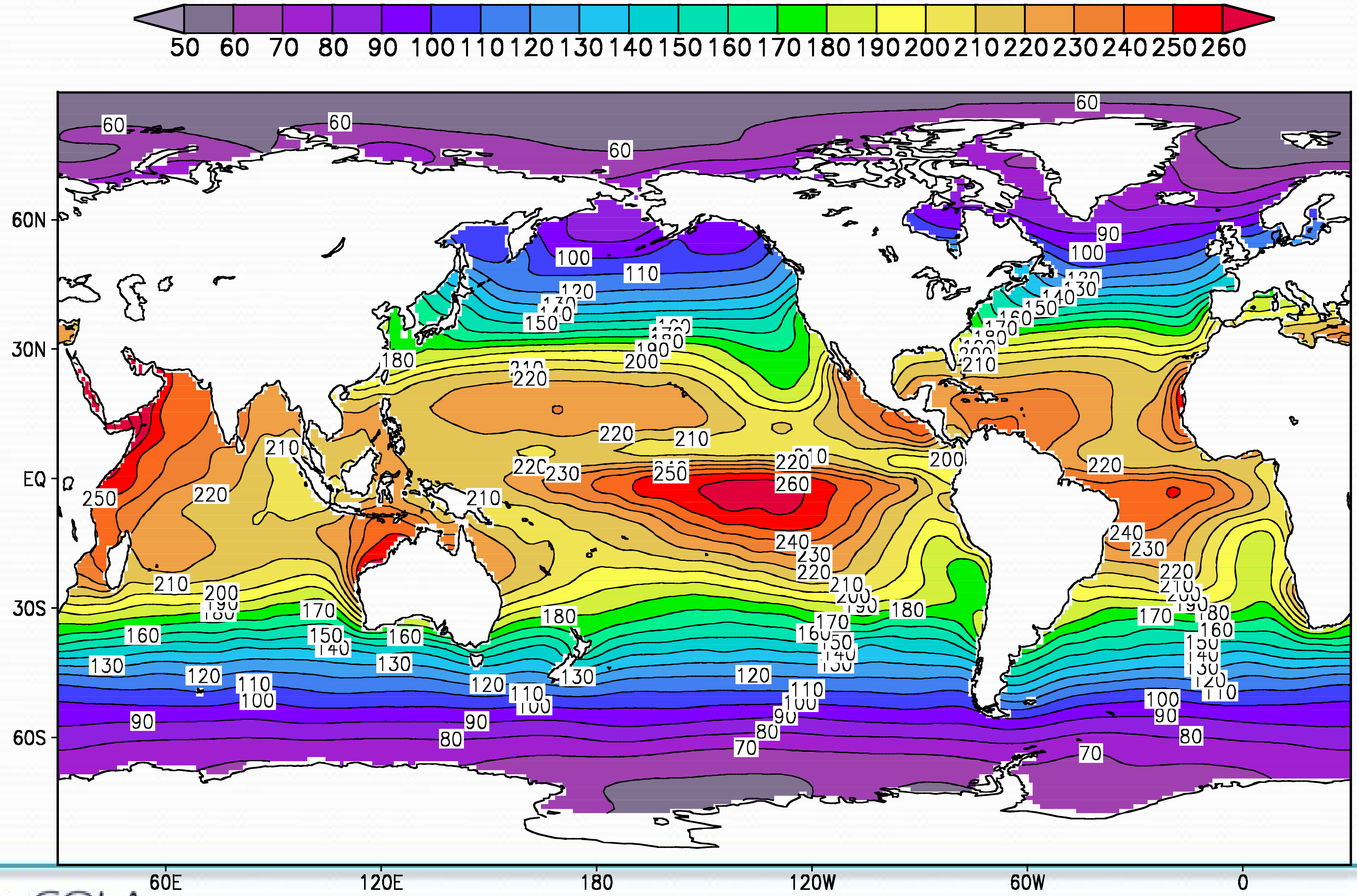

Daily Average Temperature (°F) at 49N 112W
Temperature (°F)
70
60
50
40
30
20
10
0
−10
−20
−30
JAN 1954
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
1954
Climatology

Energy and Water Balance

CLIMATE DYNAMICS OF THE PLANET EARTH:
Energy Balance

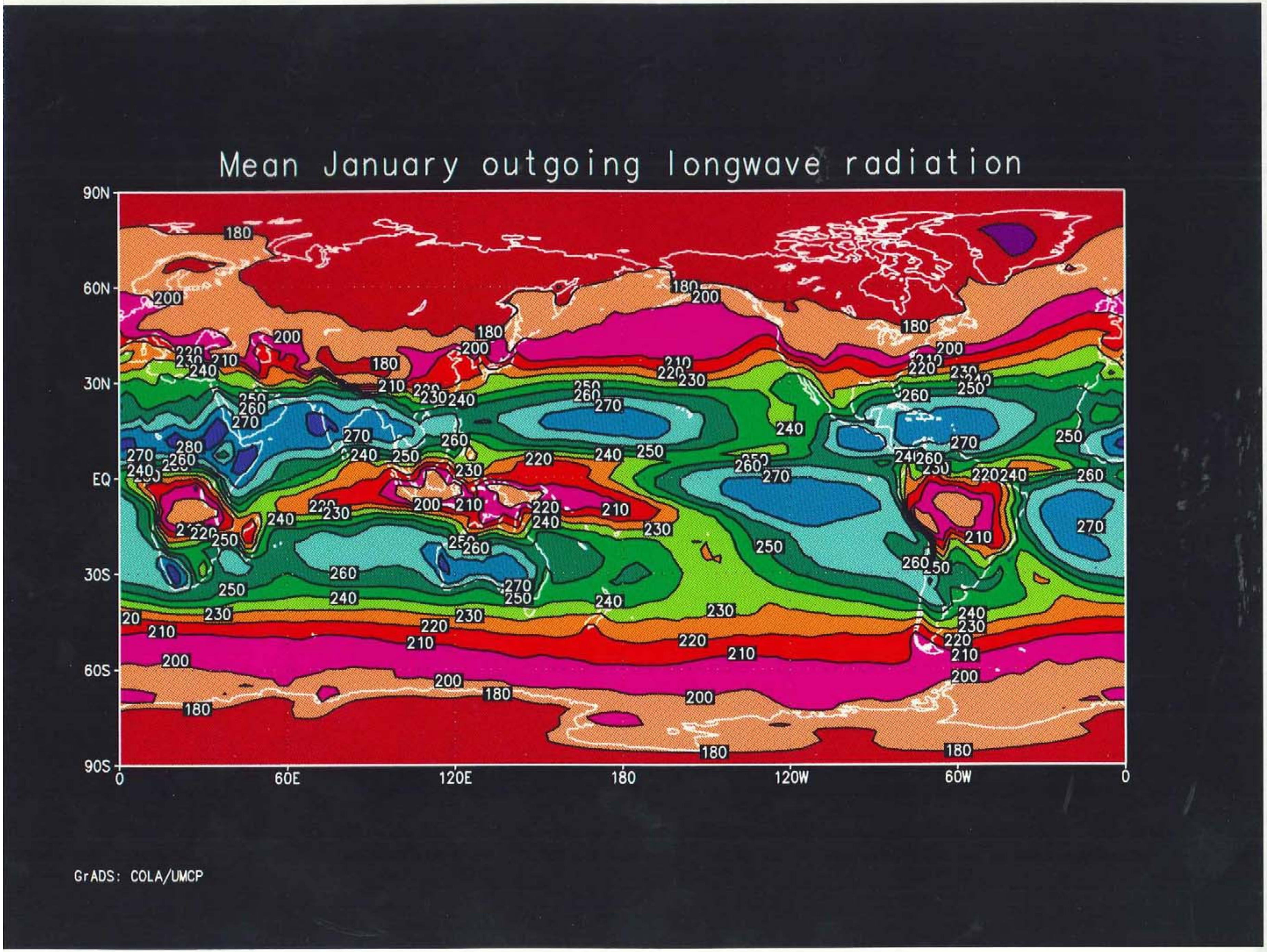


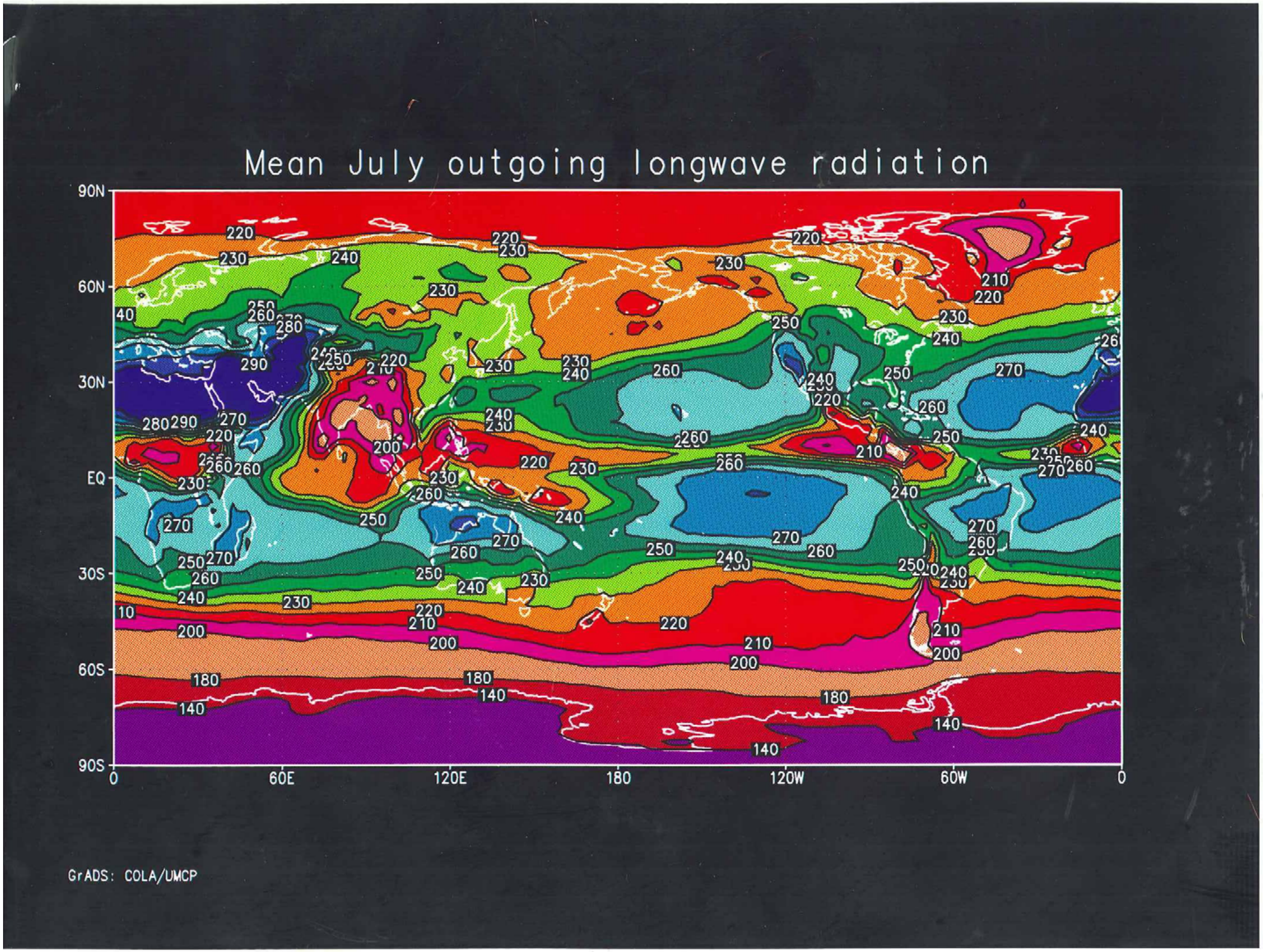
Annual Mean Solar Radiation at Sea Surface
[W/m^2] COADS



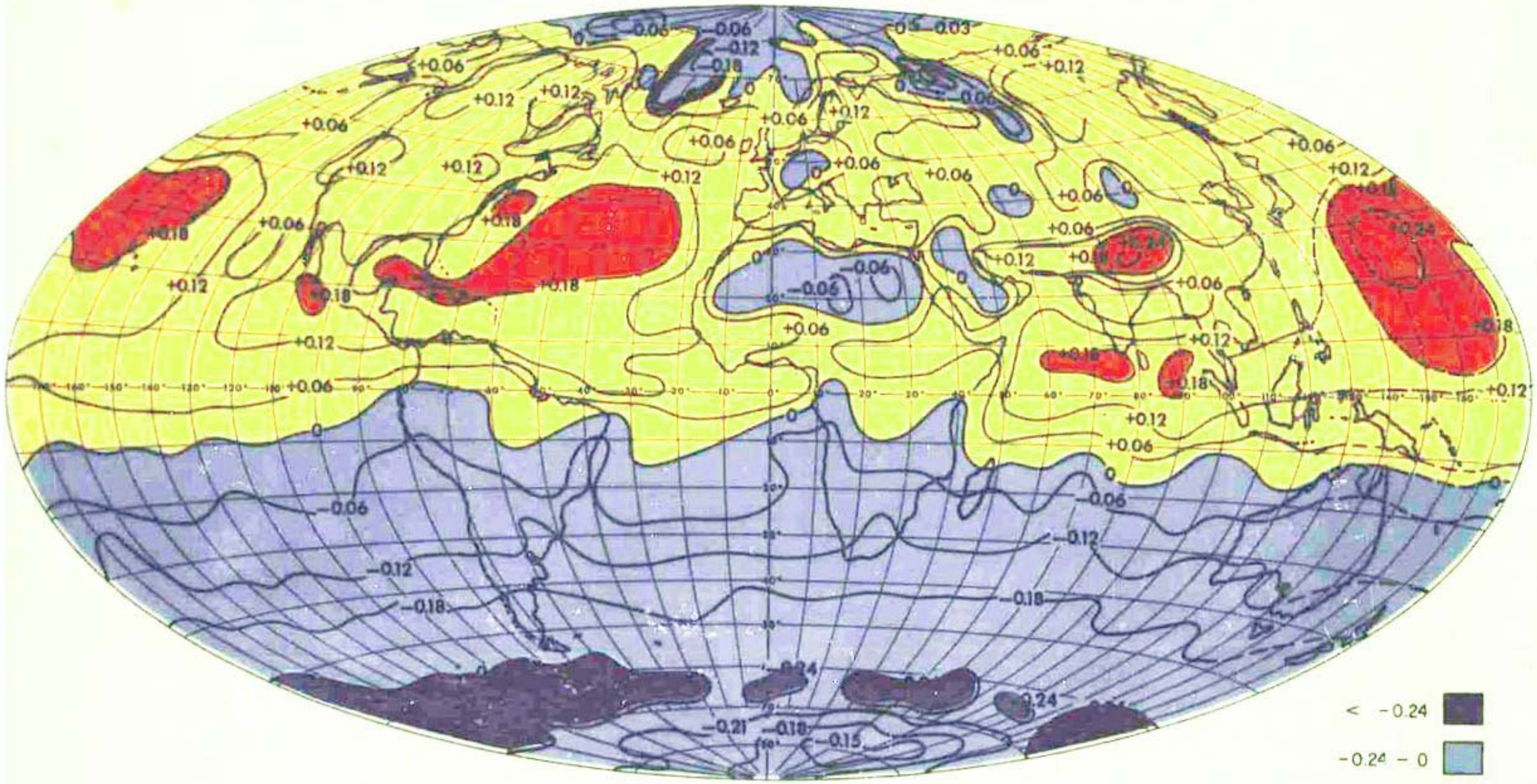
COLA Center for Ocean-Land-Atmosphere Studies

GEORGE MASON UNIVERSITY

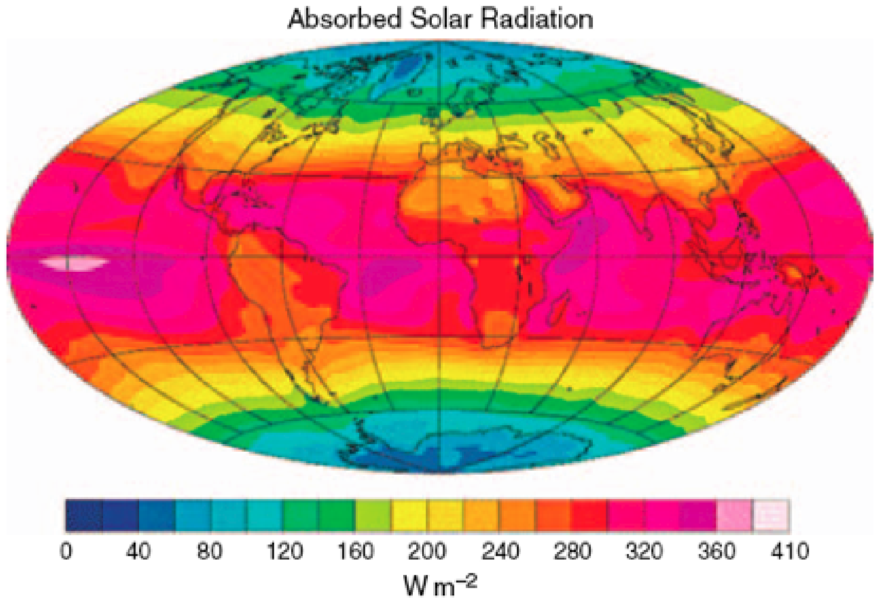

Mean January outgoing longwave radiation
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
GrADS: COLA/UMCP

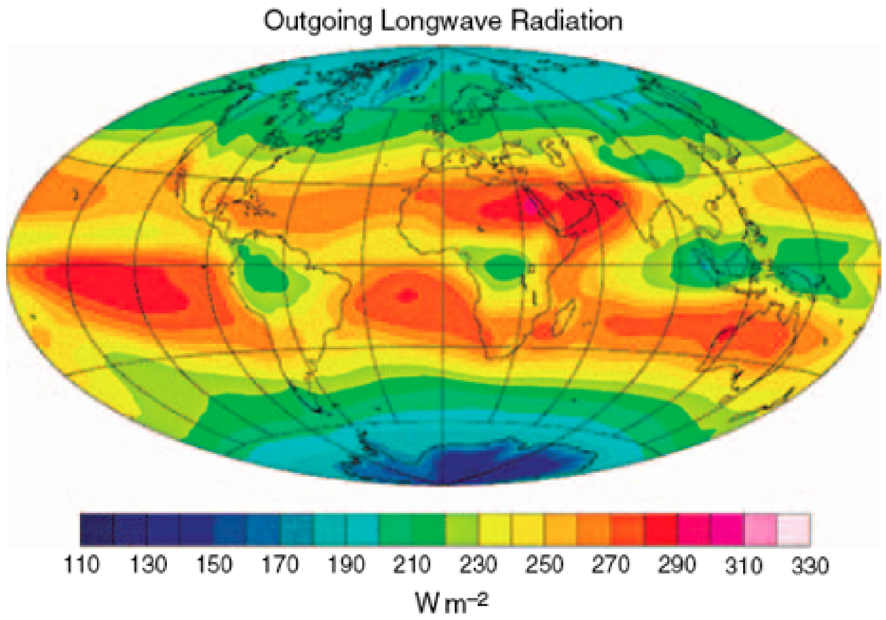

Mean July outgoing longwave radiation
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
GrADS: COLA/UMCP

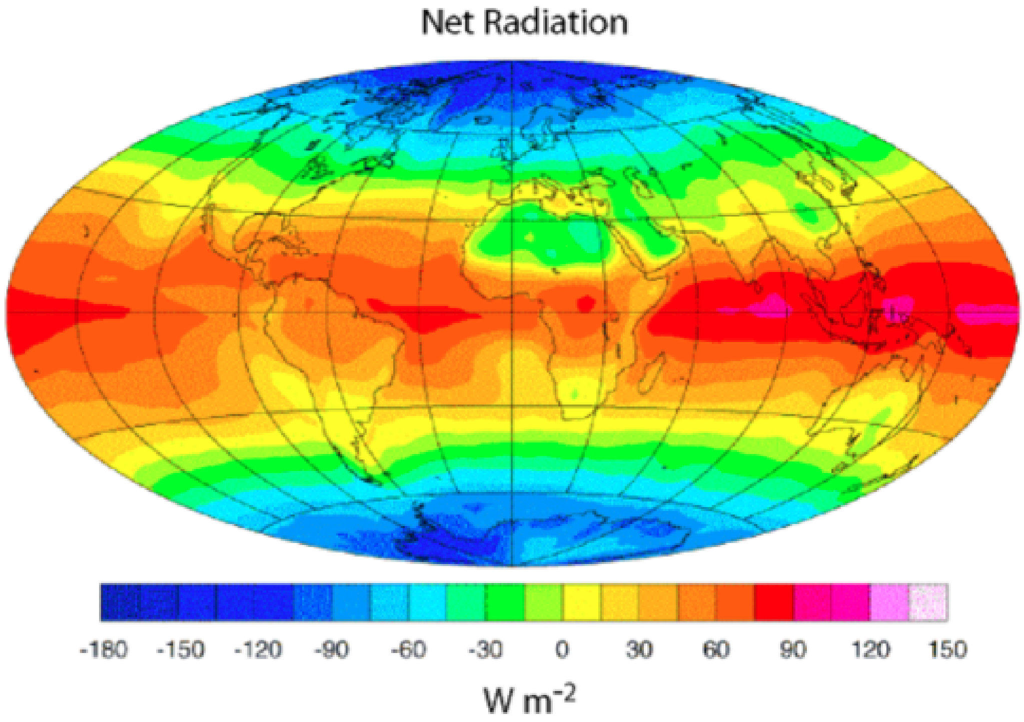
NET RADIATION FLUX AT THE TOP OF THE ATMOSPHERE [cal $cm^{-2} min^{-1}$]
NIMBUS II 16 - 28 JULY 1966



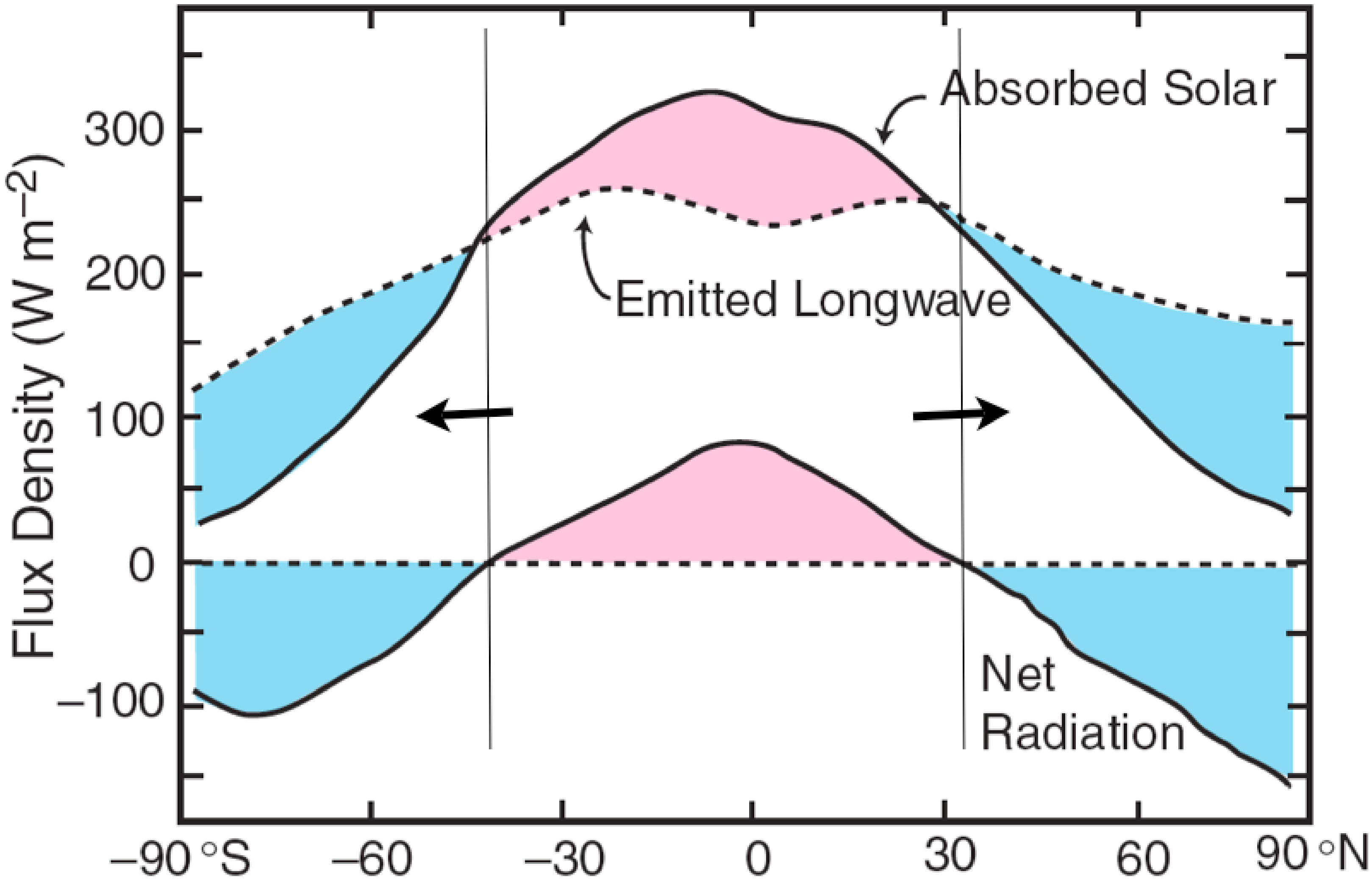
NASA ERBE Radiation





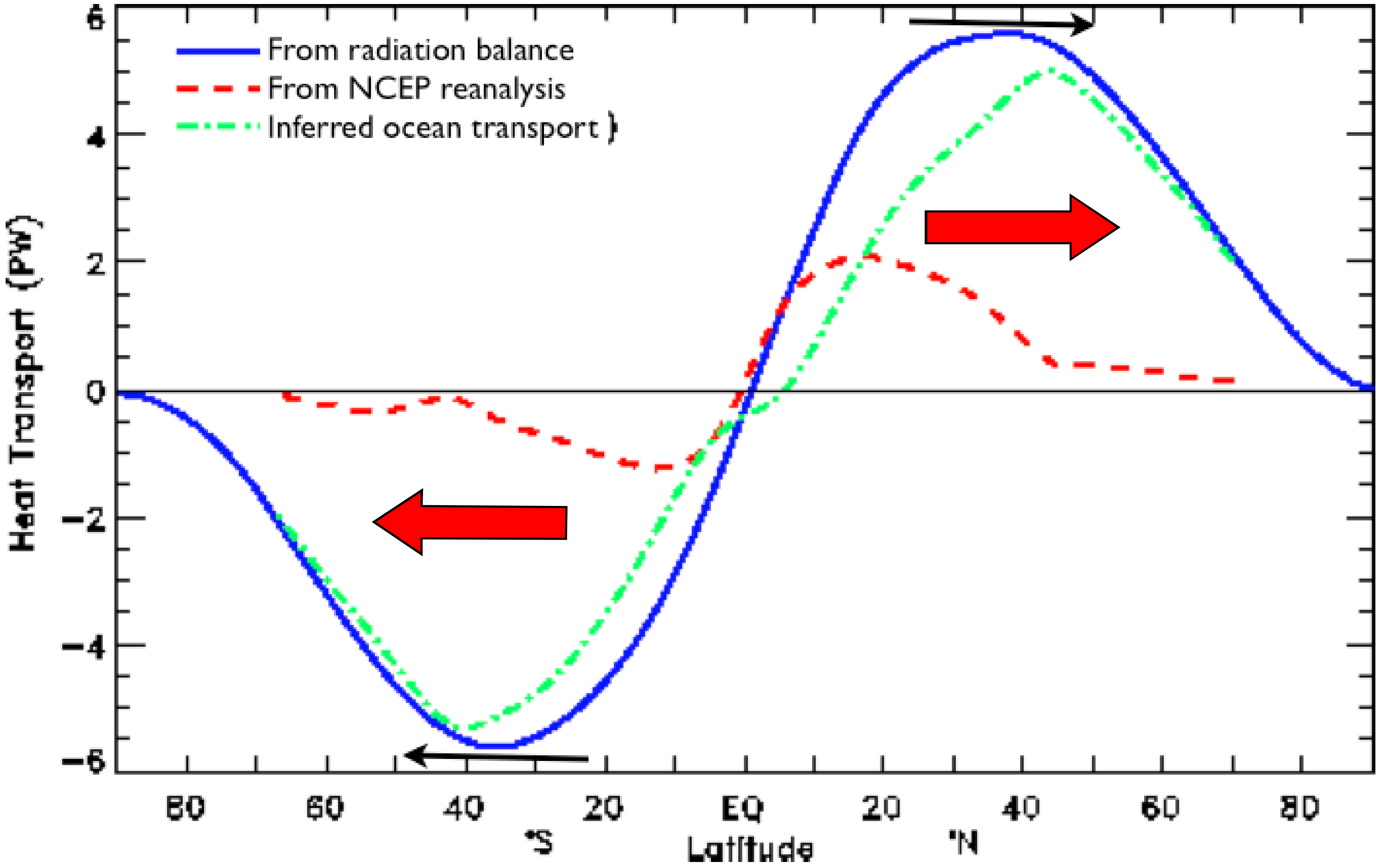


Why don't the tropics get hotter and the polar regions get colder?



Need for a poleward flux of energy across 38° latitude

Northward Energy Transport



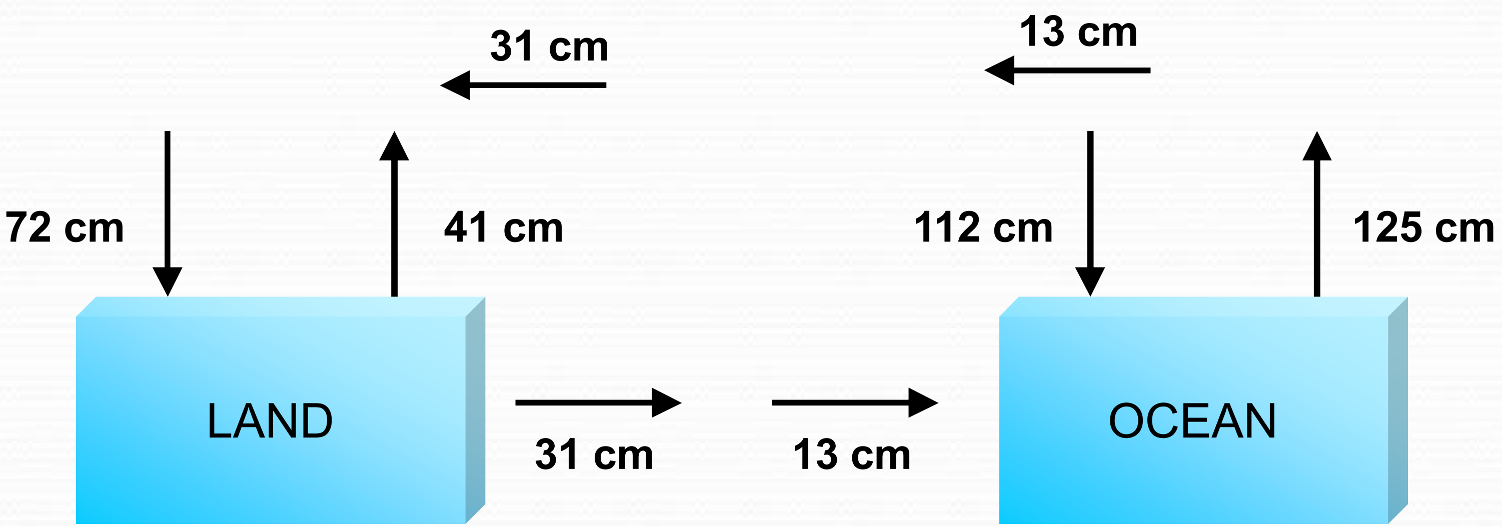
Atmosphere - Ocean General Circulations

are

Benevolent Distributionists!

The planet Earth has a stable equilibrium climate because atmosphere and ocean circulations interactively transfer heat, momentum, energy, and water/moisture from the tropical regions to the polar regions.

Global Annual Mean Hydrological Cycle



[Global, annual mean]

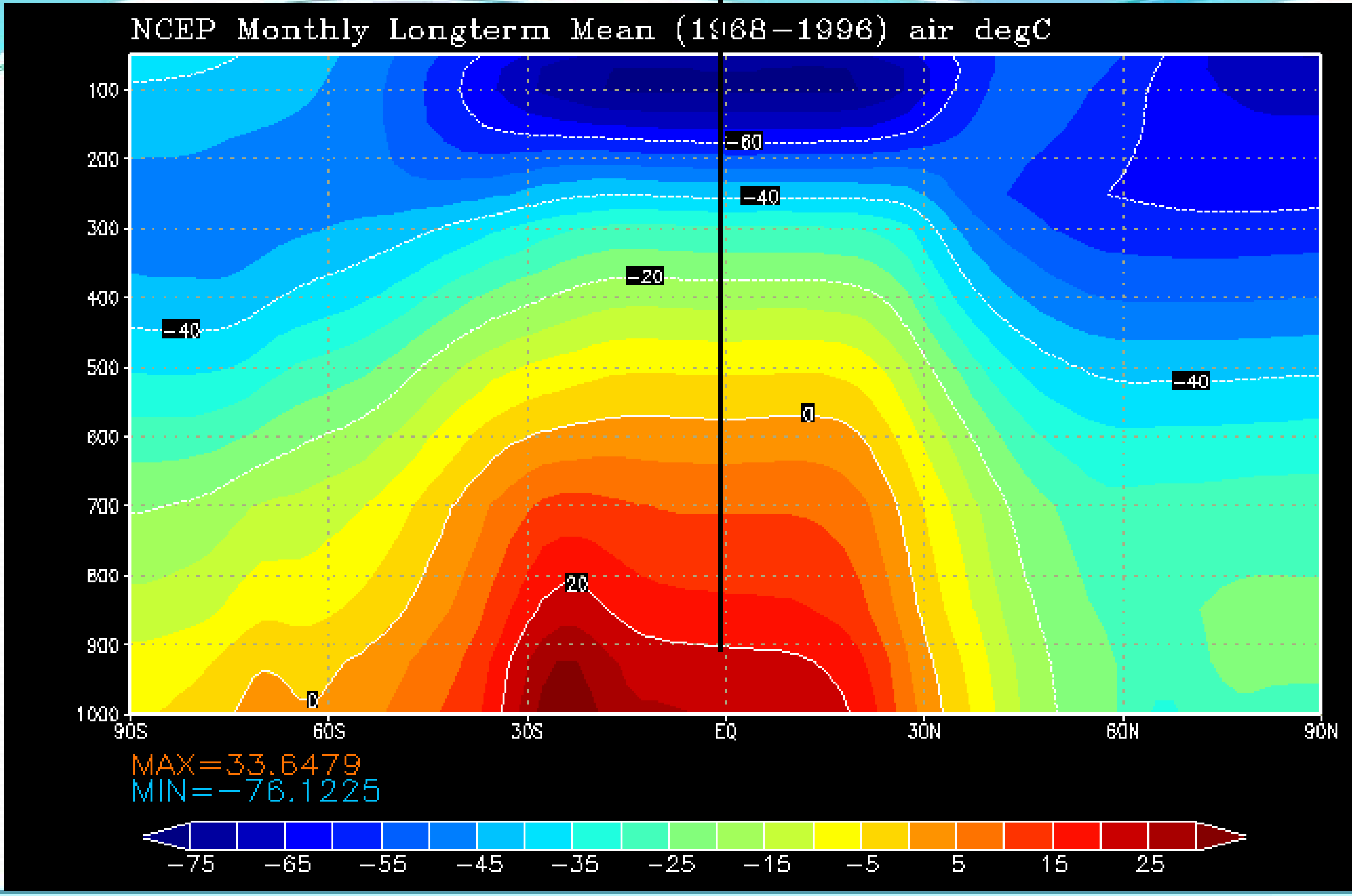
[Vertical column ~ 2-3 gm/cm^2 of water]

[Time scale ~ 3 weeks]

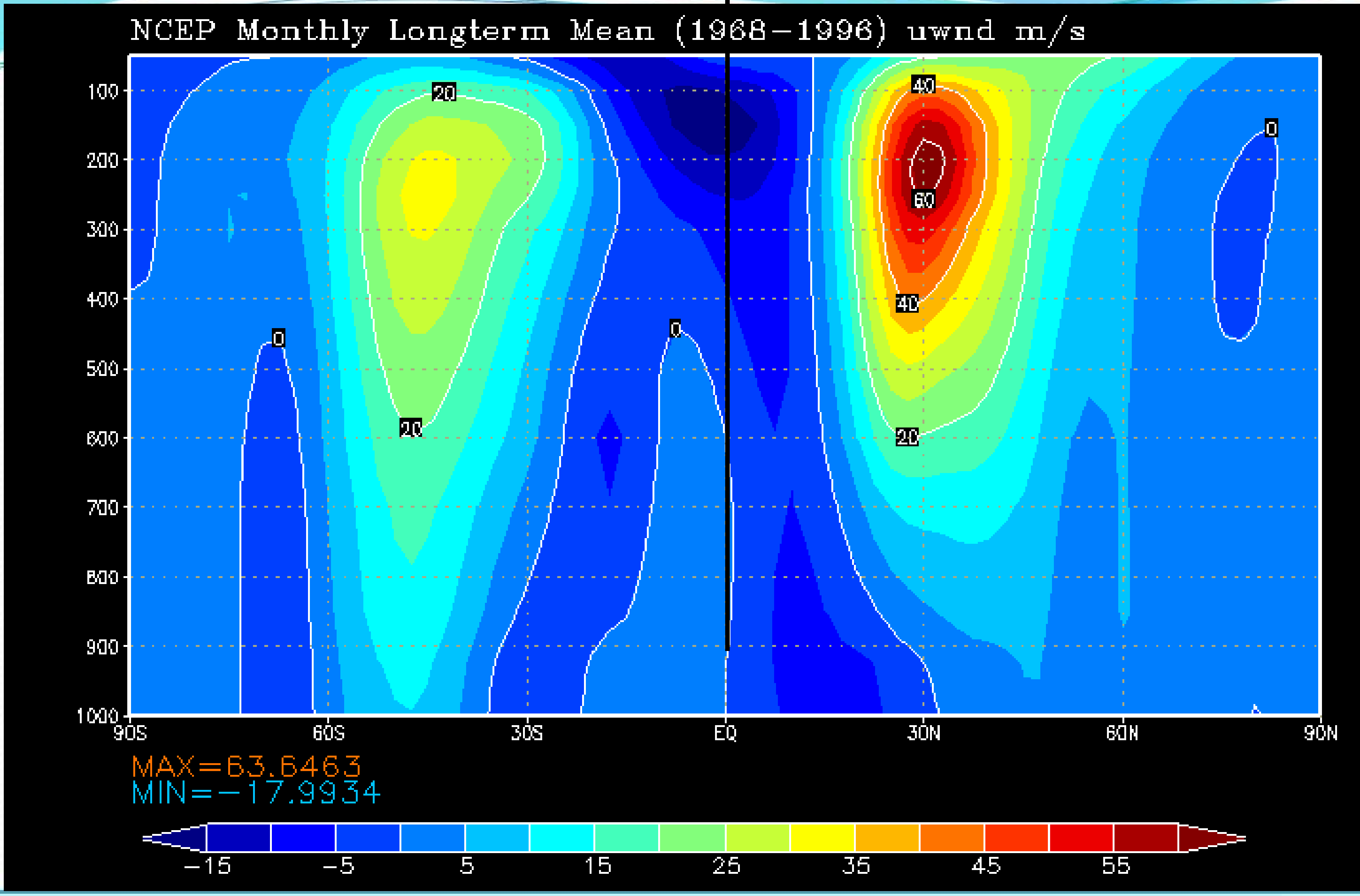
The Mean Climate

(Atmosphere)

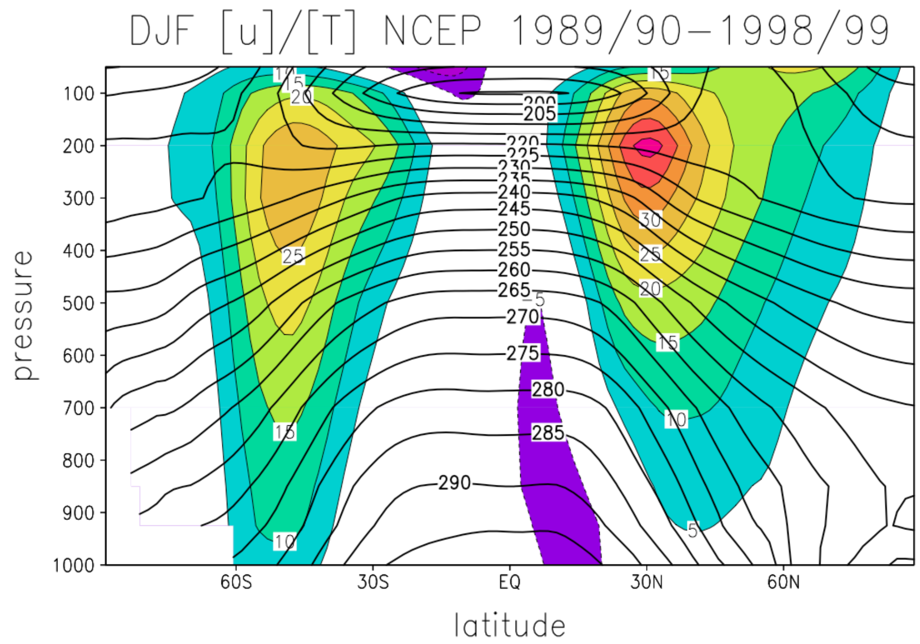
January mean, zonal mean temperature



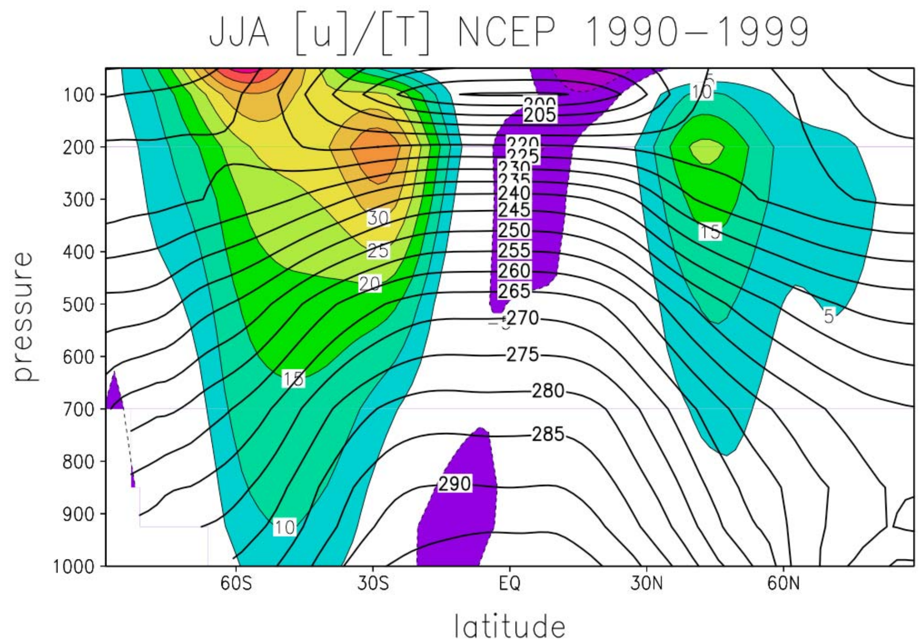
January mean, zonal mean wind



Zonal mean wind and temperature



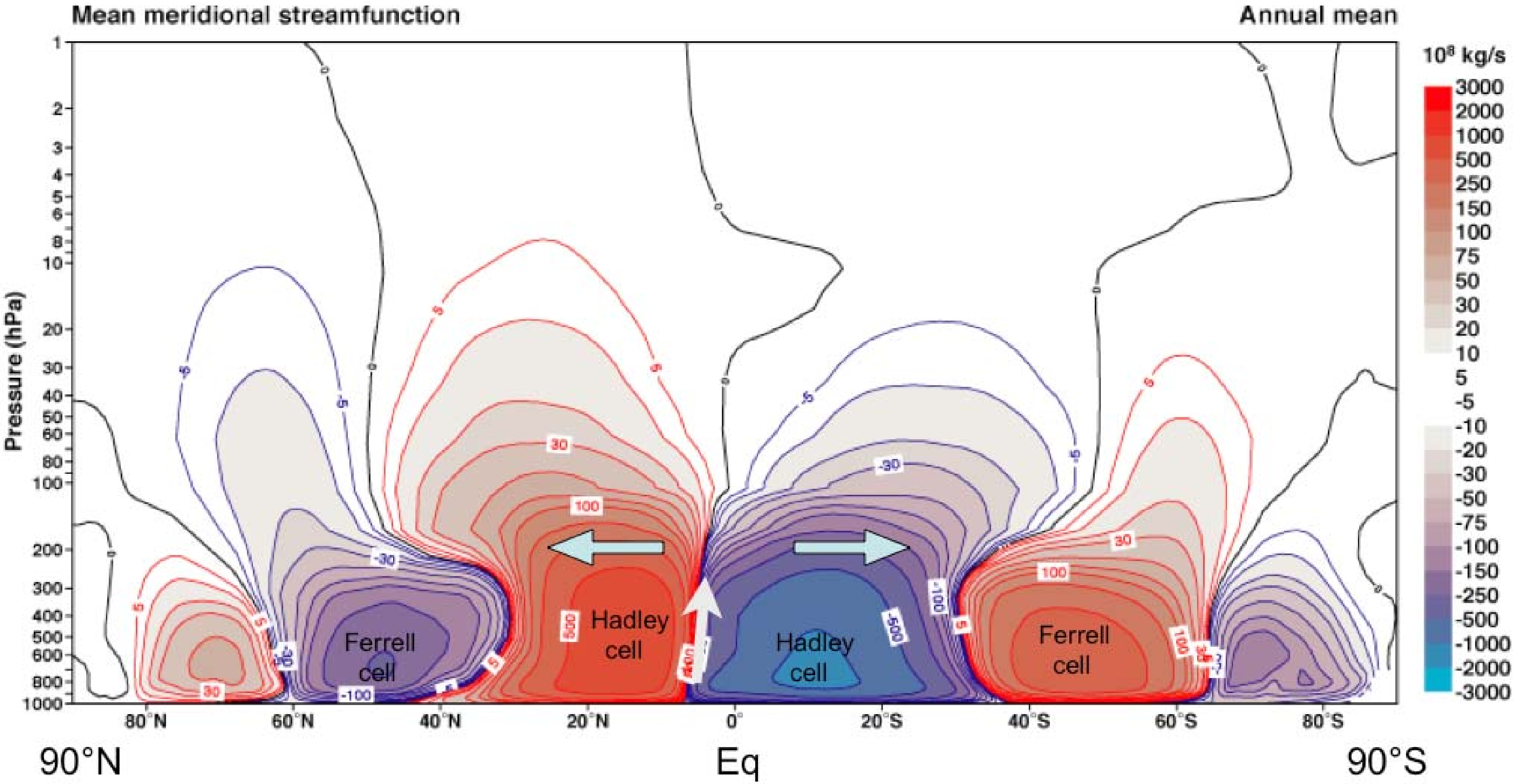
DJF



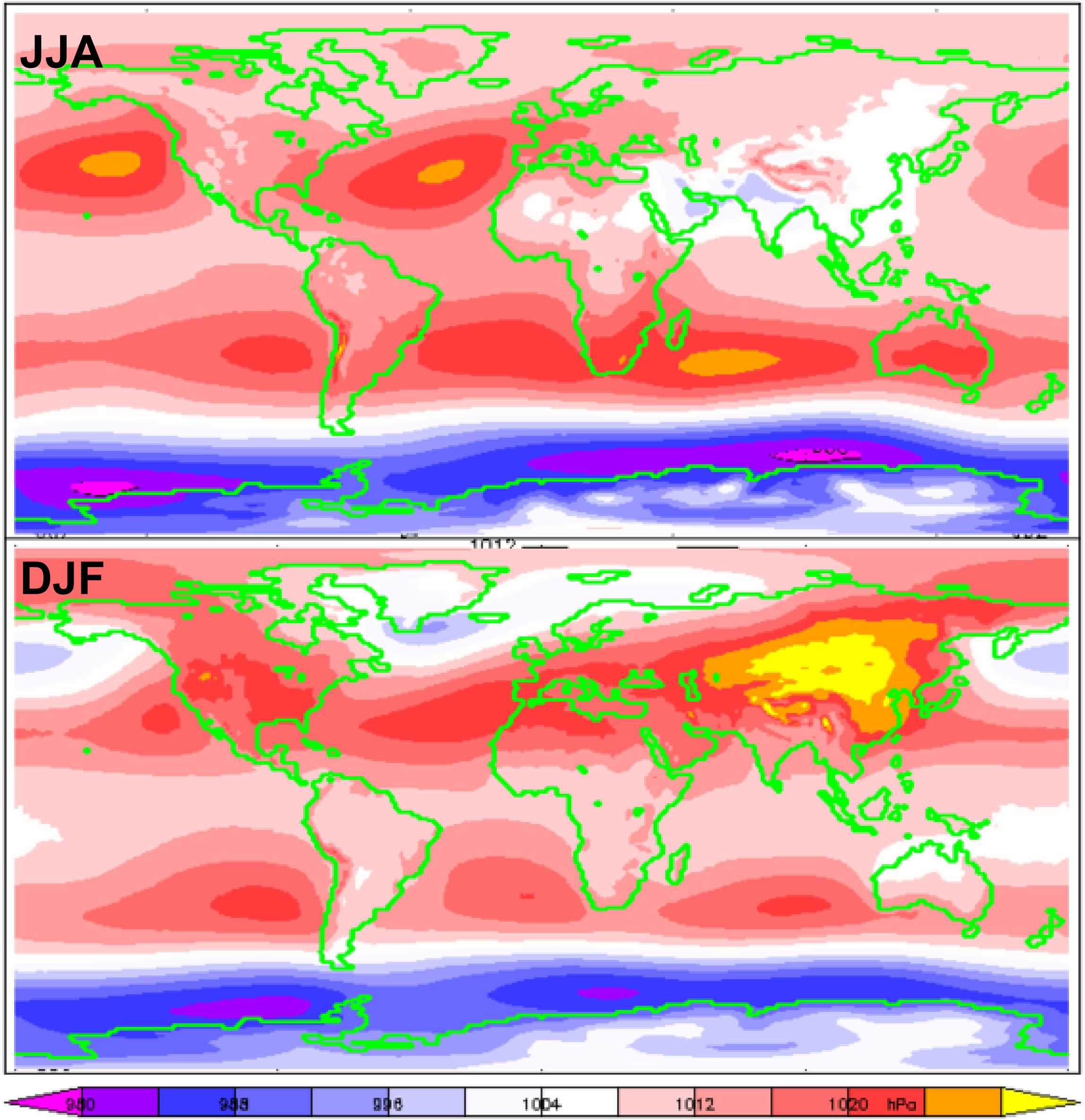
JJA

Mean Meridional Streamfunction

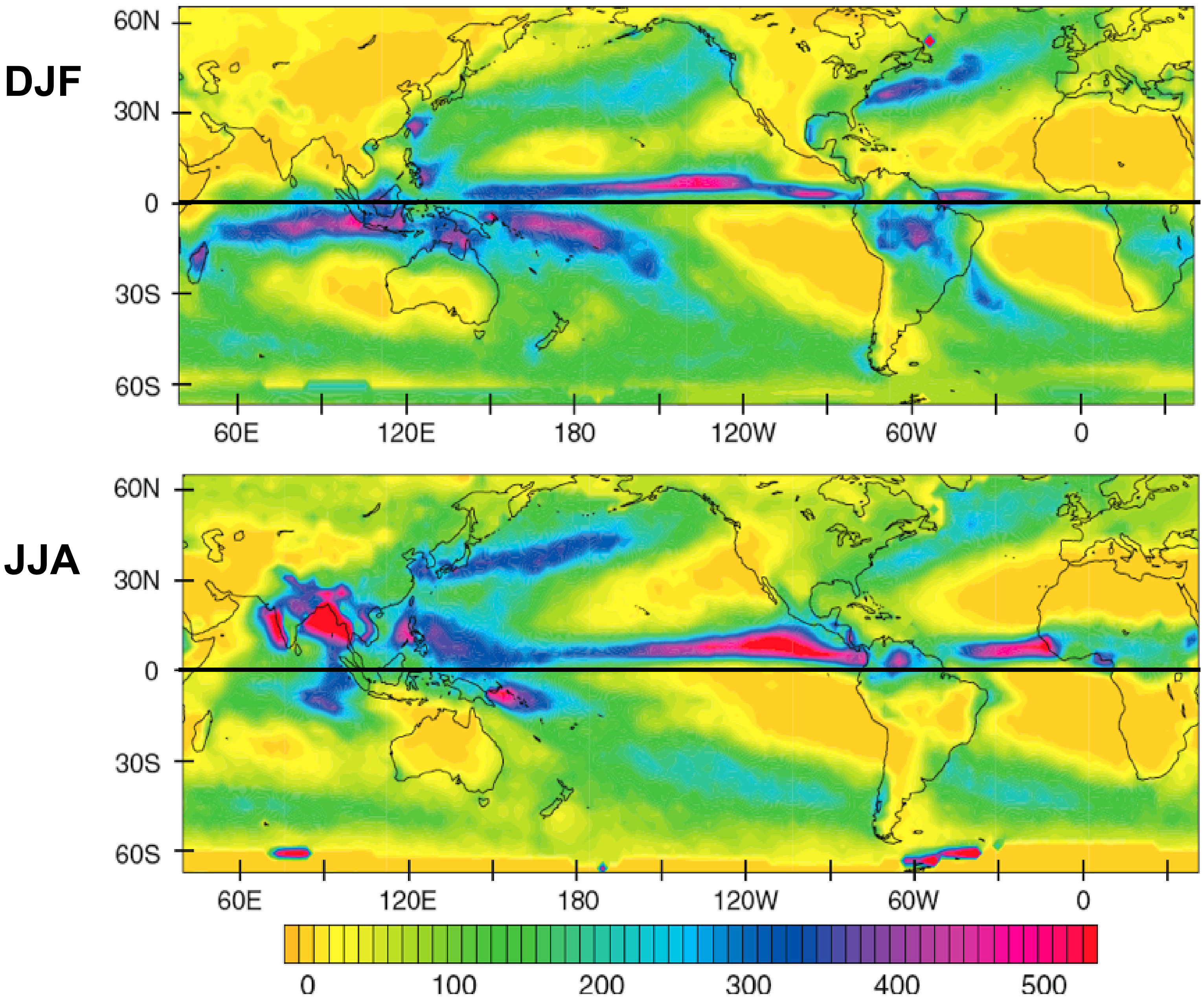
Why there are 3 cells?



Mean Sea Level Pressure for 15 years



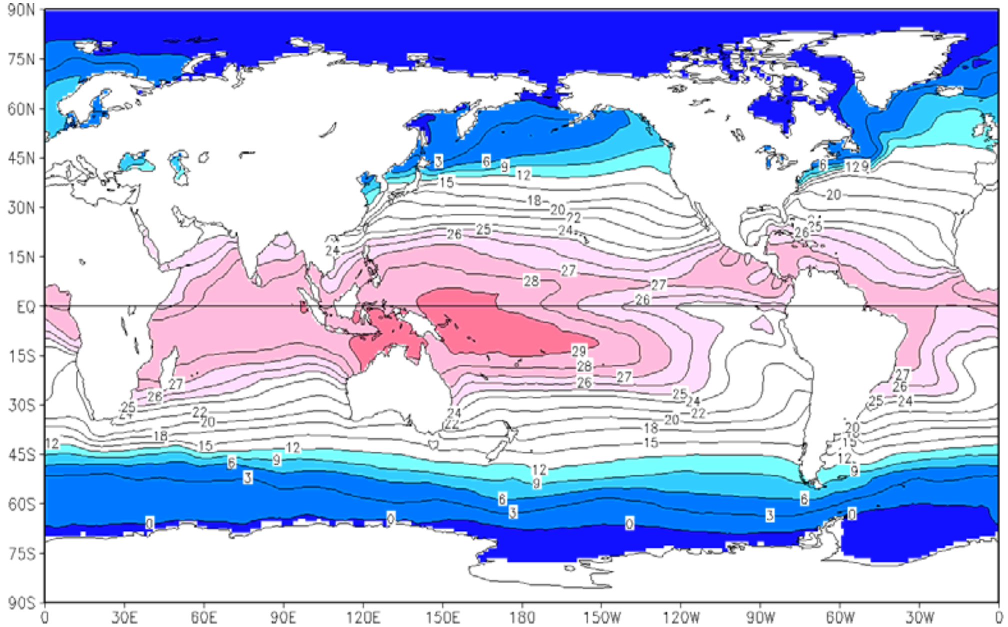
Climatology of Precipitation



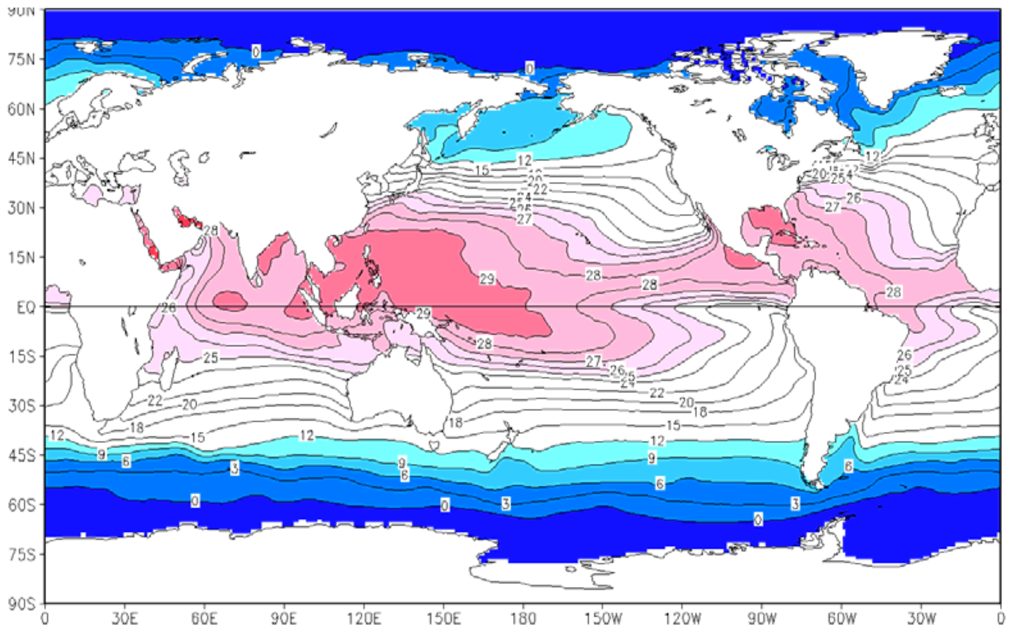
Climatology of Sea Surface Temperature

Hadely Center SST for 1979-2007 (^oC)

DJF



JJA

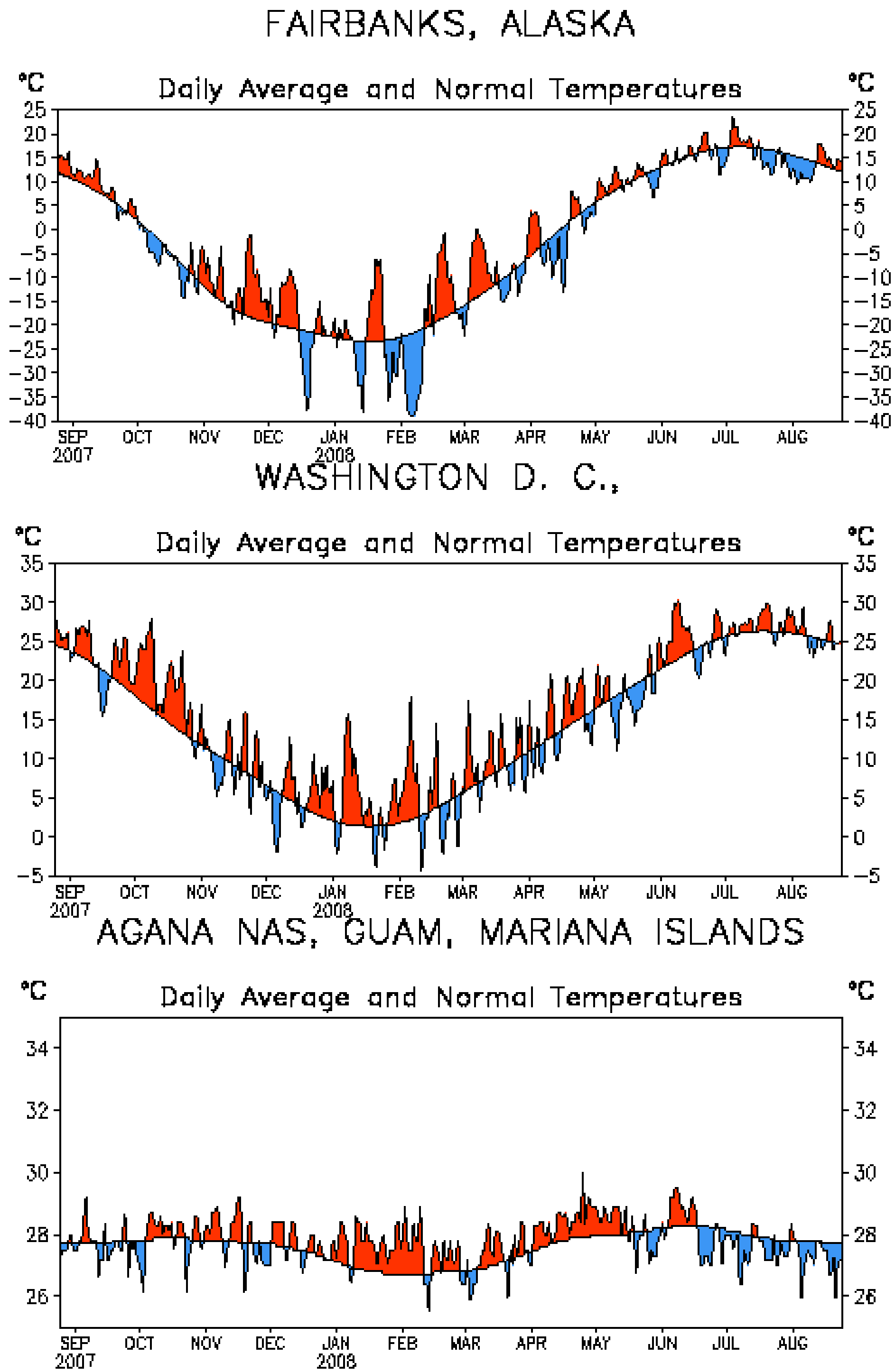


Annual Cycle

Diurnal Cycle

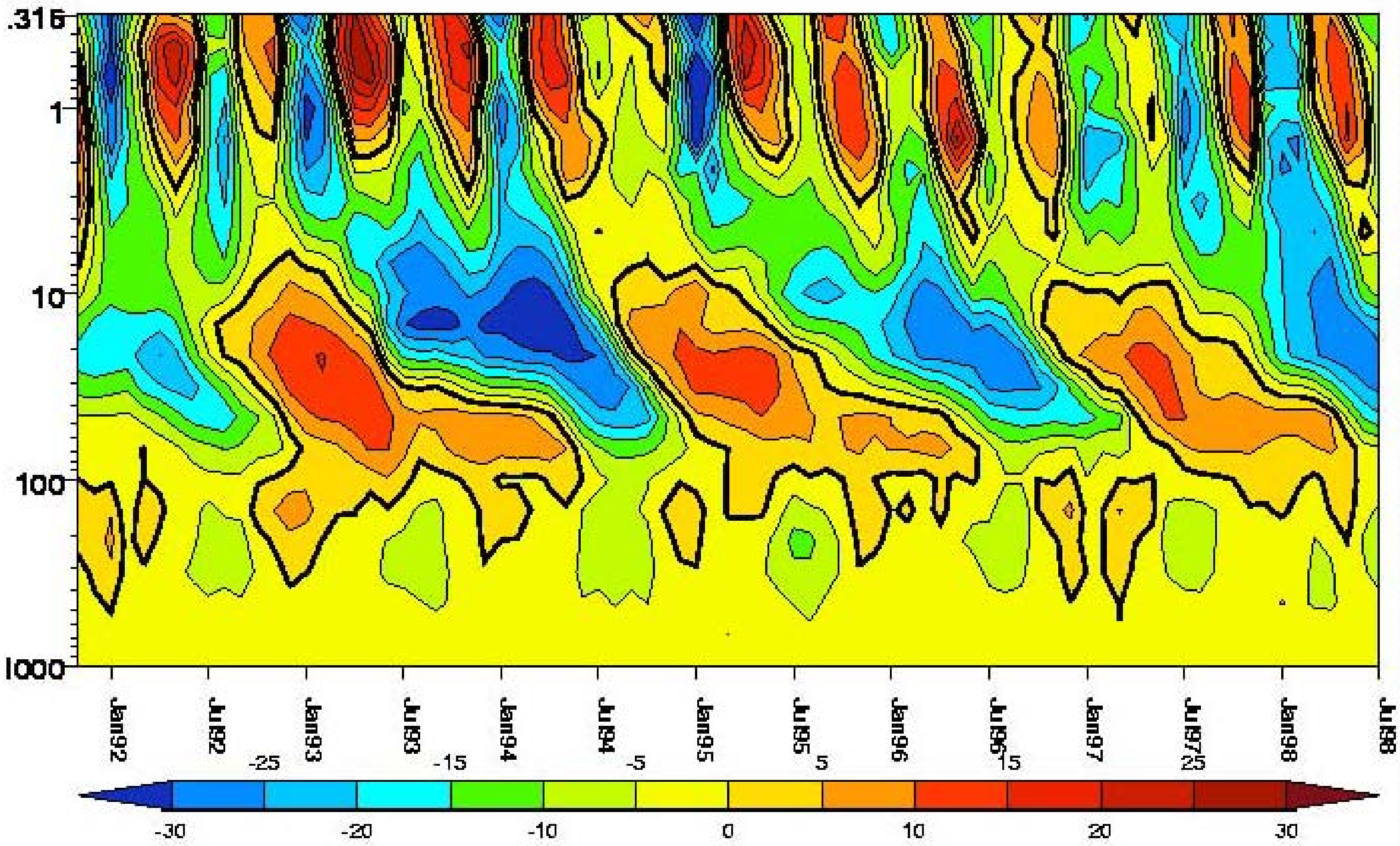
QBO

Temperature for September 2007 to August 2008

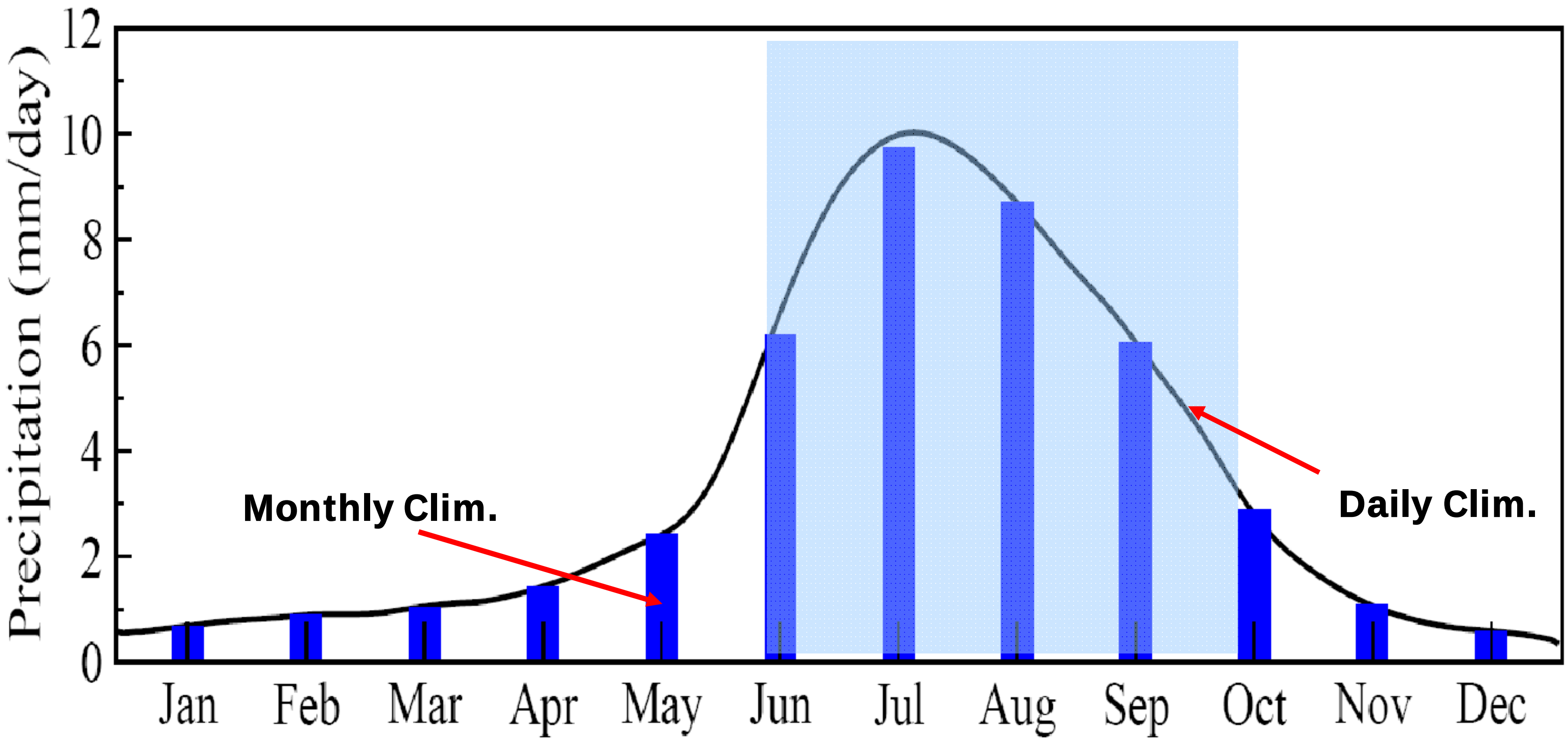


Tropical General Circulation

QBO (zonal mean U, 1.25 lat, UKMO)



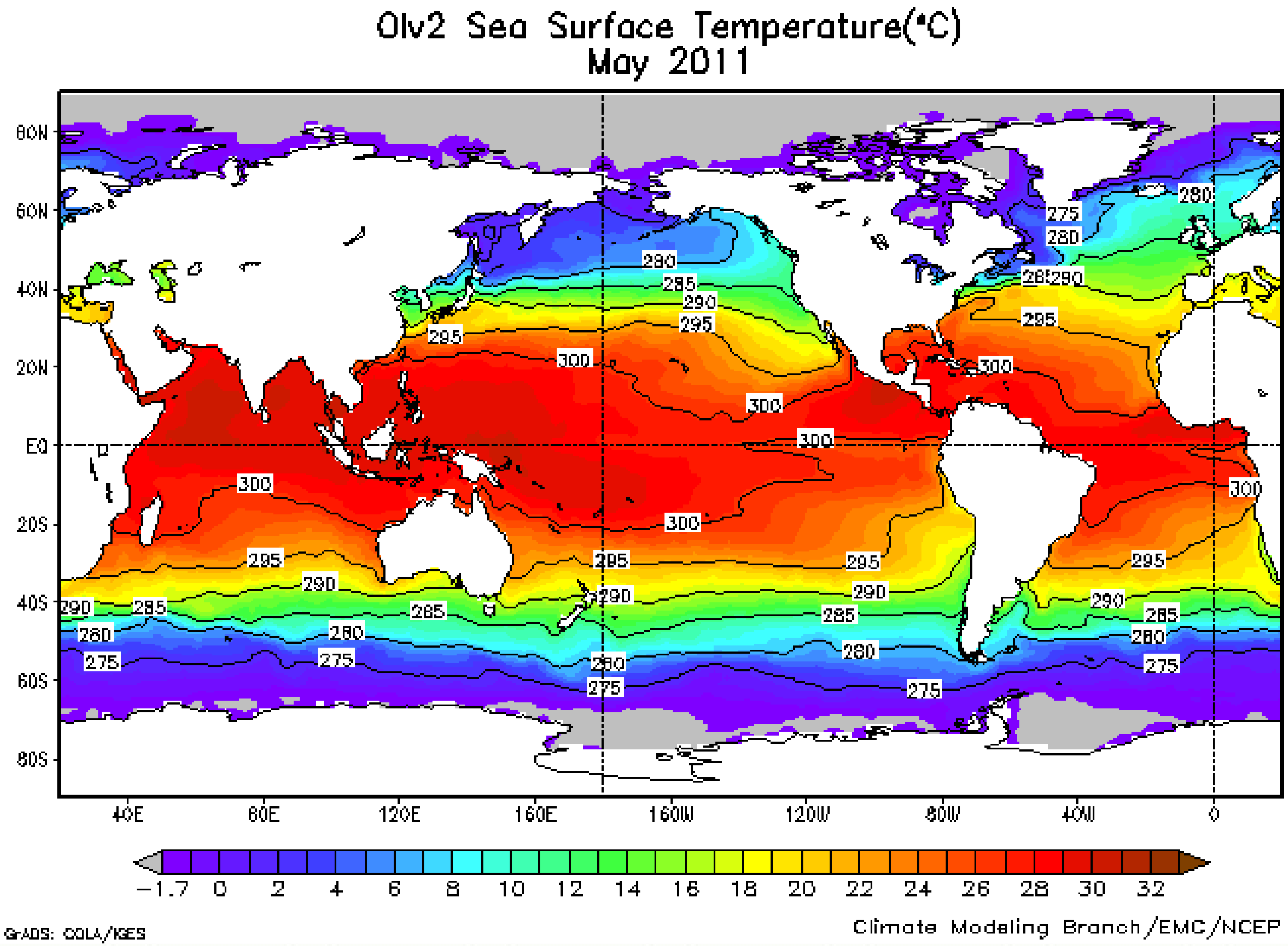
Annual cycle of Rainfall over India



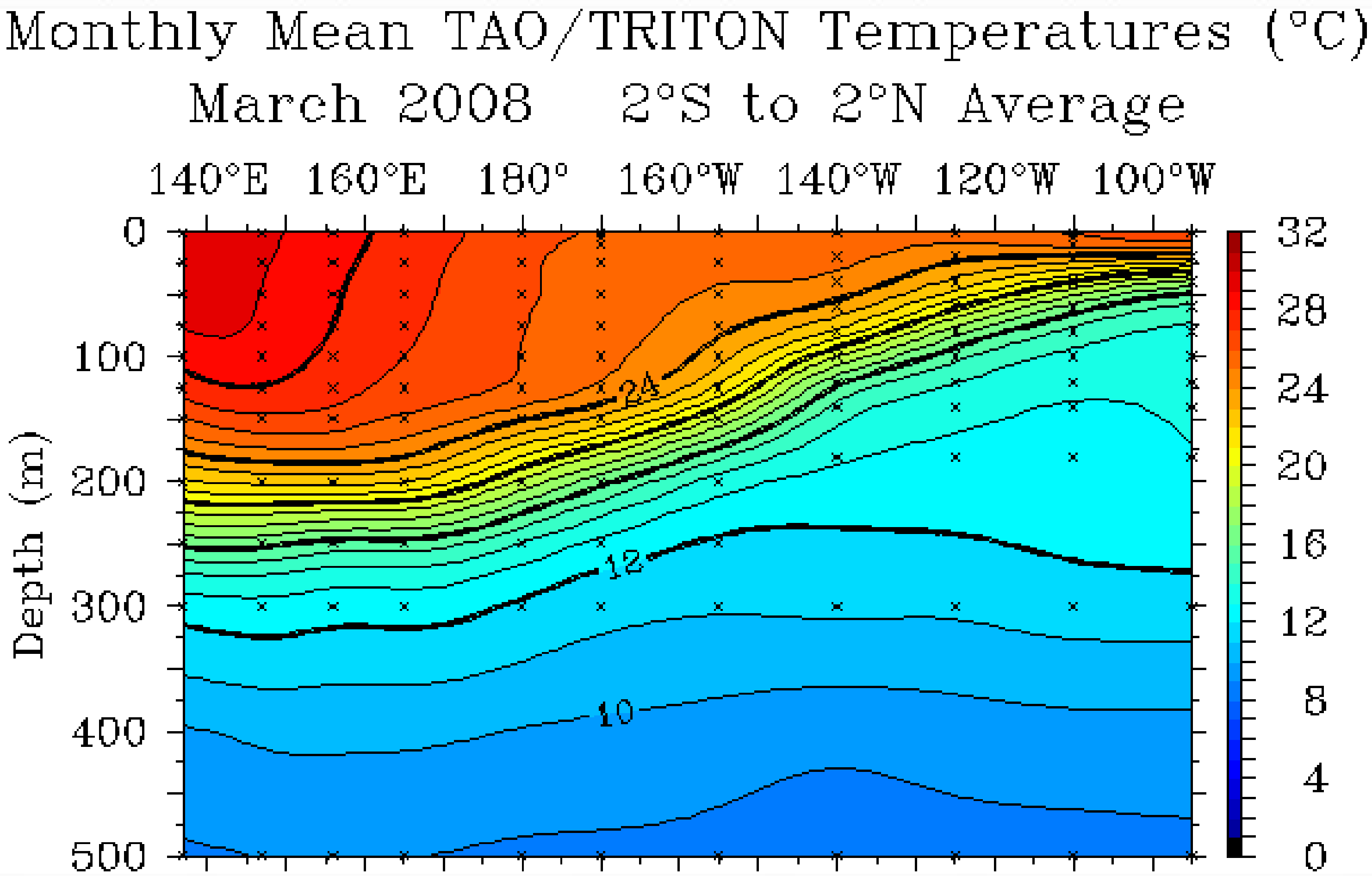
The Mean Climate

(Ocean)

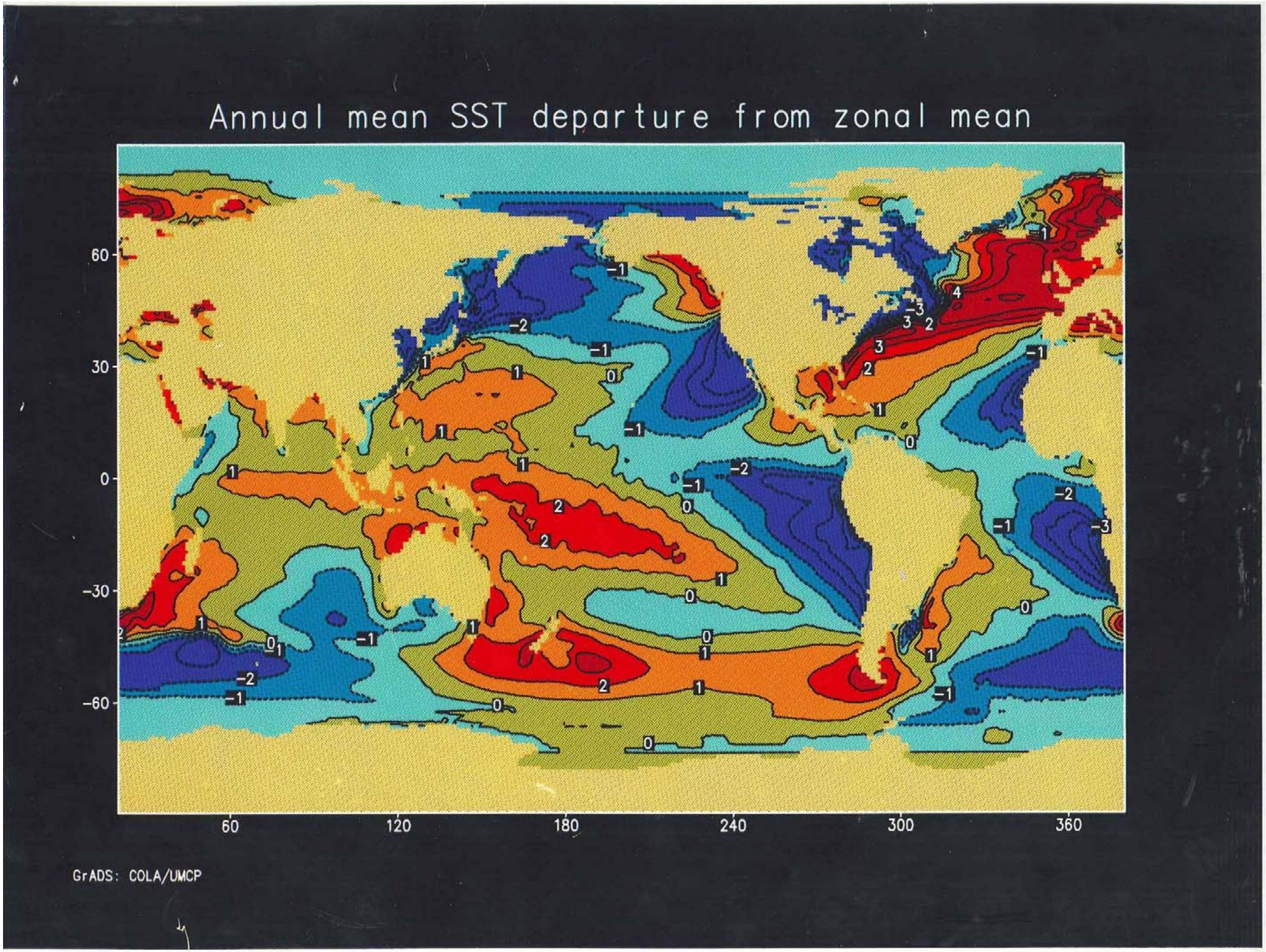
OISST version 2 SST (°C), May 2011



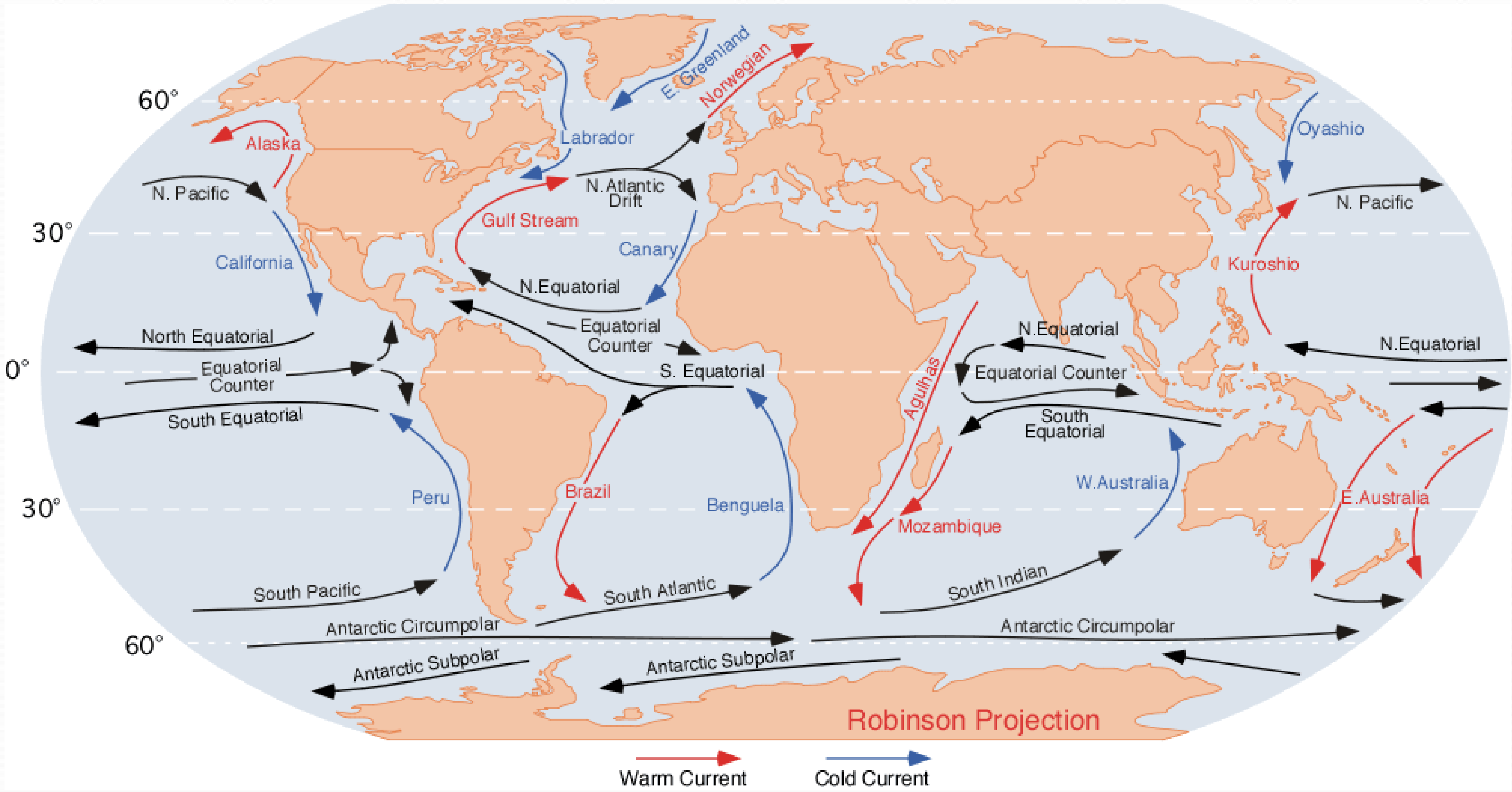
Equatorial Thermocline



Note the high vertical temperature gradient around 20°C isotherm.

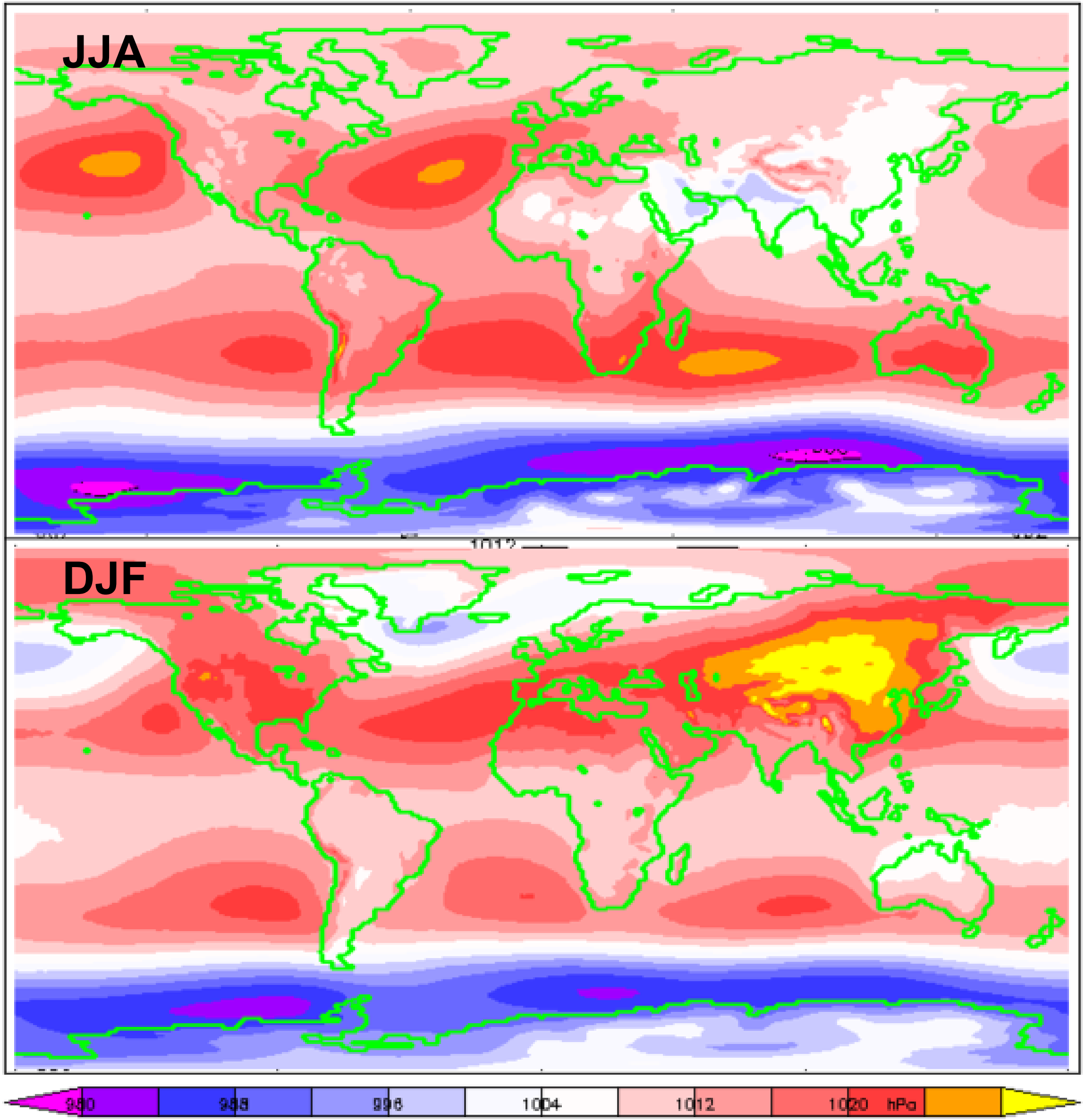

Annual mean SST departure from zonal mean
60
30
0
-30
-60
60
120
180
240
300
360
GrADS: COLA/UMCP

Schematic Picture of the Major Surface Currents of the World Oceans



Note the anticyclonic circulation in the subtropics (the subtropical gyres)

Mean Sea Level Pressure for 15 years



An Example:
Gulf Stream

Questions:

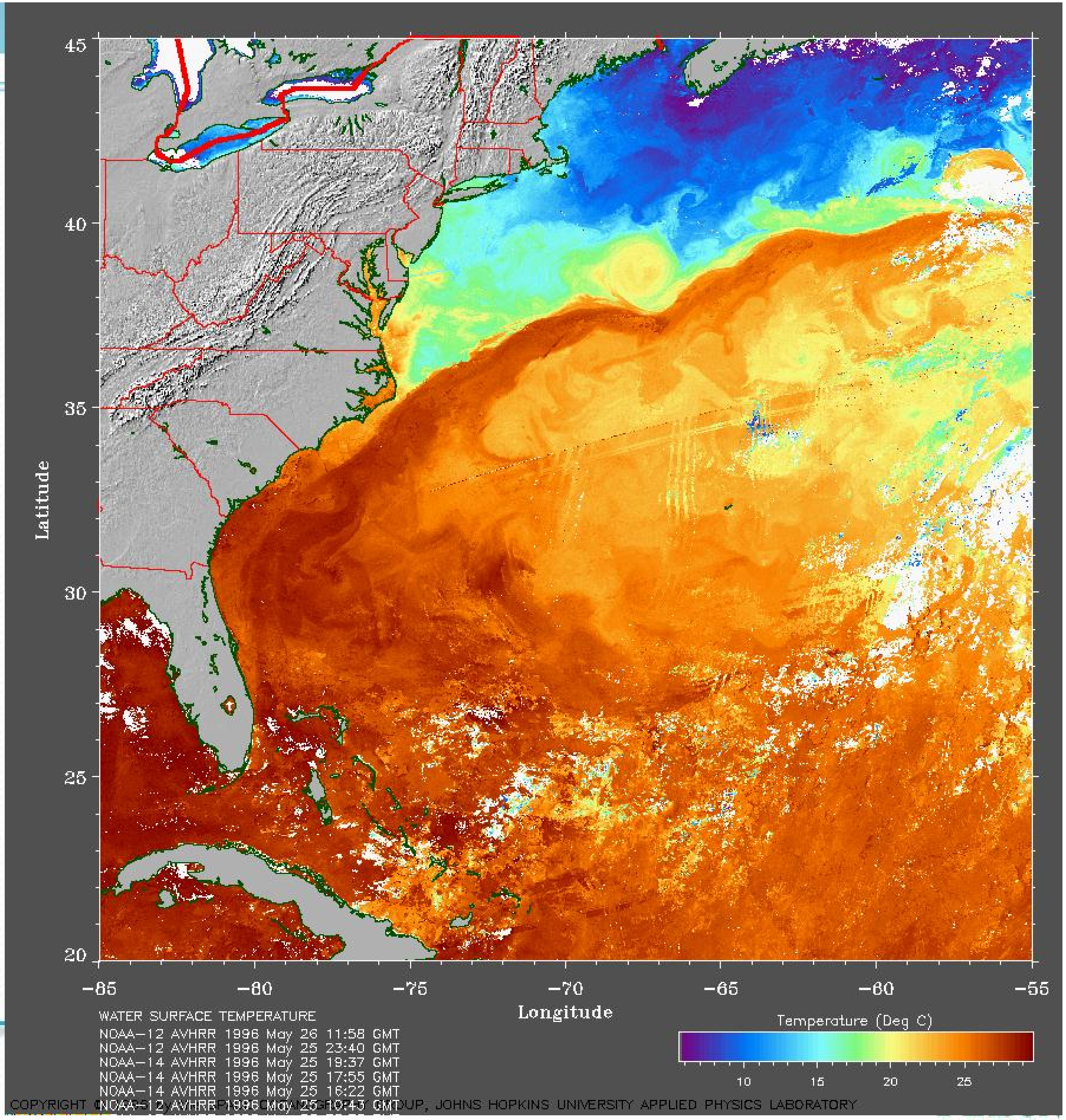
Why does the Gulf Stream concentrate near the western boundary?

What determines its width and speed?

Why are there meanders and rings?

Any climate significance?

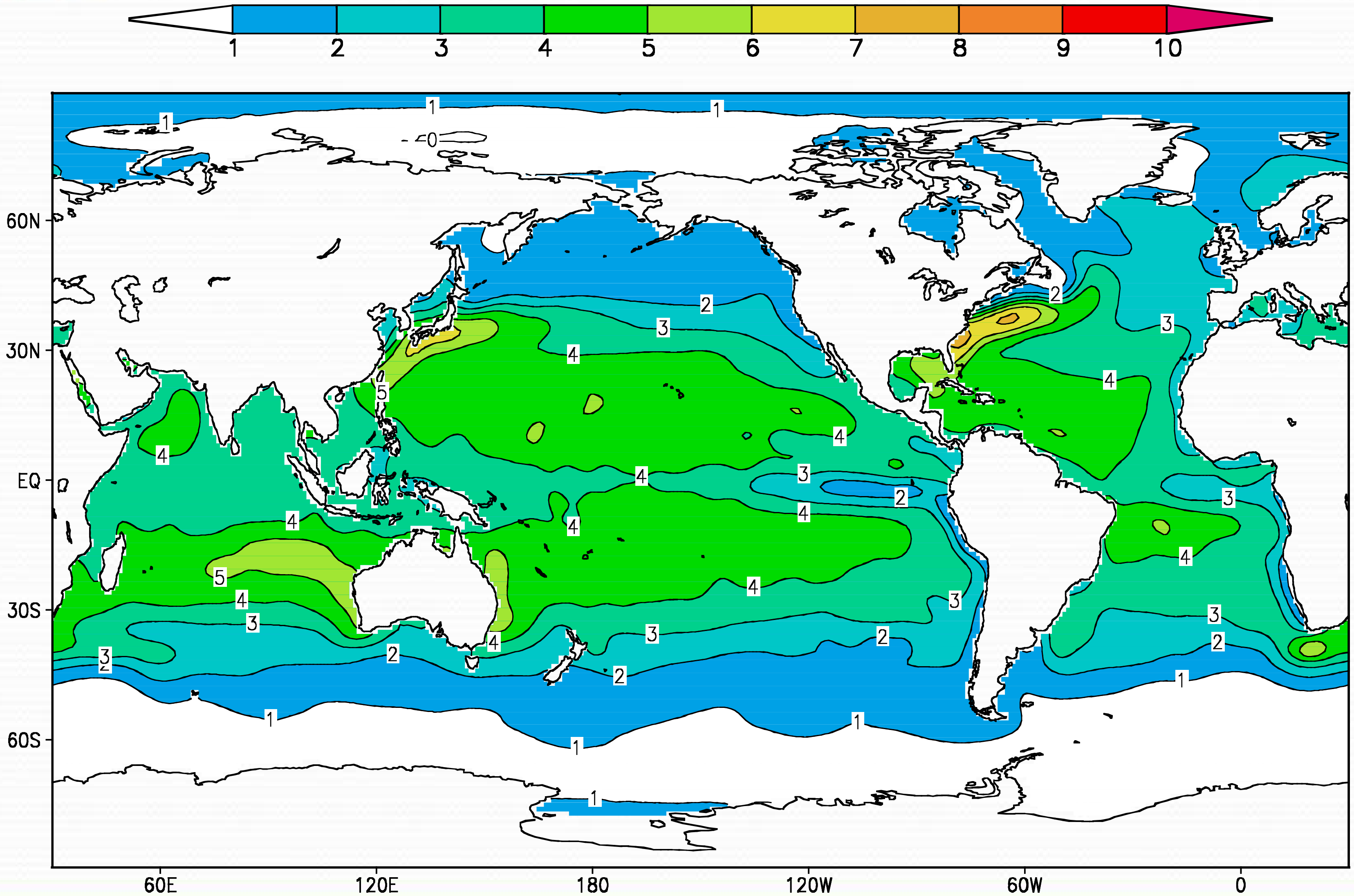
…….



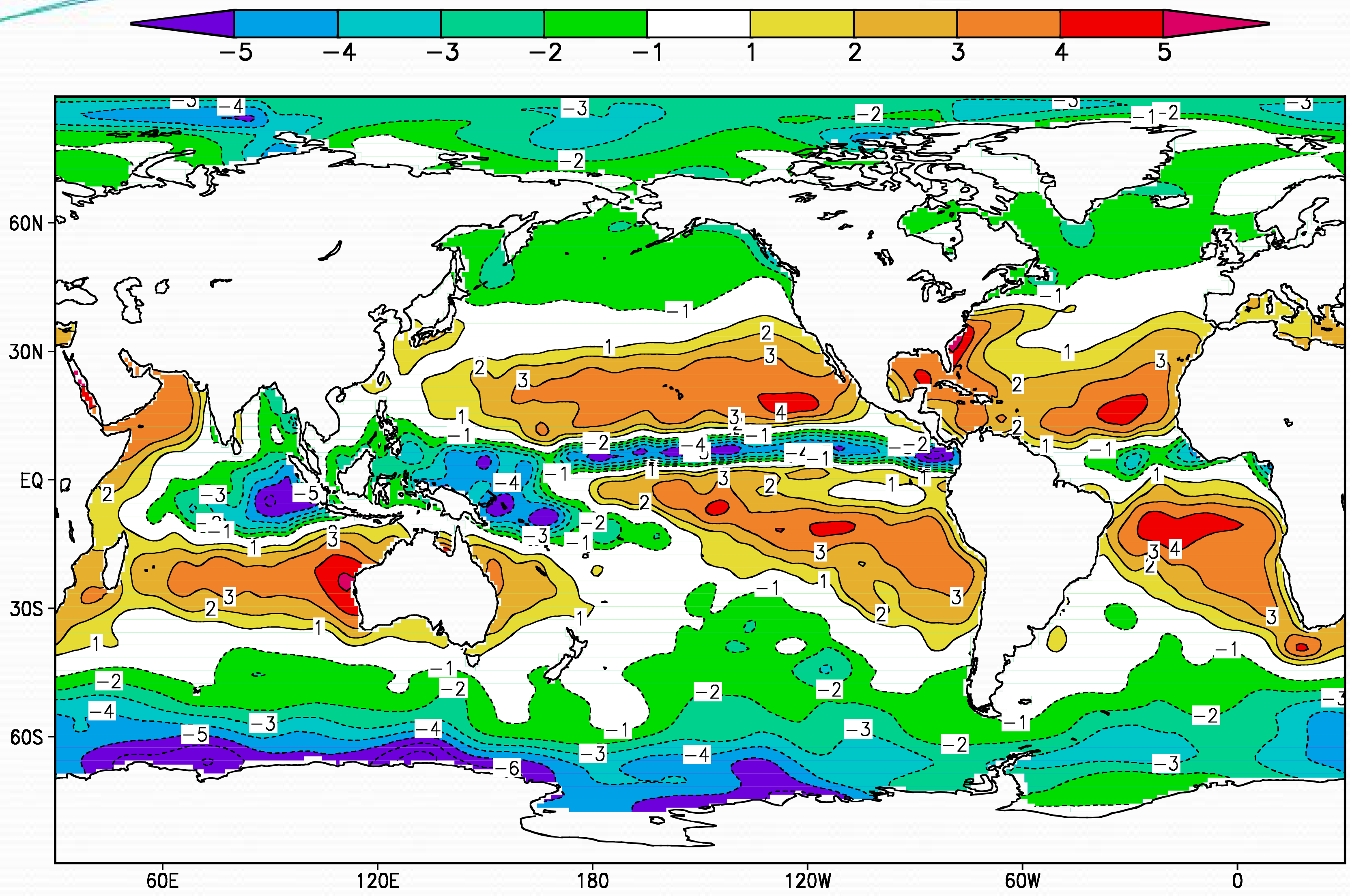
COLA

UNIVERSITY

Annual Mean Evaporation [mm/day] COADS



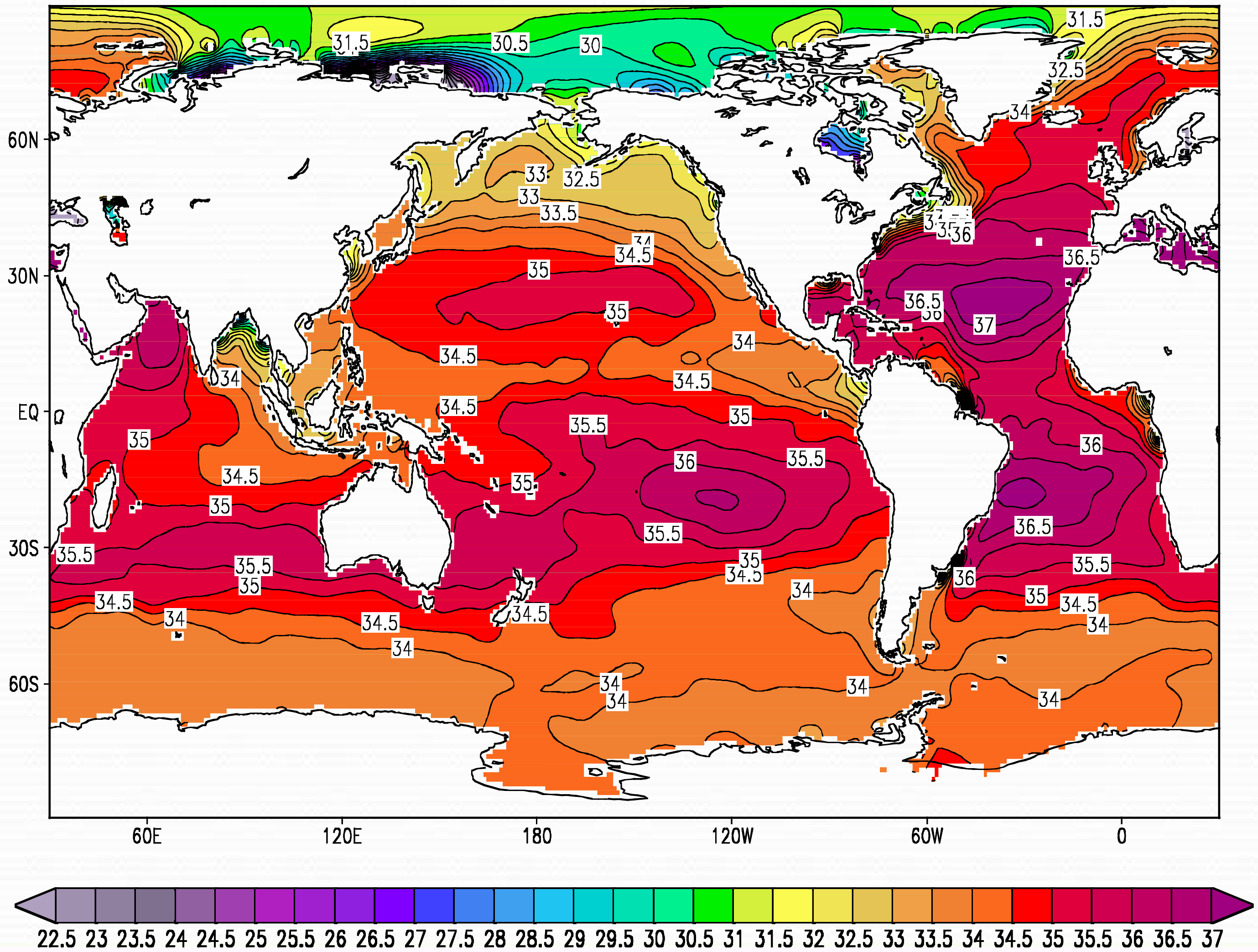
Annual Mean E-P [mm/day] COADS



NODC WOA98, *Levitus et al.*

Mean Sea Surface Salinity (SSS)

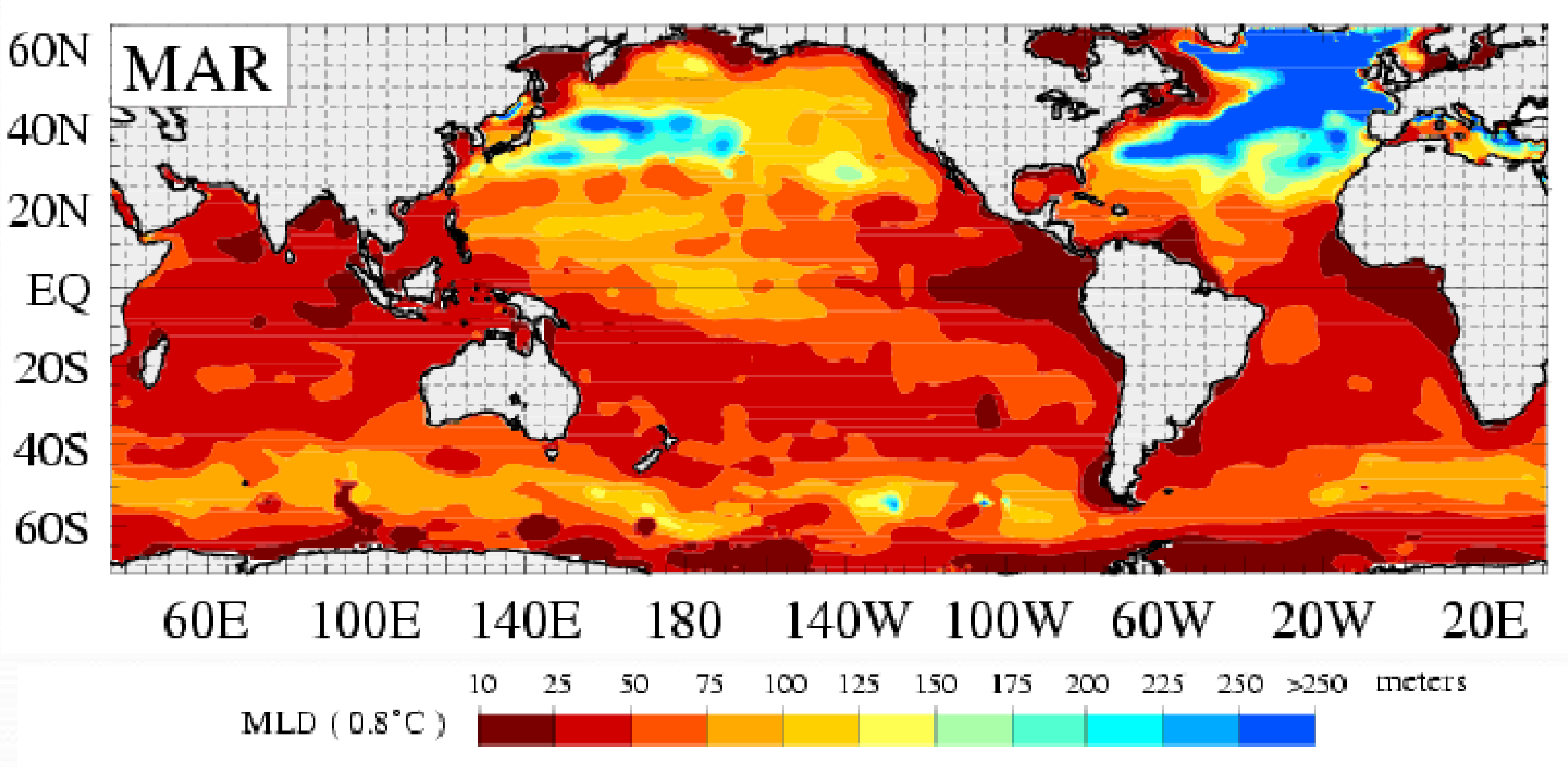
- SSS distribution is mostly zonal (range: 33-37)
- Minimum north of the equator (ITCZ)
- Maximum in subtropics (trade winds)
- Lower around coast (river) and polar region (melting ice)
- Mediterranean, 39 and Red Sea, 41 (large evaporation)



COLA

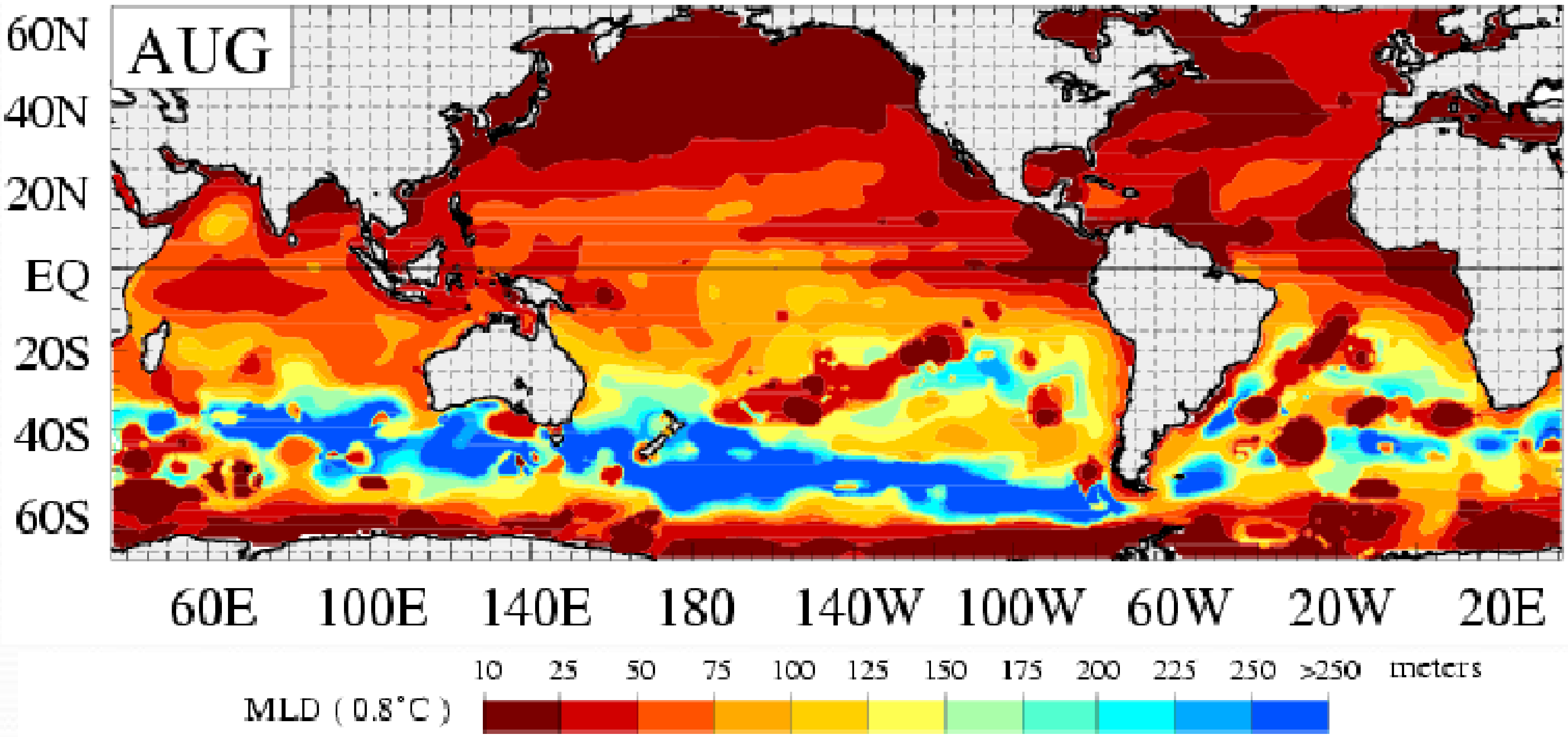
GEORGE MASON UNIVERSITY

Mixed layer depth



Kara, A. B., P. A. Rochford, and H. E. Hurlburt, 2003: Mixed layer depth variability over the global ocean. J. Geophys. Res., 108, doi:10.1029/2000C000736.

Mixed layer depth



Kara, A. B., P. A. Rochford, and H. E. Hurlburt, 2003: Mixed layer depth variability over the global ocean. J. Geophys. Res., 108, doi:10.1029/2000C000736.

Mechanisms of Seasonal-Interannual Variability

- **INTERNAL DYNAMICS**

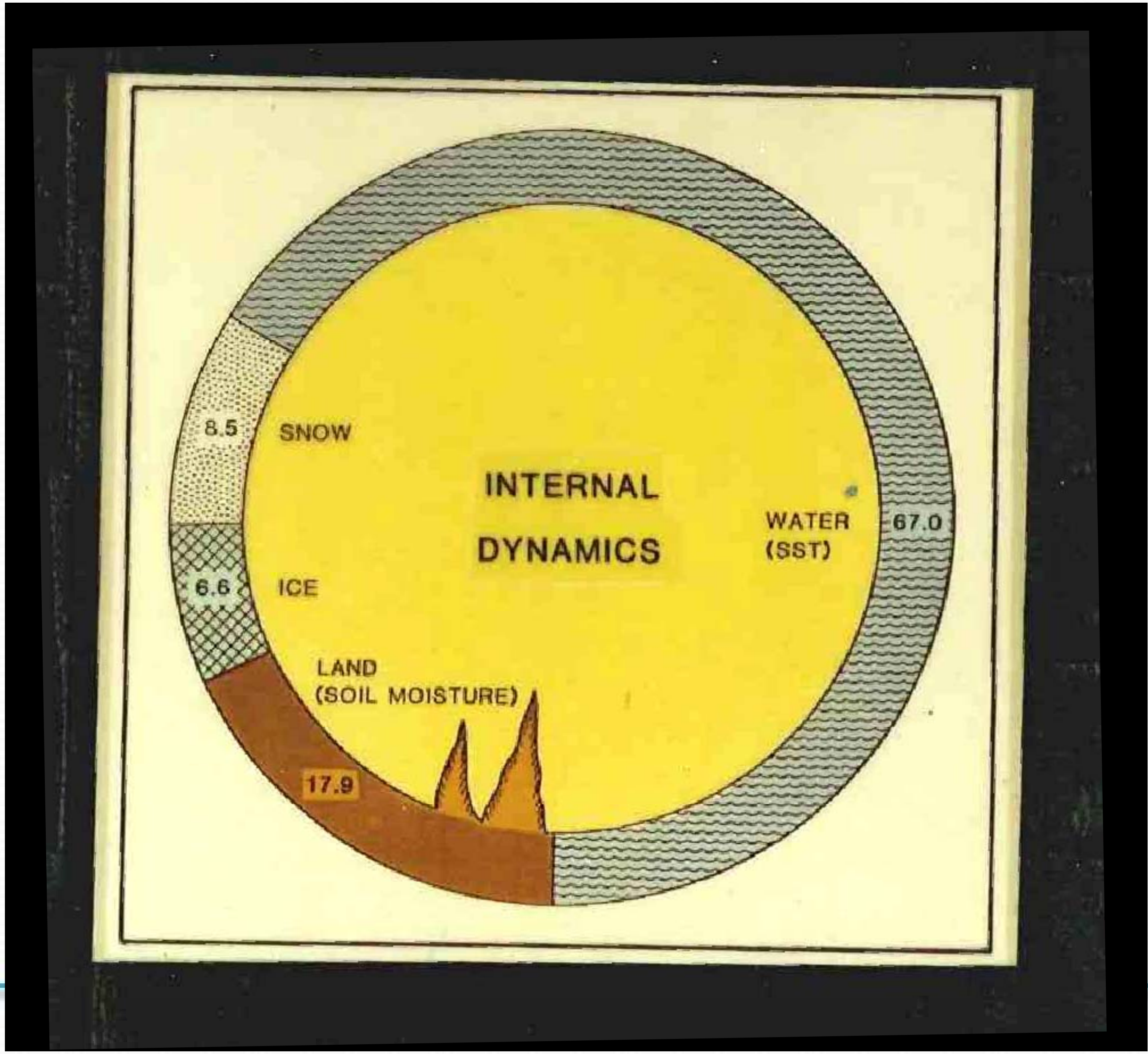
- **BOUNDARY FORCING**

  Atmosphere-Ocean Interaction

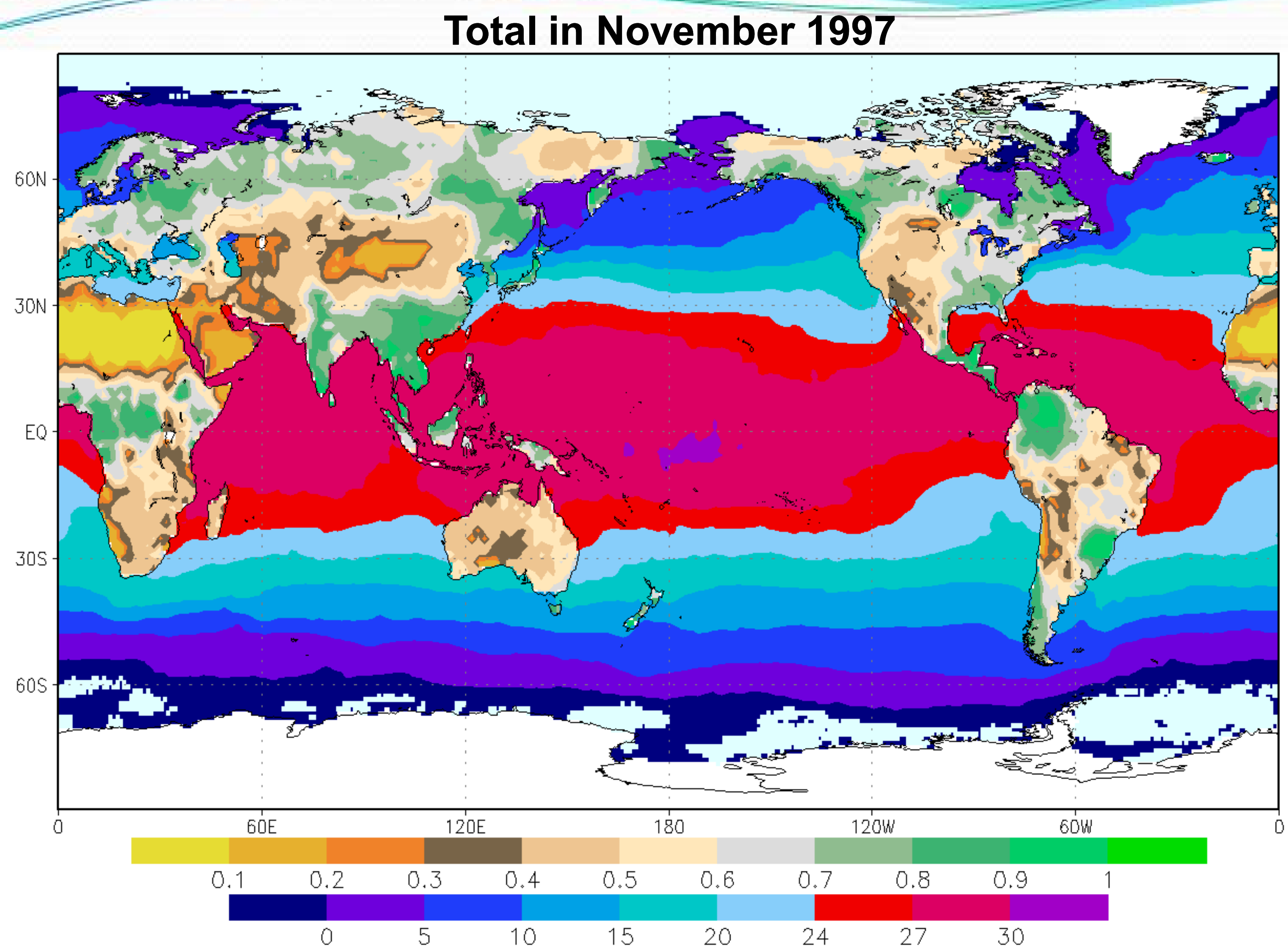
  Atmosphere-Land Interaction

  Atmosphere-Ocean-Land Interaction

Boundary Forced Predictability

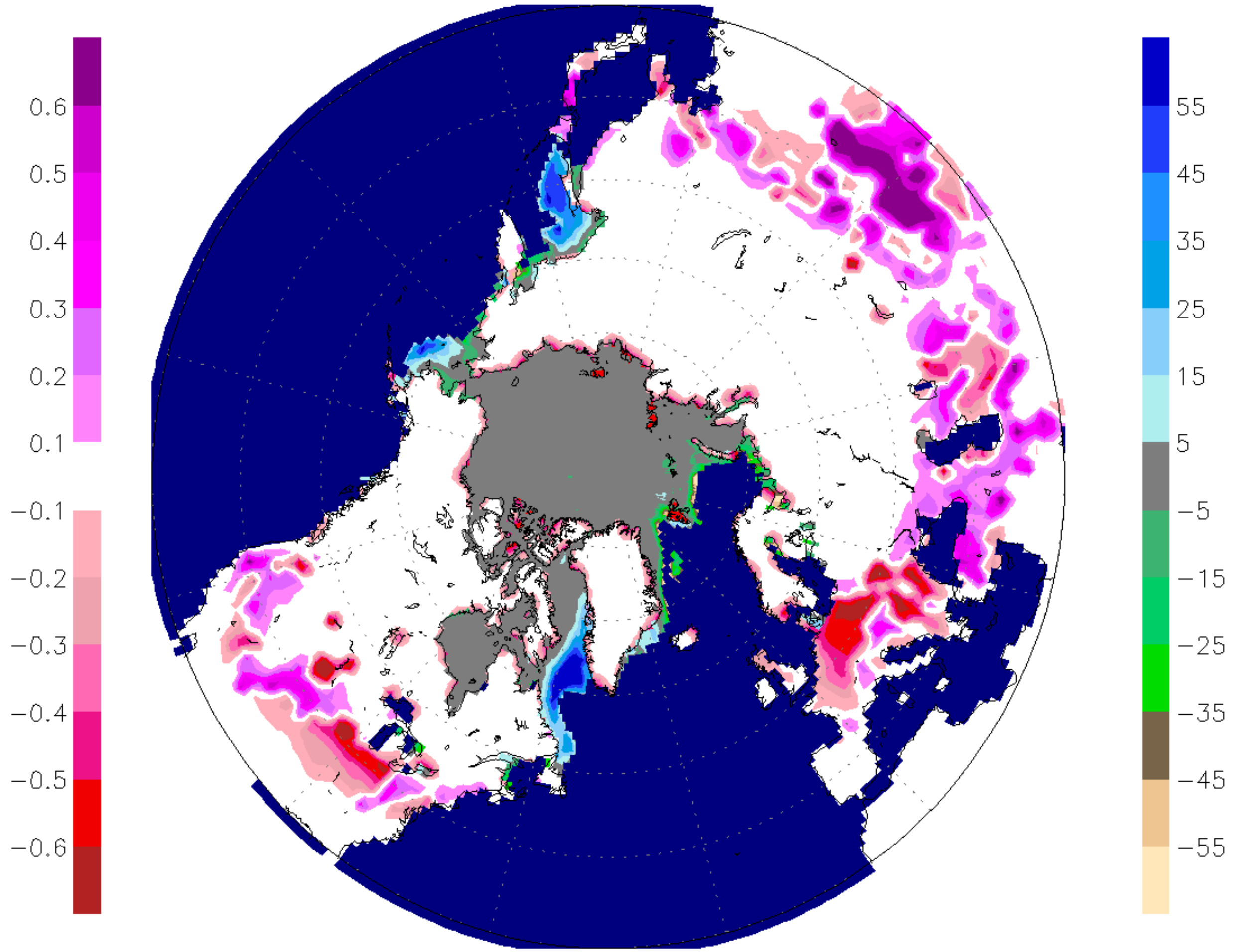


GOLD Soil Wetness (fraction) & HADISST SST (ºC)



NESDIS Snow Cover Anomaly (Fraction) and HADISST Sea Ice Anomaly (%) for Jan 1983

(1966-1990 climatology)



COLA

GEORGE MASON UNIVERSITY

Mechanisms of Variability

	Internal	External
Weather:	1. Internal Dynamics of Atmosphere	• Boundary Condition of SST, Soil wetness, Snow, Sea ice, etc.
Climate: (seasonal-decadal)	2. Internal Dynamics of Coupled Ocean-Land-Atmospshere	• Solar, Volcanoes
Climate Change:	3. Internal Dynamics of Sun-Earth System	• Human effects: (Greenhouse gases, land use changes)

Daily, Intraseasonal, Seasonal, Interannual, and Decadal Variations

- **"Short range" weather variation**
  - Hours; thunderstorms, tornadoes, squall lines, fronts, ….
  - Diurnal cycle; Organized convection
  - "Cyclones", Eeasterly waves, Depressions, ….
- **"Medium range" weather variations**
  - Blocking; Growth, decay of tropical, tropospherical disturbances
- **Intraseaonal variations**
  - Madden Julian "Oscillation" (MJO), Monsoon Intraseasonal variations, Pacific North American (PNA) variations, Annular modes
- **Seasonal mean variations**
  - Persistent droughts; Floods; Persistent "hot" and "cold" days; "Anomalous" number and tracks of cyclones
- **Interannual variations**
  - ENSO, QBO, TBO, NAO, NAM, SAM
- **Decadal variations**
  - PDO, AMO, Thermohaline circulation, Sahel drought, Decadal ENSO
- **Climate change**
  - Solar, Volcanoes, Greenhouse gases, Land use change

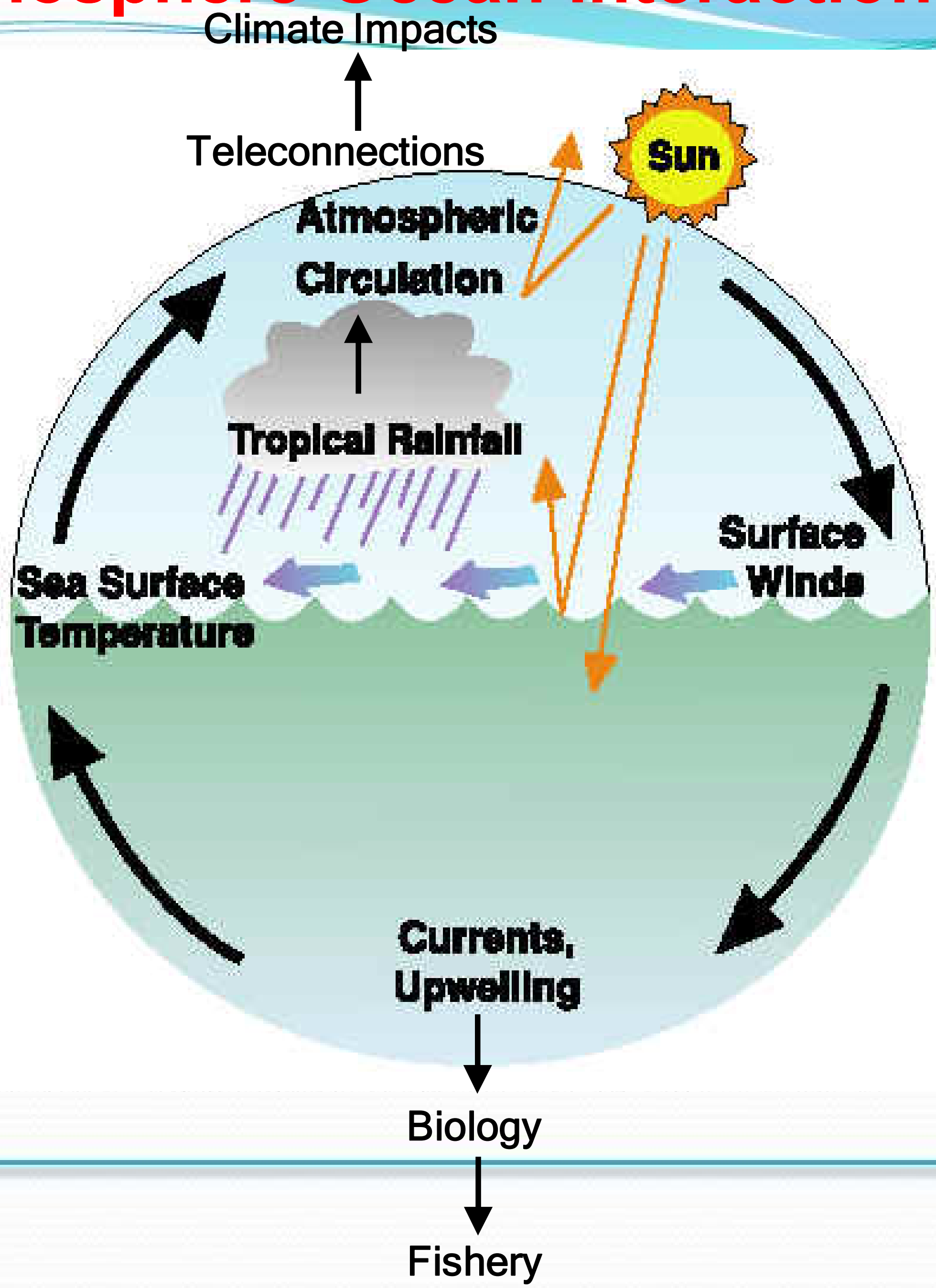
Patterns of Weather and Climate Variability

▪ **Tropics**	• **Organized convections, Hurricanes, Typhoons, Easterly waves, Monsoon depressions, Madden Julian "Oscillation" (MJO), QBO, Monsoons, ENSO, TBO, Droughts and floods, Hadley cell and Walker cell**
▪ **Extratropics**	• **Cyclones, Storms, Blocking, PNA, PDO, NAO, AMO, Ferrel cell**
▪ **Polar**	• **Arctic Oscillation (NAM), Antarctic Oscillation (SAM)**
▪ **Global**	• **Thermohaline circulation**

Examples of Weather and Climate Variability

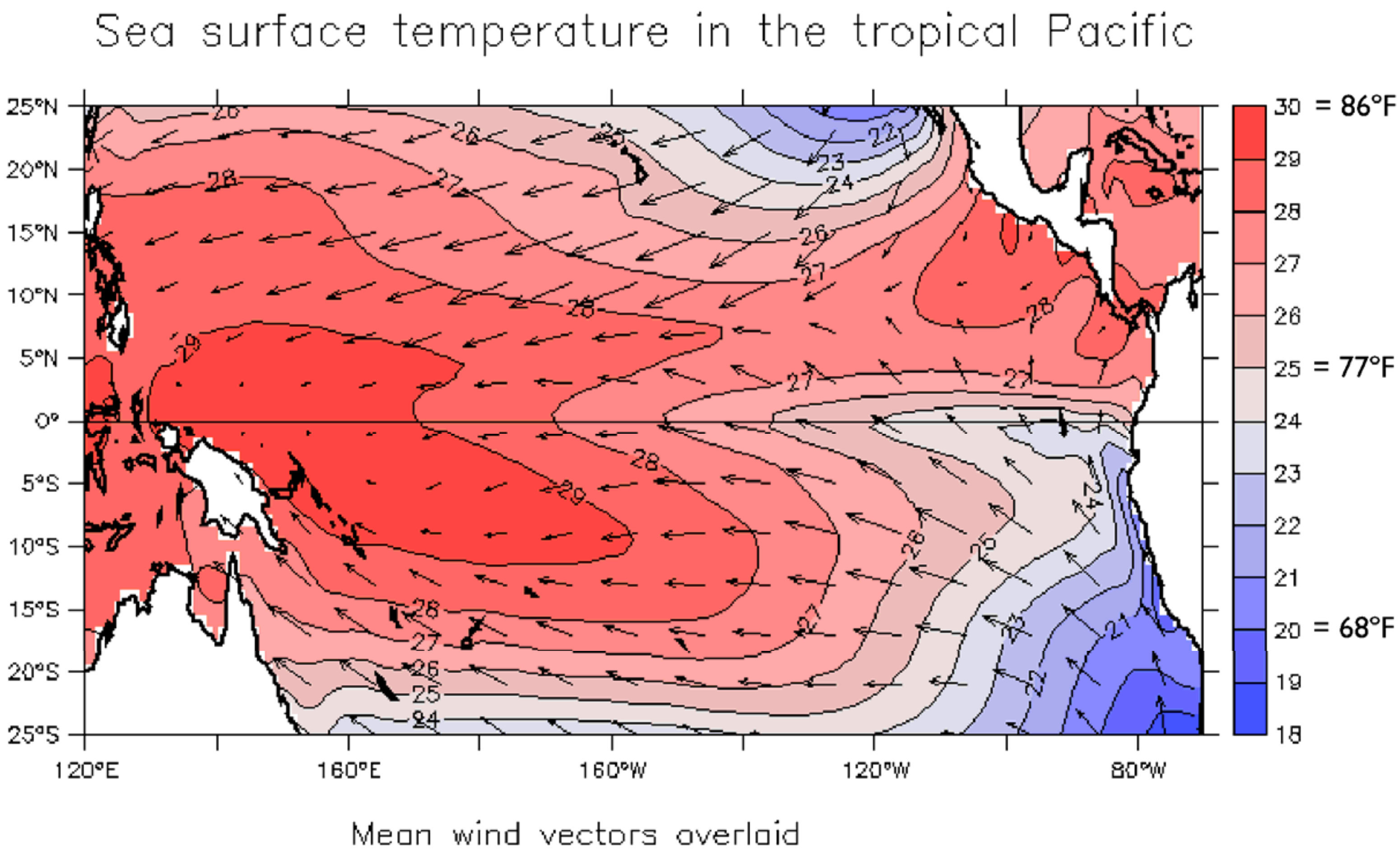
- **Annual Cycle**
- **Daily Weather**
- **Seasonal Climate**
- **Interannual (ENSO)**
- **Decadal**
- **Centennial (Climate Change)**

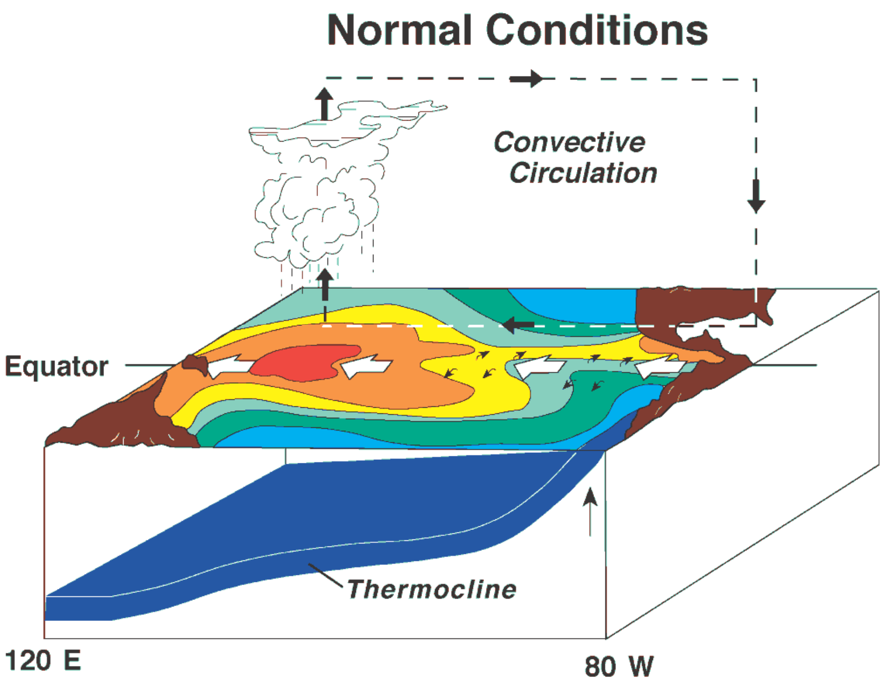
Atmosphere-Ocean Interaction

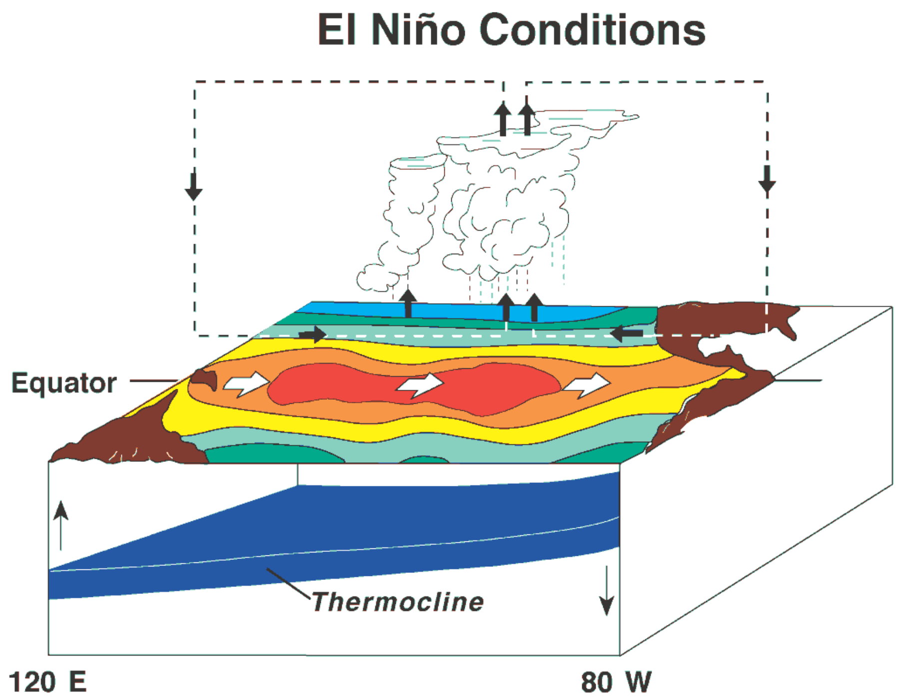


The normal situation:

- The warmest water is not at the equator!
- There is a roughly 5°C (9°F) temperature contrast from west to east.
- Winds blow from the cooler to the warmer water, and converge on the West Pacific Warm Pool.

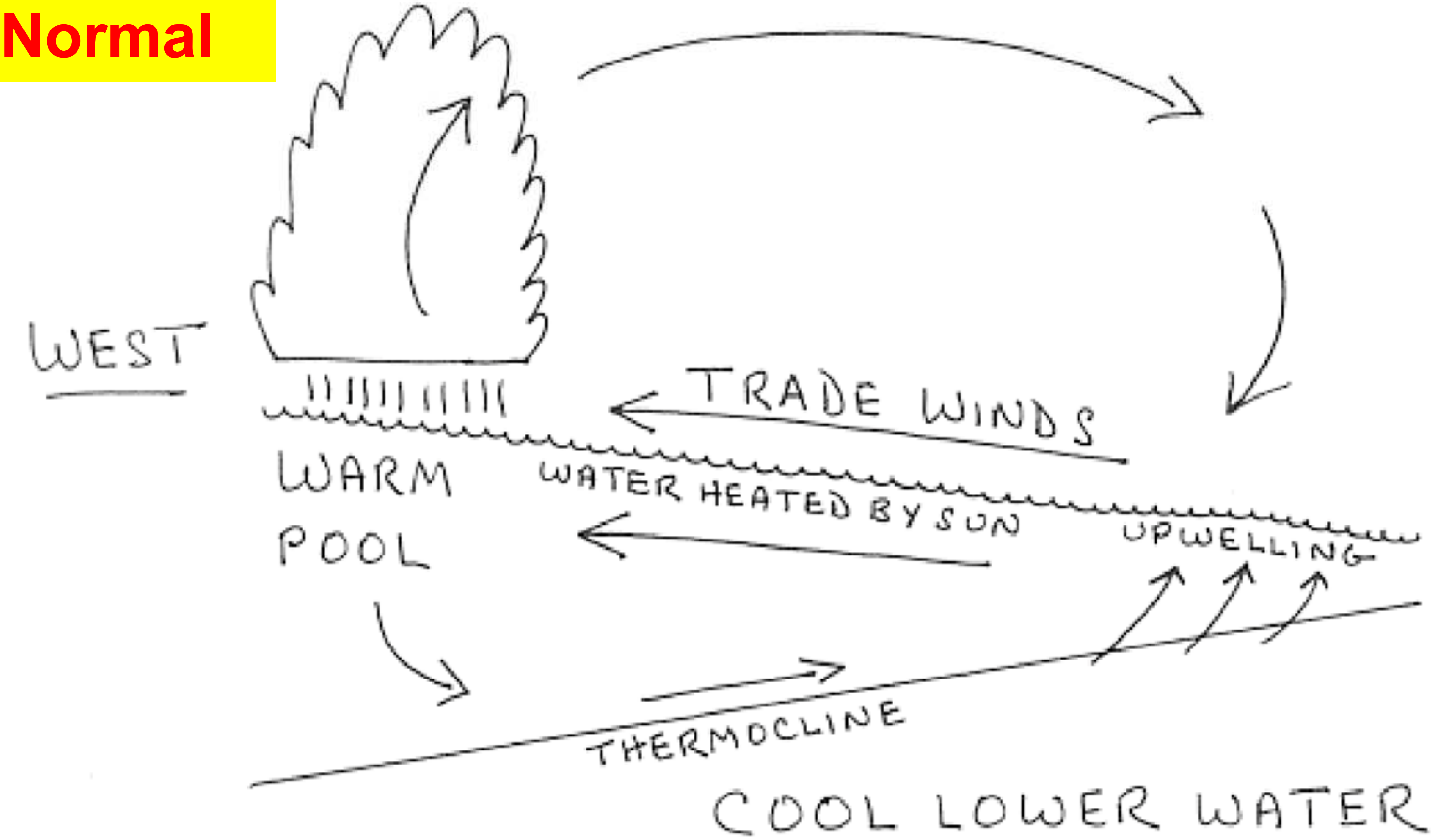



Normal Conditions
Convective Circulation
Equator
Thermocline
120 E
80 W


El Niño Conditions
Equator
Thermocline
120 E
80 W

Schematic diagram of the coupled interaction along the Pacific equator

Normal



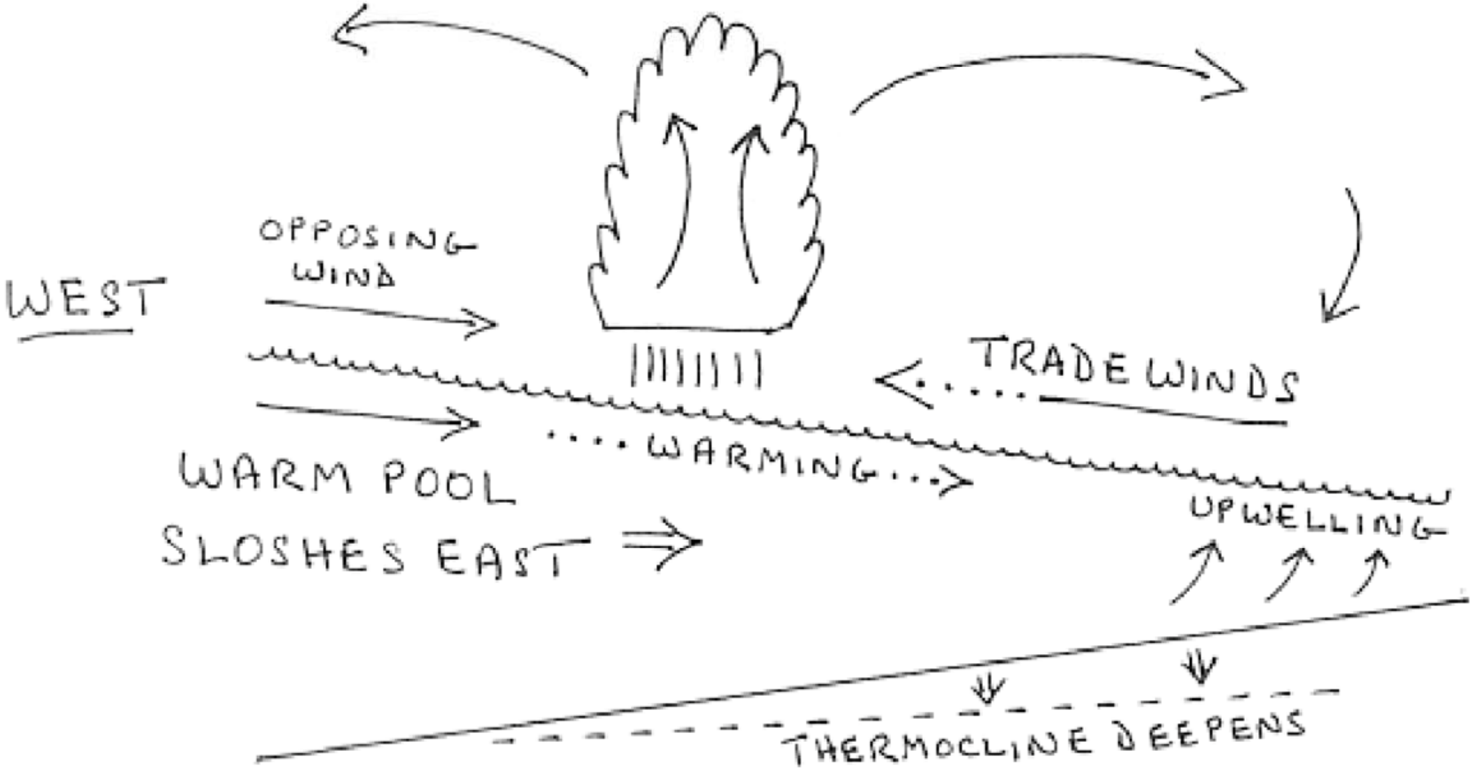
Why are there trade winds? Because the warmest water is in the west.

Why is the warmest water in the west? Because there are trade winds.

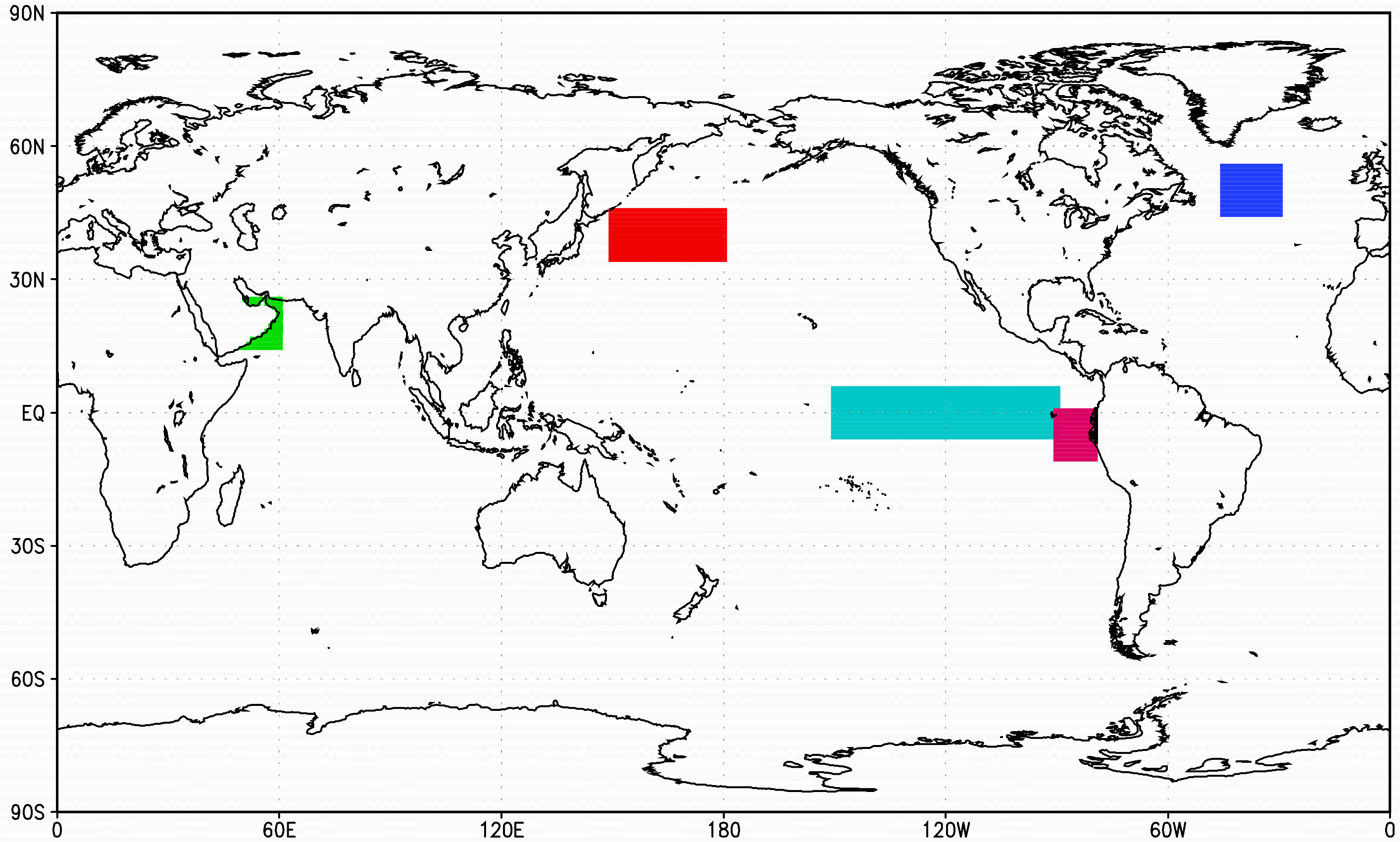
Schematic ocean-atmosphere interaction during El Niño onset:

A "coupled collapse" as the warm pool sloshes east

El Nino

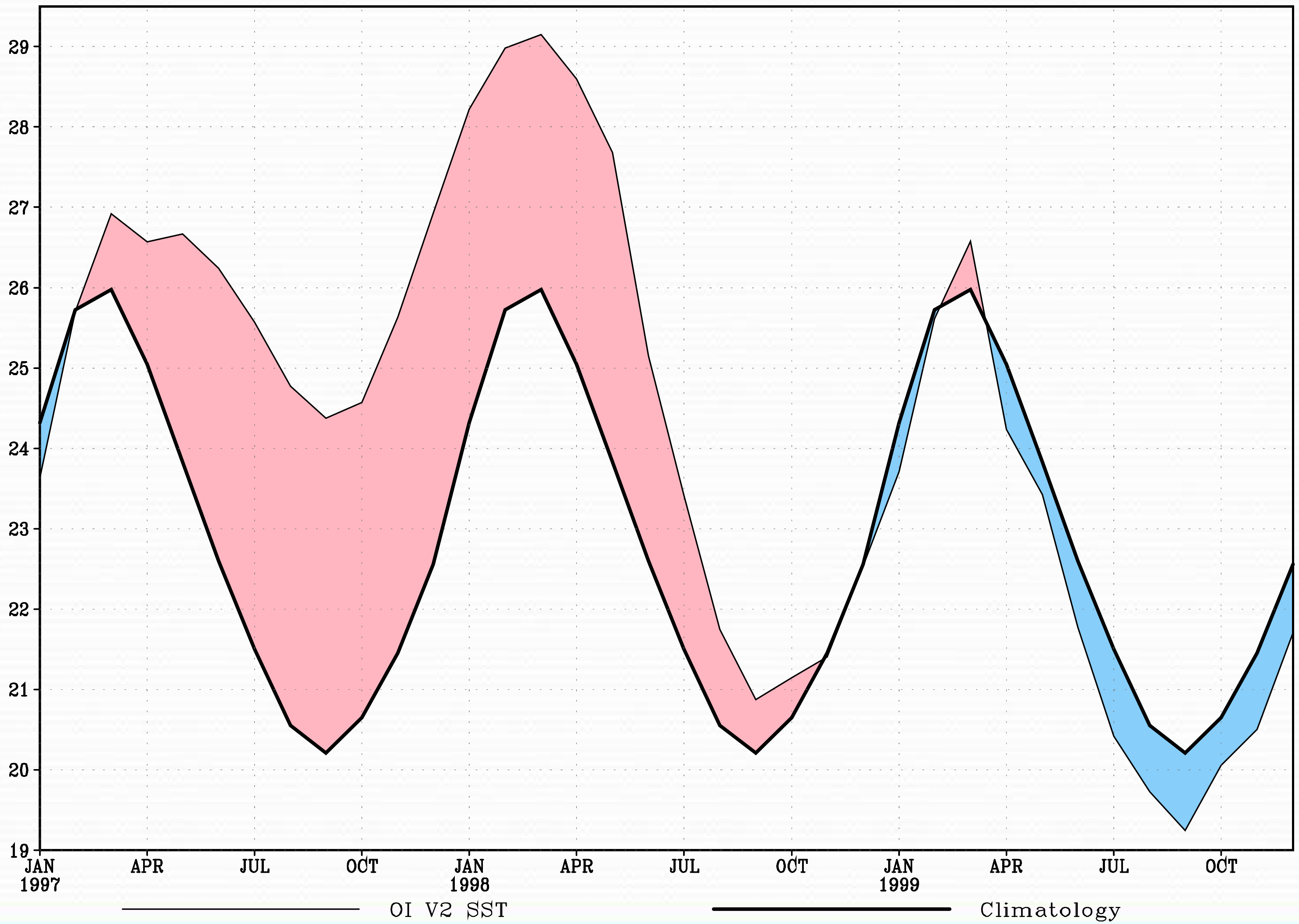


We don't know why El Niños start!


90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0

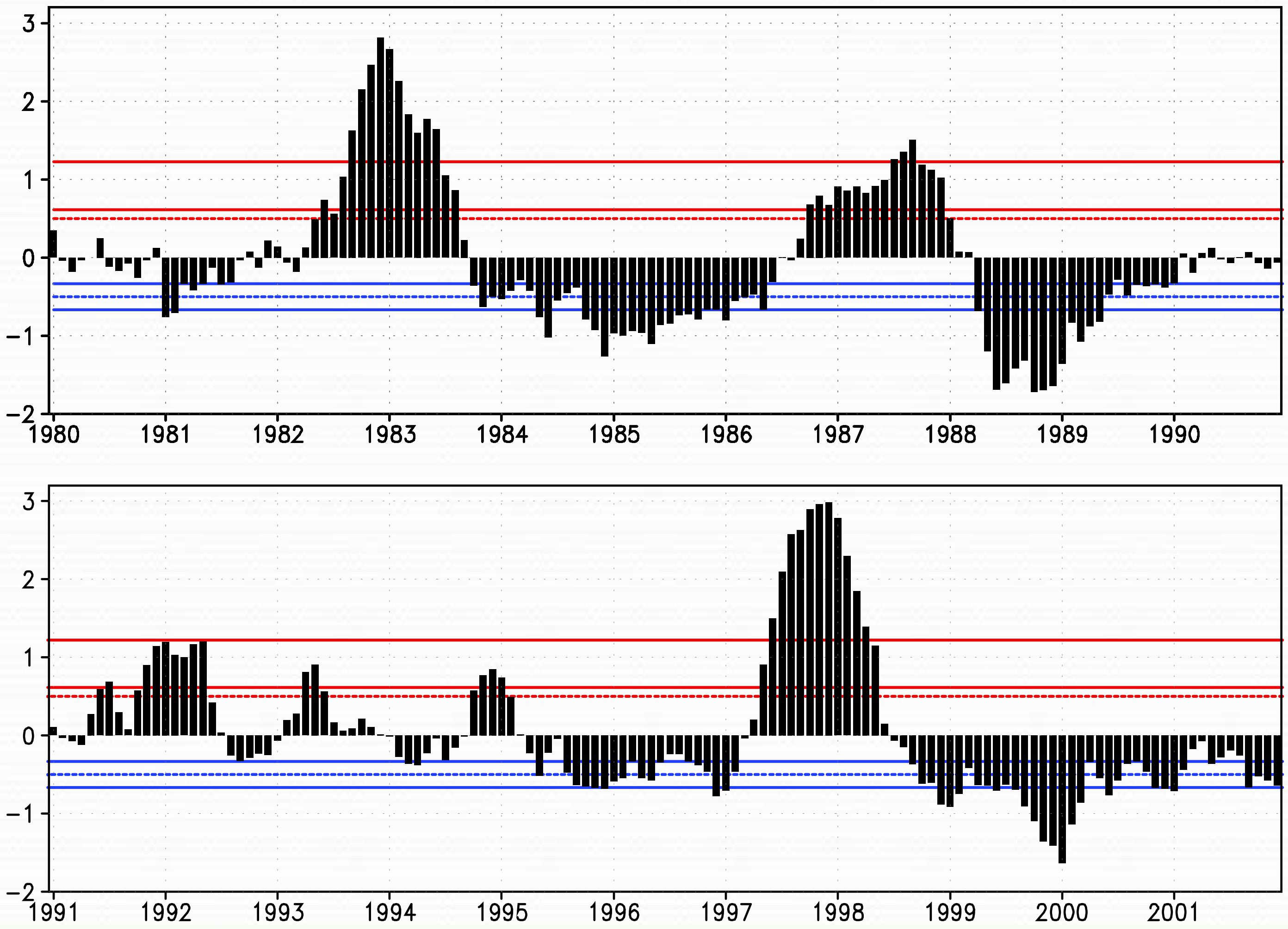
Sea Surface Temperature and Climatology

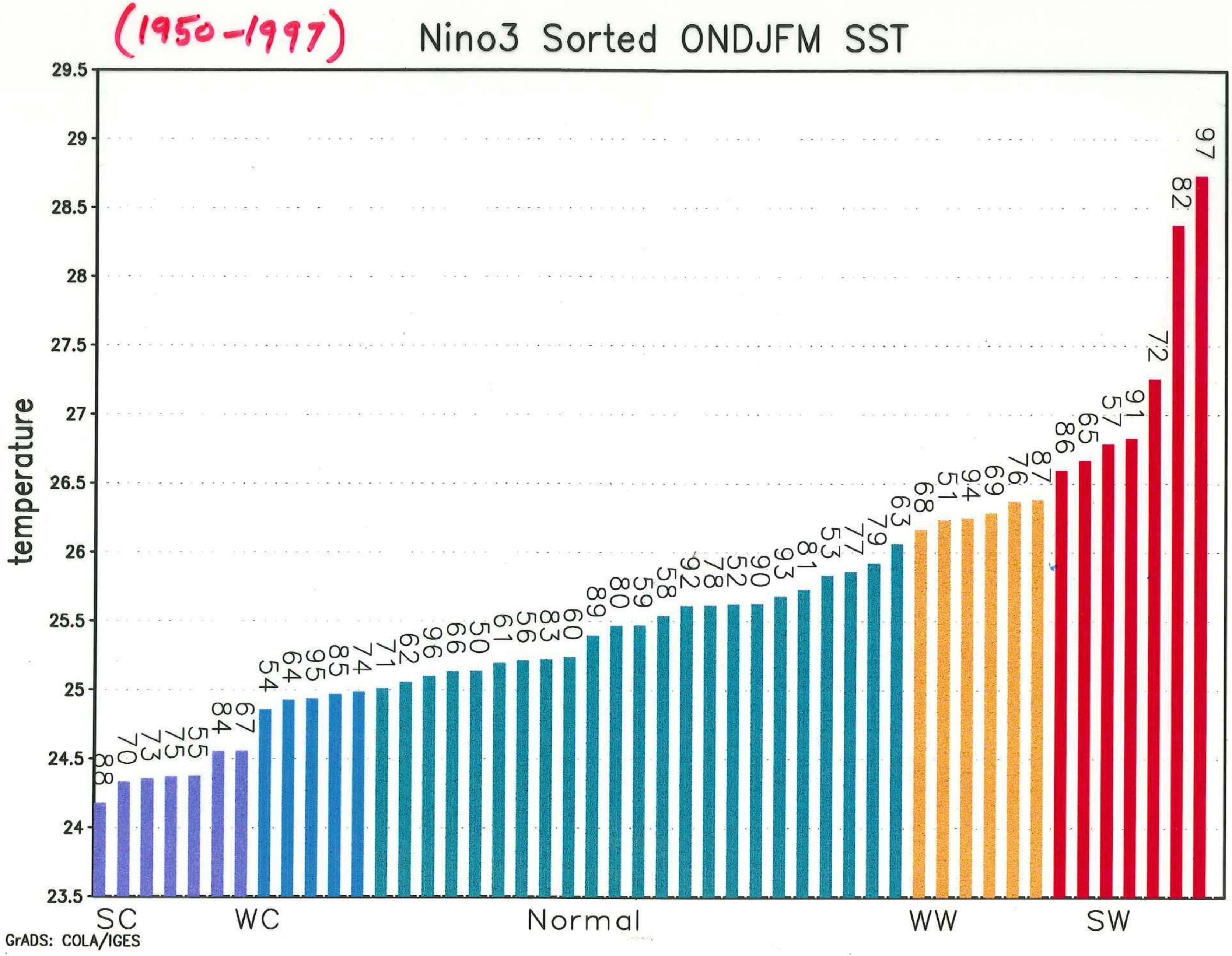
(NINO12, 90°-80°W, 10°S-Eq.)



Interannual Variability of Tropical Pacific SSTA

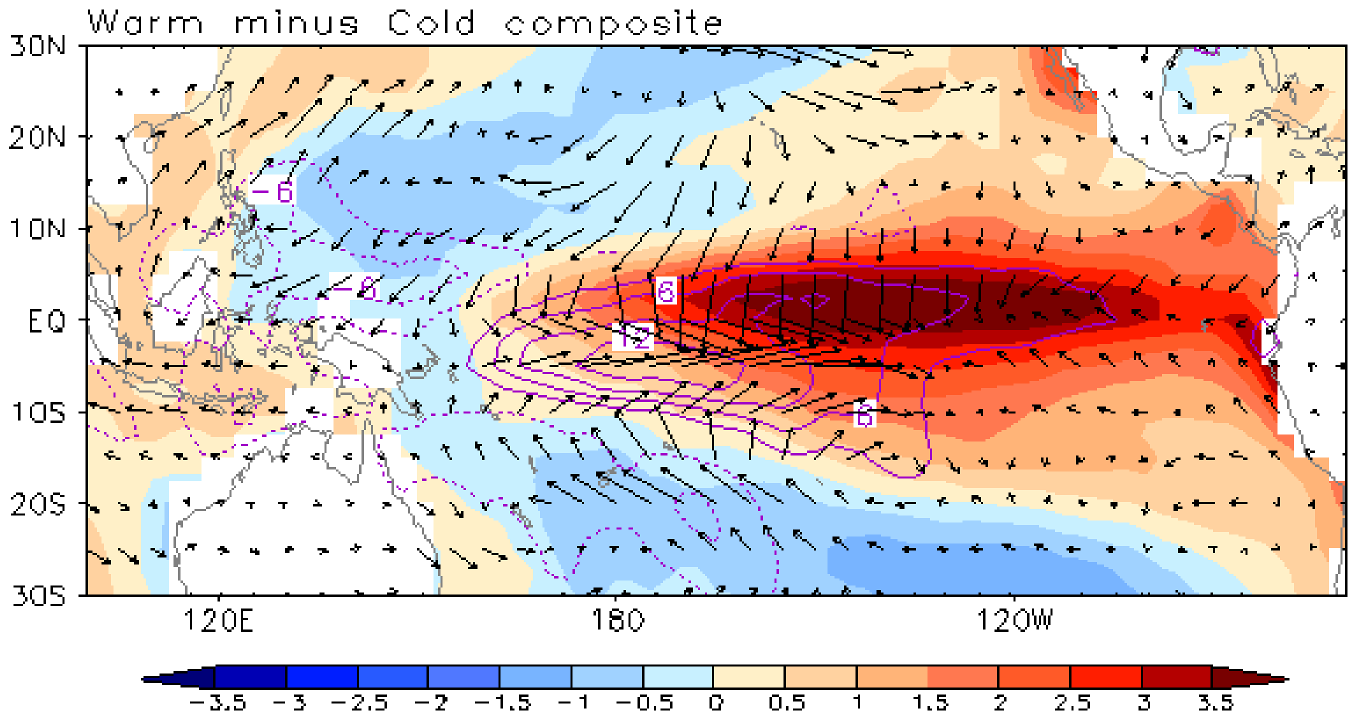
(NINO3, 150°-90°W, 5°S-5°N)

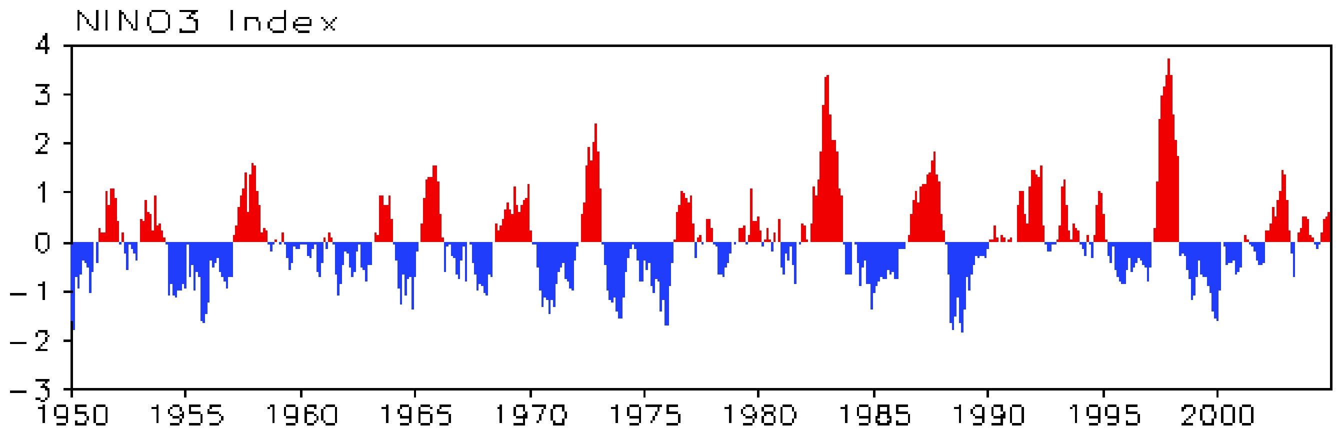




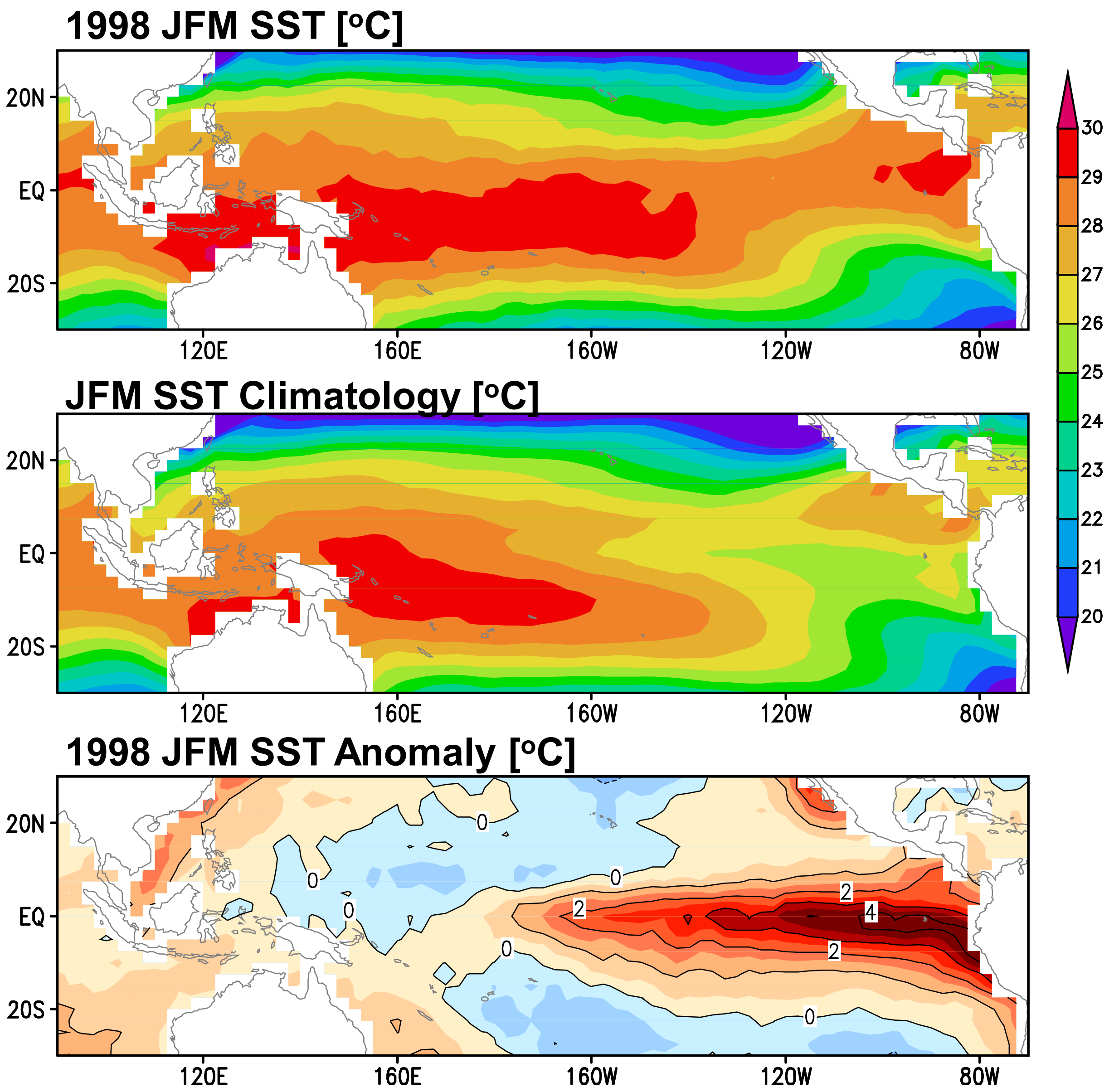
(1950-1997)
Nino3 Sorted ONDJFM SST
temperature
29.5
29
28.5
28
27.5
27
26.5
26
25.5
25
24.5
24
23.5
88
70
73
75
55
84
67
54
64
95
85
74
71
62
96
66
50
61
56
83
60
89
80
59
58
92
78
52
90
93
81
53
77
79
63
68
51
94
69
76
87
86
65
57
91
72
82
97
SC
WC
Normal
WW
SW
GrADS: COLA/IGES

El Nino/Southern Oscillation





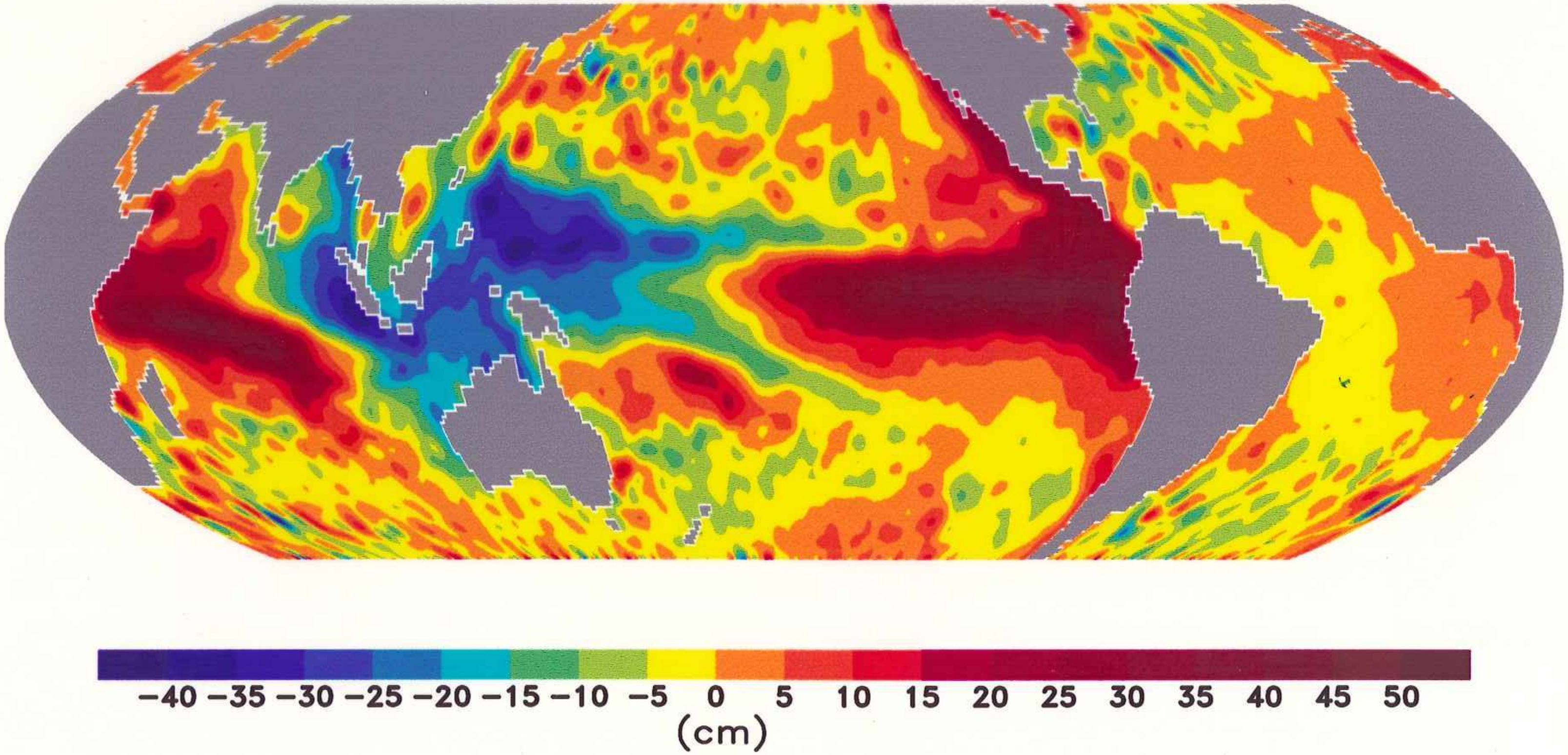
El Nino/Southern Oscillation

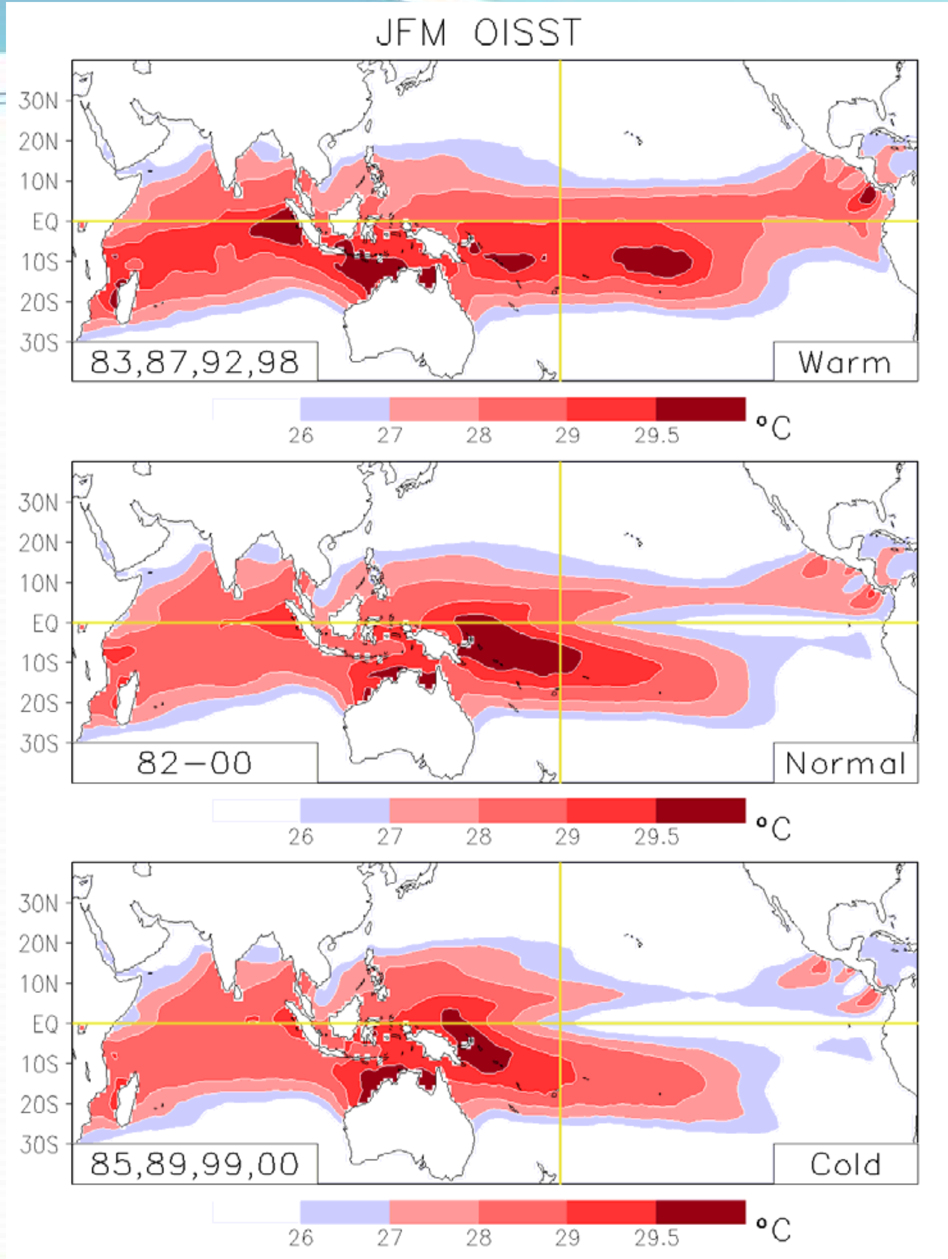


Laboratory for Hydrospheric Processes
http://nsipp.gsfc.nasa.gov

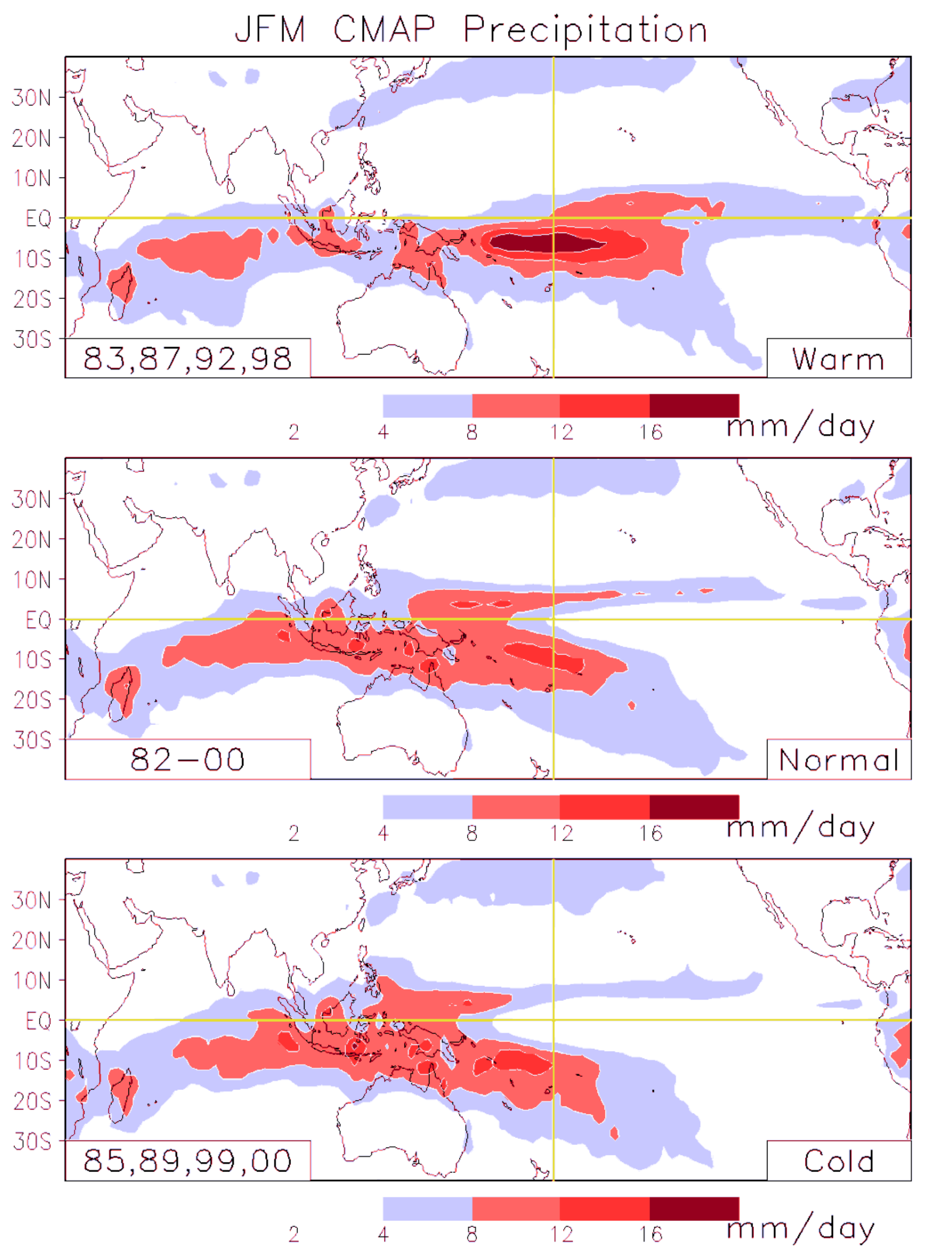
TOPEX/Poseidon Sea Level

Dec 1997 minus Dec 1998





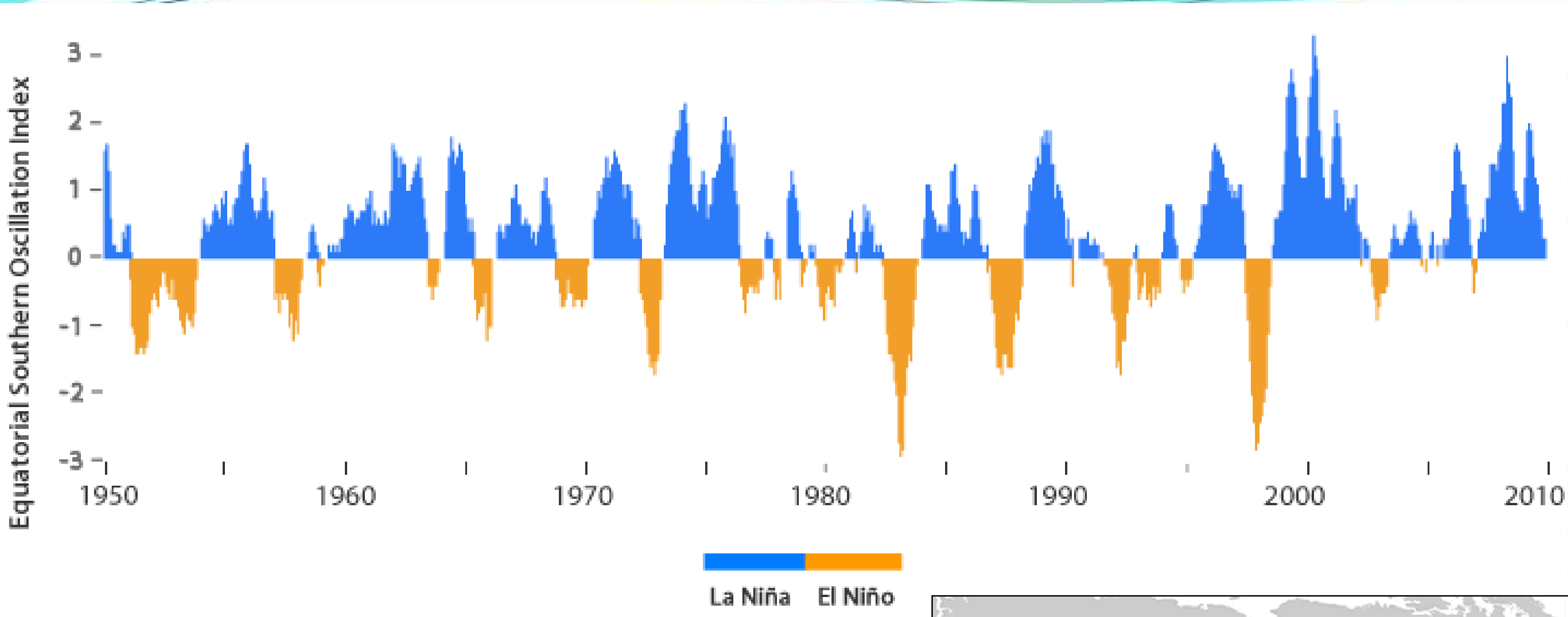
JFM OISST
30N
20N
10N
EQ
10S
20S
30S
83,87,92,98
Warm
26
27
28
29
29.5
°C
82–00
Normal
85,89,99,00
Cold

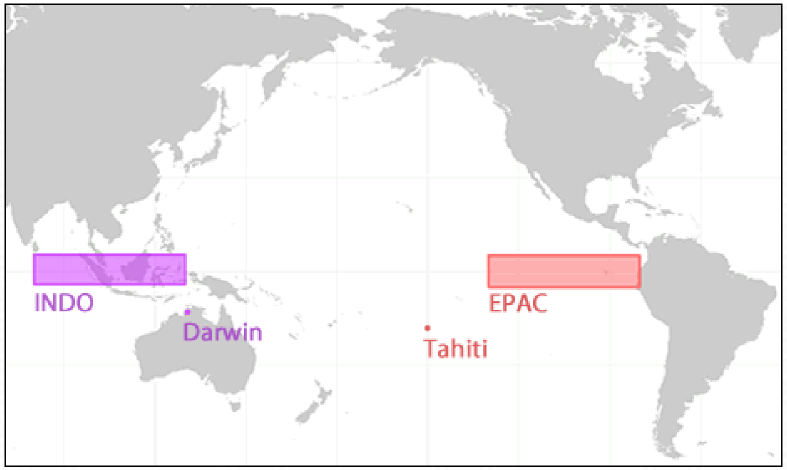


COLA
Center for Ocean-Land-Atmosphere Studies

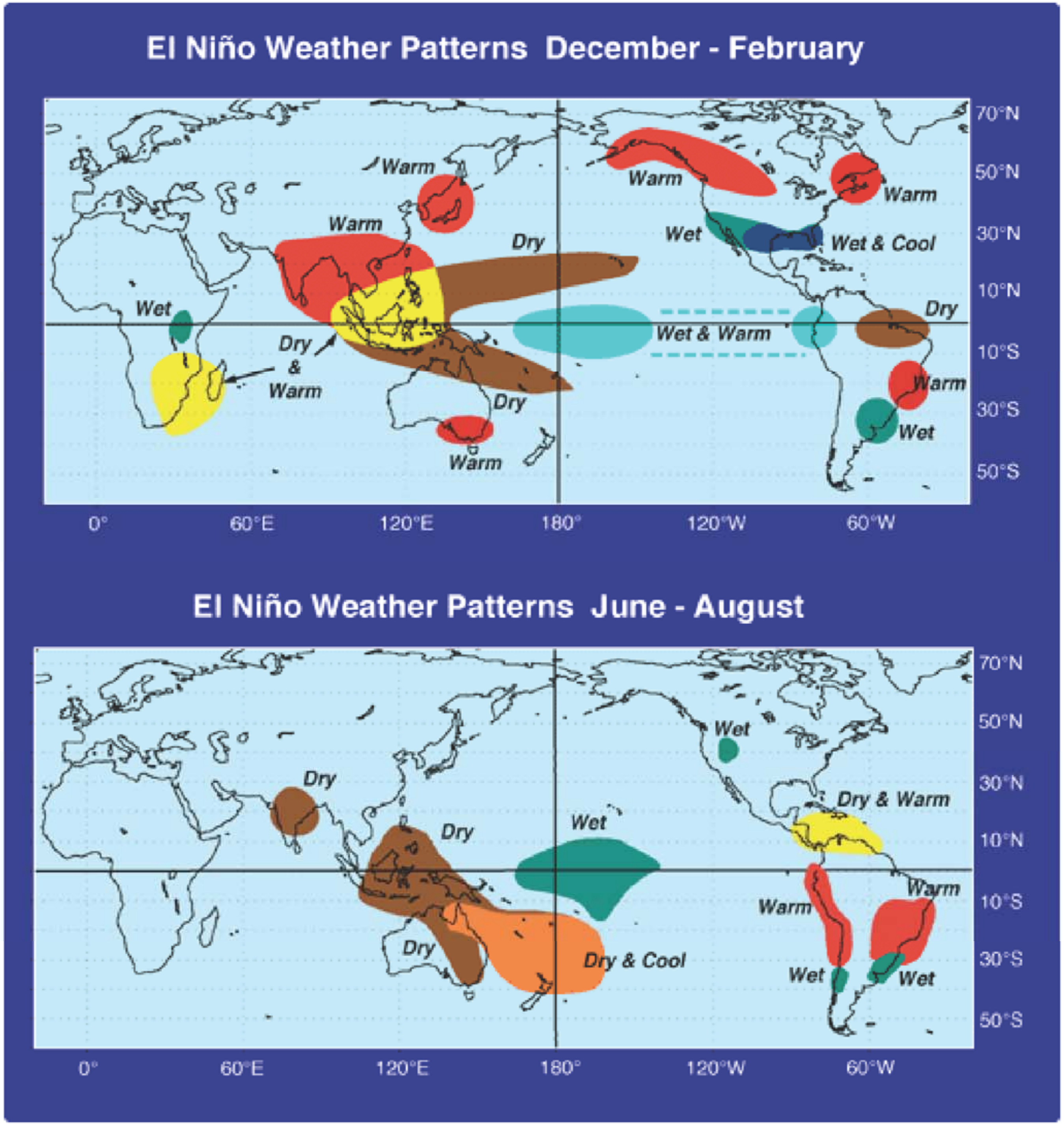
GEORGE MASON UNIVERSITY

Equatorial Southern Oscillation Index



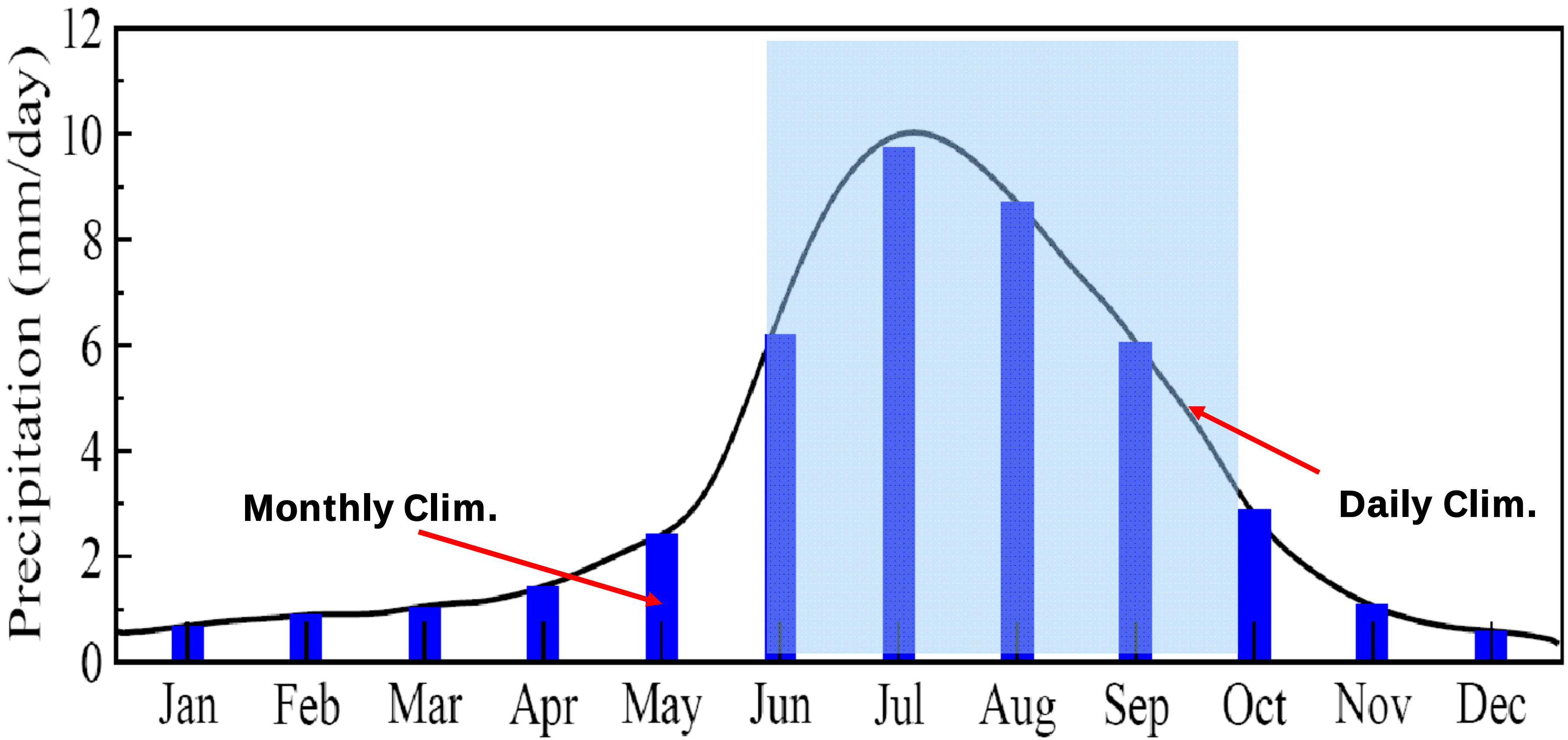


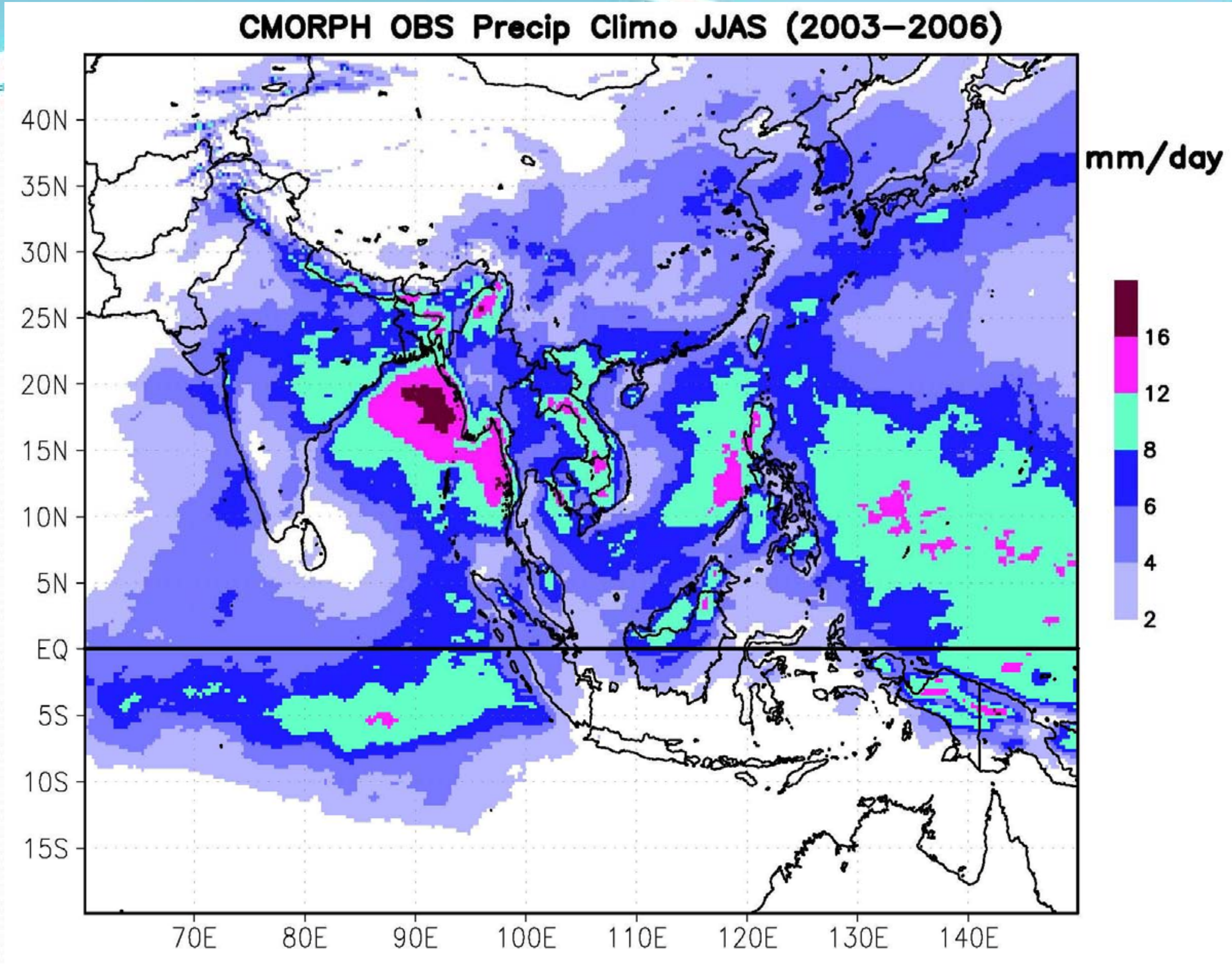
Similarly, the Equatorial Southern Oscillation Index or EQSOI represents the difference in air pressure measured over the eastern and western Pacific. The EQSOI is calculated as the difference in standardized mean sea level pressure over a swath of the eastern equatorial Pacific Ocean (5°N-5°S, 80°W-130°W) and another swath that spans Indonesia (5°N-5°S, 90°E-140°E).


El Niño Weather Patterns December - February
Warm
Warm
Warm
Warm
Dry
Wet
Wet & Cool
Wet
Dry & Warm
Wet & Warm
Dry
Dry
Warm
Wet
Warm
70°N
50°N
30°N
10°N
10°S
30°S
50°S
0°
60°E
120°E
180°
120°W
60°W
El Niño Weather Patterns June - August
Wet
Dry
Dry & Warm
Dry
Wet
Warm
Warm
Dry
Dry & Cool
Wet
Wet
70°N
50°N
30°N
10°N
10°S
30°S
50°S
0°
60°E
120°E
180°
120°W
60°W

ENSO-Monsoon

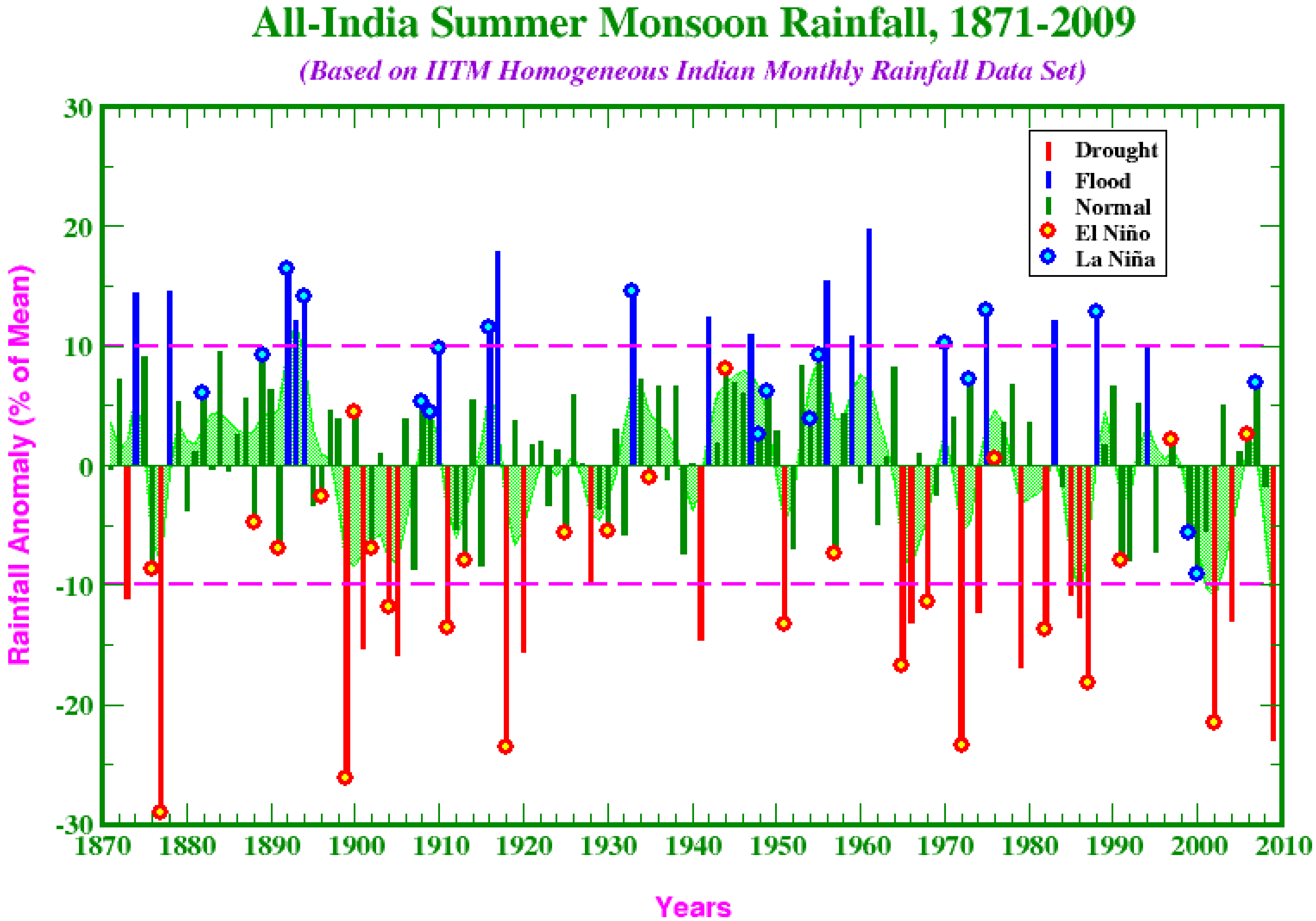
Annual cycle of Rainfall over India




CMORPH OBS Precip Climo JJAS (2003–2006)
mm/day
16
12
8
6
4
2
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
70E
80E
90E
100E
110E
120E
130E
140E

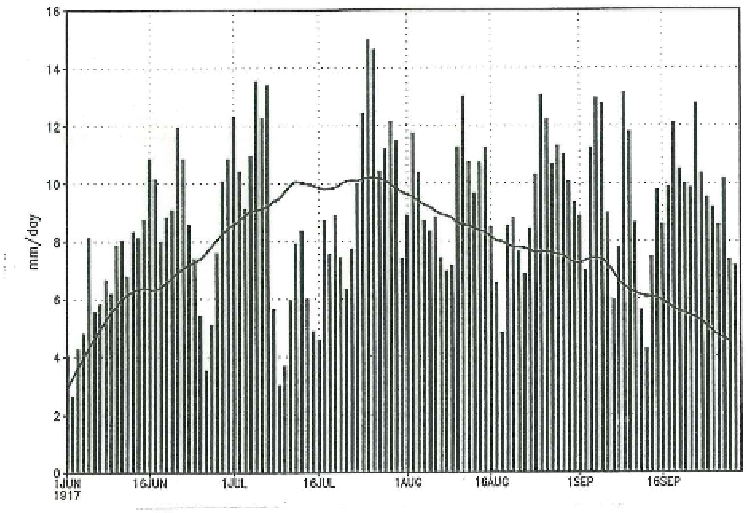
All-India Summer Monsoon Rainfall (1871-2009)

(based on IITM homogeneous Indian Monsoon Rainfall dataset)

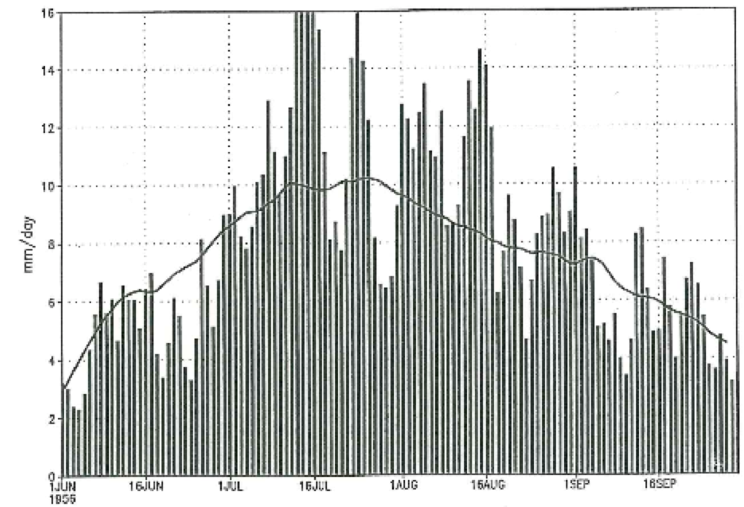


This figure shows the time series evolution of AISMR anomalies, expressed as percent departures from its long-term mean.

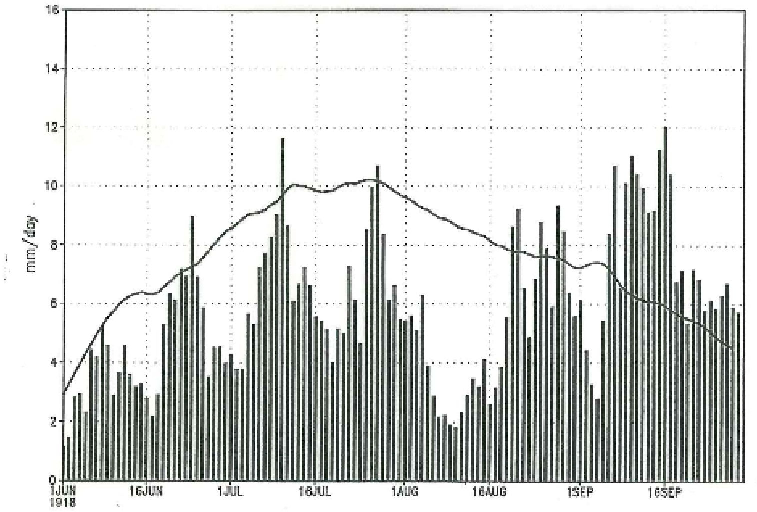
Composite All–India (land) Rainfall – 1917 (La Nina)



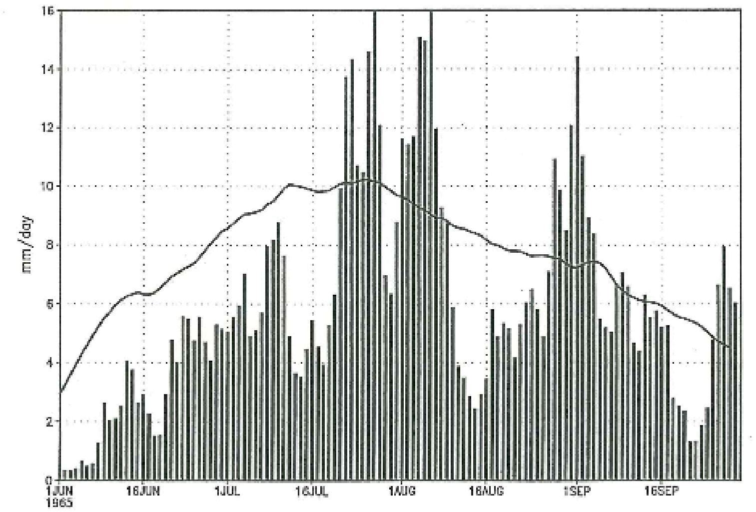
Composite All–India (land) Rainfall – 1956 (La Nina)



Composite All-India (land) Rainfall – 1918 (El Nino)



Composite All-India (land) Rainfall – 1965 (El Nino)



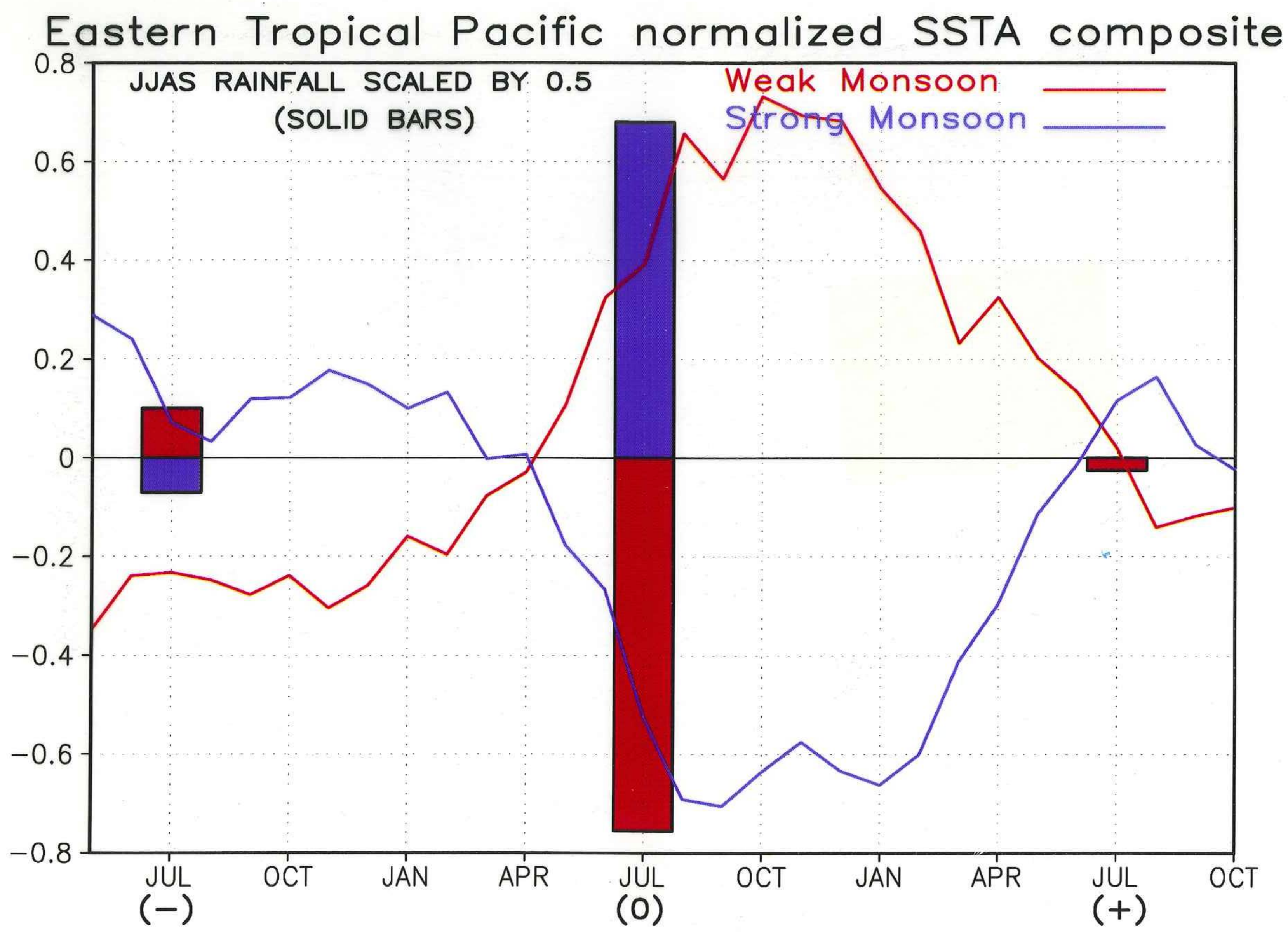
JJAS All India Rainfall

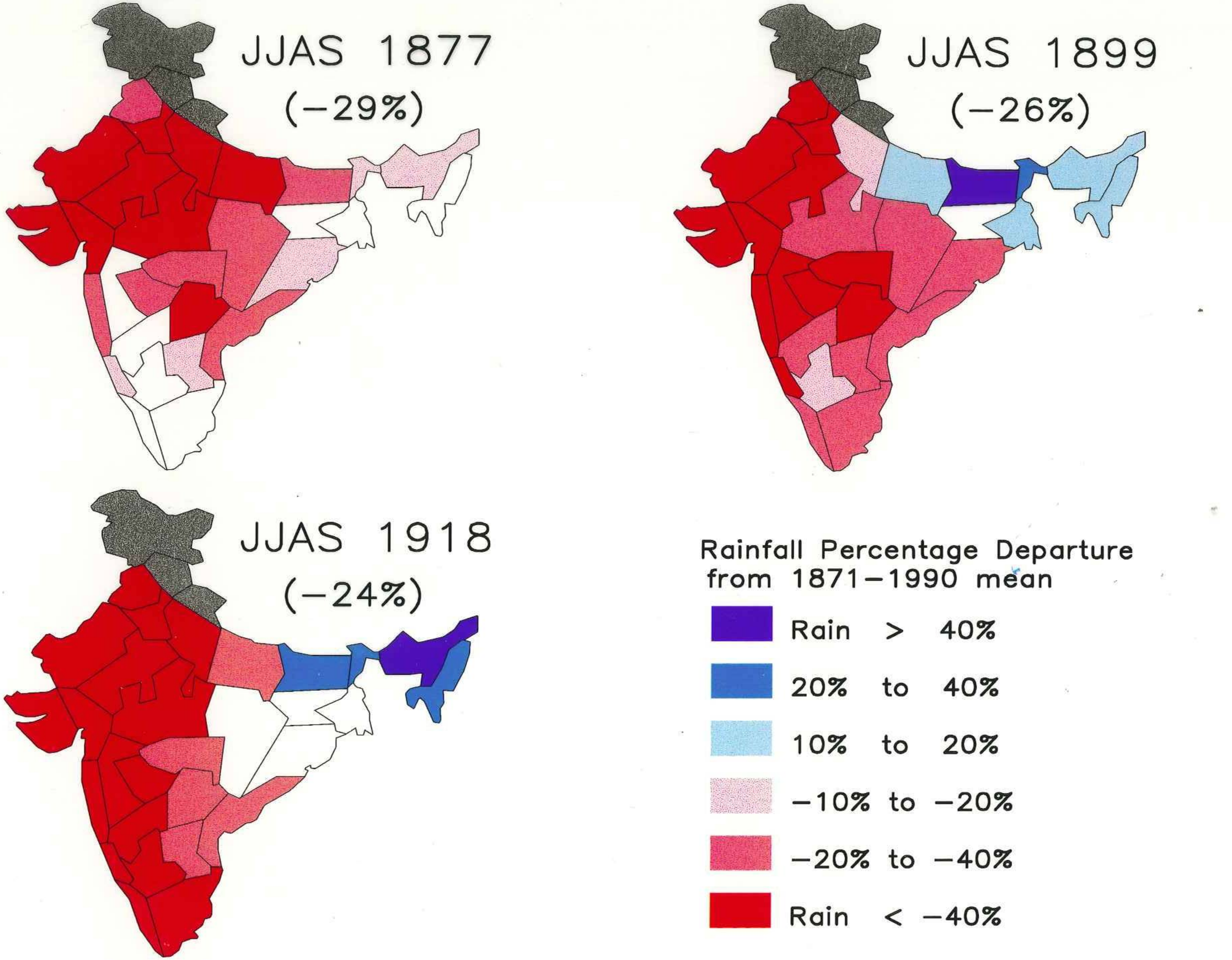
Strong Monsoon Years (> 1 SDEV)	Weak Monsoon Years (< 1 SDEV)
1916	1904
1917	1905
1933	1911
1942	1918
1947	1920
1956	1928
1959	1941
1961	1951
1970	1965
1975	1966
	1968
	1972
	1974

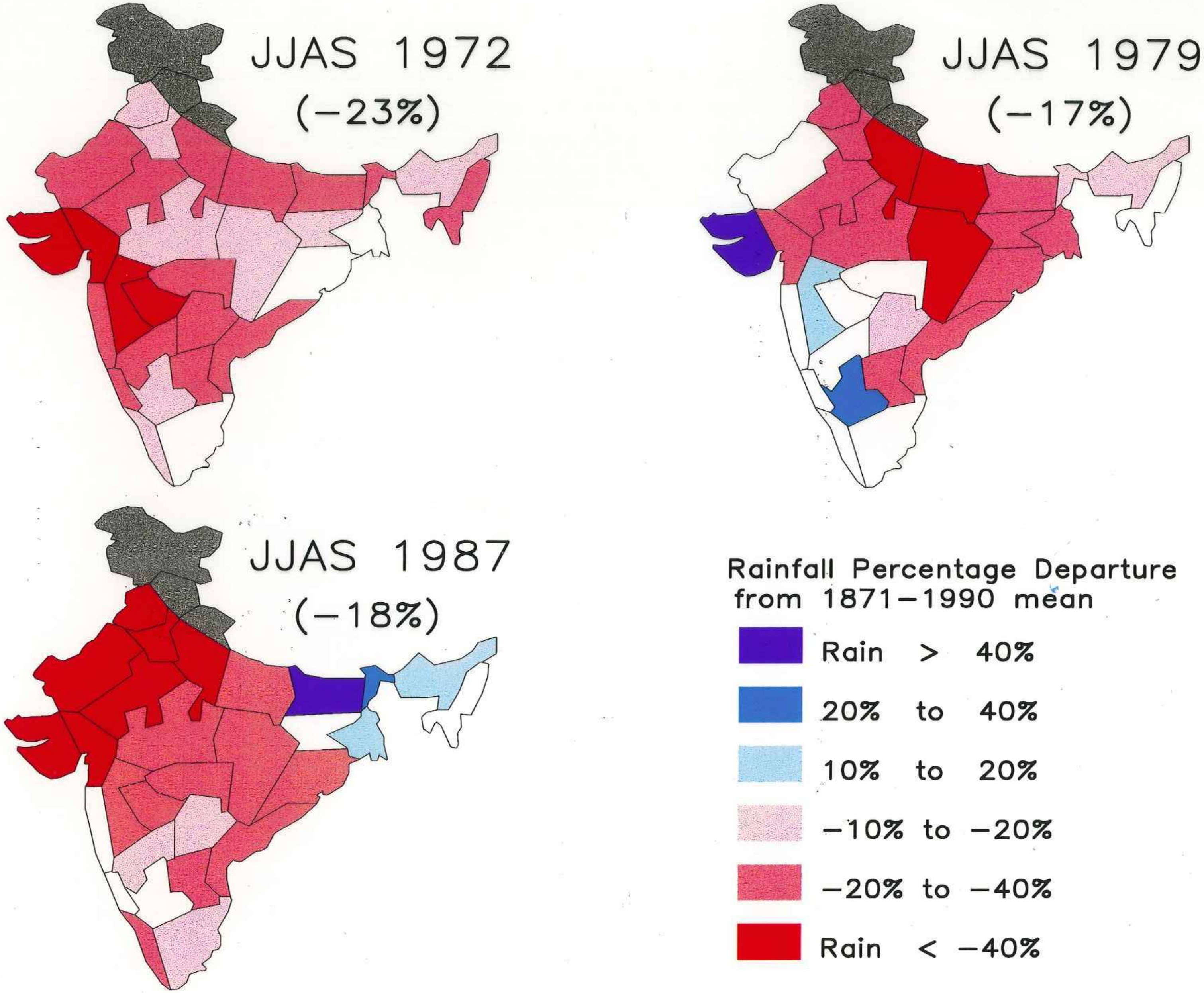
SST Composites:

Eastern Tropical Pacific: 160°E - 80°W, 10°S - 10°N

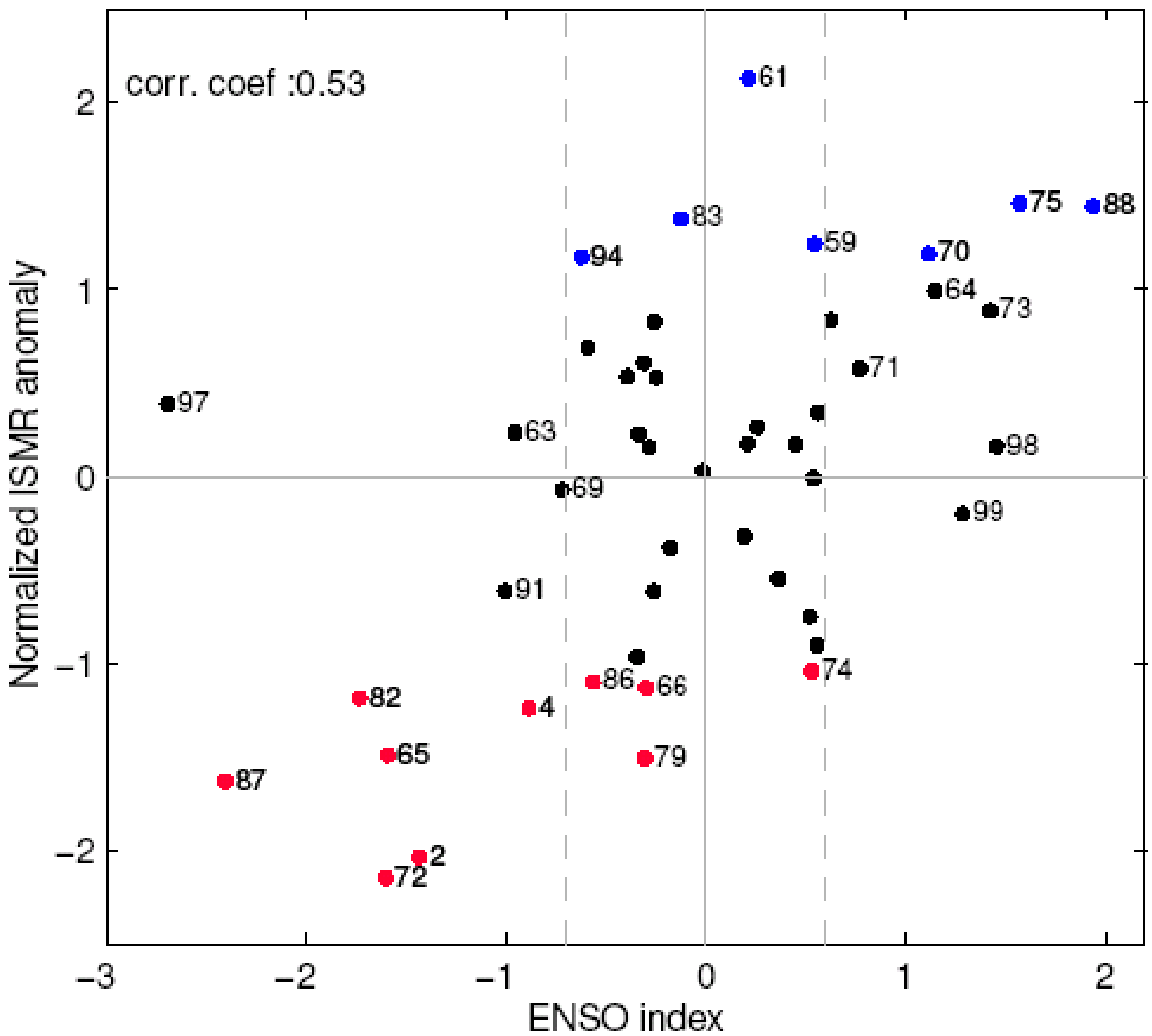
North Indian Ocean: 40 - 100°E, equator - coast


Eastern Tropical Pacific normalized SSTA composite
JJAS RAINFALL SCALED BY 0.5
(SOLID BARS)
Weak Monsoon
Strong Monsoon
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
JUL
(−)
OCT
JAN
APR
JUL
(0)
OCT
JAN
APR
JUL
(+)
OCT


JJAS 1877
(−29%)
JJAS 1899
(−26%)
JJAS 1918
(−24%)
Rainfall Percentage Departure
from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%


JJAS 1972
(−23%)
JJAS 1979
(−17%)
JJAS 1987
(−18%)
Rainfall Percentage Departure
from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%

ENSO and Monsoon rainfall over India



No droughts

when ENSO index >1

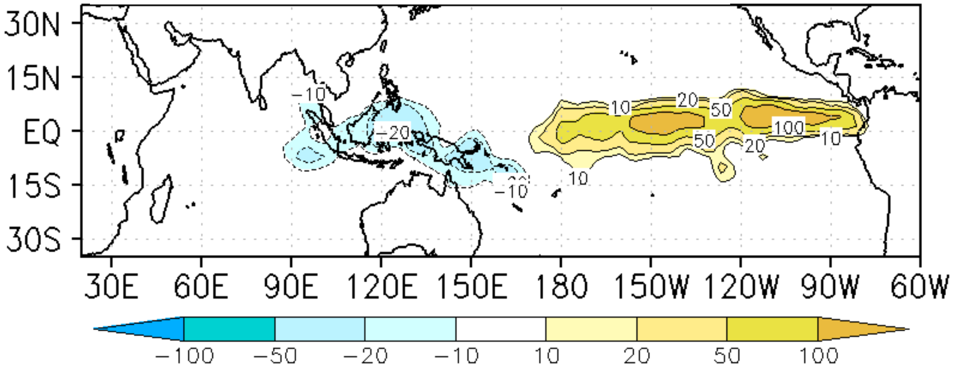
No excess rainfall

when ENSO index < -1

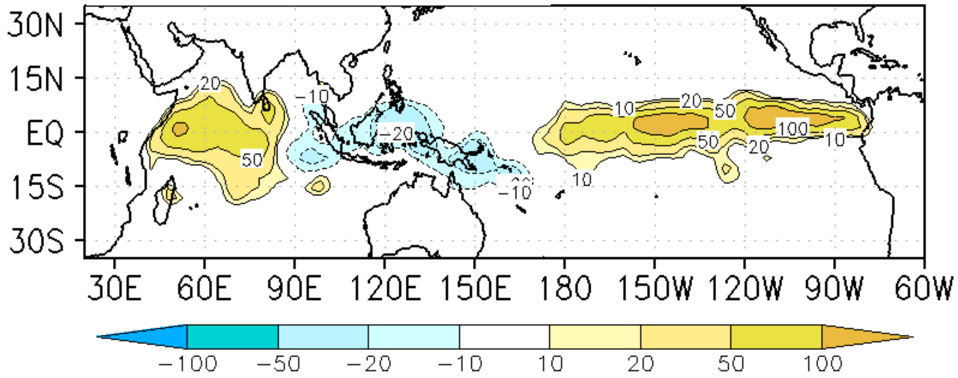
But several extremes when -1< ENSO Index < 1

Pacific Only vs. Pacific + Indian Ocean

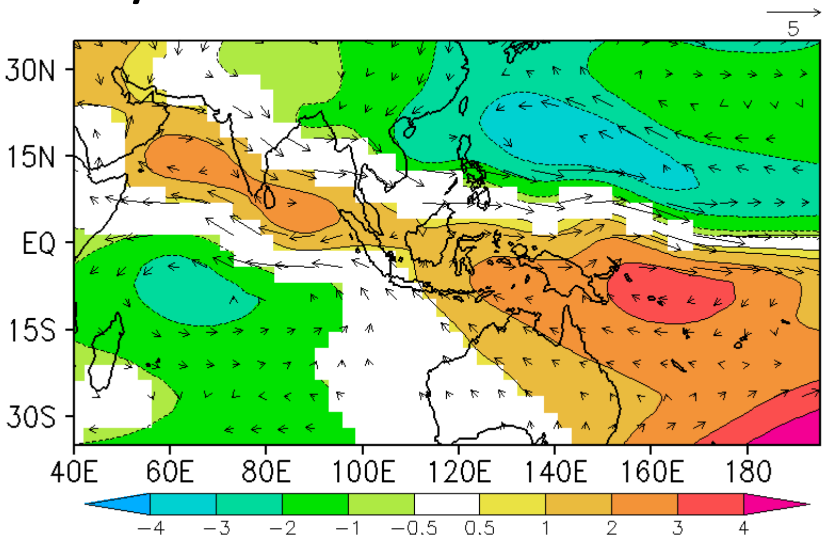
- **1997 Pacific forcing(only) W/m²**



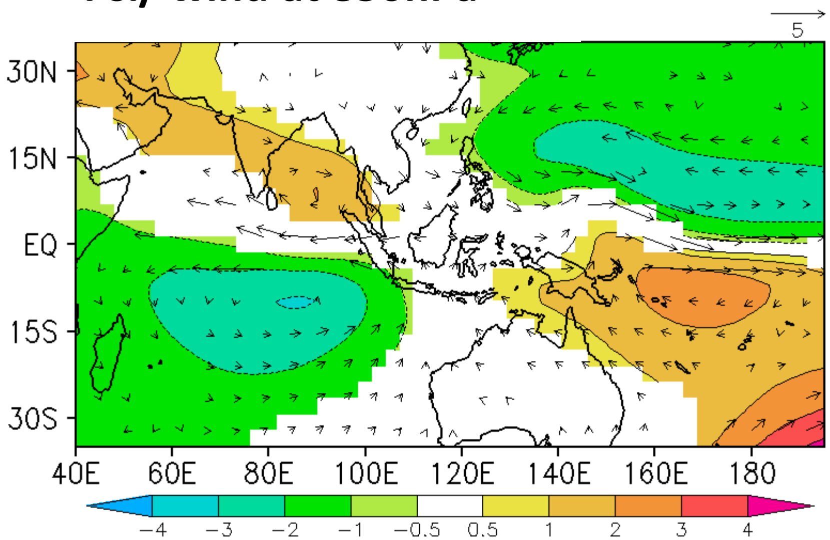
- **1997 Pacific + IO forcing W/m²**



- **Response:**
  Psi/ wind at 850hPa



- **Response:**
  Psi/ wind at 850hPa

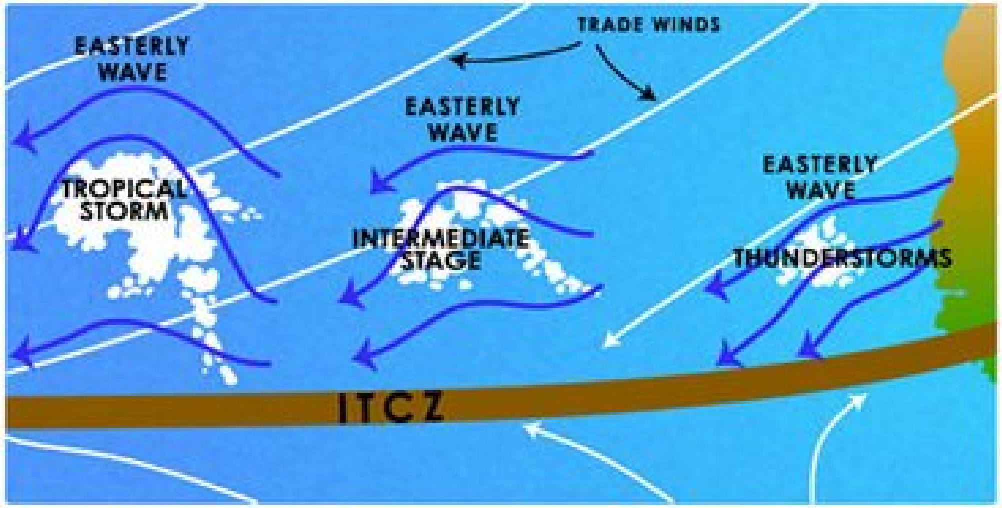


Easterly Waves (Africa)

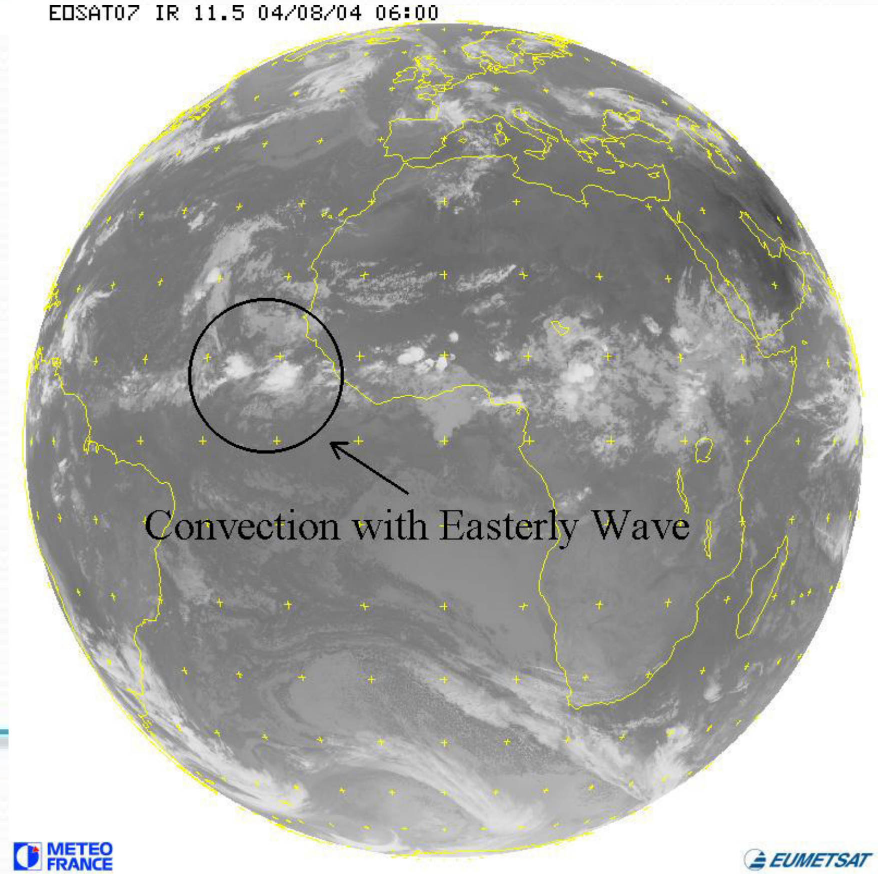
MJO

Monsoon Depressions

Hurricanes/Typhoons



Westward propagating easterly waves



COLA
Center for Ocean-Land-Atmosphere Studies

Westward propagating easterly waves

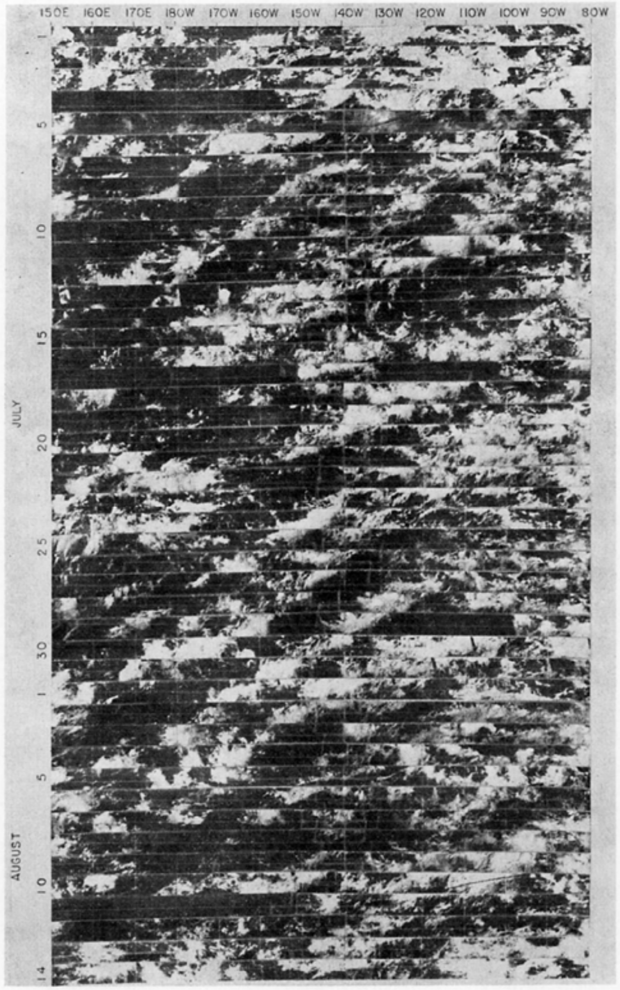


FIG. 1. Time-longitude section of satellite photographs of the period 1 July–14 August 1967 for the 5–10N latitude band in the Pacific. The following data are missing: 4 July (150E–155W), 17 July (150E–150W, 130W-100W), 29 July (130W–100W), 11 August (150E–150W).

Chang, 1970

Eastward propagating MJO (composite rainfall)

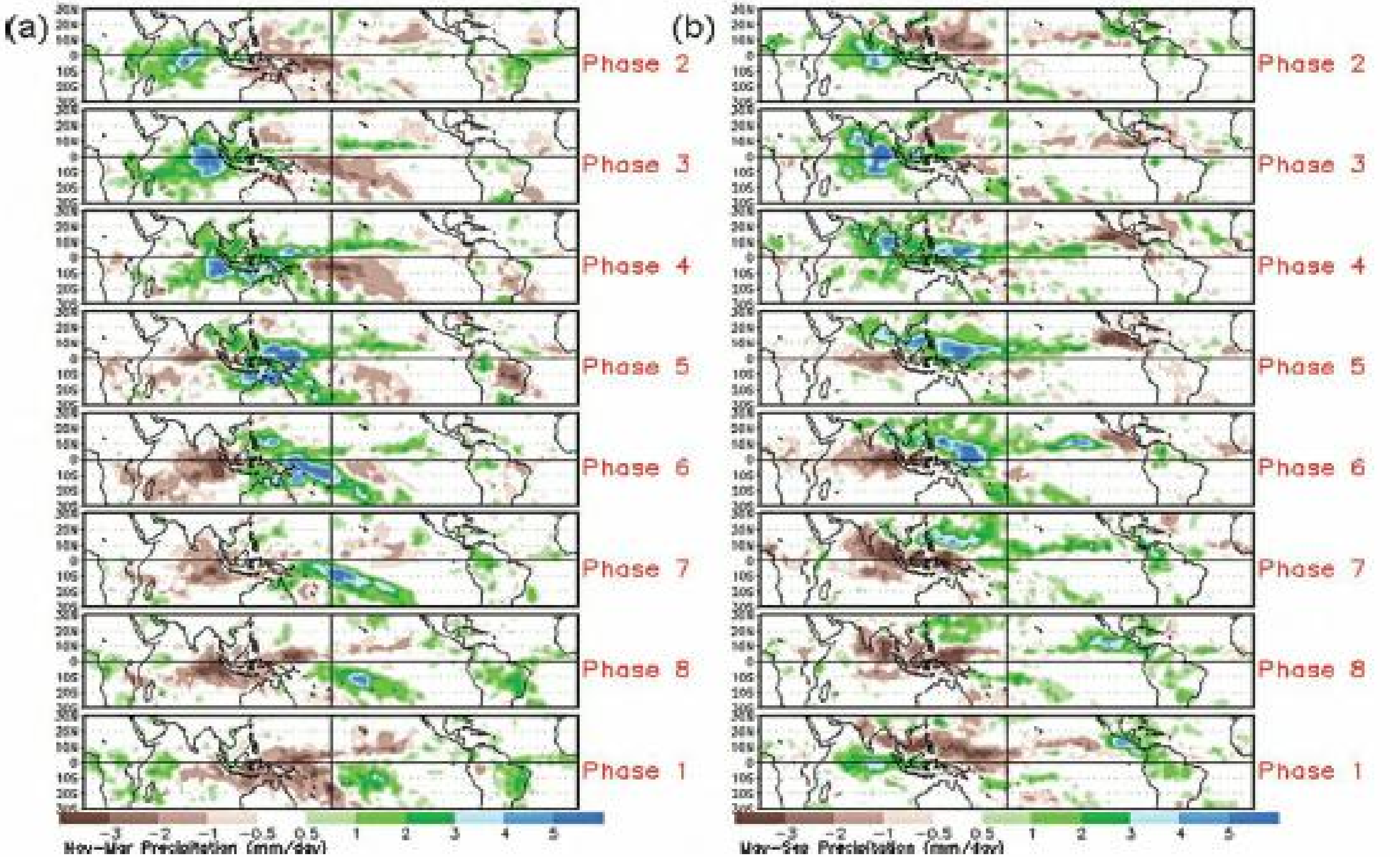
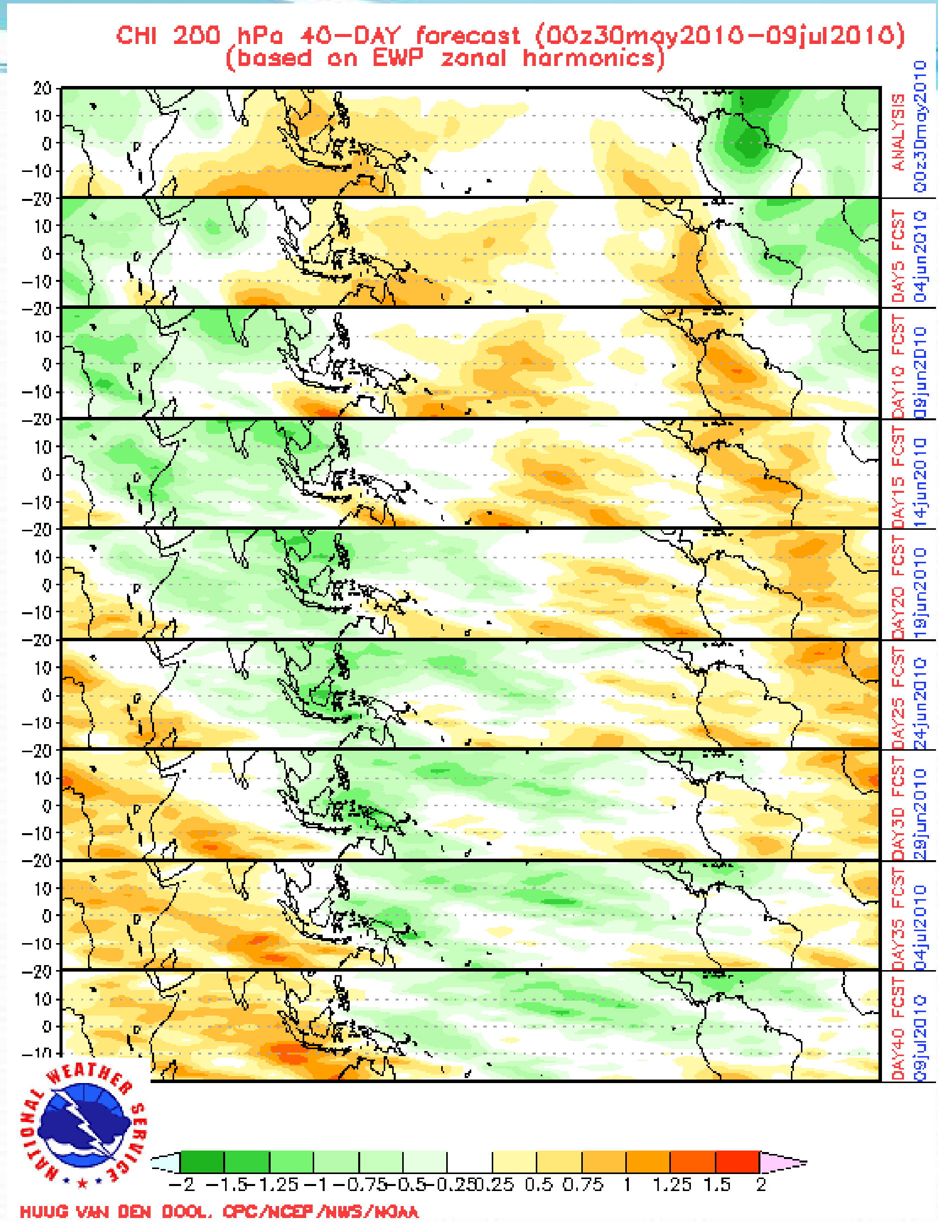
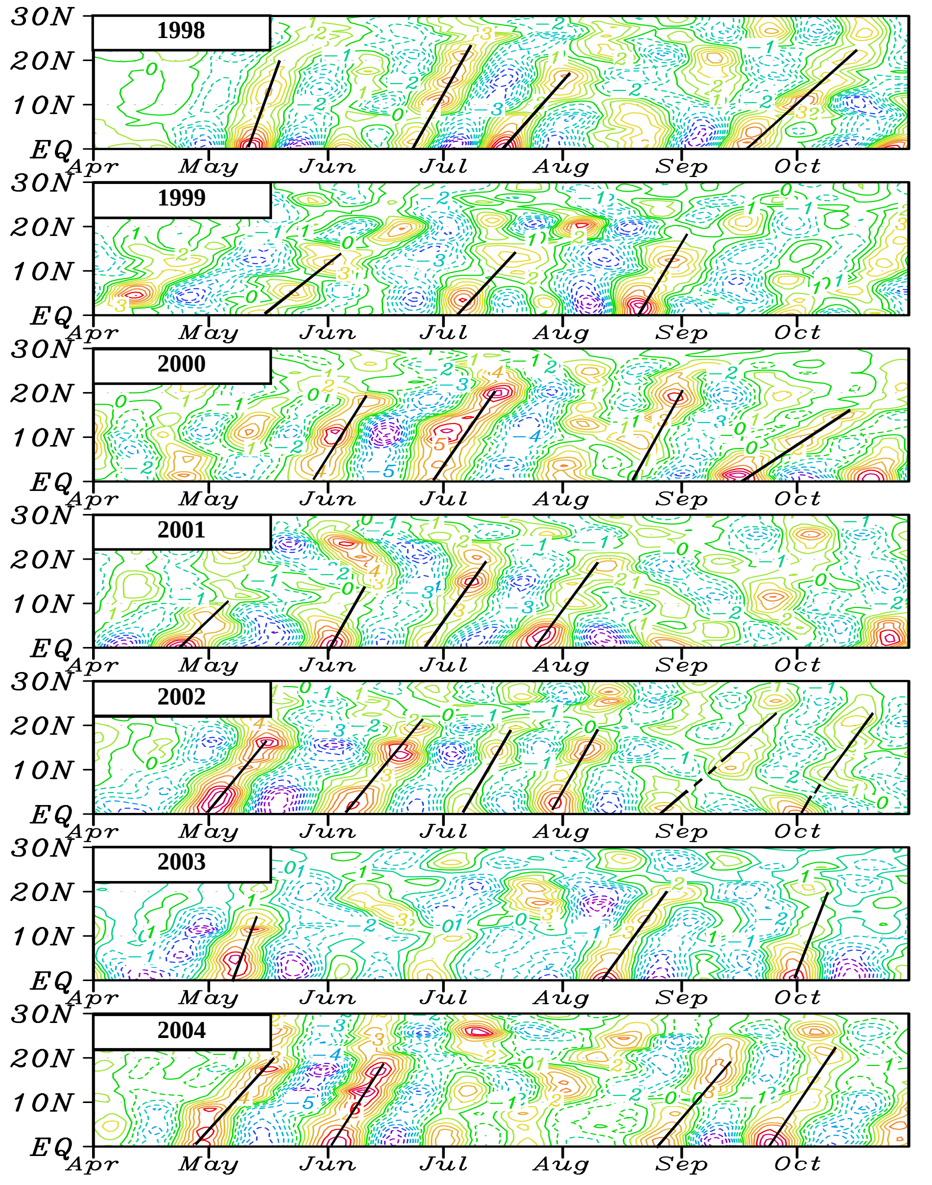


FIG. 2. Historical composites of rainfall for the (a) Nov–Mar and (b) May–Sep periods based on MJO events as characterized by the WH04 MJO index during 1979–2008. Green shades indicate enhanced precipitation and brown shades suppressed precipitation. Units are mm day^{-1}.

Eastward propagating MJO forecast (NOAA)



Northward propagating summer intraseasonal oscillation (ISO)



20-50day 3B42 rain rate (75-100E), Wang et al. 2006

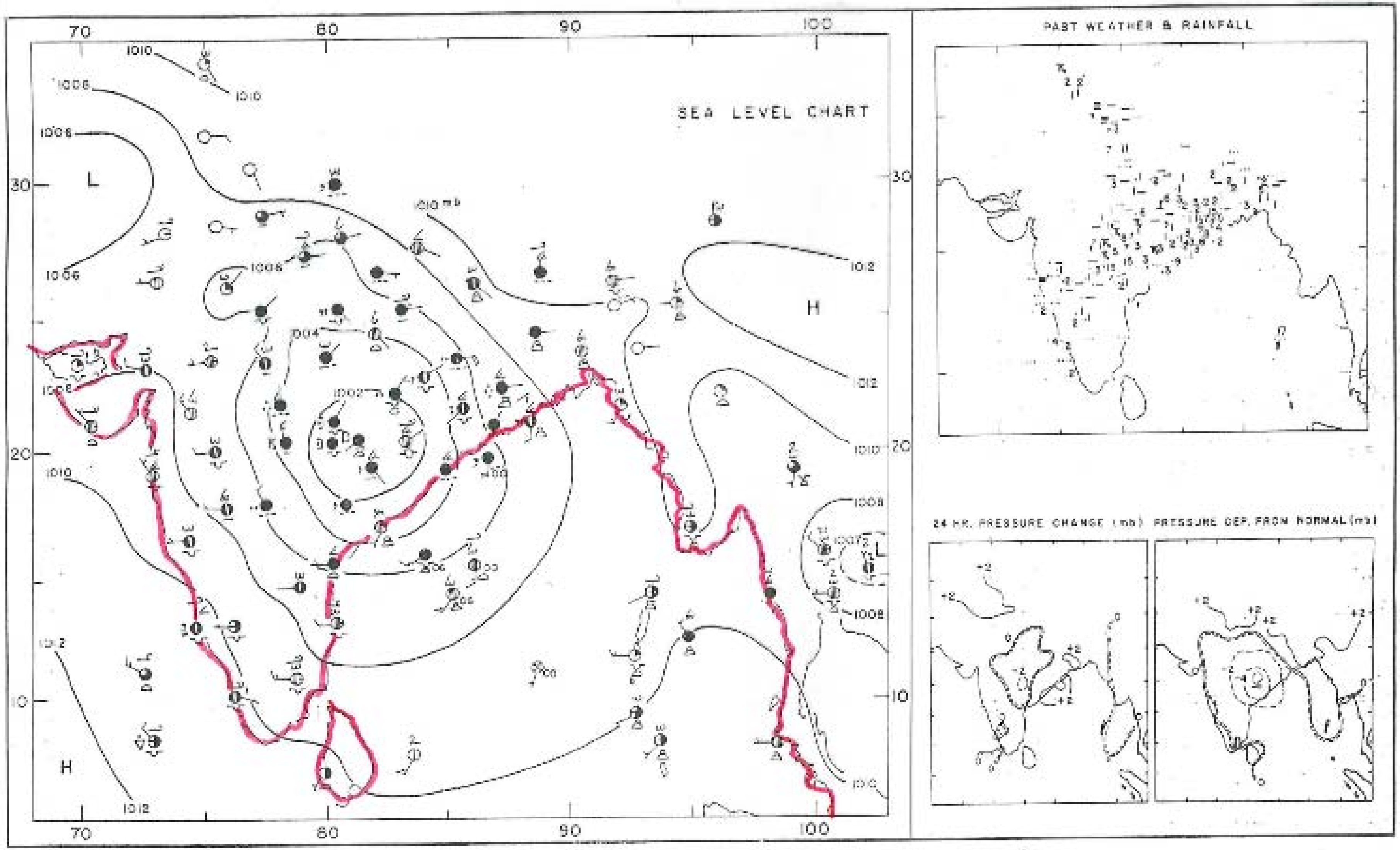


Fig.7.25(e) Synoptic charts 0300 GMT 20 September 1969.

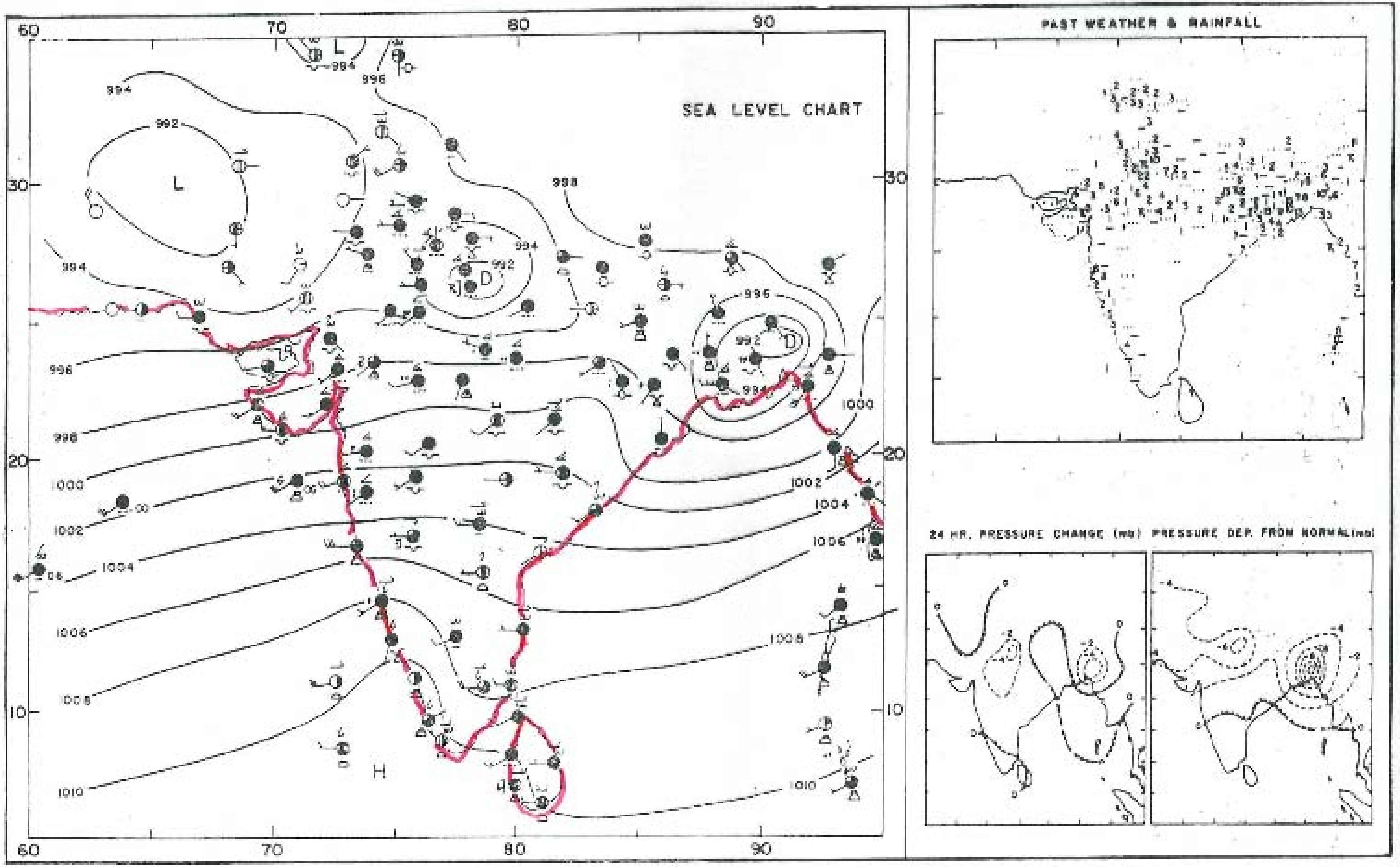
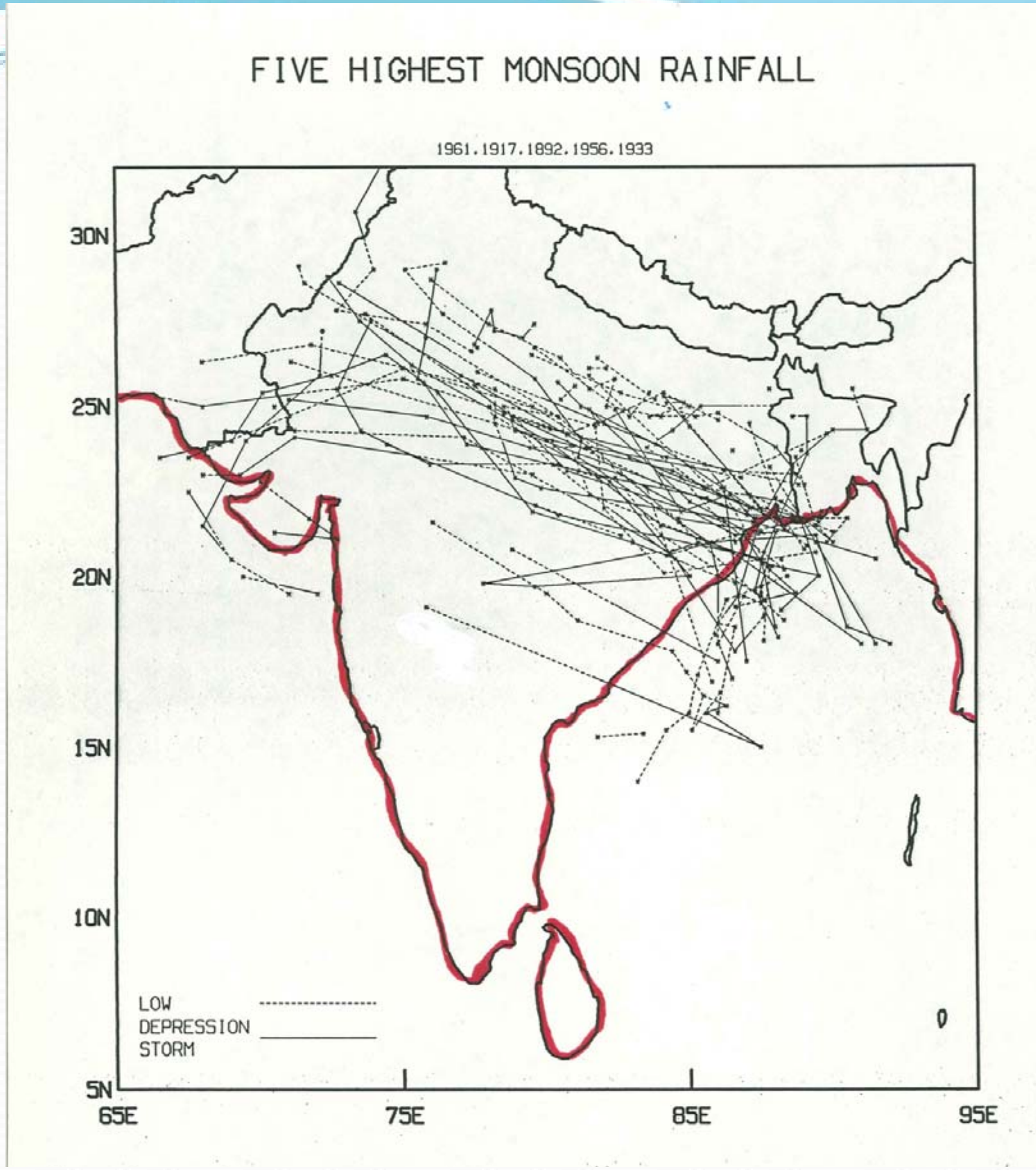


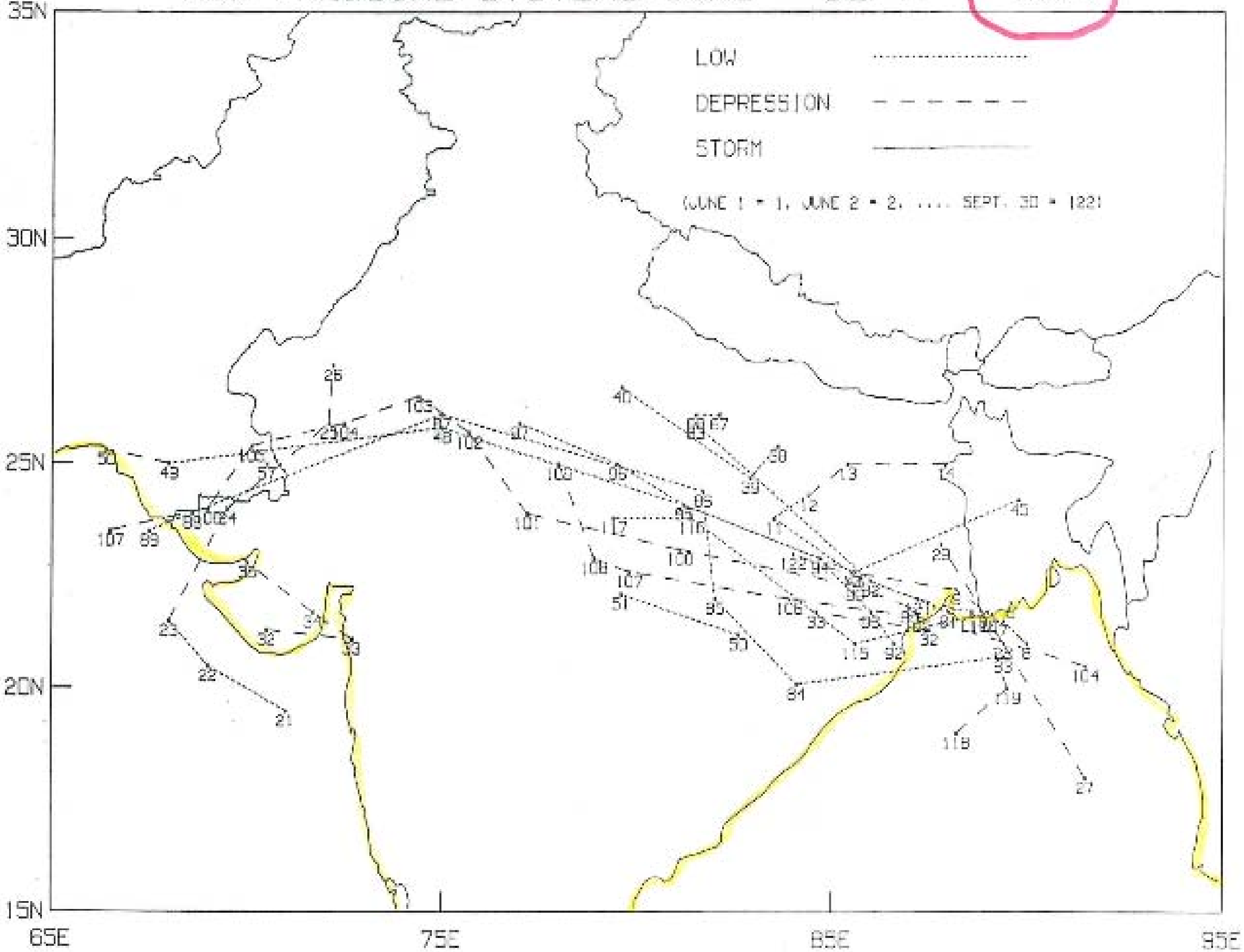
Fig.4.7(h) Synoptic charts 0300 GMT 10 July 1968.



FIVE HIGHEST MONSOON RAINFALL
1961.1917.1892.1956.1933
30N
25N
20N
15N
10N
5N
65E
75E
85E
95E
LOW
DEPRESSION
STORM

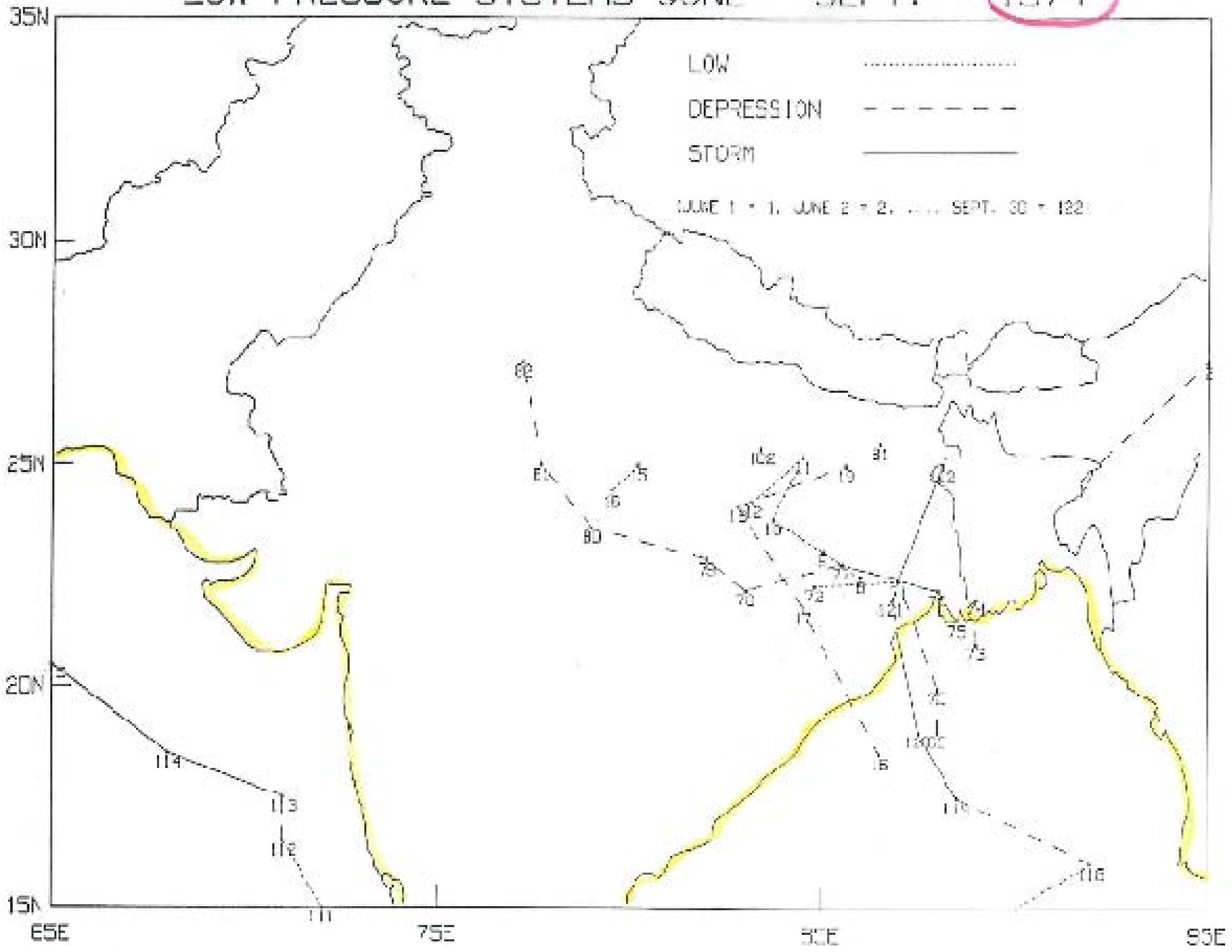
Heavy ("Good") rainfall

LOW PRESSURE SYSTEMS JUNE - SEPT. 1961



Deficient ("Bad") rainfall

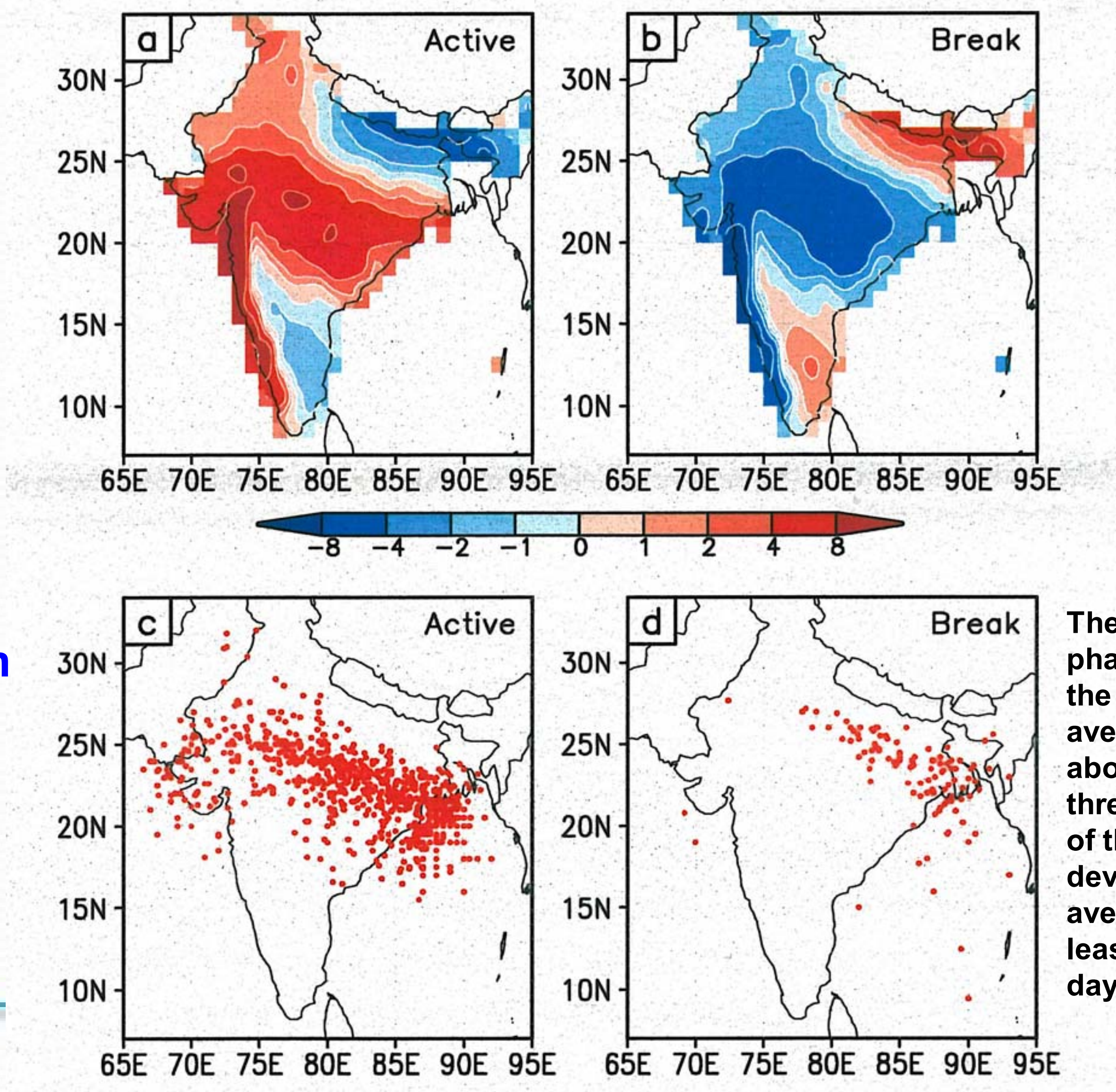
LOW PRESSURE SYSTEMS JUNE - SEPT. 1974



Active and Break Composites of Rainfall and Depressions during JJAS 1901-1970

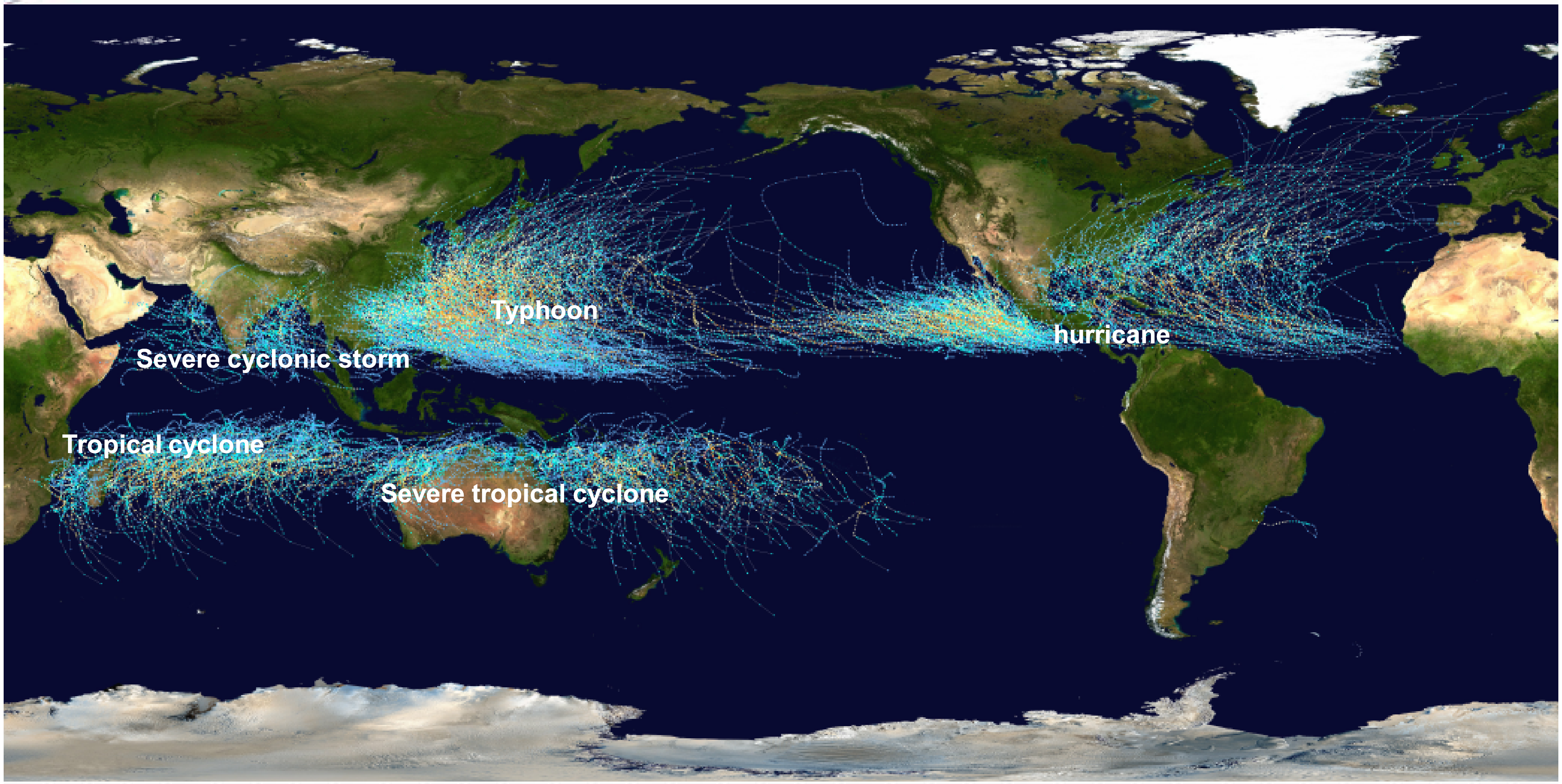
Rainfall

Depression

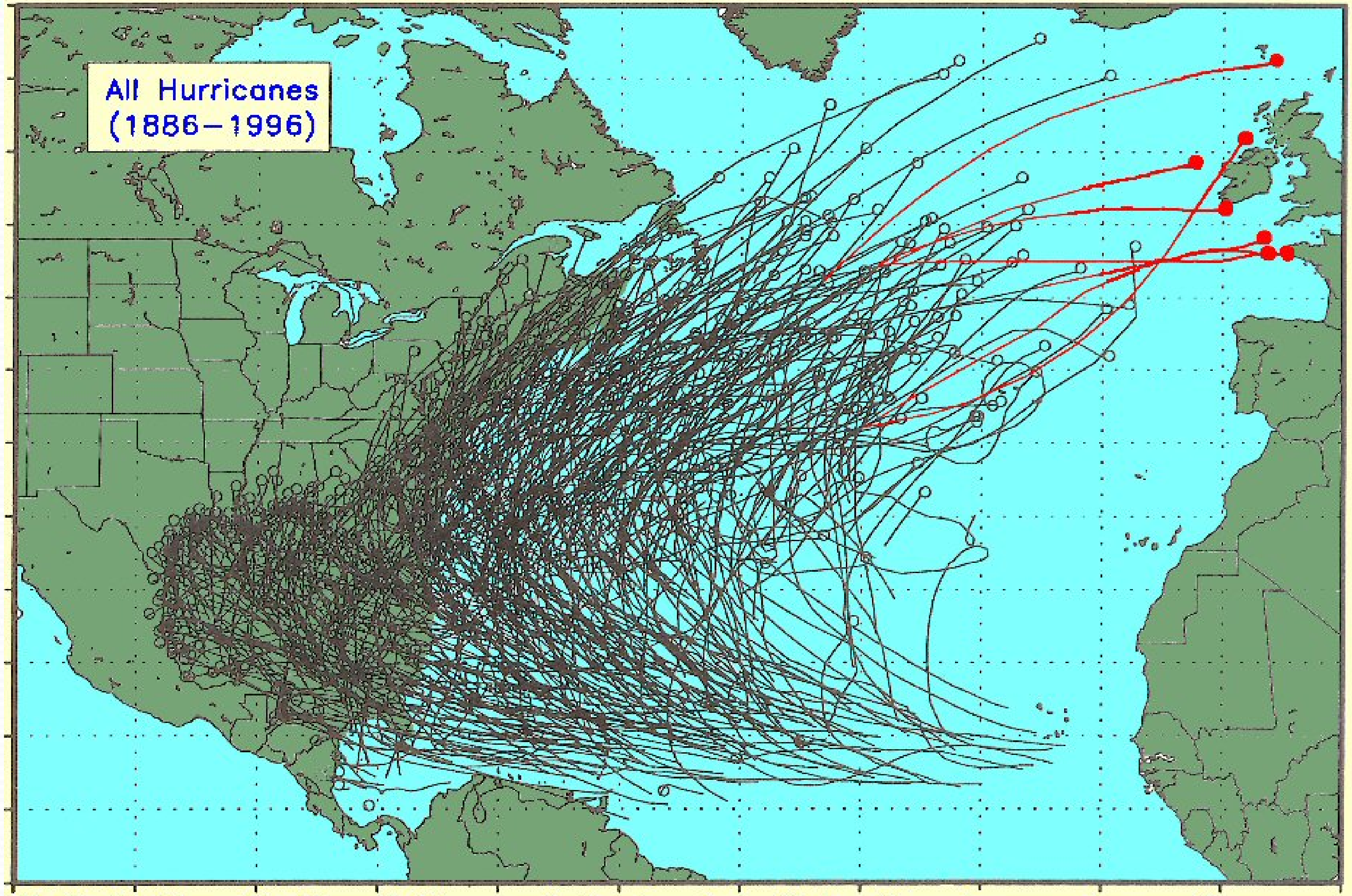


The active (break) phase is defined when the daily all-India average rainfall is above (below) a threshold of one half of the standard deviation of all-Indian average rainfall fro at least five consecutive days.

Global Tropical Cyclone Tracks (1985 – 2005)



Atlantic Hurricanes Tracks (1886 – 1996)



The English Channel is at the end of the range for hurricane tracks. Perhaps they only very rarely proceed into it without dissipation, but the sea may be in an overshoot area for exceptional hurricanes.

Modified after Elsner and Kara (1999). Ian West and Tonya West (c) 2005.

Mechanisms of Seasonal-Interannual Variability

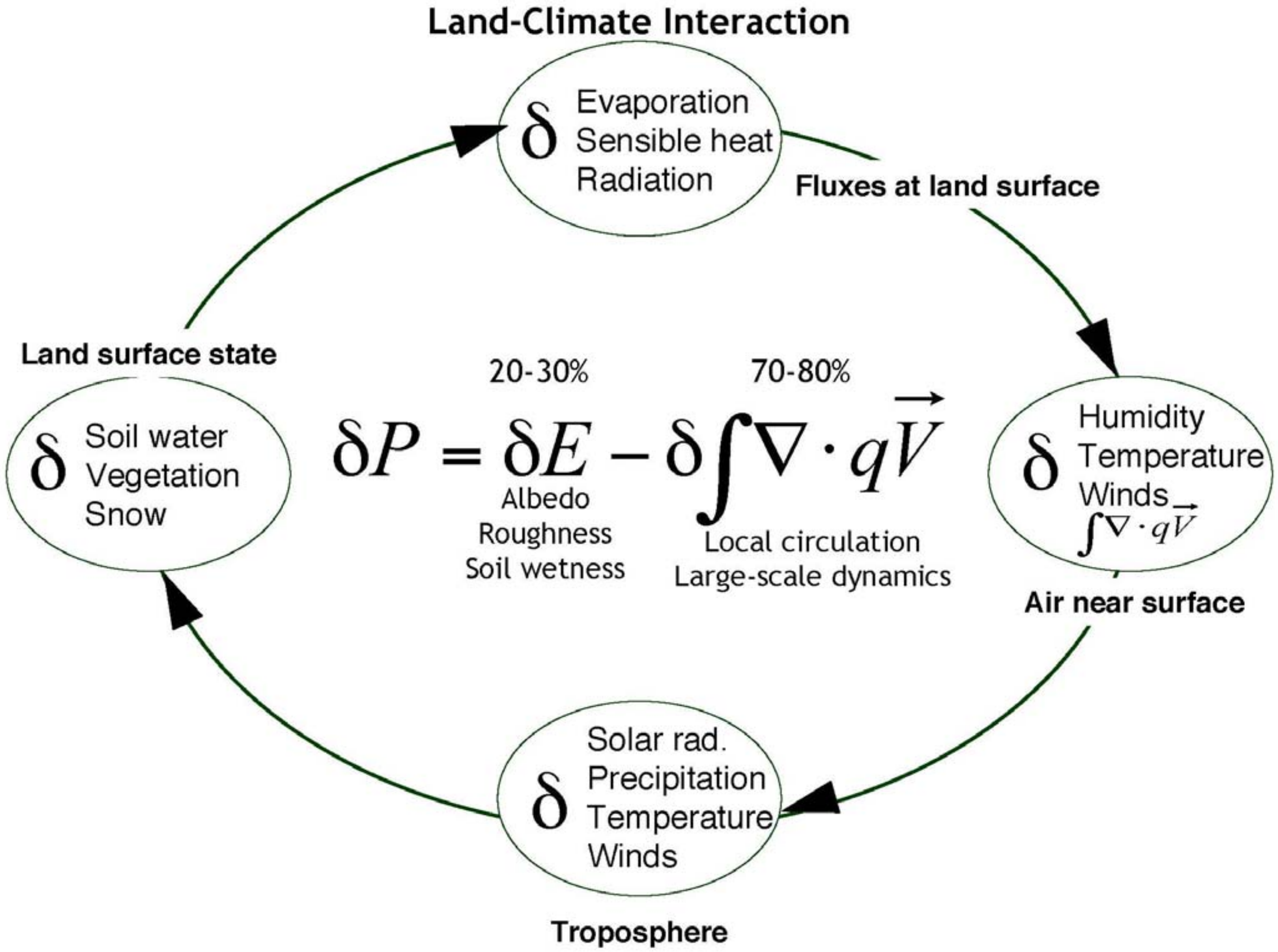
- INTERNAL DYNAMICS
- BOUNDARY FORCING

  Atmosphere-Ocean Interaction

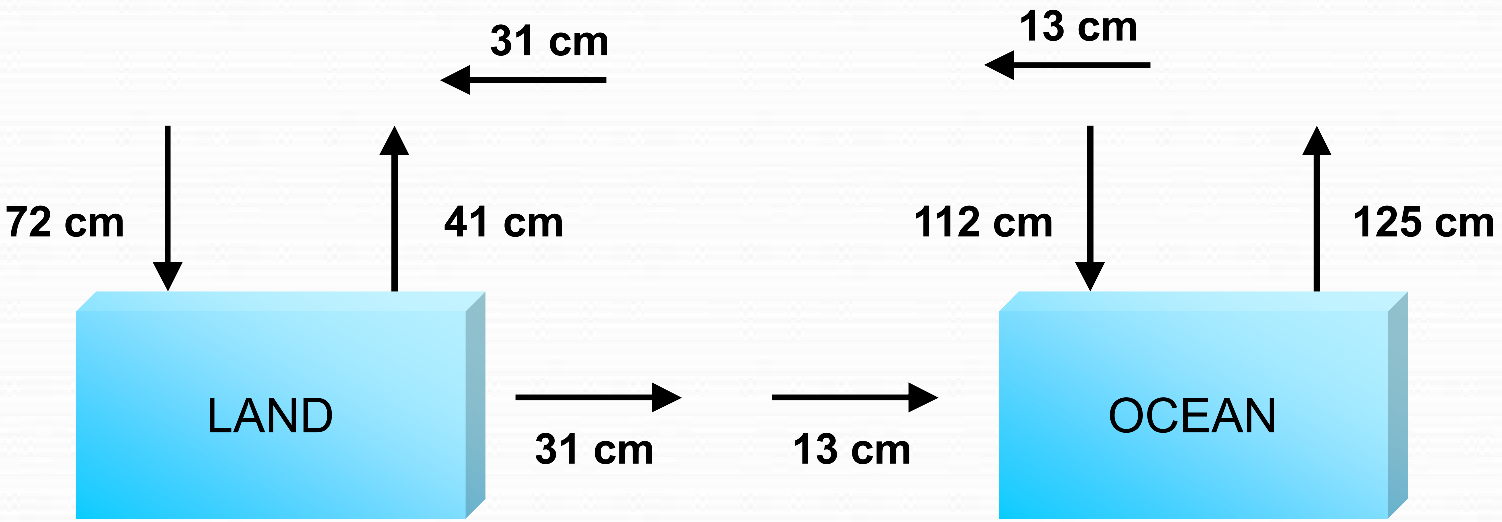
  Atmosphere-Land Interaction

  Atmosphere-Ocean-Land Interaction

Atmosphere-Land Interaction



Global Annual Mean Hydrological Cycle

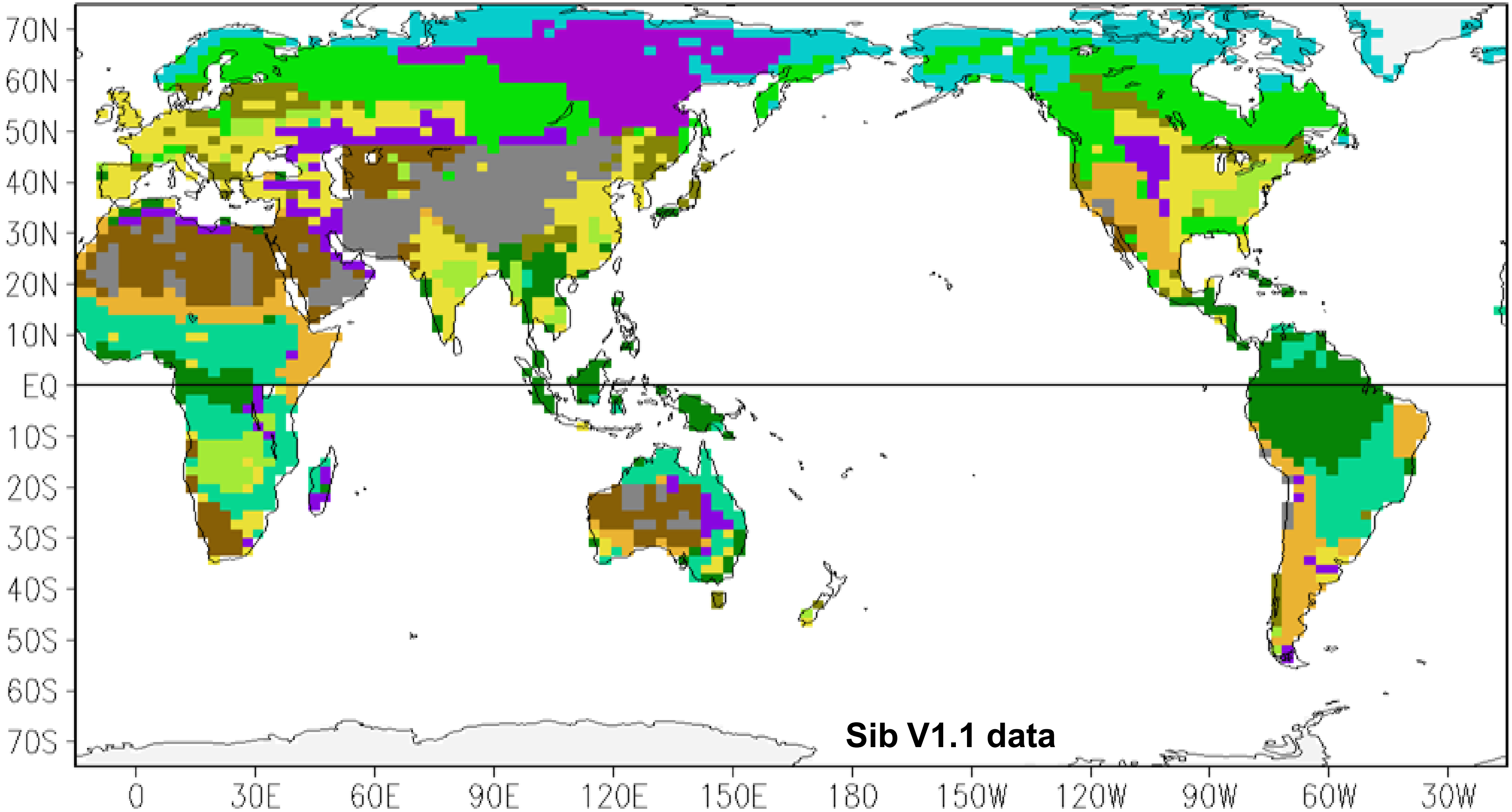


[Global, annual mean]

[Vertical column ~ 2-3 gm/cm^2 of water]

[Time scale ~ 3 weeks]

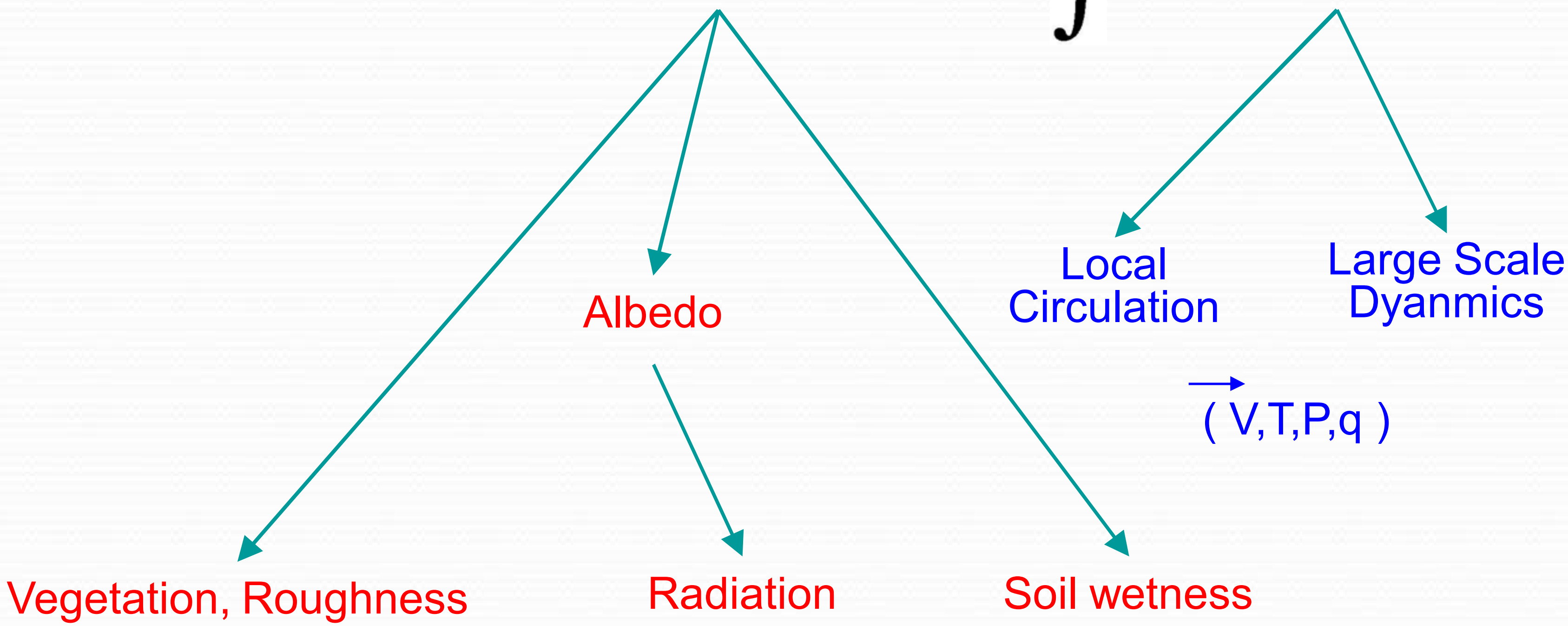
Climatological Vegetation Types



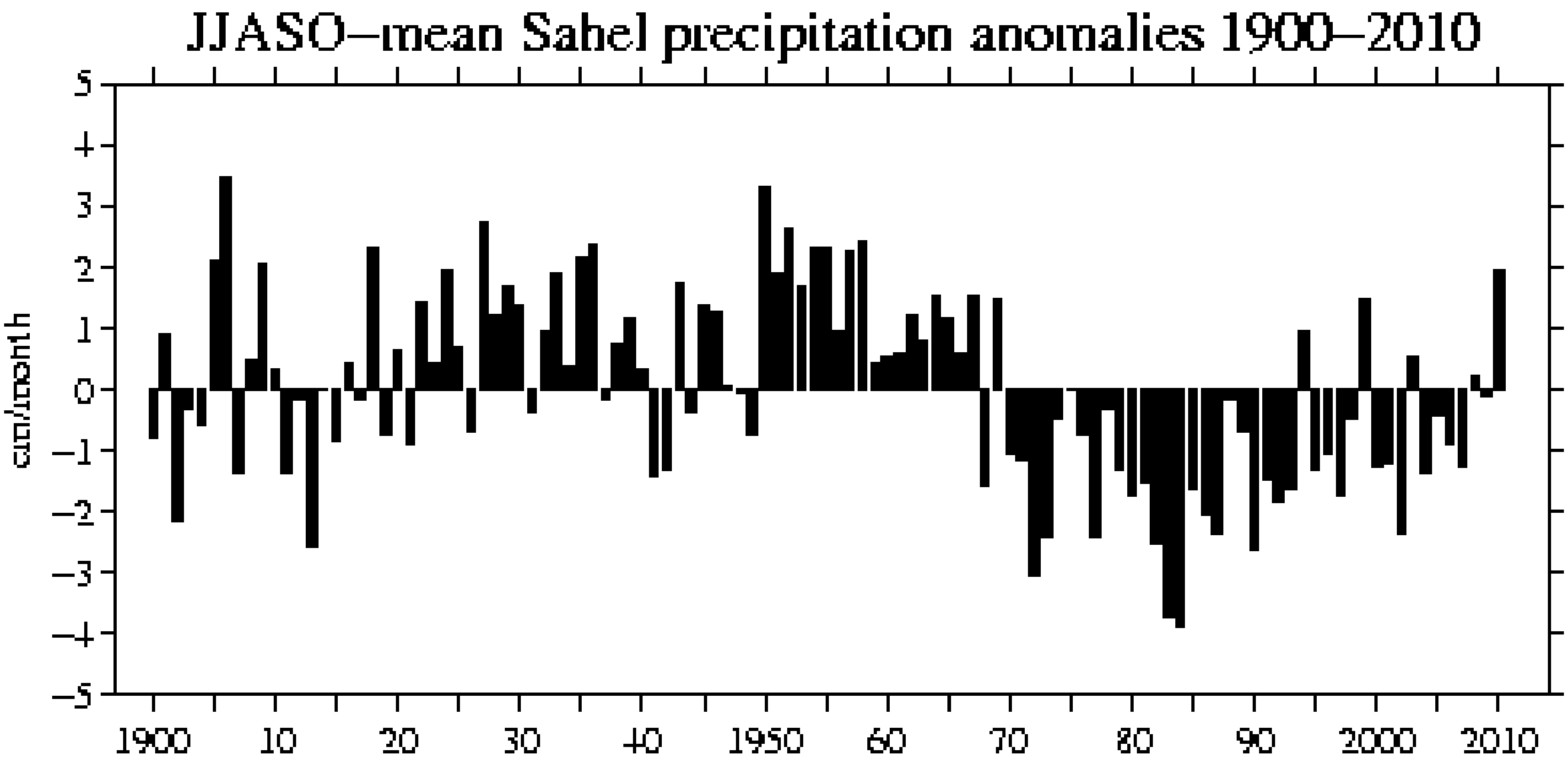
Broadleaf–evergreen trees (tropical forest)
Broadleaf–deciduous trees
Broadleaf and needleleaf trees (mixed forest)
Needleleaf–evergreen trees
Needleleaf–deciduous trees (larch)
Broadleaf trees with groundcover (savanna)
Groundcover only (perennial)
Broadleaf shrubs with perennial groundcover
Broadleaf shrubs with bare soil
Dwarf trees & shrubs w groundcover (tundra)
Bare soil
Winter wheat and broadleaf–deciduous trees

Precipitation | Evaporation | Moisture Flux Conv.

$$P = E - \int \nabla \bullet \vec{V}q$$



Sahel Rainfall

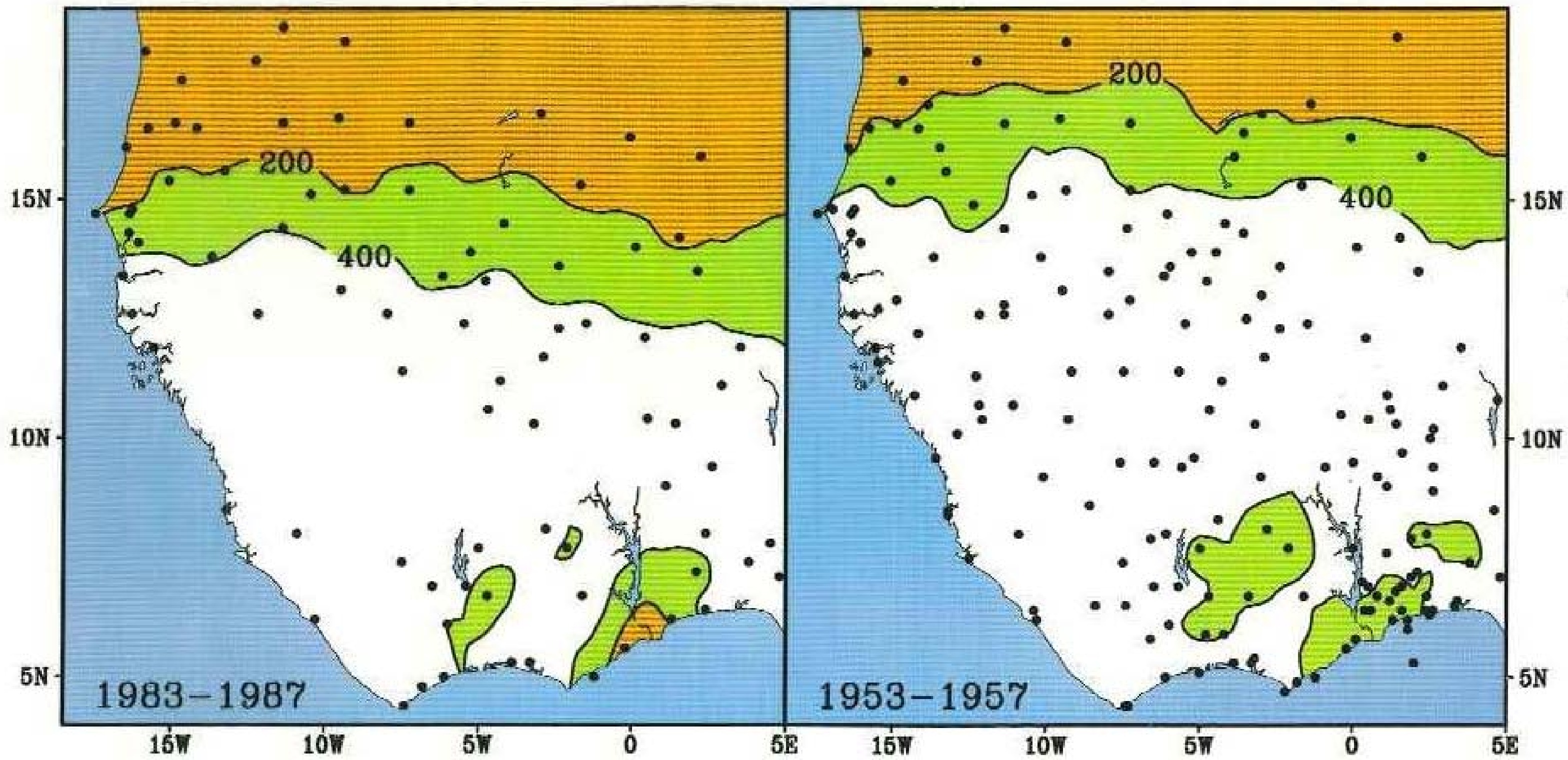


Sahel rainfall index (JJASO mean anomaly, 10-20°N, 20°W-10°E)

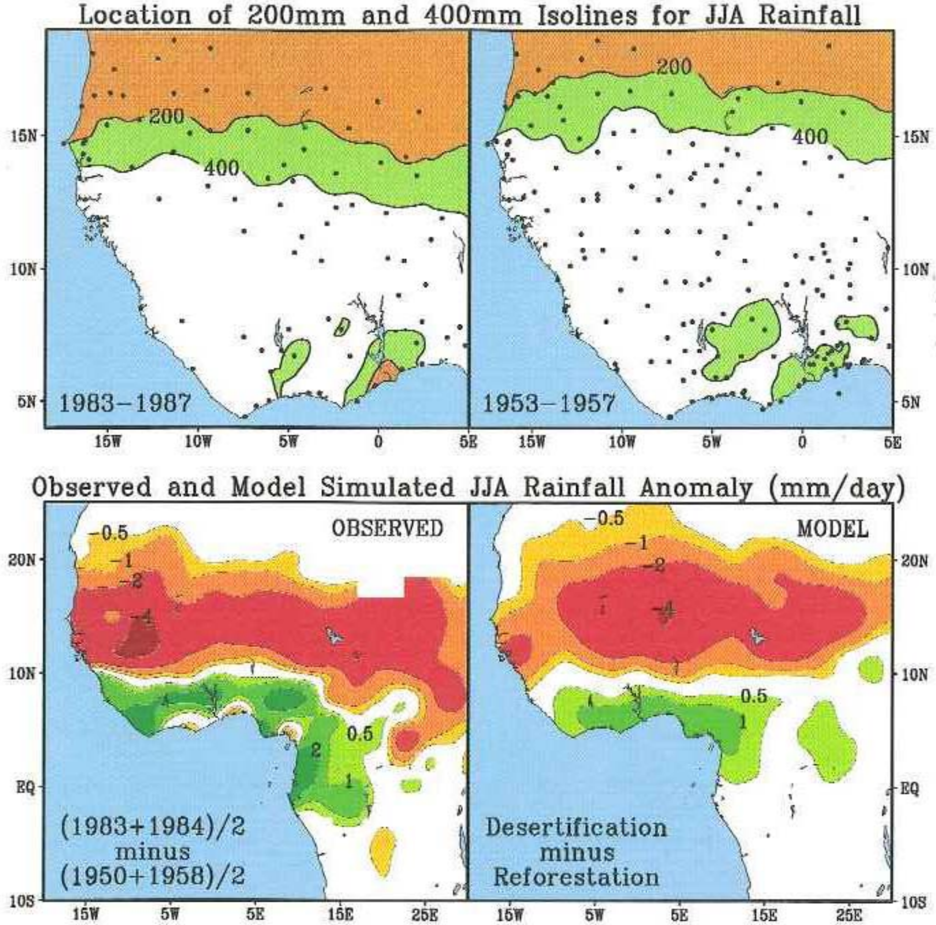
COLA Center for Ocean-Land-Atmosphere Studies

GEORGE MASON UNIVERSITY

Location of 200mm and 400mm Isolines for JJA Rainfall



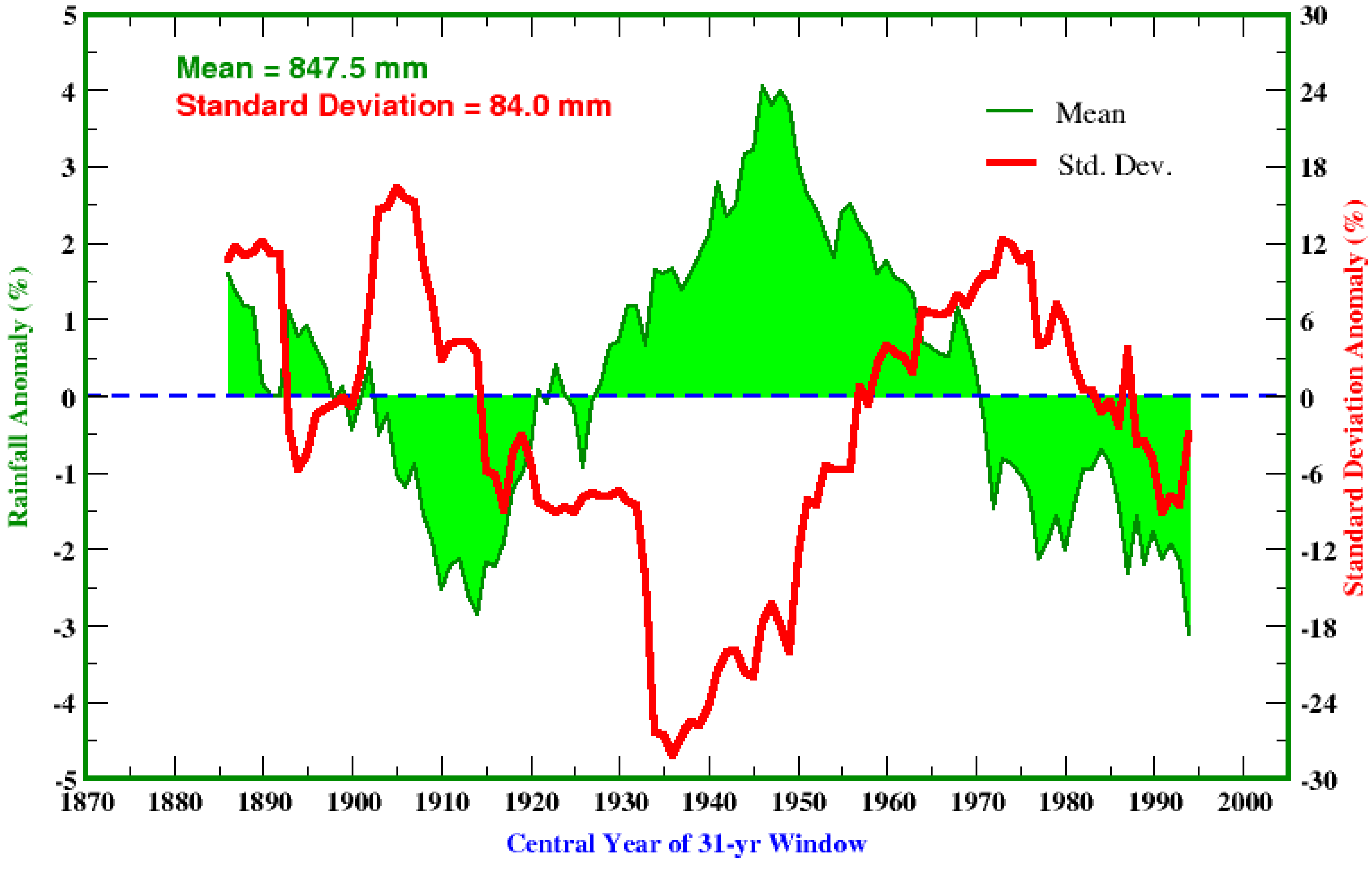
RAINFALL OBSERVATIONS SHOW A SOUTHWARD EXPANSION OF SAHARA



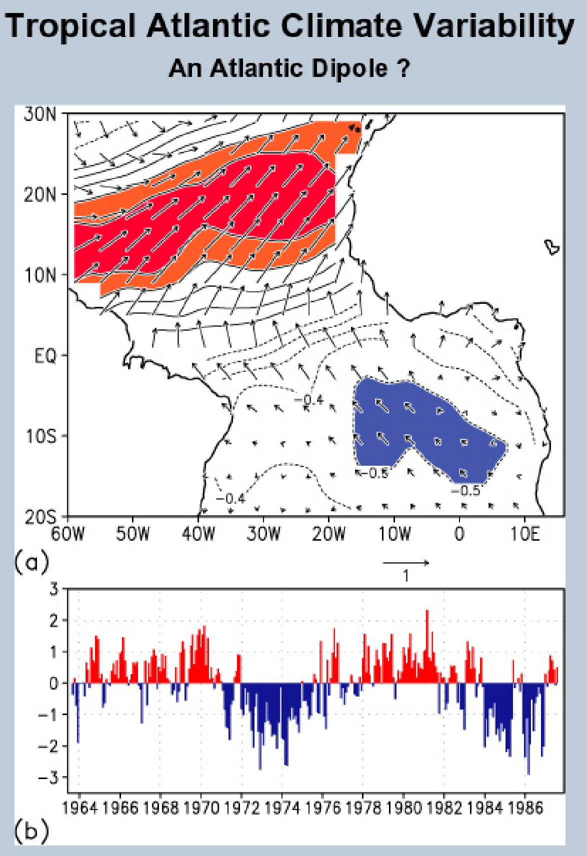
COLA model simulations show that land surface degradation is a major factor in perpetuation of the sub–Sahara drought.

Decadal Variability

Epochal Patterns of All-India Summer Monsoon Rainfall



… and the interannual variations need not be ENSO-like:

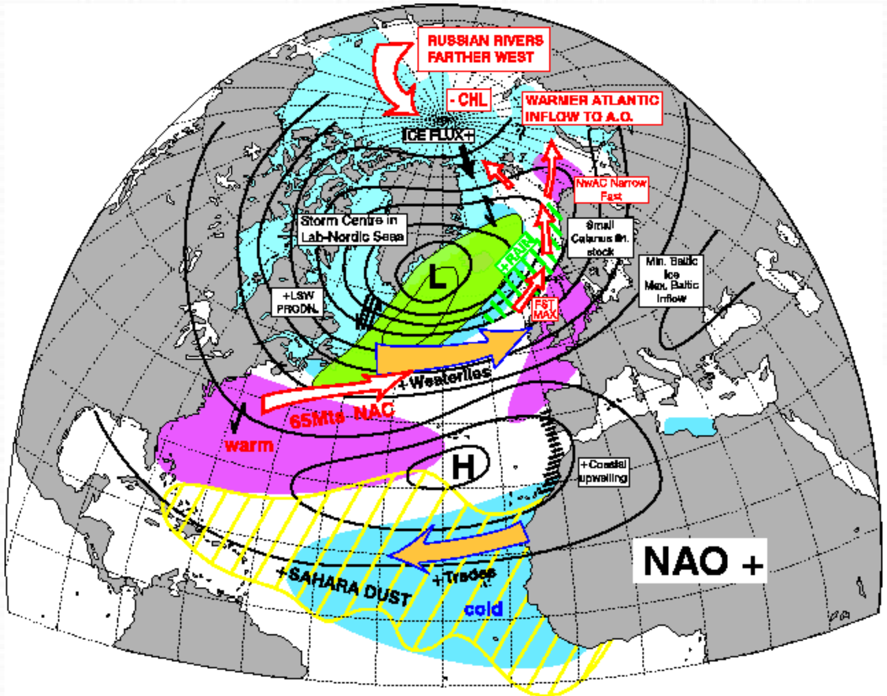


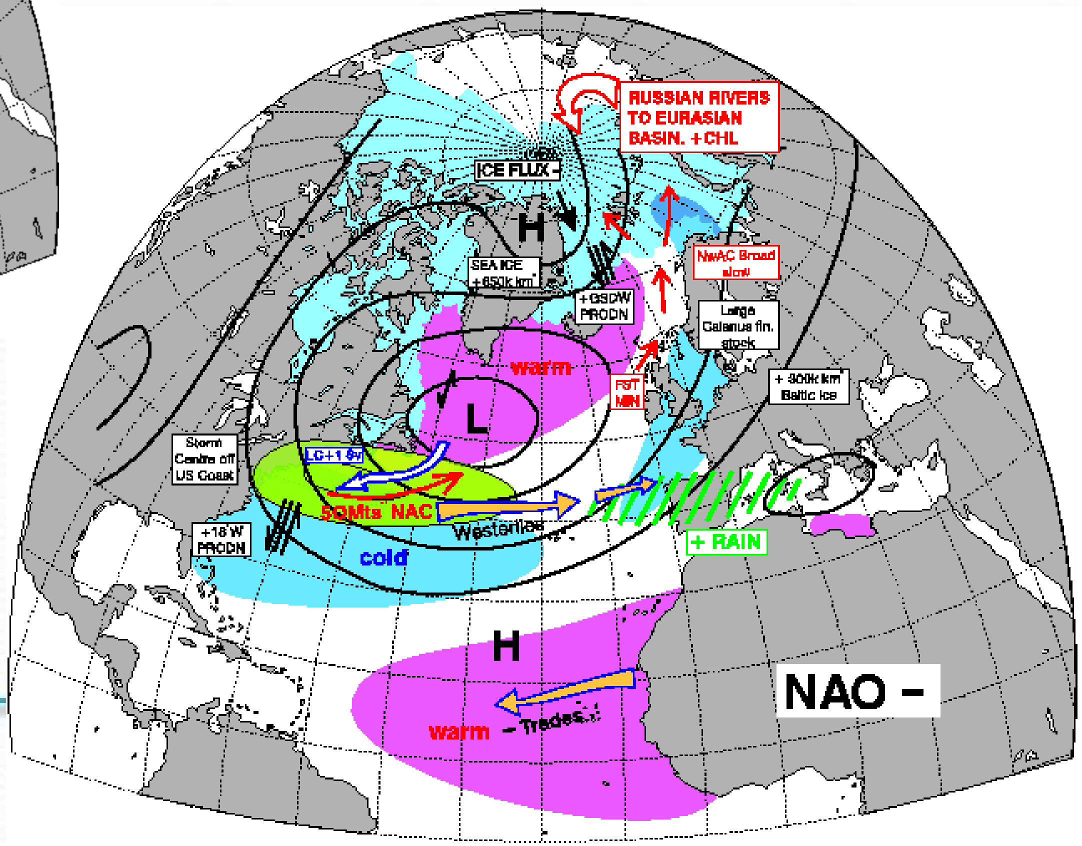
The dominant joint patterns of sea surface temperature and surface wind stress variability over the Atlantic for the period September 1963 to August 1987 and the associated time series. The time series show a dominant signal at lower frequencies but as well, there are seasonal and interannual fluctuations (Nobre and Shukla, 1996, J. Climate, 9, 2464-2479).

AV/D2/99-8

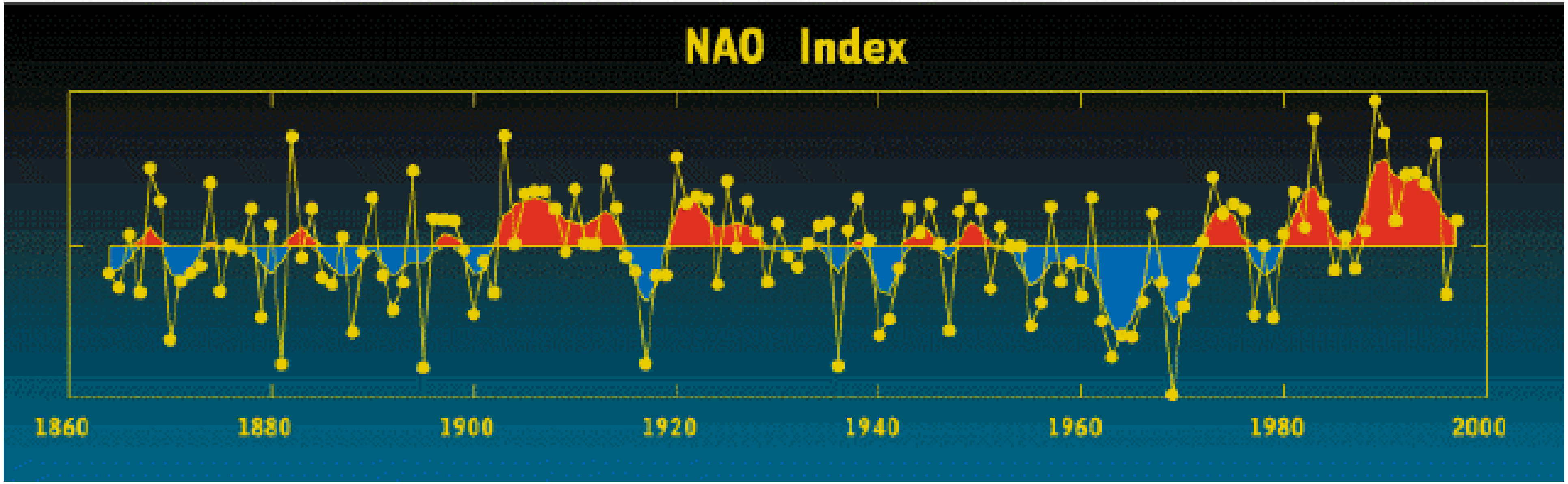
North Atlantic Oscillation:

the major mode of variation in the extra-tropical winter climate (contracted in summer)



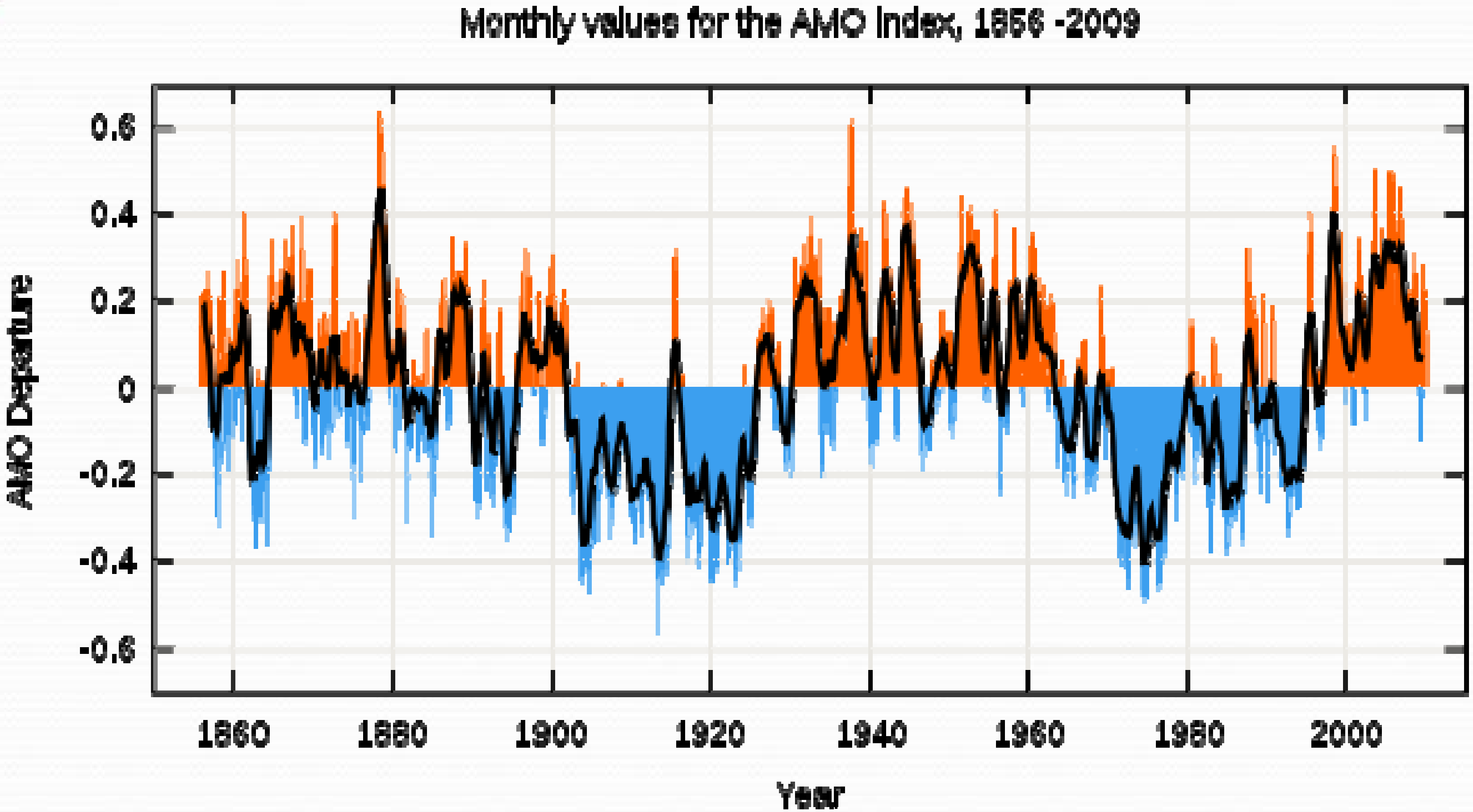


Decadal Variability of North Atlantic Oscillation



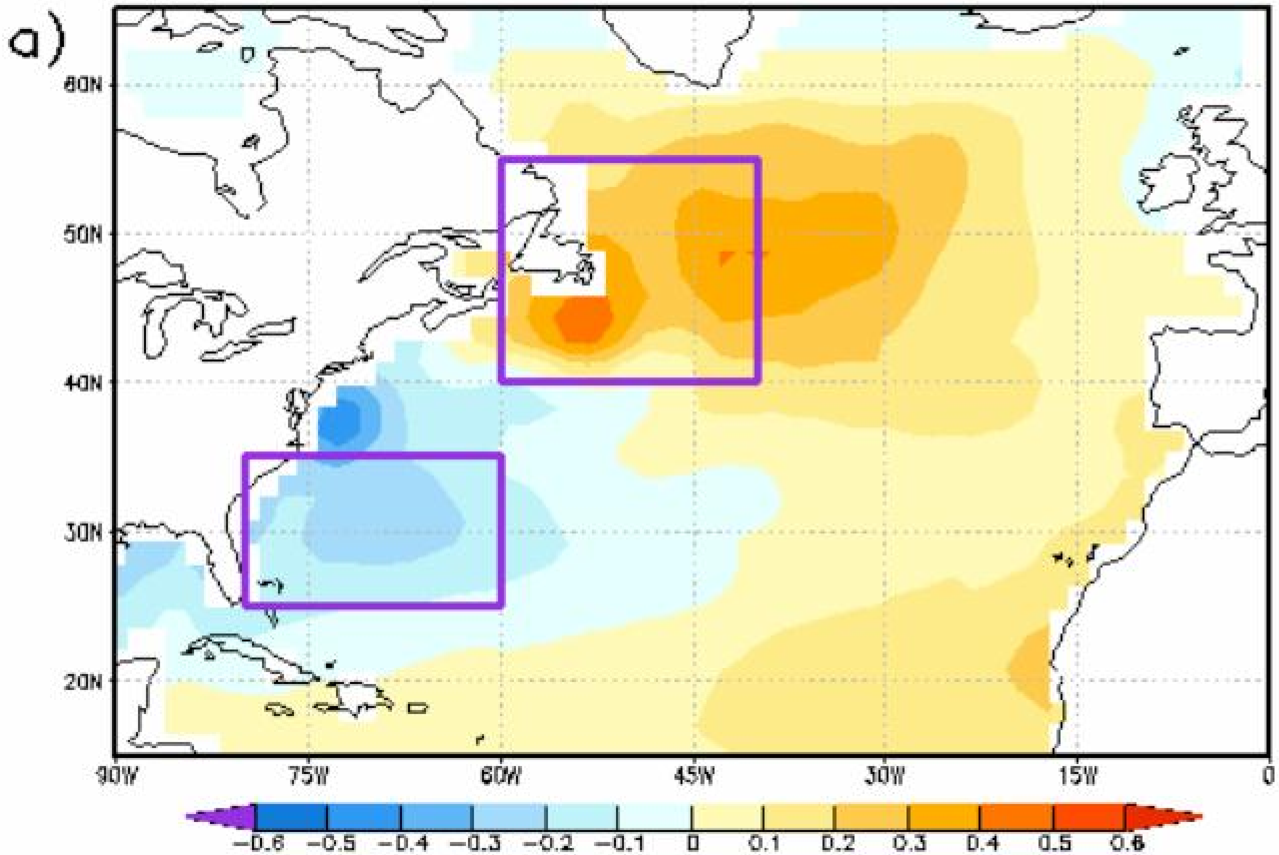
The NAO index is defined as the anomalous difference between the polar low and the subtropical high during the winter season (December through March).

Atlantic Multi-decadal Oscillation



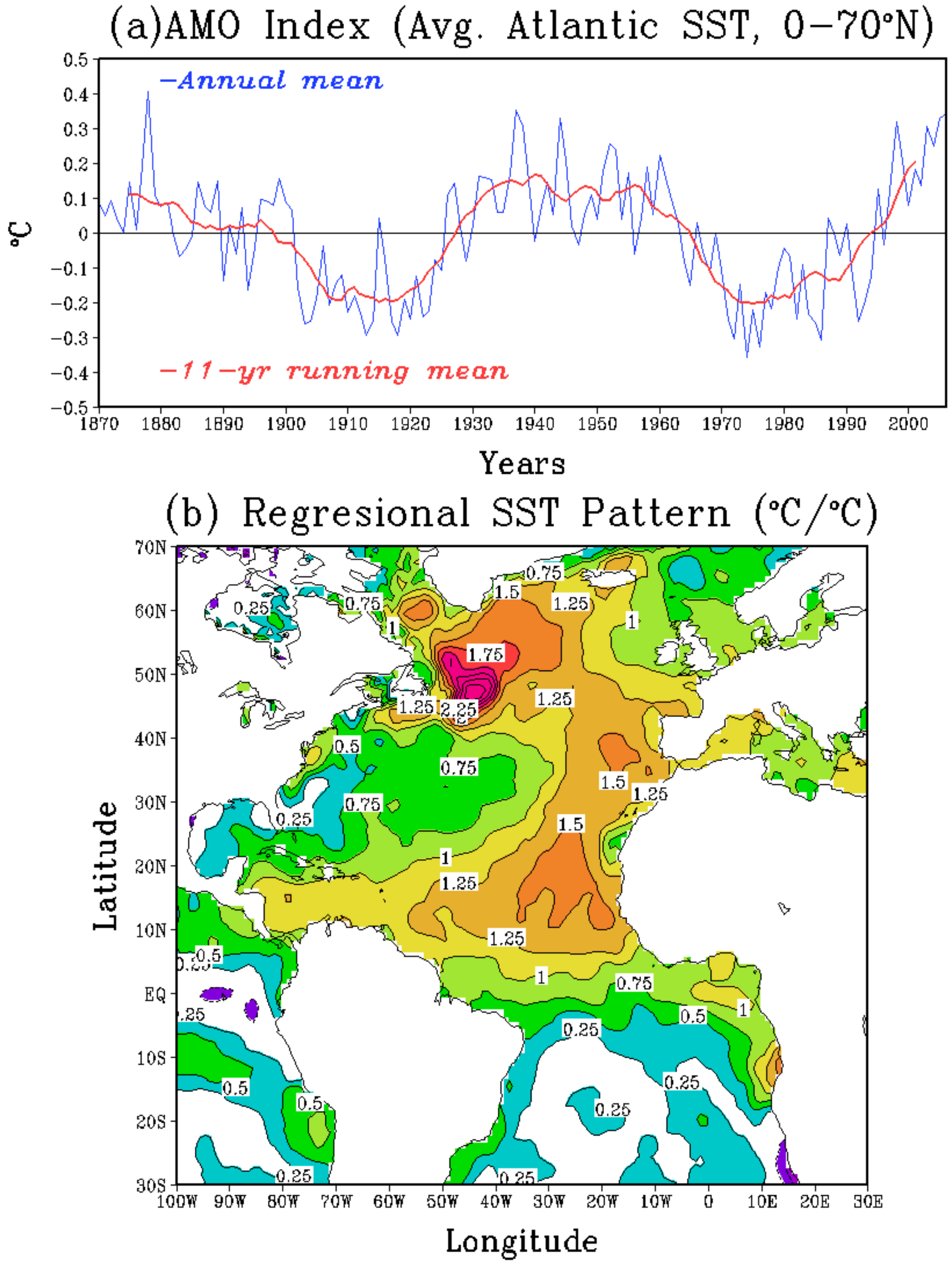
The Atlantic Multi-decadal Oscillation Index is defined as area weighted average detrended SST anomaly over the North Atlantic, 0 to 70°N.

North Atlantic Tripole Pattern



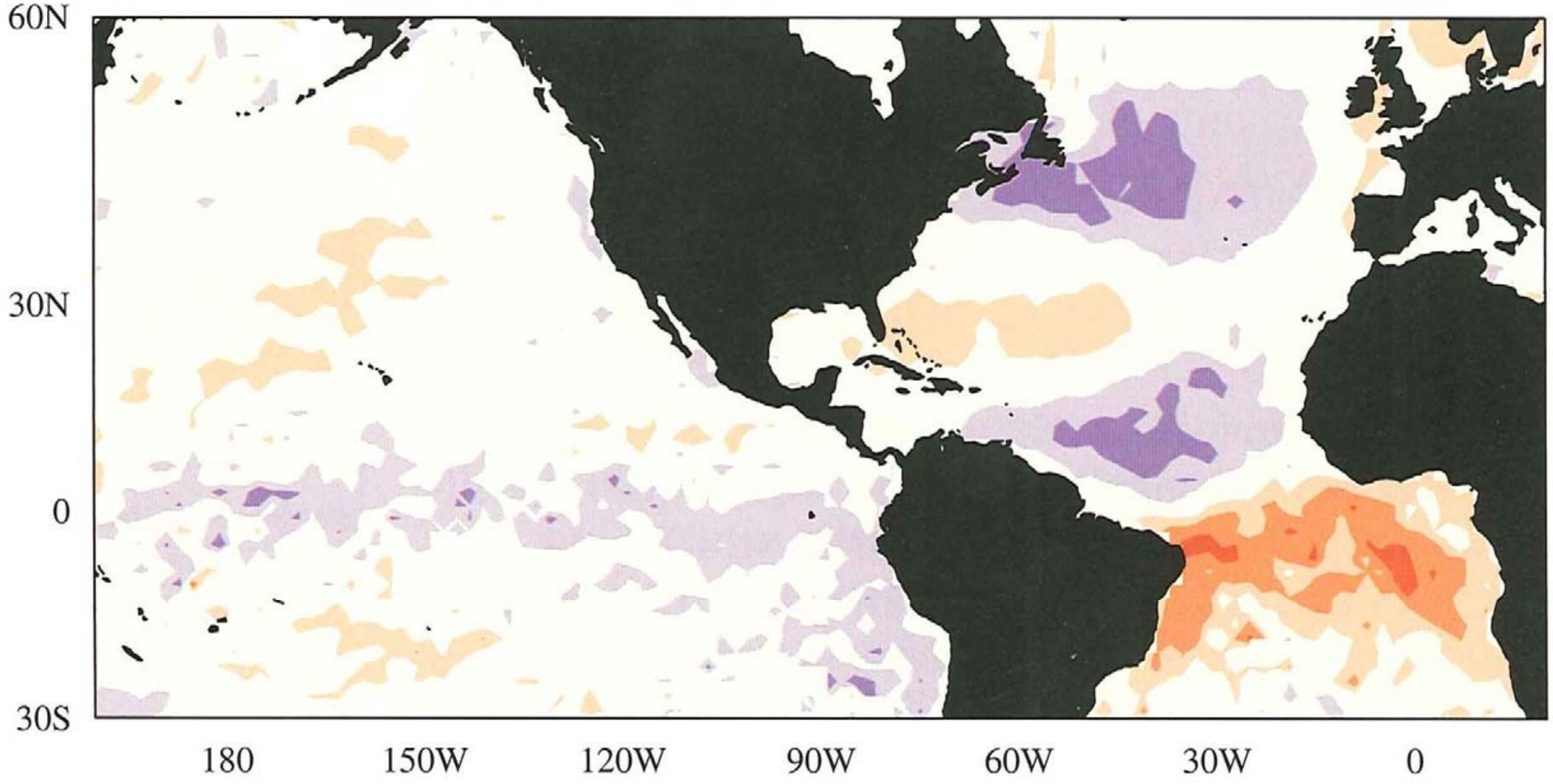
Fan and Schneider (2011)
JFM SST

Atlantic Multi-decadal Oscillation



Huang (Personal Communication)
Annual Mean Hadley SST

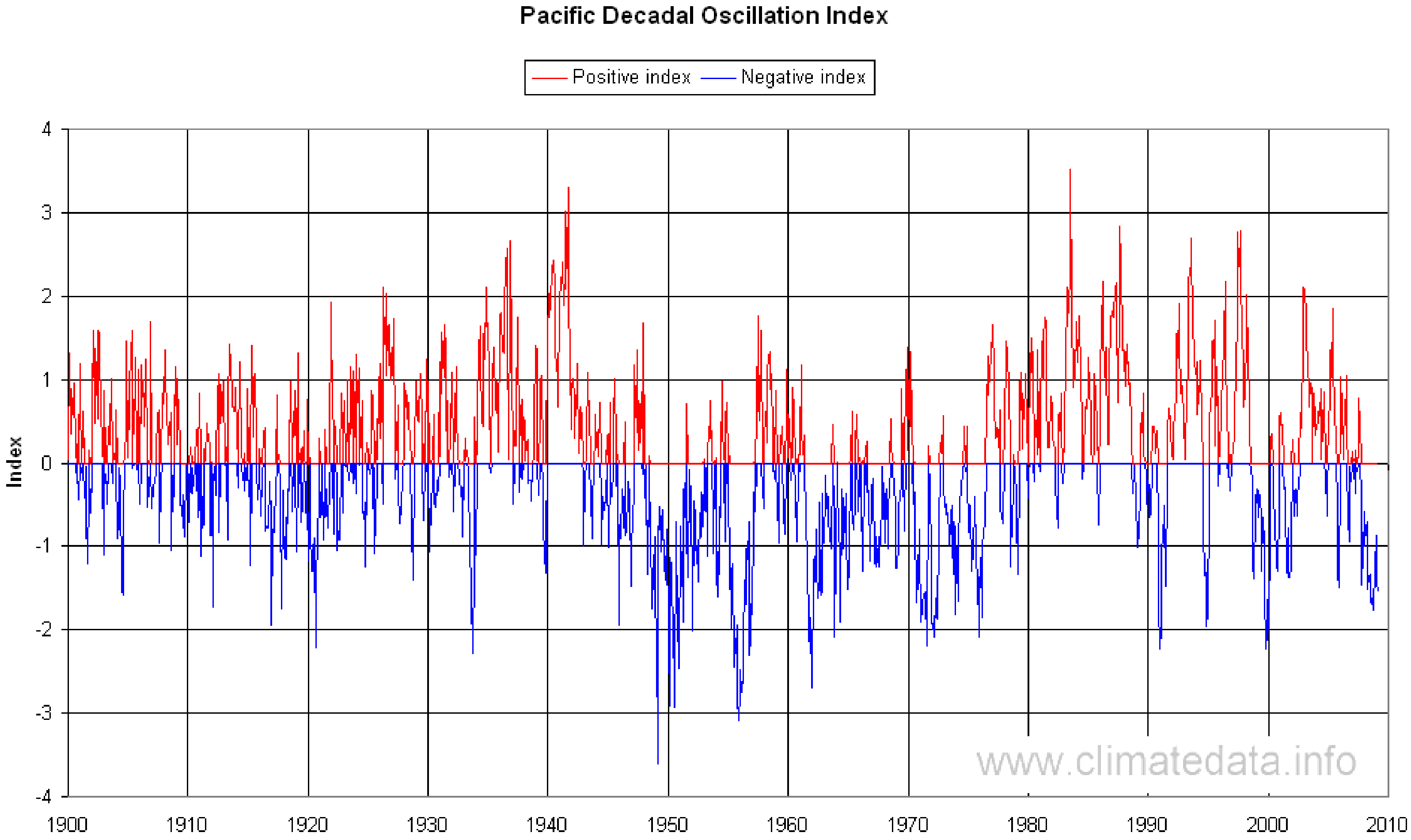
Atlantic SST Pattern



Correlation between average February through May precipitation in northeast Brazil and sea-surface temperature.

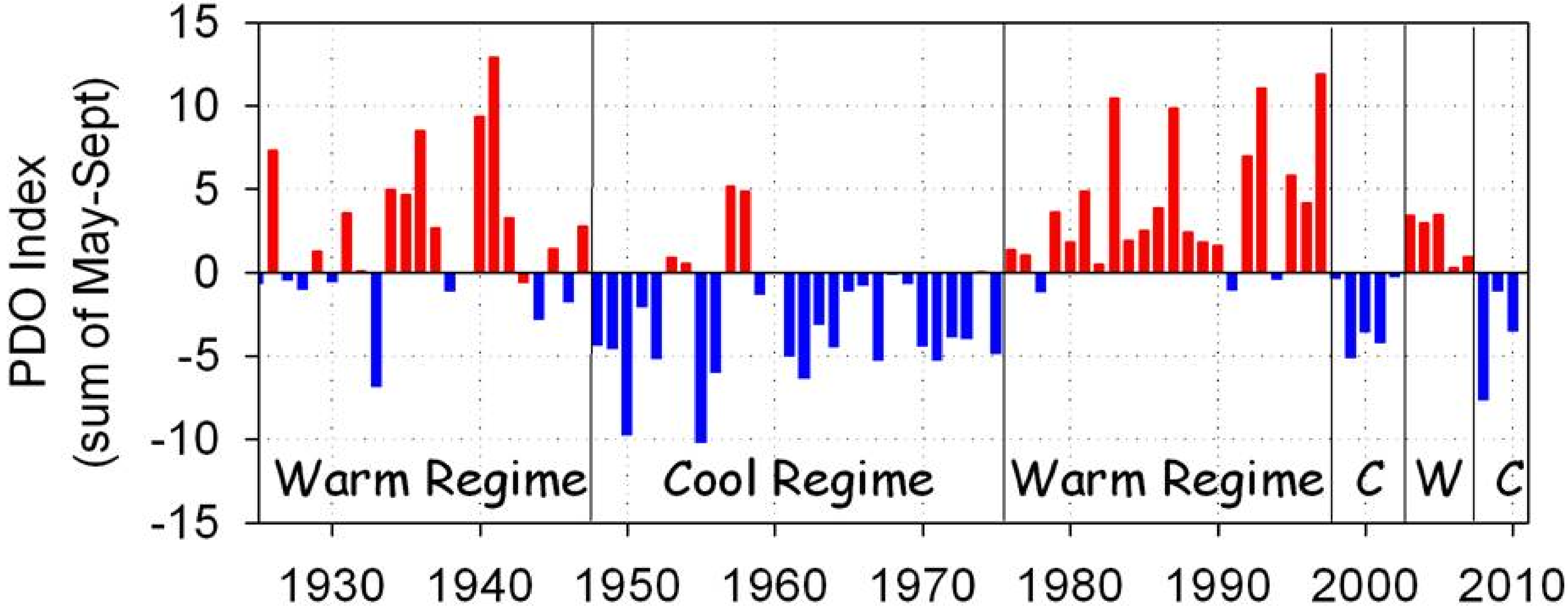
Wallace et al. (PACS)

Pacific Decadal Oscillation



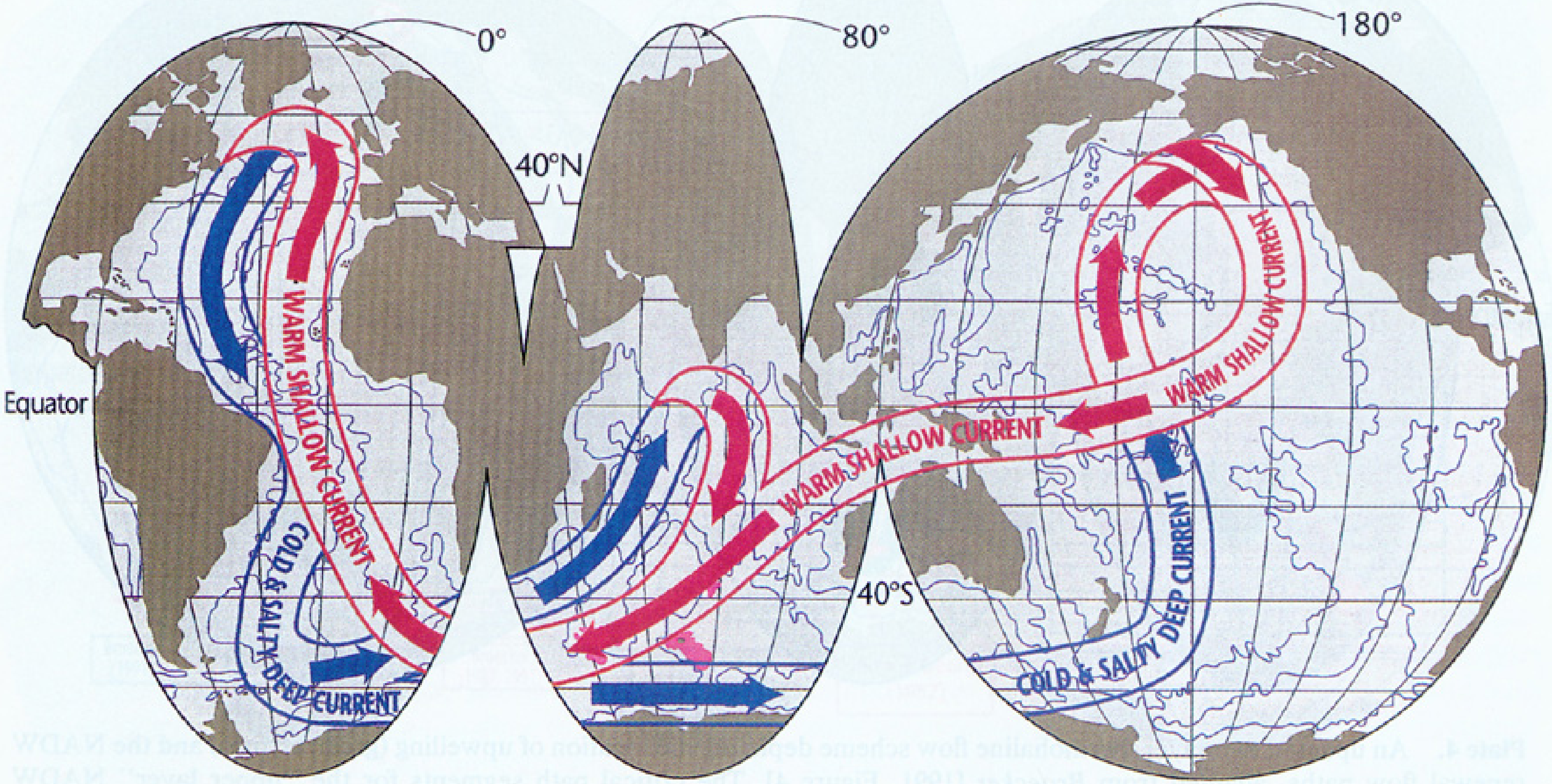
The Pacific Decadal Oscillation (PDO) Index is defined as the leading principal component of North Pacific monthly sea surface temperature variability (poleward of 20°N, Mantua et al. 1997)

Pacific Decadal Oscillation



The Pacific Decadal Oscillation (PDO) Index is defined as the leading principal component of North Pacific monthly sea surface temperature variability (poleward of 20^{o}N, Mantua et al. 1997)

Great Ocean Conveyer Belt (Broecker 1991)

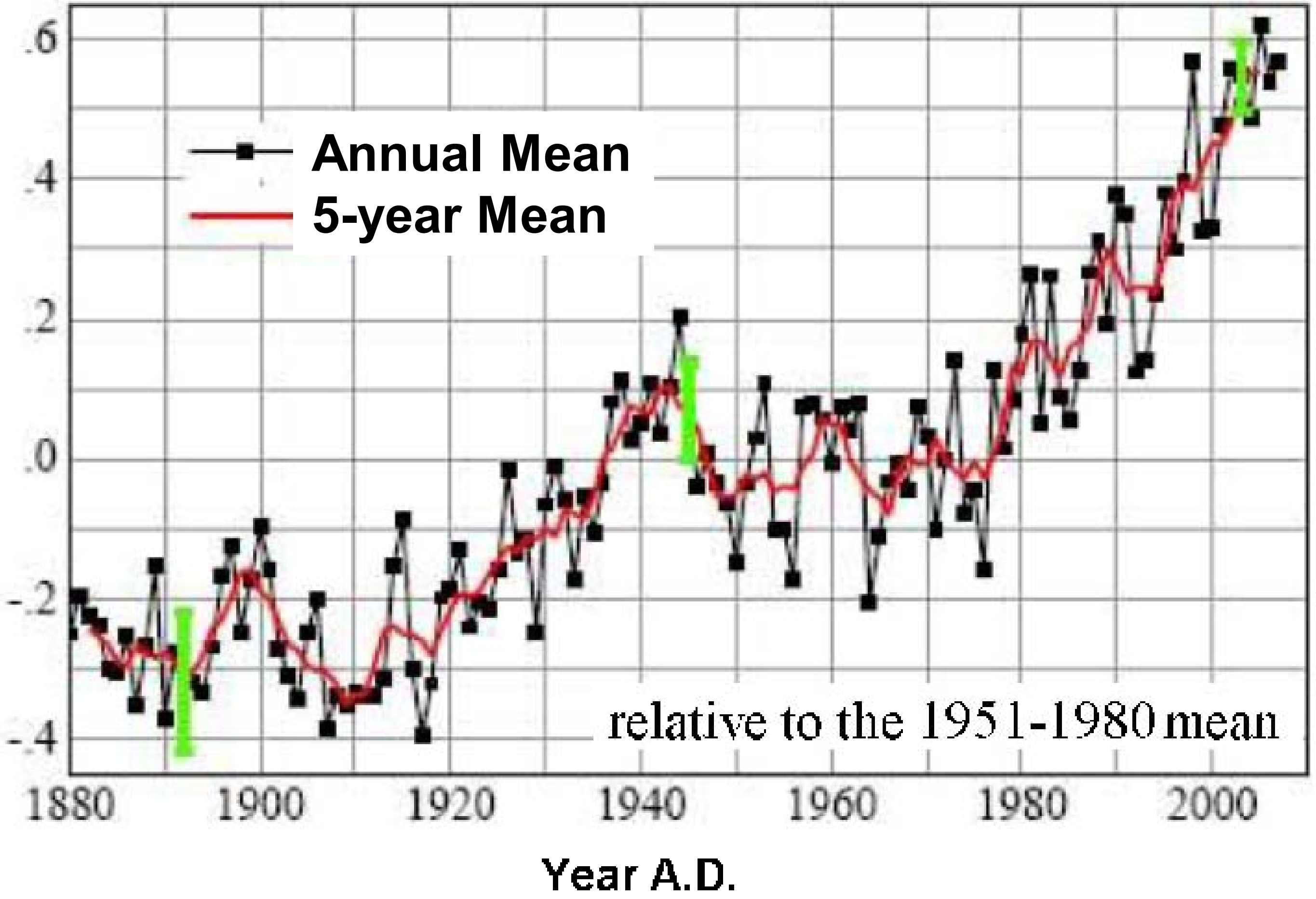


This paradigm emphasizes the role of North Atlantic Deep Water cell as well as the Indonesian through flow in the global scale of the overturning, but completely misses the Antarctic Bottom Water cell.

Global Warming

Global Warming is the increase in the average temperature of the Earth's near surface air and oceans since the mid-20th century and its projected continuation. (Wikipedia)

Global Temperature Change (°C)

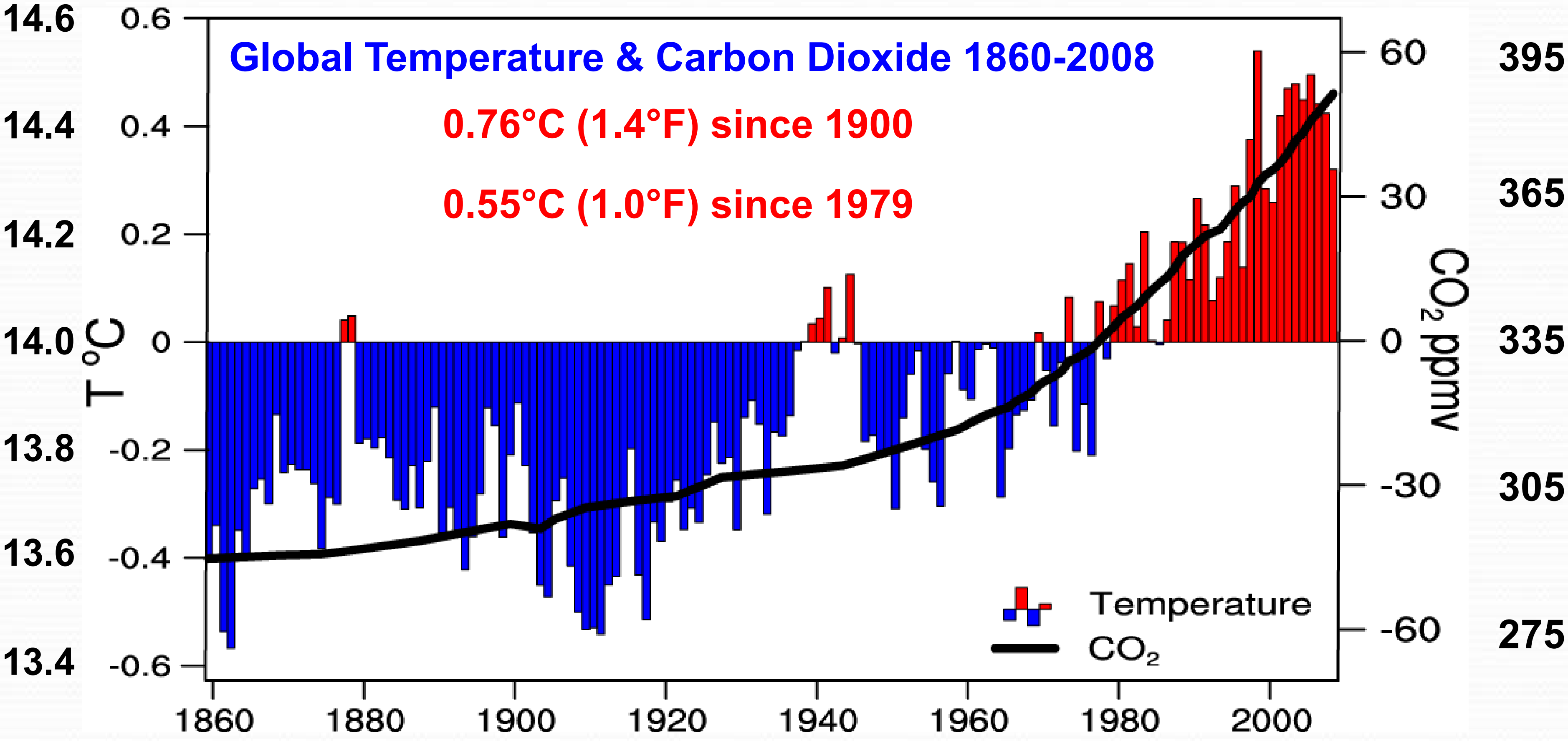


0.76°C (1.4°F) since 1900

0.55°C (1.0°F) since 1979

An Elegant Science Question:

Are increases in greenhouse gases responsible for increase in global mean temperature (global warming)?

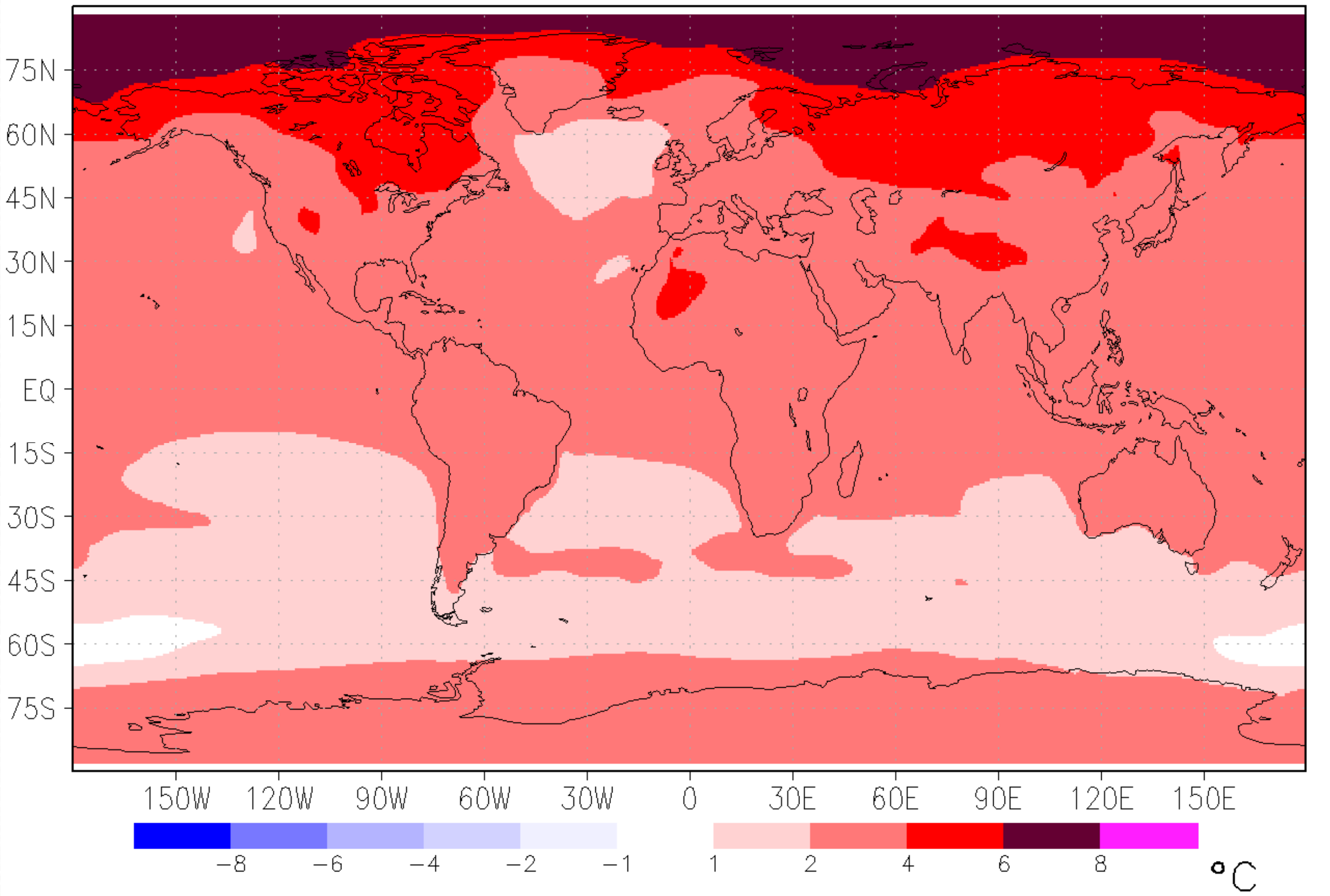


COLA
GEORGE MASON UNIVERSITY

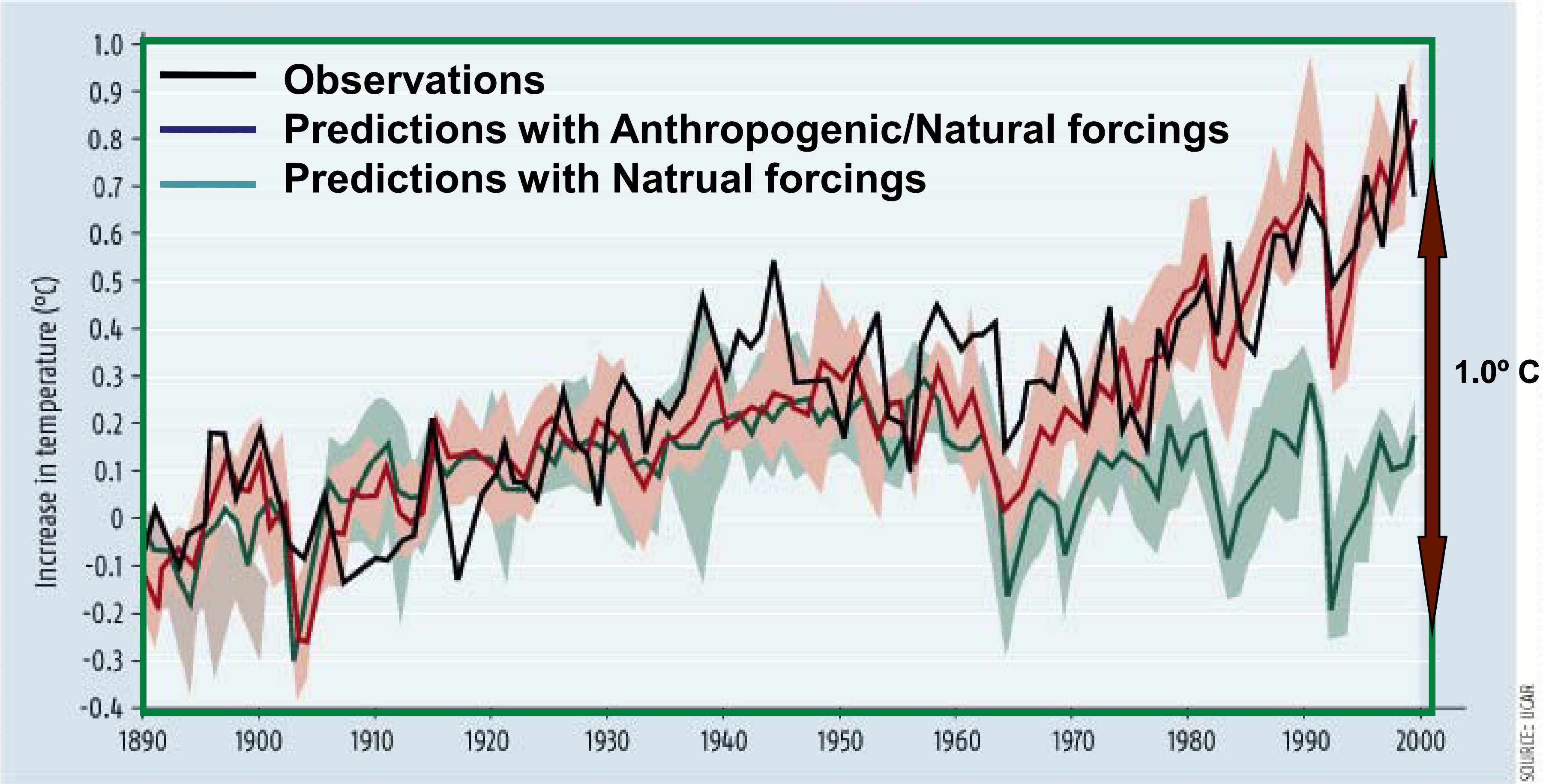
Key Assertions of Global Warming Theory

Global Warming is Real

(Sresa1b YR 71-100) minus (20c3m 1969-98), Global Average = 2.61

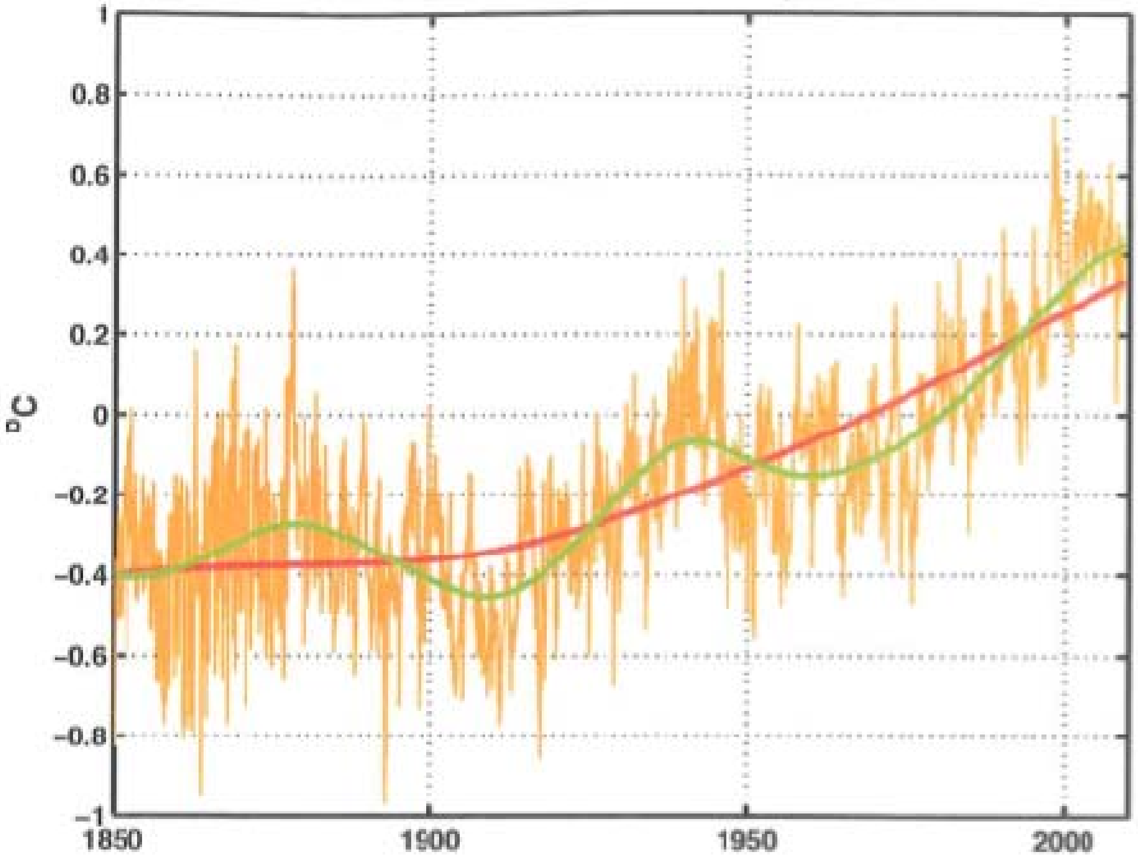


Increase in Surface Temperature



IPCC 2007

Global-mean Surface Temperature



On the Time-Varying Trend in Global-Mean Surface Temperature
by Huang, Wu, Wallace, Smoliak, Chen, Tucker
EEMD: Ensemble Empirical Mode Decomposition; MDV: Multi Decadal Variability

Figure 4: Reconstruction of the raw GST time series (brown lines) using ST only (red lines) and ST + MDV (green lines).

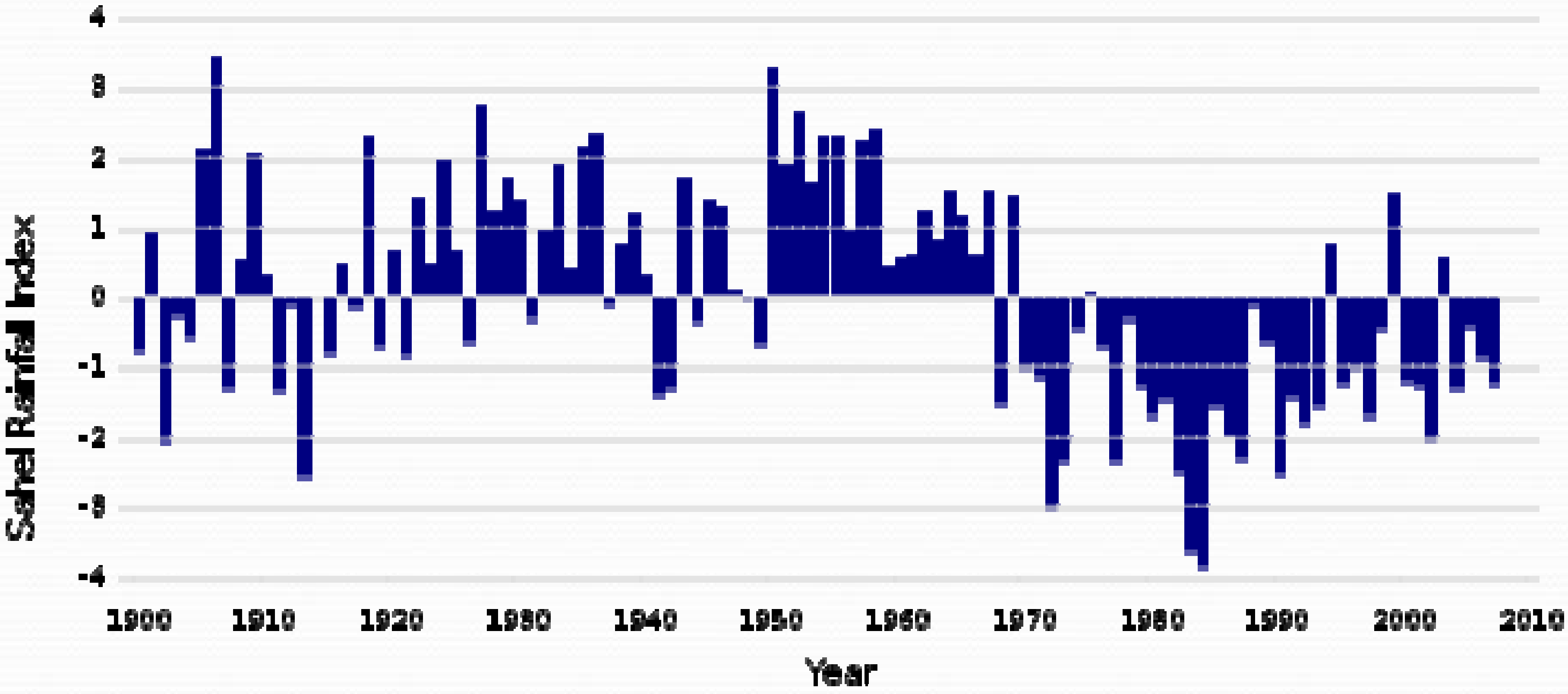
" I think the causes of the General Trade-Winds have not been fully explained by any of those who have wrote on that subject…." ***(George Hadley, 1735)***

"The (above) opening words of Hadley's classical paper afford an apt description of the state of the same subject today." ***(Edward N. Lorenz, 1967)***

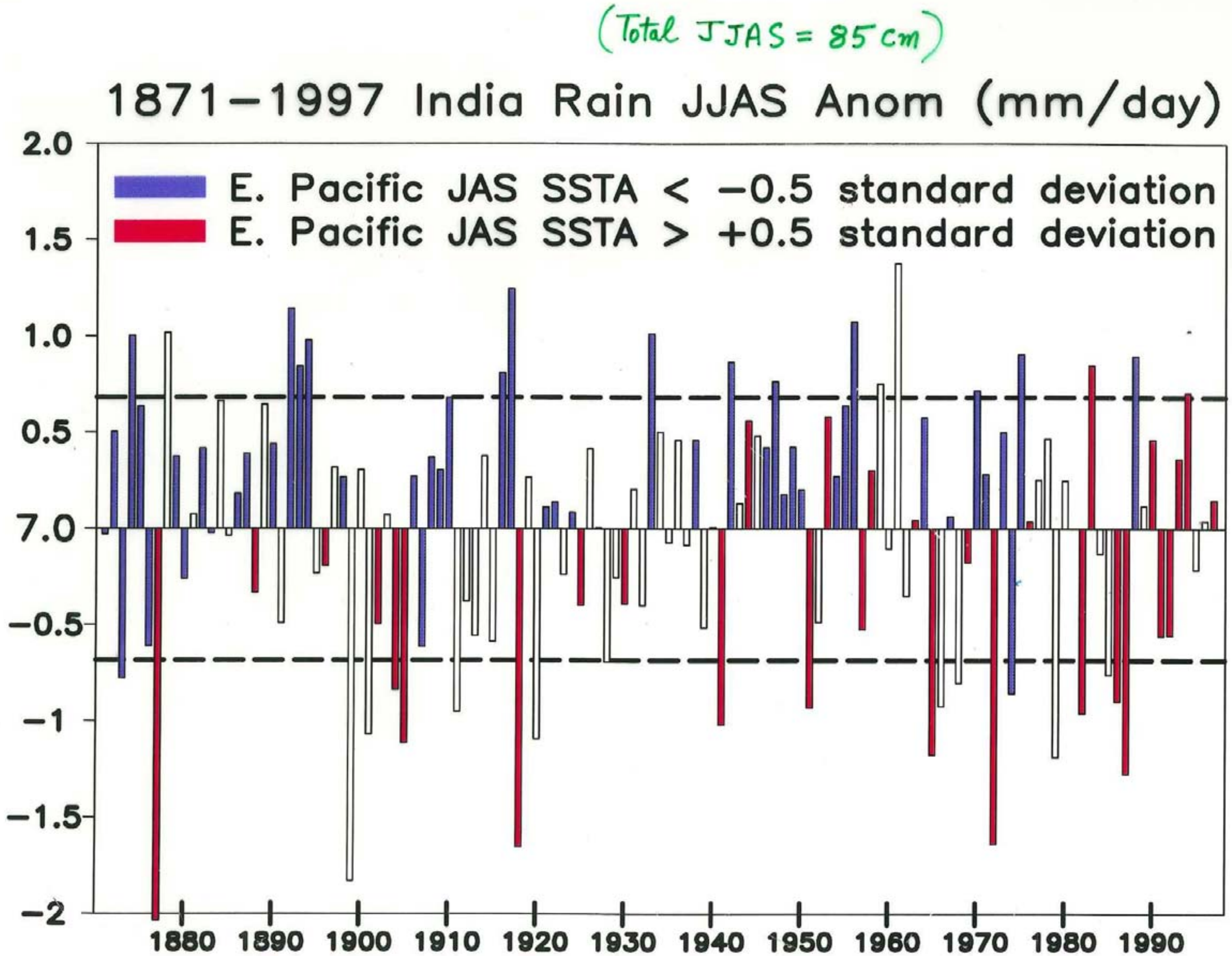
THANK YOU!

ANY QUESTIONS?

Sahel Rainfall (1900-2007)



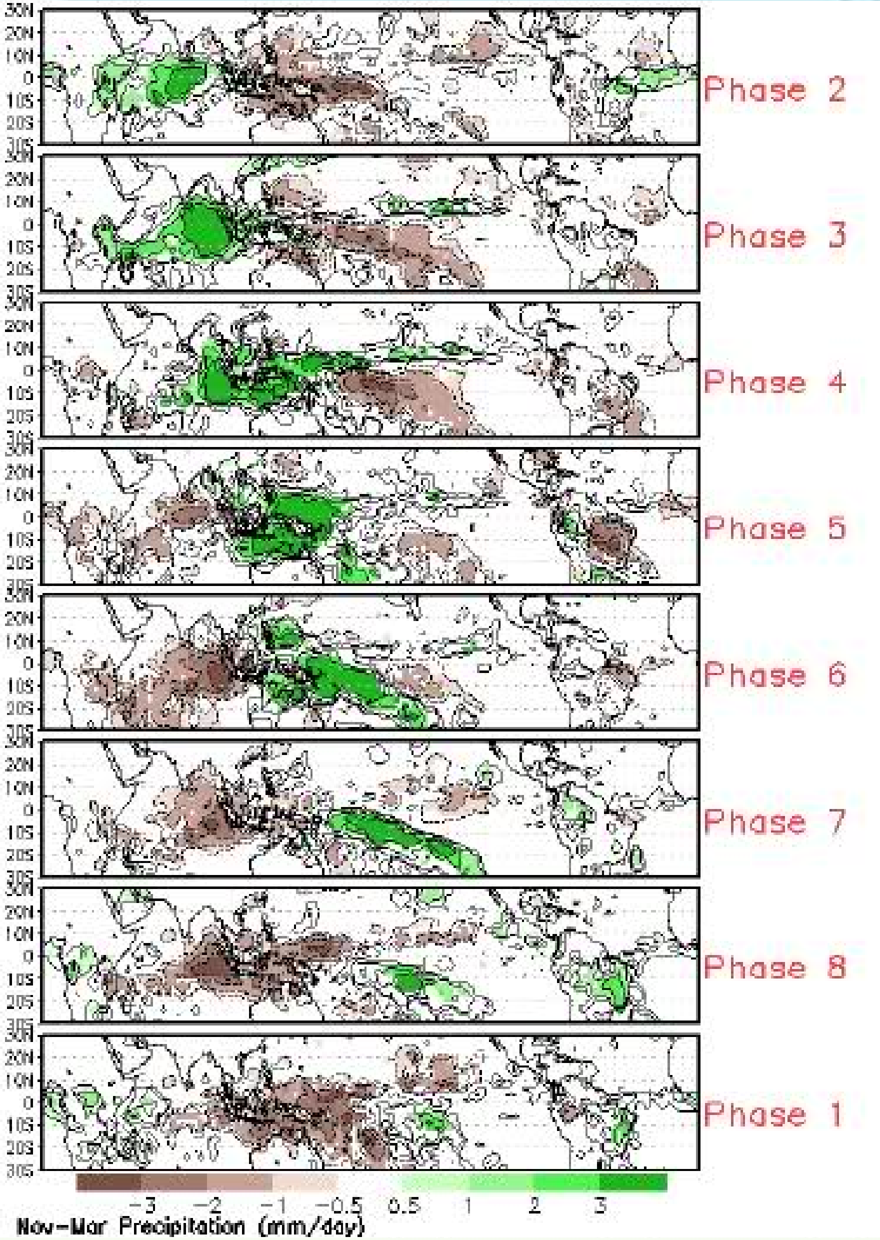
Sahel rainfall index (JJASO mean anomaly, 10-20°N, 20°W-10°E)



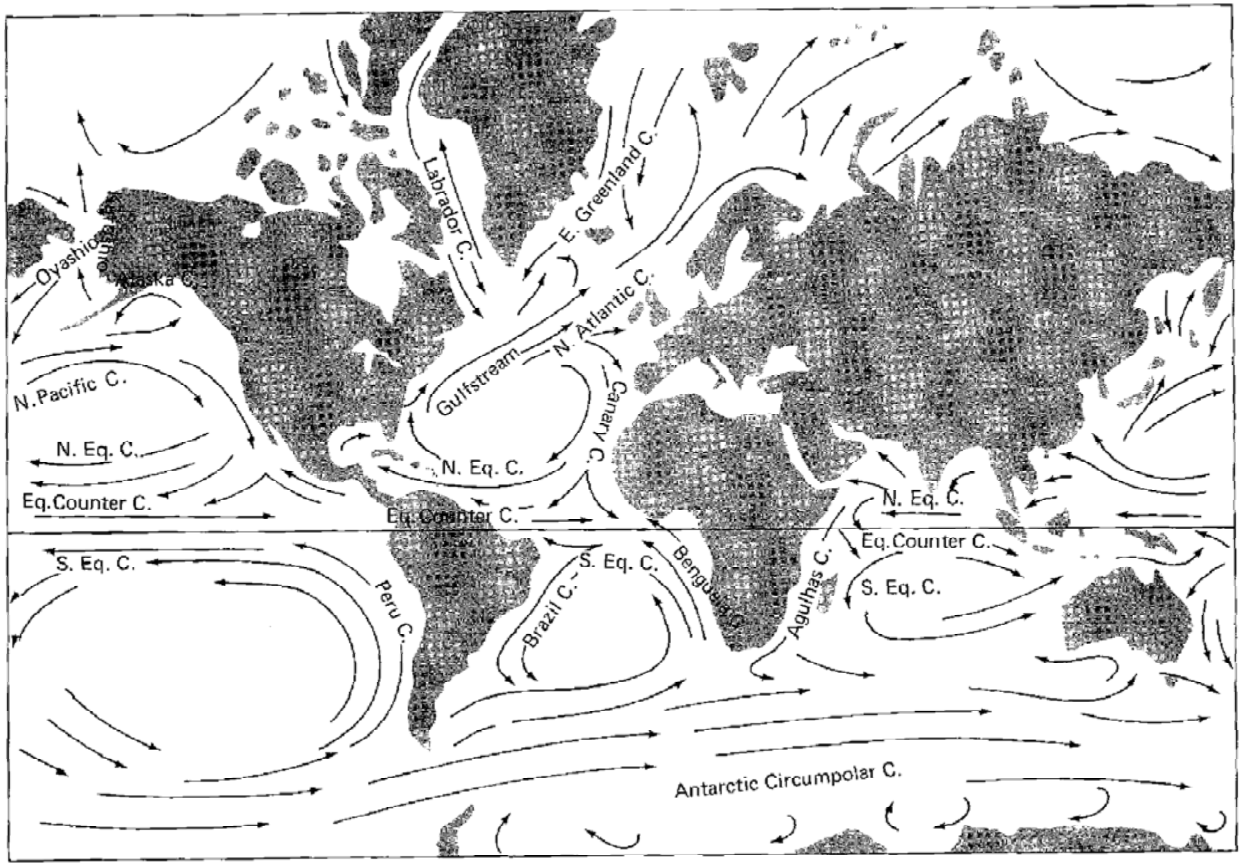
COLA Center for Ocean-Land-Atmosphere Studies

GEORGE MASON UNIVERSITY

Eastward propagating MJO (composite rainfall)

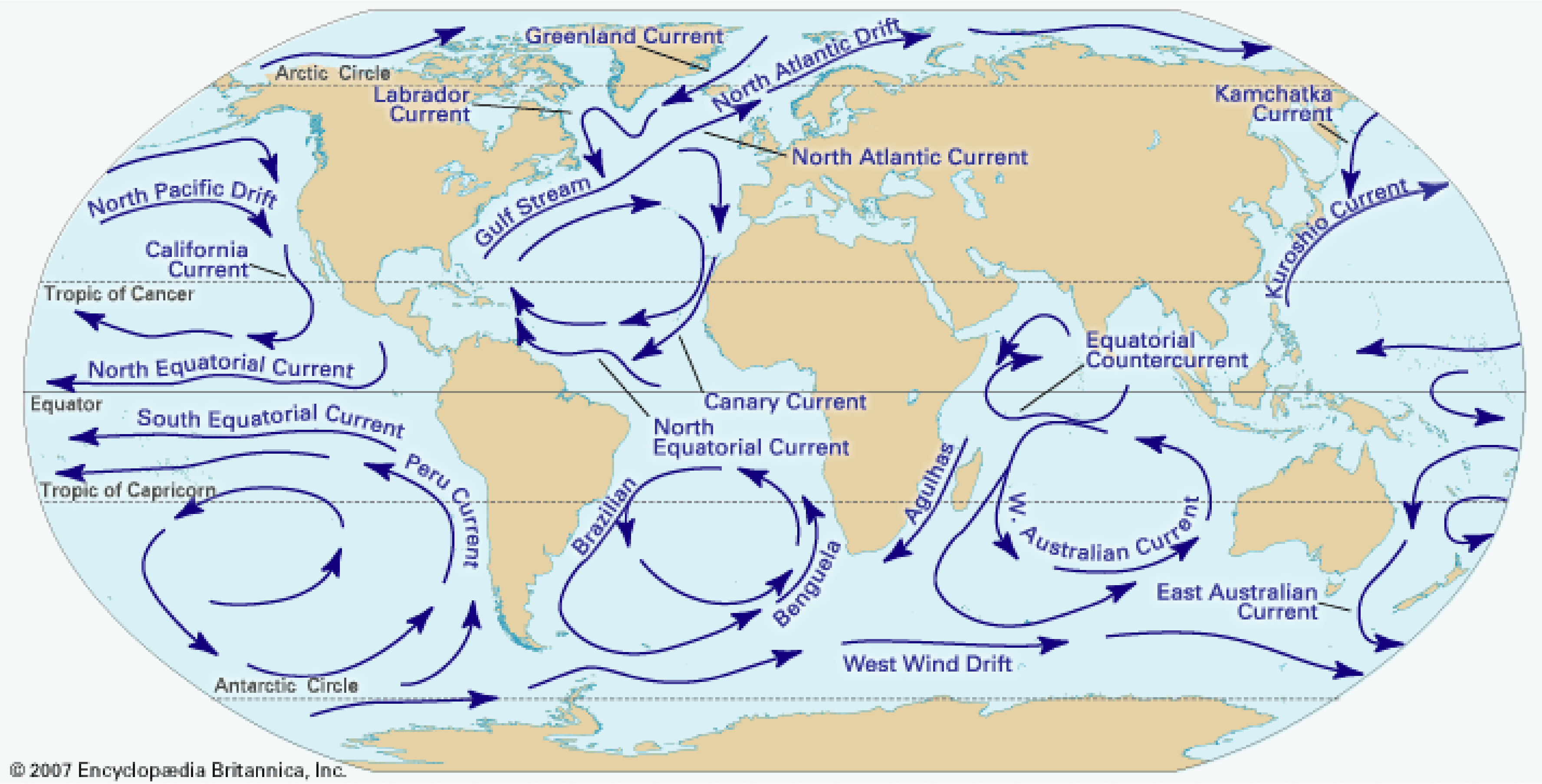


Schematic Picture of the Major Surface Currents of the World Oceans



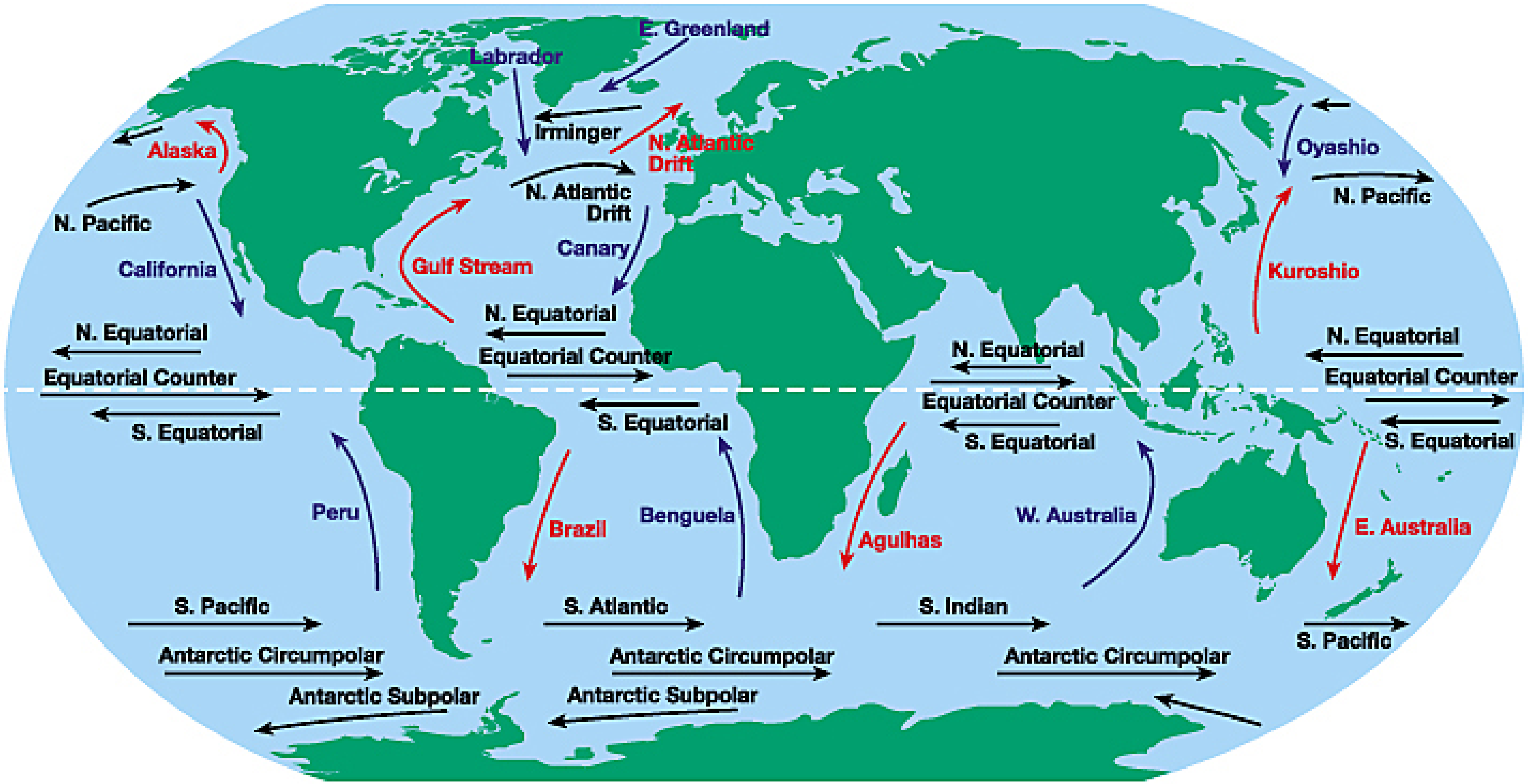
Note the anticyclonic circulation in the subtropics (the subtropical gyres)

Schematic Picture of the Major Surface Currents of the World Oceans



Note the anticyclonic circulation in the subtropics (the subtropical gyres)

Schematic Picture of the Major Surface Currents of the World Oceans



Note the anticyclonic circulation in the subtropics (the subtropical gyres)

COLA Center for Ocean-Land-Atmosphere Studies

GEORGE MASON UNIVERSITY

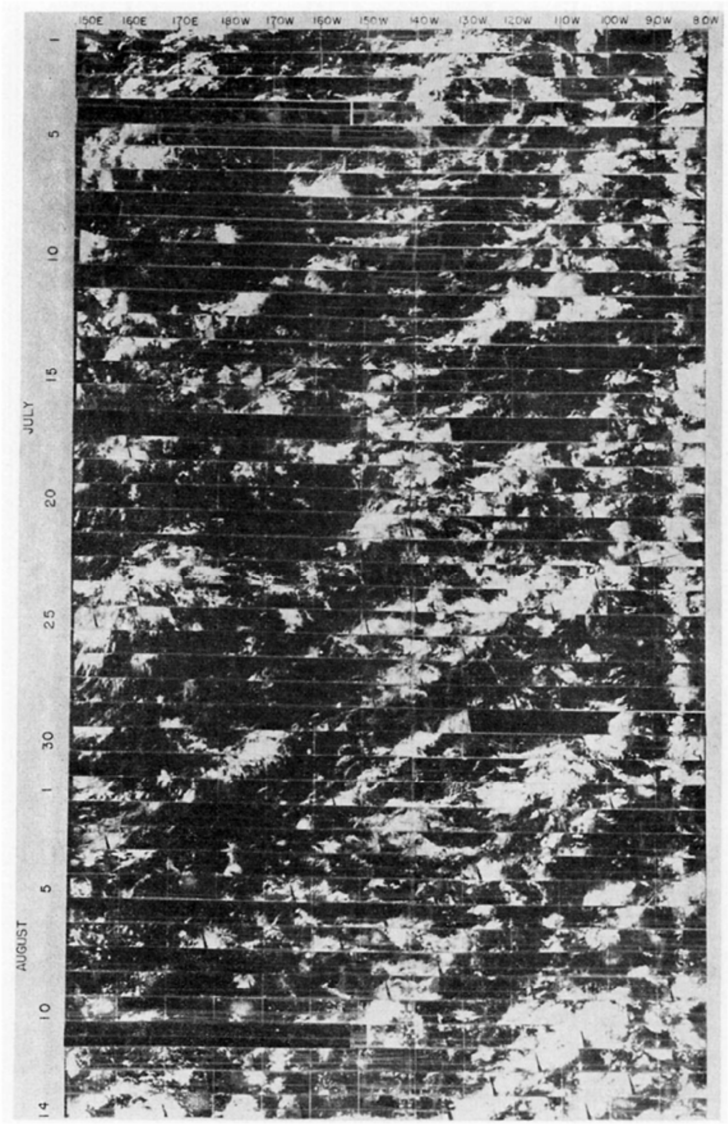


Fig. 2. Time-longitude section of satellite photographs of the period 1 July–14 August 1967 for the 10–15N latitude band in Pacific. The following data are missing: 4 July (150E–155W), 8 July (150E–160W), 17 July (150E–150W, 130W–100W), 29 July (130W–100W), 11 August (150E–150W).

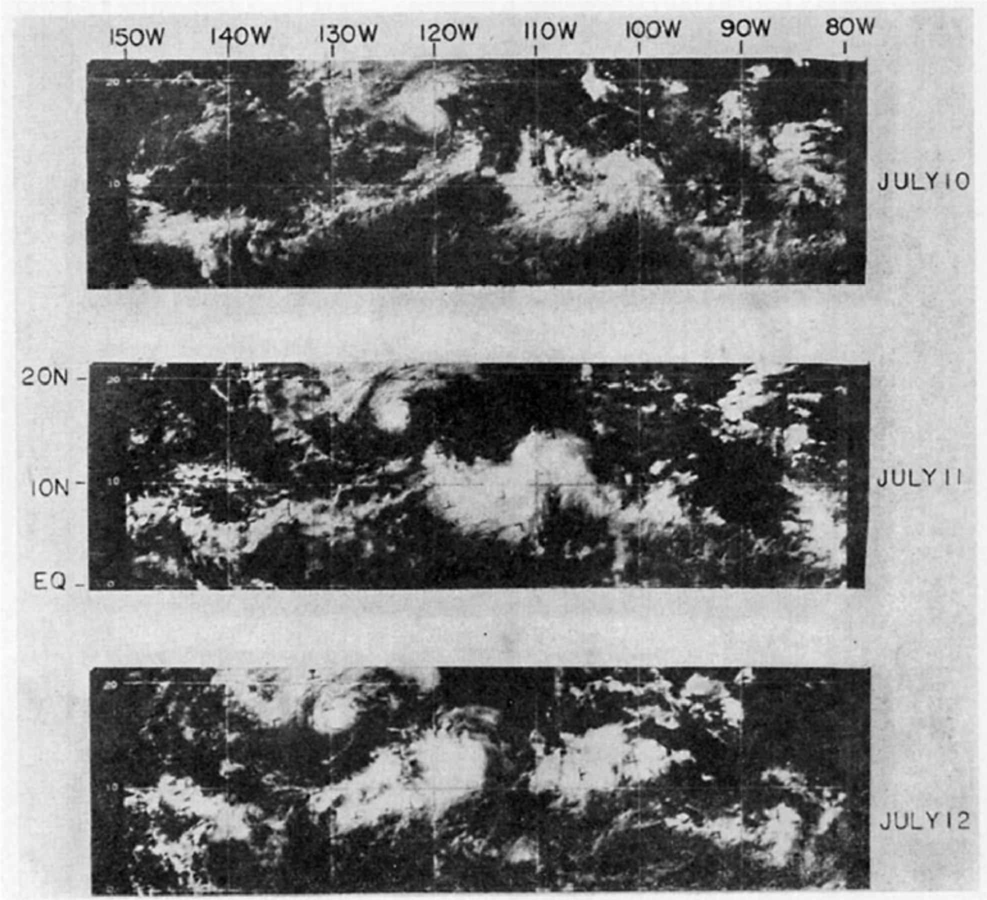
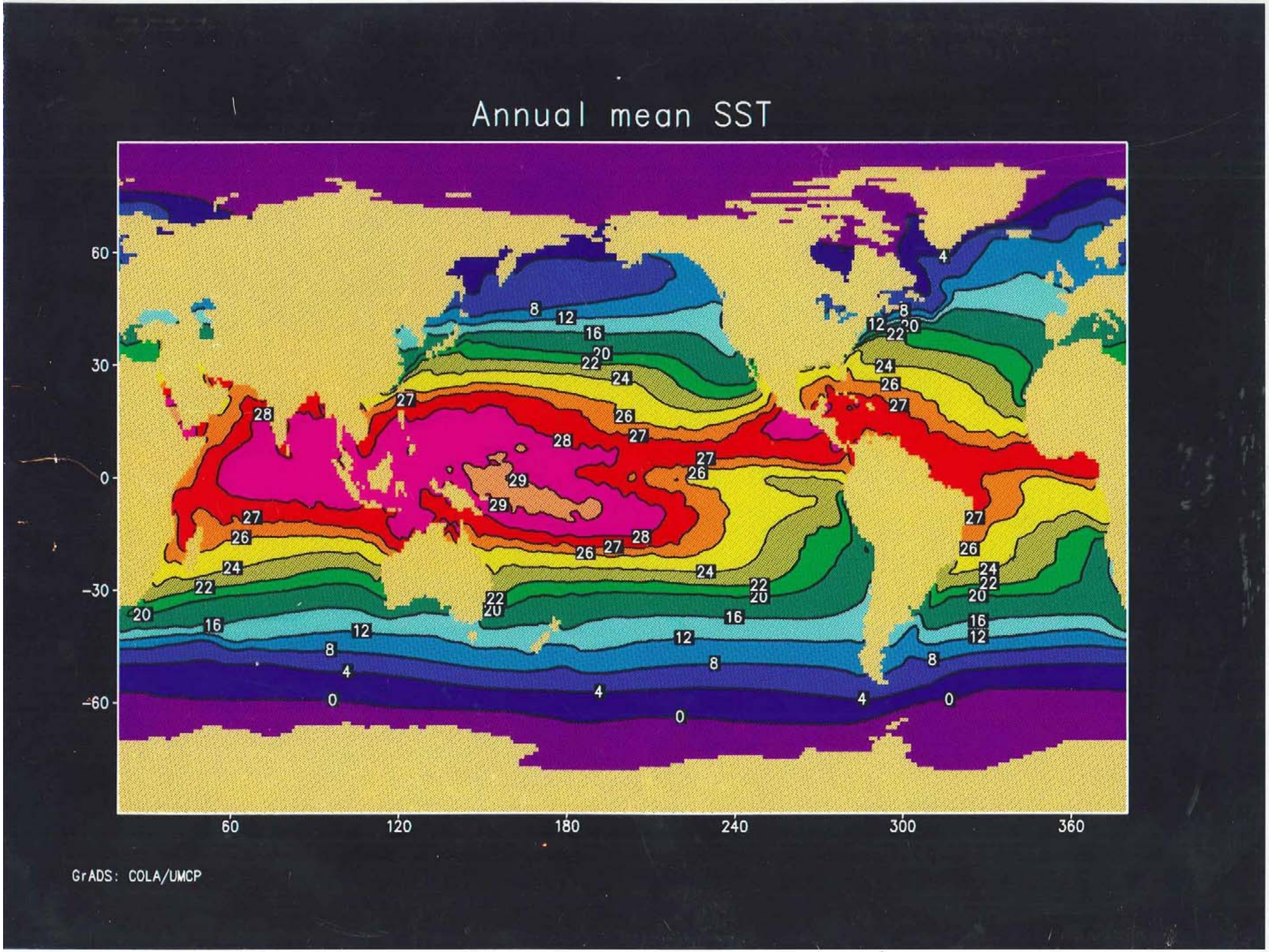
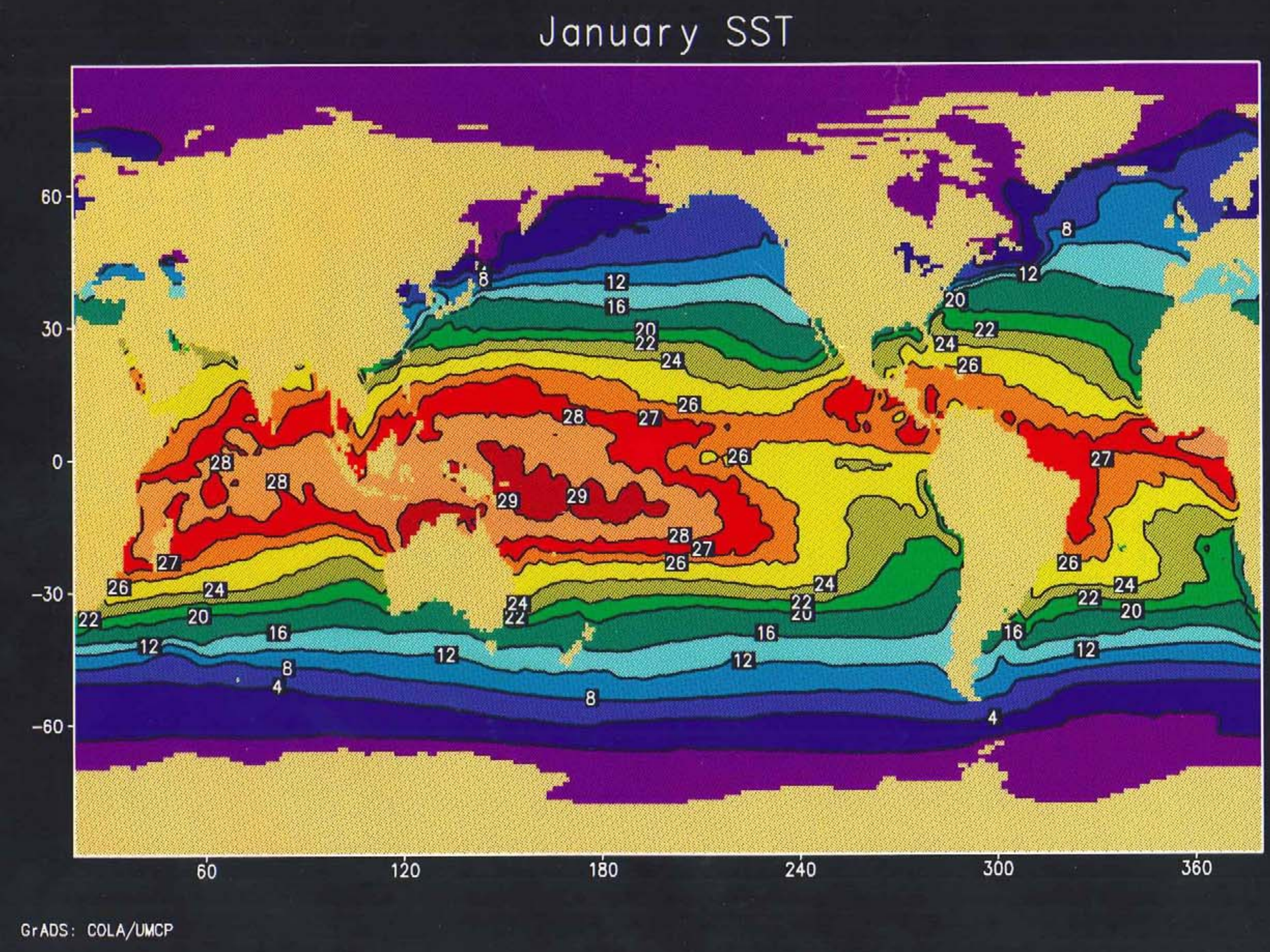
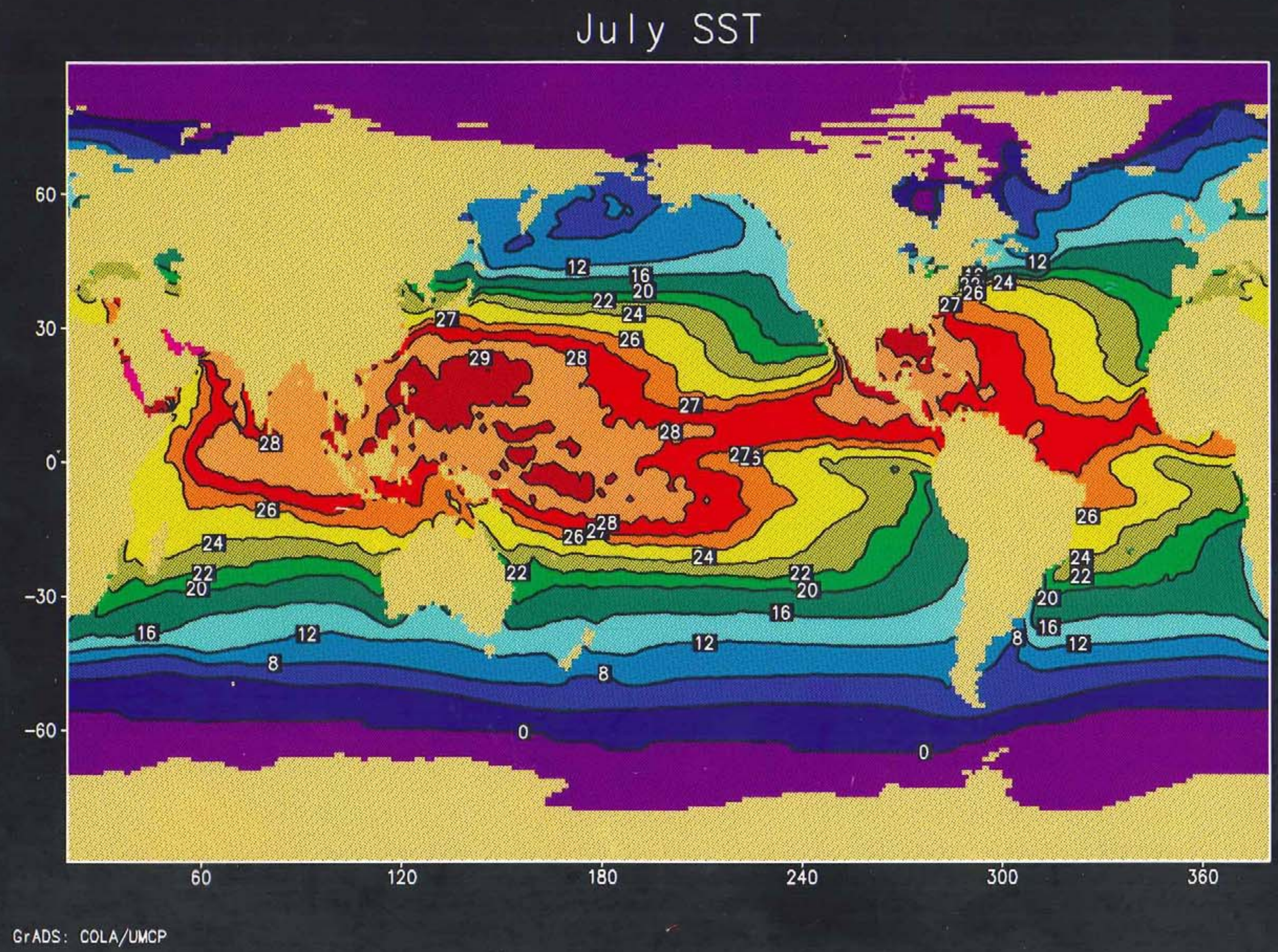
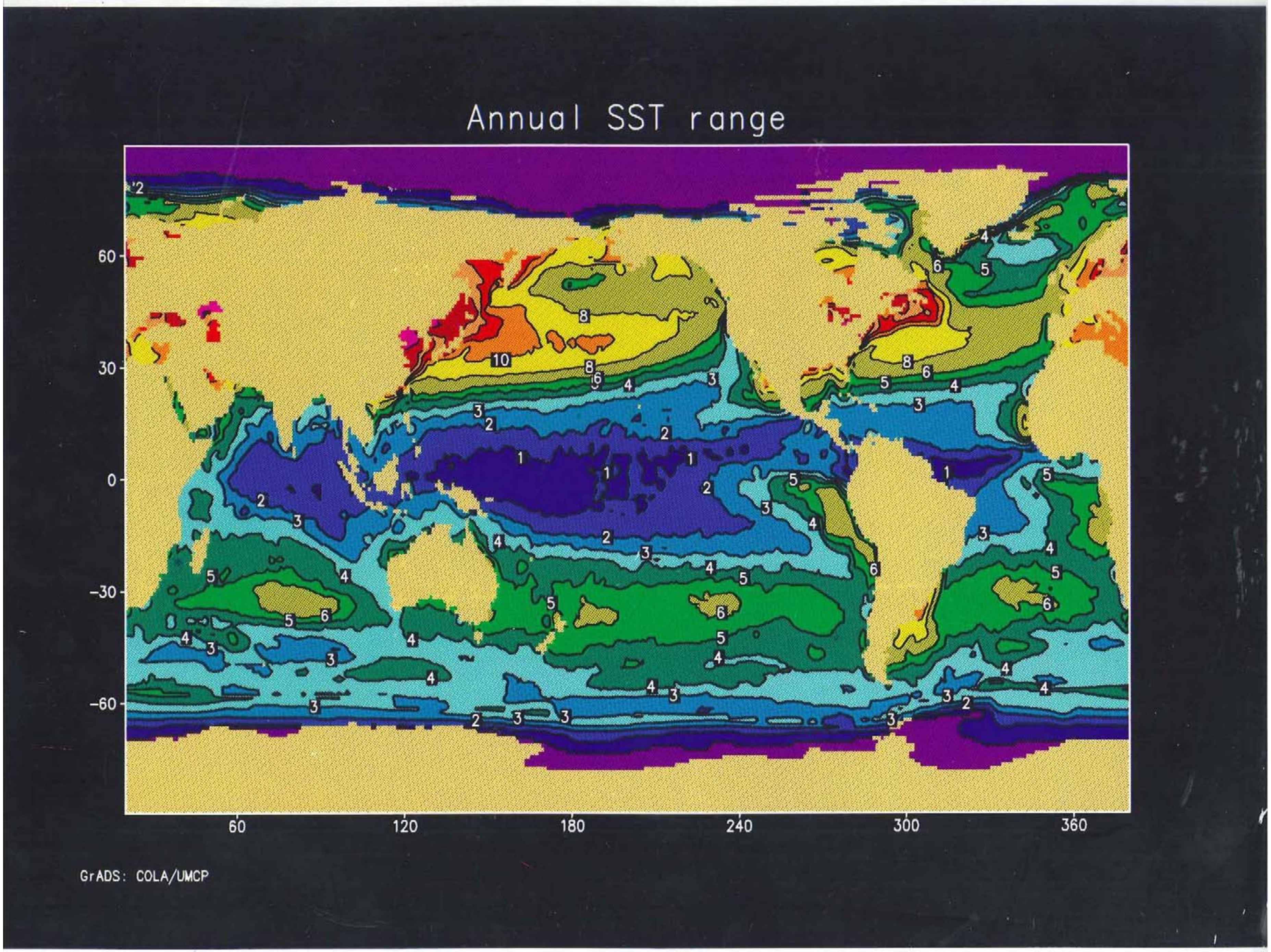


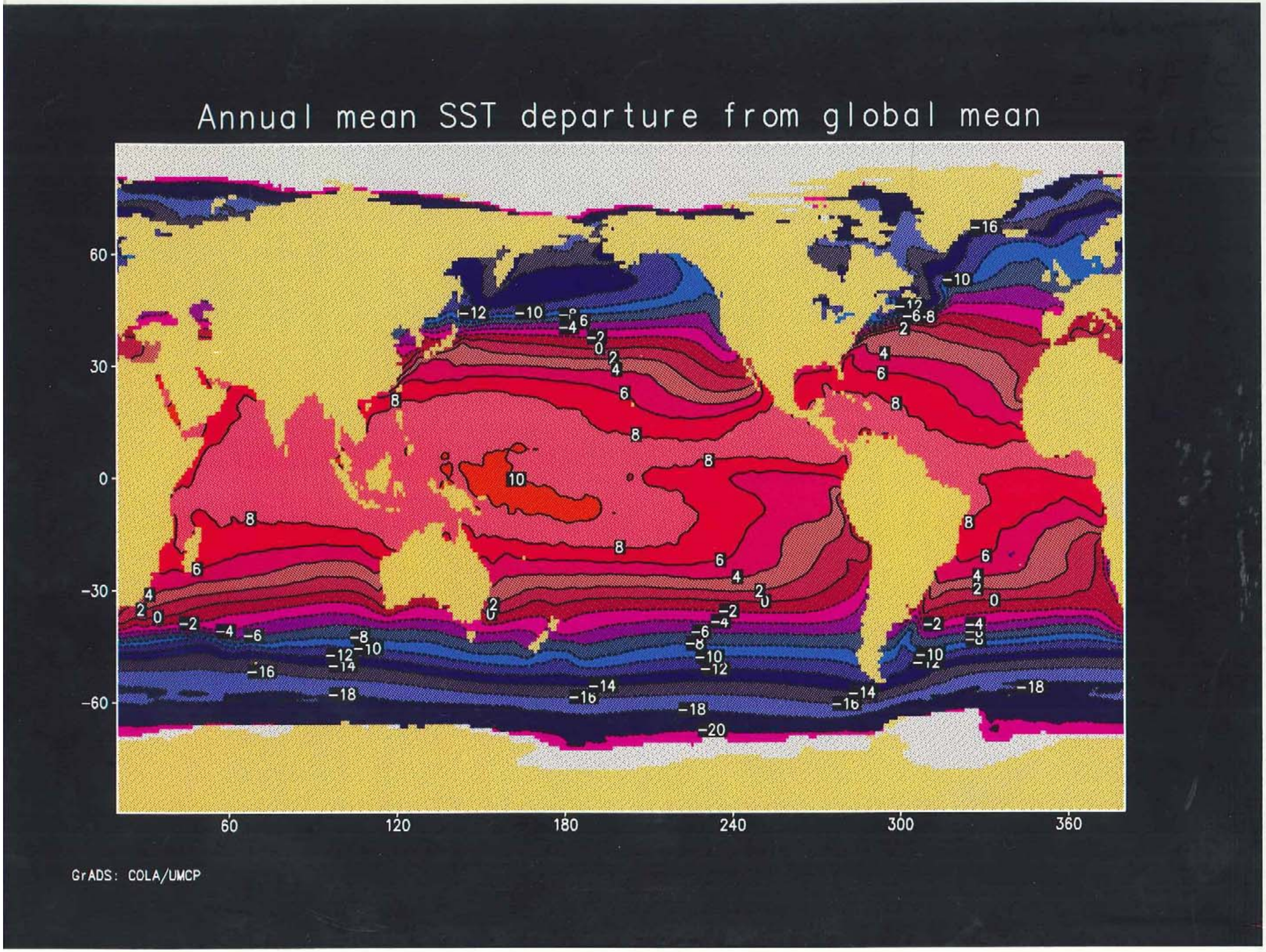
FIG. 3. Successive daily satellite photographs for 10–12 July 1967.


Annual mean SST
60
30
0
-30
-60
60
120
180
240
300
360
GrADS: COLA/UMCP

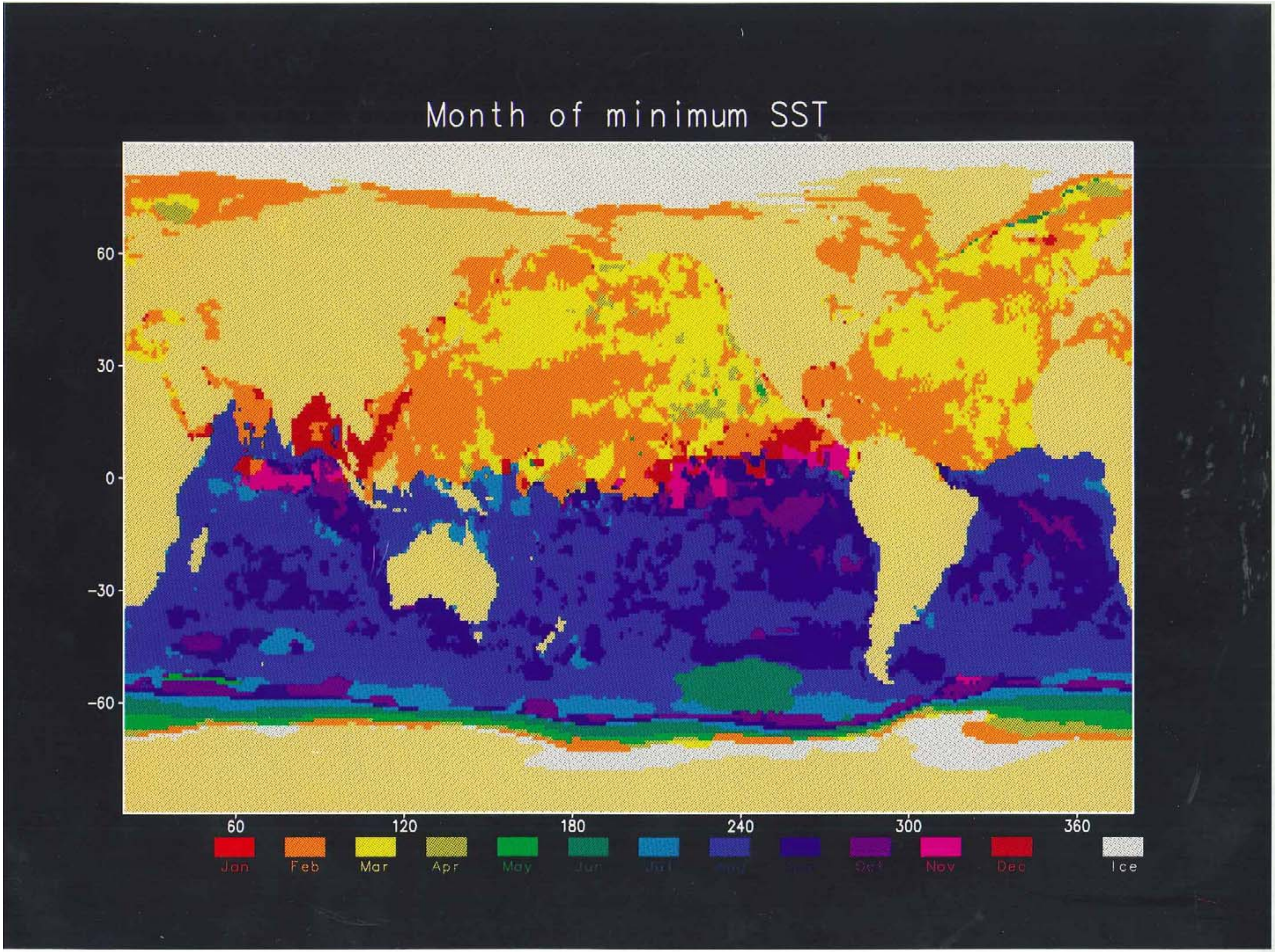

January SST
60
30
0
-30
-60
60
120
180
240
300
360
GrADS: COLA/UMCP


July SST
60
30
0
-30
-60
60
120
180
240
300
360
GrADS: COLA/UMCP

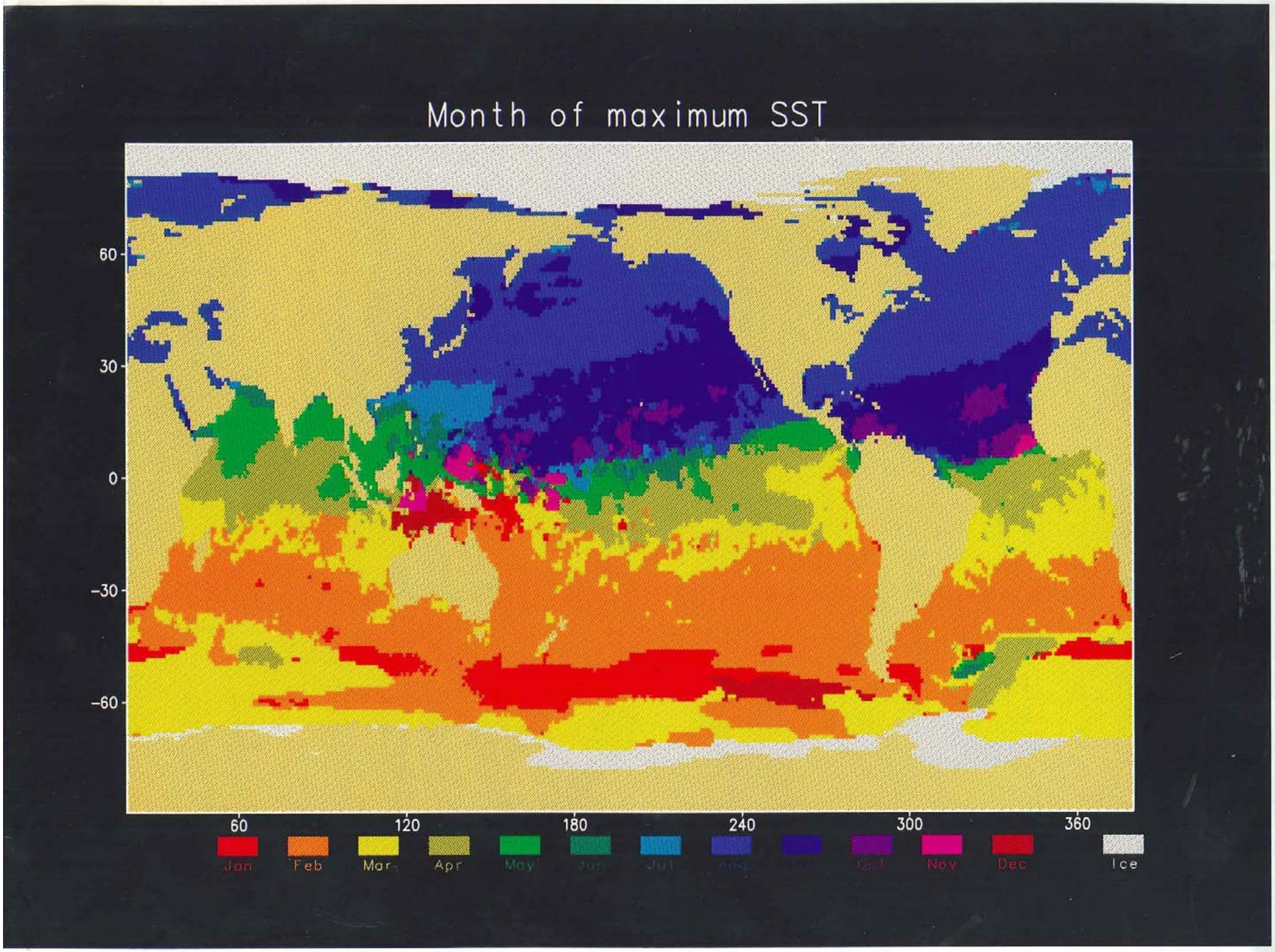

Annual SST range
60
30
0
-30
-60
60
120
180
240
300
360
GrADS: COLA/UMCP

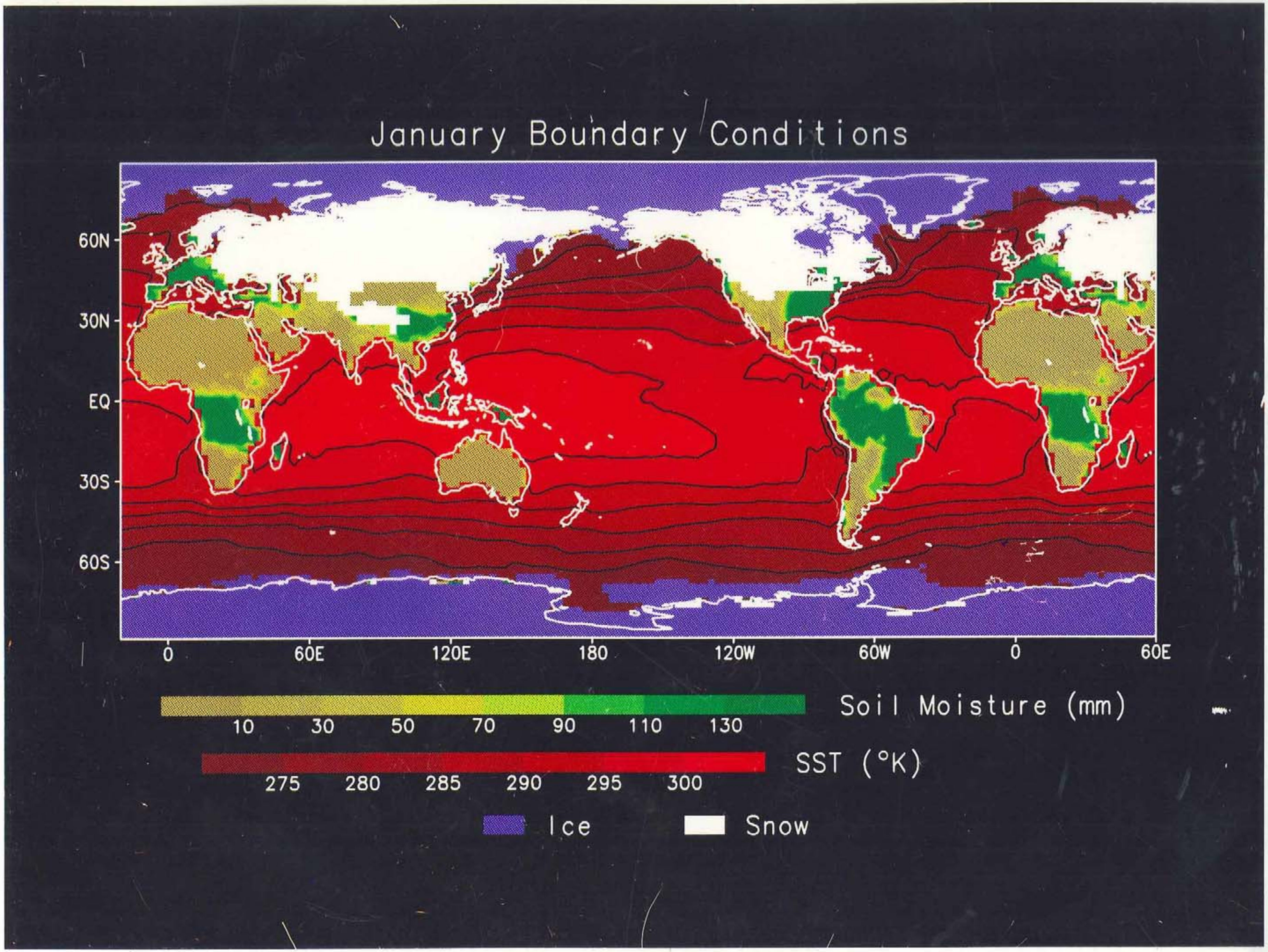


Annual mean SST departure from global mean
60
30
0
-30
-60
60
120
180
240
300
360
GrADS: COLA/UMCP



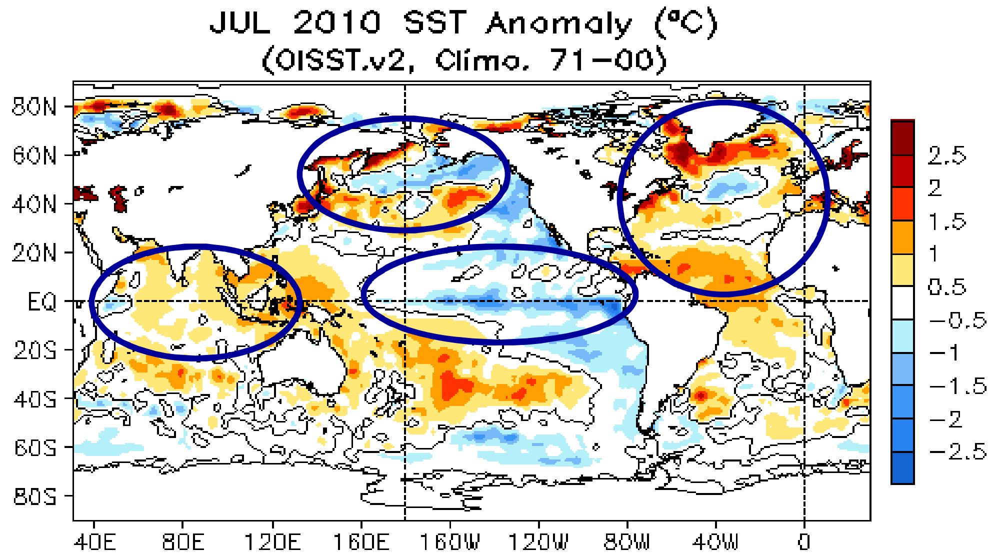
Month of minimum SST
60
30
0
-30
-60
60
120
180
240
300
360
Jan
Feb
Mar
Apr
May
Nov
Dec
Ice


Month of maximum SST
60
30
0
-30
-60
60
120
180
240
300
360
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Nov
Dec
Ice

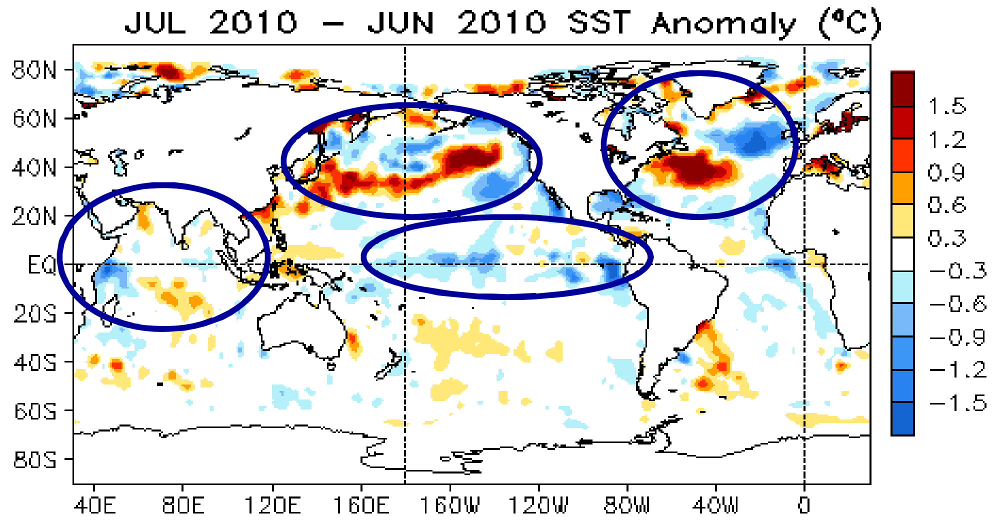


January Boundary Conditions
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
60E
Soil Moisture (mm)
10
30
50
70
90
110
130
SST (°K)
275
280
285
290
295
300
Ice
Snow

Global SST Anomaly (^{0}C) and Anomaly Tendency (from CPC)



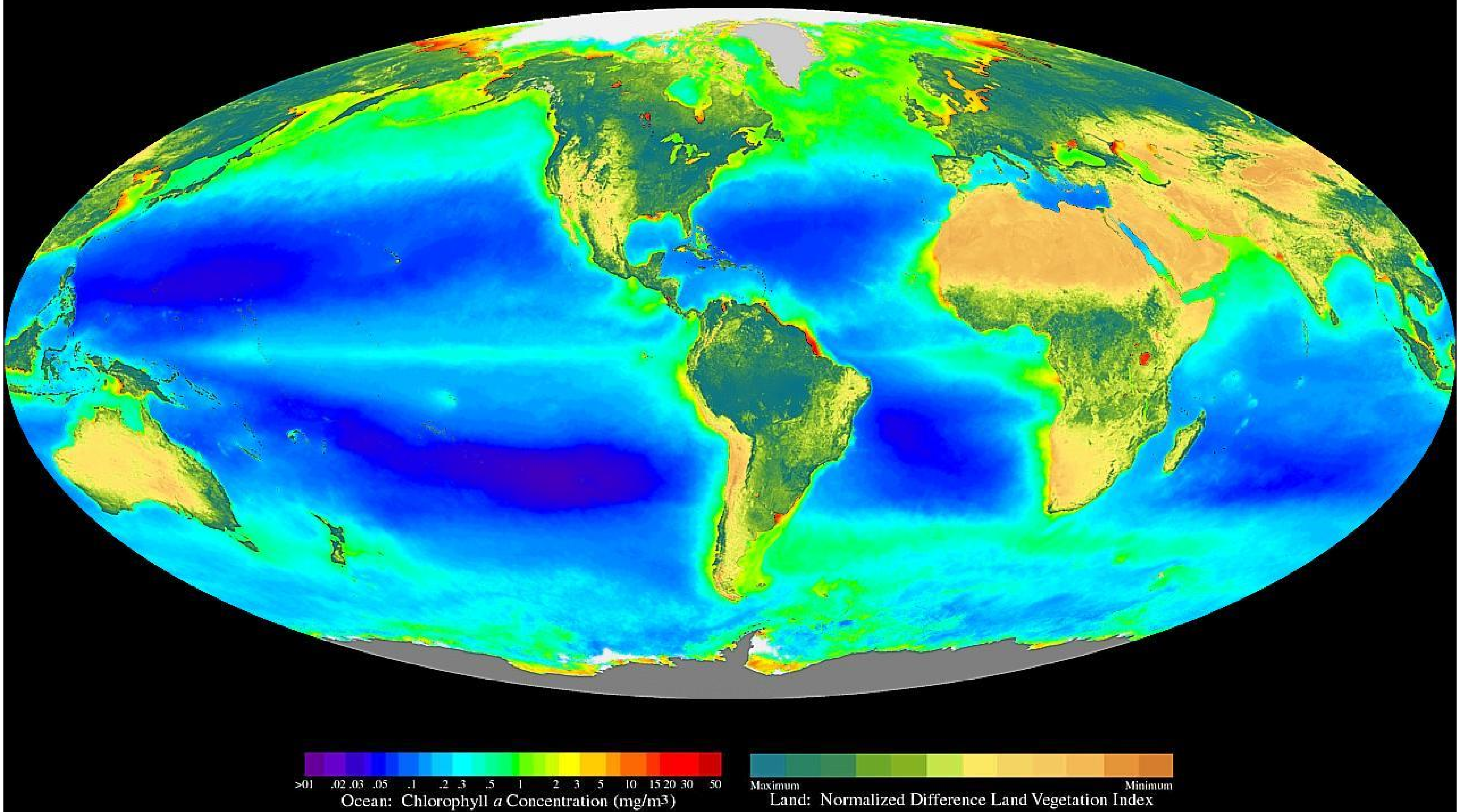
- Negative SSTA presented in the tropical eastern and central Pacific, consistent with La Niña conditions.
- Negative PDO SST pattern presented in N. Pacific.
- Positive SSTA presented in the tropical Indian Ocean and tropical W. Pacific.
- Tripole SST anomaly pattern persisted in North Atlantic, and positive SSTA in the tropical North Atlantic has been near historical high during Mar-Jul 2010.



- SSTA continuously decreased in the central and eastern tropical Pacific, suggesting strengthening of La Niña conditions.
- SST tendency was large in N. Pacific.
- Both positive and negative SST tendency existed in the tropical Indian Ocean.
- Tripole SSTA tendency pattern suggested the persistency and slightly northward shift of the tripole SSTA pattern in North Atlantic.

Fig. G1. Sea surface temperature anomalies (top) and anomaly tendency (bottom). Data are derived from the NCEP OI SST analysis, and anomalies are departures from the 1971-2000 base period means.

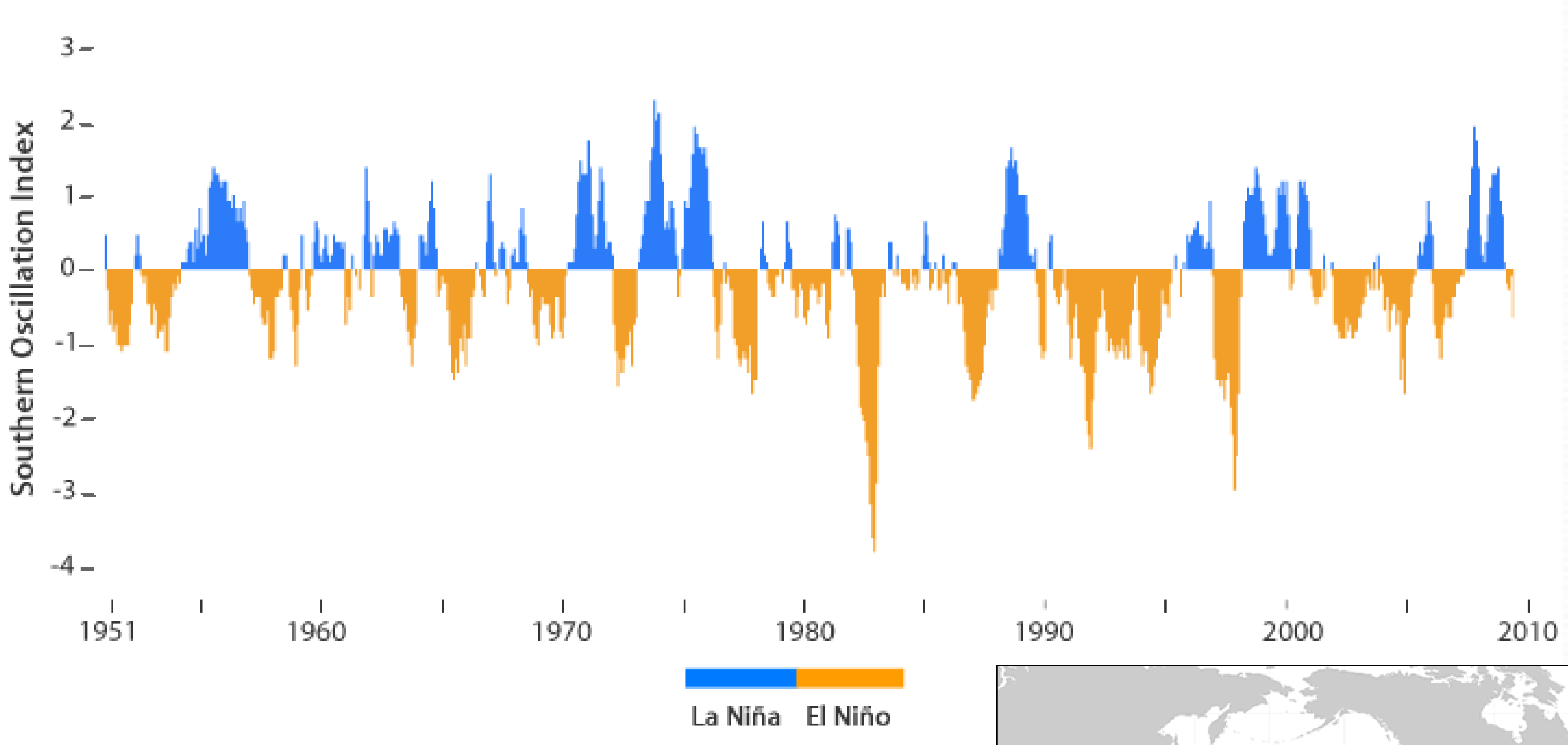
SeaWiFS Global Biosphere September 1997 – August 2000
Three Year Anniversary

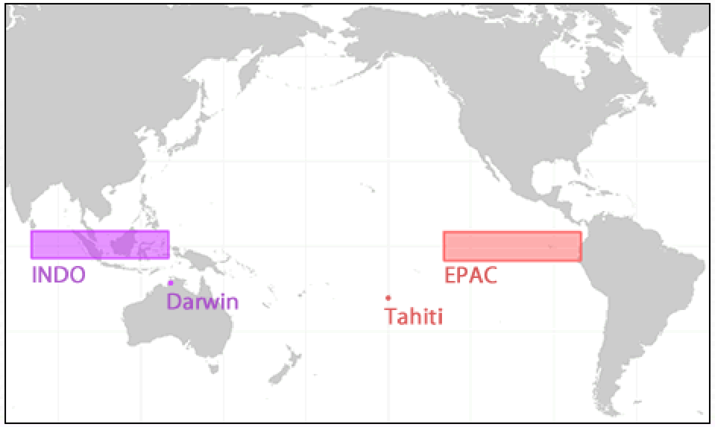


COLA Center for Ocean-Land-Atmosphere Studies

GEORGE MASON UNIVERSITY

Southern Oscillation Index (SOI)

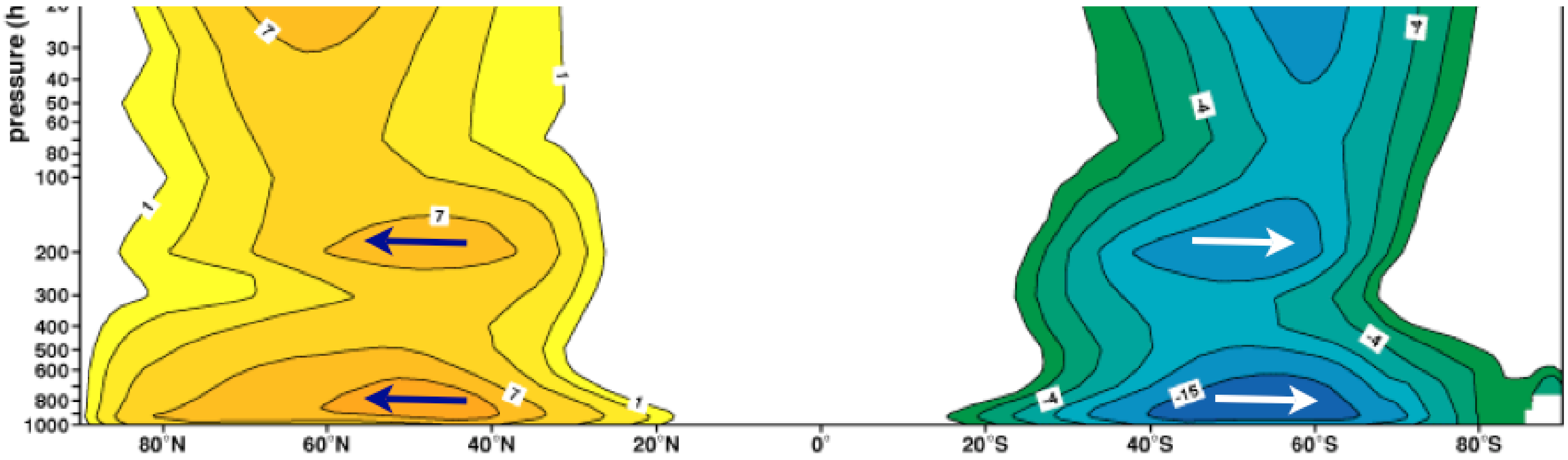




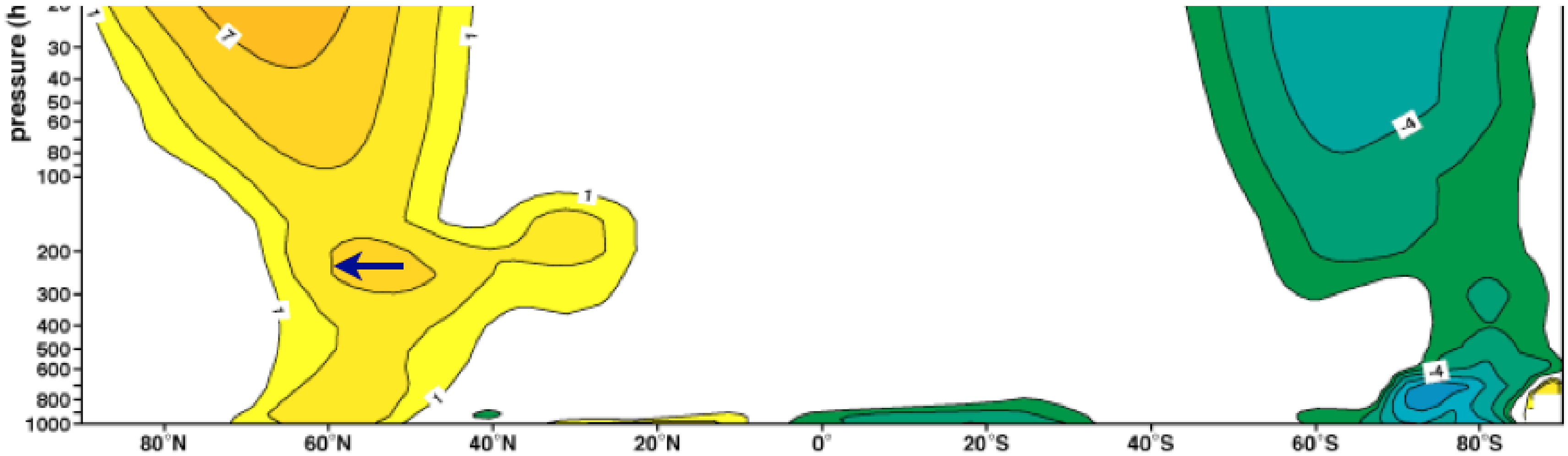
The Southern Oscillation Index or SOI represents the difference in average air pressure measured at Tahiti and Darwin, Australia. More specifically, the SOI is calculated as the difference in monthly averages of standardized mean sea level pressure at each station.

Poleward Heat Fluxes

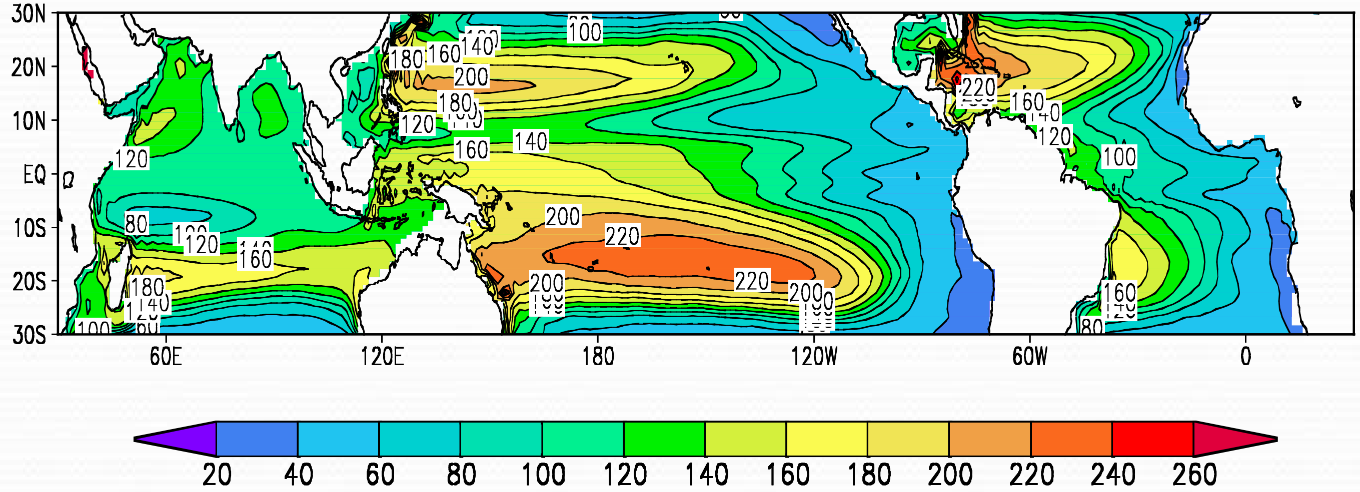
Transient eddies



Standing eddies (or stationary waves)



Mean 20°C Isotherm and Thermocline

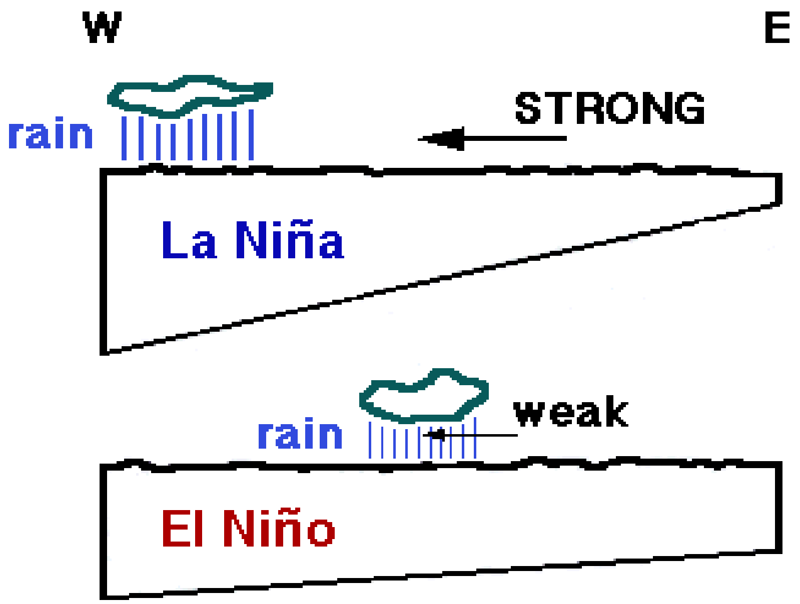


Climatology from ocean data assimilation (1958-1998)

- **The thermocline zone is sometimes characterized by the depth at which the temperature gradient is a maximum (the "thermocline depth").**
- **In the low-latitude ocean, 20°C isotherm is a good indicator of the themocline location.**
- **The maxima of the 20°C isotherm (the major warm waters in the upper ocean) are located differently from those of SST (The former is mainly determined by ocean dynamics while the latter also by surface heat flux)**

El Niño and La Niña

- Strengthening and weakening of the Hadley and Walker circulations play a crucial role in reinforcing El Niño/La Niña perturbations to the mean tropical Pacific ocean-atmosphere climatology

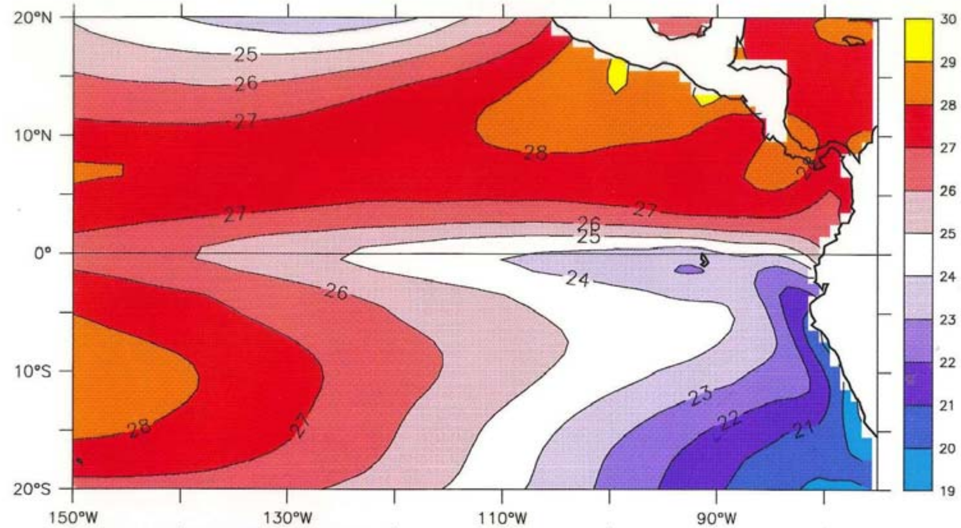


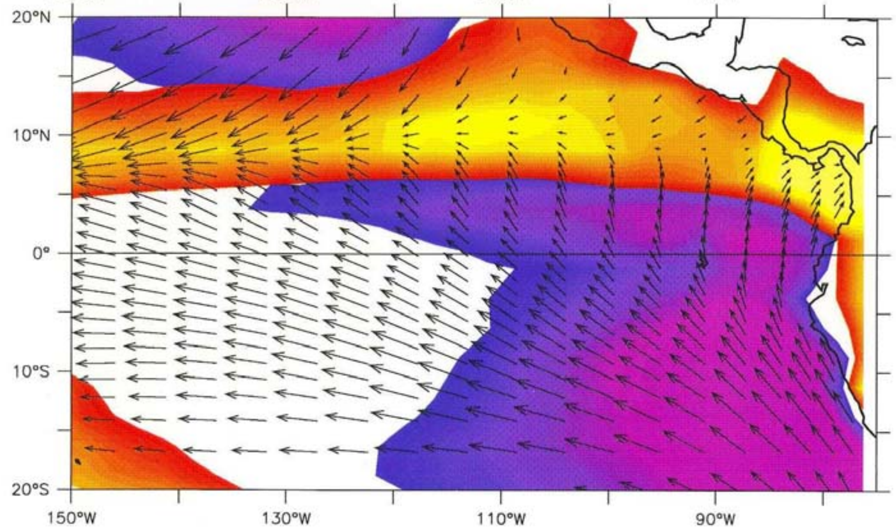
Surface Layer of Low Latitude Pacific Ocean (Warm Layer)

• La Niña Stronger than average trade winds tend to push the warm surface layer of the ocean (upper few 100 meters) towards the western end, creating a thick warm layer. It has higher than average precipitation in Australia, India & Indonesia.

• El Niño: Weaker trades relax pressure on surface ocean layer & it starts to move back across Pacific from west to east, raising SST in the eastern tropical water, including Peru, with the zone of heavy rains shifting out over the central Pacific islands.

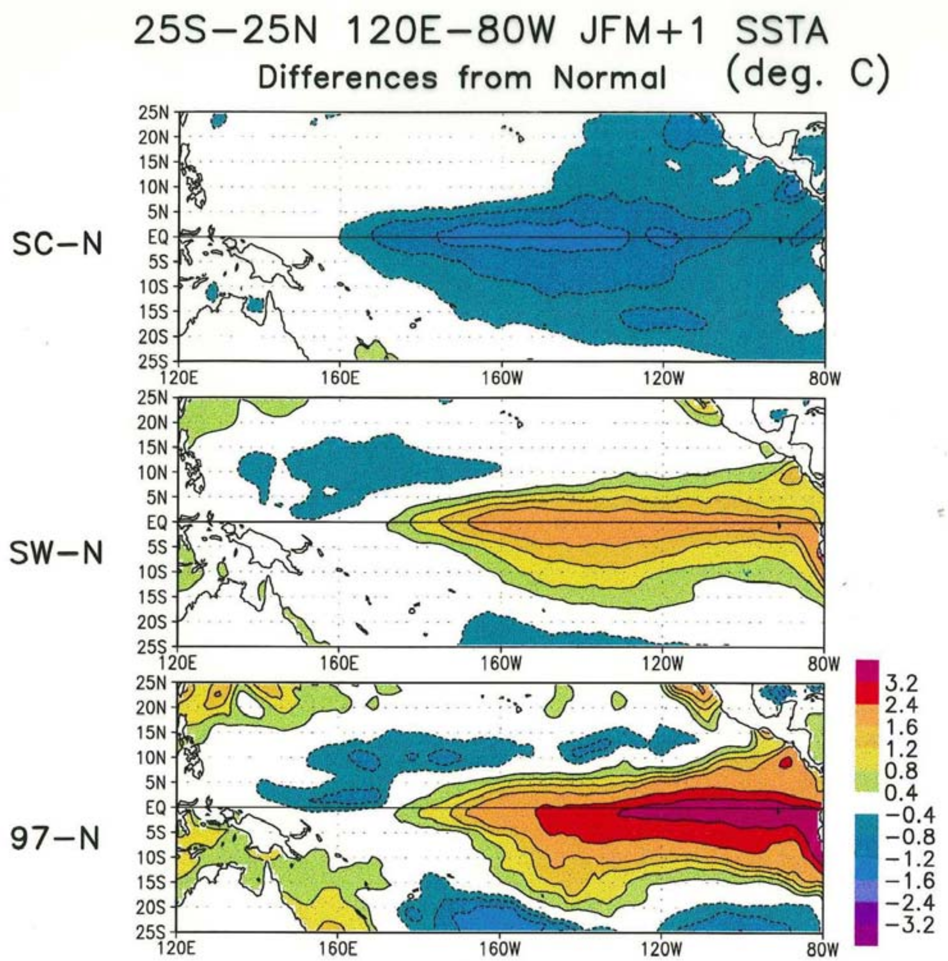
Mean SST, Winds and Clouds
in the Eastern Tropical Pacific



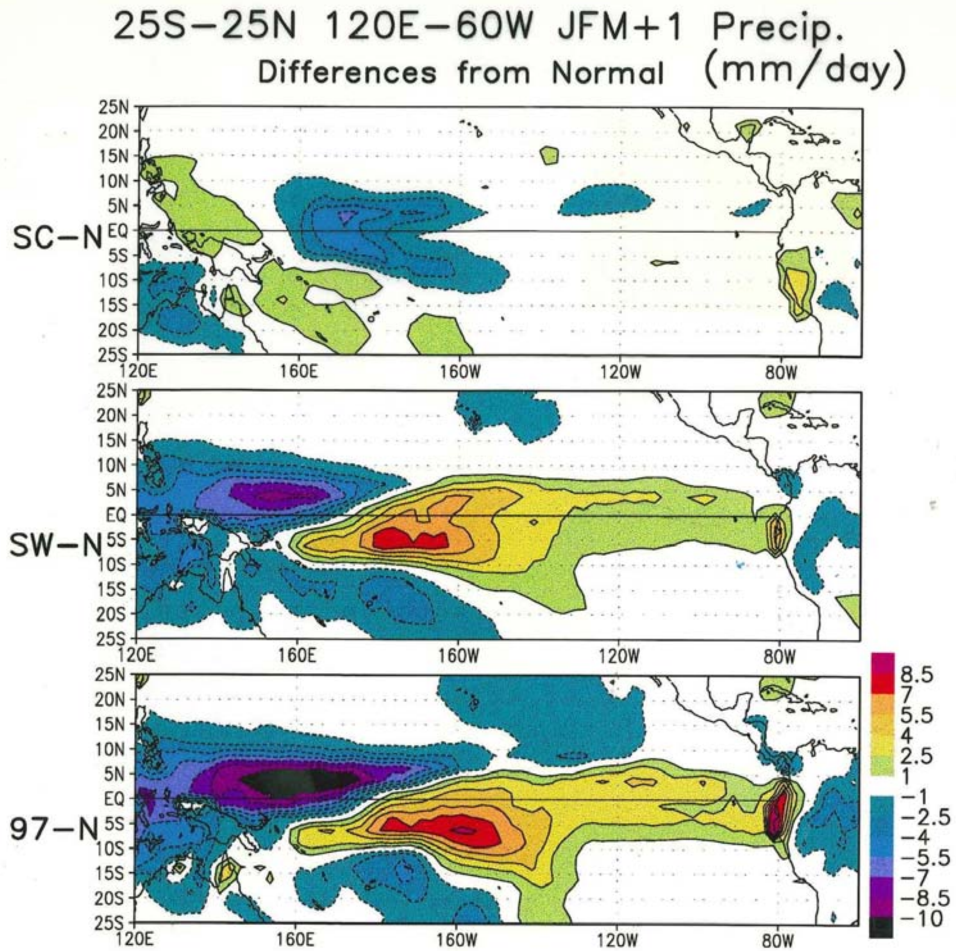


Reynolds SST (1983–94), FSU Winds (1961–90), ISCCP Clouds (1983–91)

Orange shading shows high clouds >20%, Blue shading shows stratus clouds >30%



Center for Ocean–Land–Atmosphere Studies



Center for Ocean–Land–Atmosphere Studies