Outline

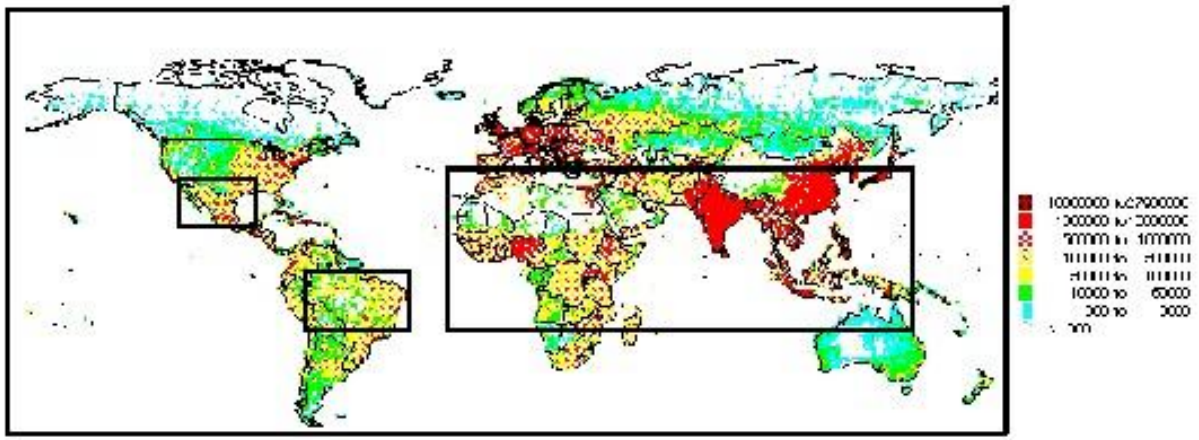
- Monsoon
- Radiative forcing
- Climate Feedbacks

Monsoon

Monsoon

- Monsoon is a climatological feature covering roughly half the tropics (1/4 of the global surface)
- Strictly, a system where the winds and precipitation reverses (summer rain, winter dry)
- Host 65% of the world's population
- Small changes in year-to-year climate can be catastrophic

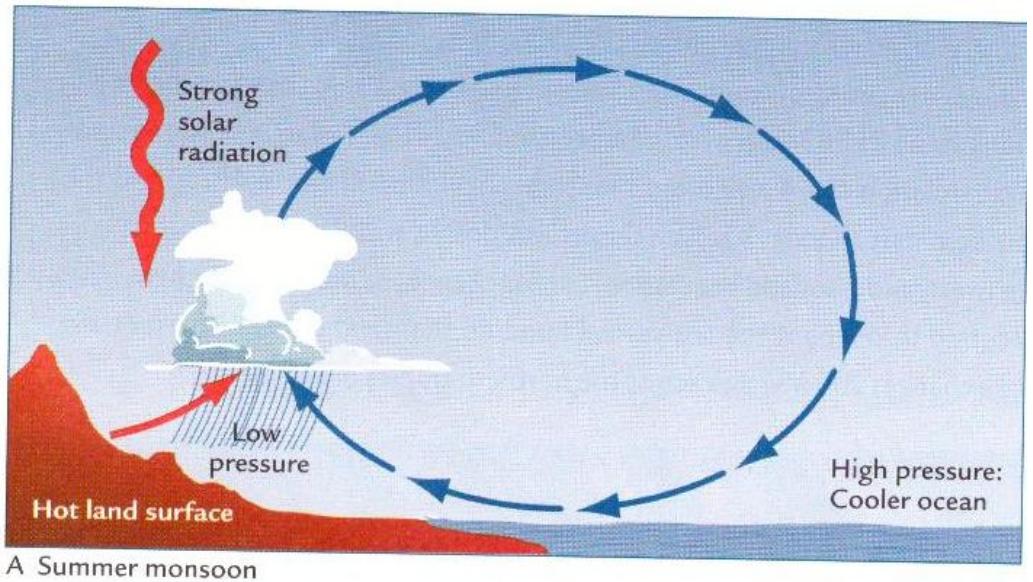
DEMOGRAPHICS OF THE MONSOON REGIONS



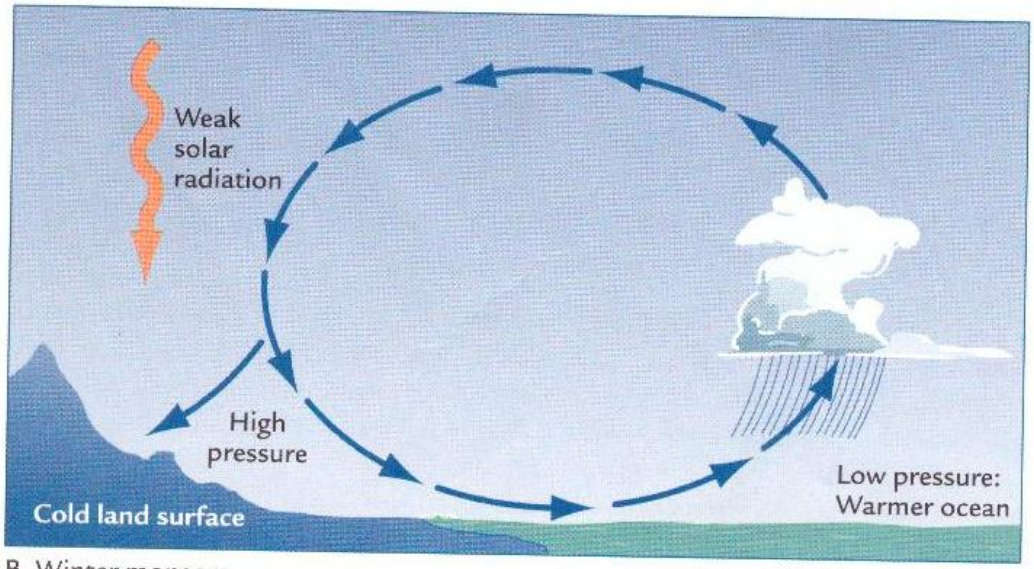
1950		1995		2025	
Rank	Country	Rank	Country	Rank	Country
1	**China**	1	**China**	1	**India**
2	**India**	2	**India**	2	**China**
3	USA	3	USA	3	**Pakistan**
4	Russia	4	**Indonesia**	4	USA
5	Japan	5	Brazil	5	**Nigeria**
6	**Indonesia**	6	Russia	6	**Indonesia**
7	Germany	7	**Pakistan**	7	Brazil
8	Brazil	8	Japan	8	**Bangladesh**
9	UK	9	**Bangladesh**	9	**Ethopia**
10	Itlay	10	**Nigeria**	10	**Iran**

Data from World Population Estimate (1995).

Seasonal monsoon circulations

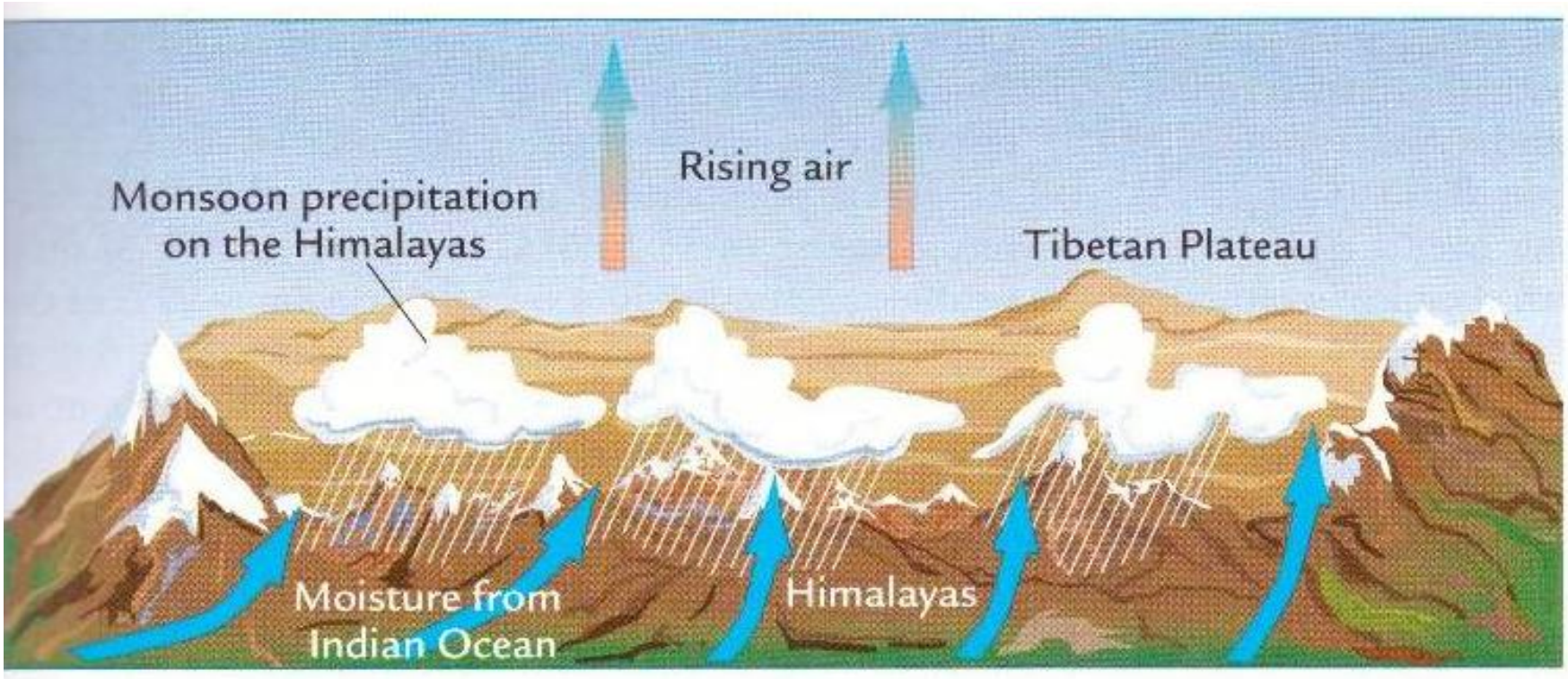


A Summer monsoon

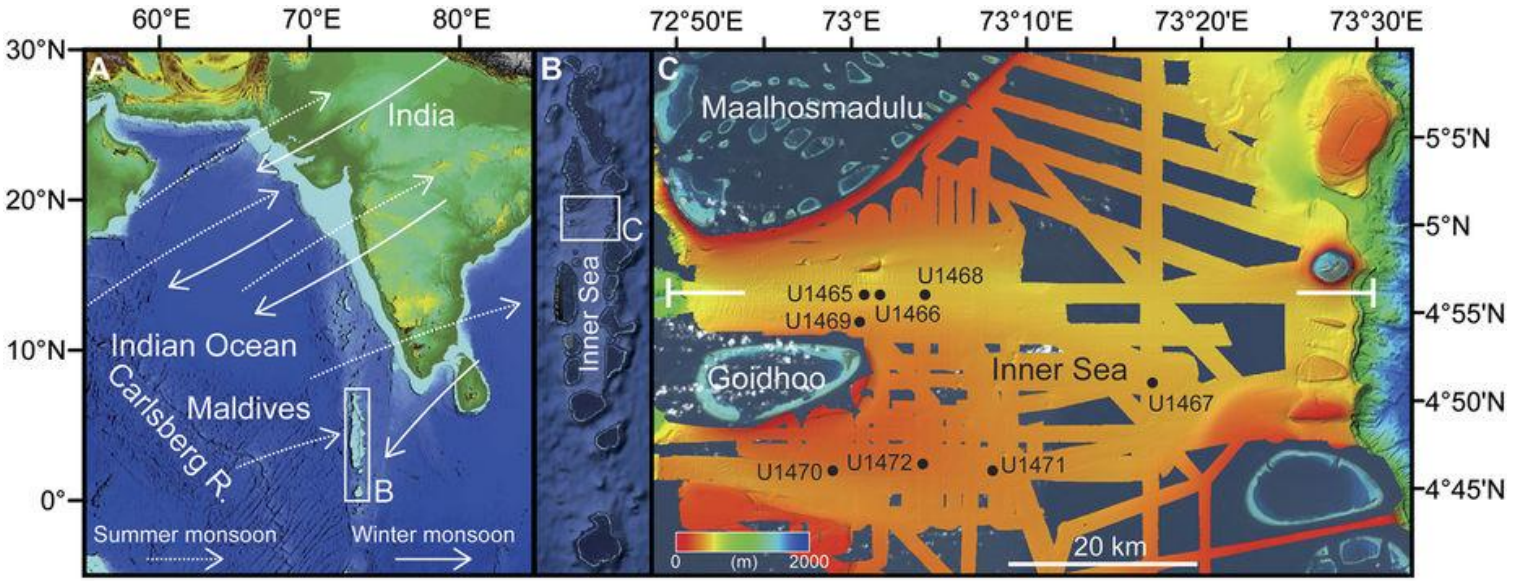


B Winter monsoon

Seasonal monsoon circulations



The abrupt onset of the modern South Asian Monsoon winds



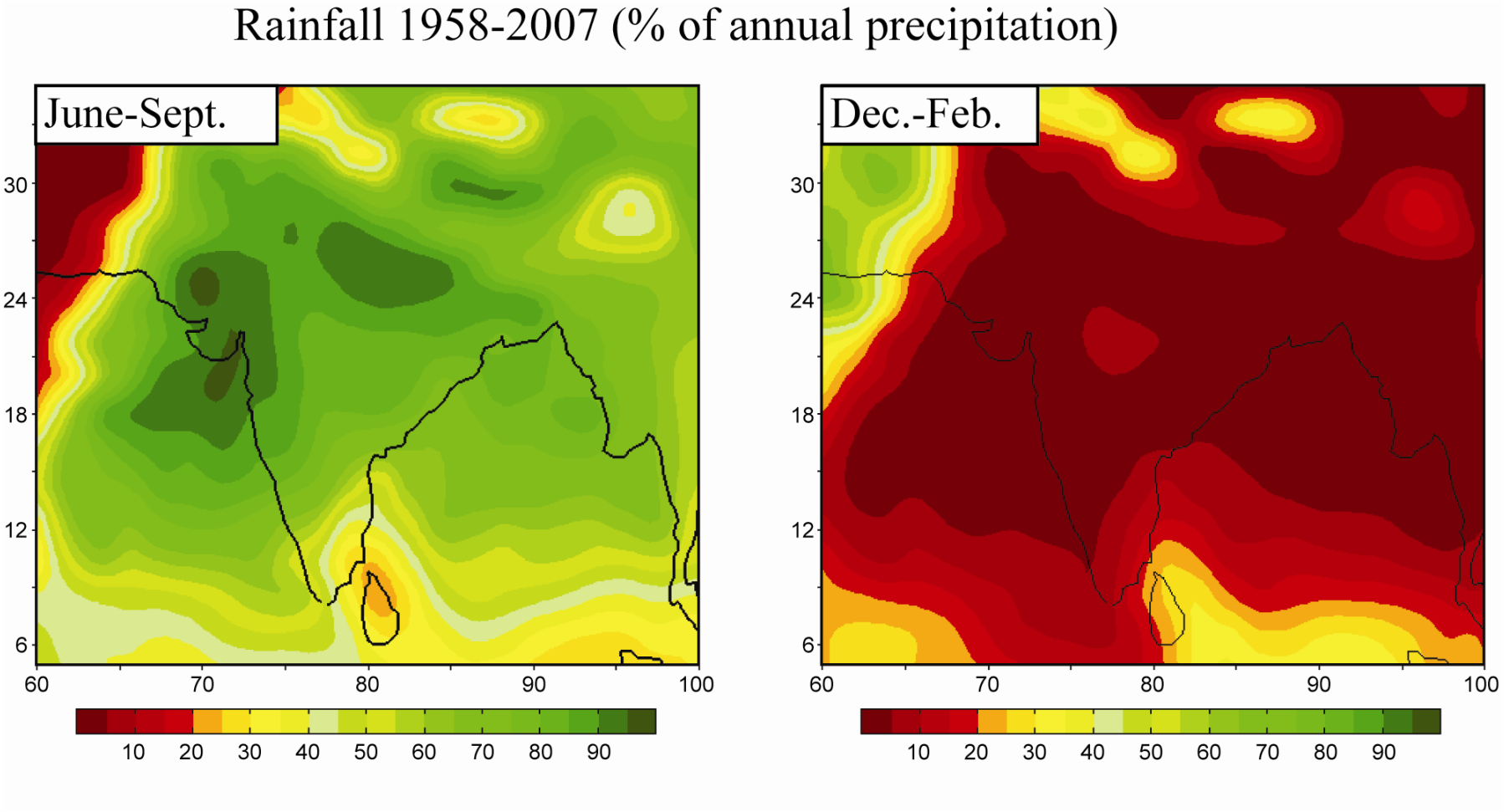
Dating the deposits of SAM wind-driven currents in IODP cores from the Maldives yields an age of 12. 9 Ma indicating an abrupt Monsoon onset

Betzler et al., 2016, Scientific reports

The Winter Monsoon

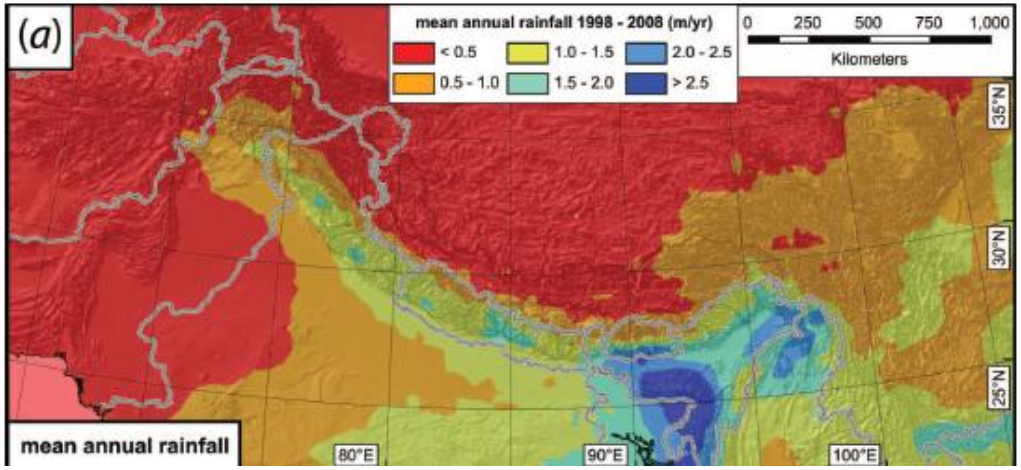
- During autumn and winter, air above land cools faster than over the water.
- The winds are reversed from the summer monsoon flow—at the surface from land to sea
- Winter monsoon is a dry season

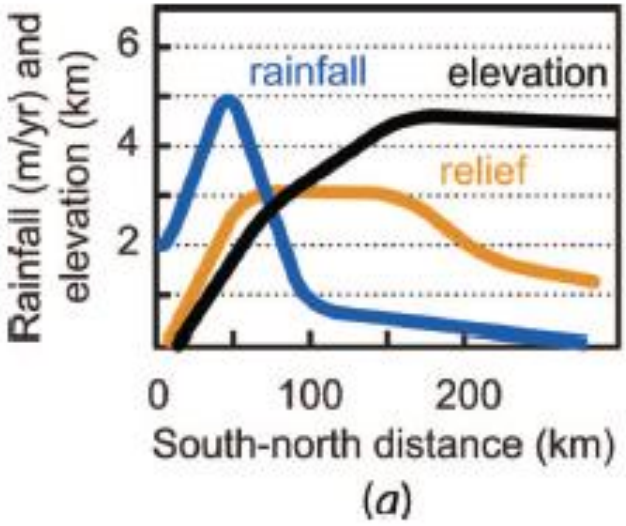
Modern Precipitation



Modern Precipitation

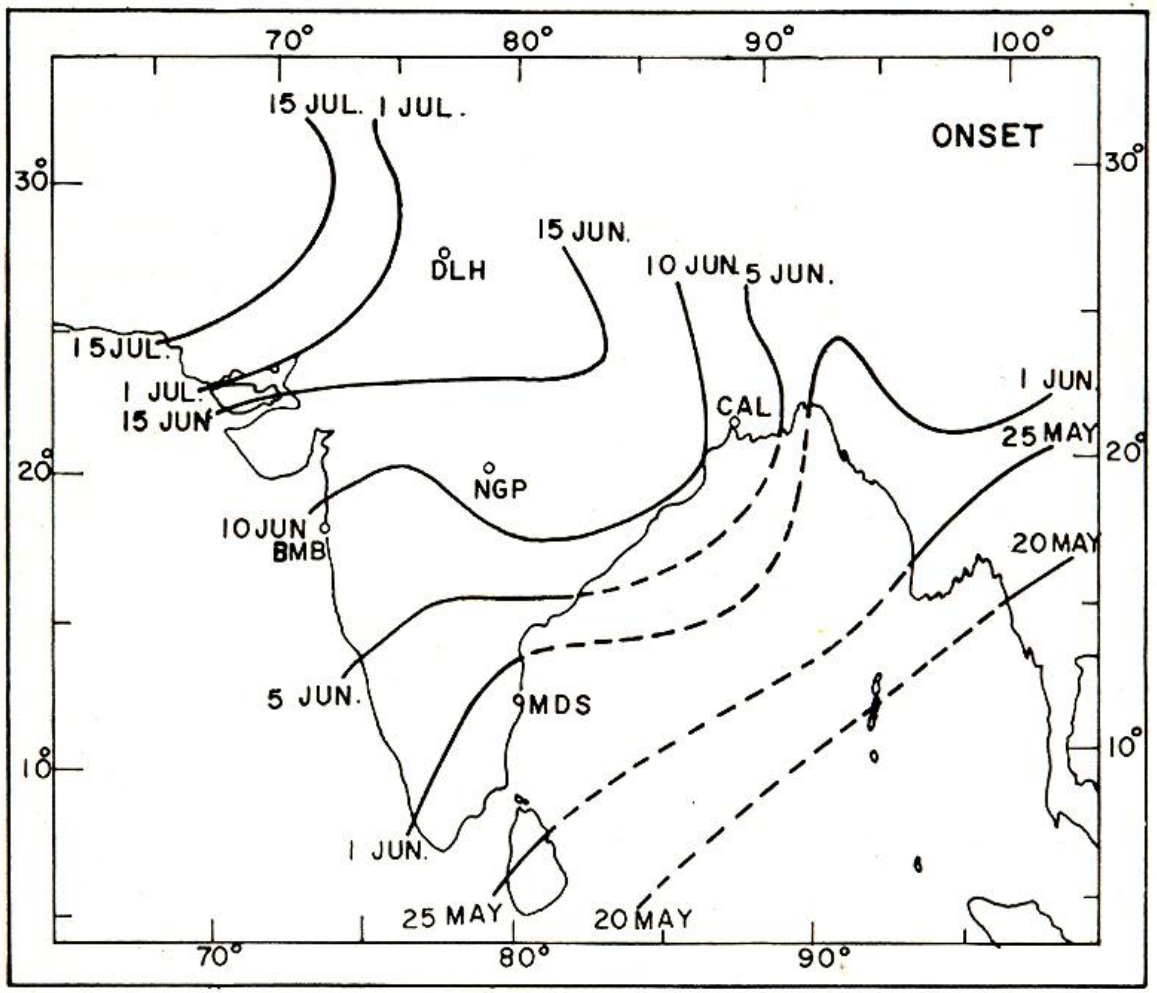
Abnormal monsoon years





Bookhagen et al., 2005

Monsoon-onset phase



Monsoon precipitation

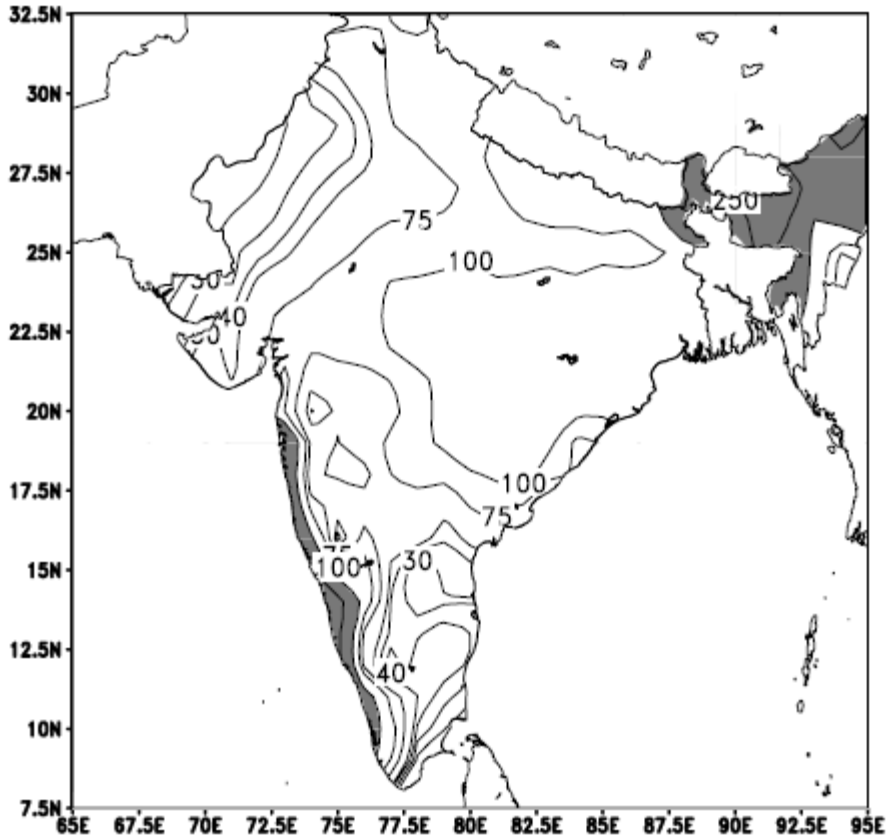
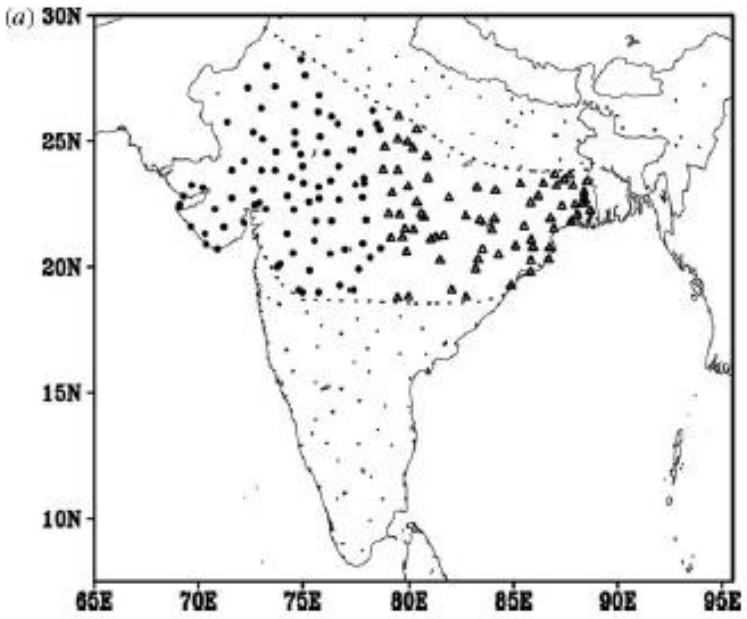
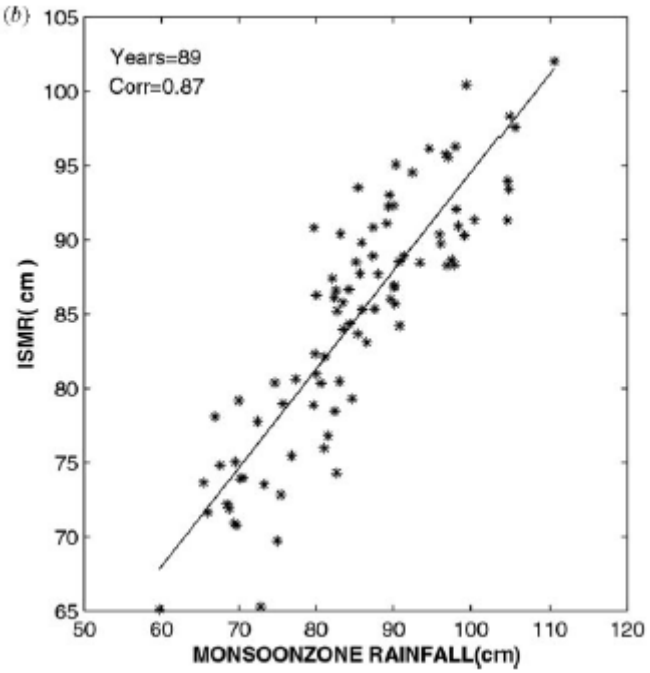


Figure 2 Mean June–September rainfall over the Indian region south of 30° N.

Source: Gadgil, 2003

Core monsoon zone





Source: Gadgil, 2003

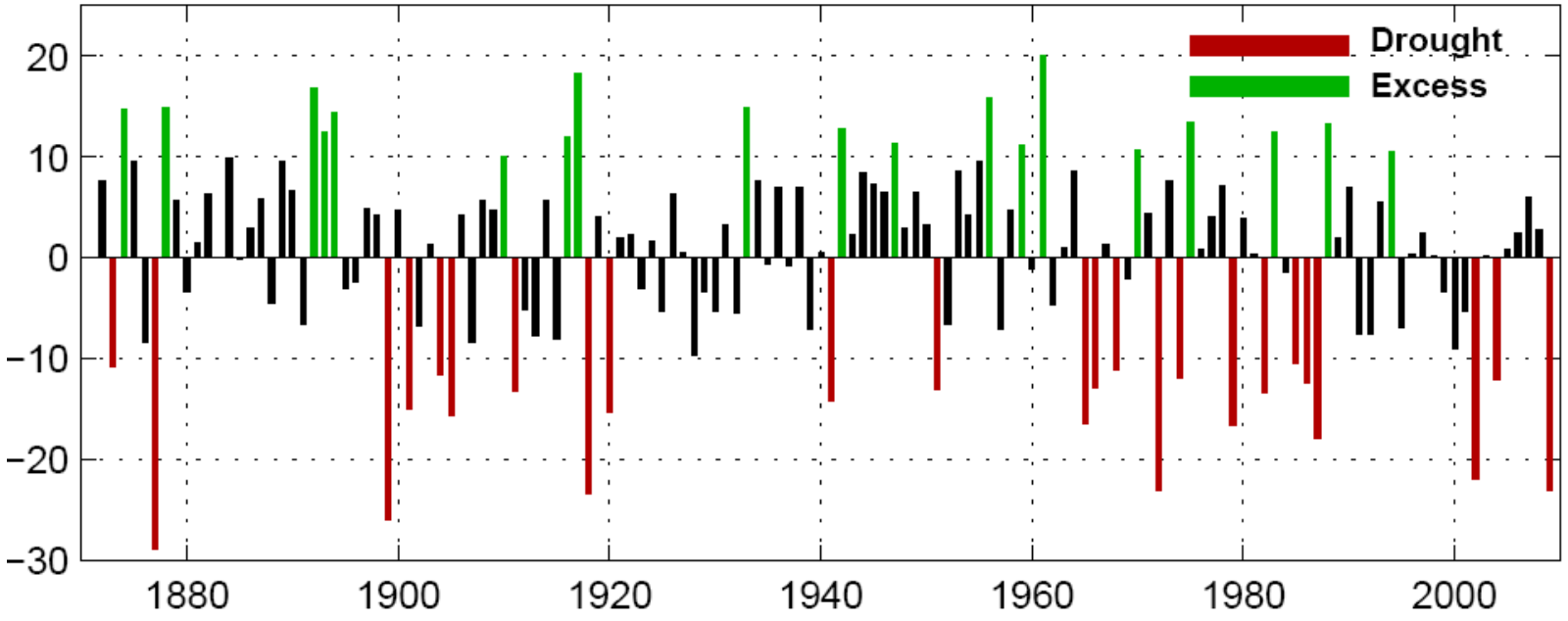
Interannual and Interdecedal variability

Interannual variability

•The long term mean of the Indian summer monsoon rainfall (ISMR) is about 85cm.

•Consider the interannual (year to year) variation of the anomaly (defined as the actual value in any year minus the mean value) of ISMR as a percentage of the mean value during 1876-2010.

Interannual Variation of the anomaly of ISMR (as % of the mean) during 1876-2010



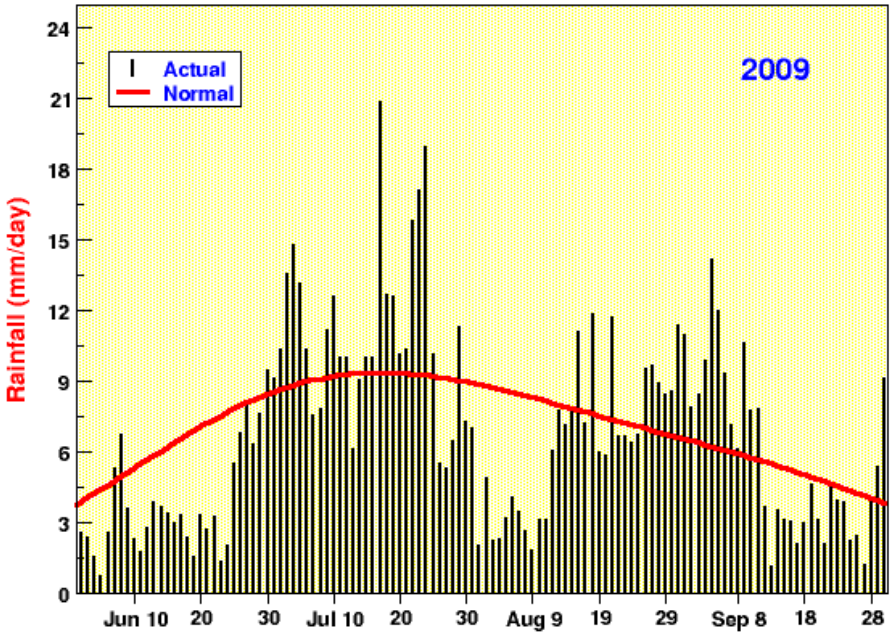
Drought: ISMR anomaly <-10% of the mean

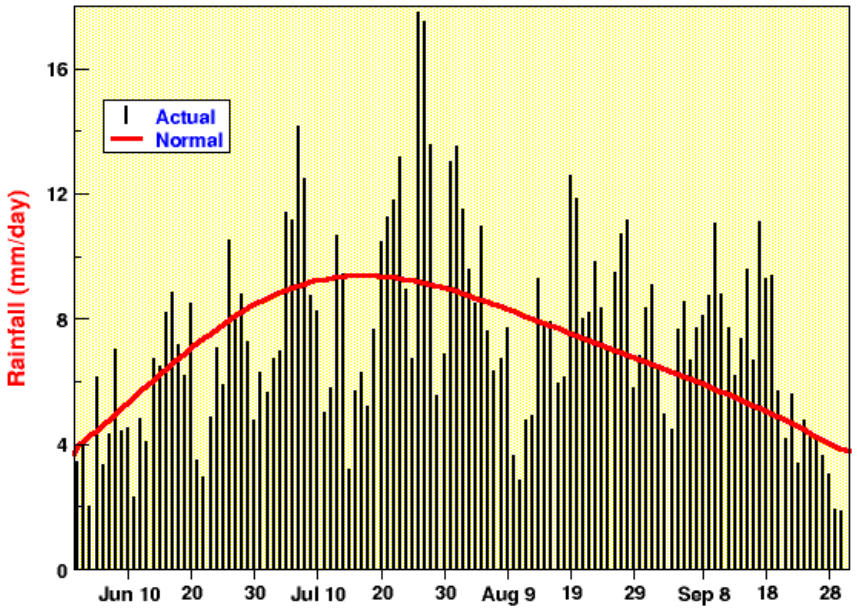
Excess rainfall seasons: ISMR anomaly >10% of the mean

Frequent droughts: 1899-1920 (7 in 21 years) ;1965-87 (10 in 28years) and again since 2002

Less frequent during 1878-98 (0 in 21years); 1921-64 (2 in 44 years)

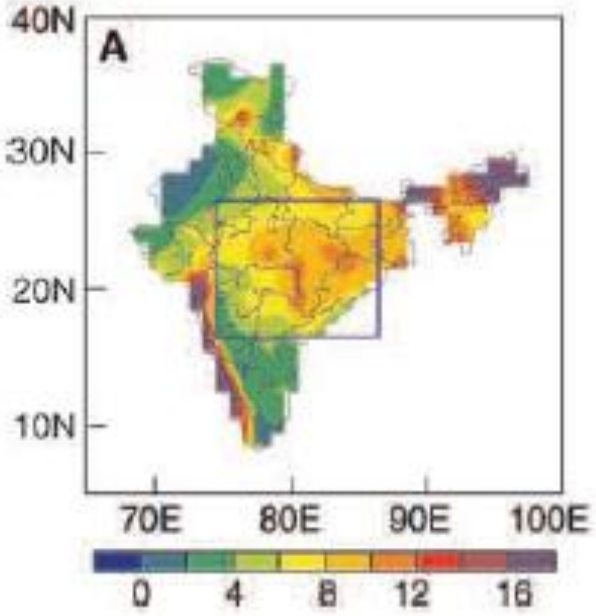
Variation of the all-India daily rainfall during the summer monsoon seasons of 2009 and 2010

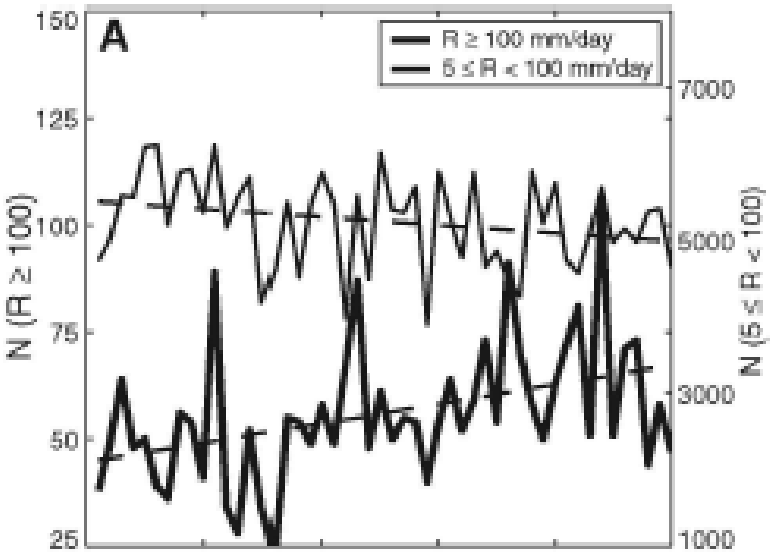




Increasing Trend of Extreme Rain Events Over India in a Warming Environment

B. N. Goswami,[1]* V. Venugopal,[2] D. Sengupta,[2] M. S. Madhusoodanan,[2] Prince K. Xavier[2]





Forcing factors of Indian monsoon

Snow cover

- Indian Monsoon
- North American Monsoon

  - Connection with neighboring snow cover of the preceding winter.

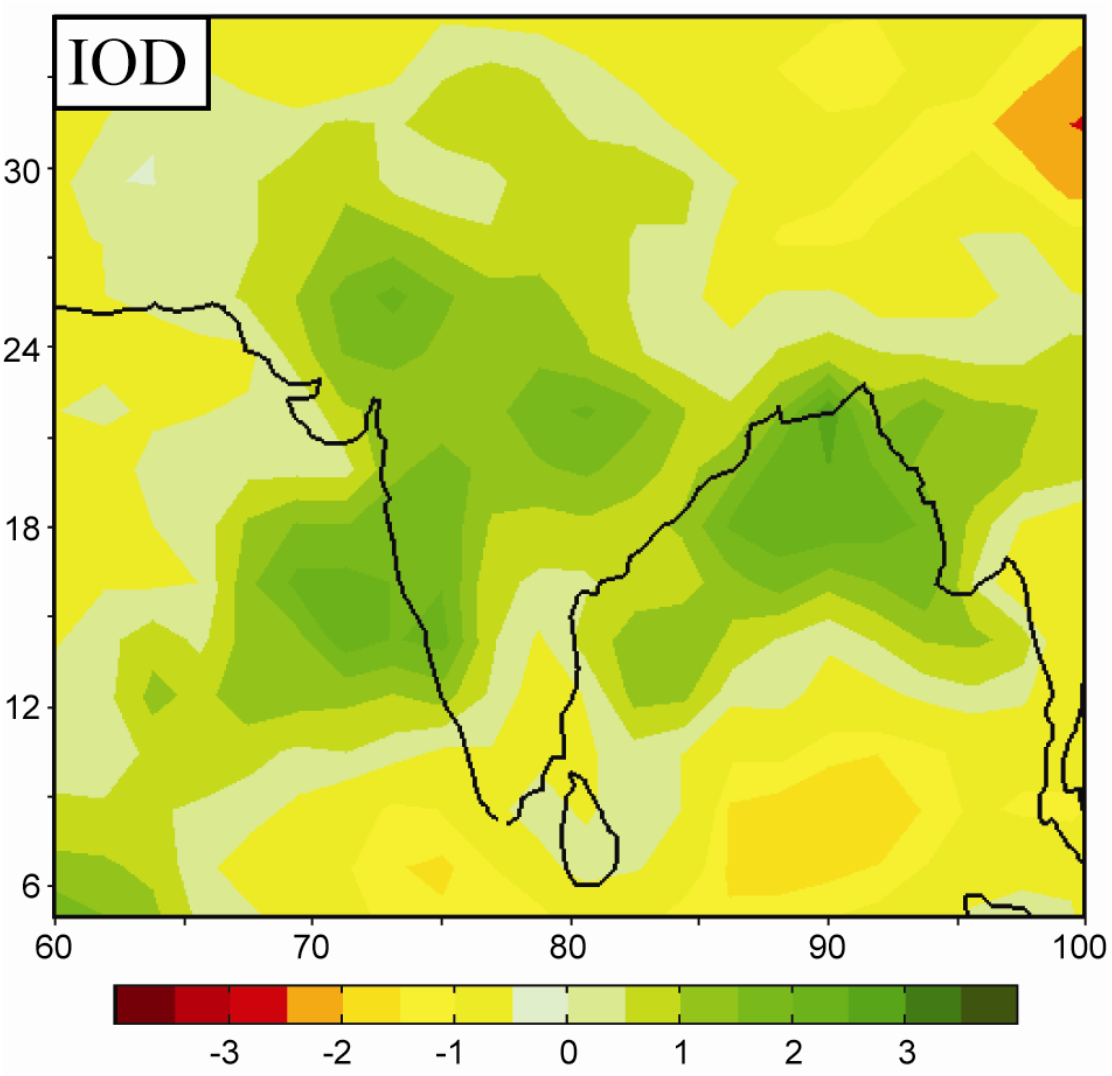
  - *Blanford Hypothesis*: Winter/Spring snow cover in the Himalayas mountain region has an inverse relationship with June-September Indian rainfall.

Snow cover

Contradictory results

- In recent years there have been contradictions against the Blanford Hypothesis.
- Fusallo (2004), Bamzai & Shukla (1999) and Ye & Bao (2001):
  - Positive correlation between snow cover and monsoonal rainfall anomalies
  - These results are at odds with the Blanford Hypothesis for the spatial distribution of snow cover.

Indian Ocean Dipole



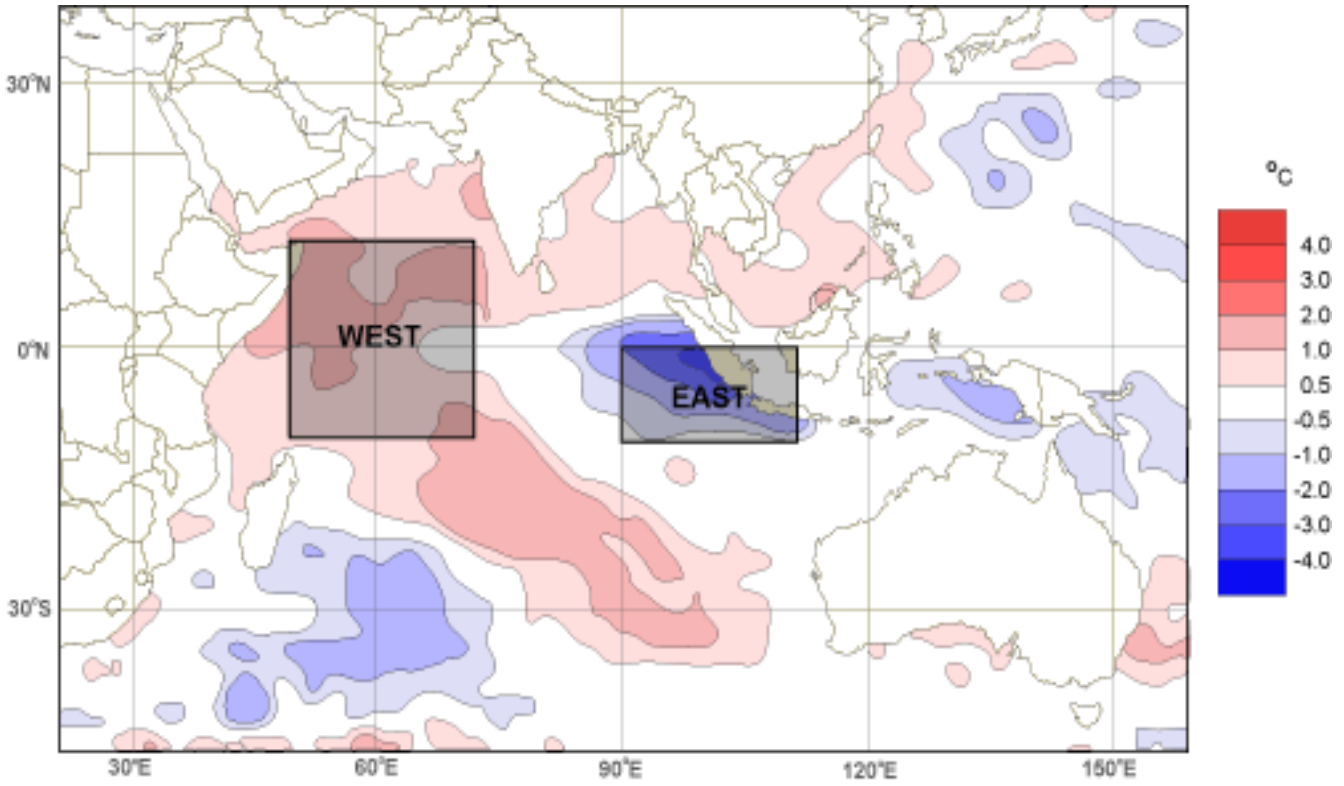
What is IOD?

- First described by Dr. Saji et al. in 1999
- Dipole Mode Index (DMI)

A dipole mode in the tropical Indian Ocean

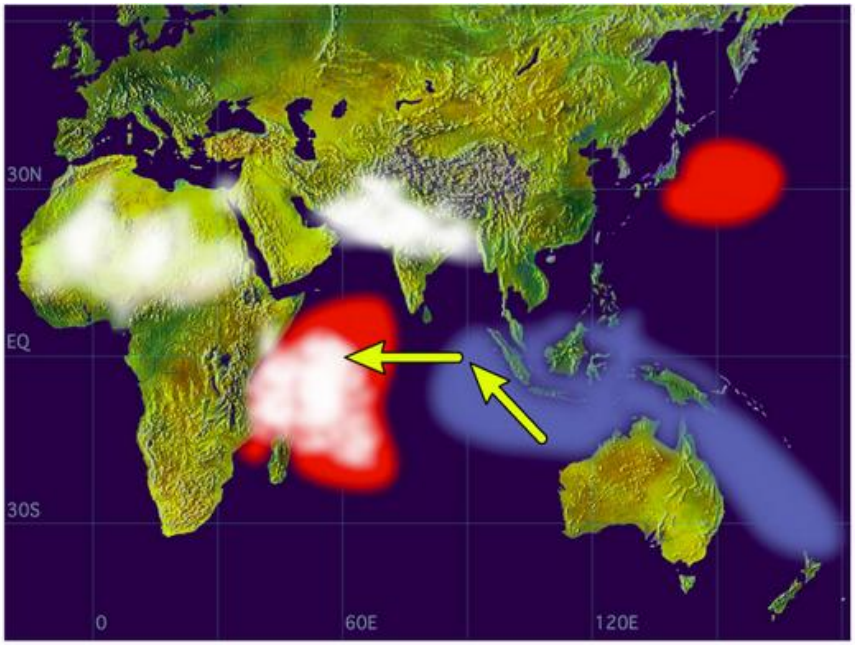
N. H. Saji*, B. N. Goswami†, P. N. Vinayachandran* & T. Yamagata*‡

*Institute for Global Change Research, SEAVANS N 7F, 1-2-1 Shibaura, Minato-ku, Tokyo 105 6791, Japan
†Center for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore 560 012, India
‡Department of Earth and Planetary Physics, Graduate School of Science, The University of Tokyo, Tokyo 113 0033, Japan

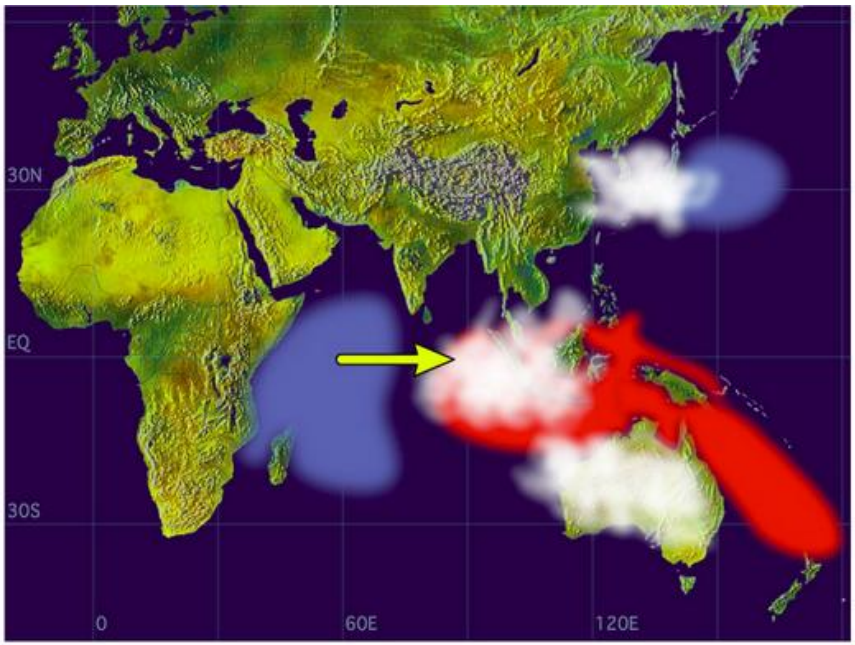


Positive & Negative Phases of IOD

- Positive: cooler in the tropical eastern Indian Ocean and warmer in the tropical western Indian Ocean
- Negative: warmer in the tropical eastern Indian Ocean and cooler in the tropical western Indian Ocean



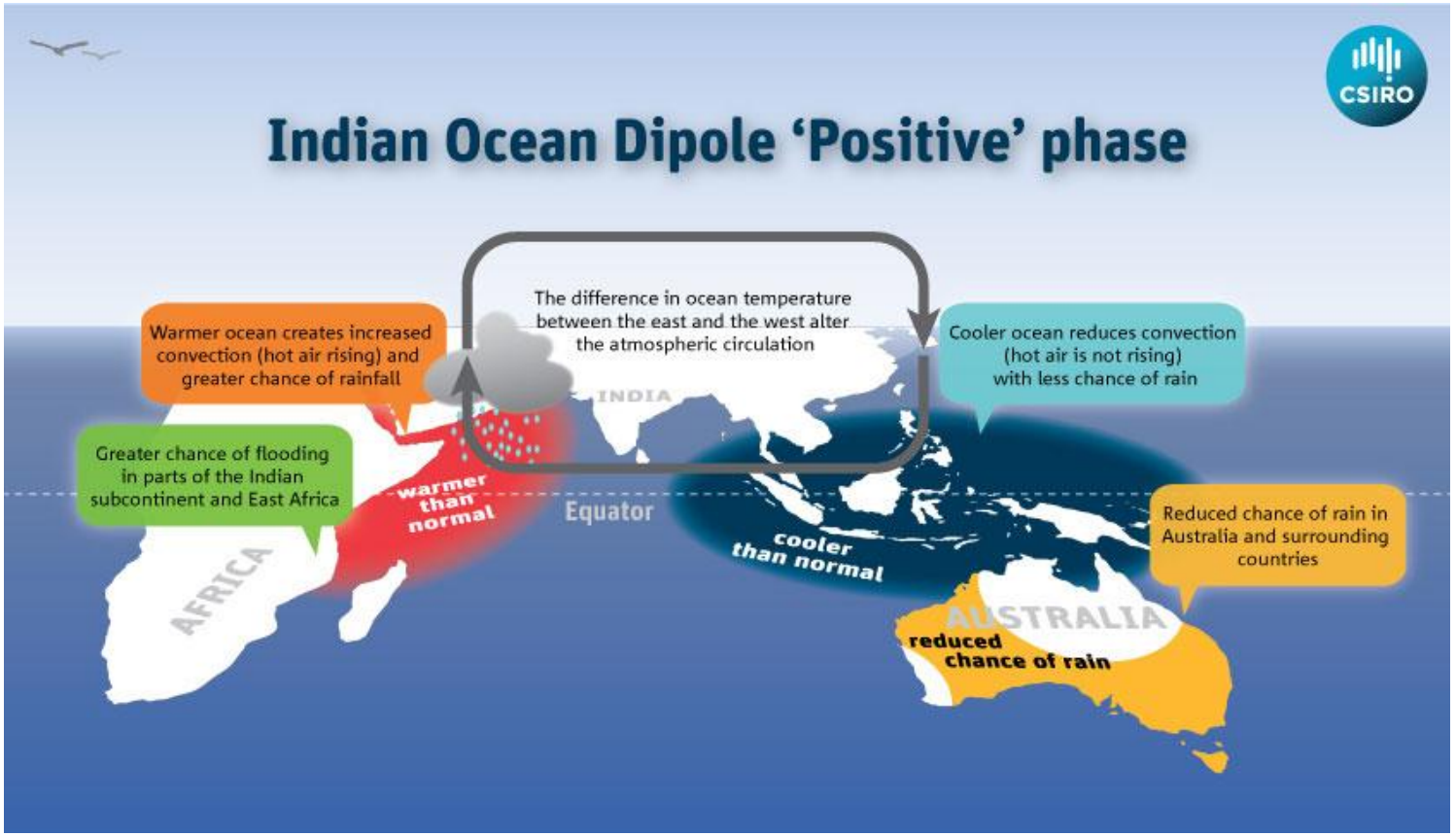
Positive IOD Phase



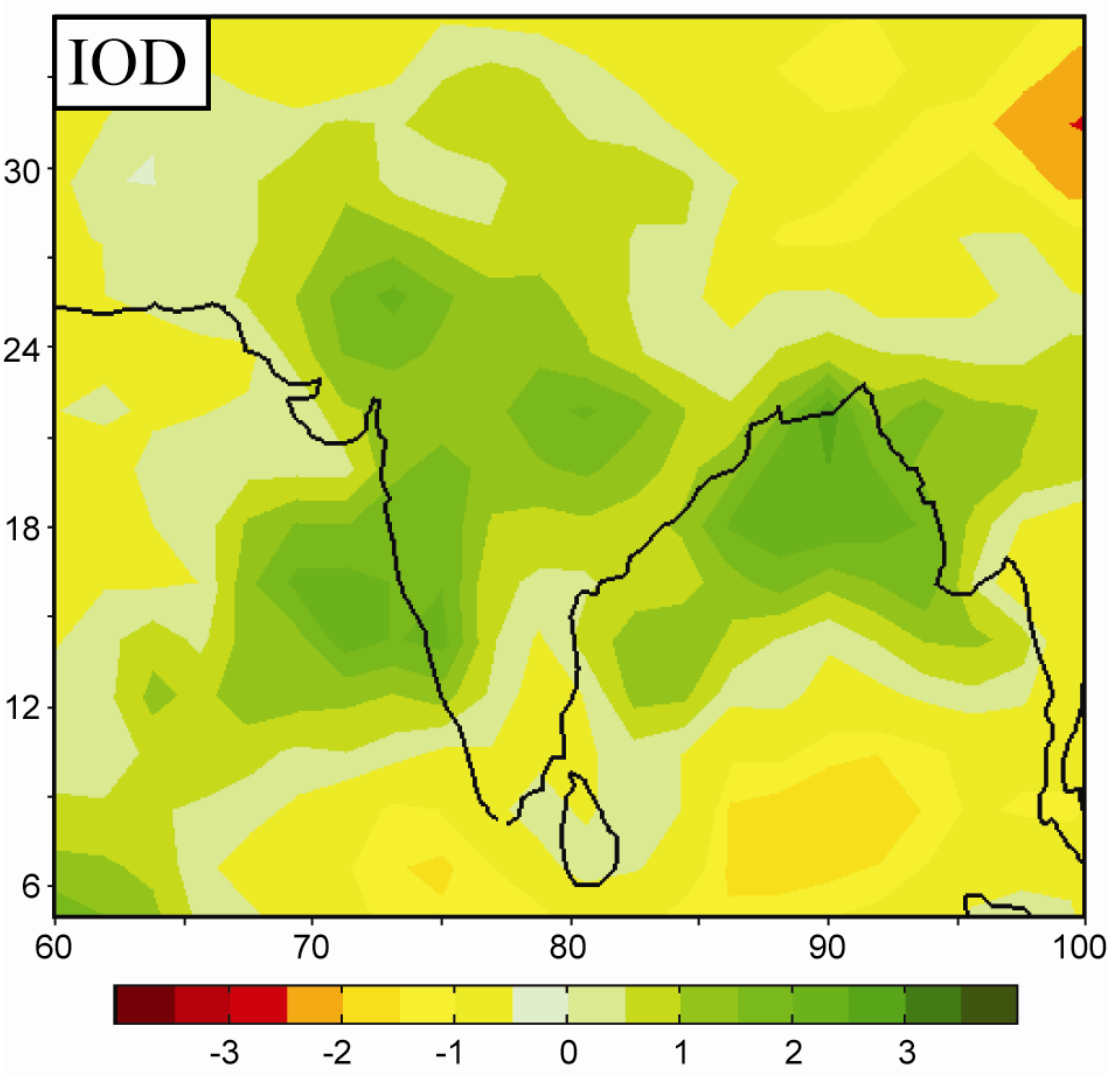
Negative IOD Phase

IOD Influence on Surrounding Climate

- A positive phase of the IOD tends to cause droughts in East Asia and Australia, and flooding in parts of the Indian subcontinent and East Africa.



Indian Ocean Dipole

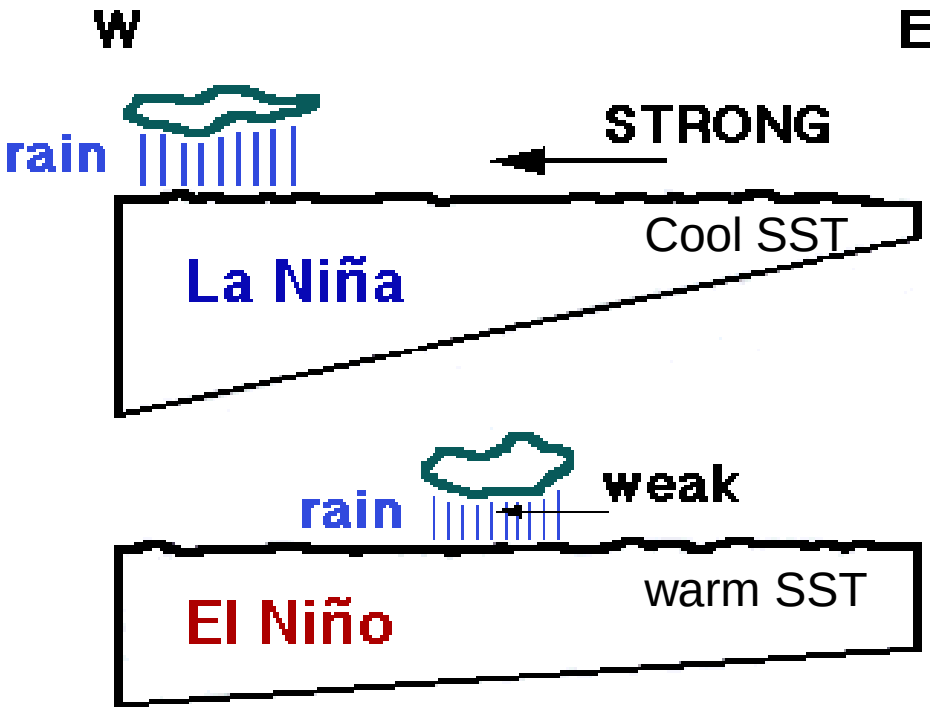


Questions still unsolved?

A better understanding of the relationship between the Indian Ocean Dipole and extreme weather events

- How IOD formed
- Relationship between ENSO and IOD
- How they affect the climate together

ENSO-monsoon teleconnections



Cold phase

Warm Phase

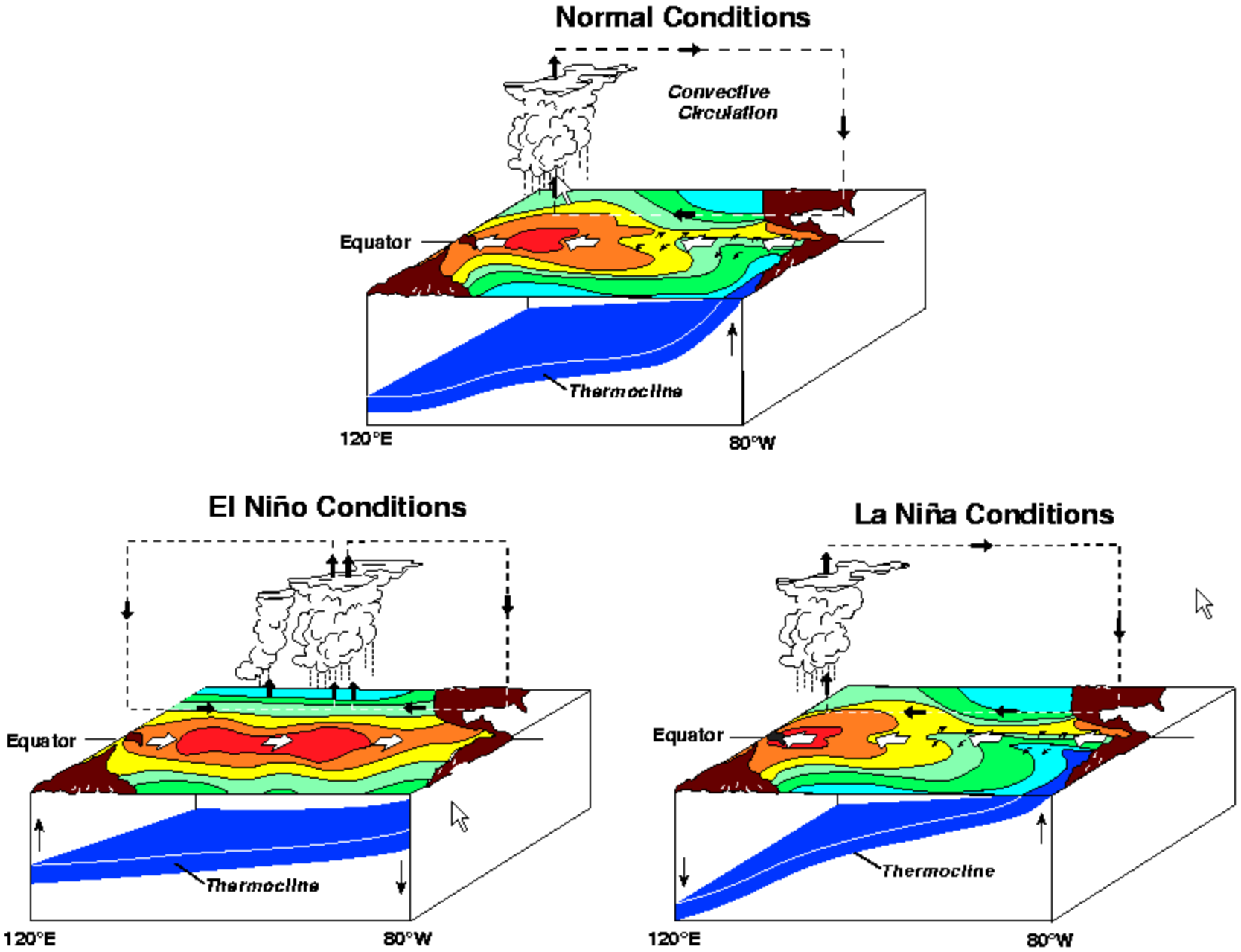
Surface Layer of Low Latitude Pacific Ocean (Warm Layer)

τ of oscillation ~ 4 years

Historically Speaking

El Niño and La Niña events tend to develop during the period Apr-Jun and they:

- *Tend to reach their maximum strength during Dec-Feb*
- *Typically persist for 9-12 months, though occasionally persisting for up to 2 years*
- *Typically recur every 2 to 7 years*

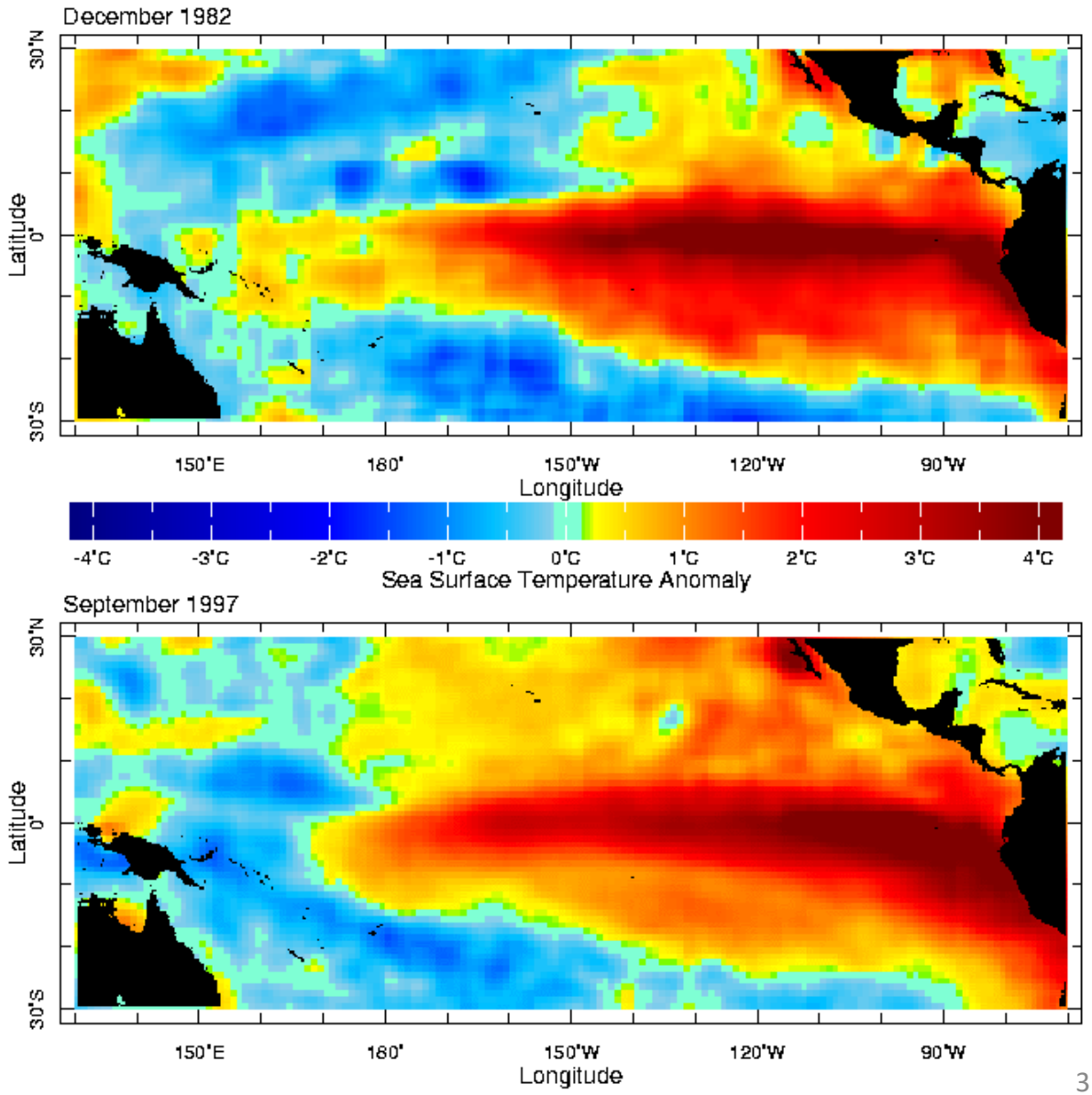

Normal Conditions
Convective Circulation
Equator
Thermocline
120°E
80°W
El Niño Conditions
Equator
Thermocline
120°E
80°W
La Niña Conditions
Equator
Thermocline
120°E
80°W

Largest El Niños of 20th century

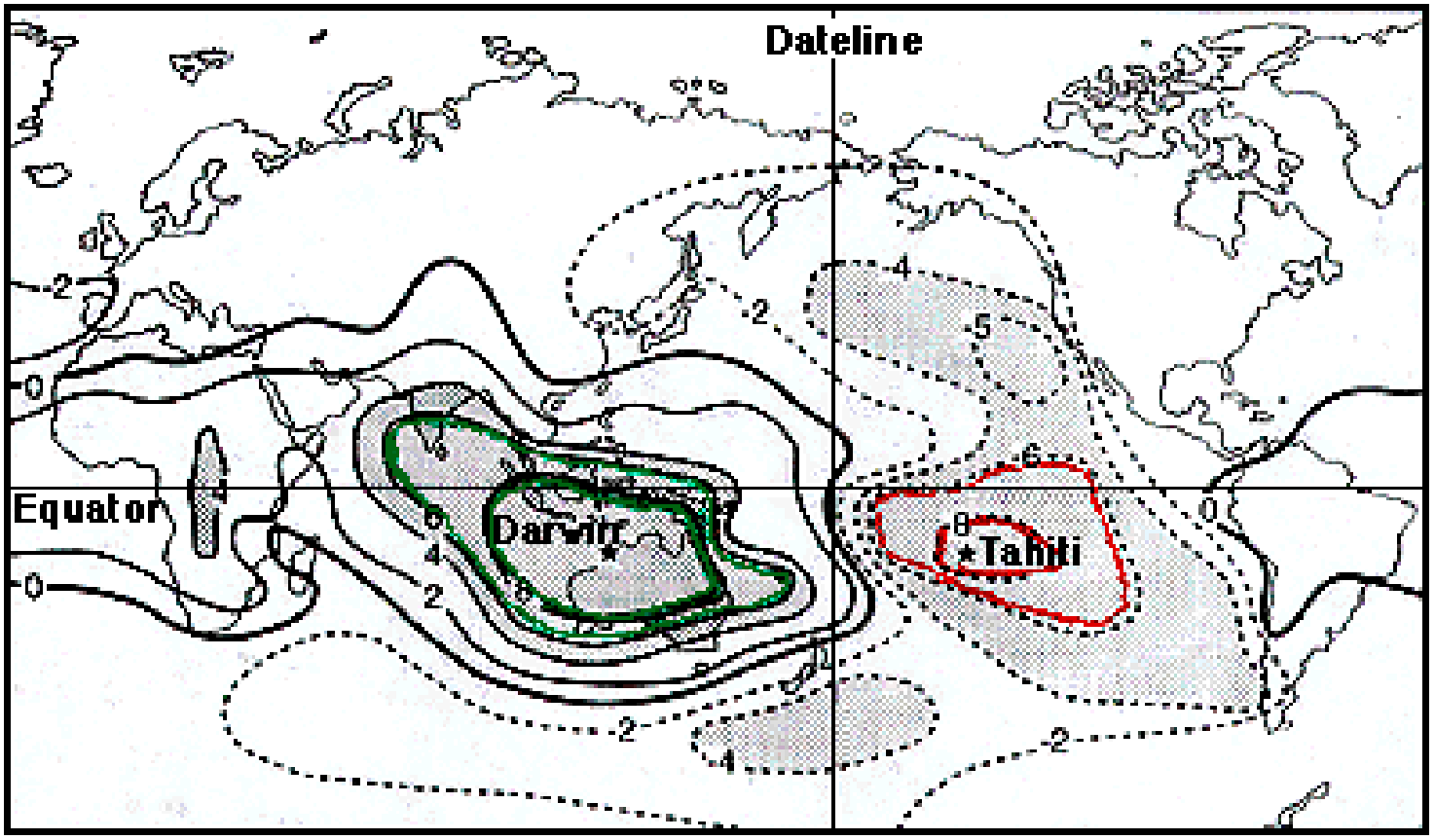
1982

SST Anomaly (relative to the average state)

1997



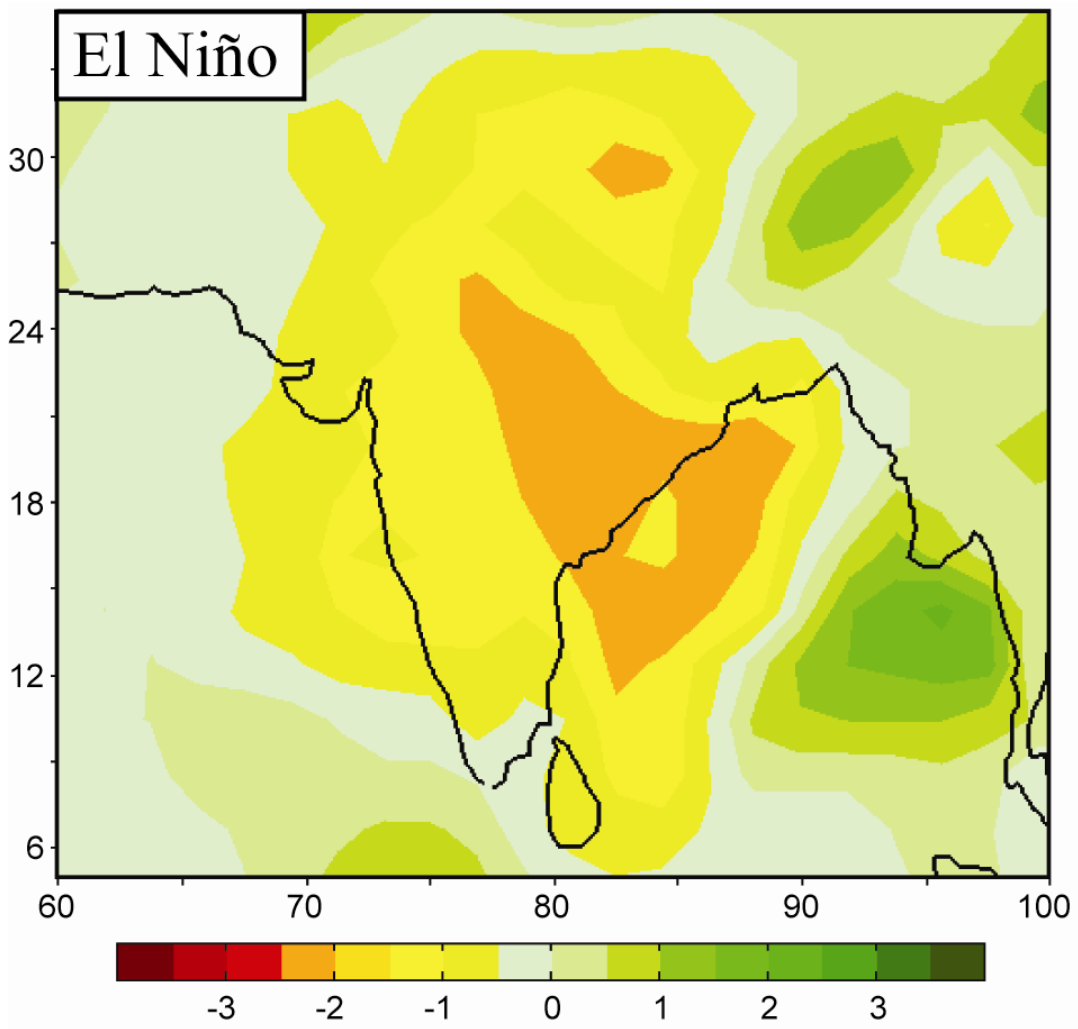
SOI: Tahiti and Darwin as "centers of action", mslp correlations between two locations



Tahiti and Darwin are at opposite ends of the Southern Oscillation's seesaw.

SOI = Tahiti SLP - Darwin SLP

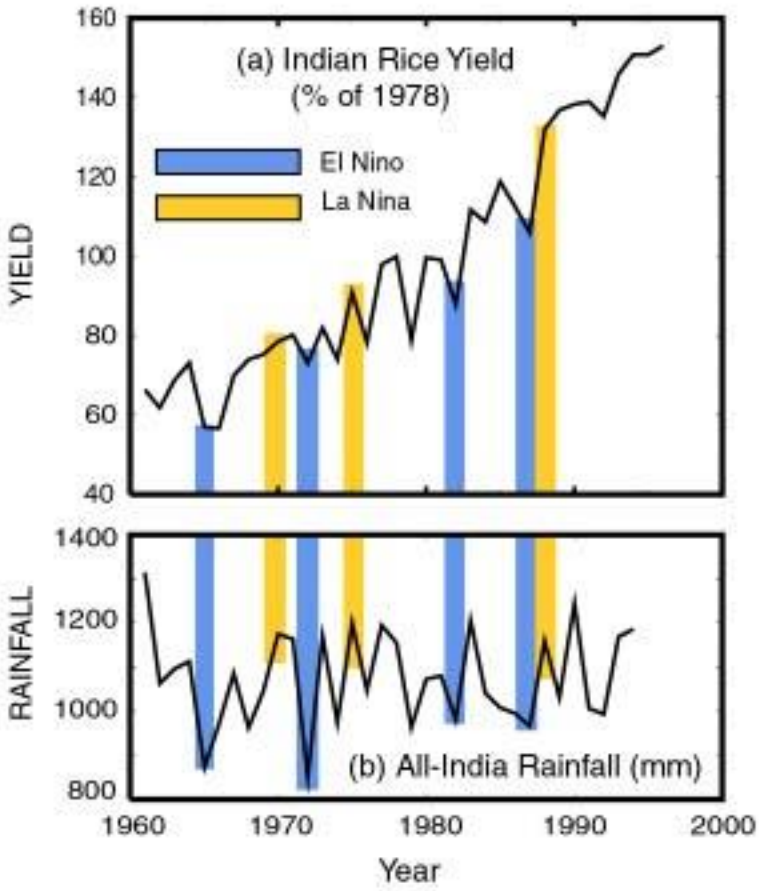
Global teleconnections : ENSO



Spatial inhomogeneity in monsoon precipitation associated with teleconnections

(Anoop, 2013)

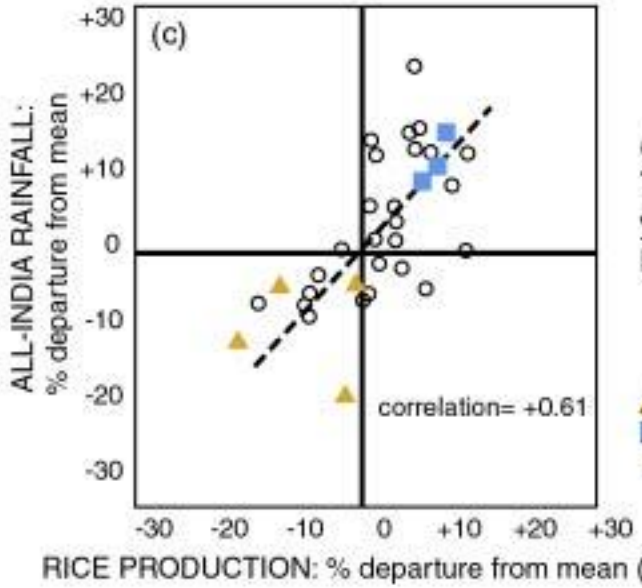
Association of monsoon rainfall and agriculture



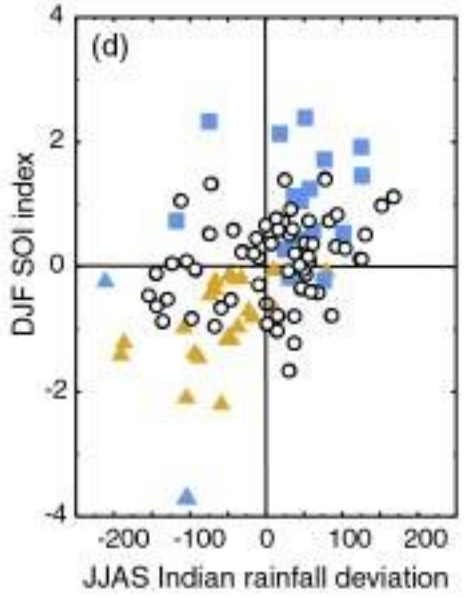
From Webster et al. (1998)

(a) The relationship between Indian rainfall and rice production from 1960 to 1996 relative to 1978 production.

(b) the All-India rainfall Index for the corresponding years:,



(c) linear regression plot. Yellow indicate El Nino years; blue indicate La Nina years.

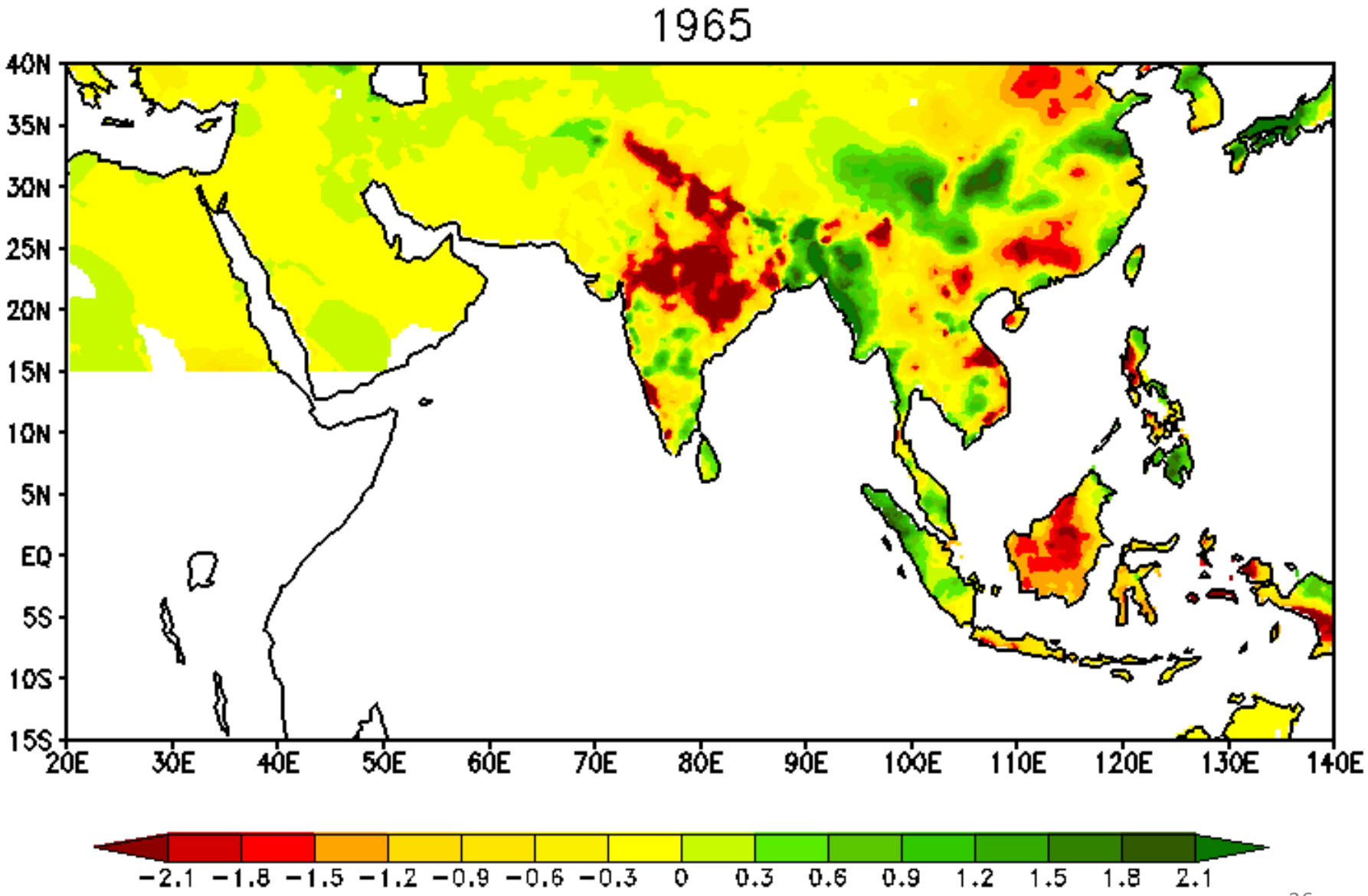


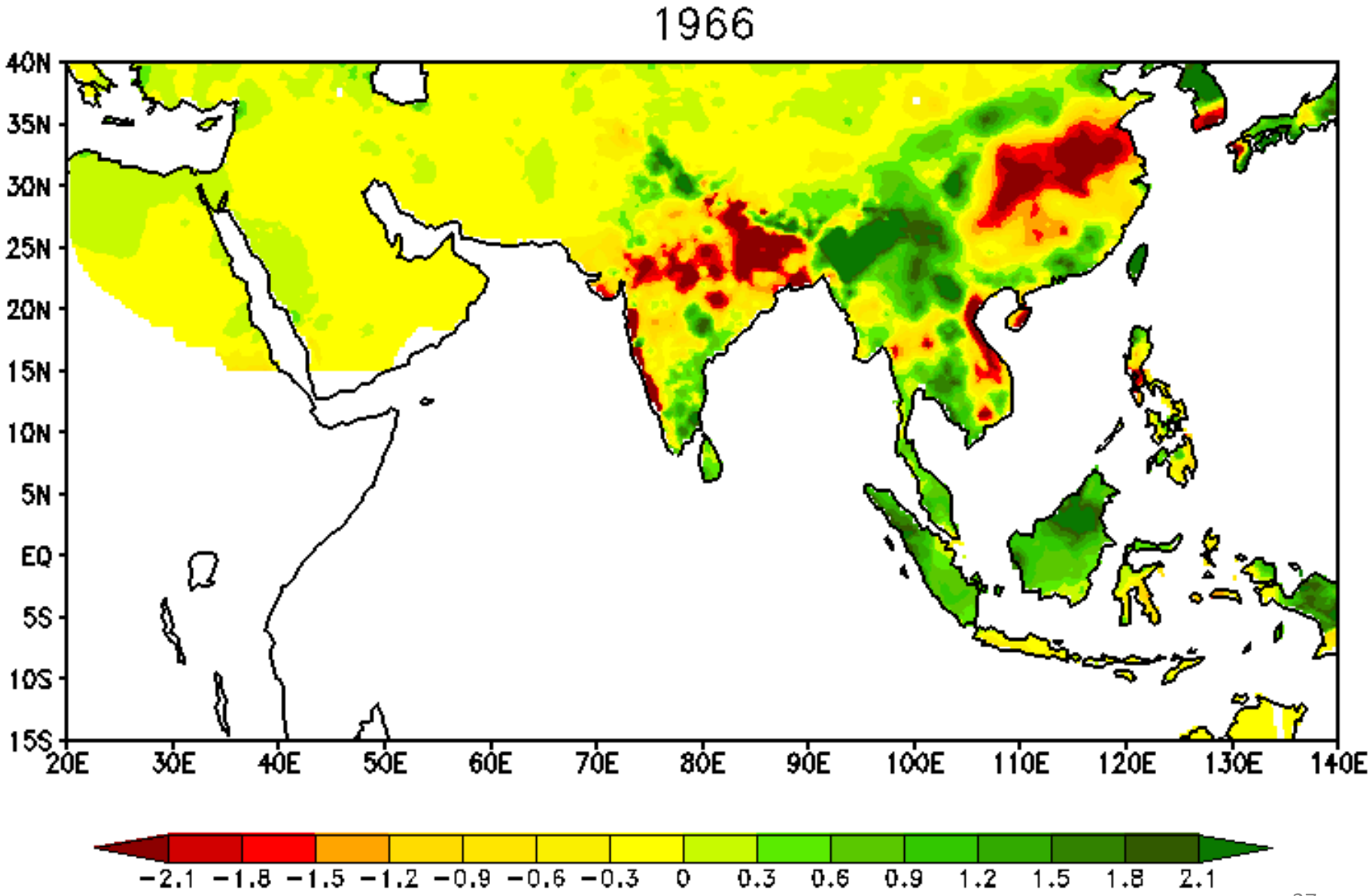
(d) Association of Indian rainfall and ENSO

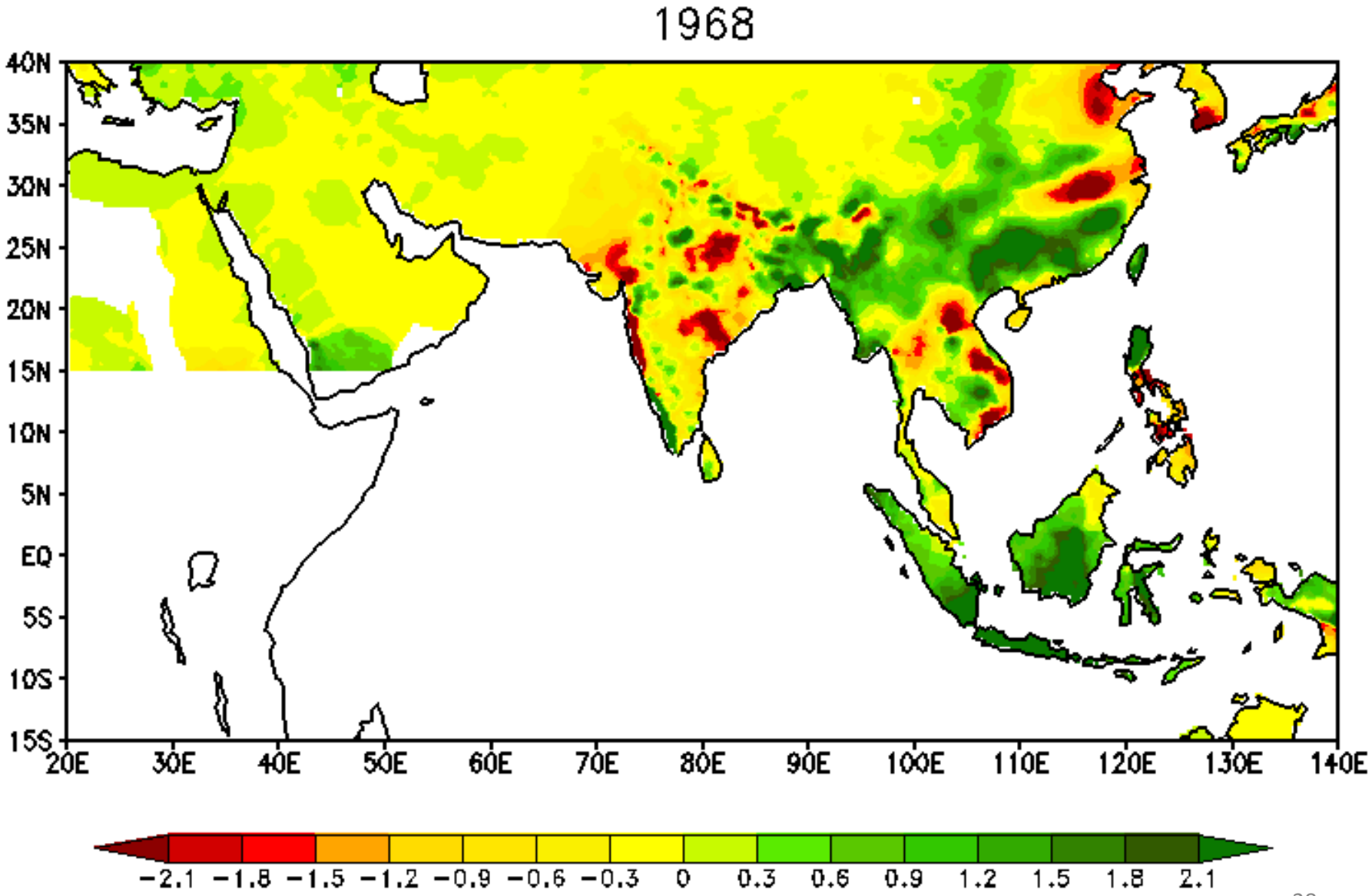
On the Weakening Relationship Between the Indian Monsoon and ENSO

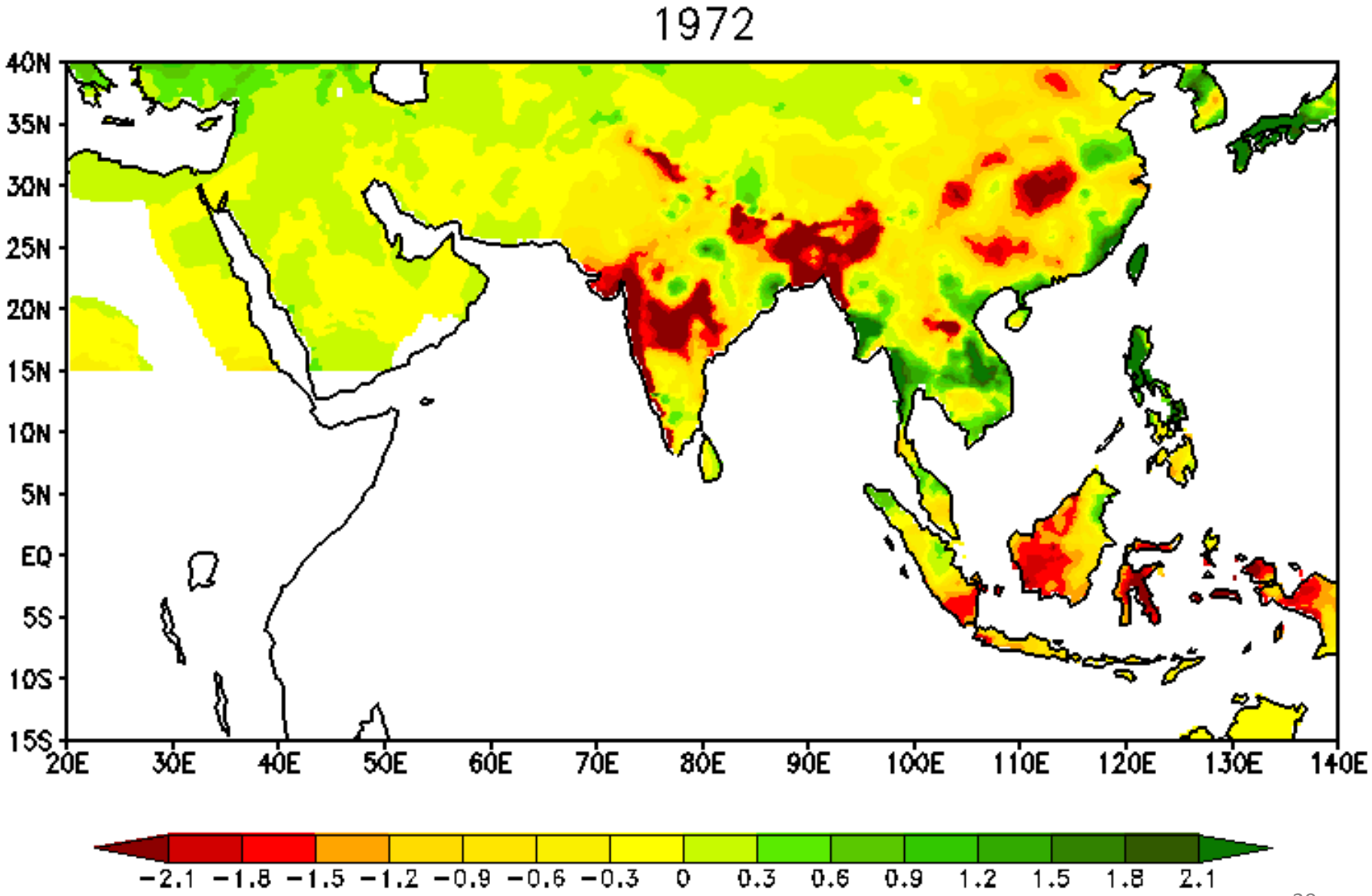
K. Krishna Kumar,[1]*† Balaji Rajagopalan,[2] Mark A. Cane[2]

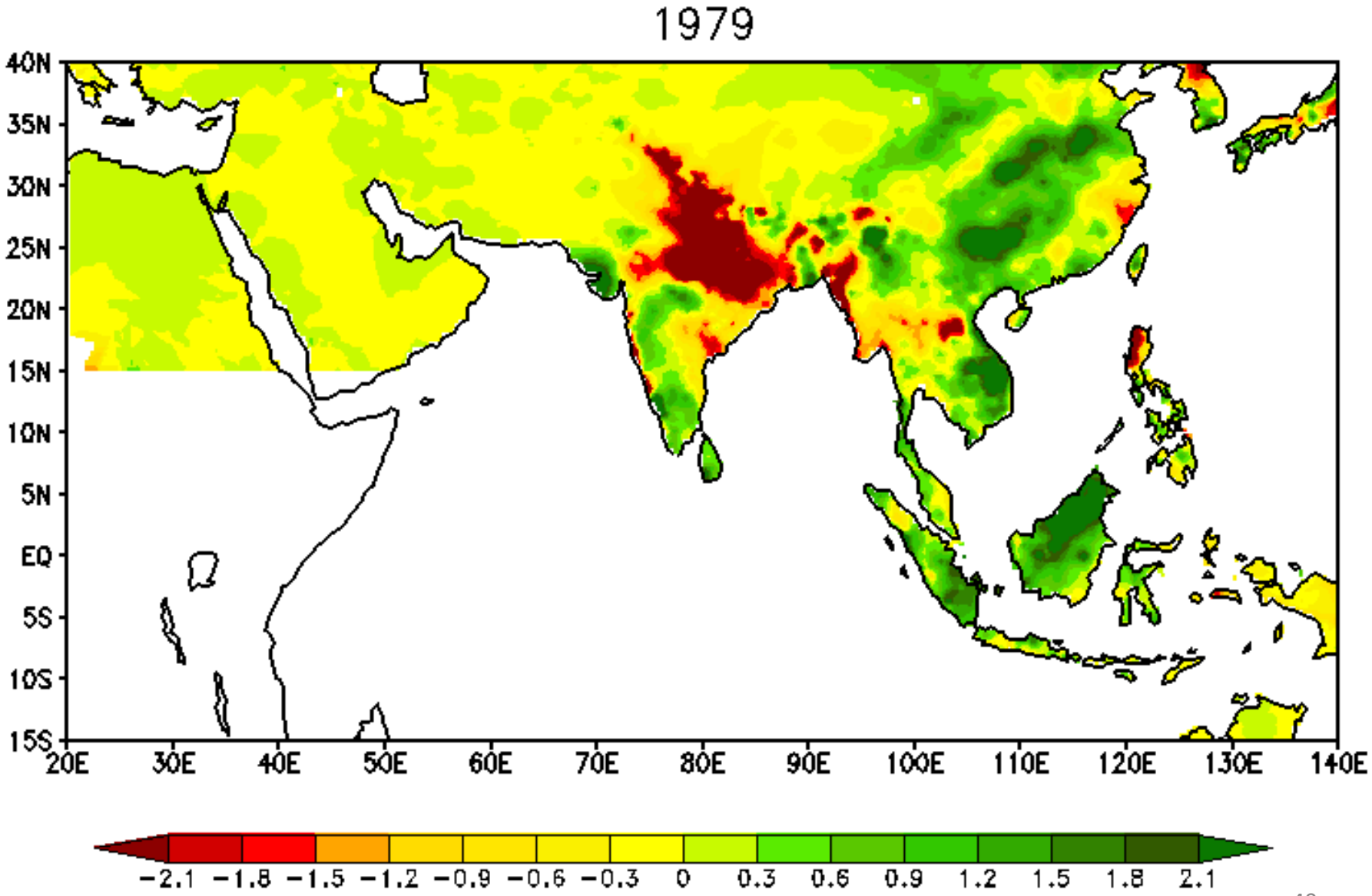
Analysis of the 140-year historical record suggests that the inverse relationship between the El Niño–Southern Oscillation (ENSO) and the Indian summer monsoon (weak monsoon arising from warm ENSO event) has broken down in recent decades. Two possible reasons emerge from the analyses. A southeastward shift in the Walker circulation anomalies associated with ENSO events may lead to a reduced subsidence over the Indian region, thus favoring normal monsoon conditions. Additionally, increased surface temperatures over Eurasia in winter and spring, which are a part of the midlatitude continental warming trend, may favor the enhanced land-ocean thermal gradient conducive to a strong monsoon. These observations raise the possibility that the Eurasian warming in recent decades helps to sustain the monsoon rainfall at a normal level, despite strong ENSO events.

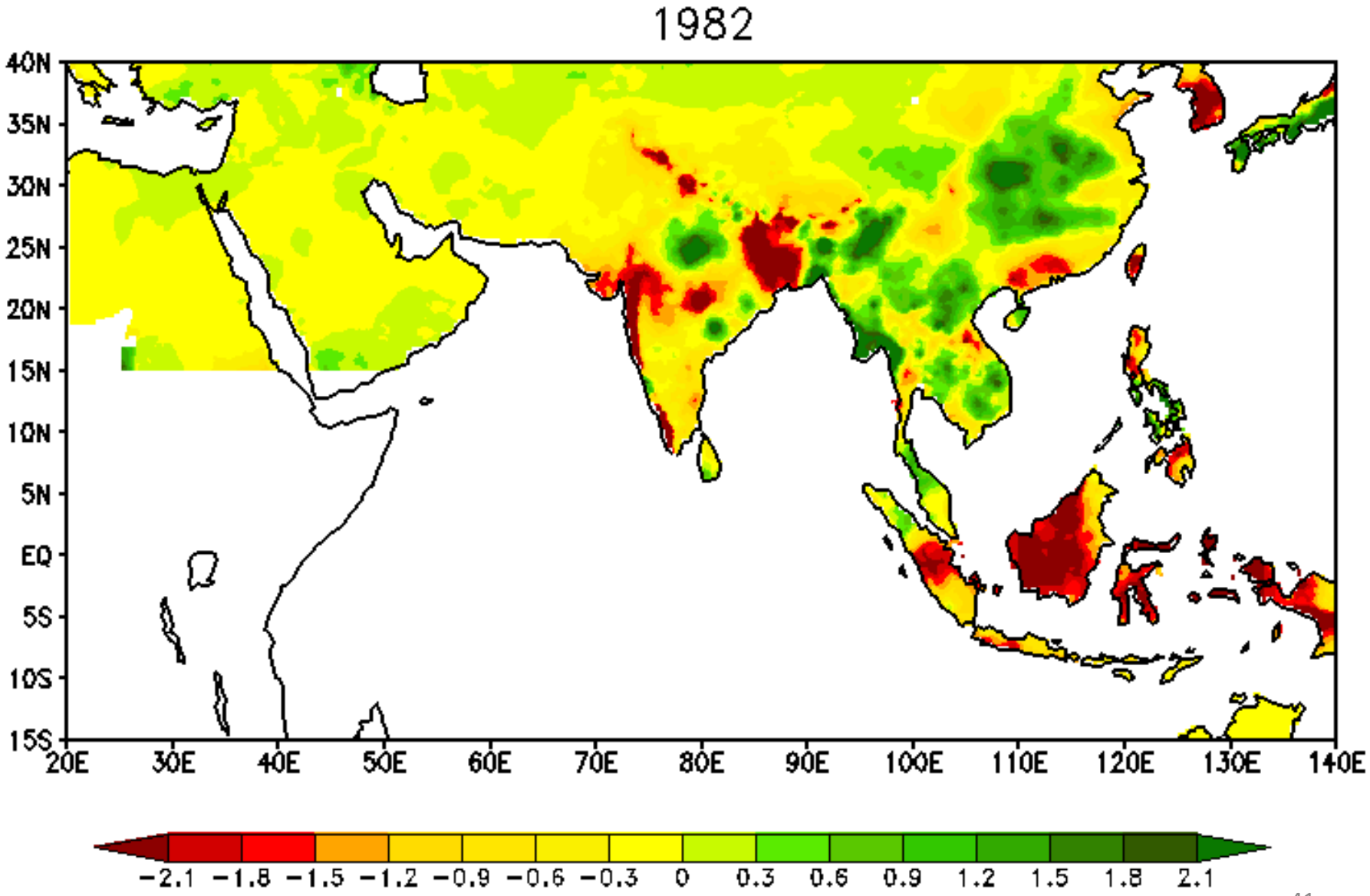

1965
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1

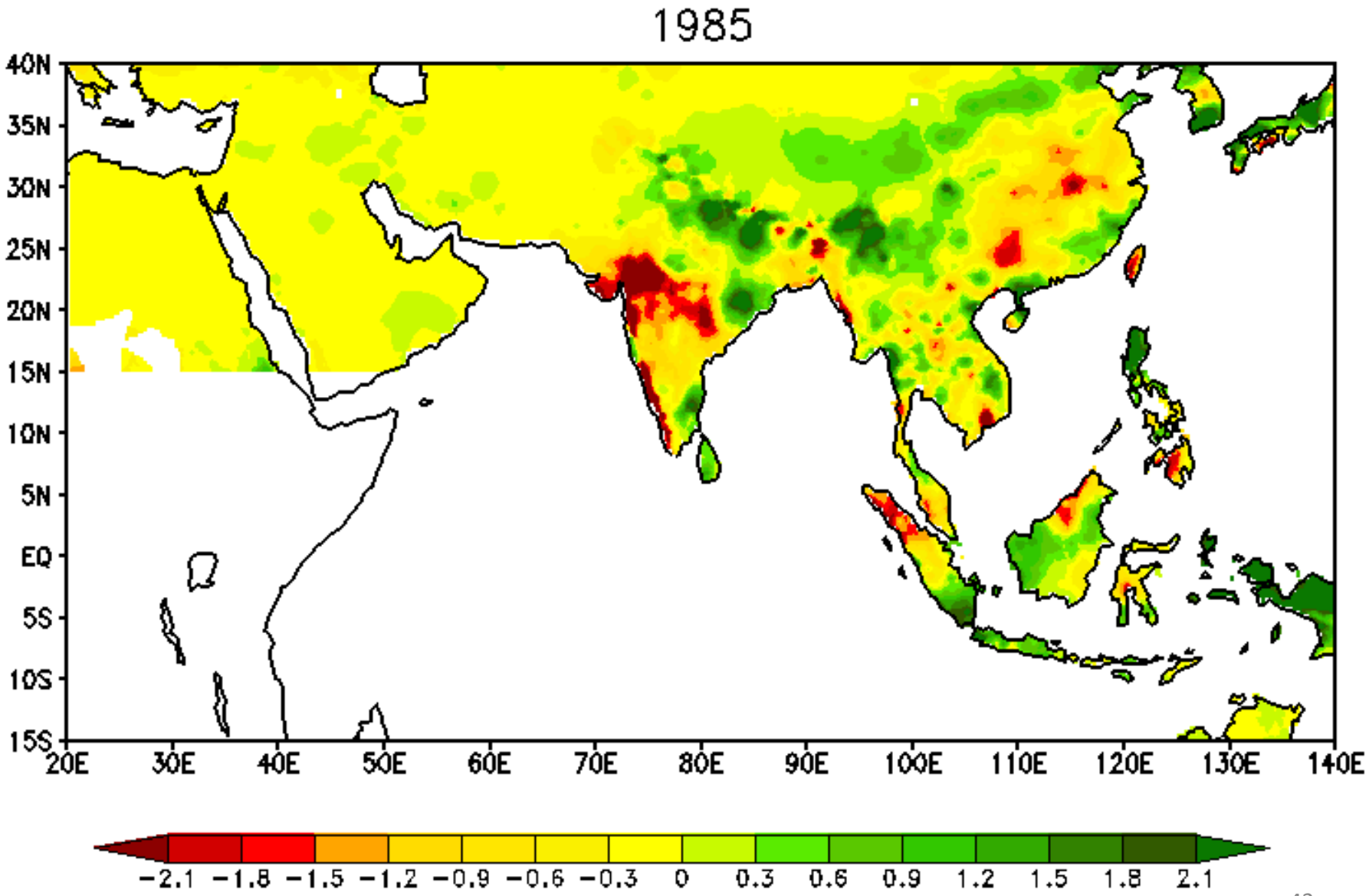

1966
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1

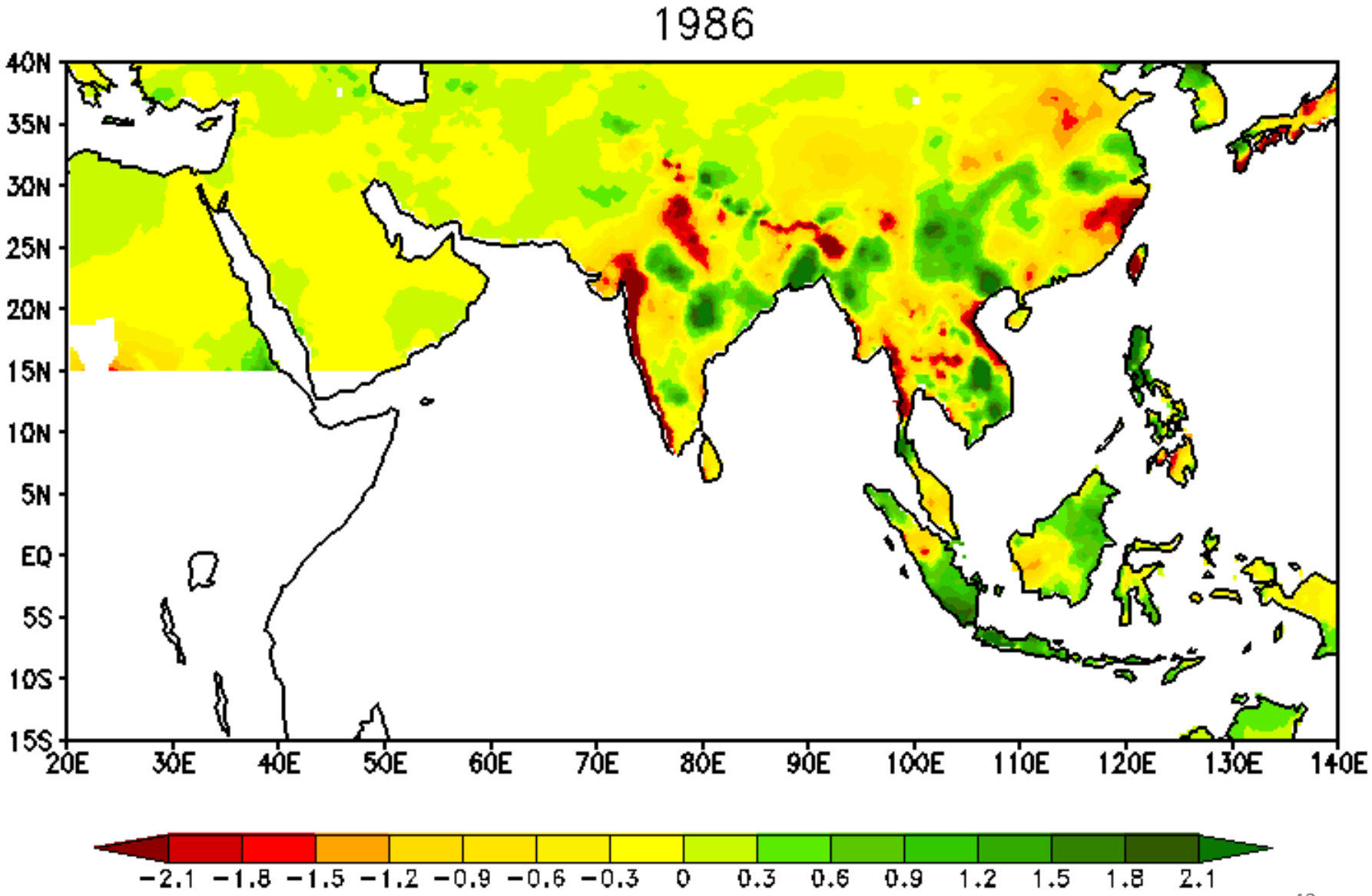

1968
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1

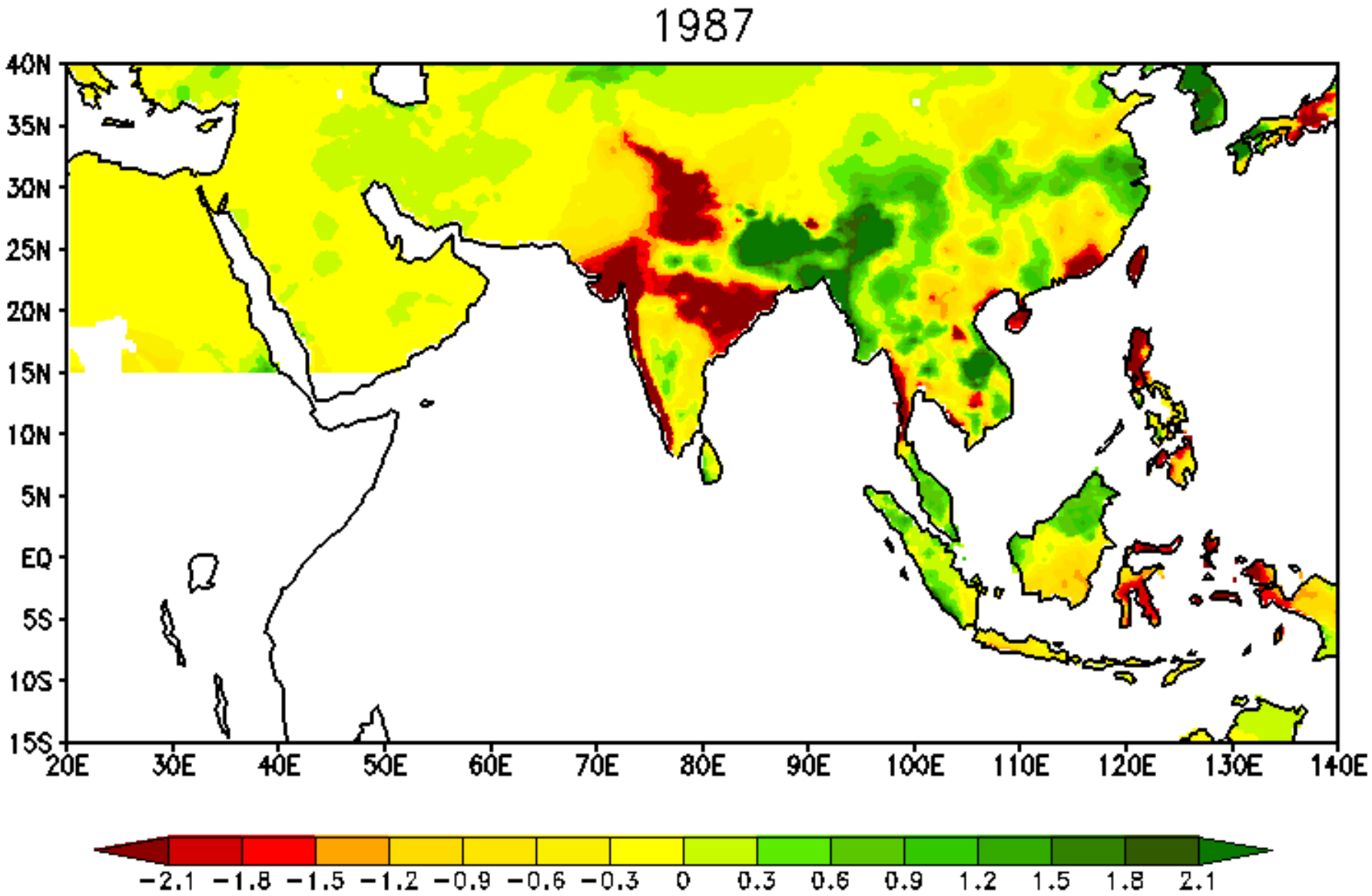

1972
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1

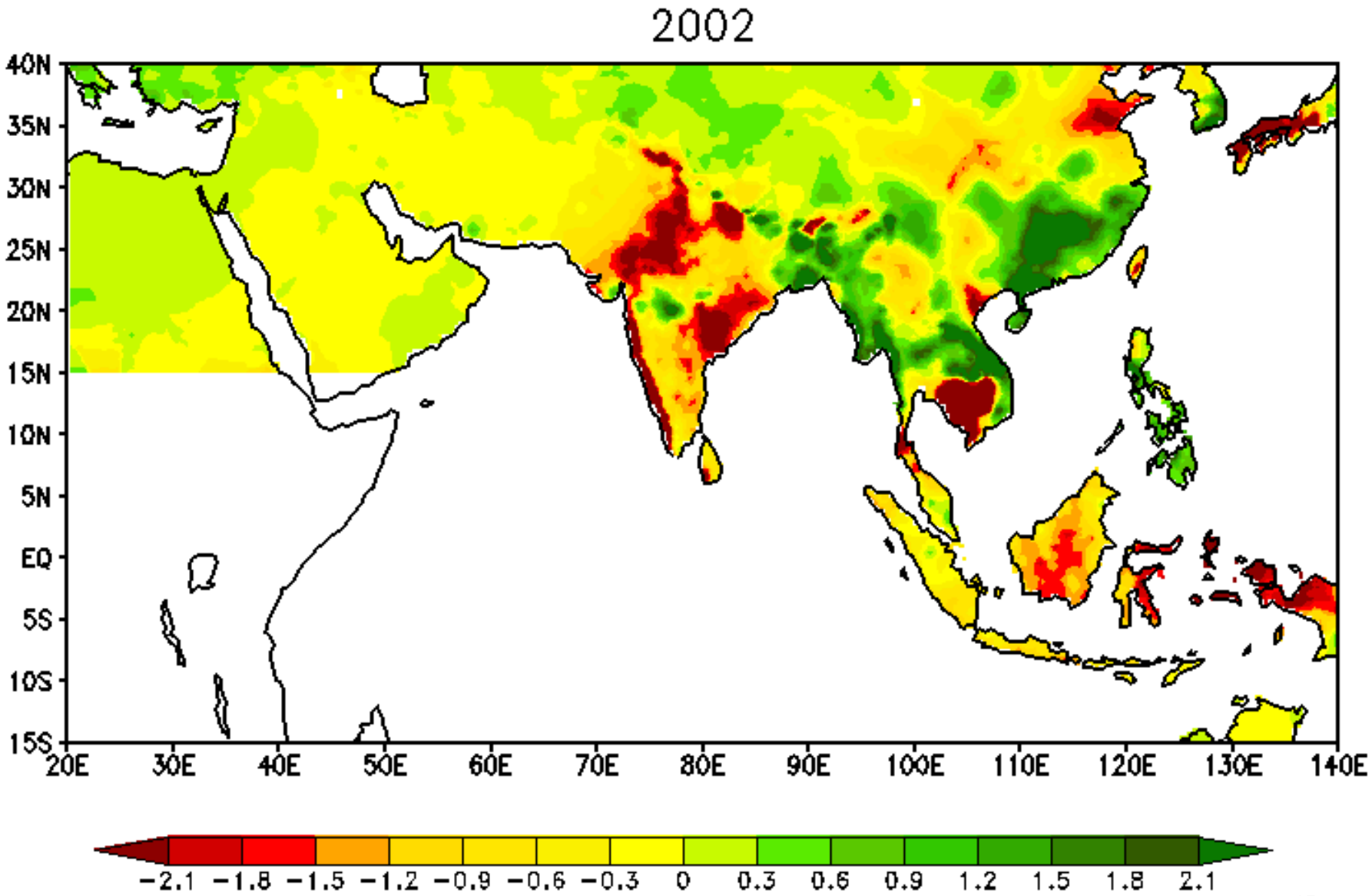

1979
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1


1982
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1


1985
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1

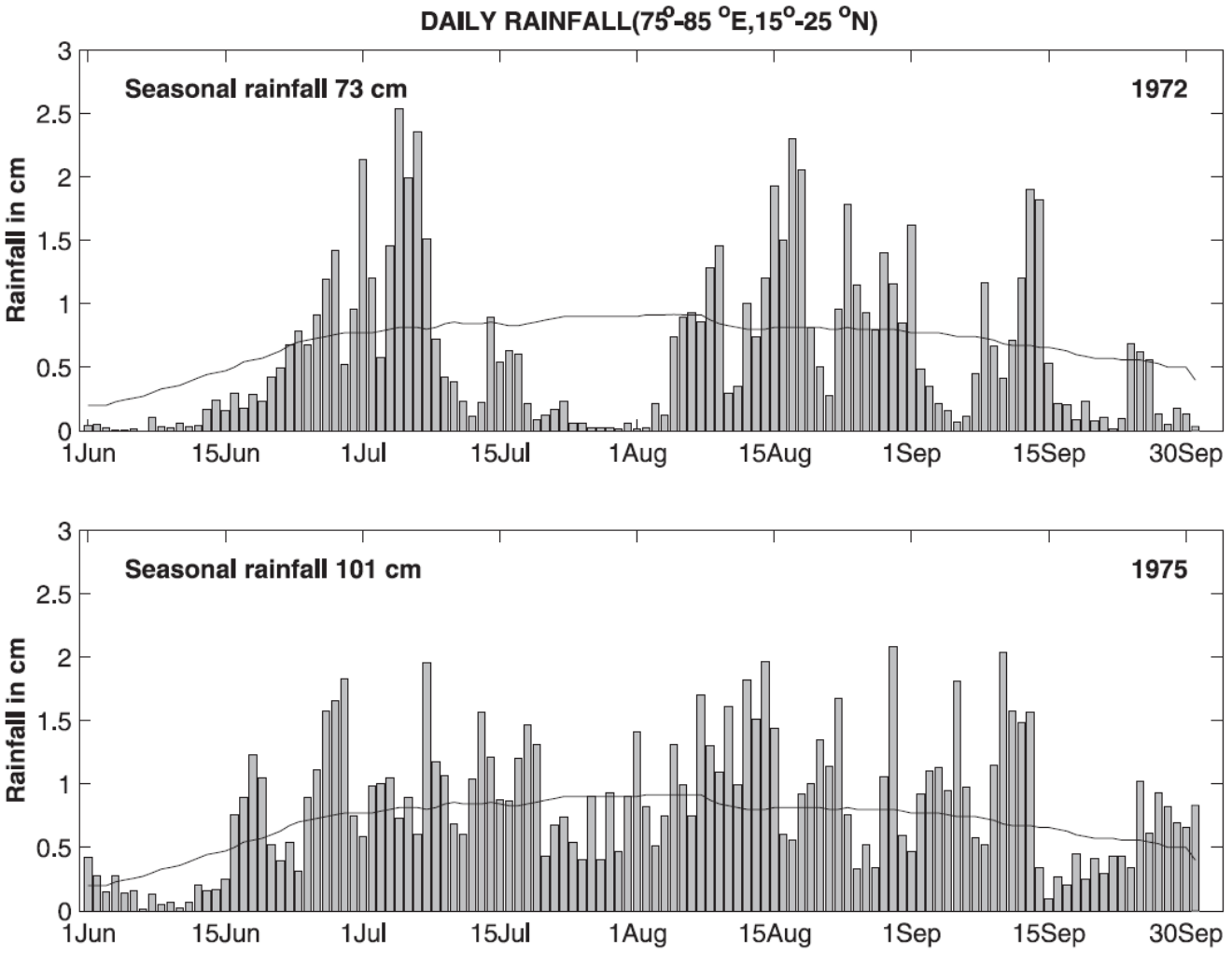

1986
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1


1987
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1

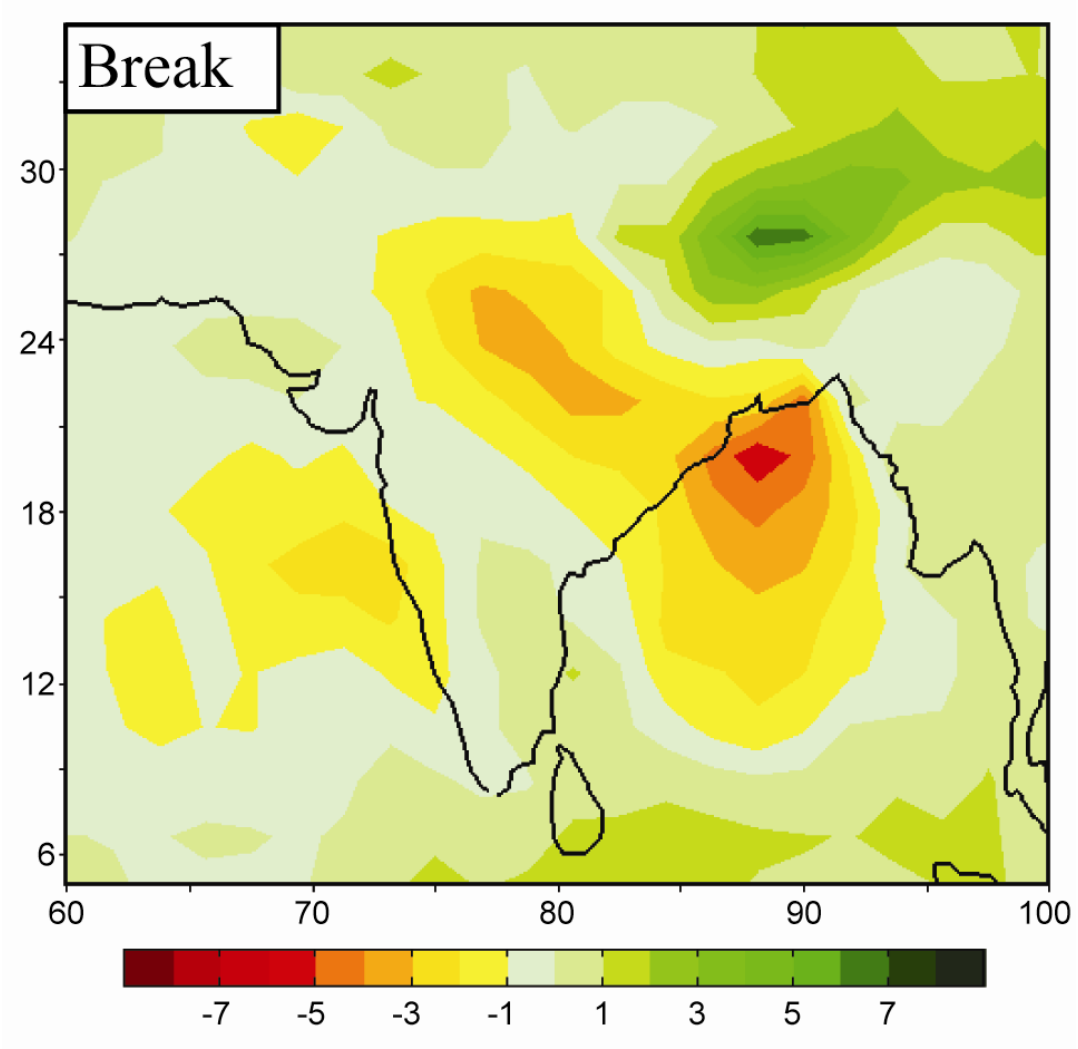

2002
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
−2.1 −1.8 −1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1

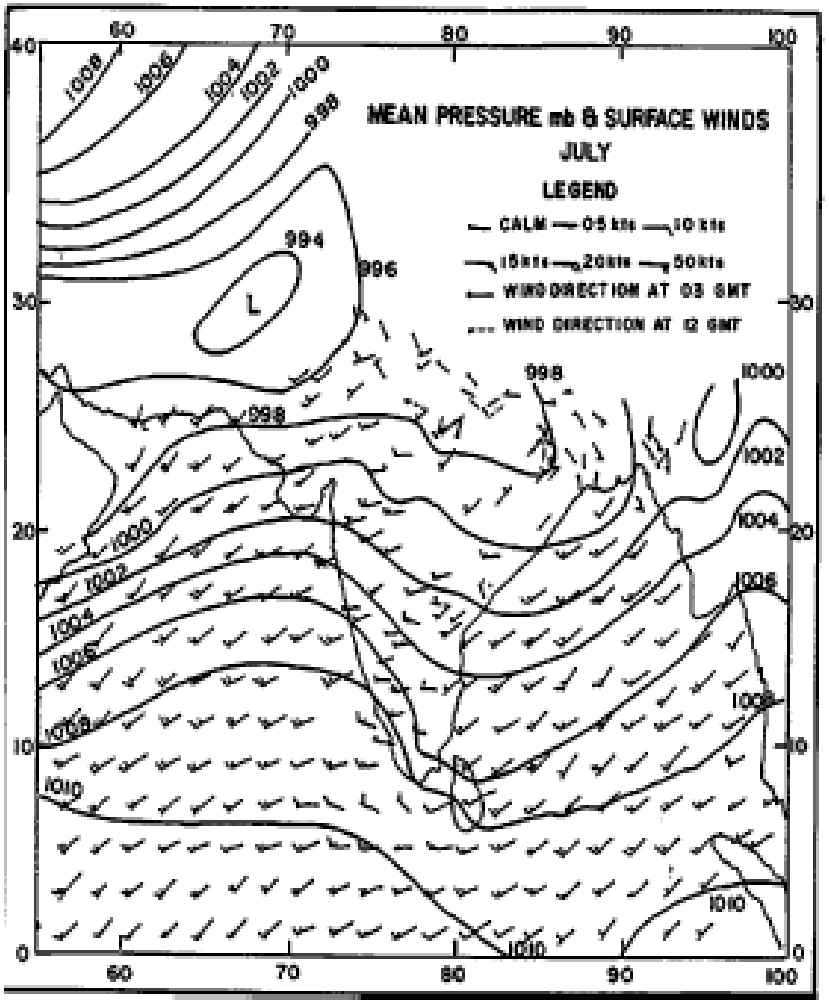
Break Monsoon

Breaks in Indian summer monsoon



Breaks in Indian summer monsoon




MEAN PRESSURE mb & SURFACE WINDS
JULY
LEGEND
CALM — 0-5 kts — 10 kts
15 kts — 20 kts — 50 kts
WIND DIRECTION AT 03 GMT
WIND DIRECTION AT 12 GMT
60
70
80
90
100
40
30
20
10
0
L
994
996
998
1000
1002
1004
1006
1008
1010

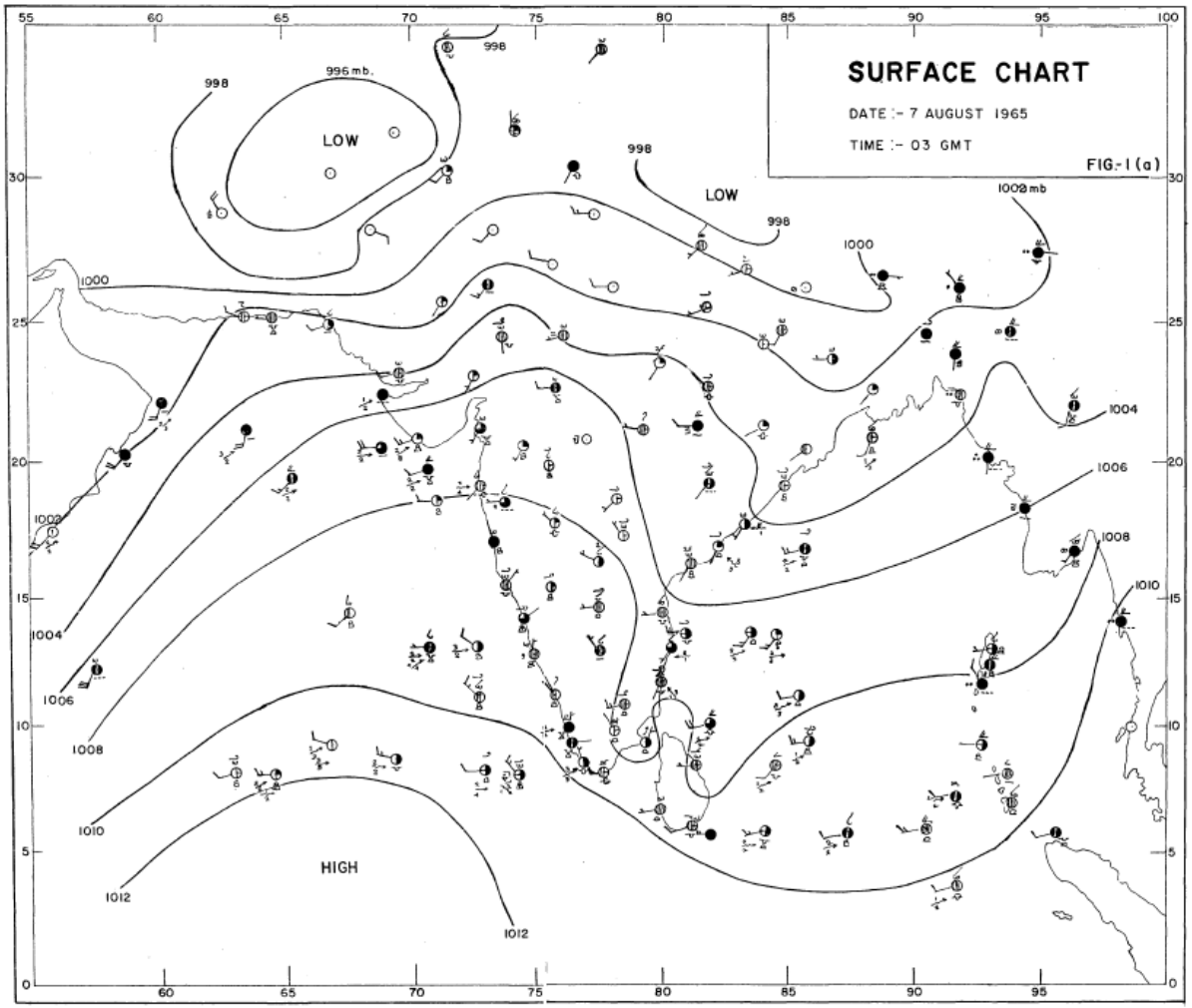

SURFACE CHART
DATE :- 7 AUGUST 1965
TIME :- 03 GMT
FIG:-1(a)
LOW
996 mb.
998
LOW
998
998
1002 mb
1000
1000
1004
1006
1008
1010
1012
1004
1006
1008
1010
1012
HIGH
55
60
65
70
75
80
85
90
95
100
0
5
10
15
20
25
30

Plate tectonic processes

1. **Continents near poles:** Continental ice sheets that are characteristic of ice ages can only form on land. Glaciation on the ancient supercontinent, Pangaea, occurred when several continents were grouped around the South Pole.

2. **Uplift associated with continental collisions**: the mountains changed the regional (maybe even global) atmospheric circulation patterns that contributed to a changing climate.

3. **Reduction/Increase in greenhouse gas concentrations:** A. Increased rainfall following uplift may have stripped carbon dioxide from the atmosphere to be used in chemical weathering. B. volcanic activity

The Supercontinent of Pangaea
(237 million years ago)

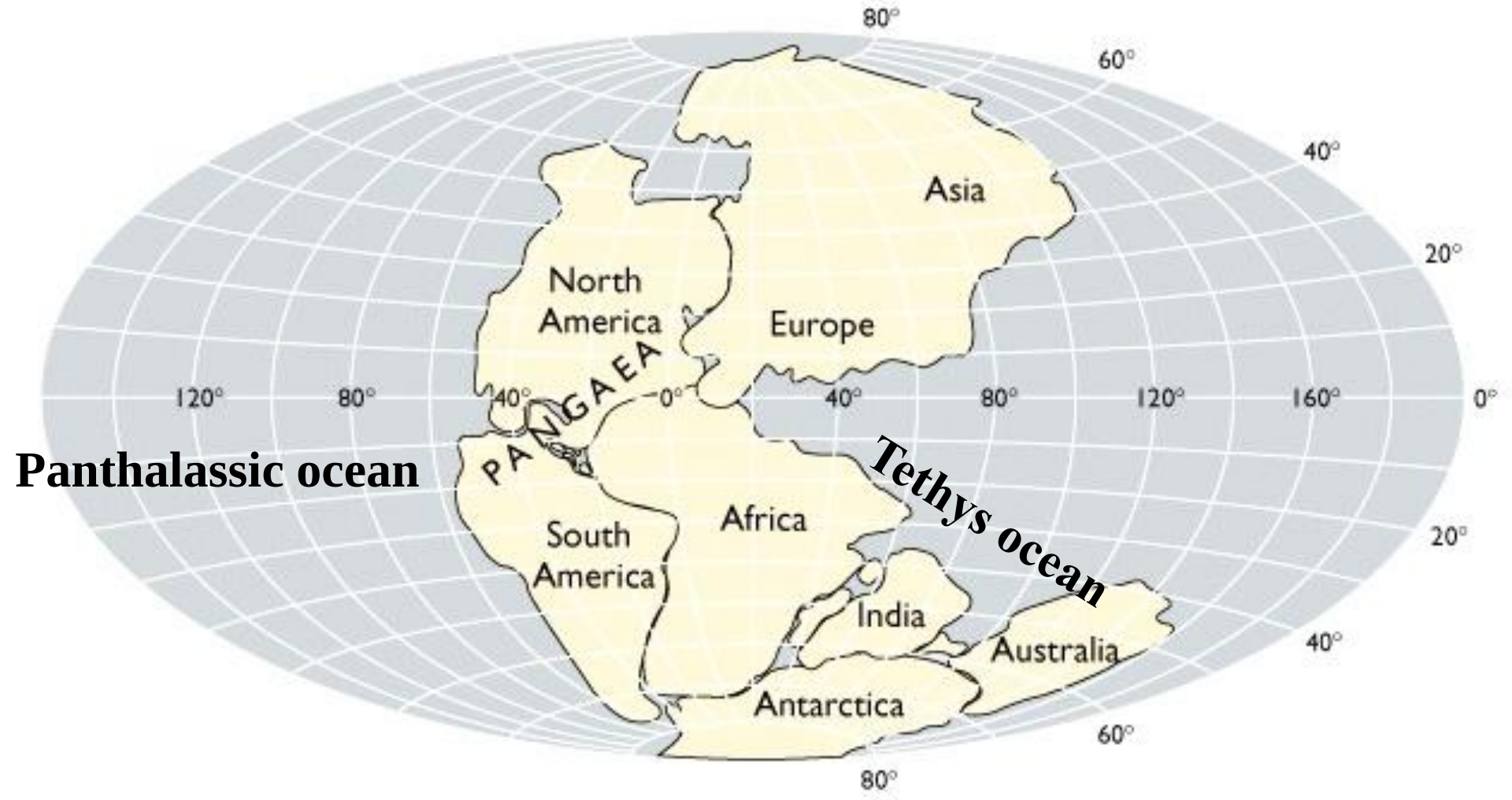
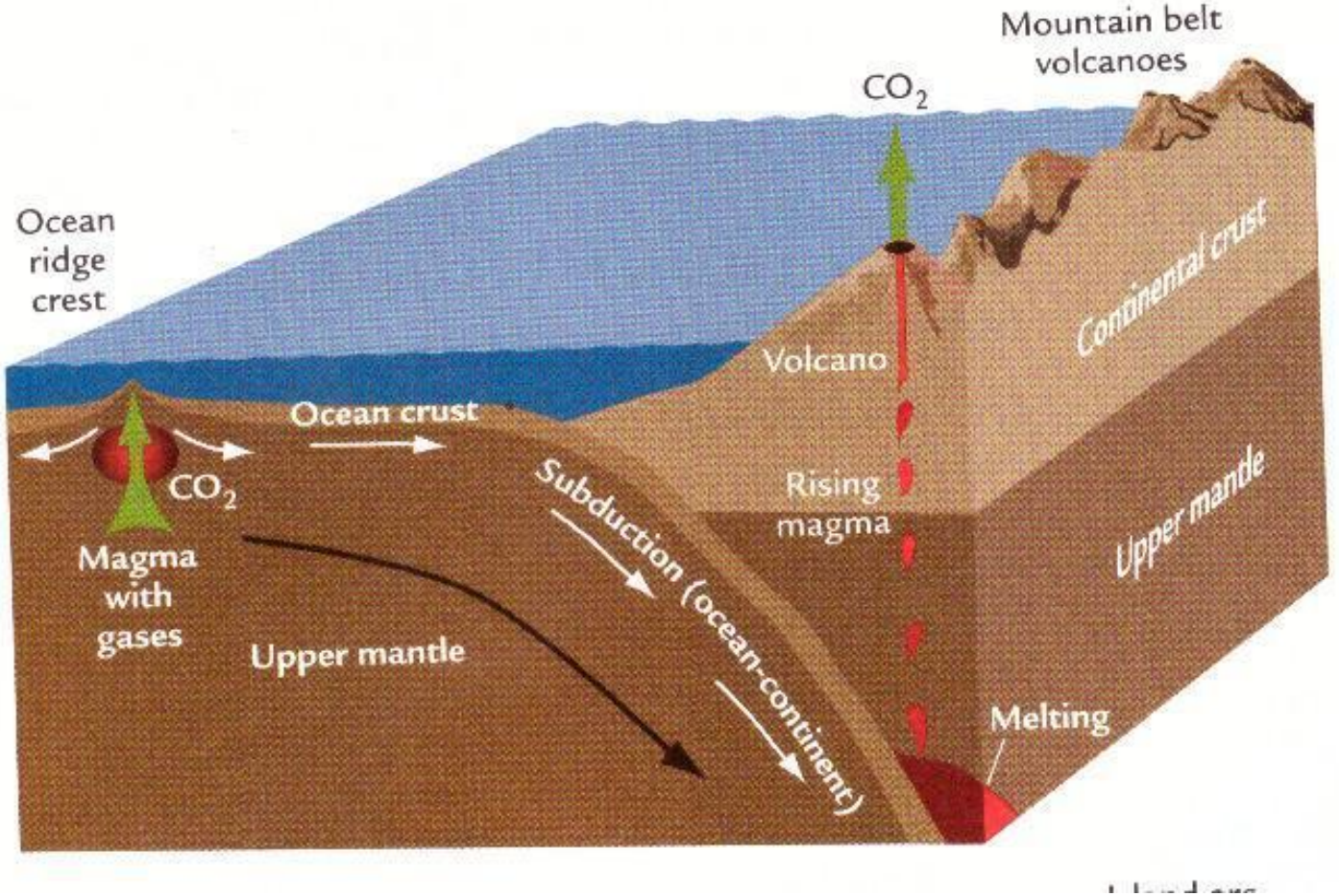
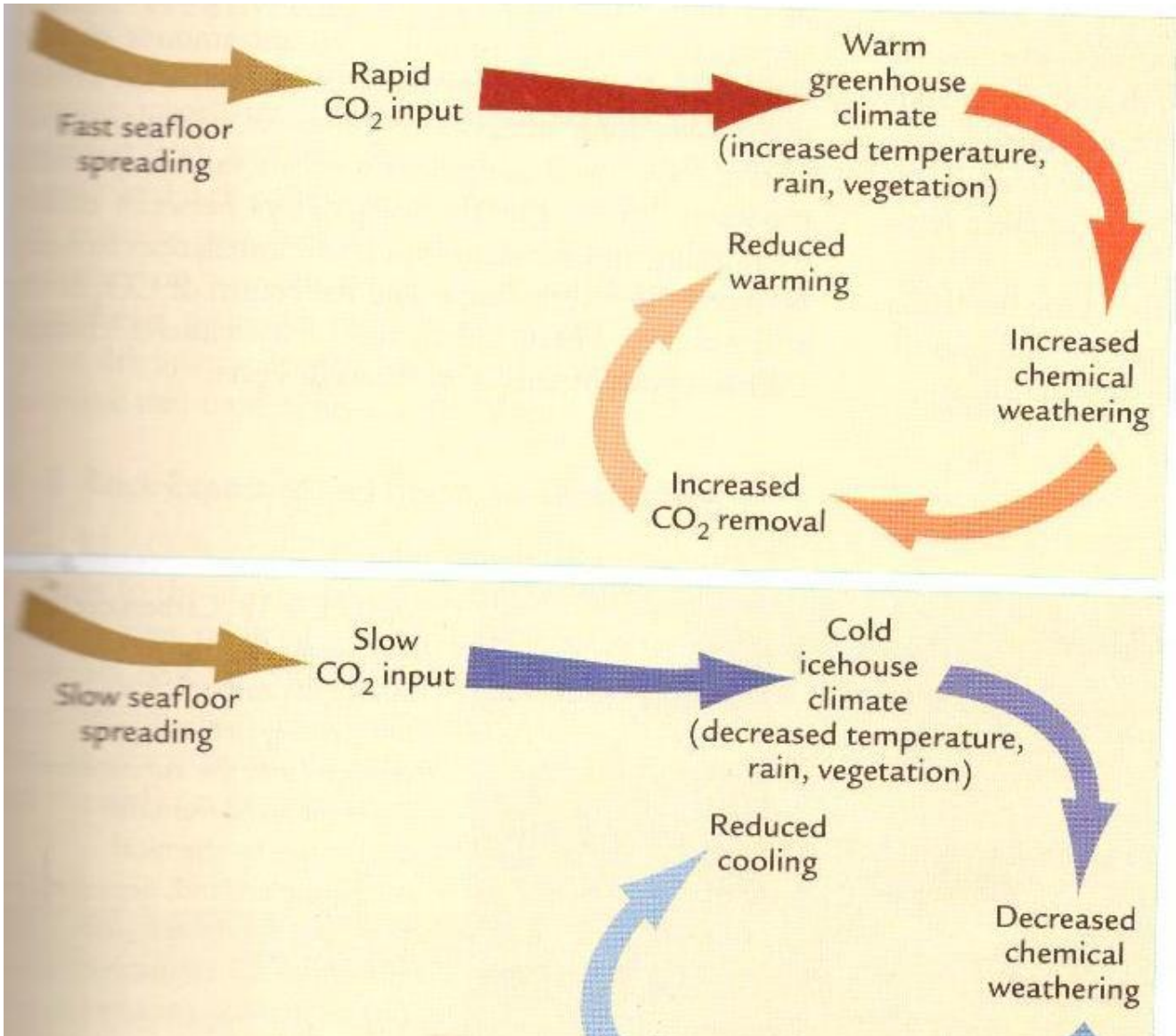


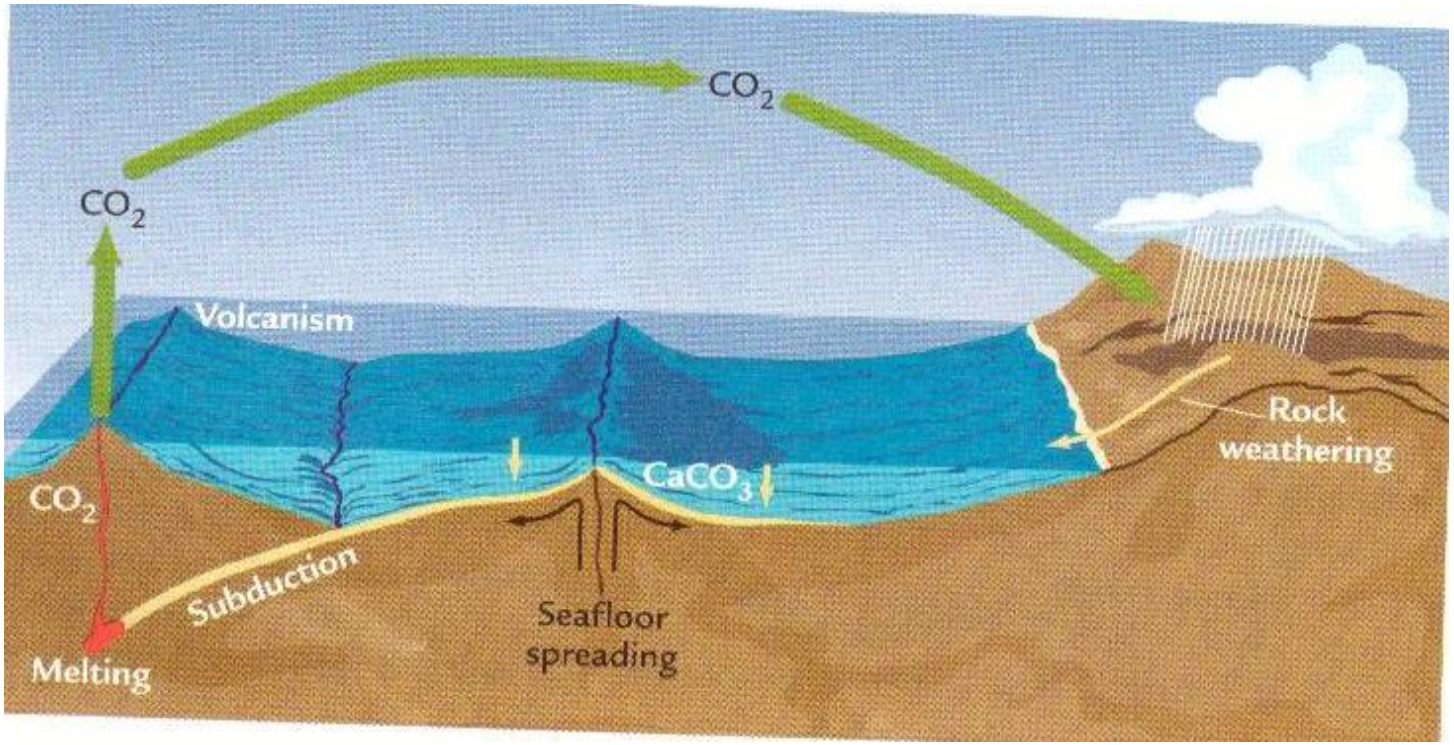
Plate tectonics and Increase in greenhouse gas concentrations



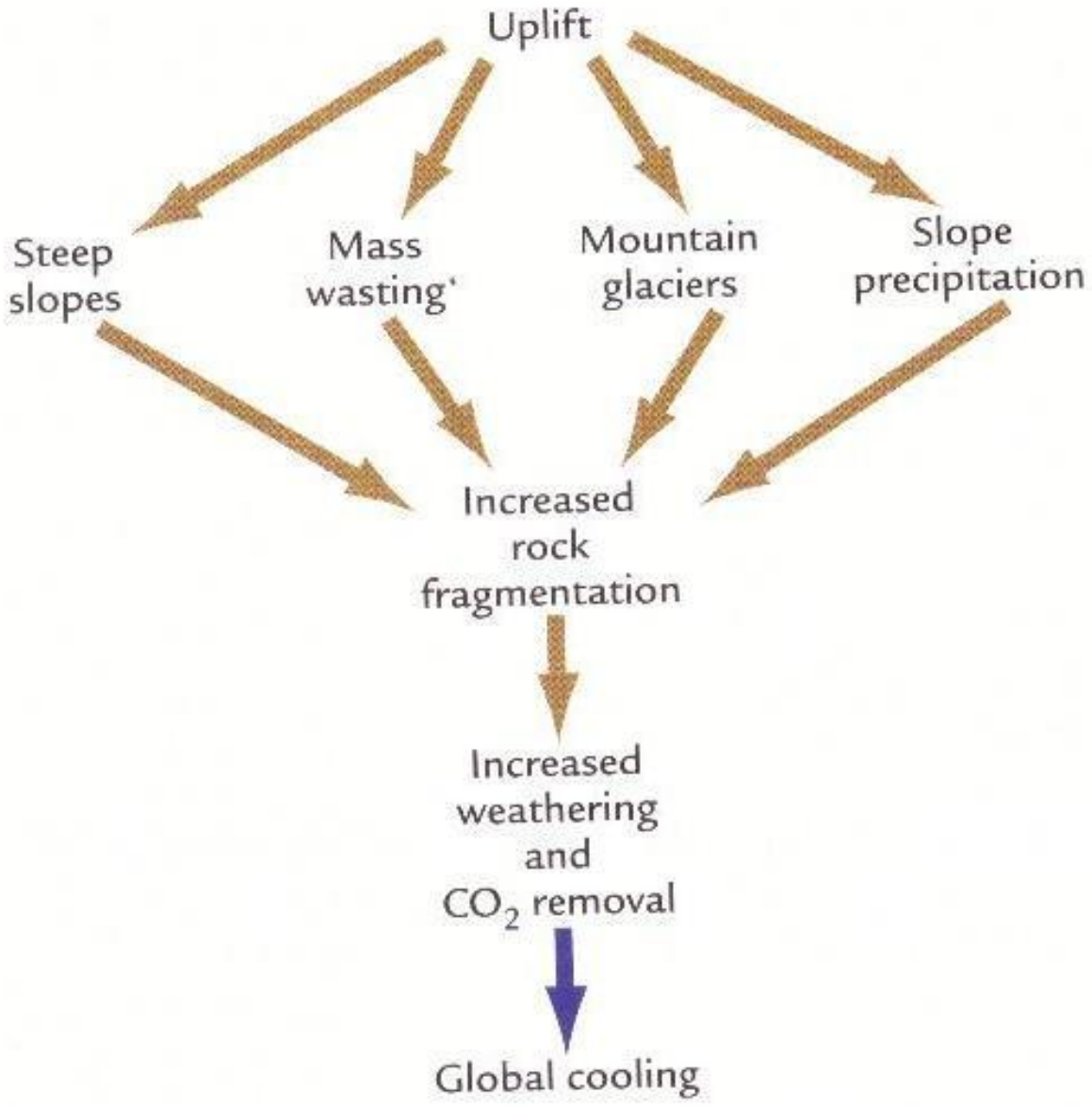
The spreading rate (BLAG) hypothesis



The spreading rate (BLAG) hypothesis



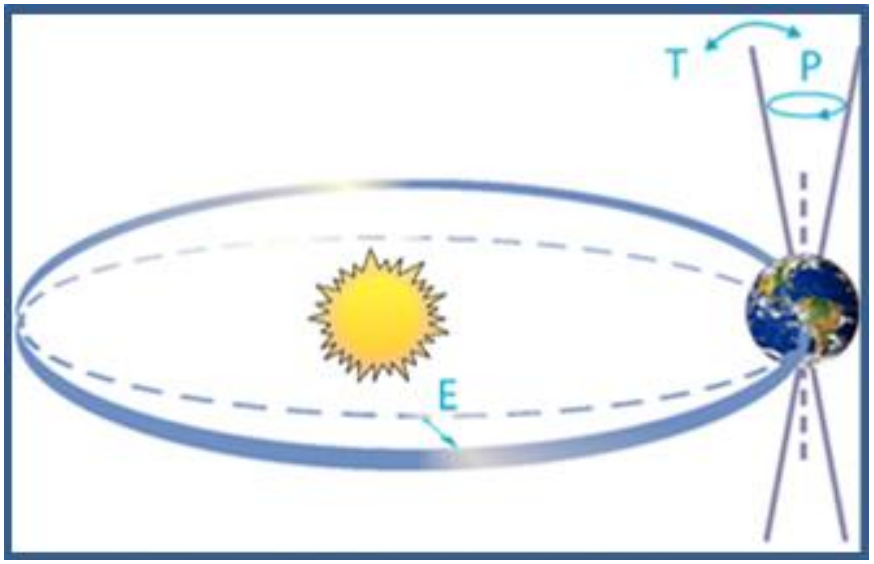
Uplift weathering hypothesis



Milankovitch Theory
(Orbital Parameter Theory of Ice Ages)

Regular changes in the Earth's orbital **parameters alter the distribution of solar radiation enough to trigger ice ages.**

Milankovitch Cycles



IPCC 2007

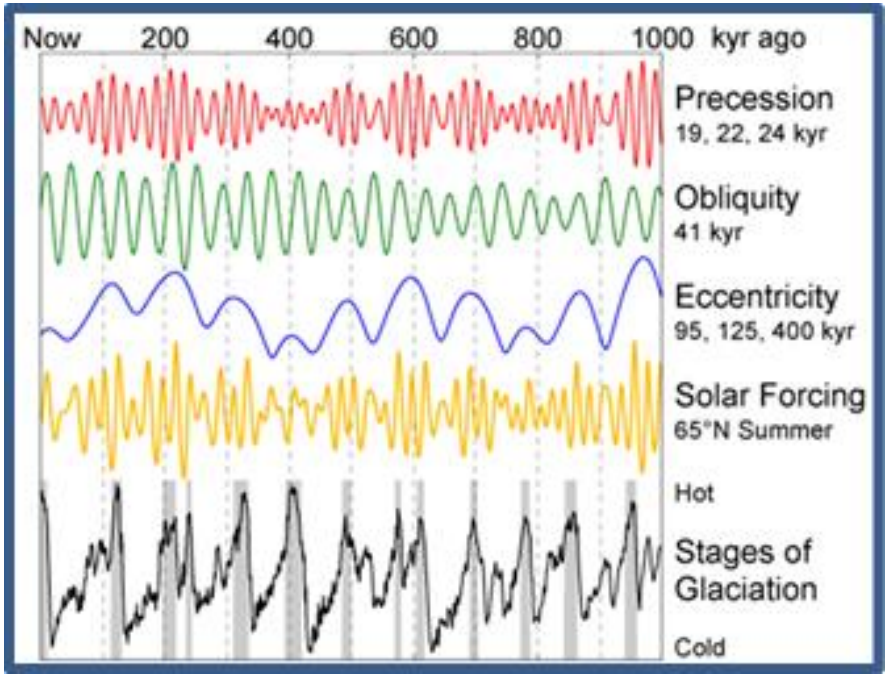
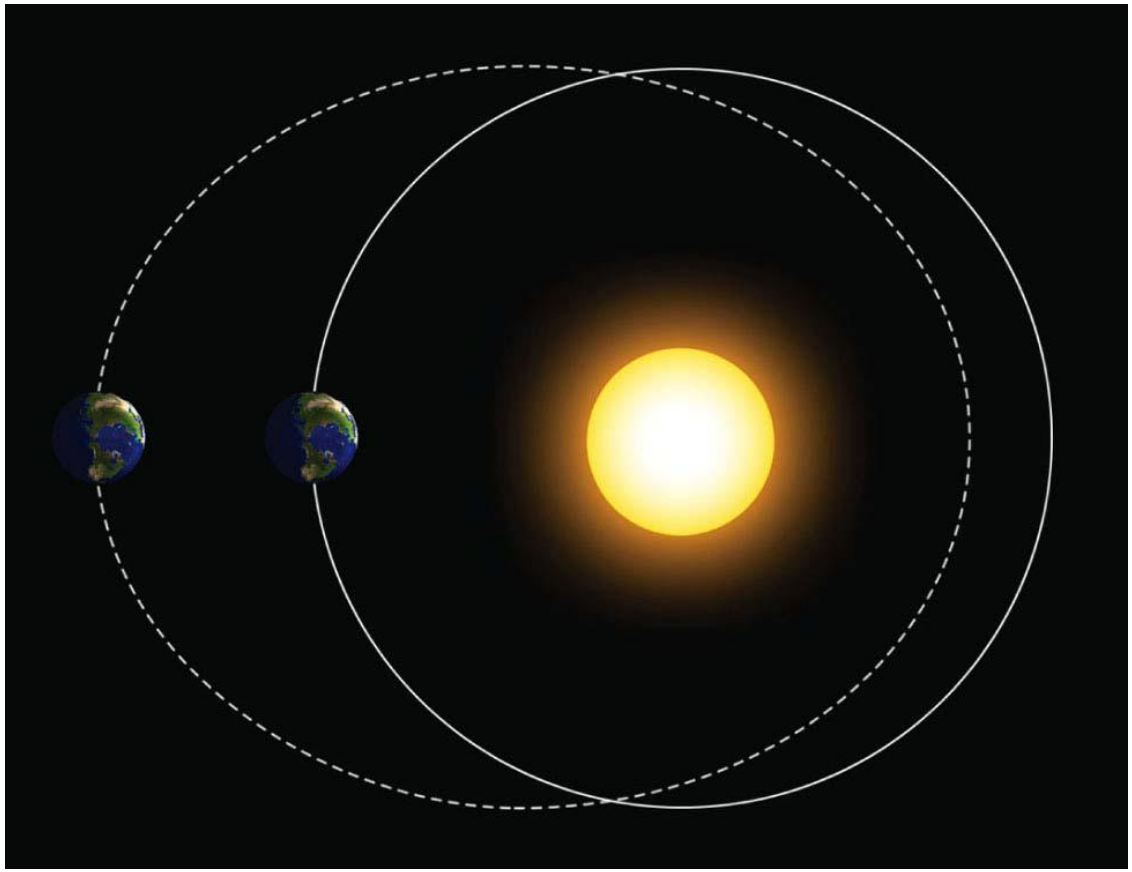


Image: Robert A. Rhodes, Global Warming Art

- Eccentricity (a cycle of around 100,000 years)
- Tilt or Obliquity (a cycle of around 41,000 years)
- Precession (a cycle of around 24,000 years)

Eccentricity

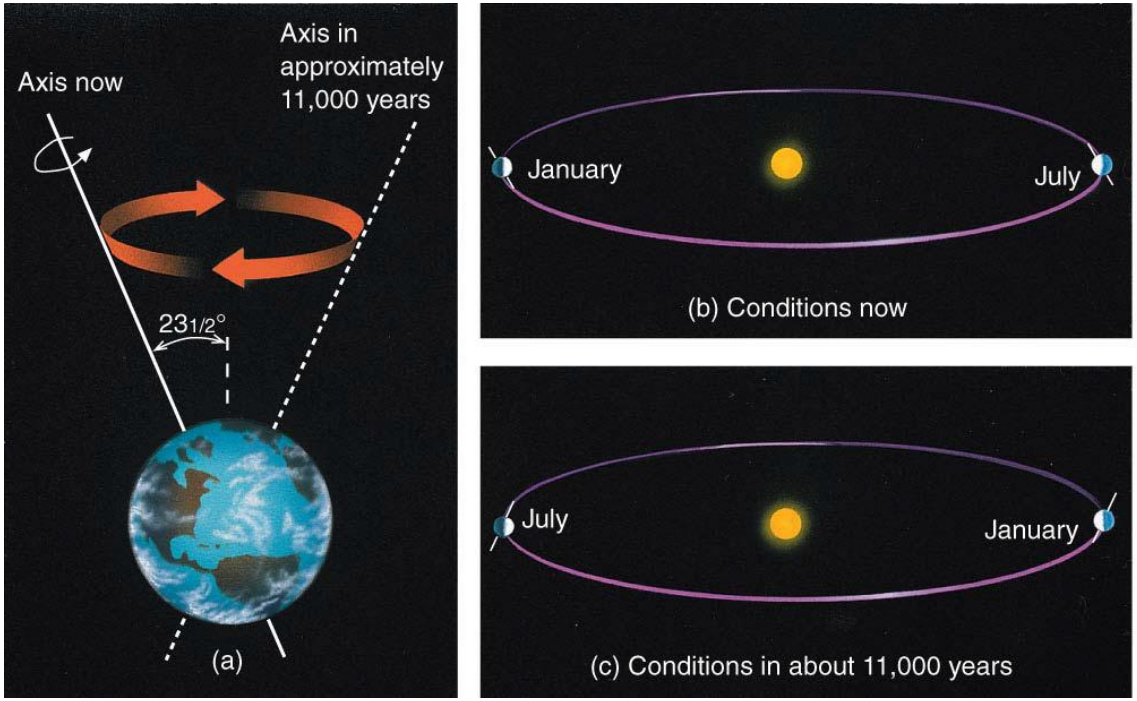
1. The eccentricity of Earth's orbit. The exact path of the orbit around the Sun changes with time and may become less eccentric (more circular) or more eccentric (more elliptical). These changes occur on a 100,000-year cycle.



Changes in the tilt of Earth's axis.

The tilt of Earth's axis is currently tilted at 23.5 but axial tilt ranges from approximately 22 to 25 degrees over a 41,000-year cycle.

Decreasing tilt **reduces the contrast of insolation associated with the seasons**, **increasing tilt exaggerates seasonal differences**.



Milankovitch Theory

The precession of Earth on its axis

Earth "wobbles" on its axis (precession), changing the direction of axial tilt.

Precession occurs on a **26,000-year cycle** - the length of time taken for the axis to trace a complete loop.

Climate Forcings

Internal Forcings

- Greenhouse gases
- Tropospheric aerosols
- Land surface changes
- Volcanoes

Greenhouse Gases

Greenhouse gases absorb and emit radiation within the thermal infrared range

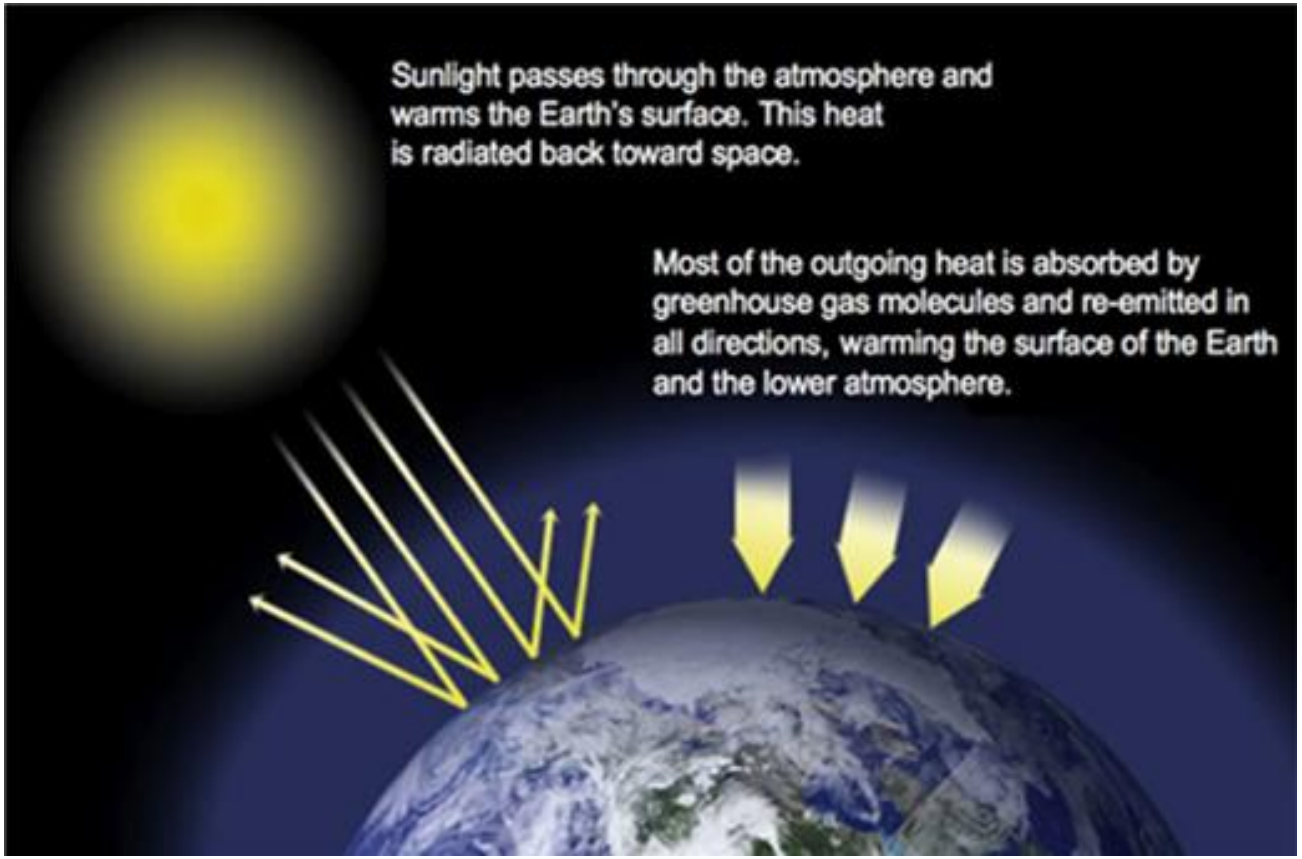


Image: www.climate.nasa.gov

Greenhouse gases include:

- water vapour,
- carbon dioxide,
- methane,
- nitrous oxide,
- ozone,
- CFCs

…and others

Tropospheric Aerosols

Aerosols:

- Scatter and absorb radiation, bringing about complex interactions with climate
- Play a role in cloud formation
- Create positive and negative forcing:
    - Sulphate aerosols persist over time and reflect energy from the sun resulting in cooling
    - Black carbon particles settle on Earth and reduce albedo which causes warming

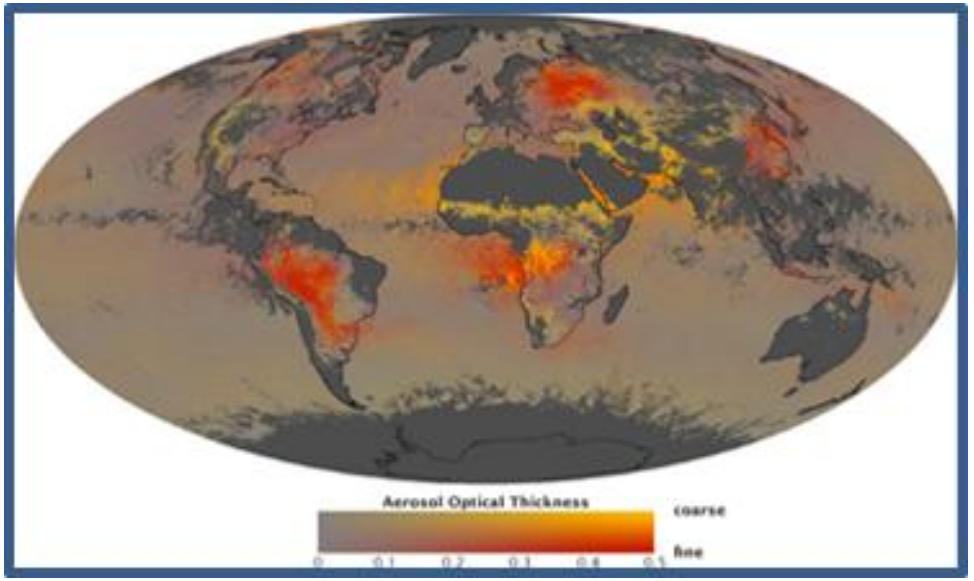


Image: www.nasa.gov

Land Surface Changes

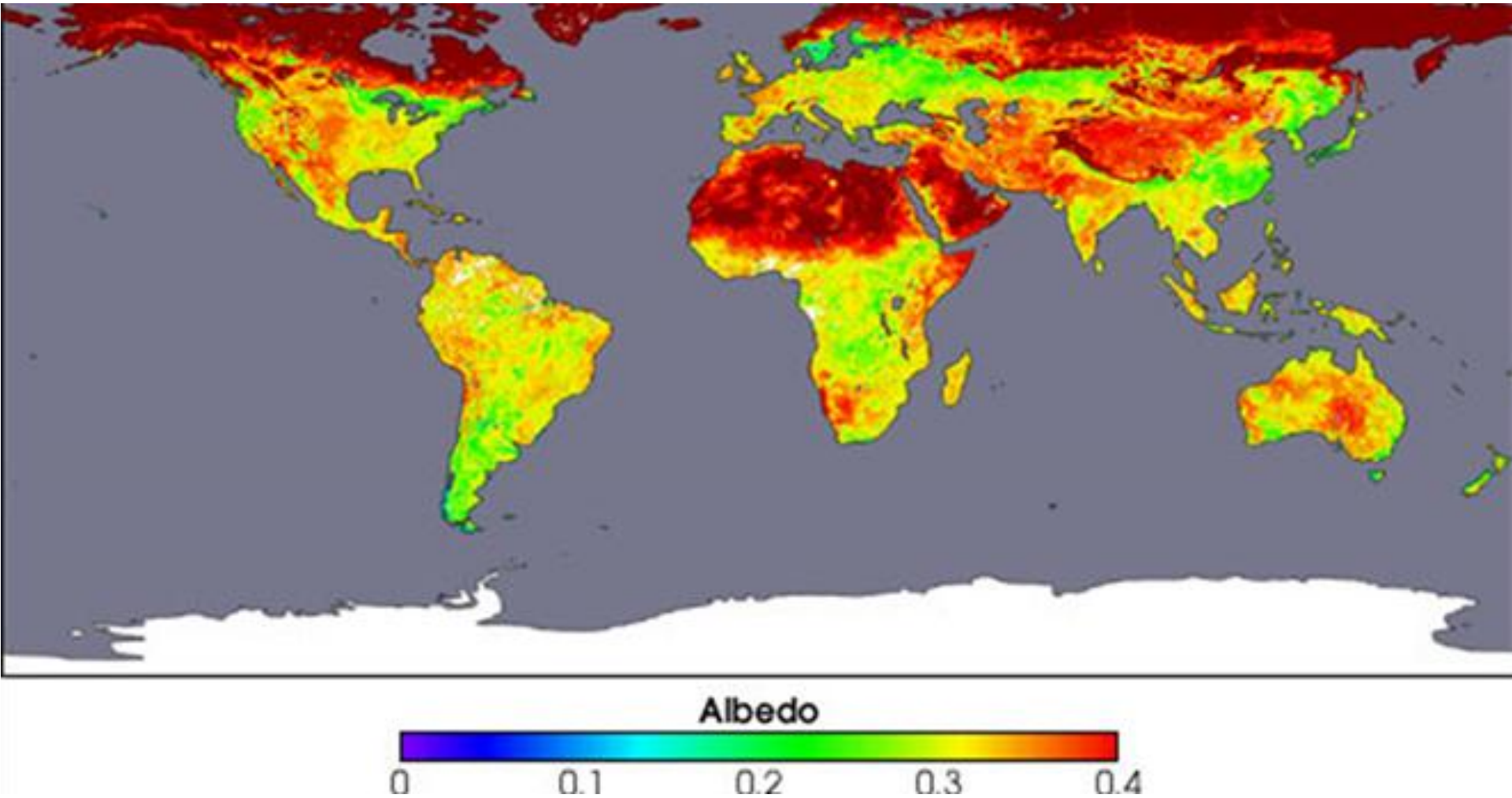


Image: www.nasa.gov

Volcanos

Image: NASA

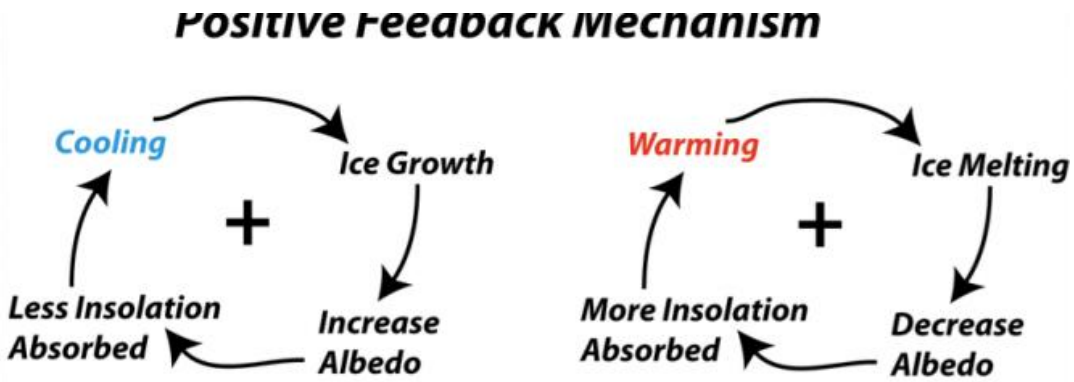
A volcano is a rupture in the Earth's crust from which magma, ash and gases can escape.

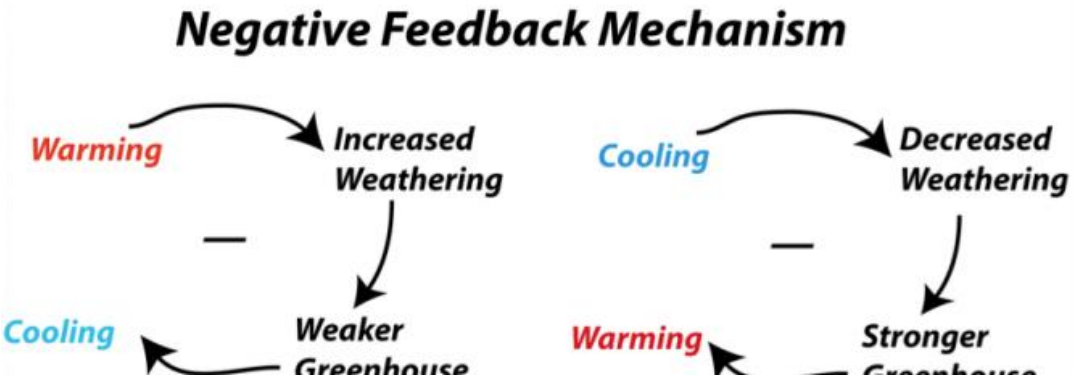
They have far-reaching atmospheric effects.

Climate feedbacks

Feedbacks occur when an internal or external forcing results in changes to the climate system which further impact on climate system dynamics in a feedback loop.

- Positive feedback
- Negative feedback


Positive Feedback Mechanism
Cooling
Ice Growth
+
Less Insolation Absorbed
Increase Albedo
Warming
Ice Melting
+
More Insolation Absorbed
Decrease Albedo


Negative Feedback Mechanism
Warming
Increased Weathering
—
Cooling
Weaker Greenhouse
Cooling
Decreased Weathering
—
Warming
Stronger