The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1956-9

Targeted Training Activity: Seasonal Predictability in Tropical Regions to be followed by Workshop on Multi-scale Predictions of the Asian and African Summer Monsoon

4 - 15 August 2008

The Indian Summer Monsoon : An Overview of Mean and Variability.

Goswami B.N.

Indian Institute of Tropical Meteorology
Ministry of Science & Technology. Government of India
Dr.Homi Bhabha Road, Ncl Post Office, Pashan, 411 008 Pune
INDIA

The Indian Summer Monsoon : An Overview of Mean and Variability

B. N. Goswami

Indian Institute of Tropical Meteorology (IITM)

Outline

- Indian summer monsoon: A phase of the Monsoon Annual Cycle
- Some basic characteristics
- A critique of classical land-ocean contrast theory of monsoon and fixed length monsoon season
- Interannual Variability : A new teleconnection pathway for ENSO monsoon relation
- Interdecadal variability and AMO : A physical linkage with NA
- Global warming vs Indian monsoon

What is the Indian Summer Monsoon?

A manifestation of seasonal northward migration of the Rain Band or Tropical Convergence Zone (TCZ)

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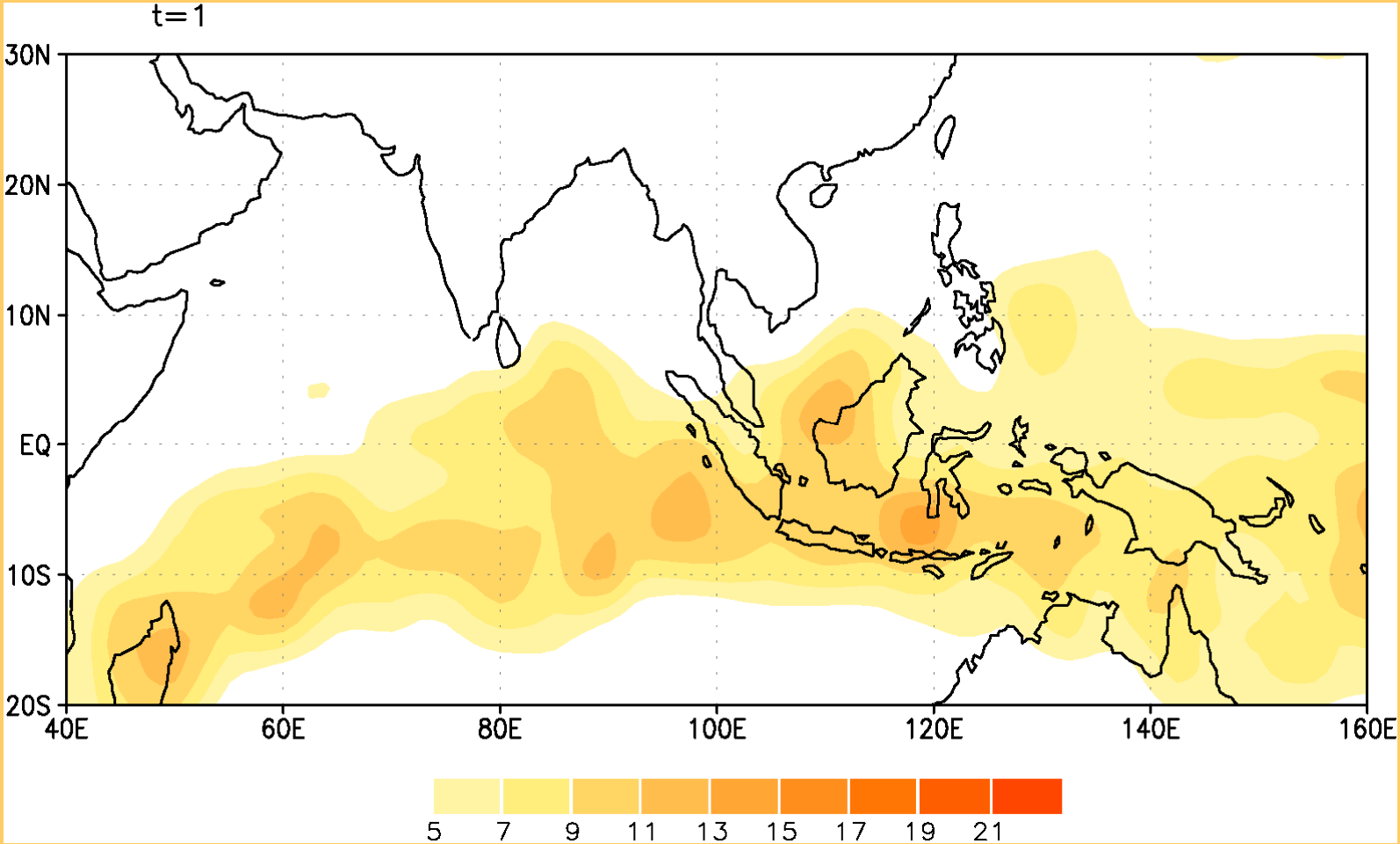
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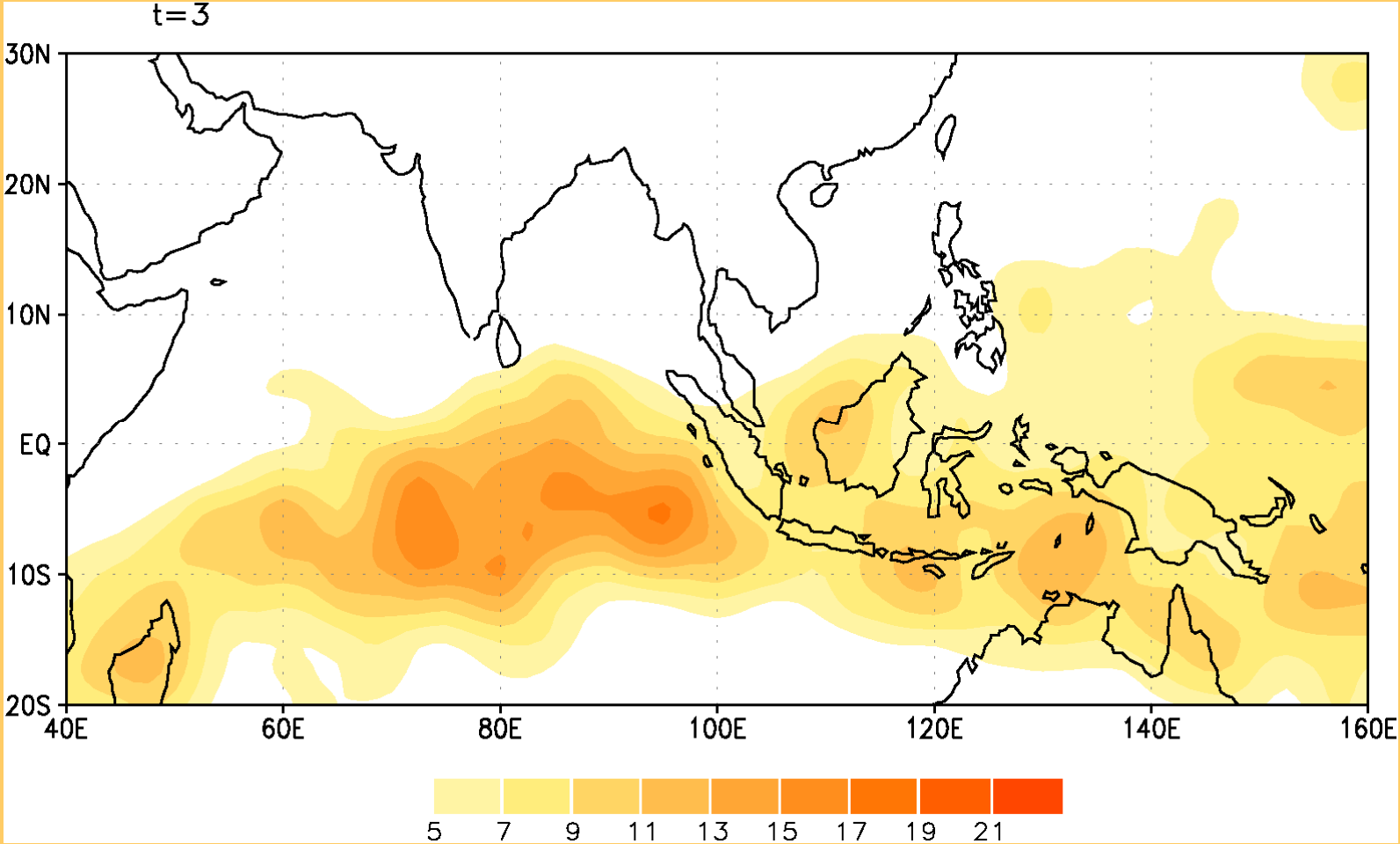
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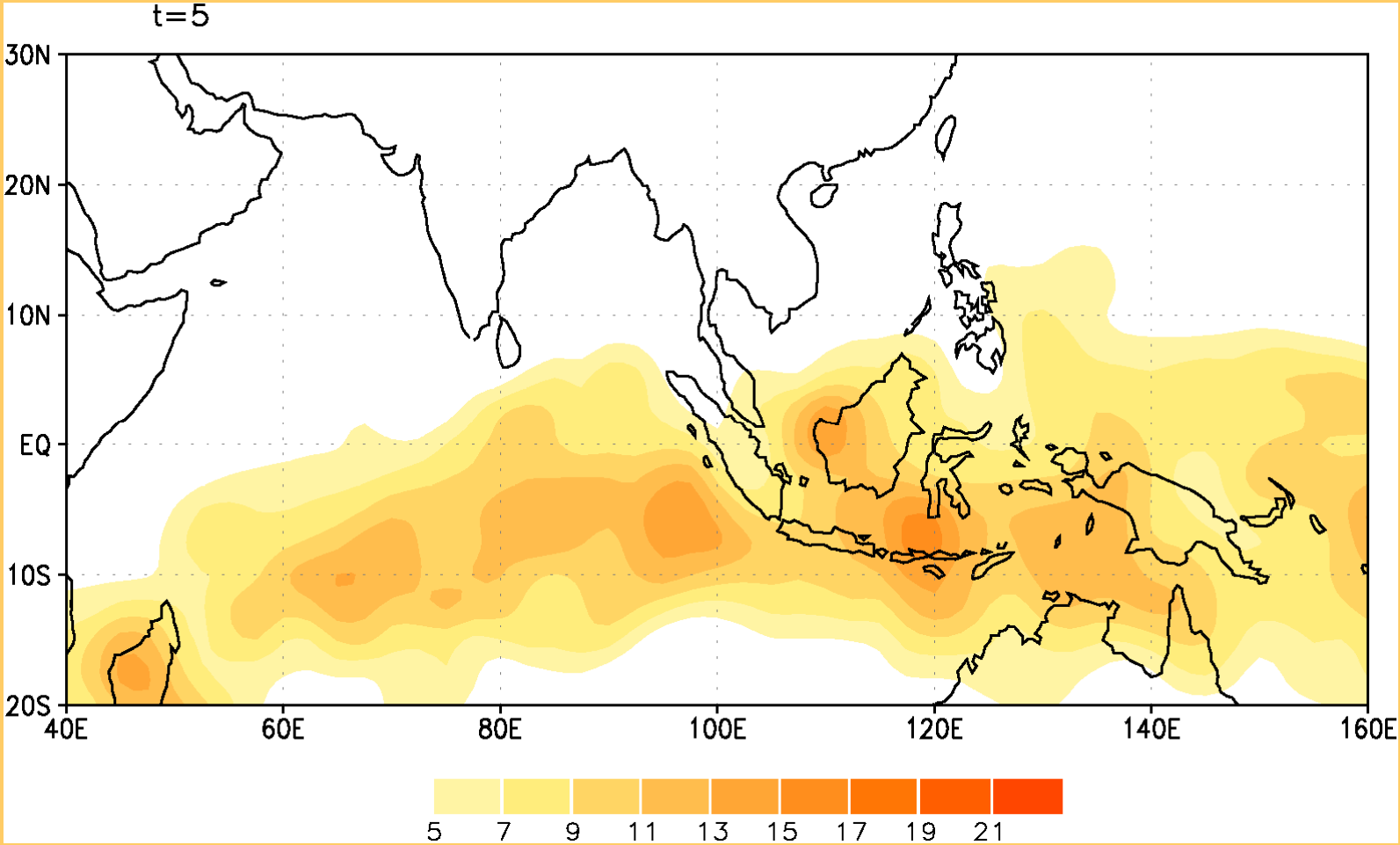
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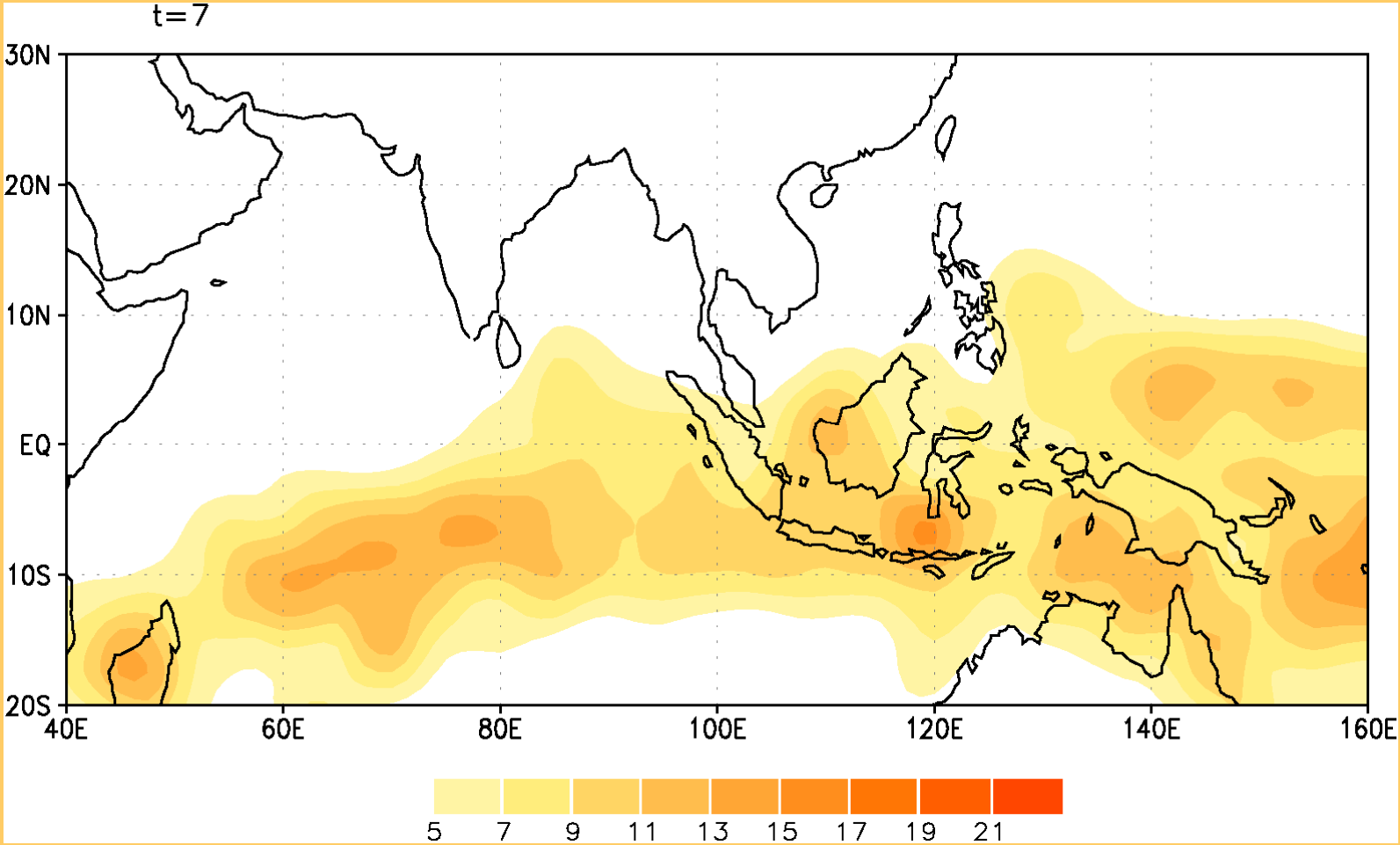
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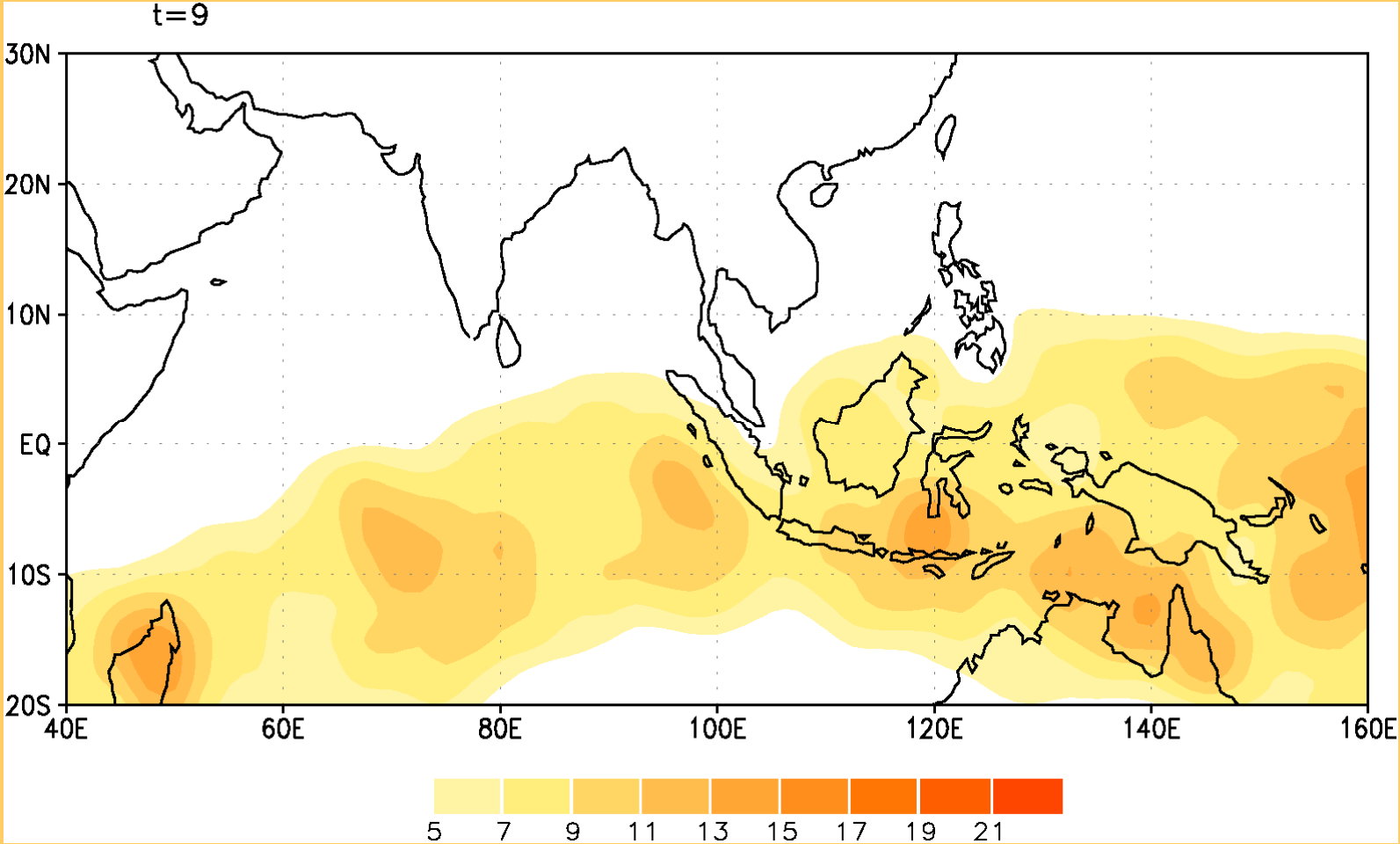
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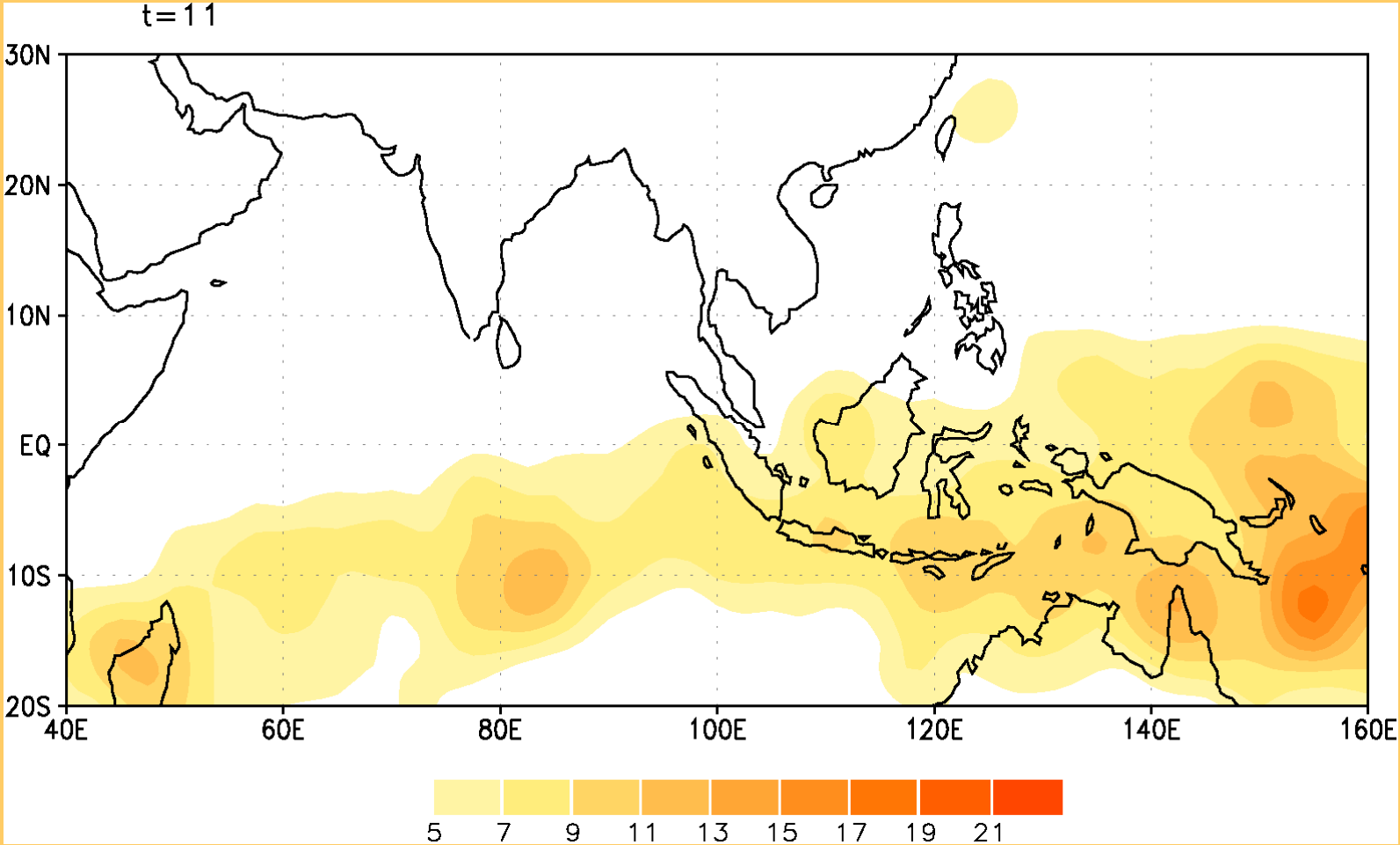
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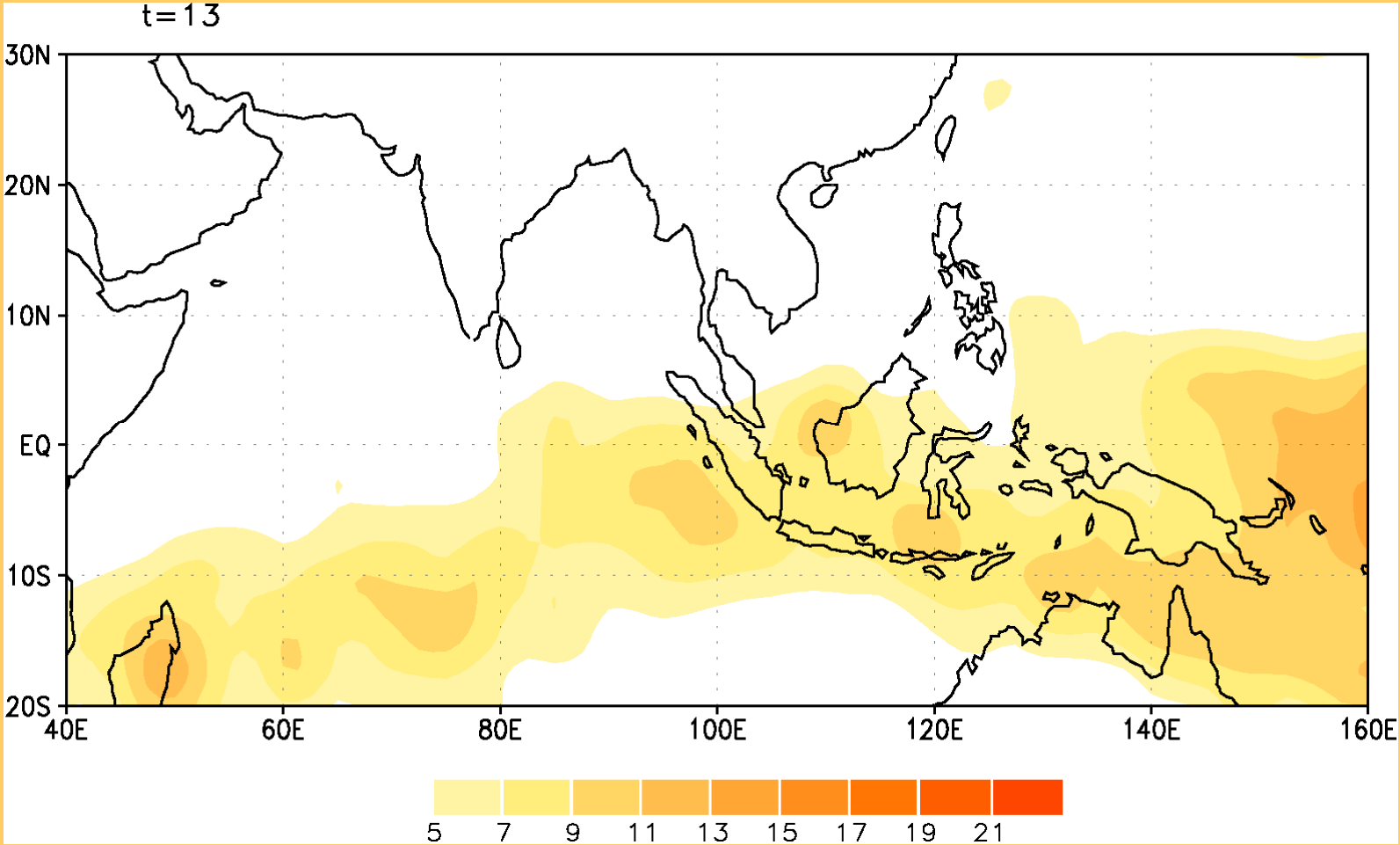
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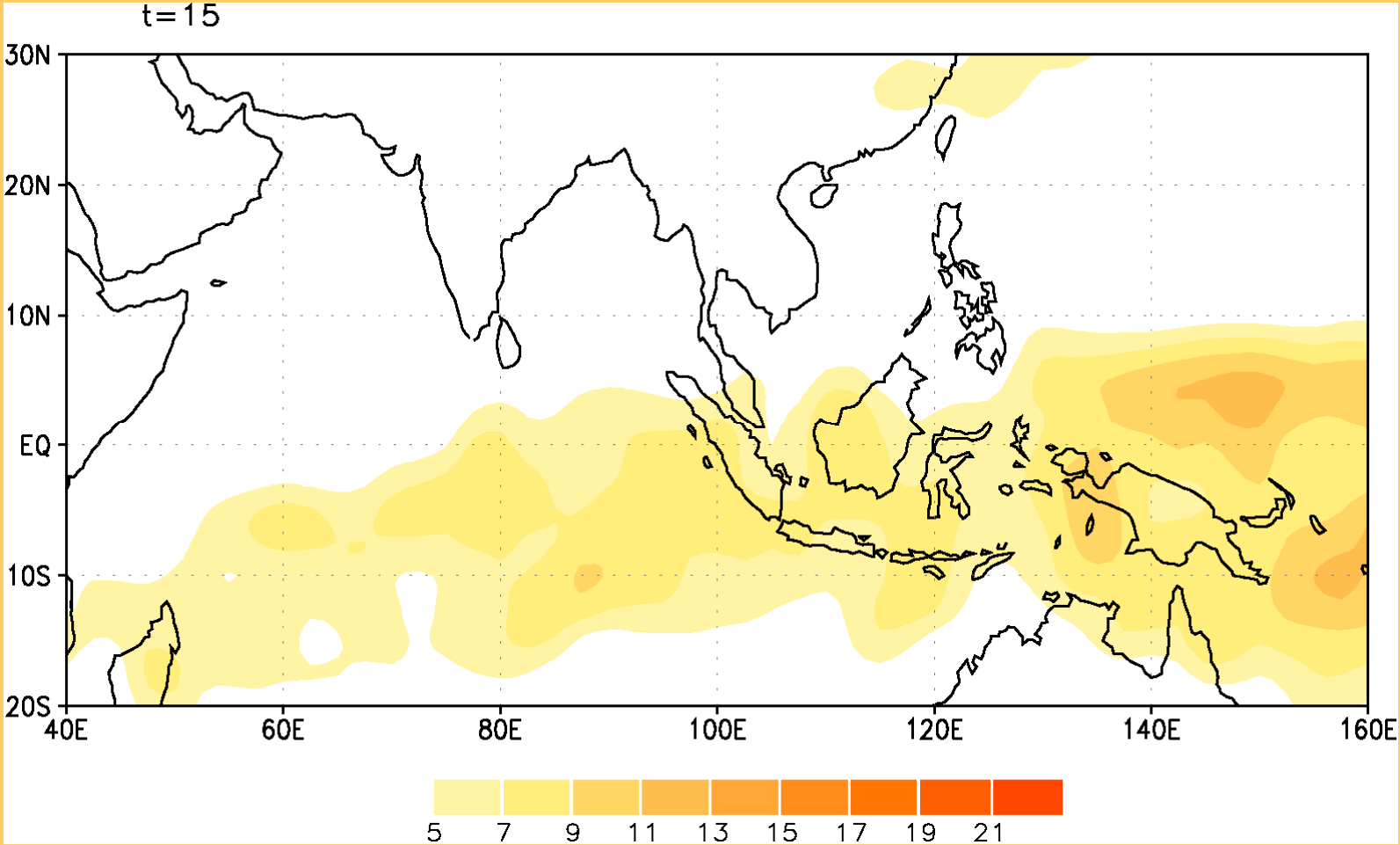
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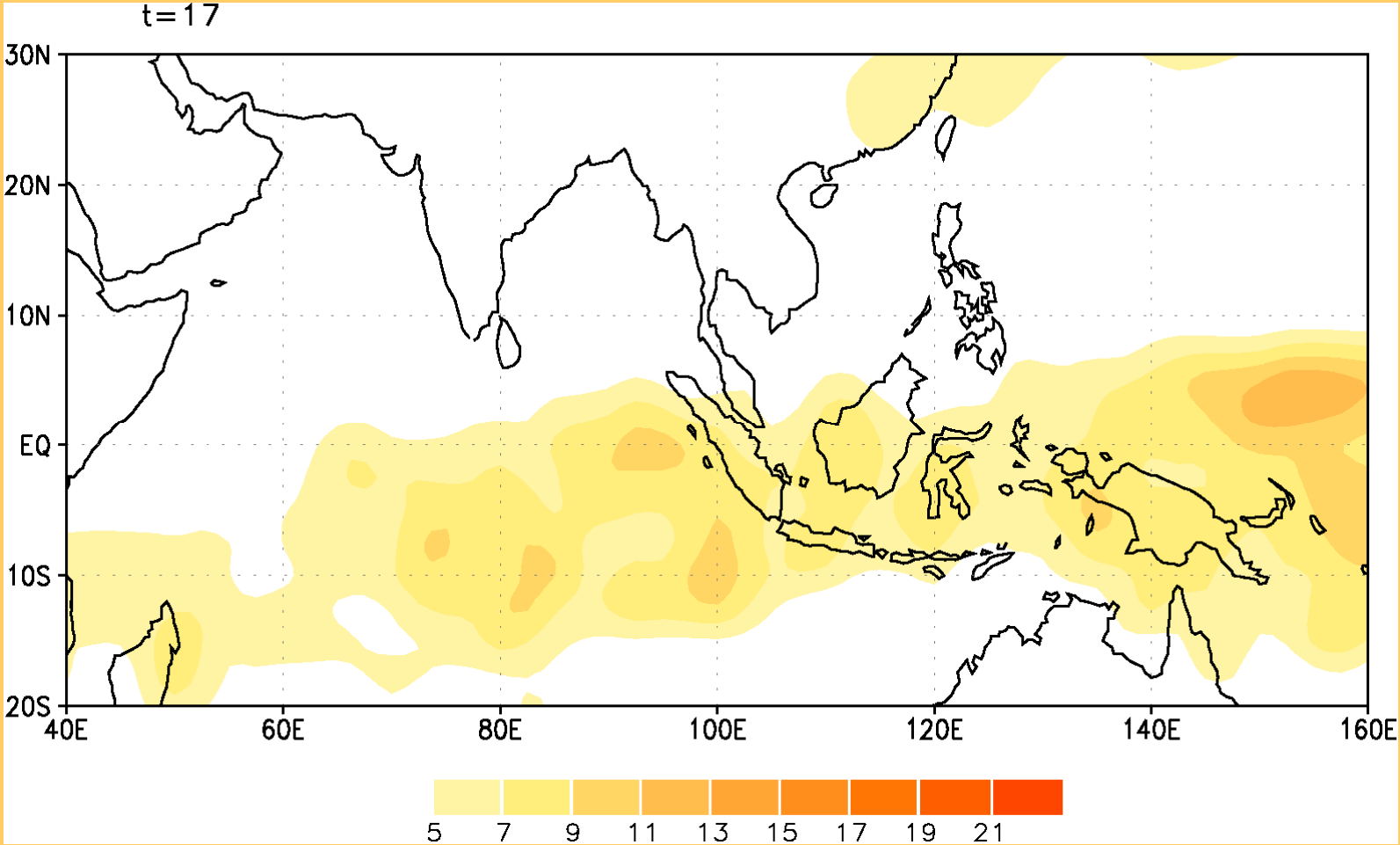
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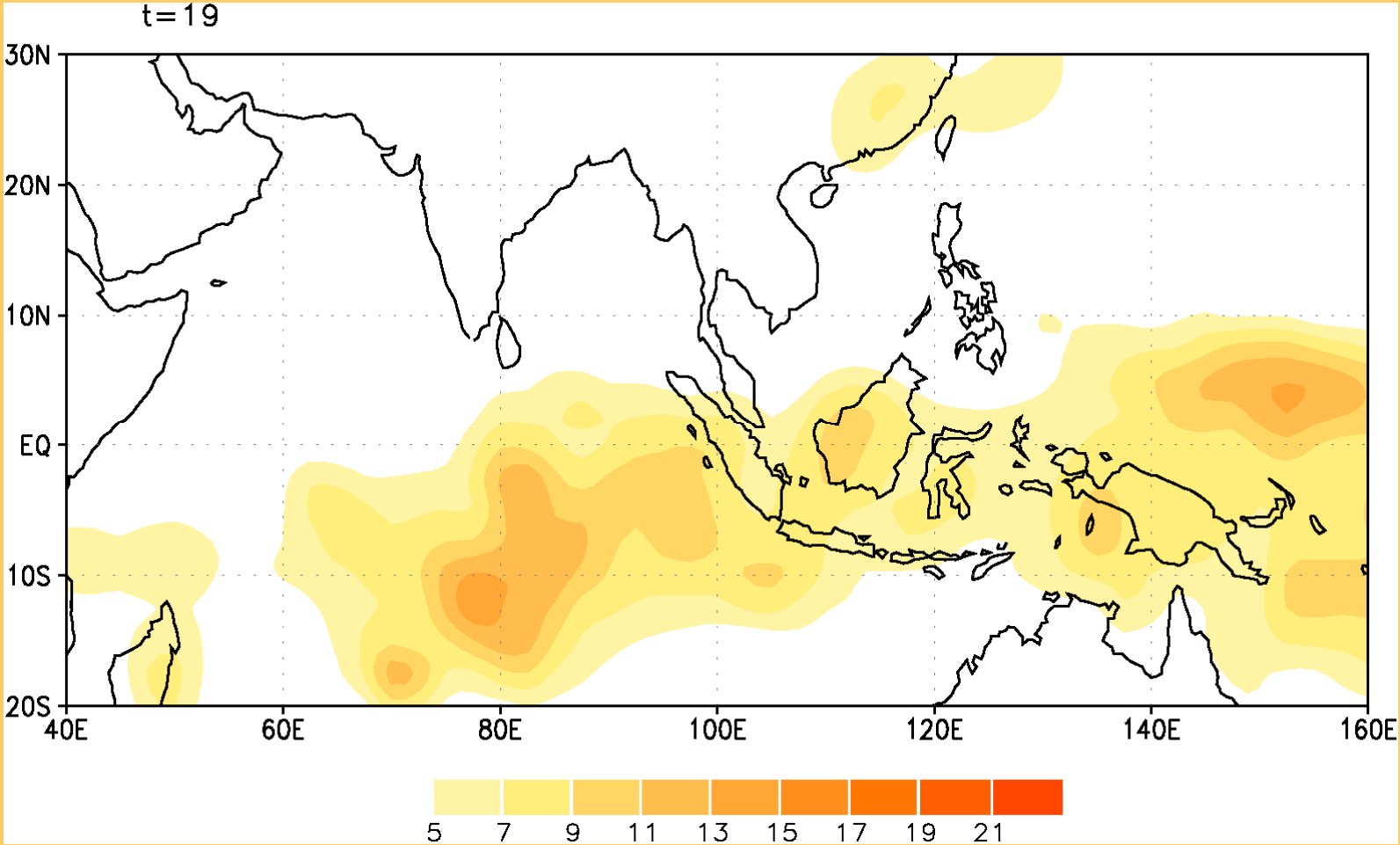
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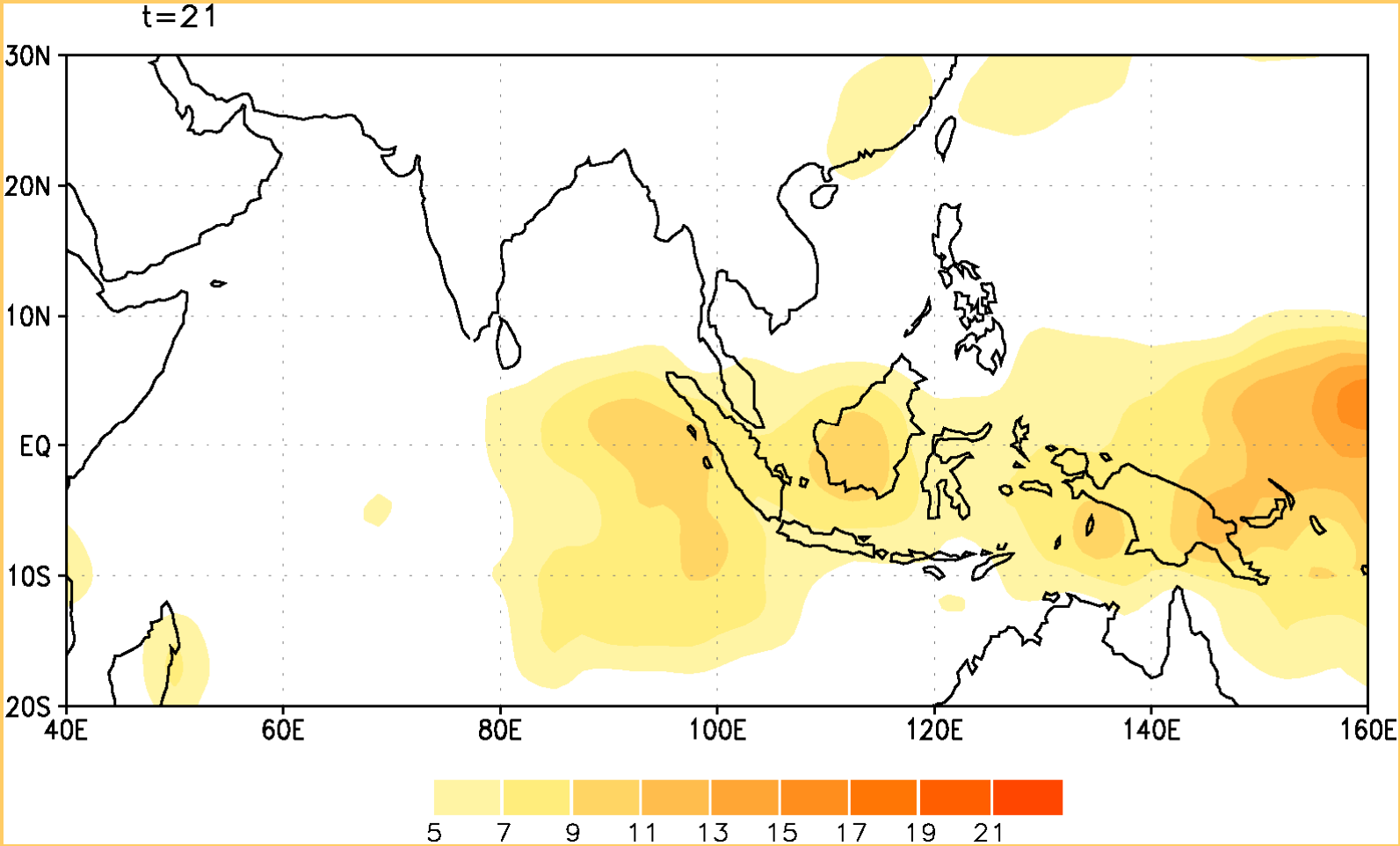
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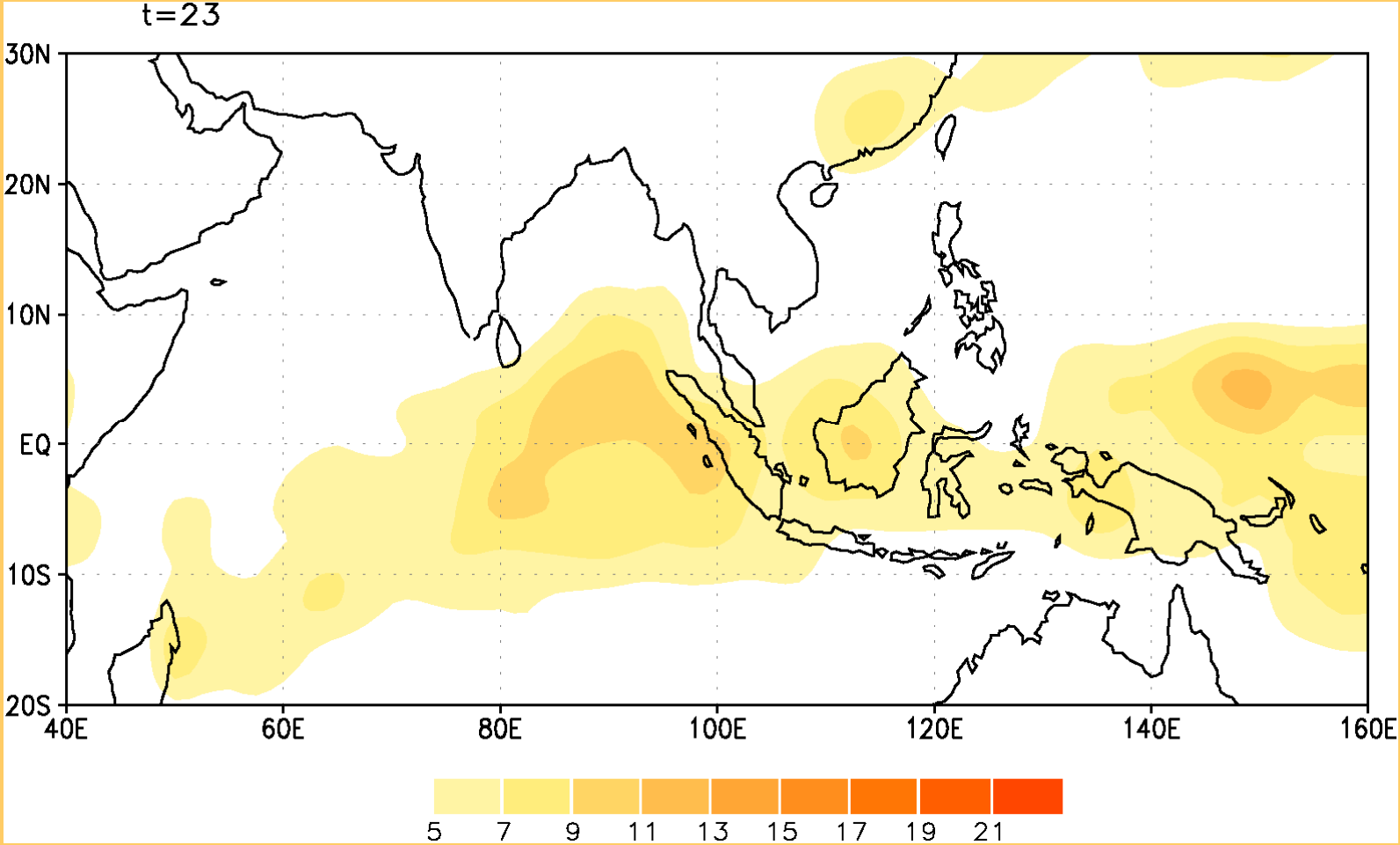
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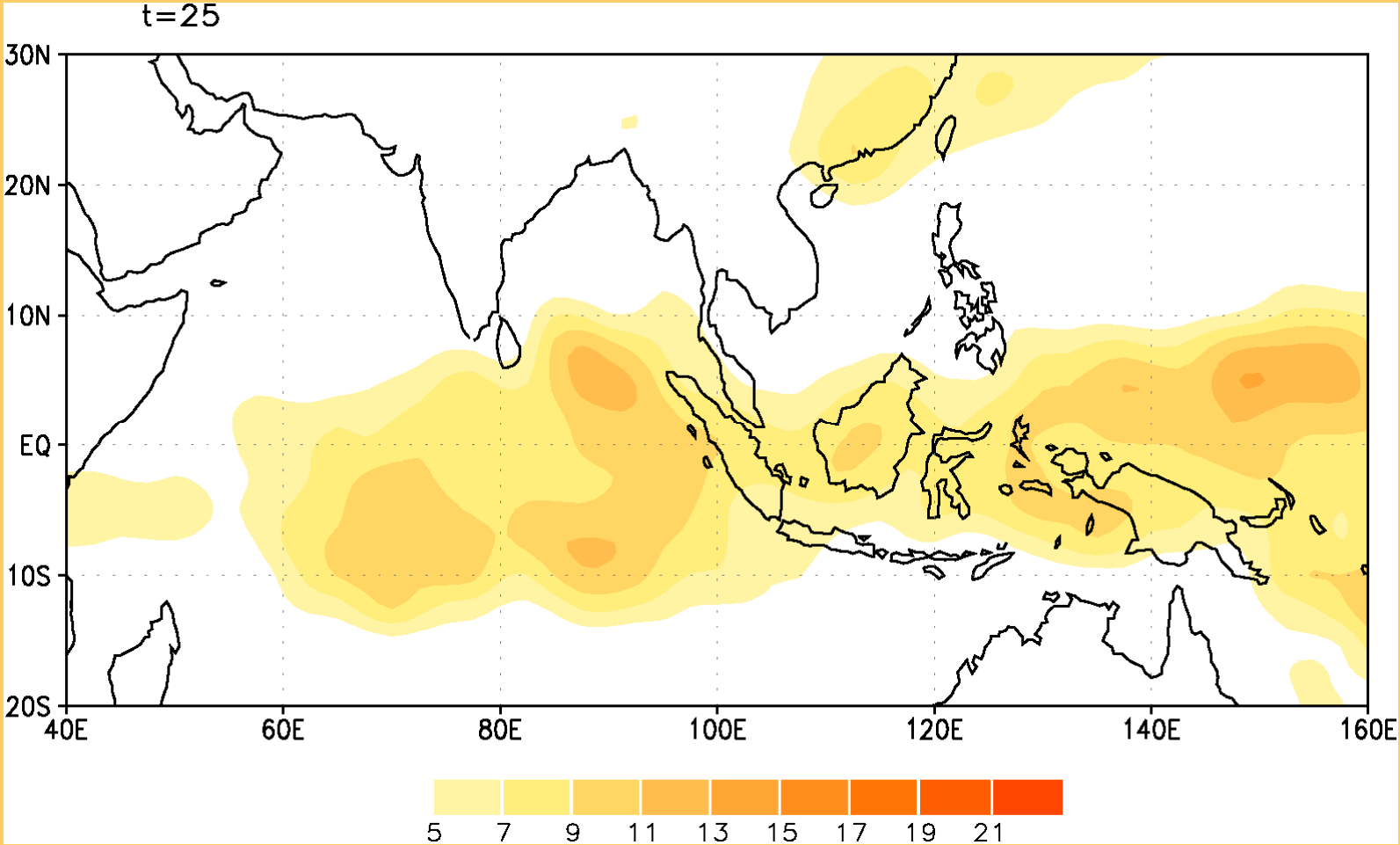
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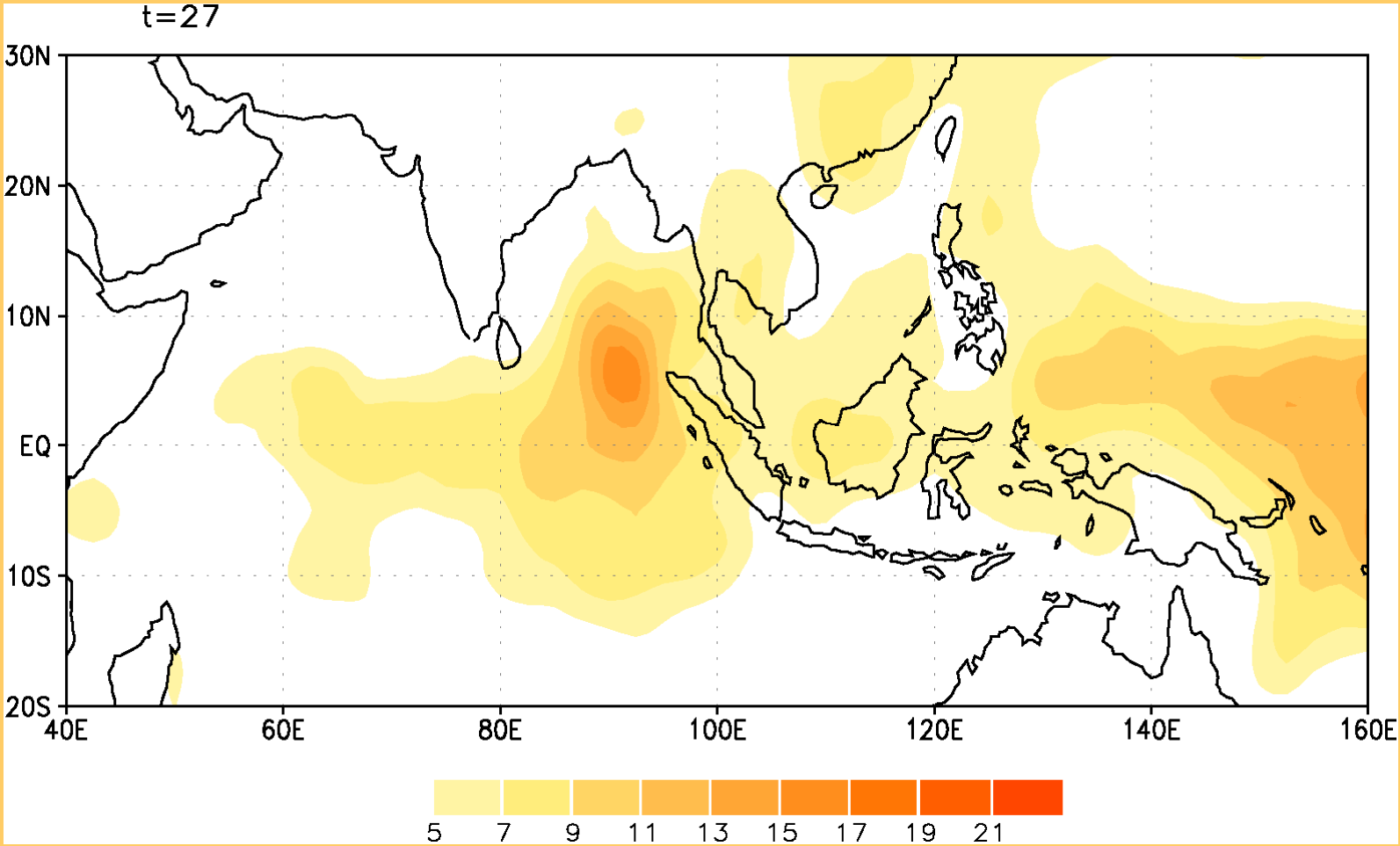
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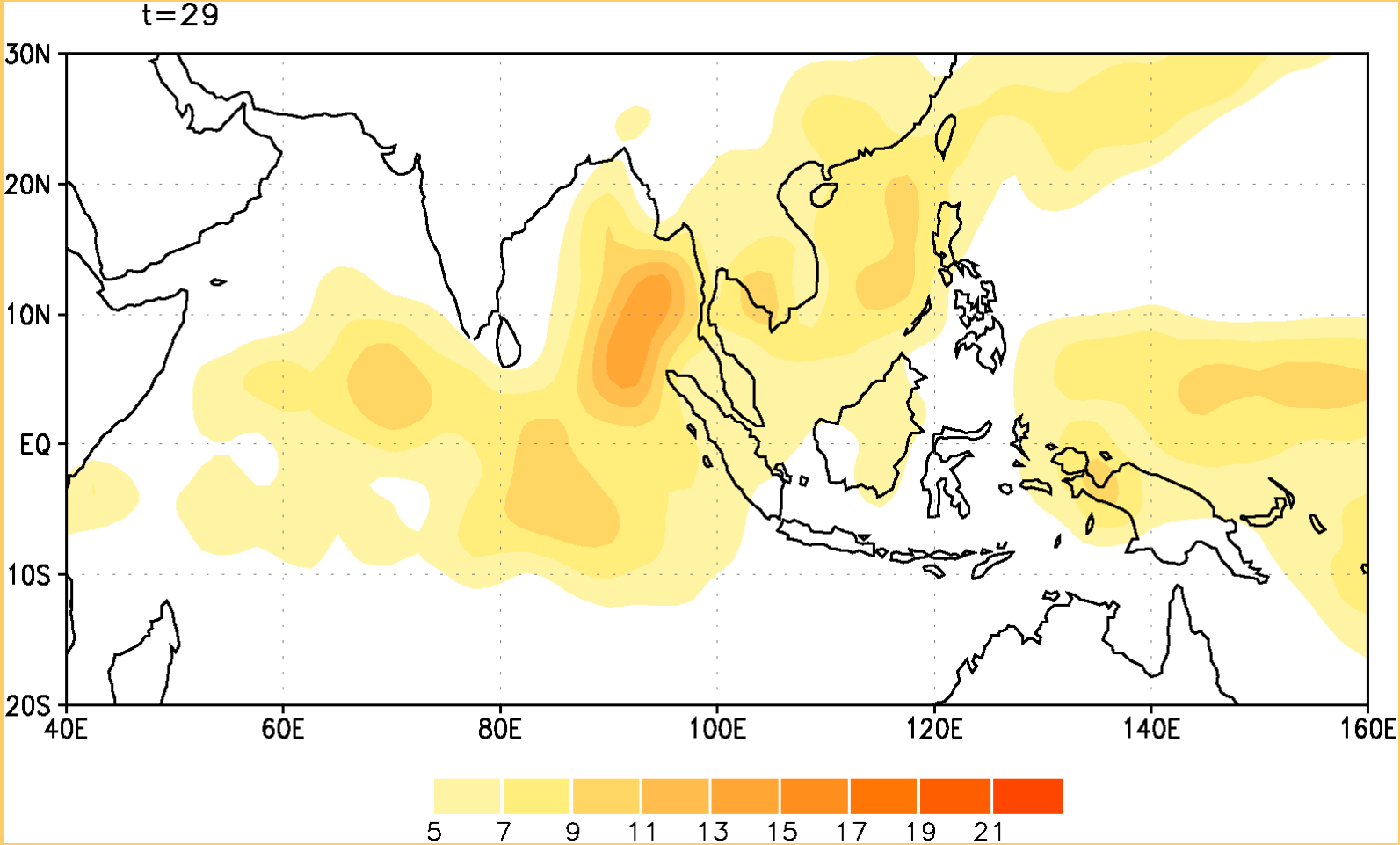
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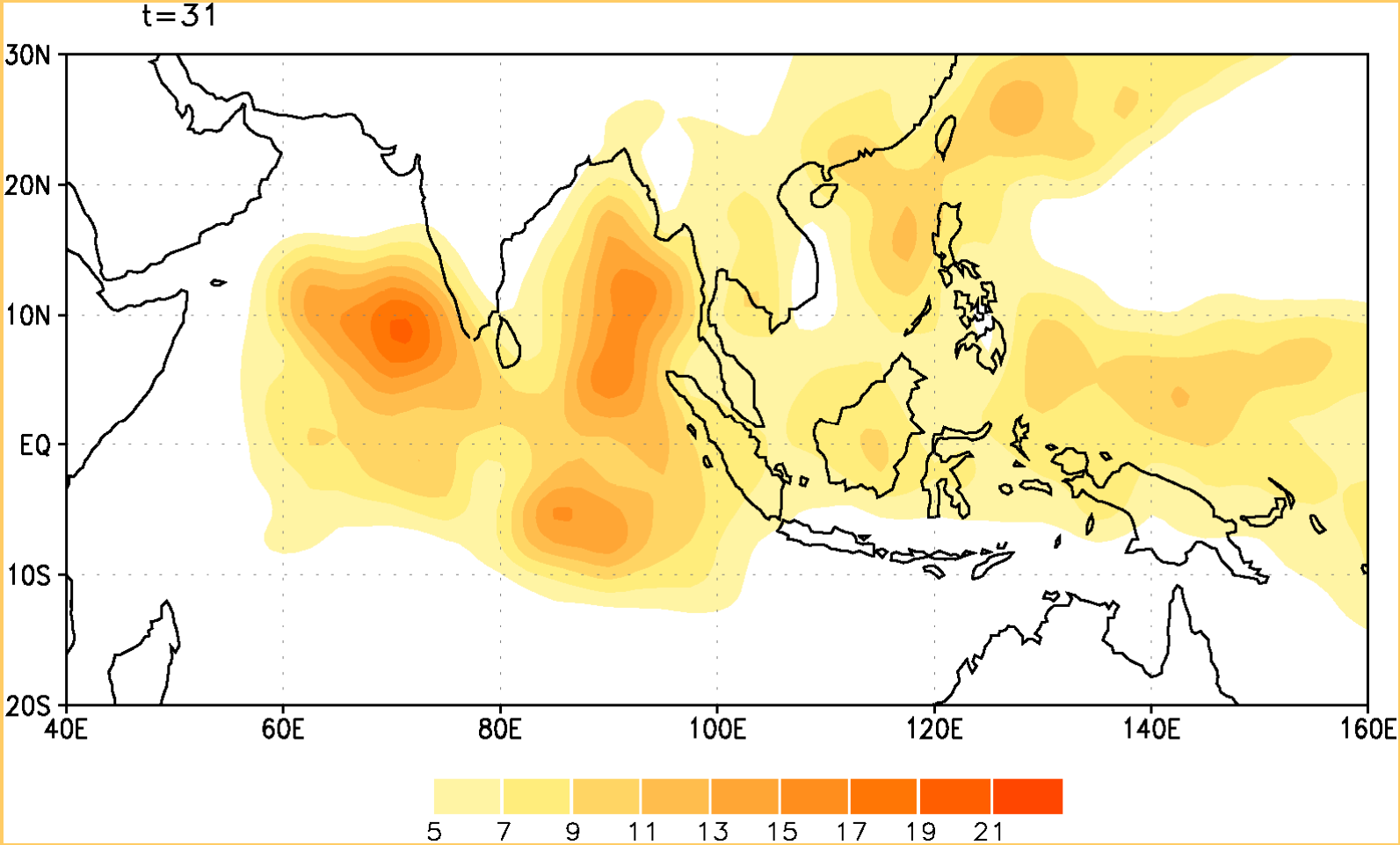
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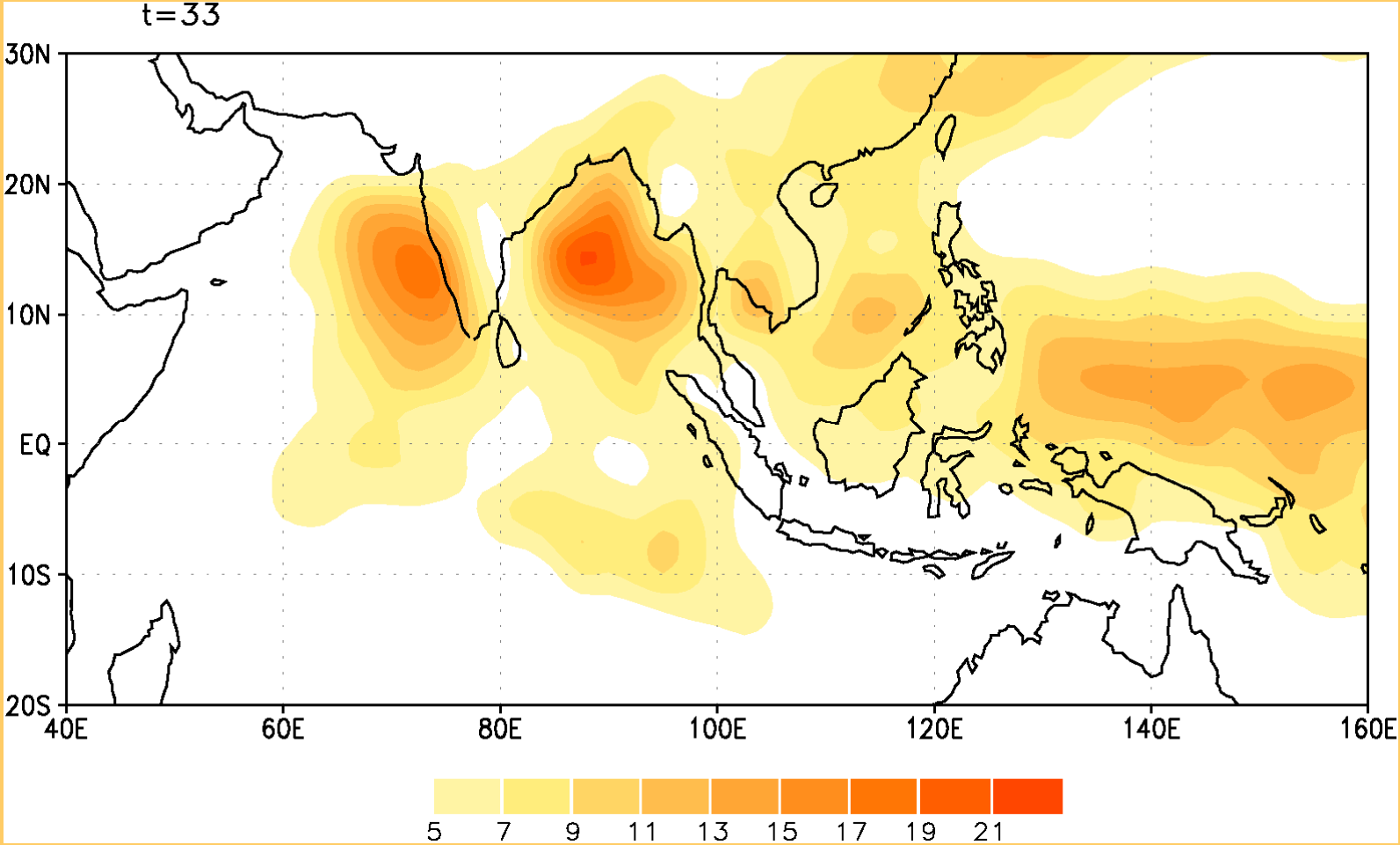
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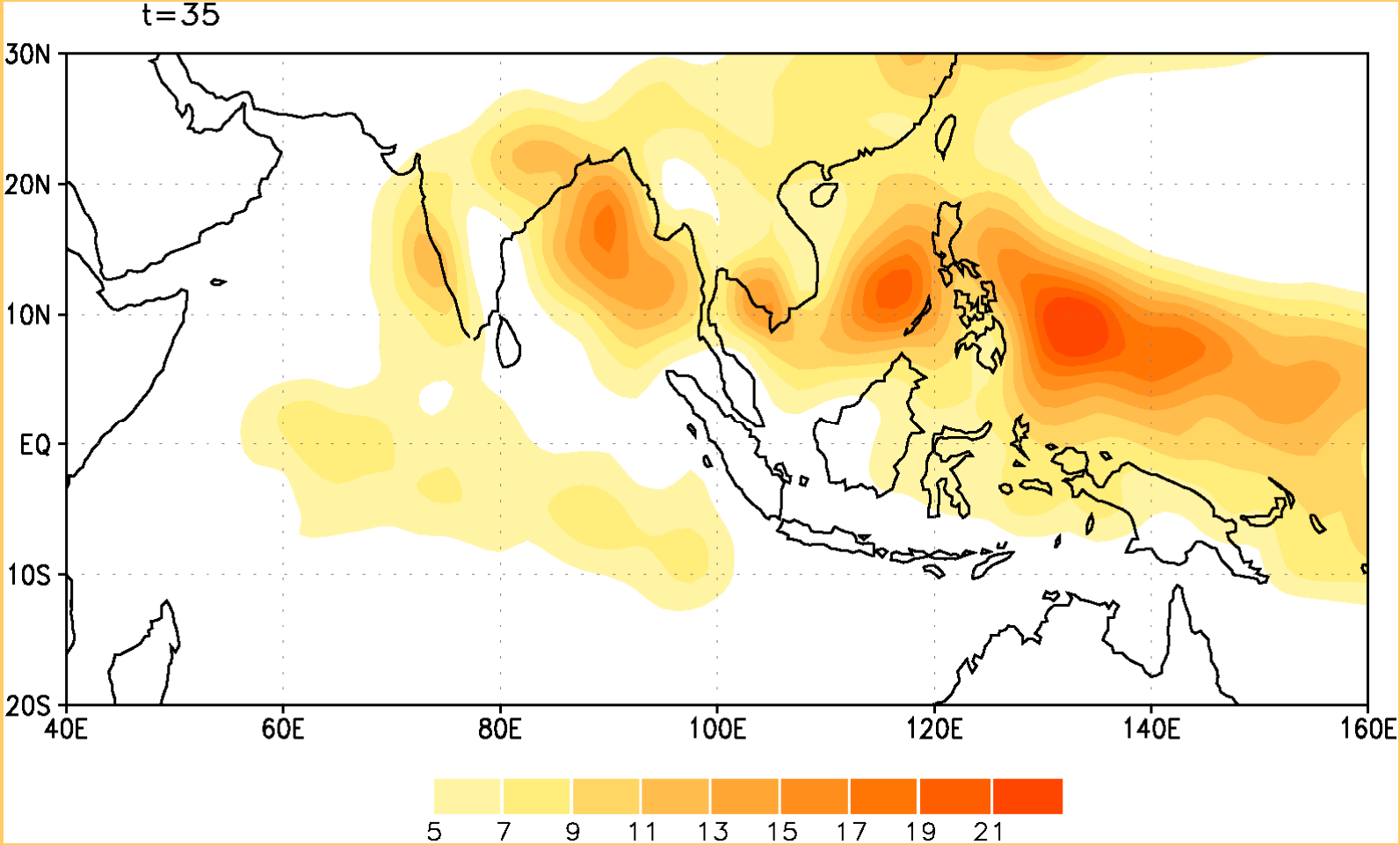
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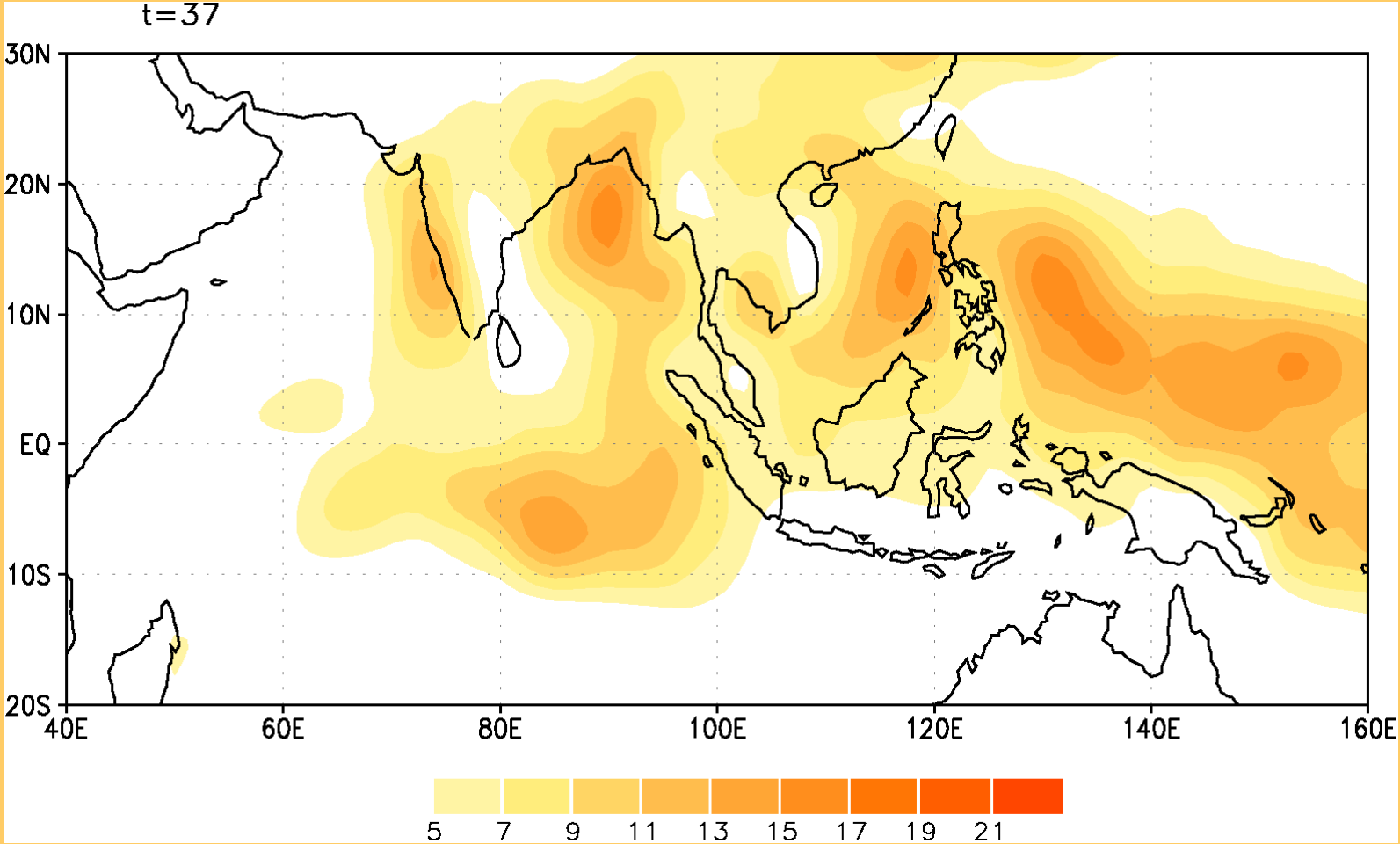
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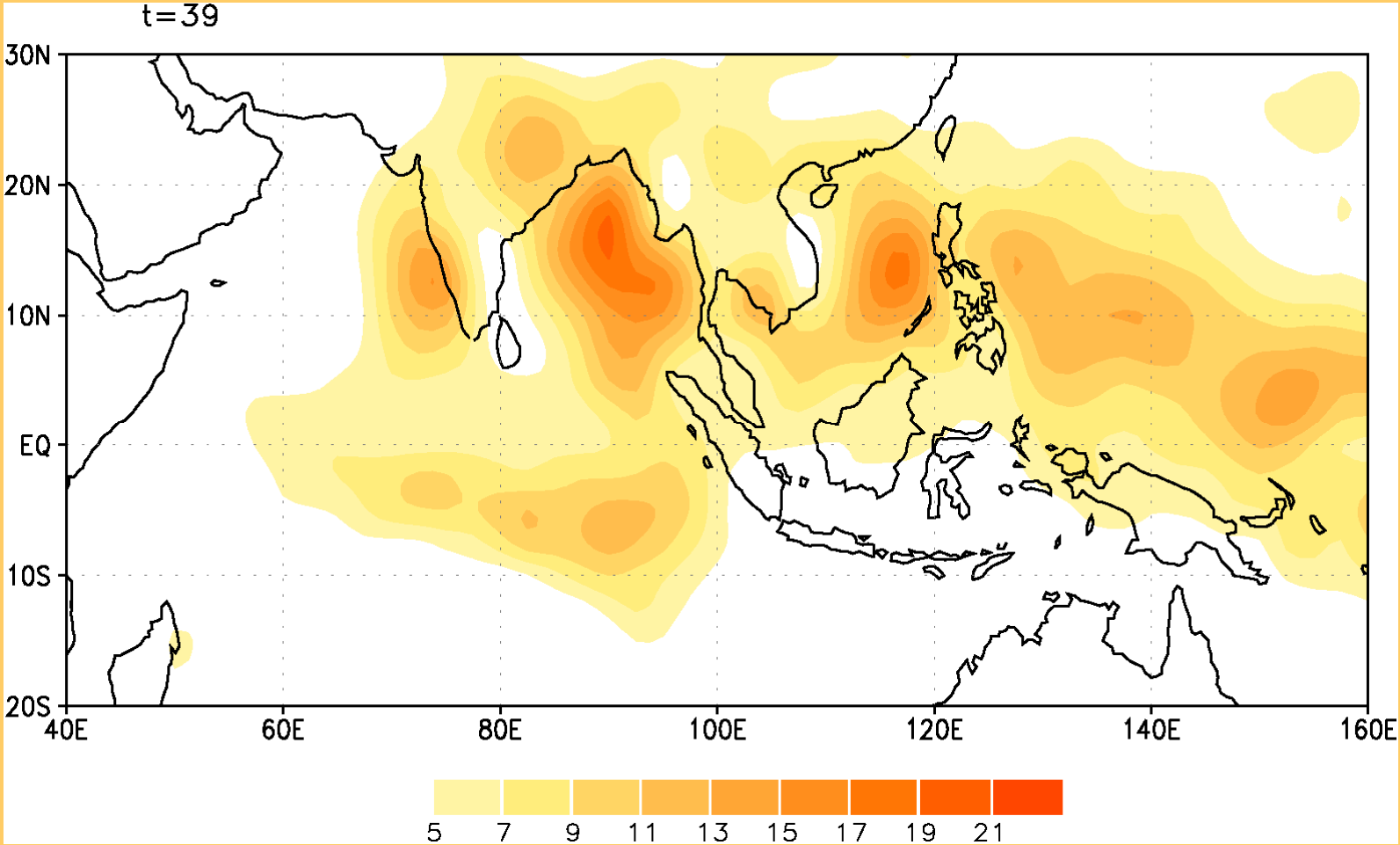
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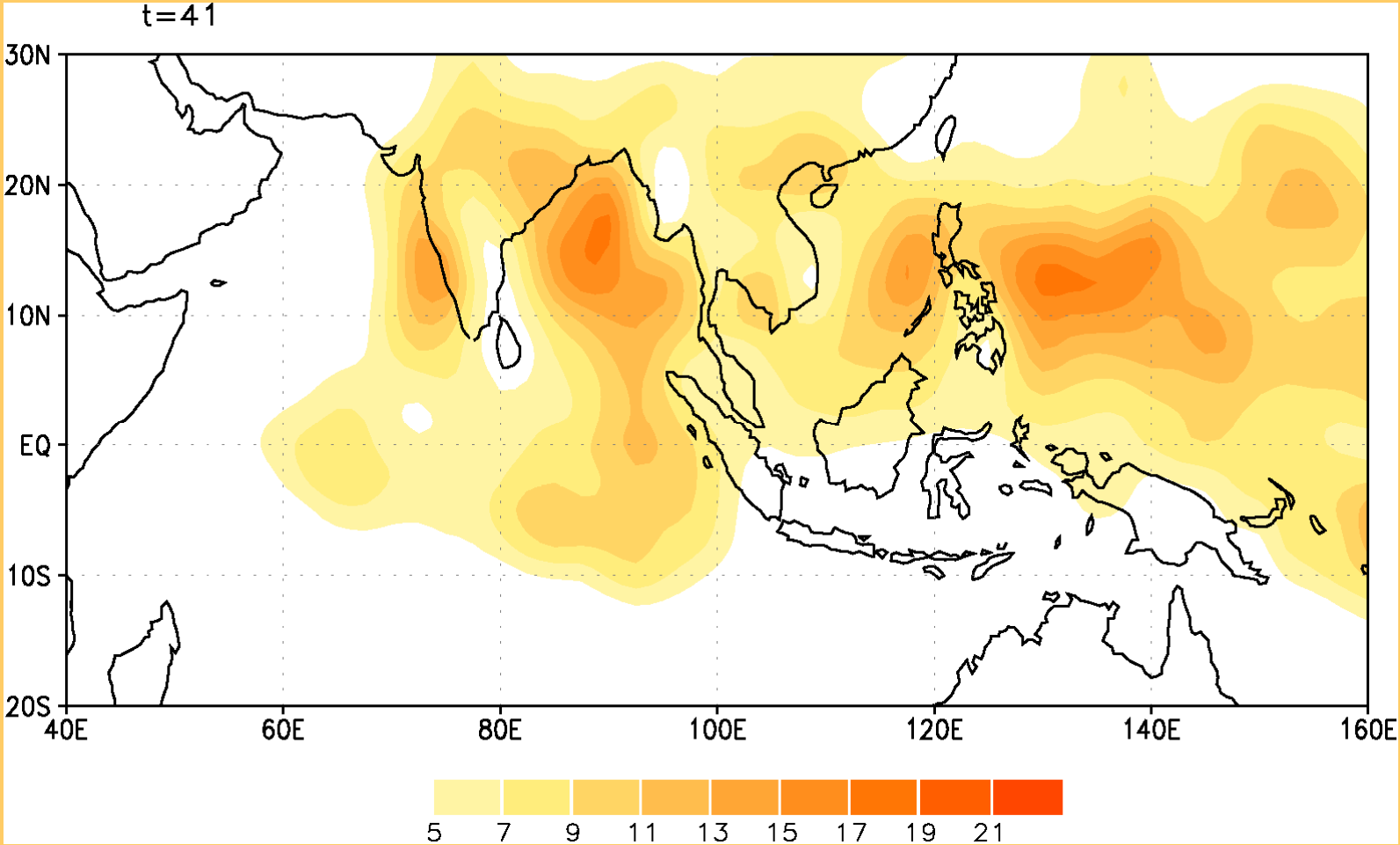
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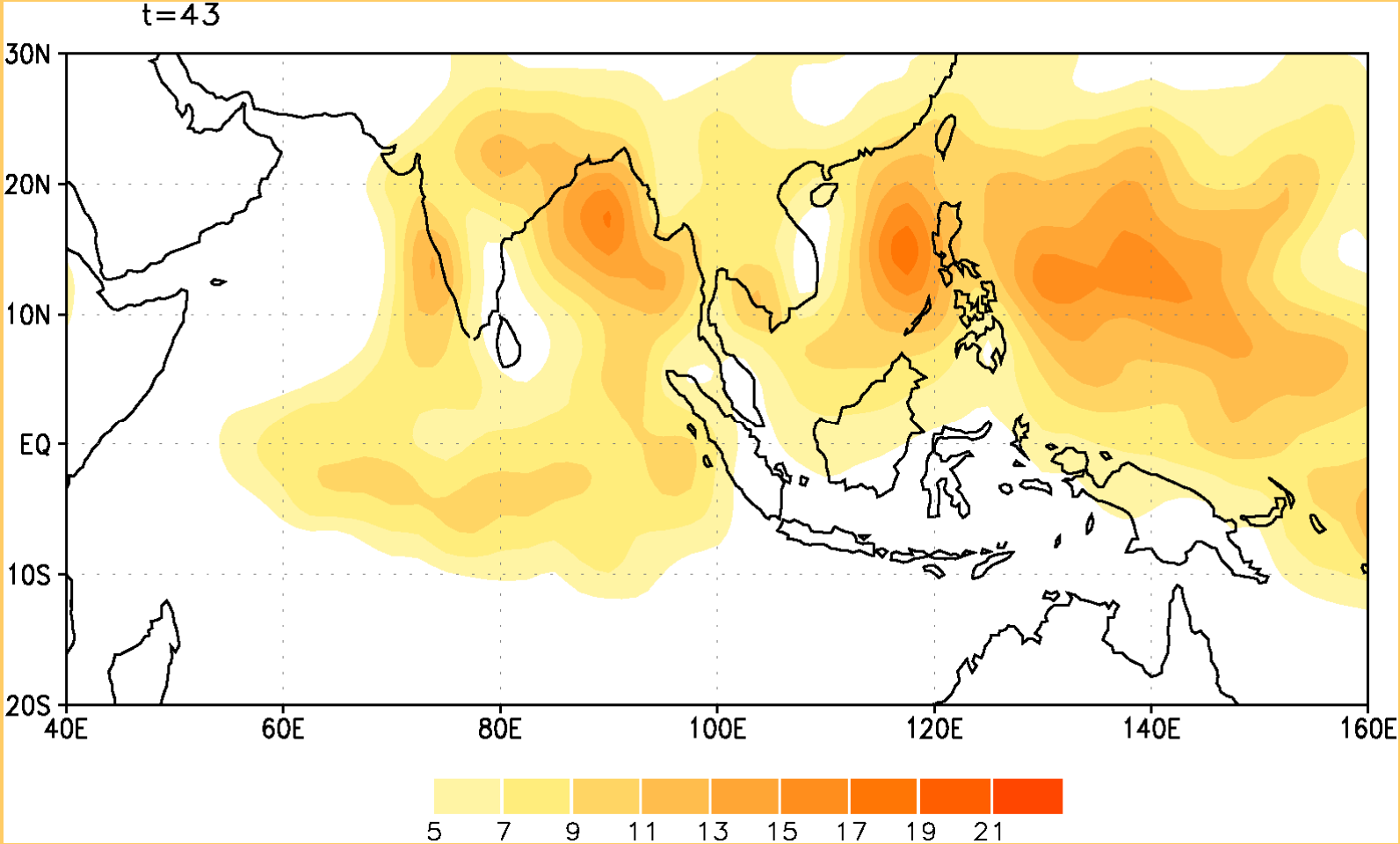
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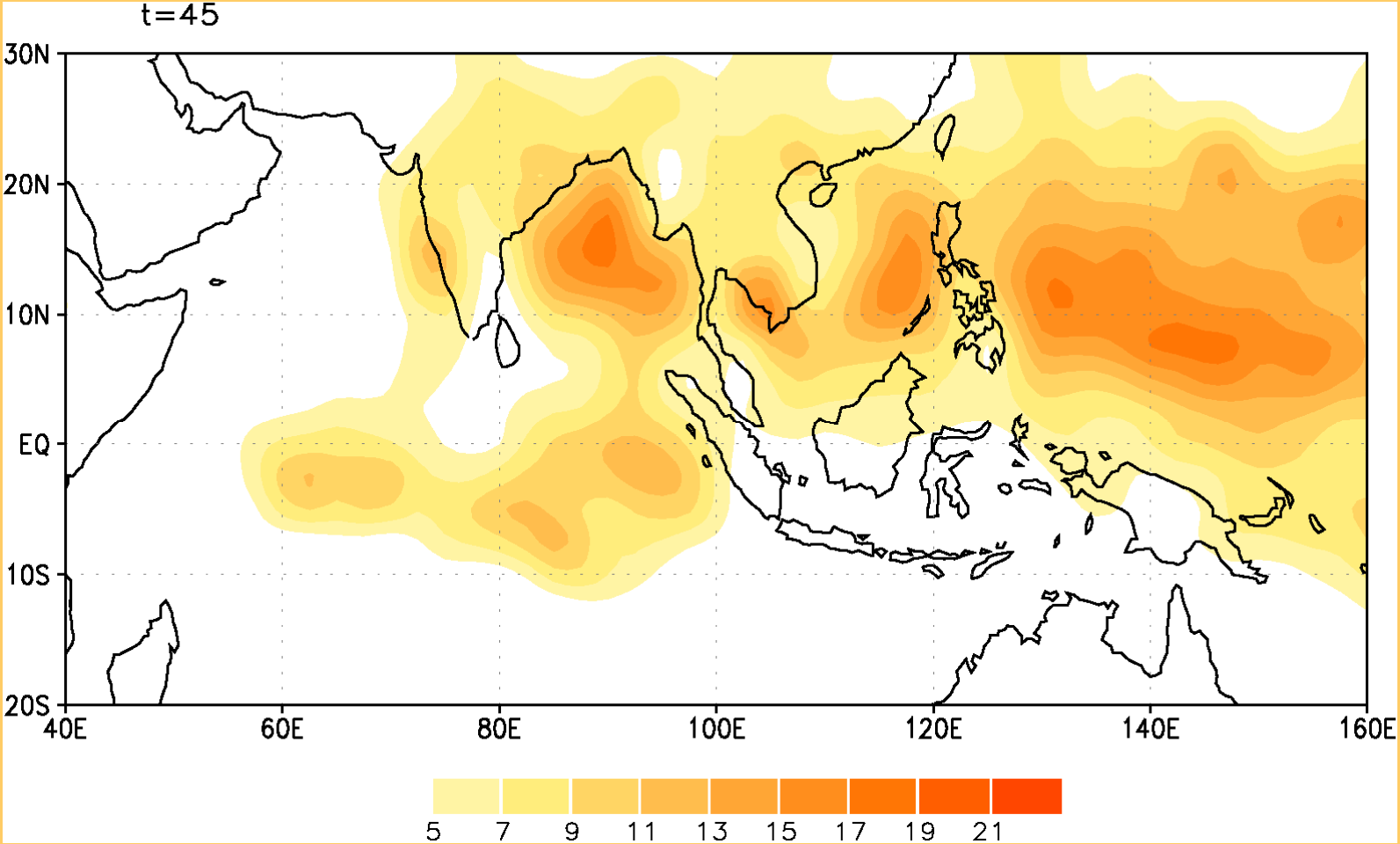
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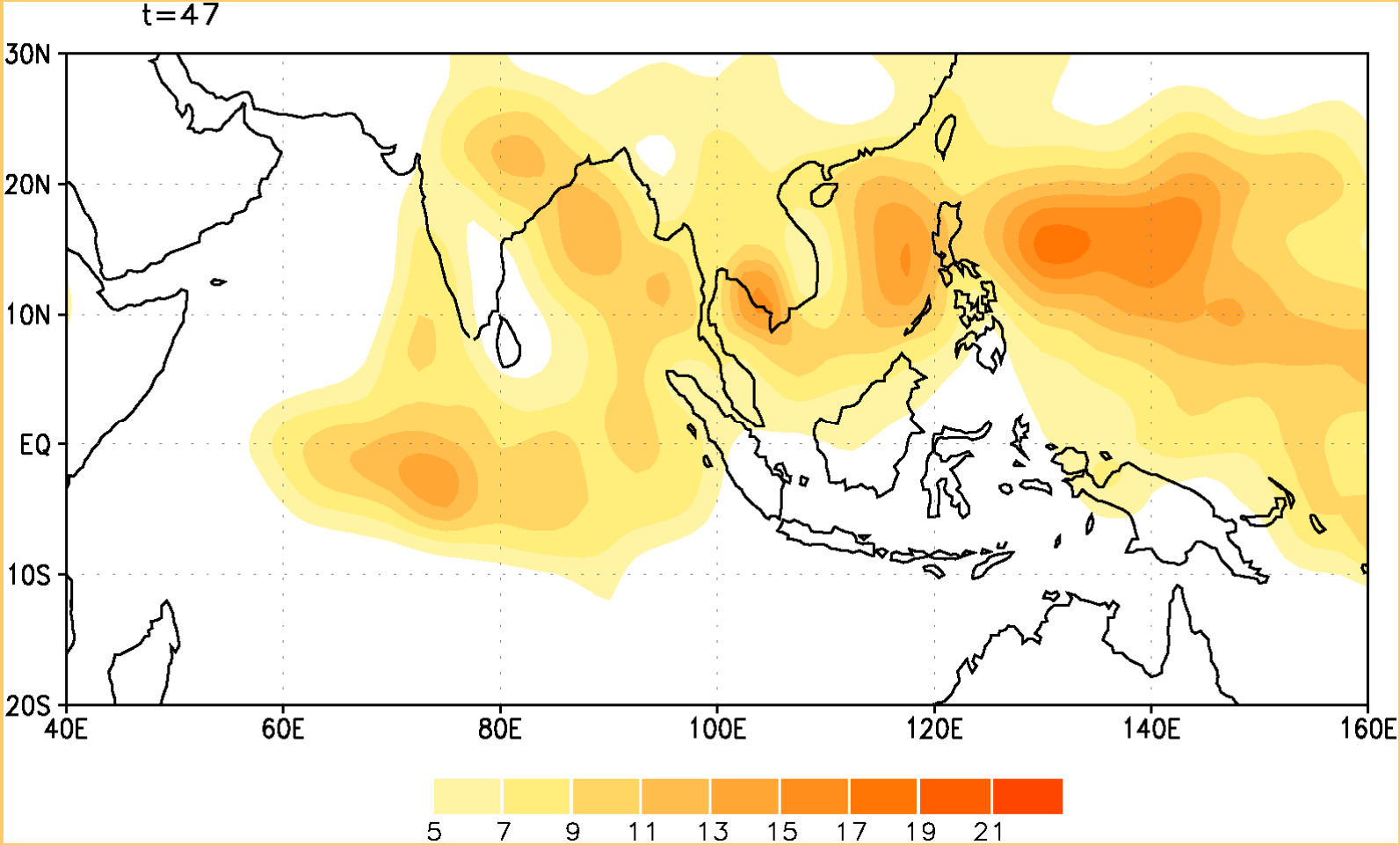
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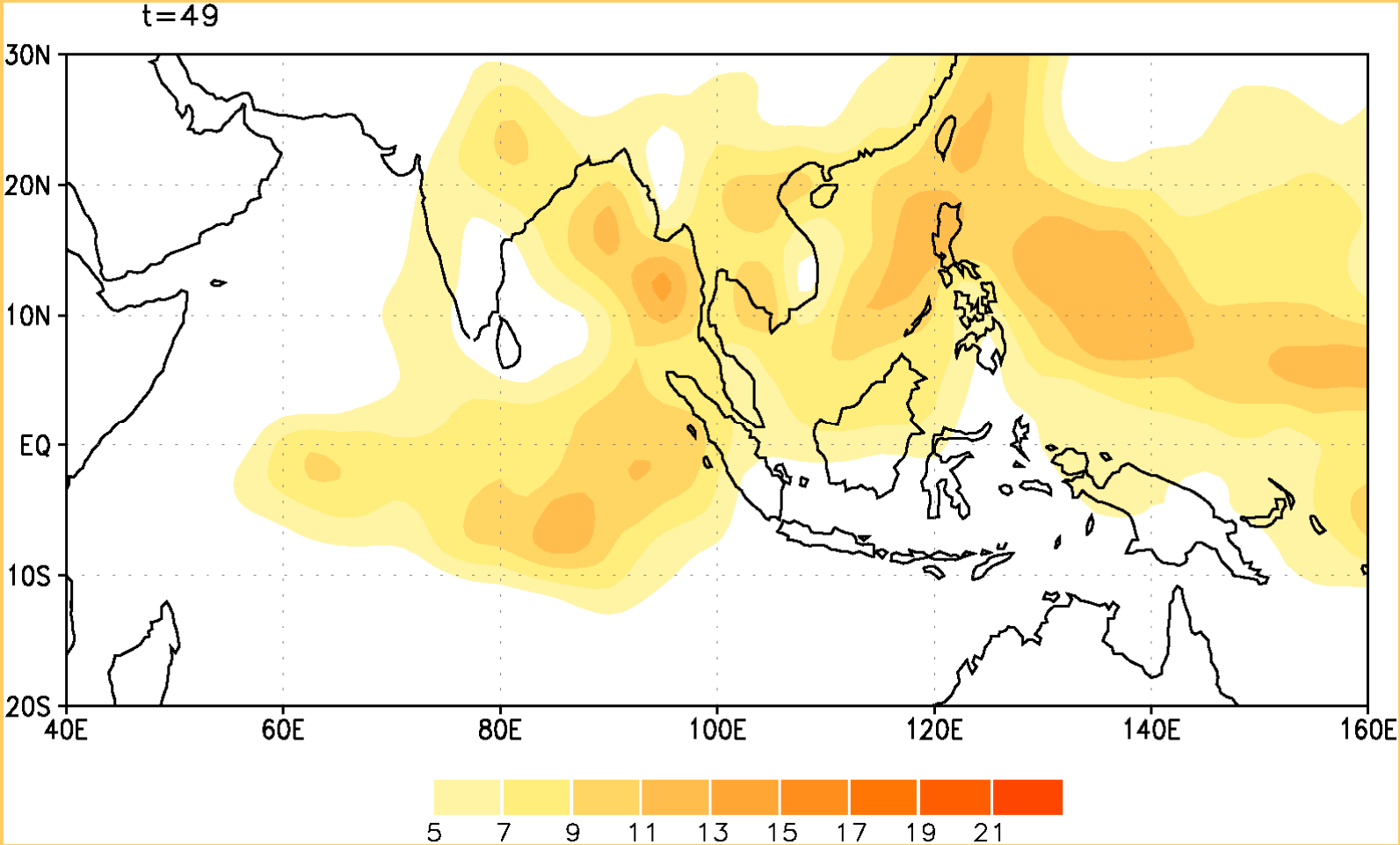
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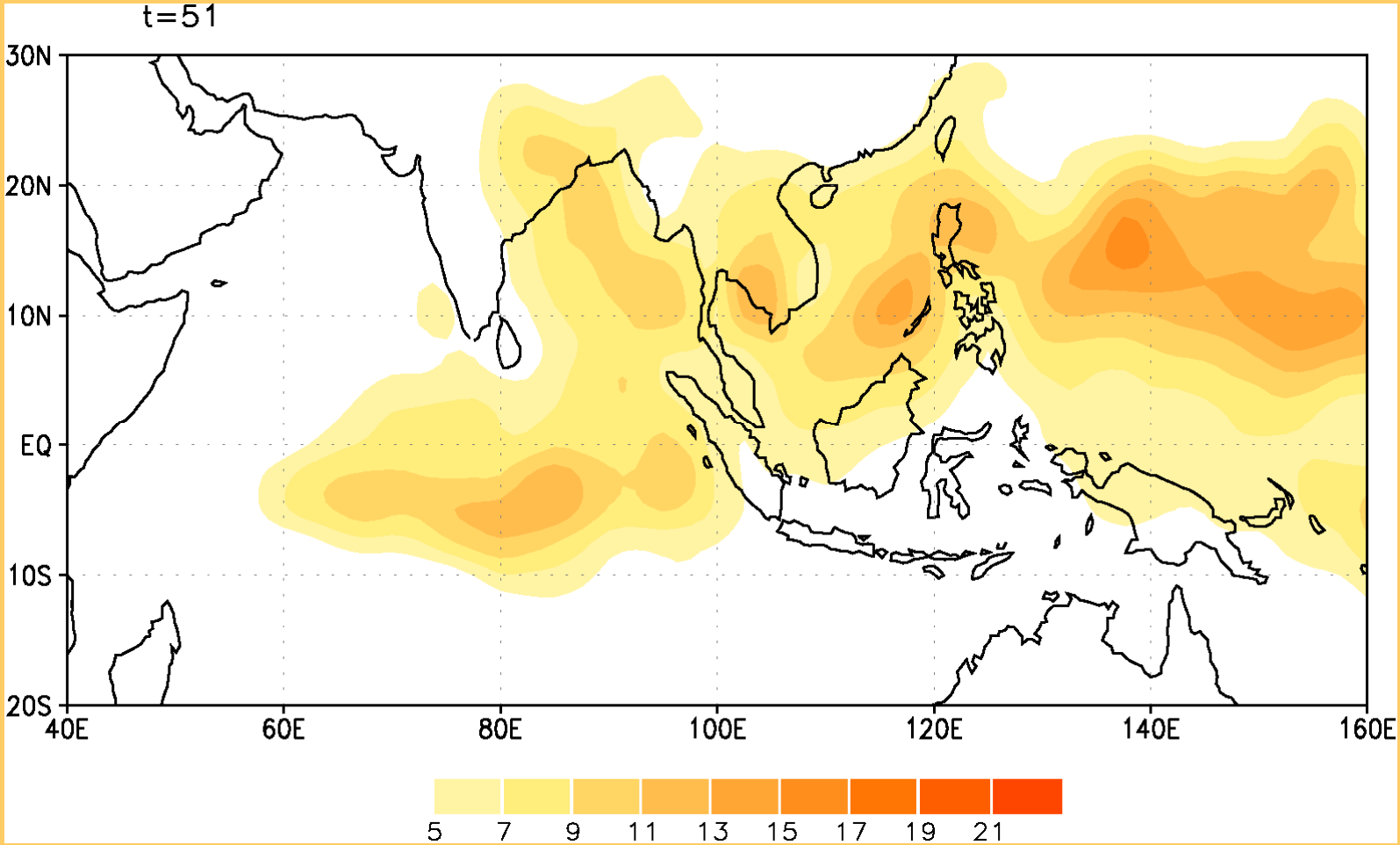
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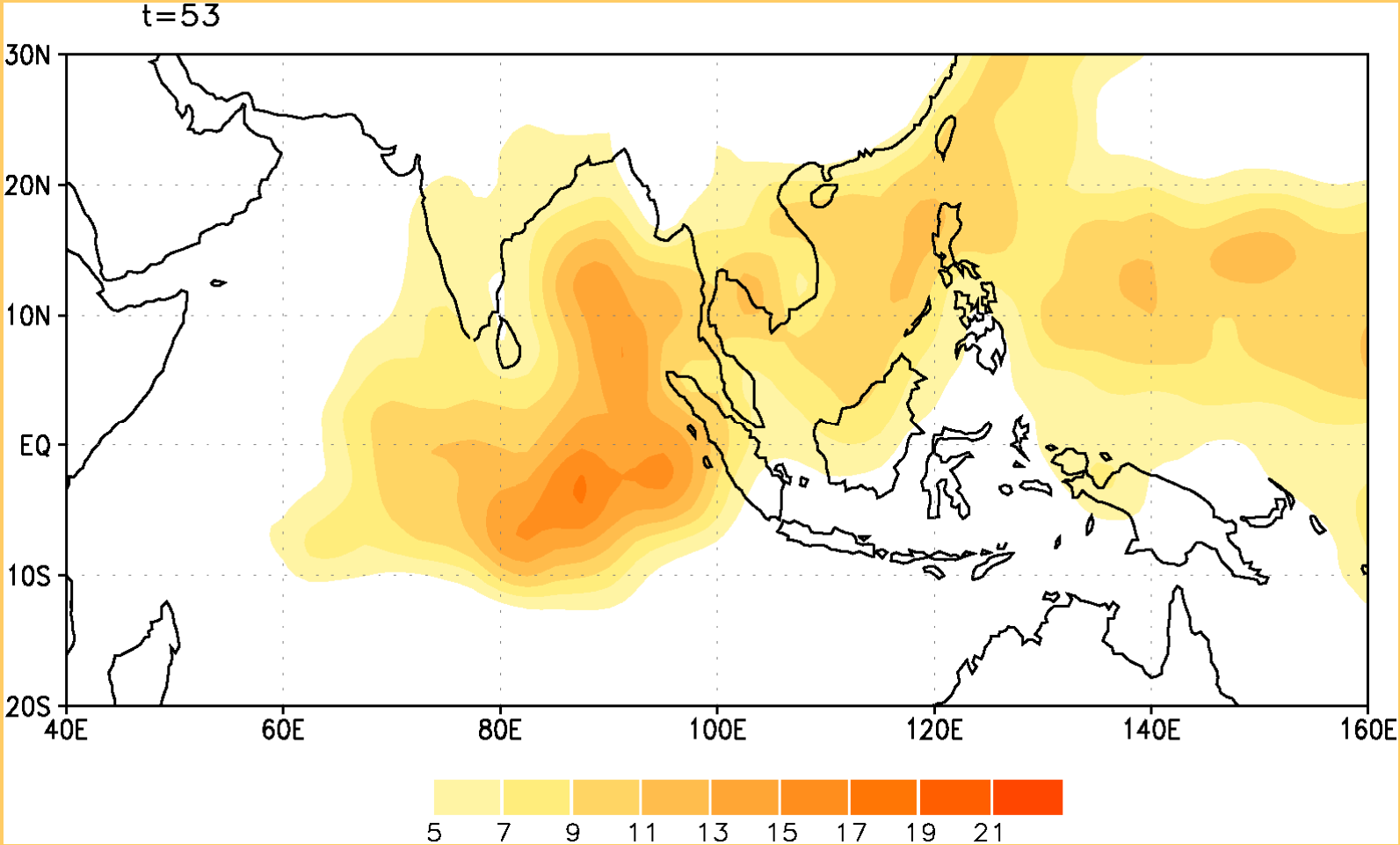

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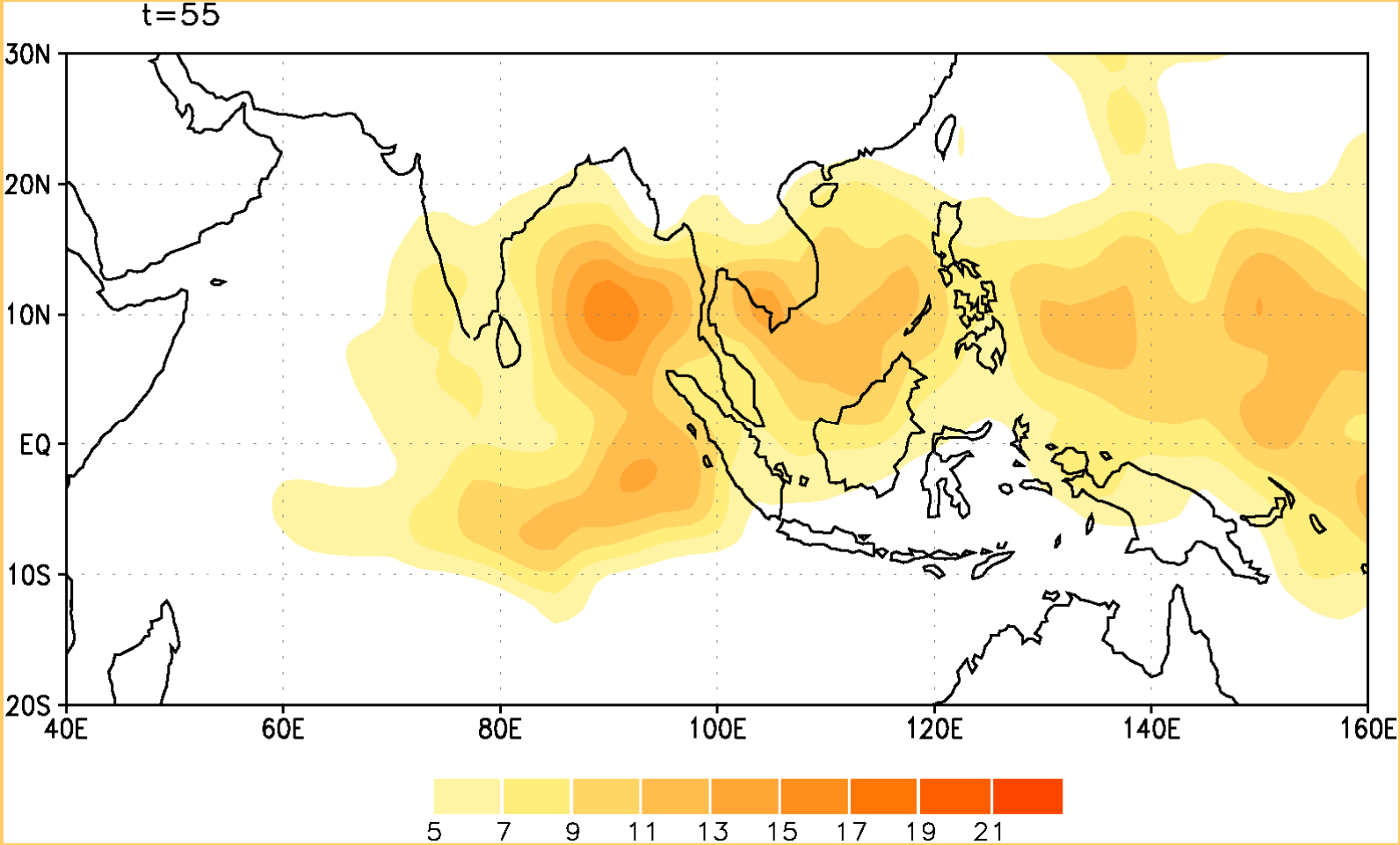

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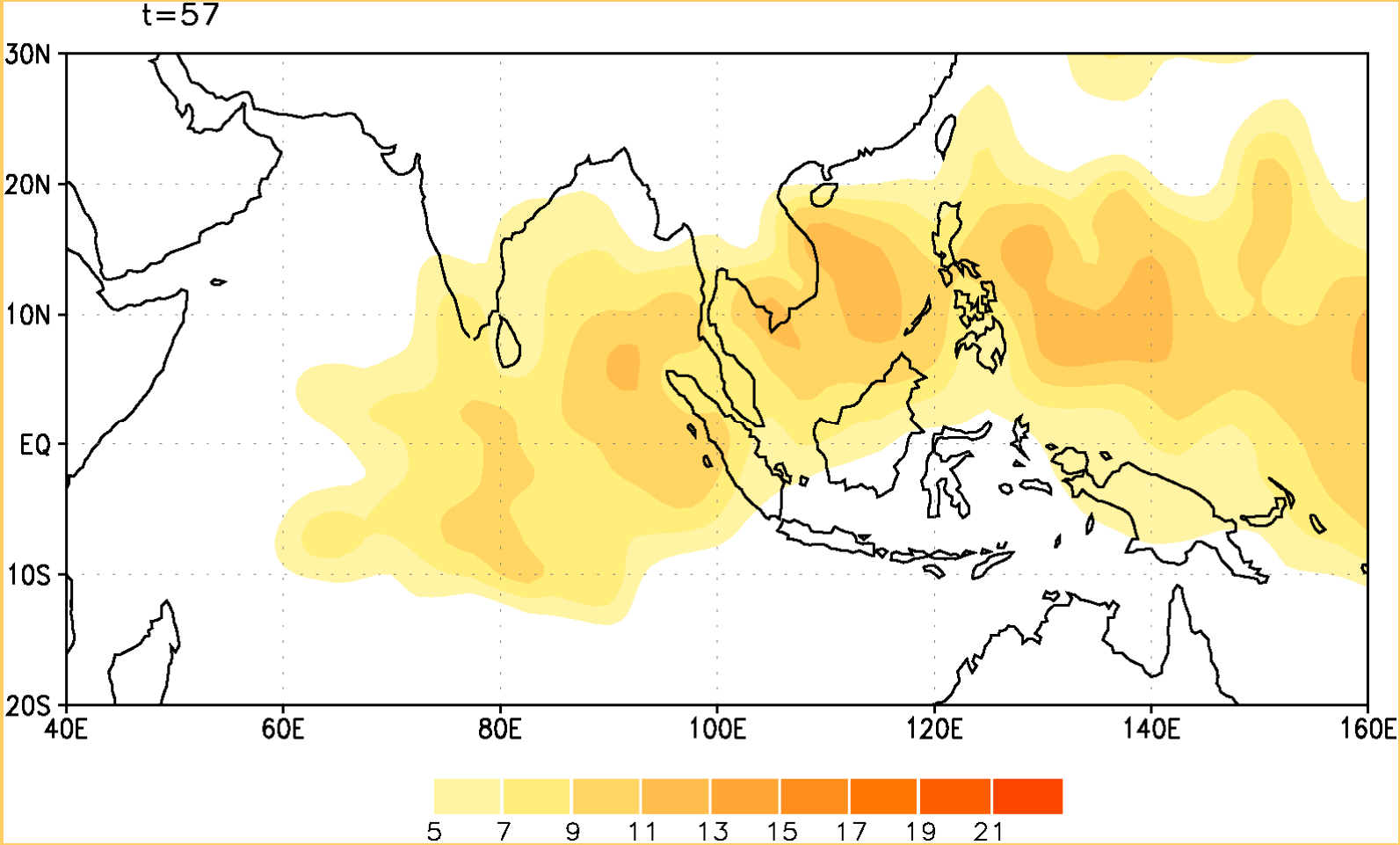
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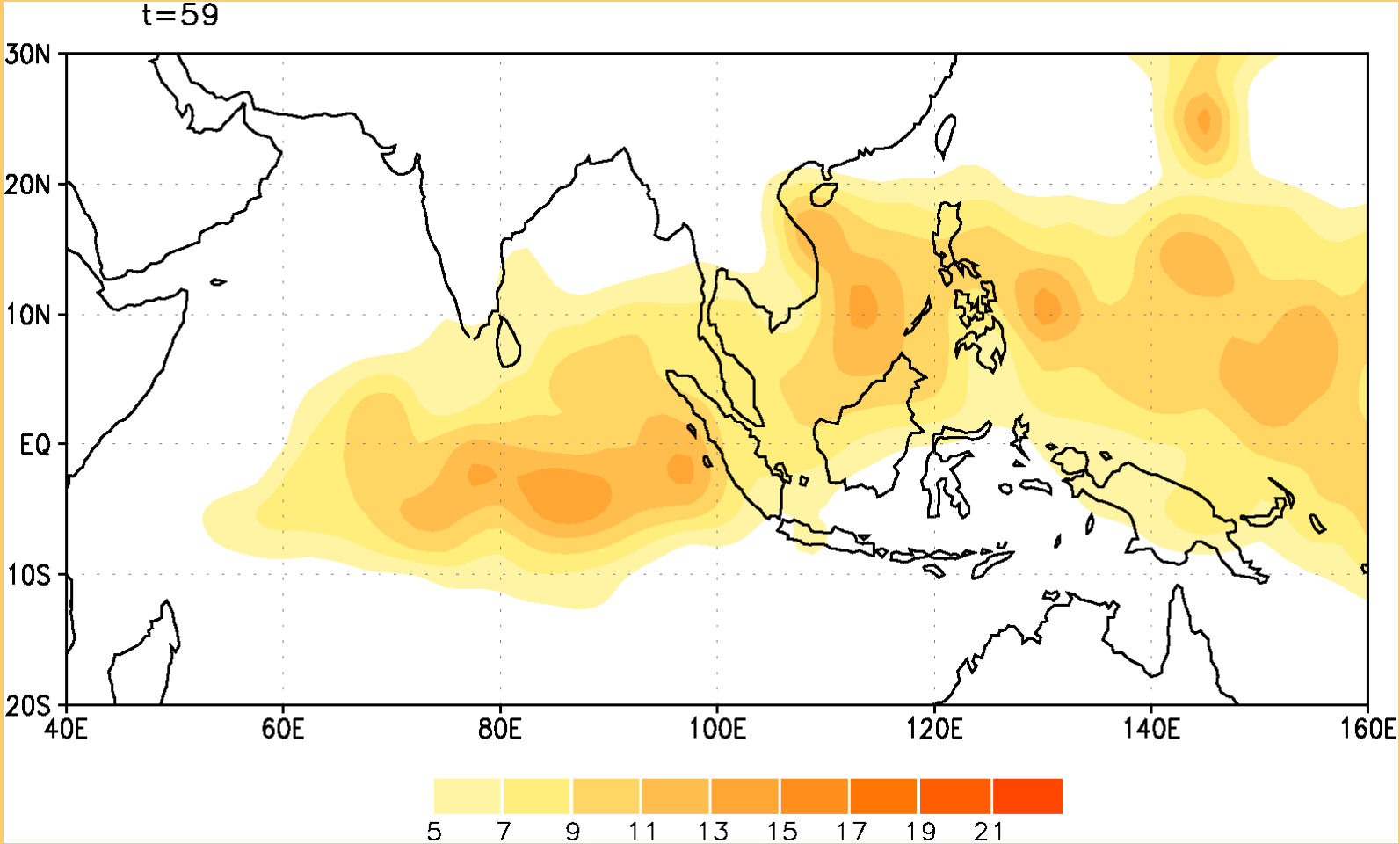
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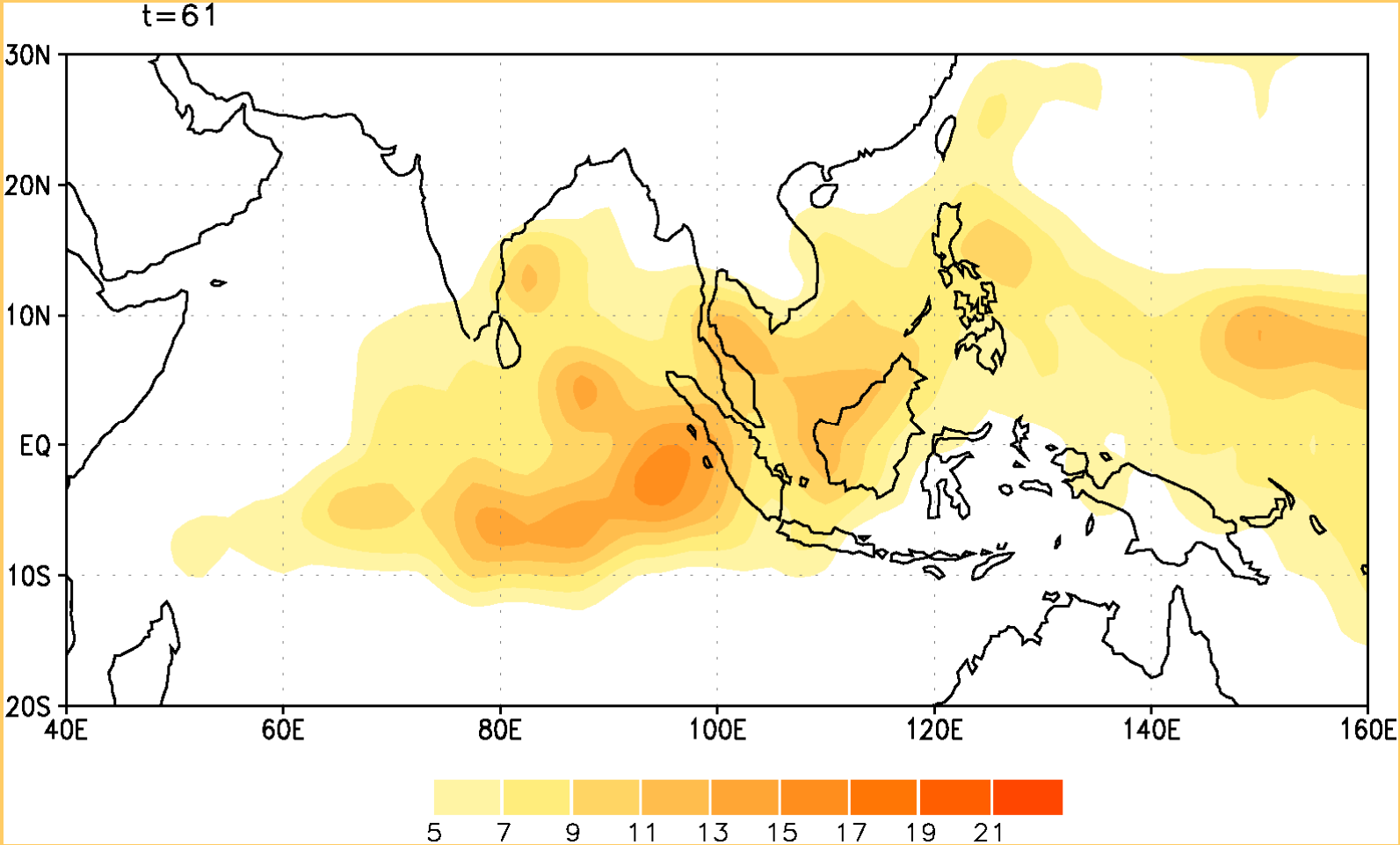
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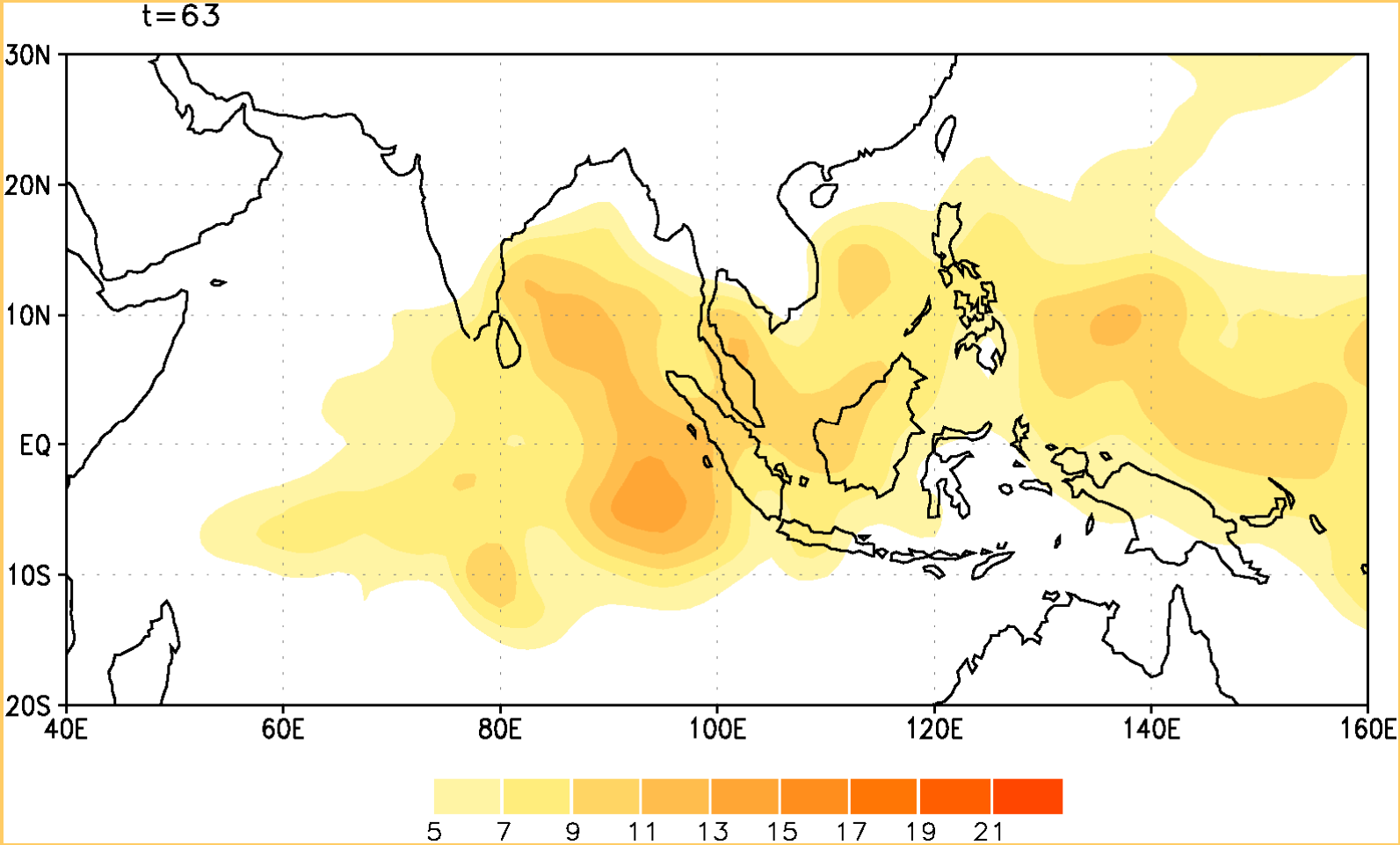
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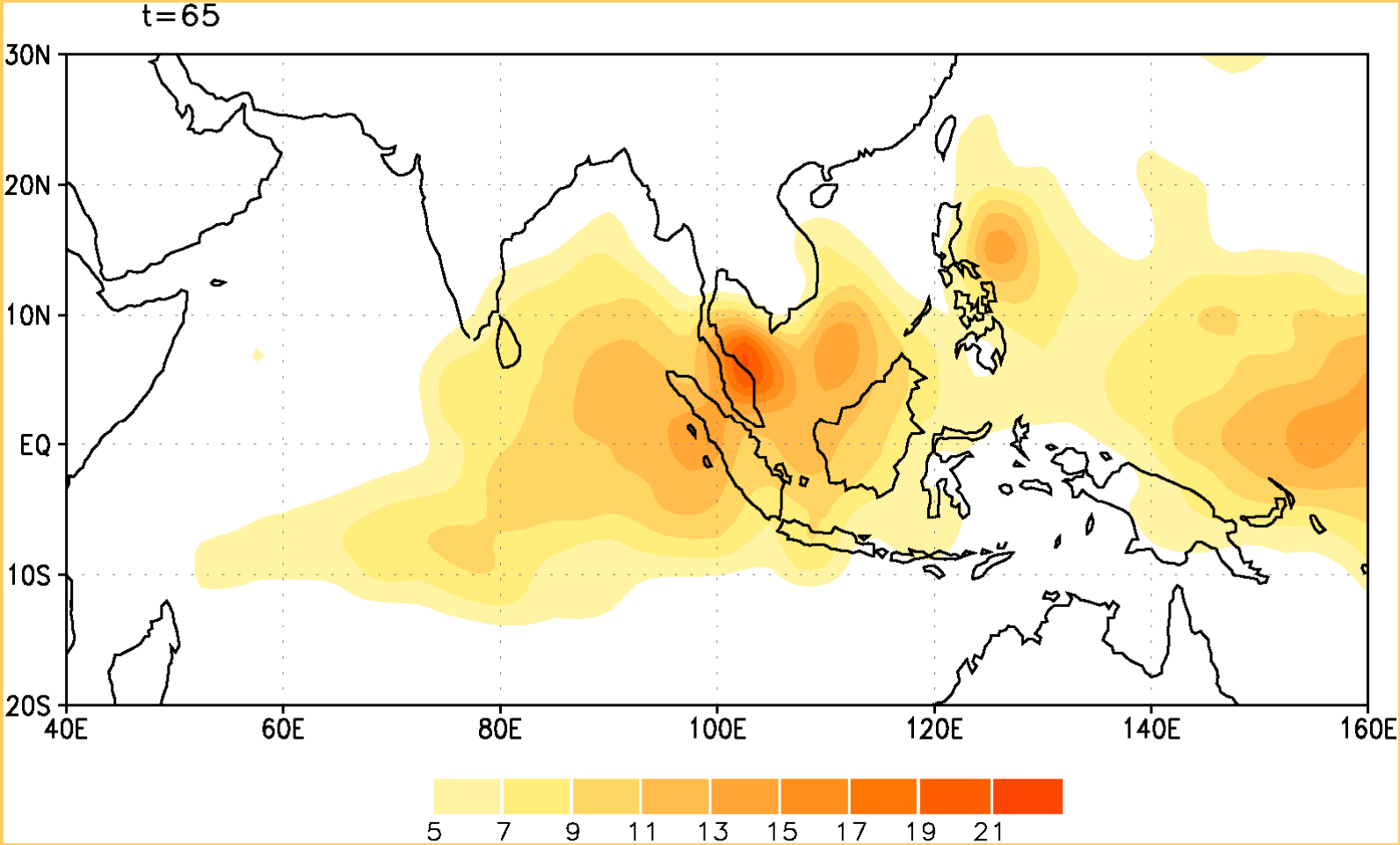
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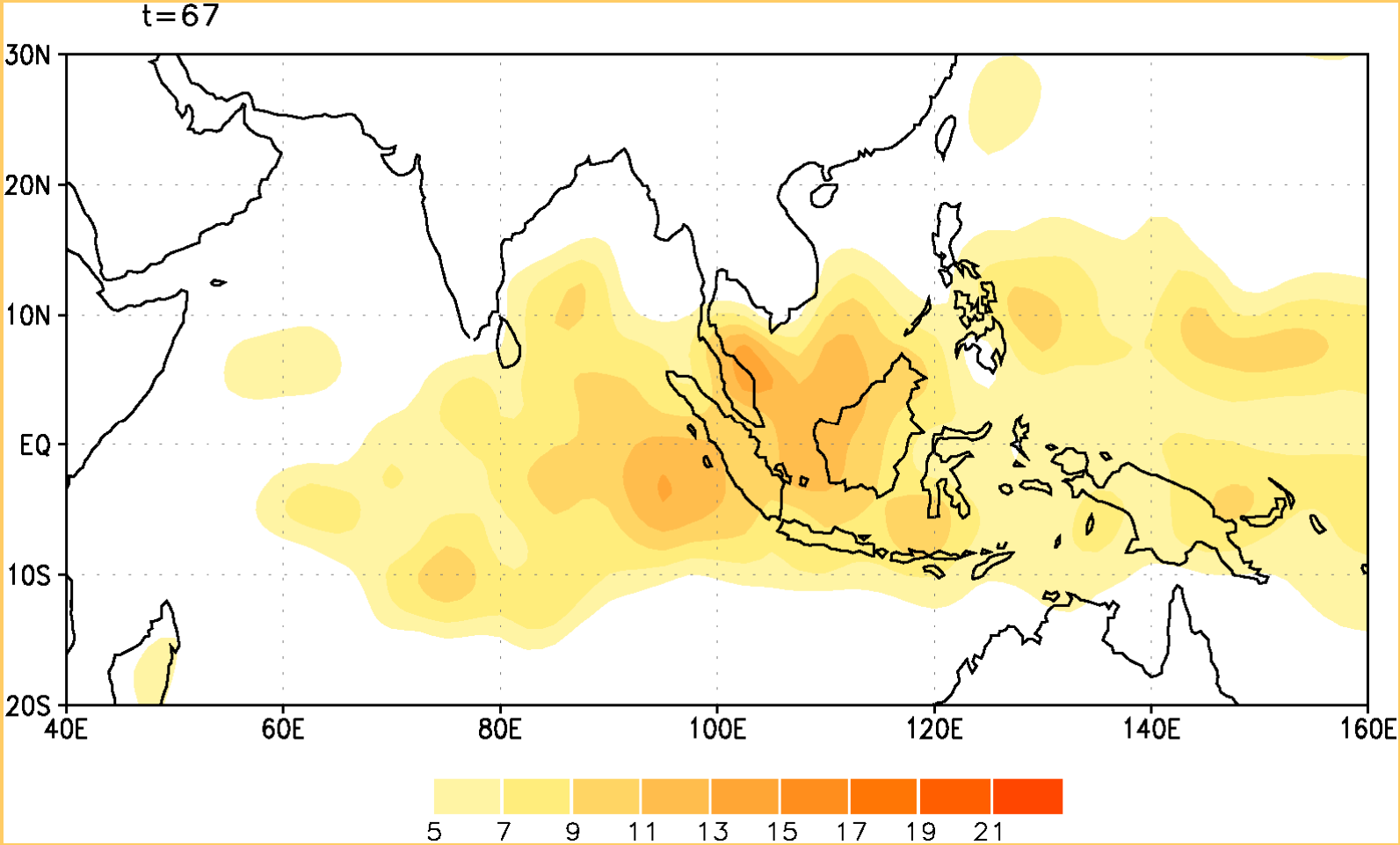
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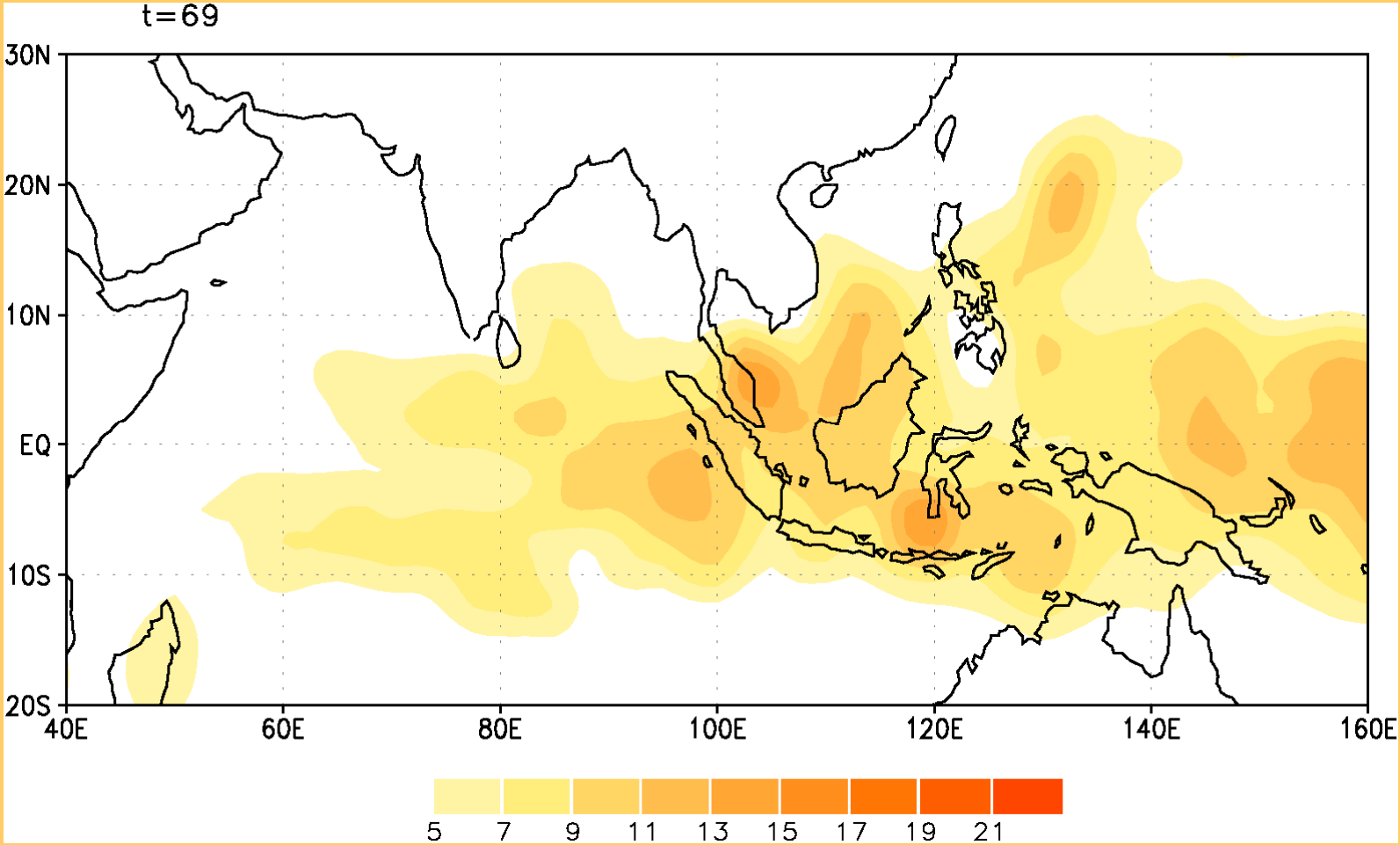
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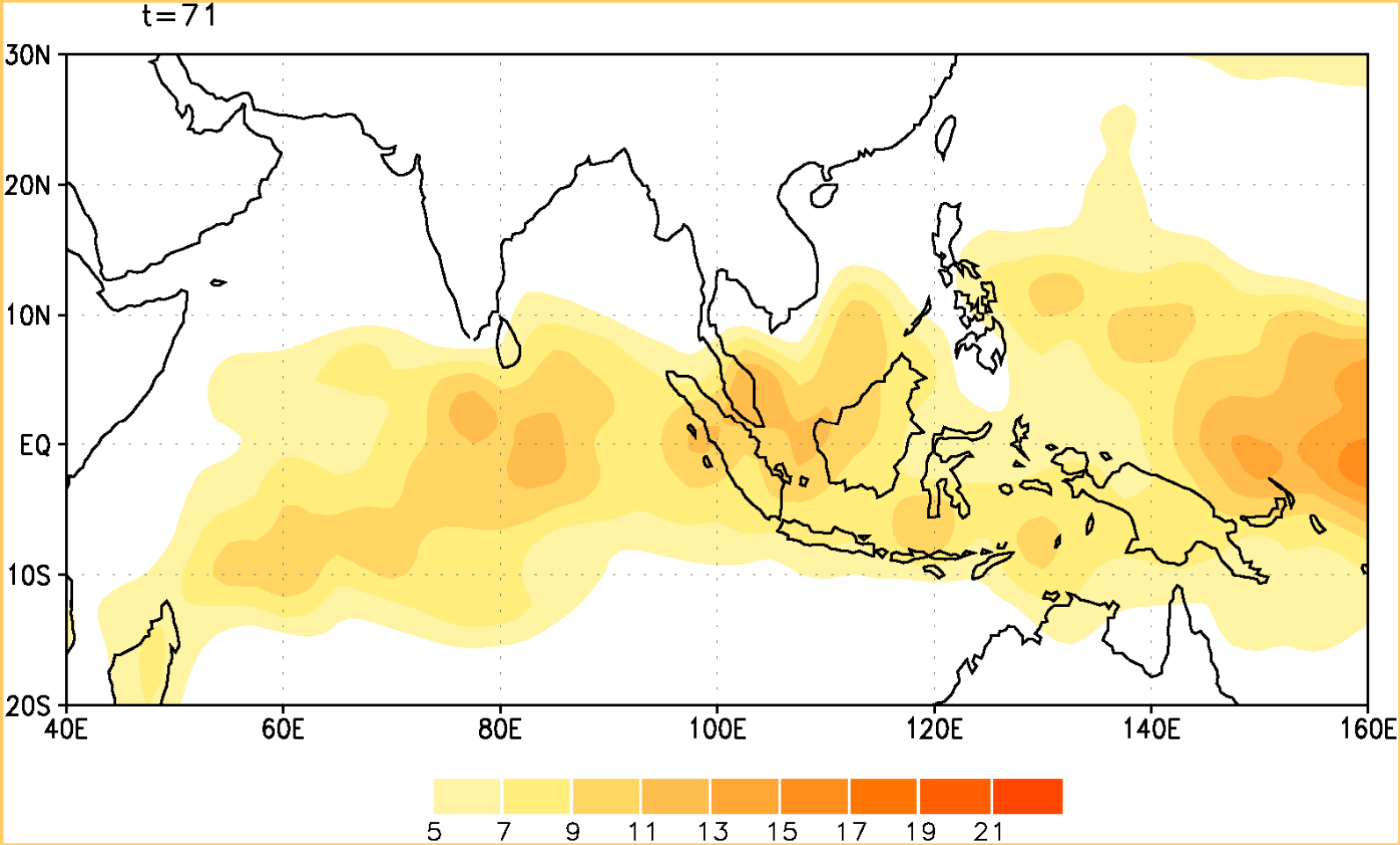
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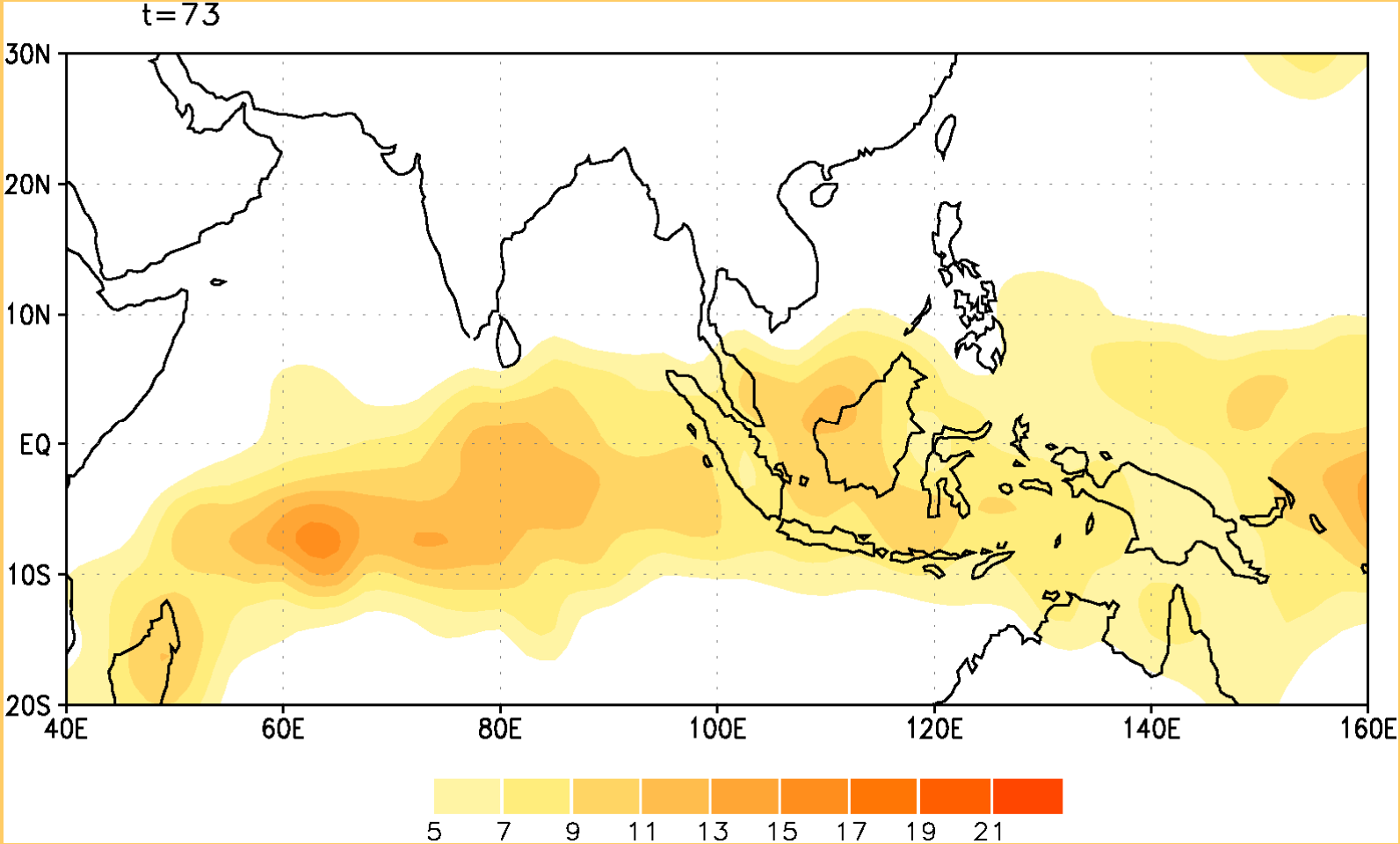
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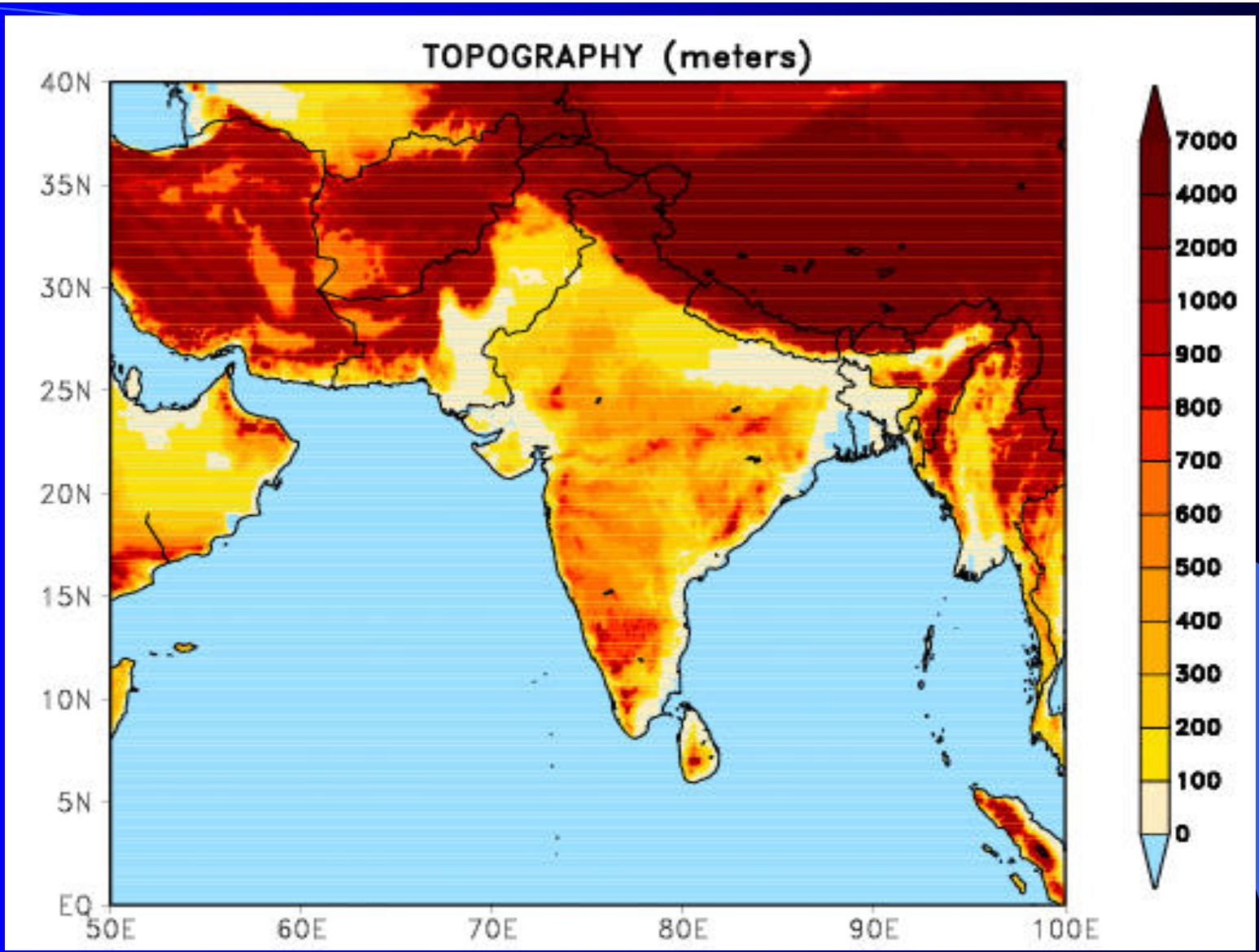
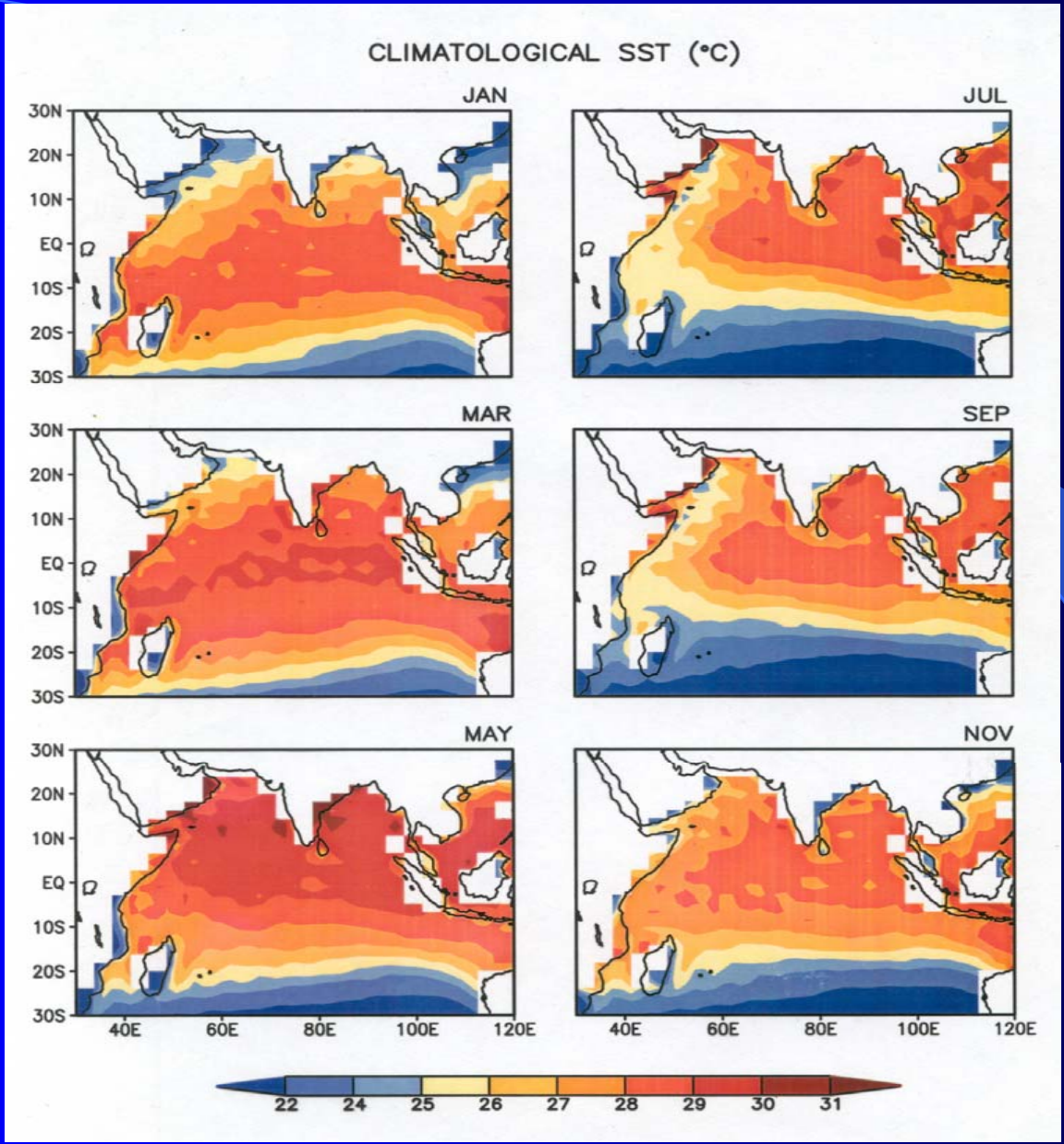
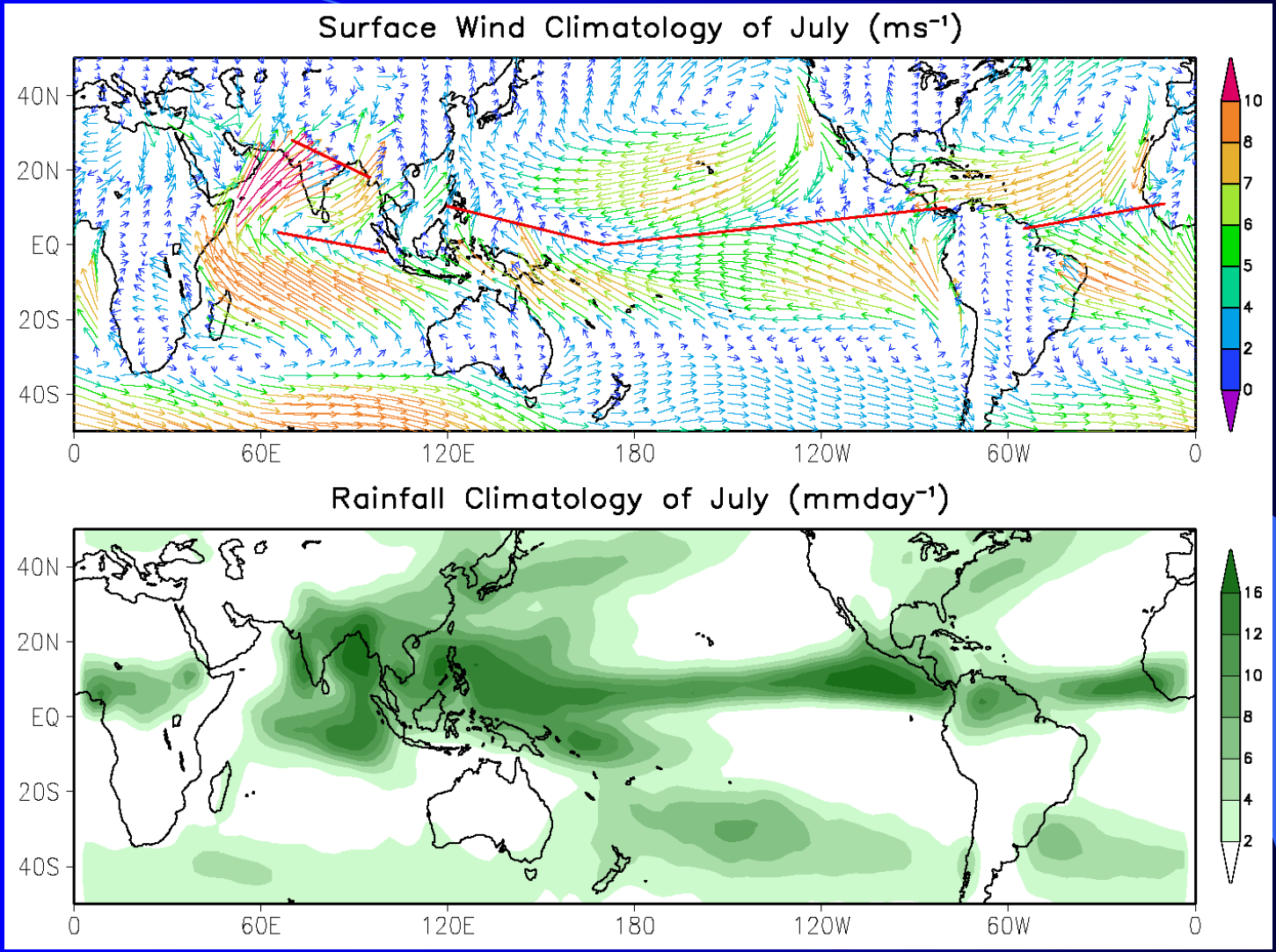
Animate again

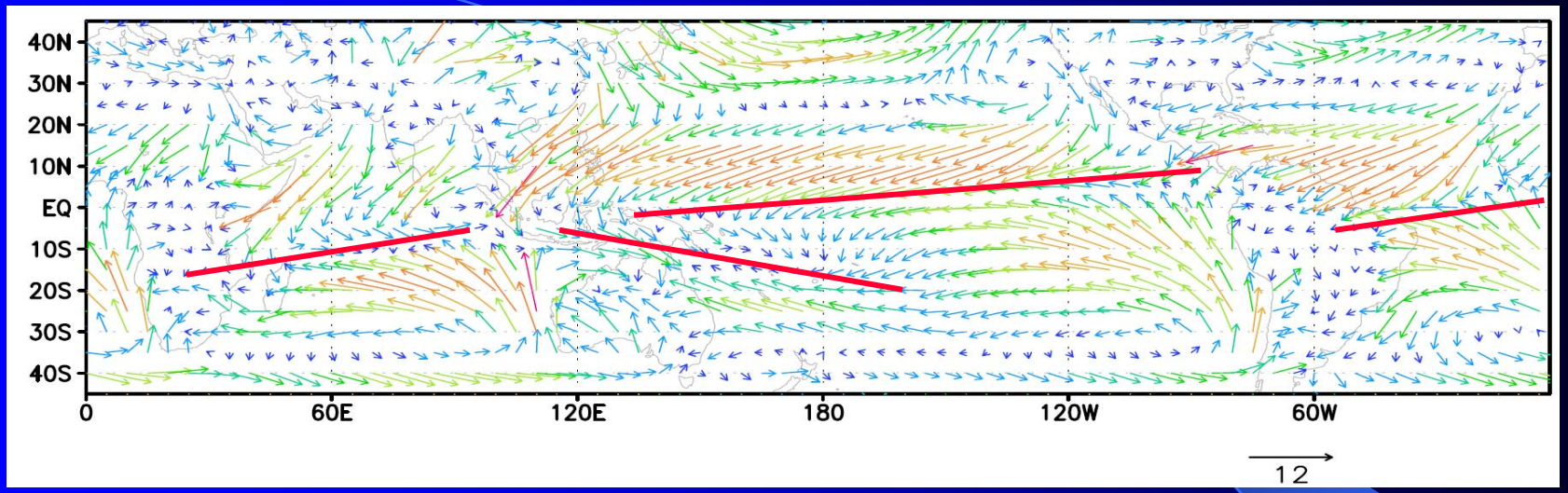

TOPOGRAPHY (meters)
40N
35N
30N
25N
20N
15N
10N
5N
EQ
50E
60E
70E
80E
90E
100E
7000
4000
2000
1000
900
800
700
600
500
400
300
200
100
0

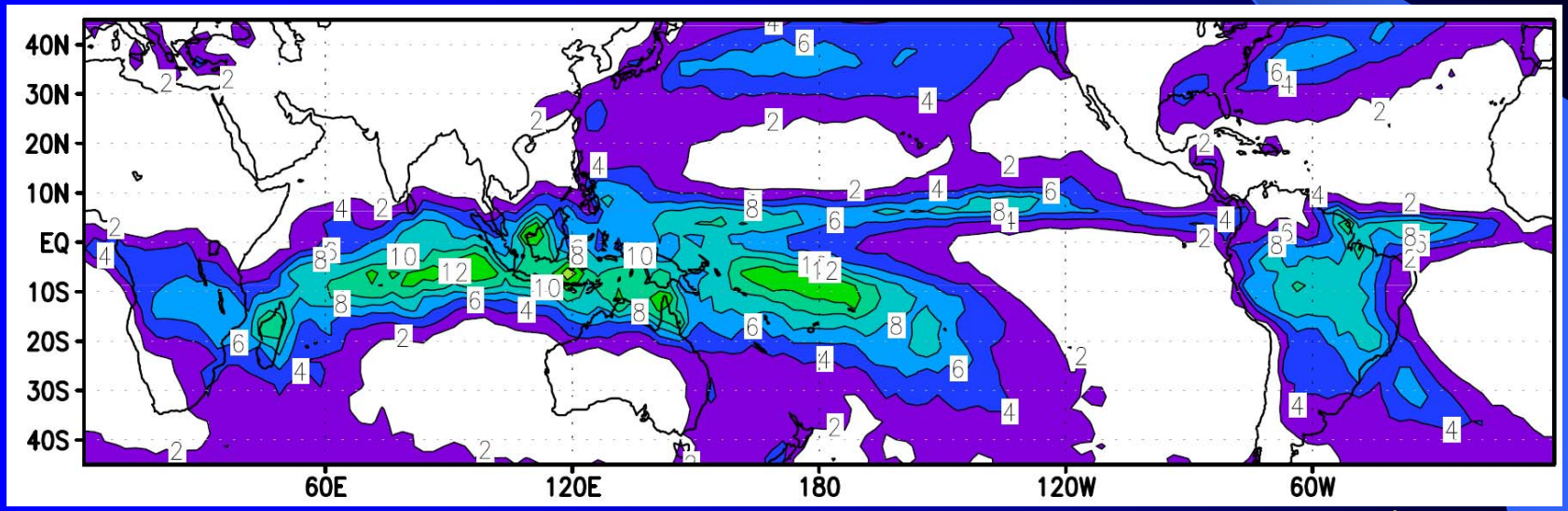

CLIMATOLOGICAL SST (°C)
JAN
JUL
MAR
SEP
MAY
NOV
30N
20N
10N
EQ
10S
20S
30S
40E
60E
80E
100E
120E
22
24
25
26
27
28
29
30
31

Mean July rainfall and surface wind convergence

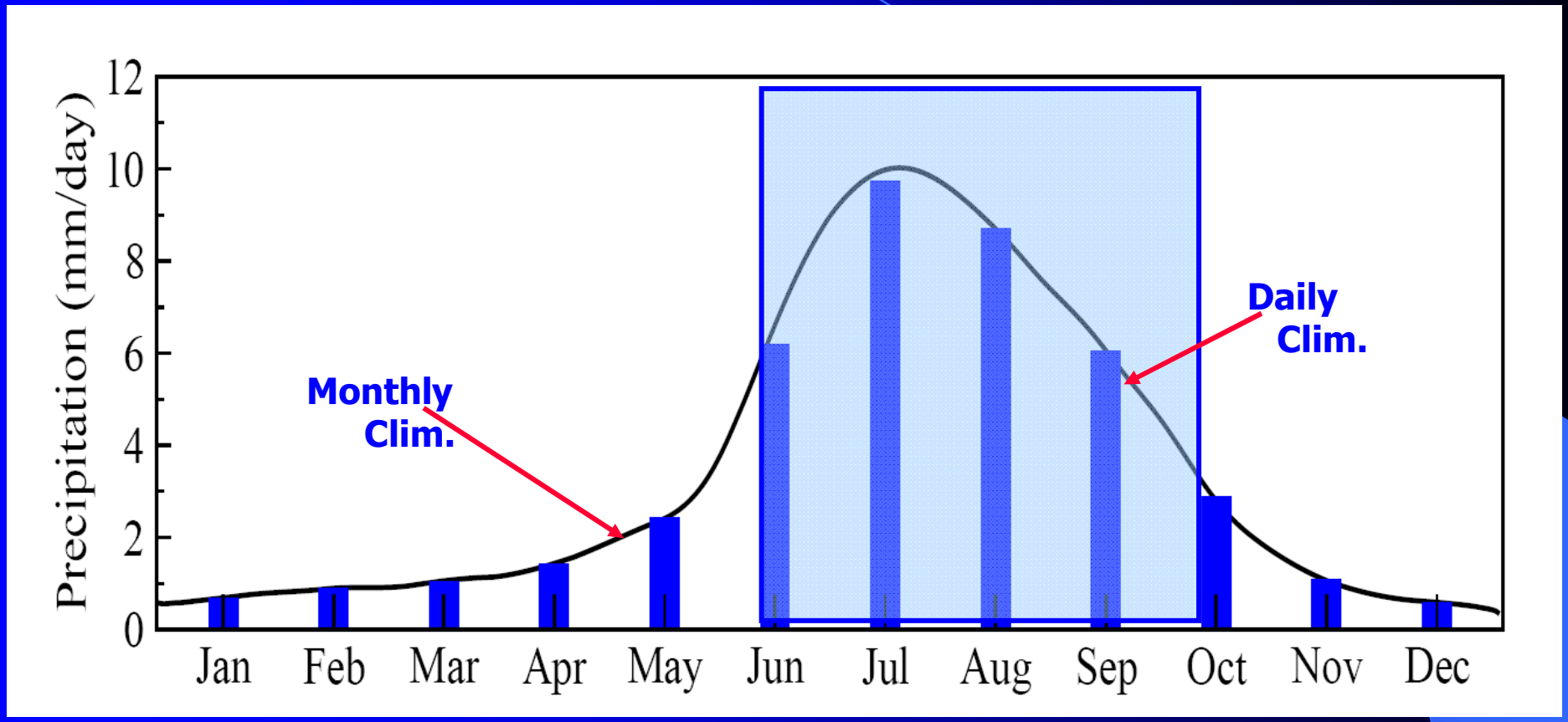


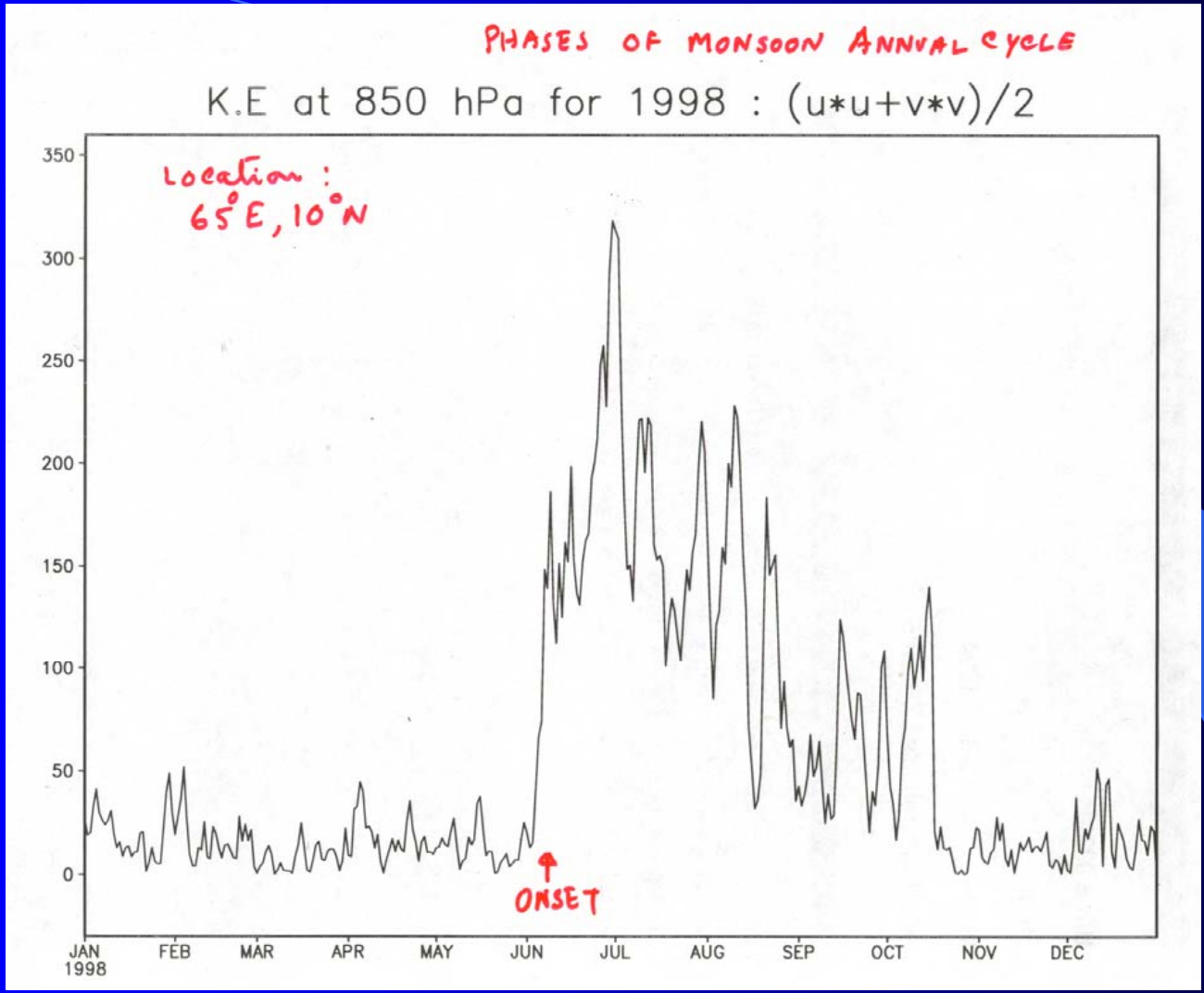
Mean January rainfall and surface wind convergence





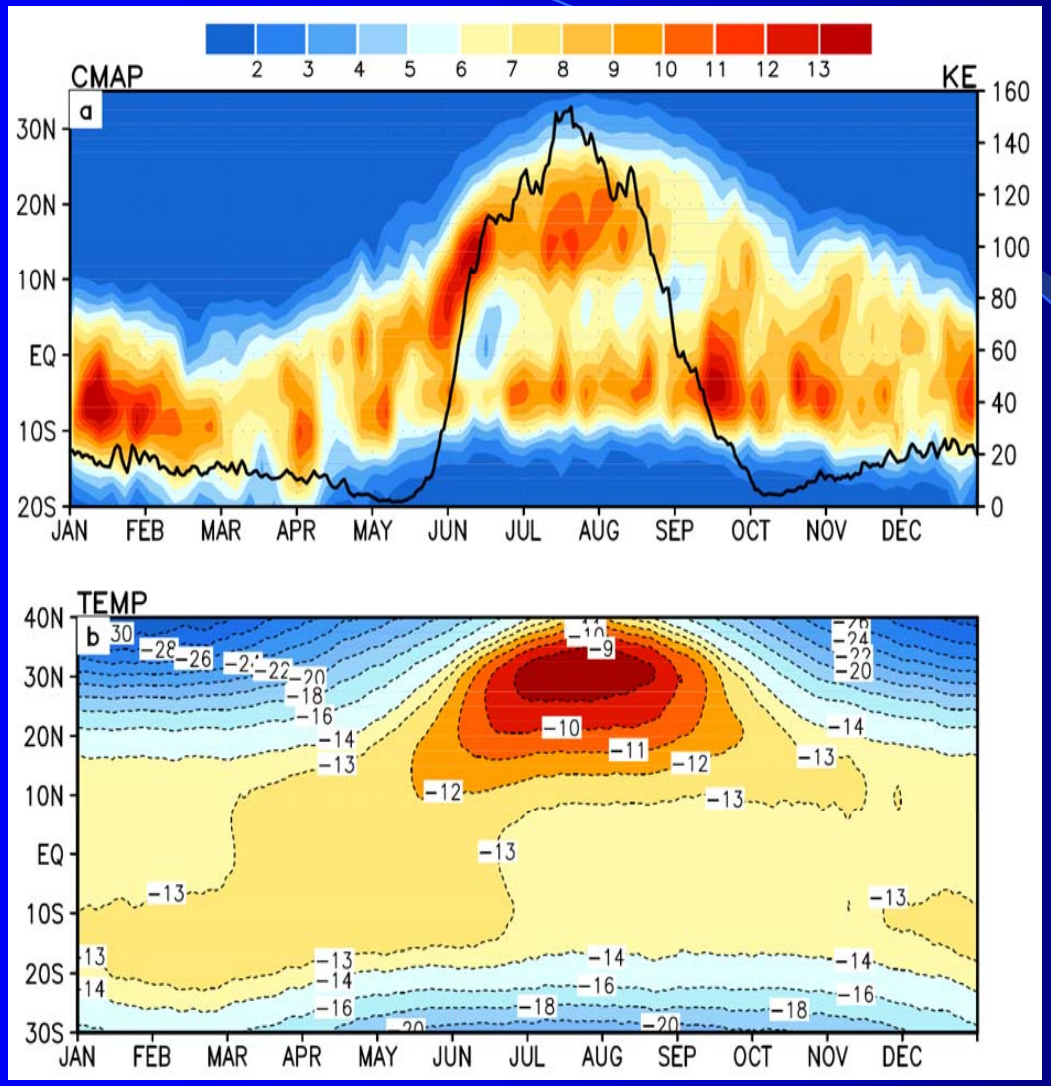
Annual cycle of Rainfall over India





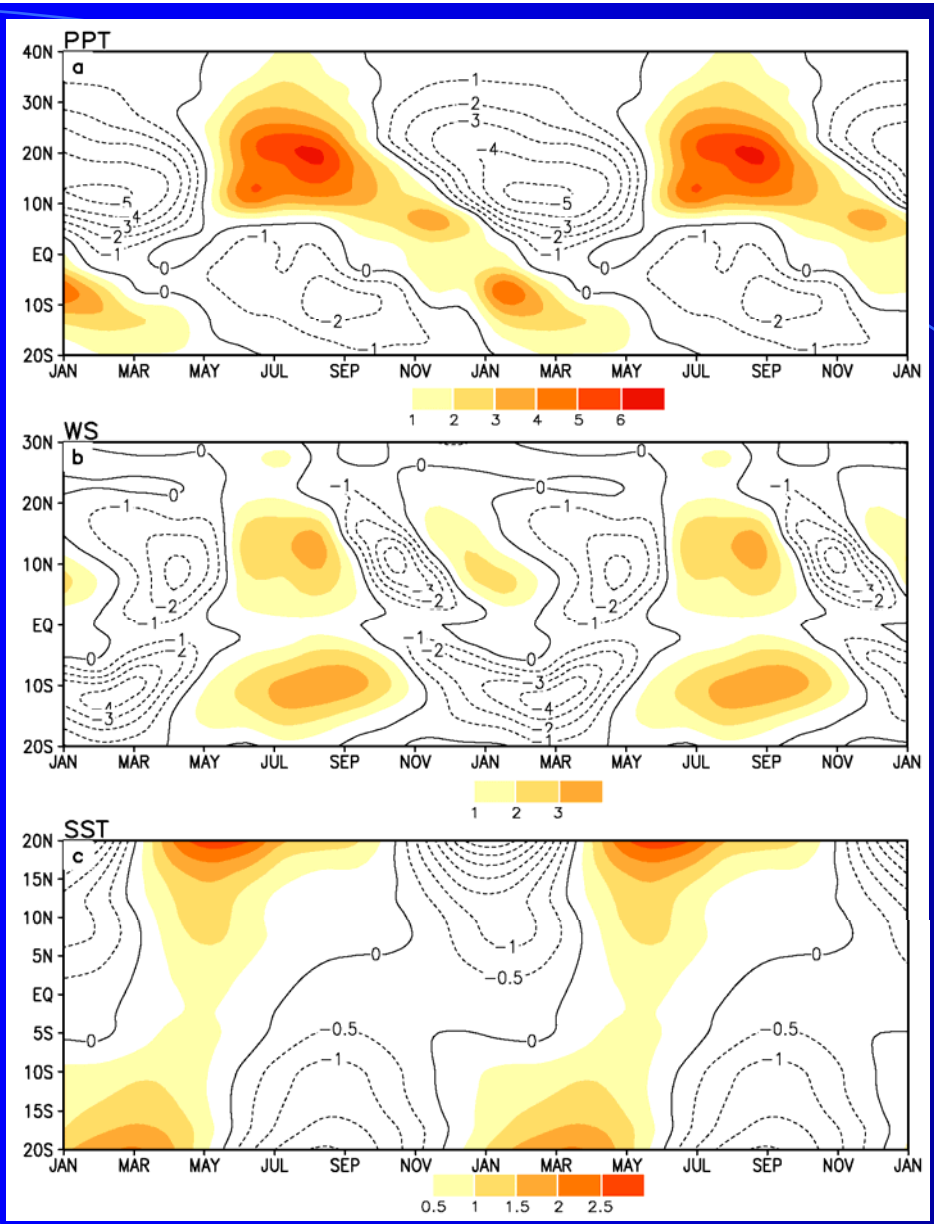
Onset of the monsoon

Annual Cycle of the TCZ and Monsoon Onset



Annual evolution precipitation <70E-90E> and K.E of the LLJ <50E-65E,5N-15N>

Annual evolution tropospheric temp. <700hPa-200 hPa> averaged over <30E-110E>



An Asymmetry in annual cycle of evolution of the ITCZ

Deviation of monthly climate from annual mean <80E-120E>

ASM→AuSM … Smooth

AuSM→ASM … abrupt

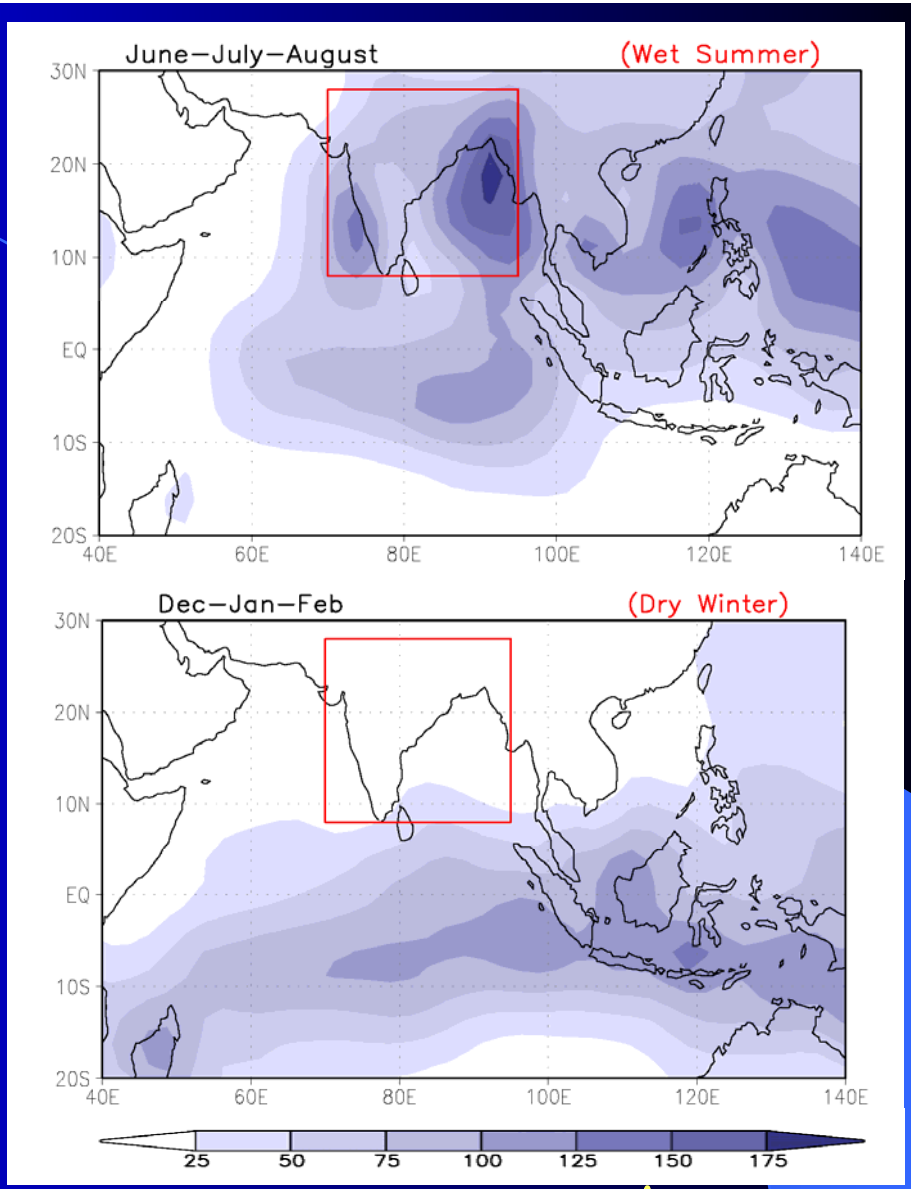
Special distribution Asian and Australian land mass and possible air-sea interactions

Hung et al, 2004,J.Climate; Chang et al 2004, J. Climate

Long term mean

JJA precipitation and

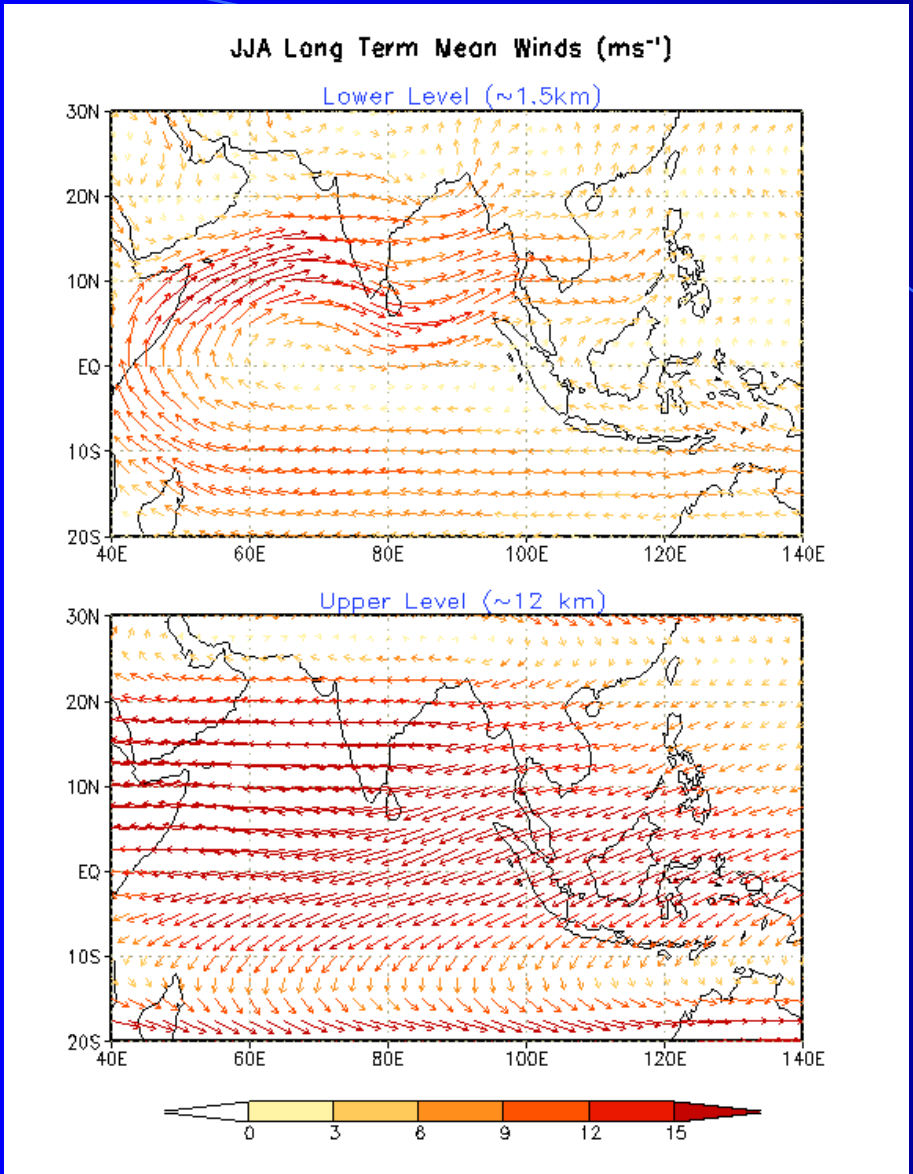
DJF precipitation



Monsoon ?

Wet- summer

Dry - winter



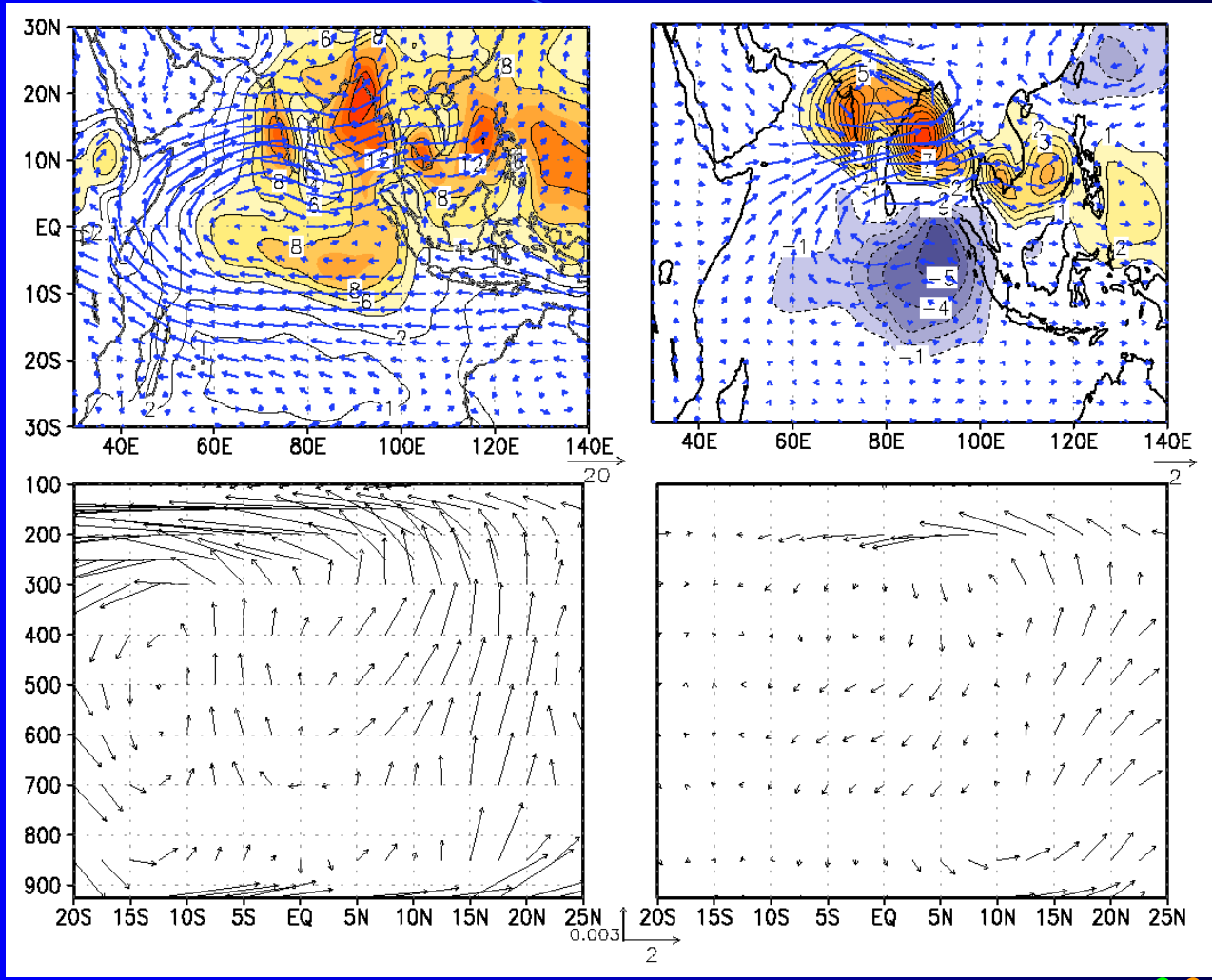
Characteristic features of summer monsoon circulation

Low level, cross-equatorial flow, south-westerlies, westerly jet in Arabian sea

Upper level easterlies, Monsoon Easterly Jet

Climatological mean JJAS P and 850 hPa winds

P and 850 hPa wind anoms during 'Active' phase



Mean monsoon Hadley circul.

70E-90E

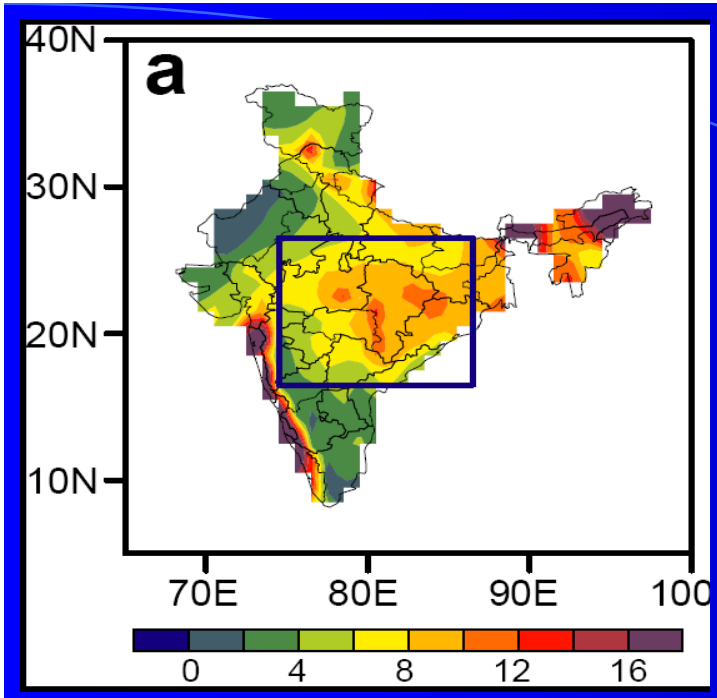
Anom. Hadley circul. In an 'active' phase,

70E-90E

Major characteristic of Seasonal Mean Indian monsoon

- wet summer and dry winter
- Manifestation of annual march of the TCZ from south of Equator to about 25N during northern summer
- Deep baroclinic vertical structure
- Abrupt onset

All India Rainfall

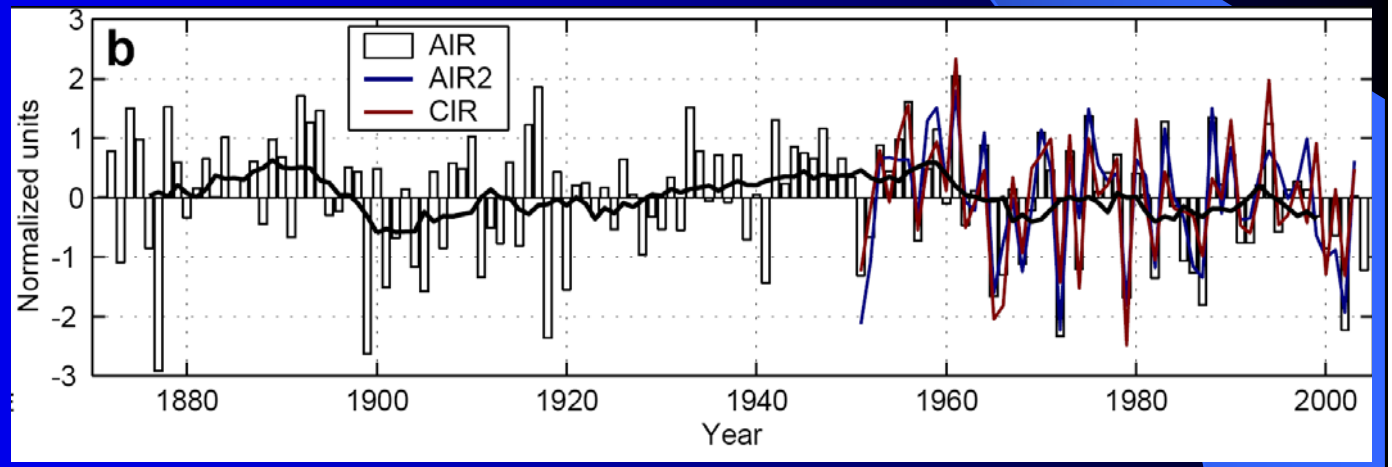


JJAS Mean

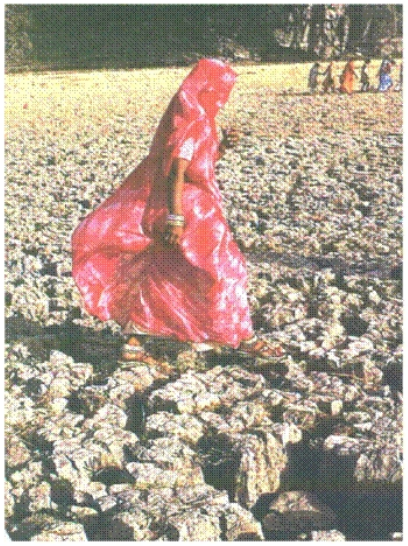
AIR Mean : 86 cm

AIR S.D. : 8.6 cm

Interannual Variability



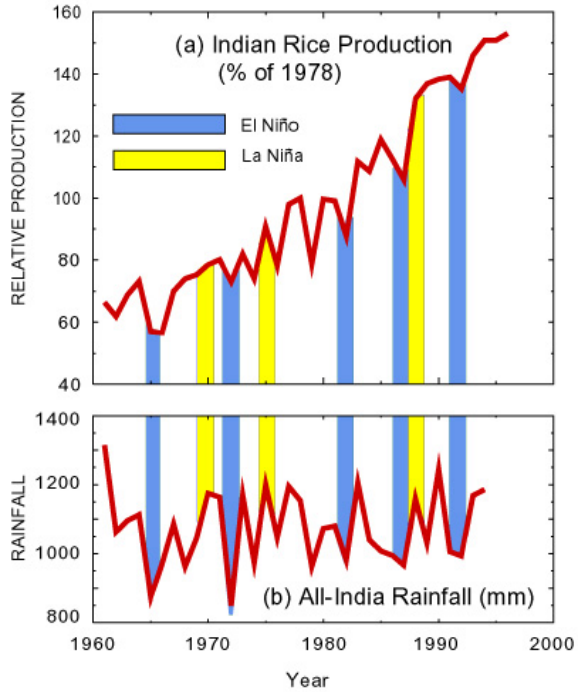
Goswami et al. 2006, Science



Extremes of Indian summer monsoon such as a large scale Drought and Flood, determine the economy of our country.

The Asian - Australian Monsoon System

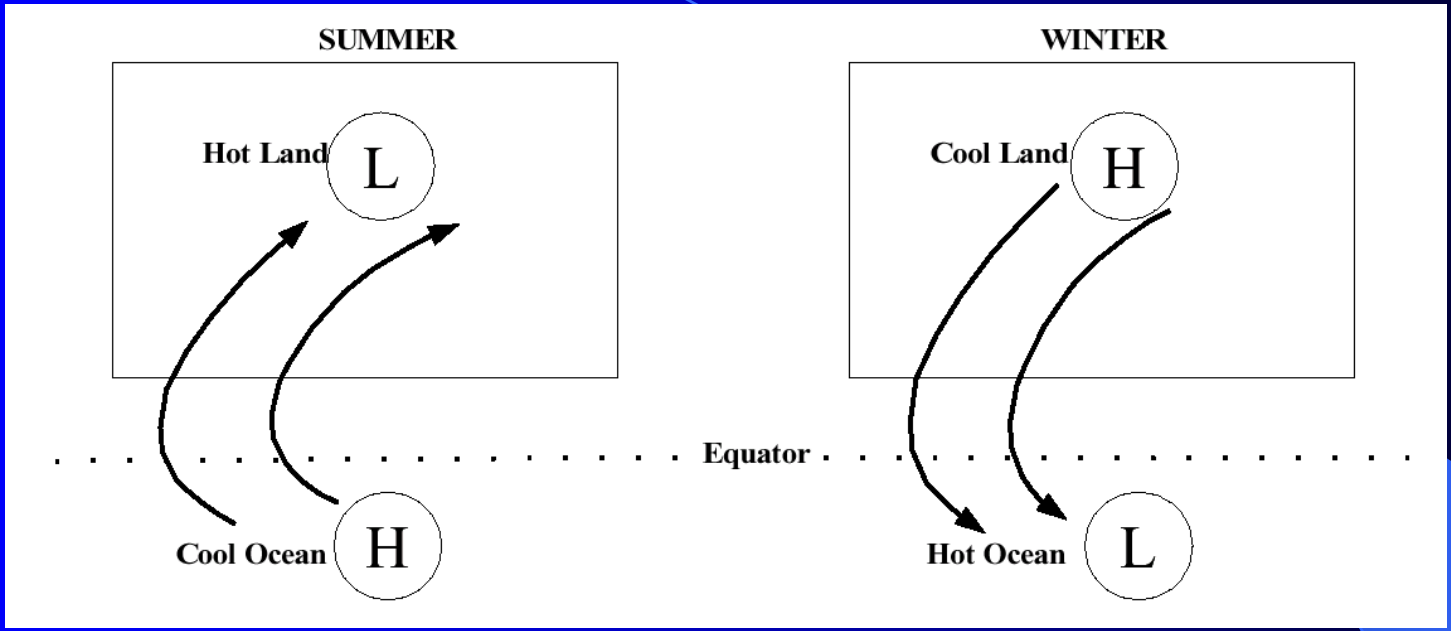
Relationship of Indian Rice Production and Indian Rainfall



Crop production vs. Indian monsoon rainfall. Notwithstanding the overall growth in rice production in India due to better farming practices and technological development, year-to-year fluctuations in production are determined largely by the success or failure of the summer monsoon which is in turn affected by the particular phase of the El Niño/Southern Oscillation phenomenon (from Webster et al. (1998, J. Geophys. Res., 103, 14451-14510), adapted from Gadgil, 1995, Current Science, 69, 649-659).

LB/G2/99-1

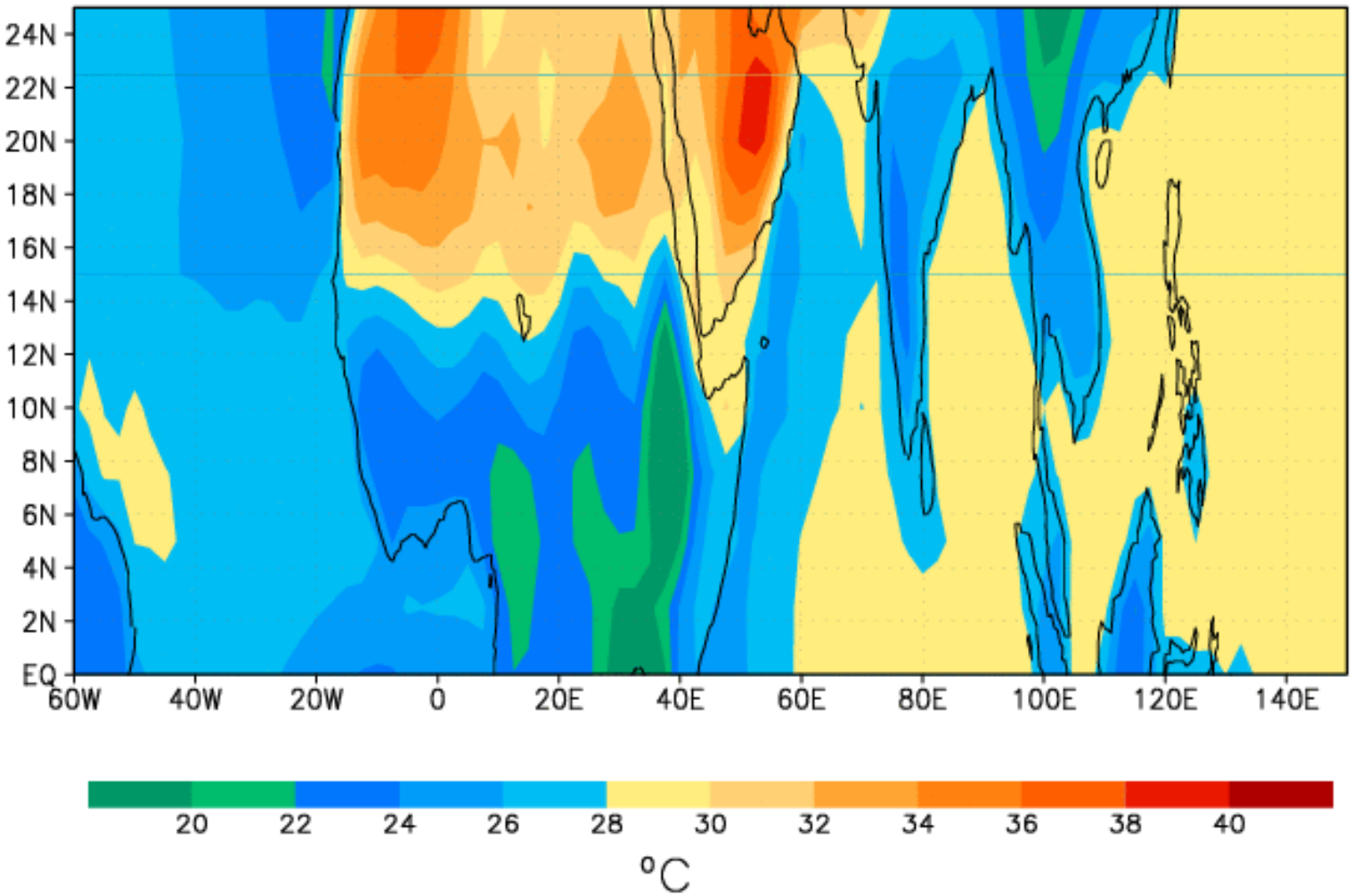
Classical model of monsoon: Large land-sea Breeze



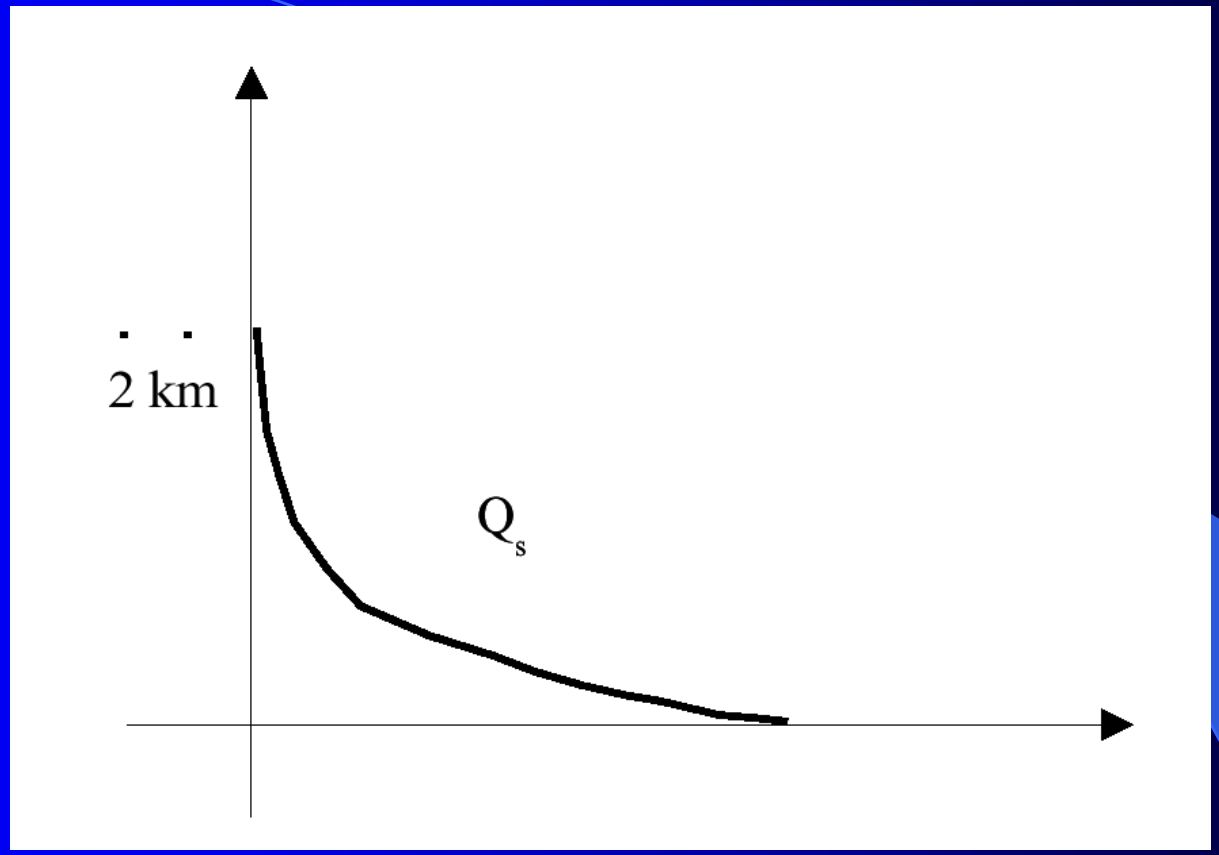
Cannot Explain:

- Vertical structure of circulation:Low level conv. , upper level div.
- Also, after the initial rainfall, the land temperature is actually cooler than that of the ocean

SKIN TEMPERATURE NCEP–REANALYSIS AVERAGE OF ALL JULYs (1949–2002)



Schematic of the vertical profile of surface heating

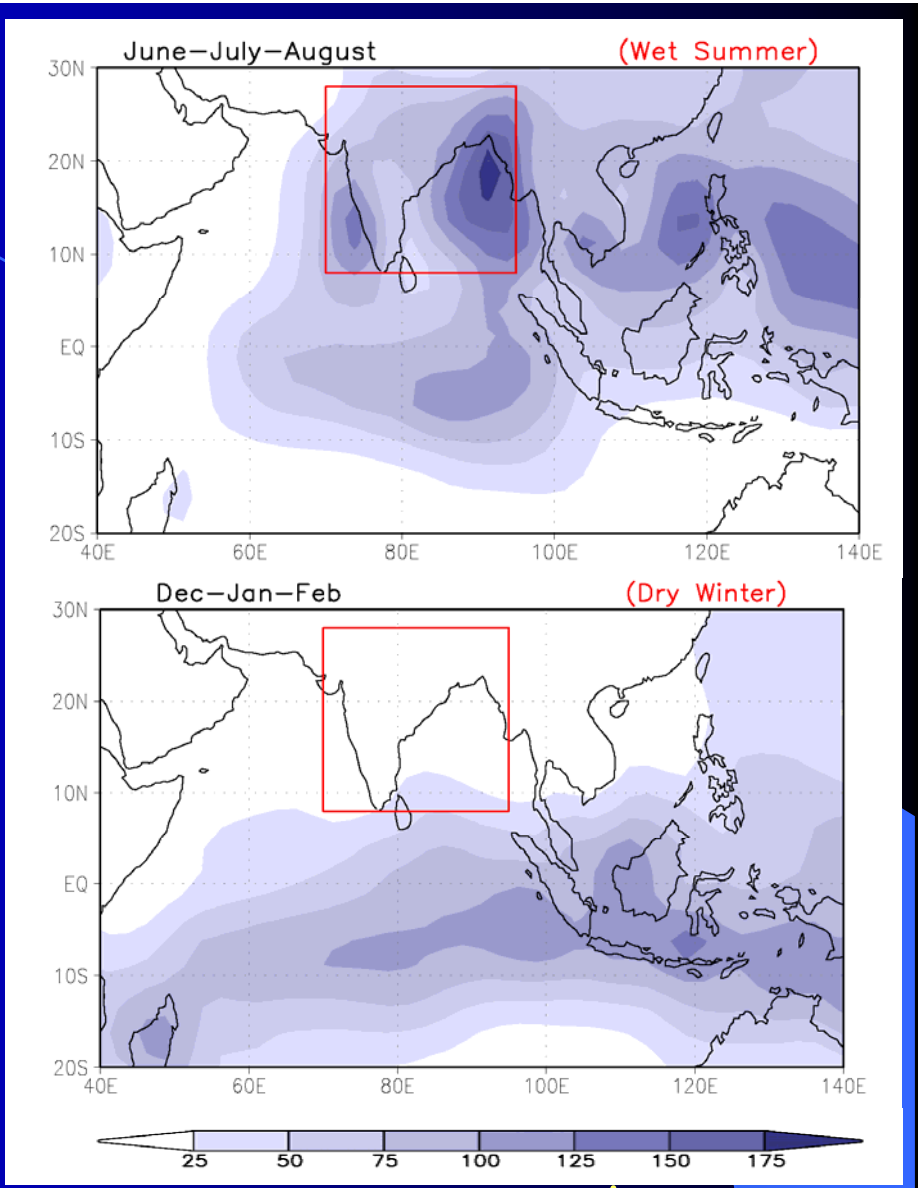


Another problem with the surface heating theory is that such a heating profile is confined to the lower layer as shown above and can not force deep vertical circulation as observed

Long term mean

JJA precipitation and

DJF precipitation

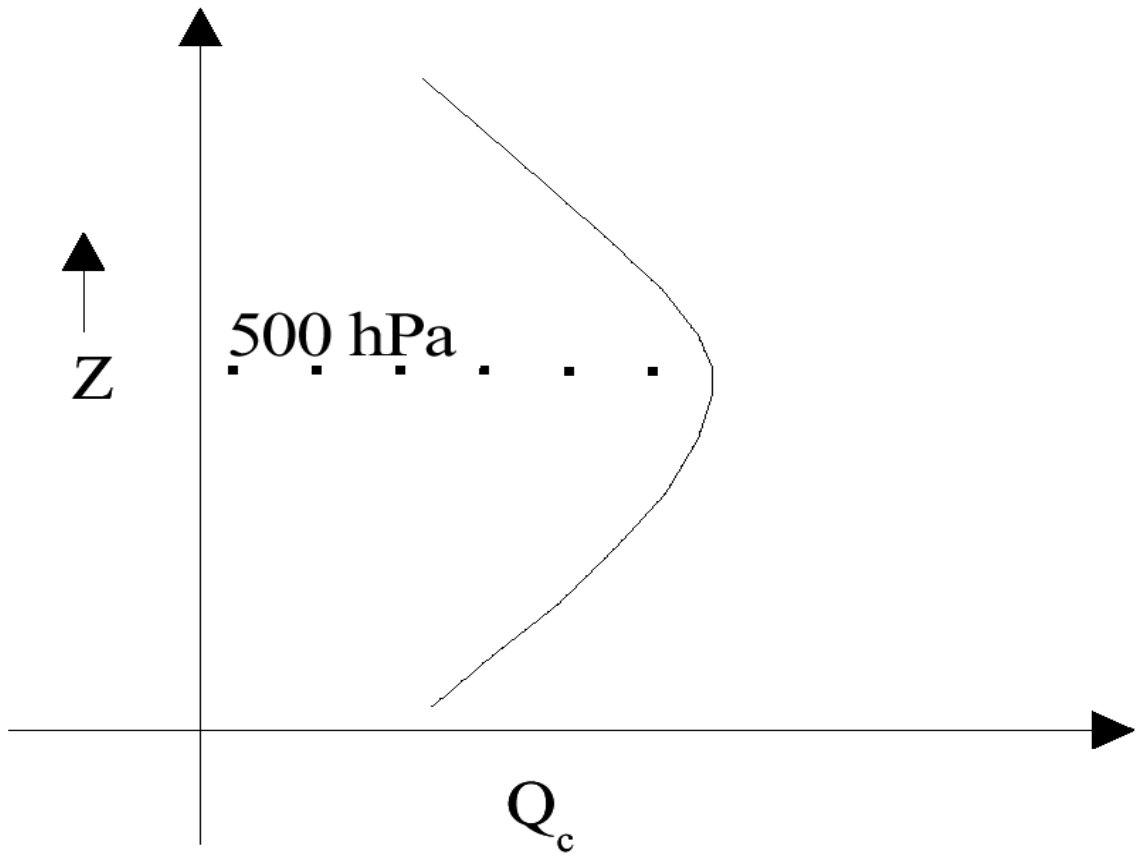


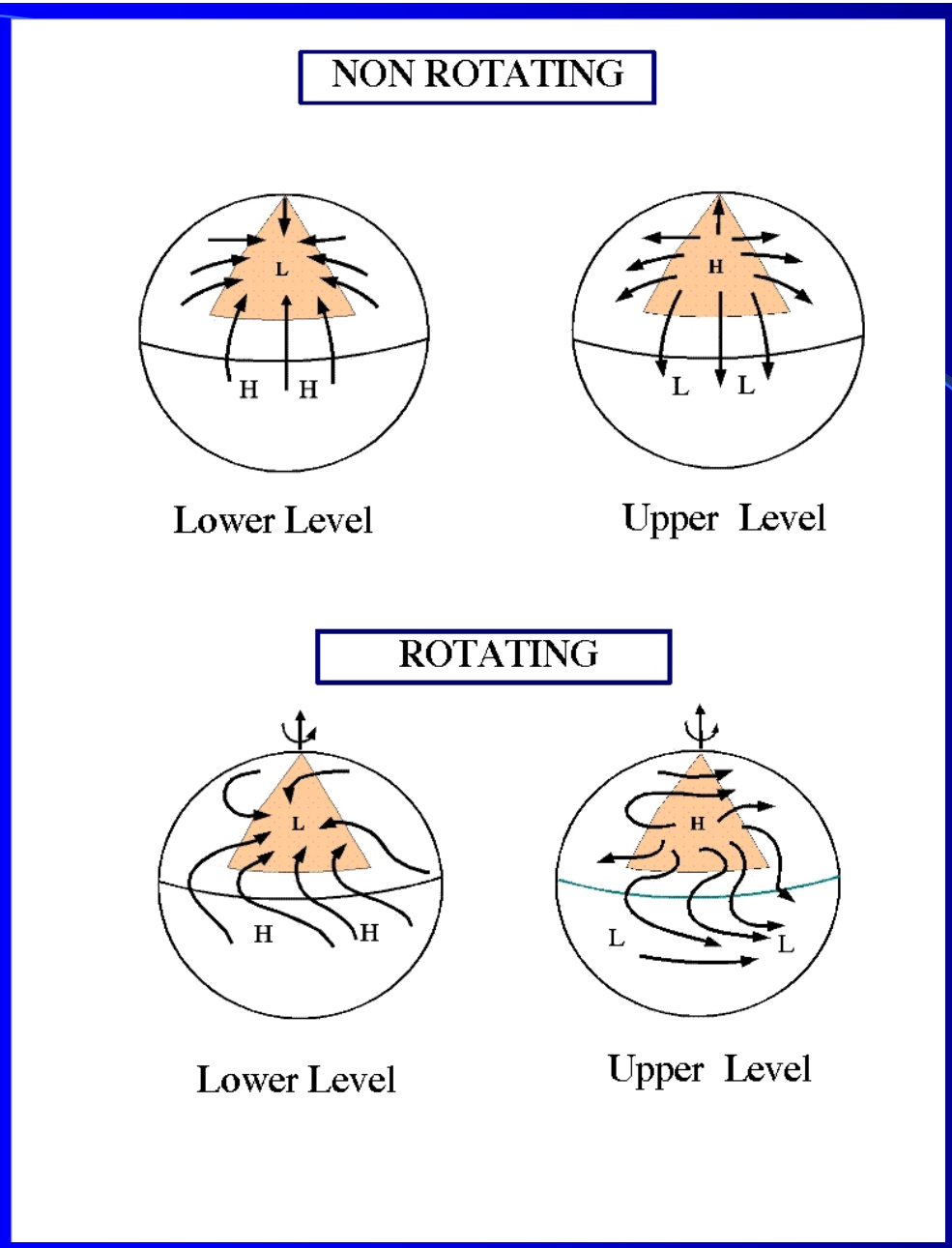
Monsoon ?

Wet- summer

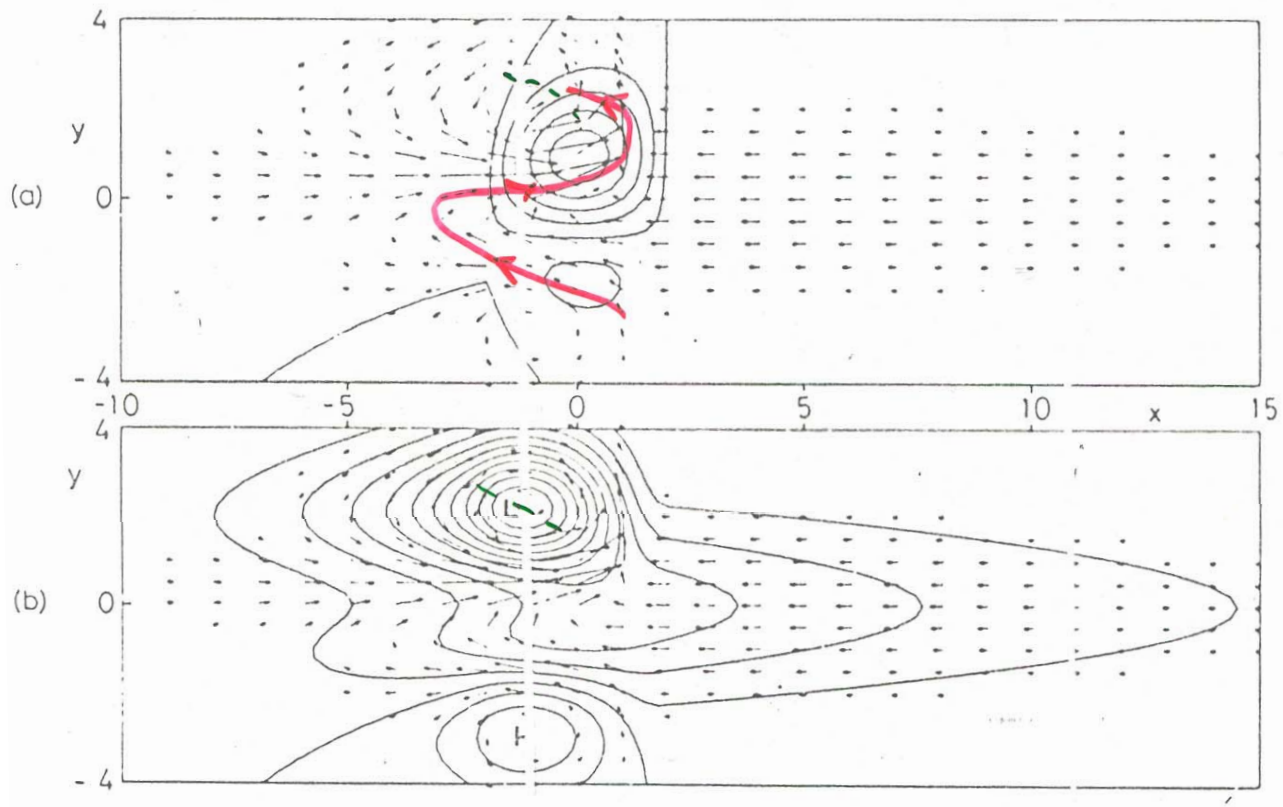
Dry - winter

The vertical structure of the non-adiabatic heating





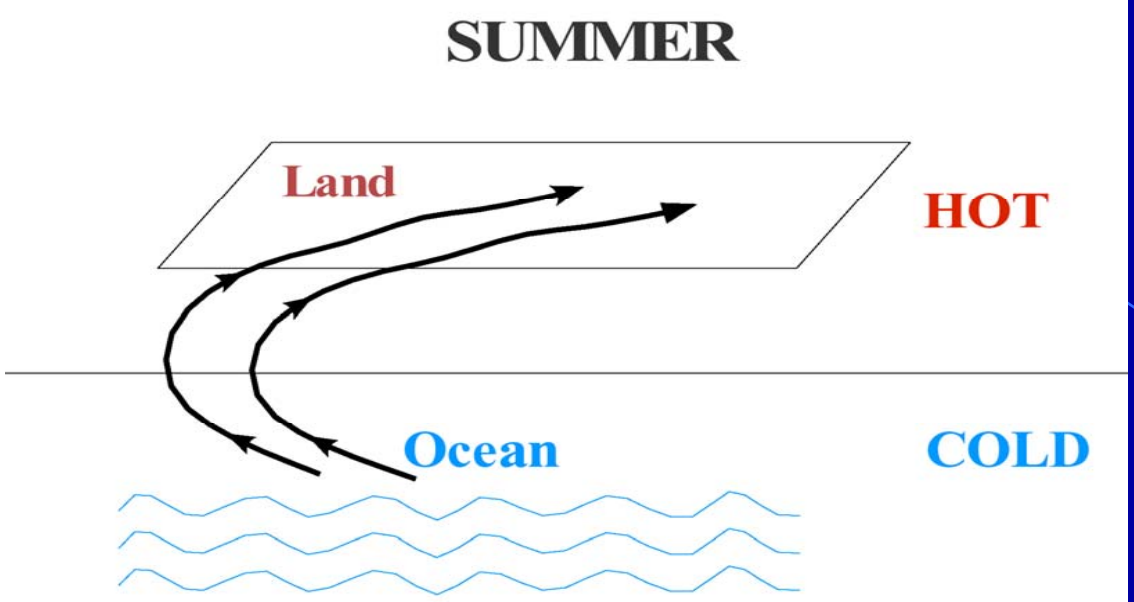
After the onset, the monsoon is maintained by latent heat released from convection. Such heating has maximum at the middle troposphere and leads to baroclinic structure of the circulation.



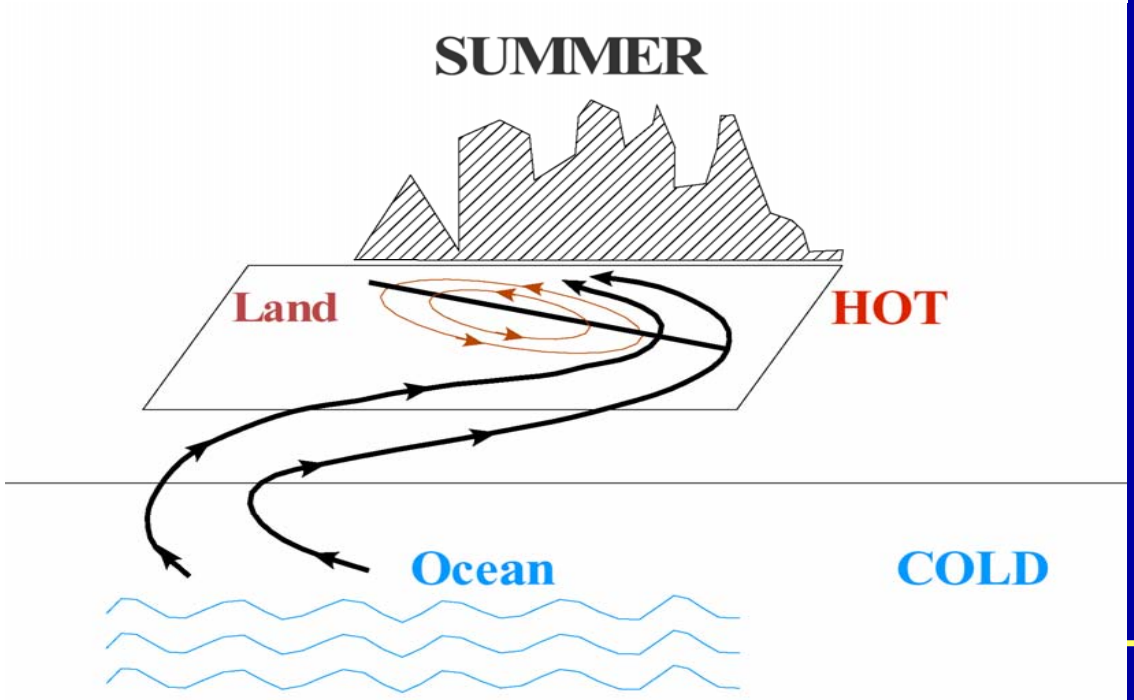
ig. 9.16. Distribution of the flow obtained by the addition of the response to heating nfined about the equator and heating which is concentrated to the north of the uator. Upper diagram shows the distribution of vertical velocity and the lower agram the perturbation pressure pattern. Vectors indicate the horizontal flow field. (From Gill, 1980.)

- The Off equatorial heating due to precipitation is therefore important in explaining the monsoon circulation.

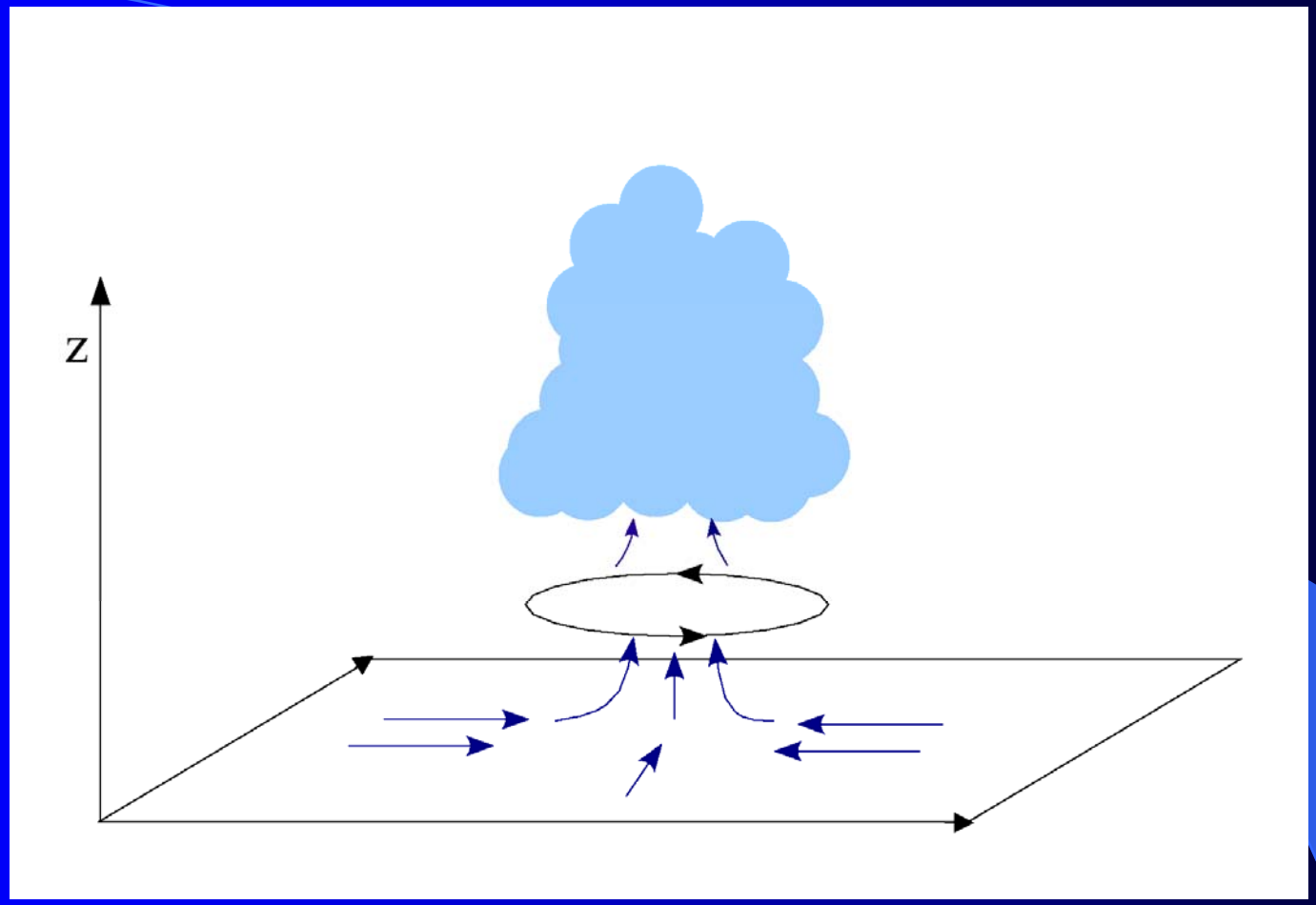
- What is responsible for the large northward excursion of the ITCZ to about 25 N in the Indian monsoon region?



In the absence of Himalayas, land-ocean contrast would result in south-westerlies but no monsoon trough.



Interaction of the Himalayas and the south-westerlies produces a quasi-stationary cyclonic vortex at low level known as the ‘monsoon trough’



Cyclonic vorticity forced by the Himalayas ⇒ Frictional convergence in planetary boundary layer ⇒ lifting of moist air to the lifting condensation level ⇒ free convection

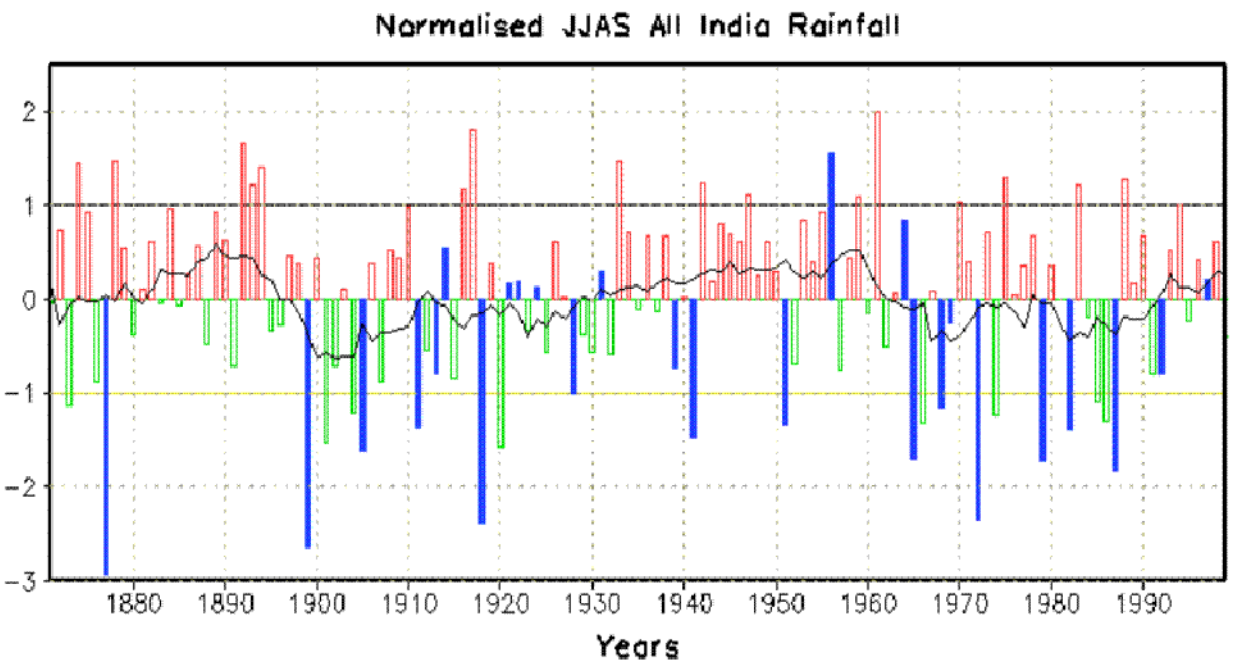
Thus, the classical concept of Indian monsoon being driven by north-south gradient of surface temperature is incorrect!

So, what exactly dives the Indian monsoon?

Meridional gradient of Tropospheric heating drives the monsoon circulation!

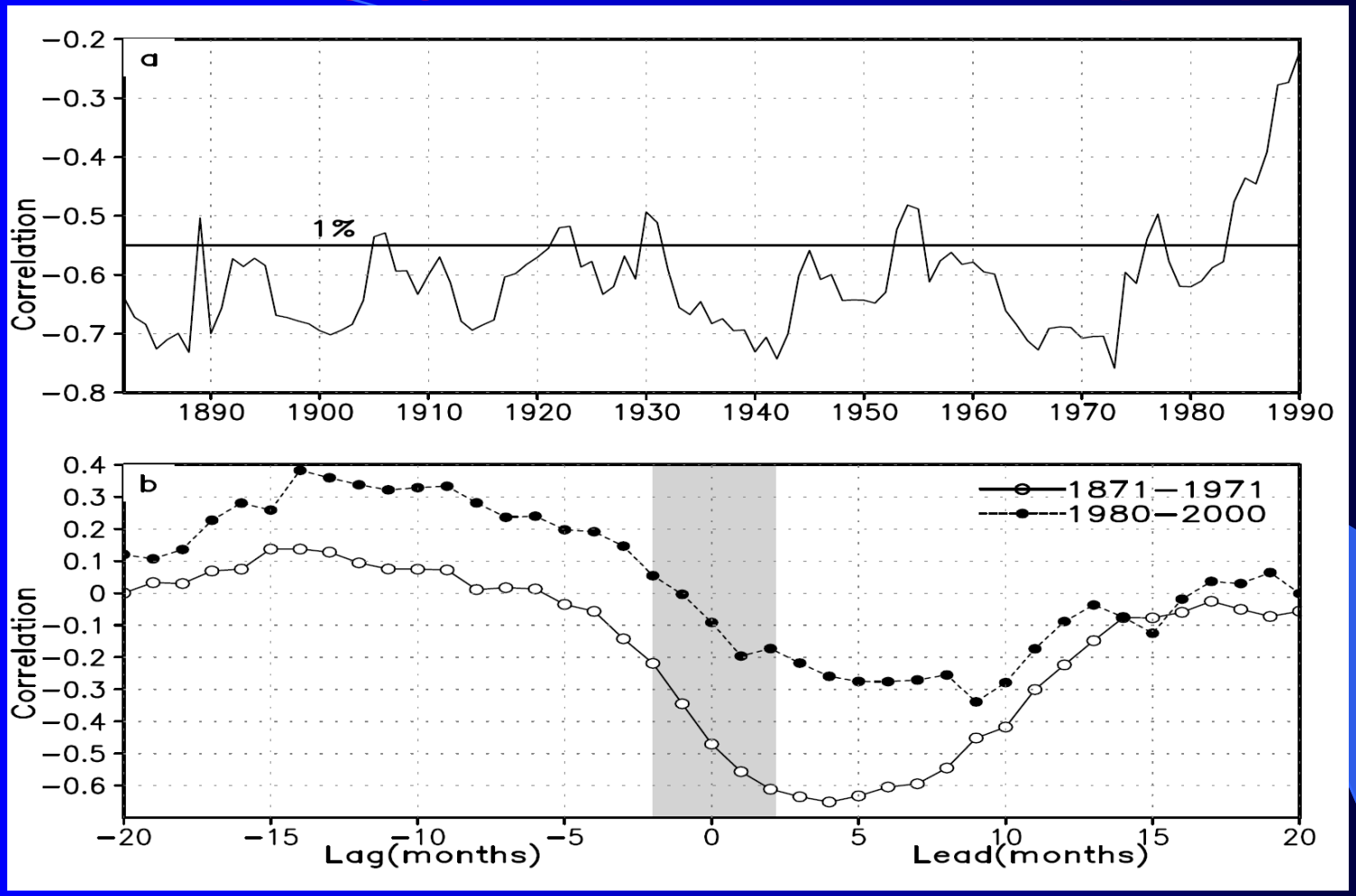
Meridional gradient of Tropospheric Heating → **Meridional gradient of Tropospheric Temperature (TT)**

Interannual variability of the Indian summer monsoon

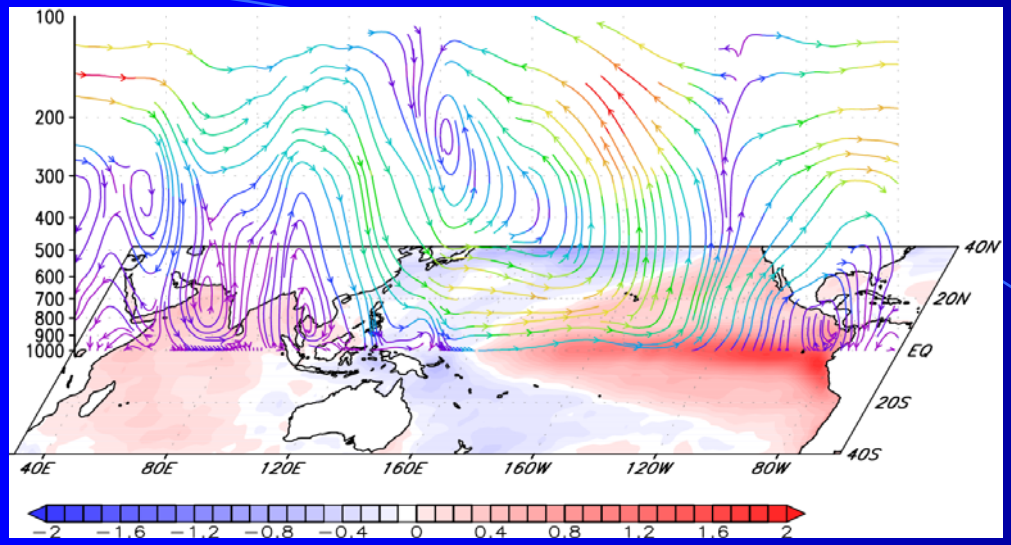


India has long records of rainfall over the country. Here departure from long term mean of seasonal mean rainfall over the whole country for about 130 years is shown. All India seasonal mean rainfall is about 90 cm. The departures are shown in units of 9 cm (about 10% of the mean). Large positive departures means flood while large negative departures means drought. It may be noted that monsoon rainfall is not monotonically increasing with global warming, but has a decadal variation.

Changing ENSO-Monsoon Relationship

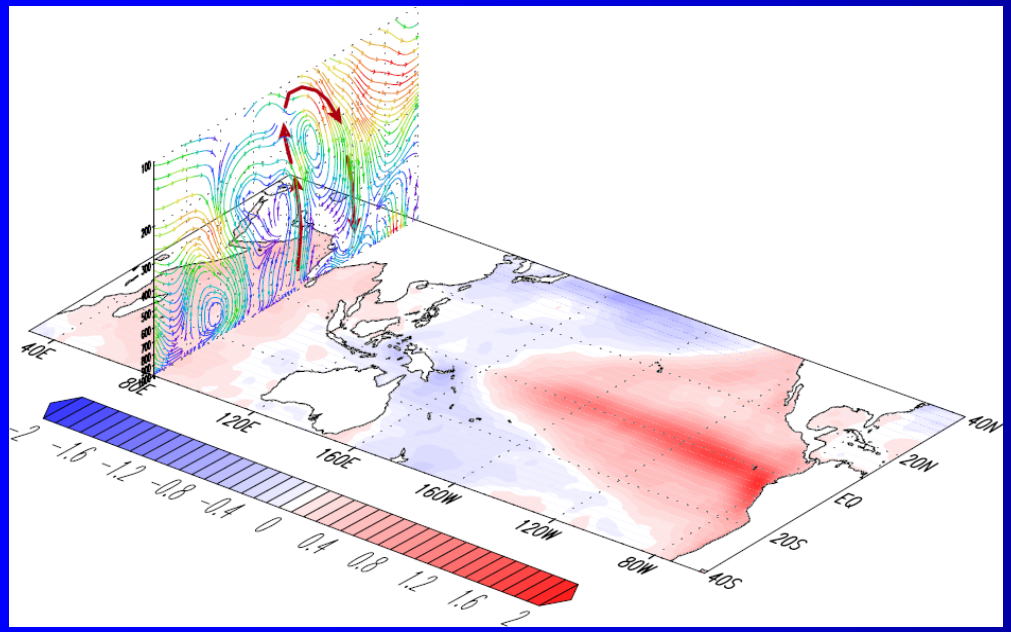


(a) 21-year sliding window correlation between AIR and Nino3 SST, (b) lead-lag correlation between AIR and Nino3 SST during the period 1871-1971 and 1980-2000.



JJAS Composite of Walker circulation {(U,-ω) averaged <5S-5N>} based on 11 El Ninos between 1950 and 2002

(composite of El Nino SST (JJAS) is shown in the horizontal plane (shaded))



JJAS Composite of monsoon Hadley (MH) circulation {(V,-ω) averaged <70E-100E>} based on 11 El Ninos between 1950 and 2002

How does ENSO induces decreased Indian summer monsoon precipitation?

Current paradigm:

Large scale circulation changes associated with ENSO introduces inhibition for organized convection over Indian region.

Eastward shift of the Walker Circ. With +ve ENSO

→

Decreased low level divergence over the Equatorial IO.

↓

Increased convection over the Equatorial IO.

←

Increased subsidence over continental India.

←

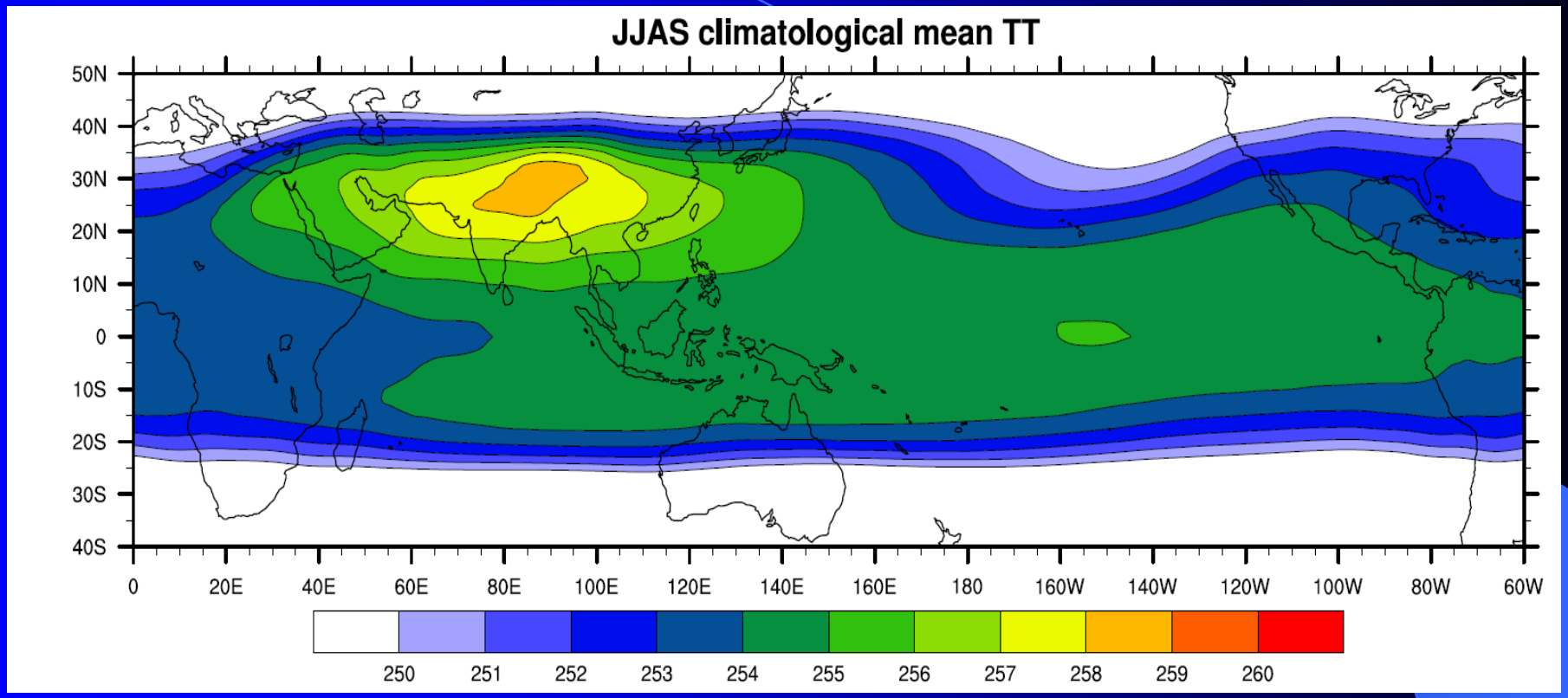
Decreased monsoon rainfall over India.

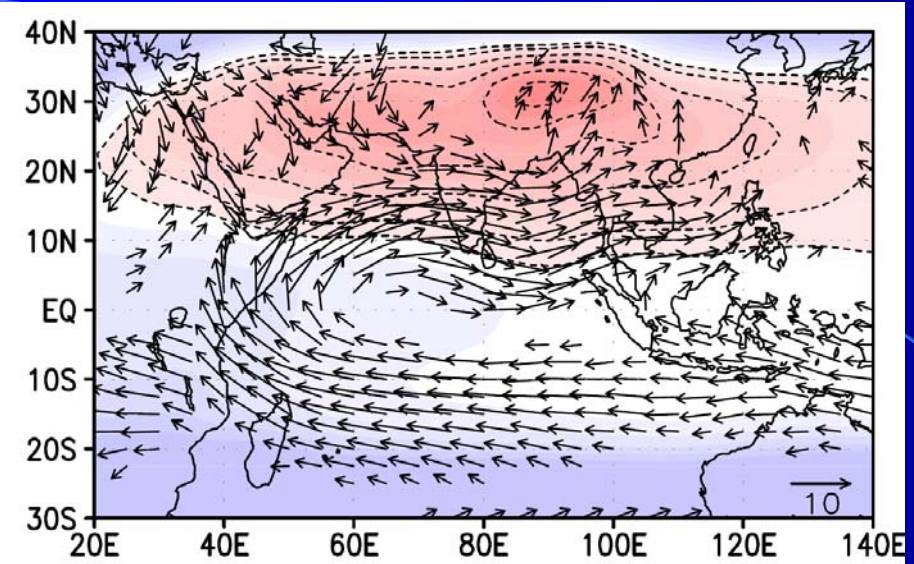
Implicit in all these is an assumption that the 'Indian summer monsoon season' is of fixed duration!

The 'Indian summer monsoon' is a physical phenomenon driven by large scale heating gradients that vary in intensity and duration from year to year. Therefore, the actual length of the physical monsoon season may vary from year to year.

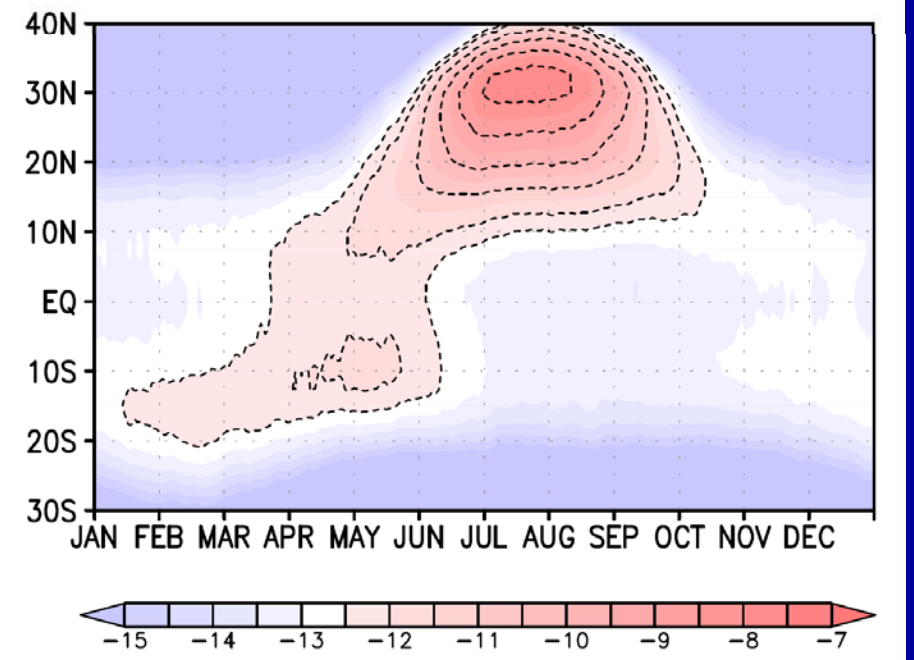
Thus, there is another degree of freedom , namely the length of the rainy season (LRS) that may influence the ENSO-Monsoon relationship.

➔ There is a need for an objective definition to delineate the Indian summer monsoon SEASON.

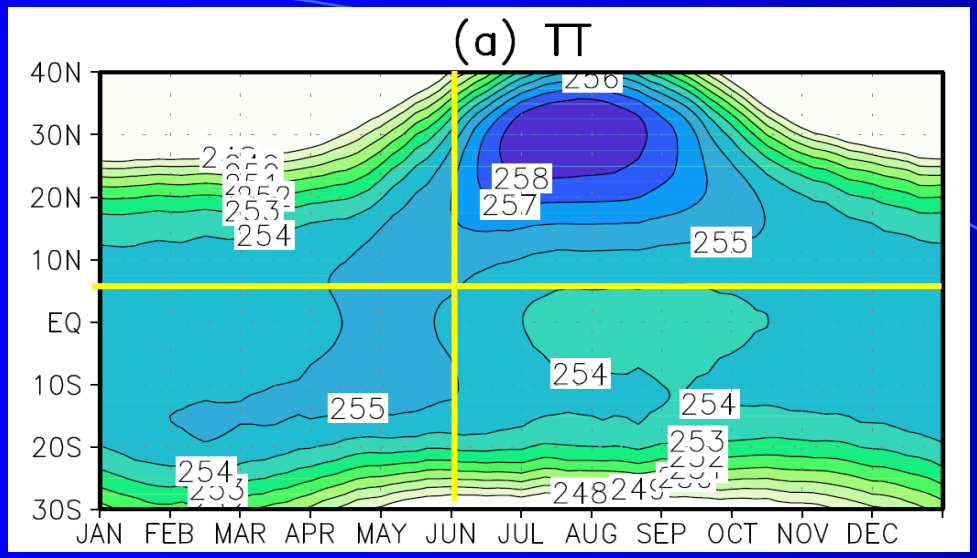

JJAS climatological mean TT
50N
40N
30N
20N
10N
0
10S
20S
30S
40S
0
20E
40E
60E
80E
100E
120E
140E
160E
180
160W
140W
120W
100W
80W
60W
250
251
252
253
254
255
256
257
258
259
260



Tropospheric temperature (TT, in °C) averaged over 200 hPa-700 hPa (shaded) and 850 hPa winds. JJAS average.

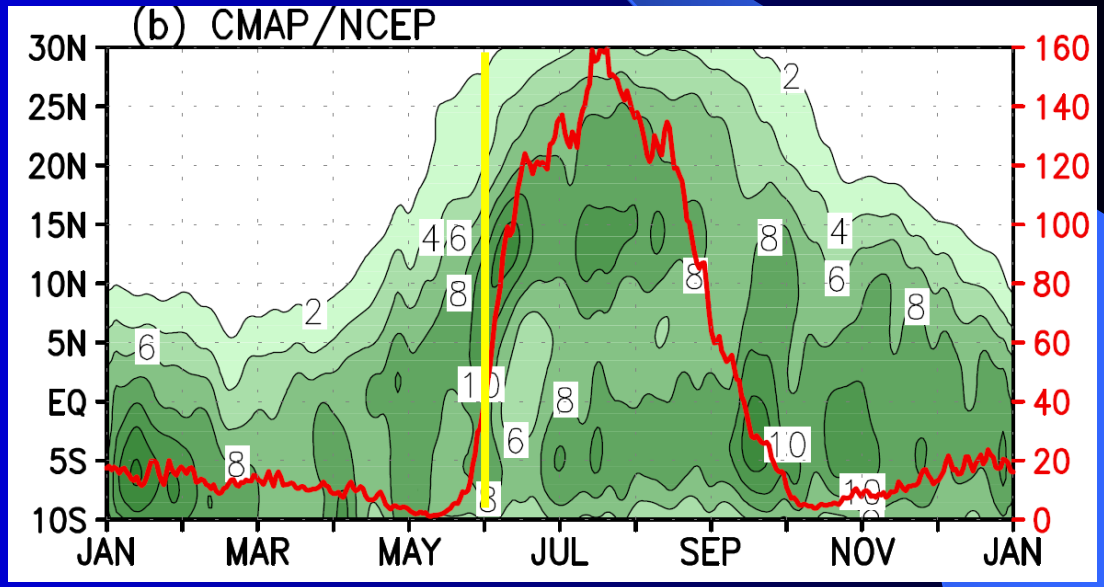


TT (in °C) averaged over 200 hPa- 700 hPa (shaded) averaged between 70E-100E as a function of time and latitude.



Tropospheric temperature averaged between 200 and 600 hPa (TT) averaged between 40E and 100E

CMAP precipitation averaged between 70E and 90E (green) & K.E. at 850 hPa averaged over low level jet region (red line)



Goswami and Xavier 2005, GRL, doi:10.1029/2005GL023216

Events that lead to the Indian summer monsoon 'Onset' (MOK)

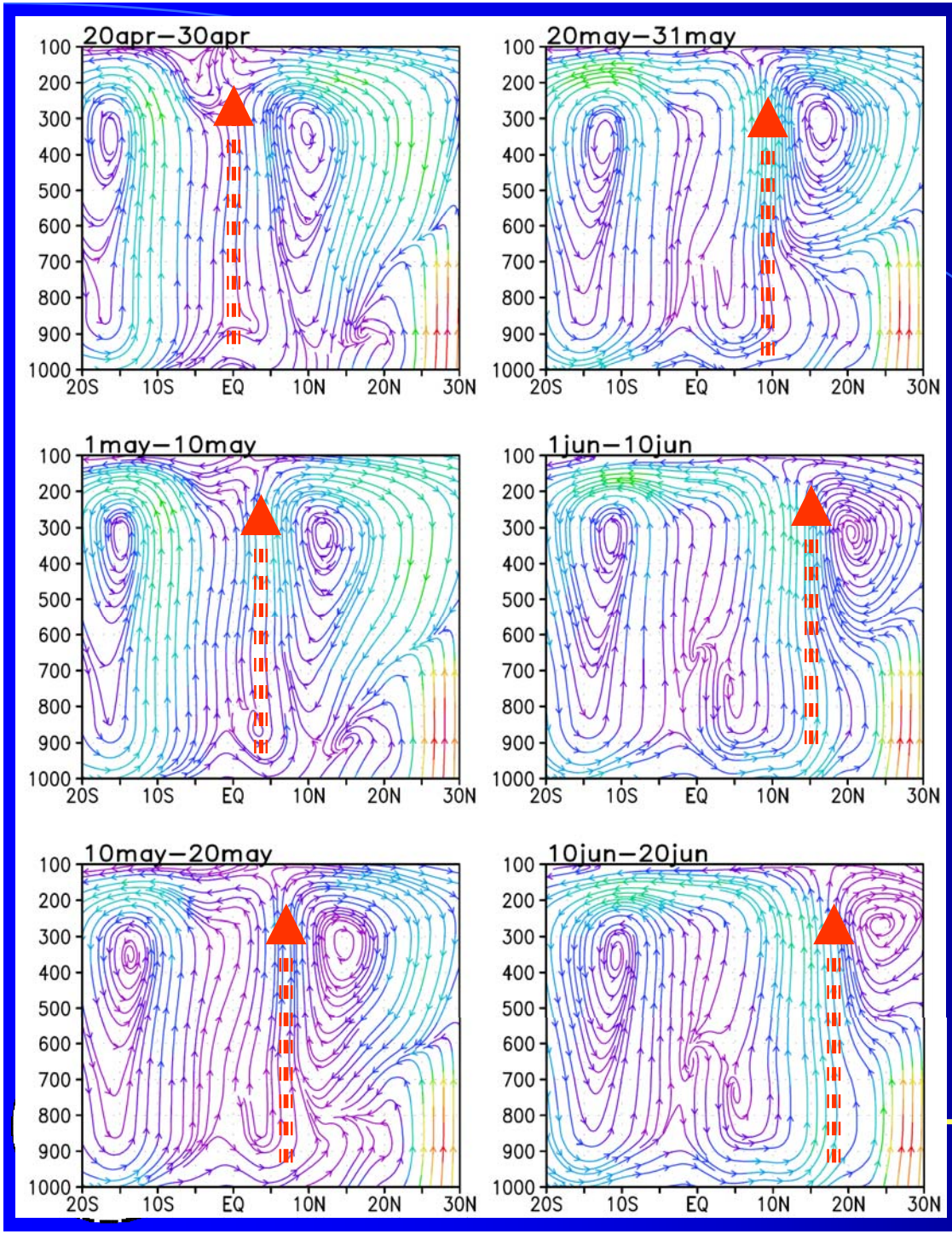
Surface heating (land-ocean contrast) during pre-monsoon season produces cross-equatorial flow near the surface but is capped by subsidence and a southward flow above the PBL. Builds up potential convective instability, but can not be realized.

When tropospheric heating gradient changes sign, primarily due to the influence of the Tibetan Plateau heating, cross equatorial flow and a large scale cyclonic vorticity above the PBL is set up.

Zero absolute vorticity line at 850 hPa moves north to about 5N and conditions for dry symmetric inertial instability as well as conditional moist inertial instability is established.

Dry inertial instability overcomes the inhibition of subsidence, moist inertial instability takes over and explosive organized convection takes place.

Onset has arrived!



Streamlines of climatological mean (omega,V) averaged between 60E-95E, over 10-day periods from mid-April to mid-June.

To note:

1.Northward movement of deep upward motion (TCZ), rapid between last week of May and first week of June.

2.The barrier of massive descending motion is overcome at the time 'Onset'.

3.The shallow meridional circulation during pre-onset takes north warm moist air near the surface and brings south dry air above PBL

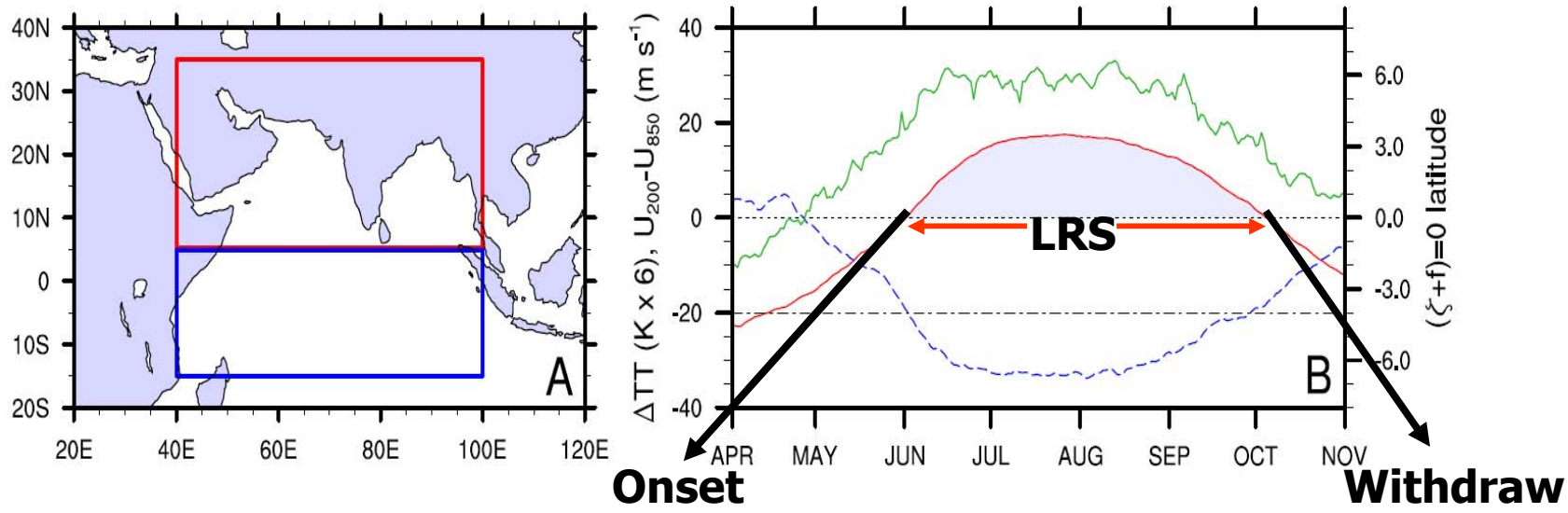


FIGURE 3.3: (A) The area used to define ΔTT. (B) Shows the evolution of climatological values of ΔTT (K×6, solid red line, scale to the left) and the climatological mean vertical shear of zonal winds (U_{200} - U_{850}) averaged over 50°-95°E, 0°-15°N (m s^{-1}, dashed blue line, scale to the left). The latitude of zero absolute vorticity averaged between 50°E and 100°E (solid green line, scale to the right). Shaded area under the ΔTT curve represents the climatological value of TISM (Section 3.1.1).

Green → absolute vorticity (ζ + f) averaged between 50E -100E

Red → Meridional gradient of TT ($\Delta TT = TT_n - TT_s$)

Blue → Vertical shear of zonal wind ($U_{200} - U_{850}$) ave (50E-95E, 0-15N)

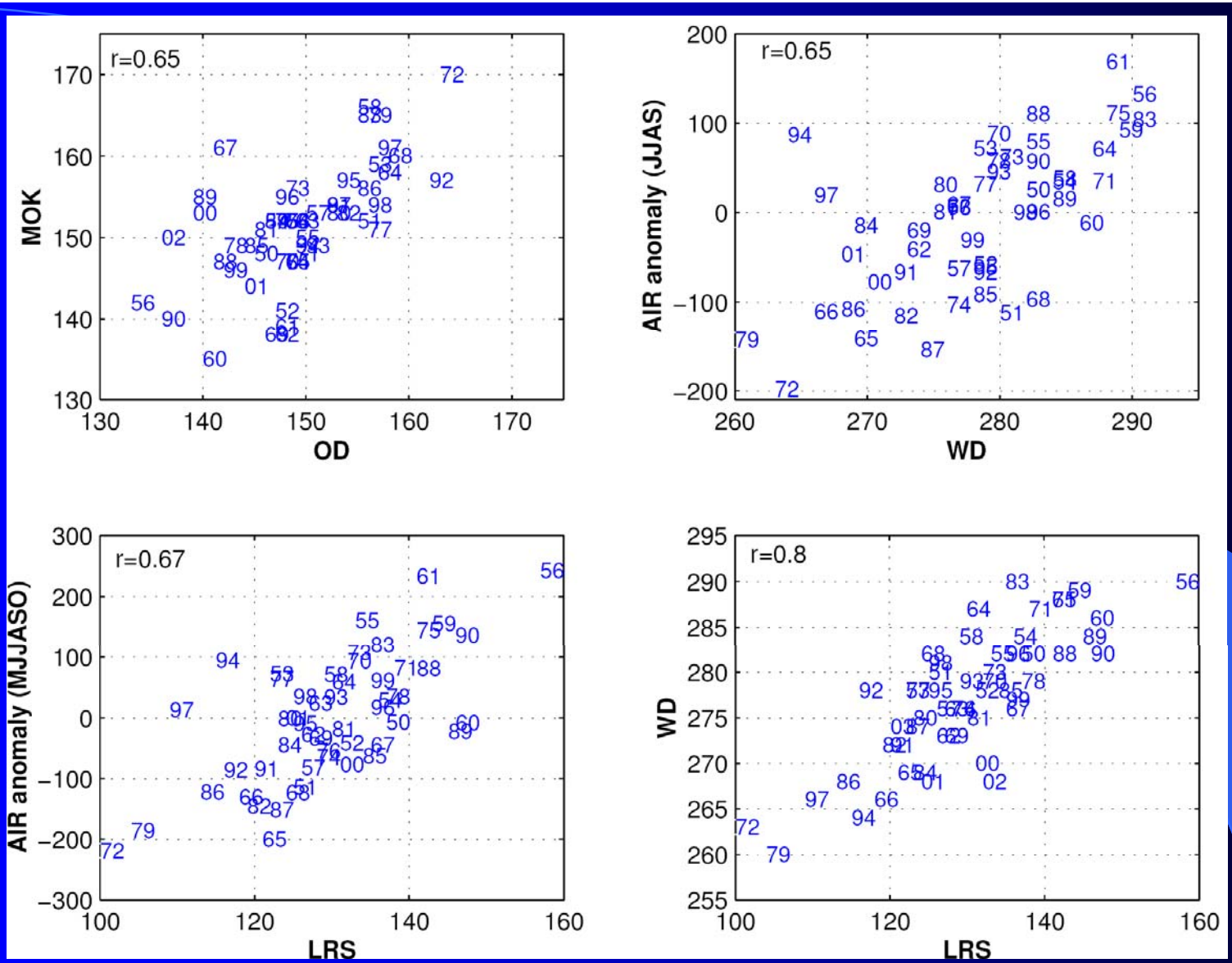
Table 3.1: Statistics of OD, WD, and LRS from NCEP and ERA

	NCEP			ERA		
	OD	WD	LRS (days)	OD	WD	LRS (days)
Earliest/minimum	14 May	16 Sep	98	10 May	20 Sep	105
Latest/maximum	13 Jun	20 Oct	159	10 Jun	18 Oct	159
Mean	30 May	10 Oct	129	26 May	6 Oct	131
S.D. (days)	7	9	12	7	8	11

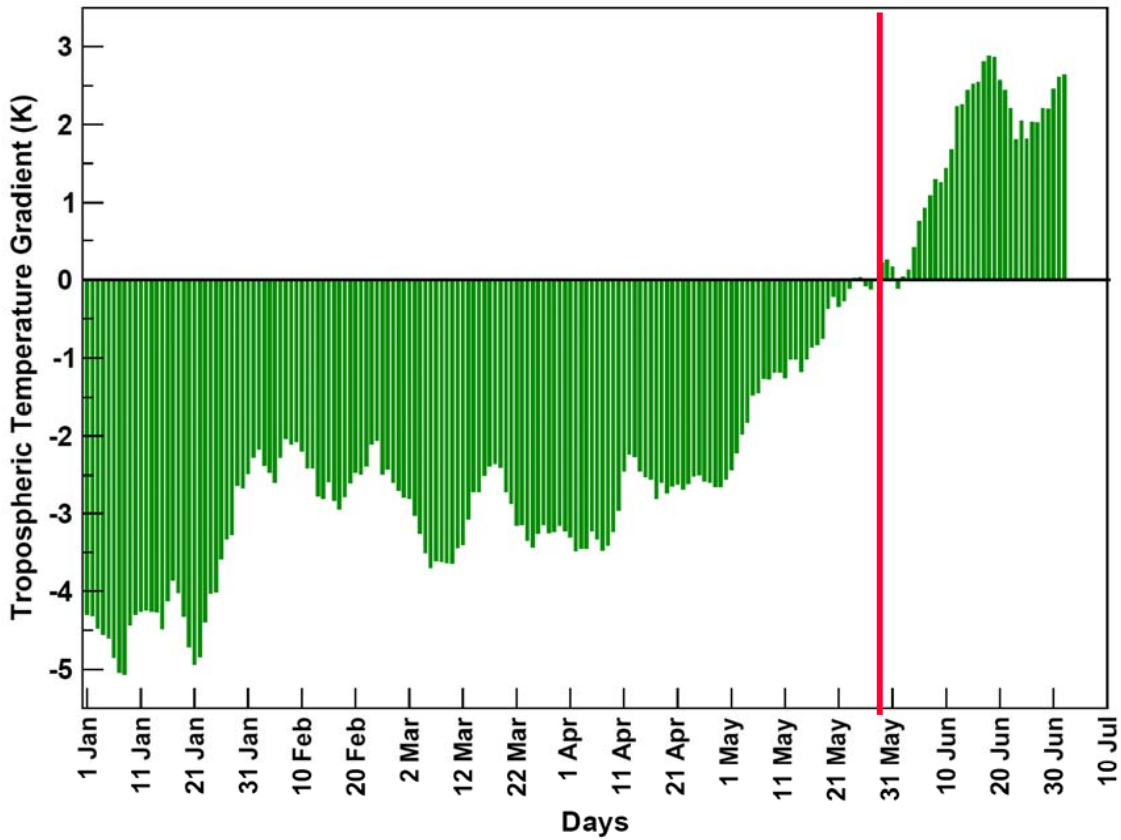
Statistics of Onset dates (OD), withdrawal dates (WD) and length of the rainy season (LRS) in Julian days from NCEP/NCAR reanalysis between 1950-2002.

Climatological mean OD → 30th May

Climatological mean WD→ 10th October


r=0.65
MOK
OD
r=0.65
AIR anomaly (JJAS)
WD
r=0.67
AIR anomaly (MJJASO)
LRS
r=0.8
WD
LRS

TT Gradient during 2008 so far



TT gradient has slightly changed sign from negative to positive on 23rd May. But after two days, it has again gone to negative side. The data is up to 1st July. On 28th May, again TT gradient has become positive, became negative on 31st May. 1st June onwards, it is in the positive side.

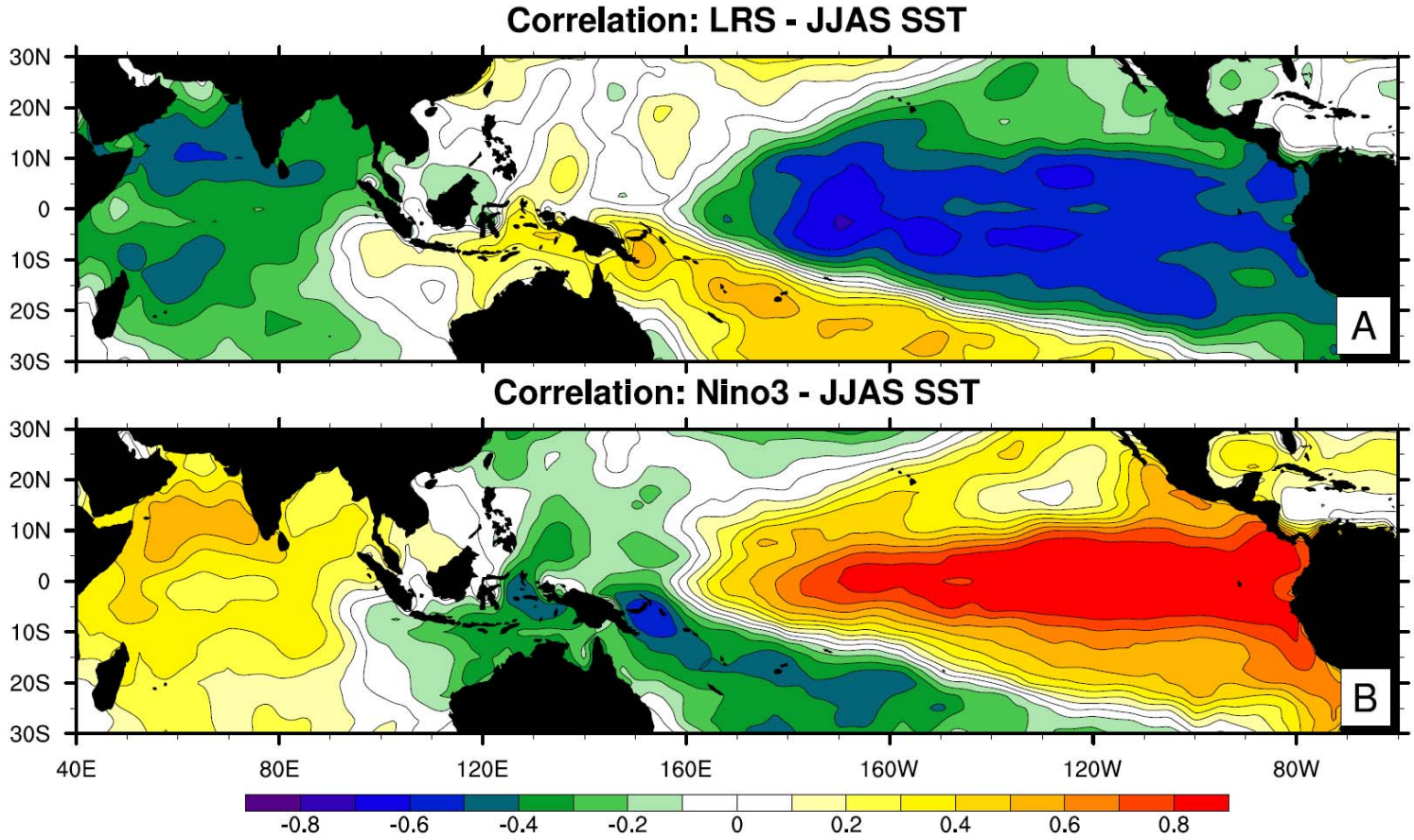
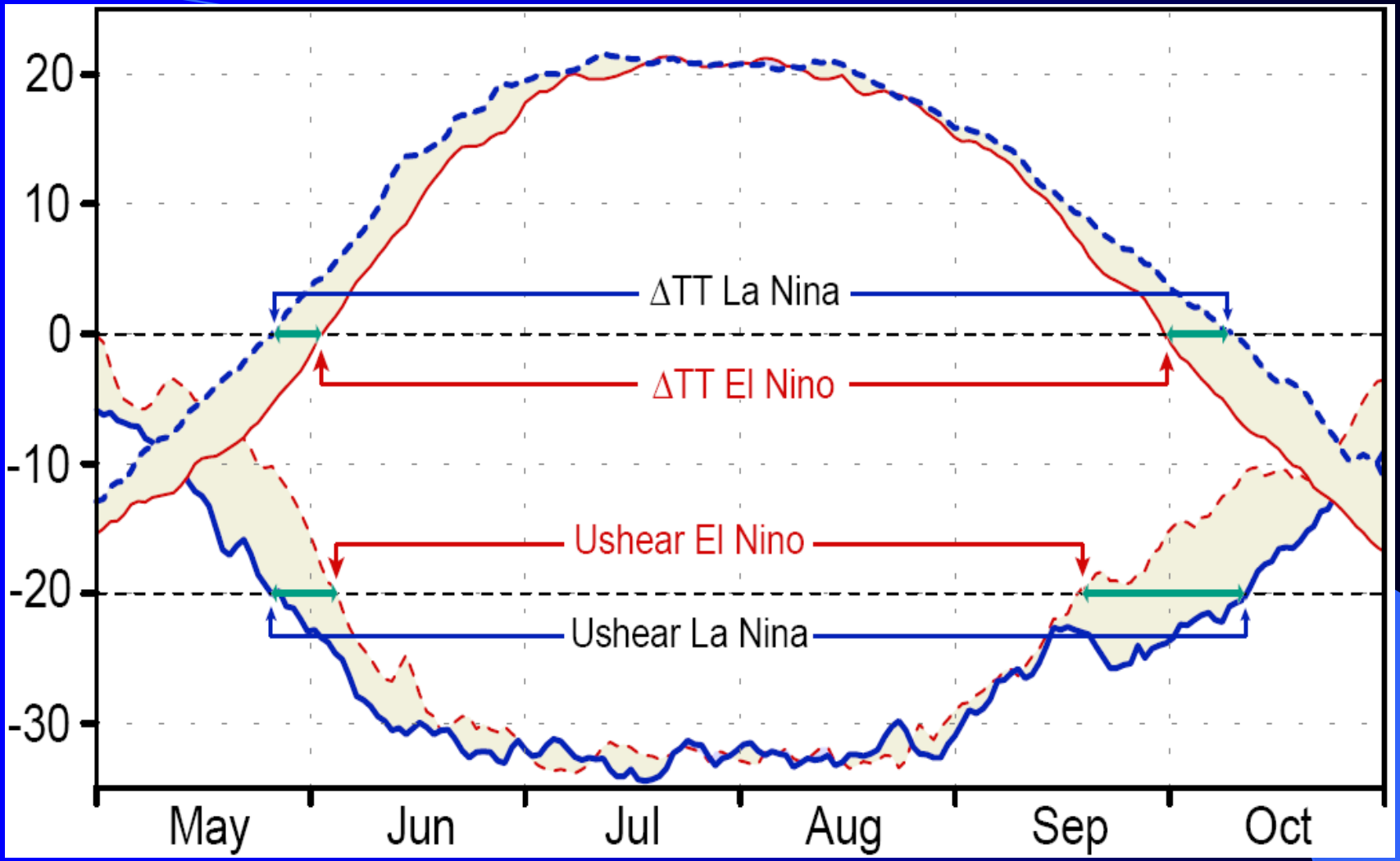


FIGURE 3.8: Correlation coefficient of June-September SST anomalies at every grid box with (A) LRS and (B) with Niño 3 SST anomalies, based on data between 1950 and 2003.



EL Nino and La Nina Composite of ΔTT and Ushear

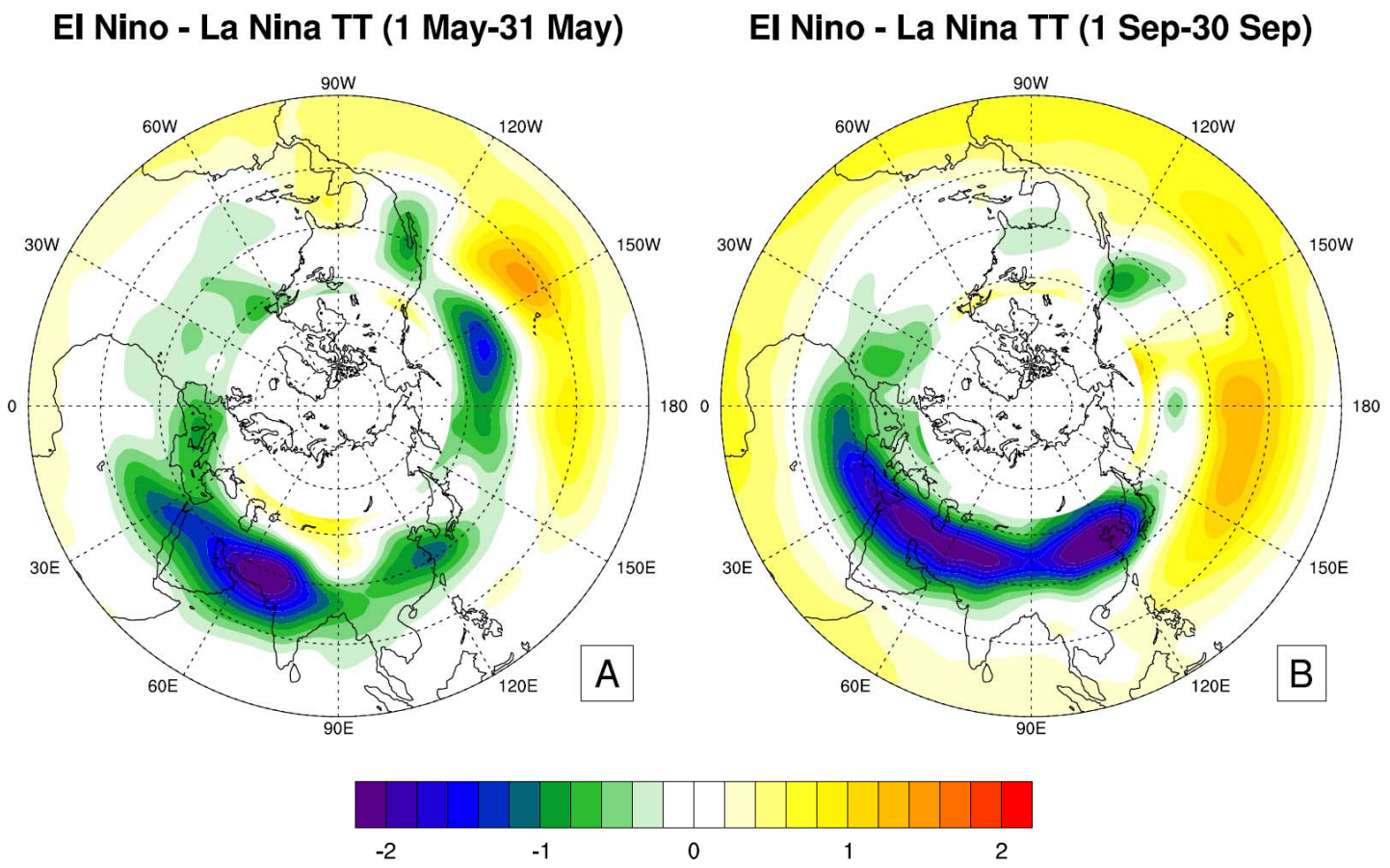
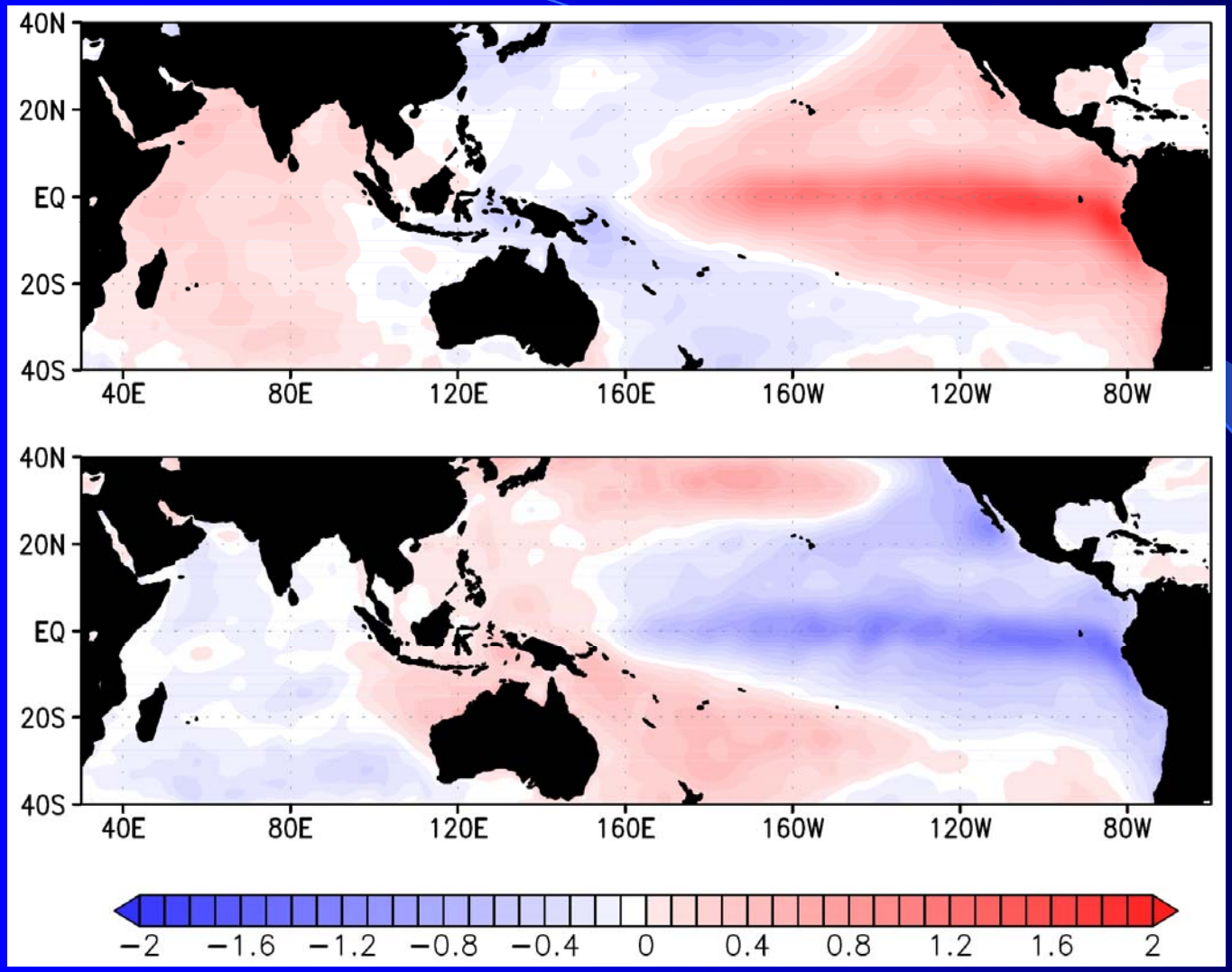


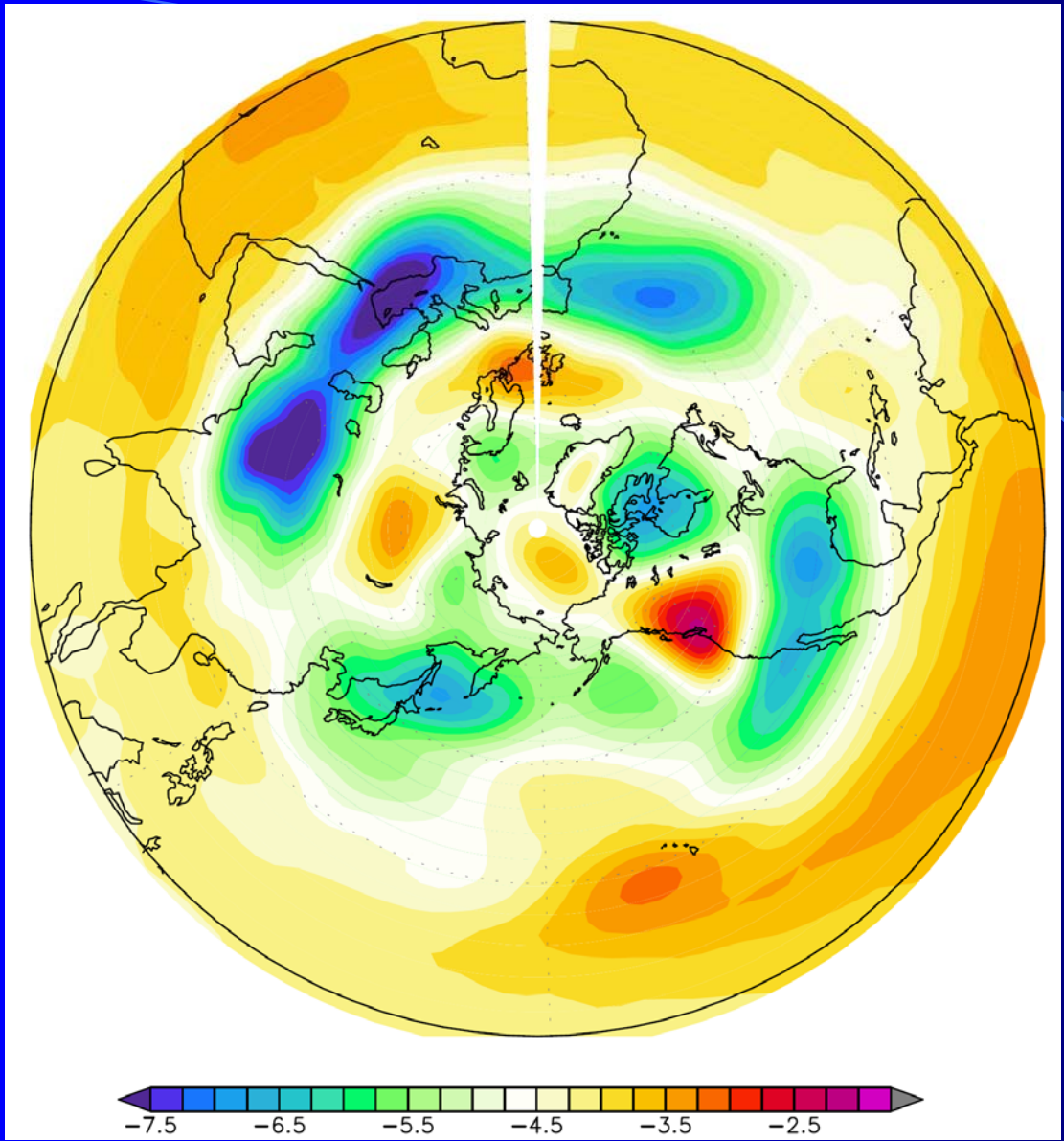
FIGURE 3.9: El Niño minus La Niña composites of TT (K) averaged between (A) 1 May and 31 May and (B) 1 September and 30 September. These are based on 11 El Niño (10 La Niña) years defined using normalized Niño3 SST anomalies being > 1 (< -1).

Composite SST anomalies (JJAS)



El Nino

La Nina



AGCM simulation to understand the extra-tropical teleconnection rout for ENSO-monsoon connection

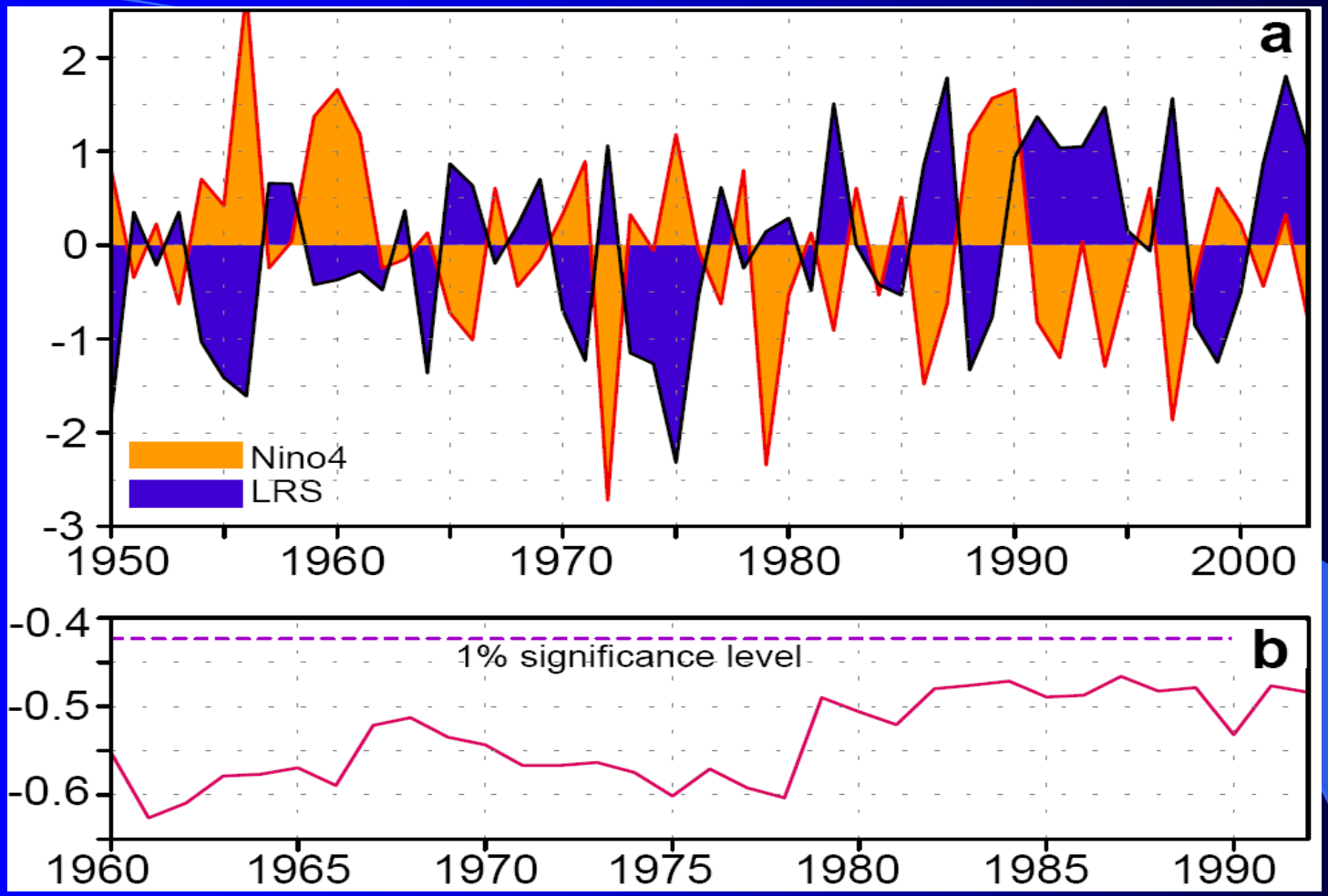
TT averaged between 15 May and 15 June simulated by an AGCM forced by composite El Nino SST minus 'control' forced by climatological SST

How does the ENSO SST controls the LRS?

During positive ENSO phase (El Nino), SST results in positive P anom over central and eastern Pacific and negative P anom over western Pacific and maritime continent.

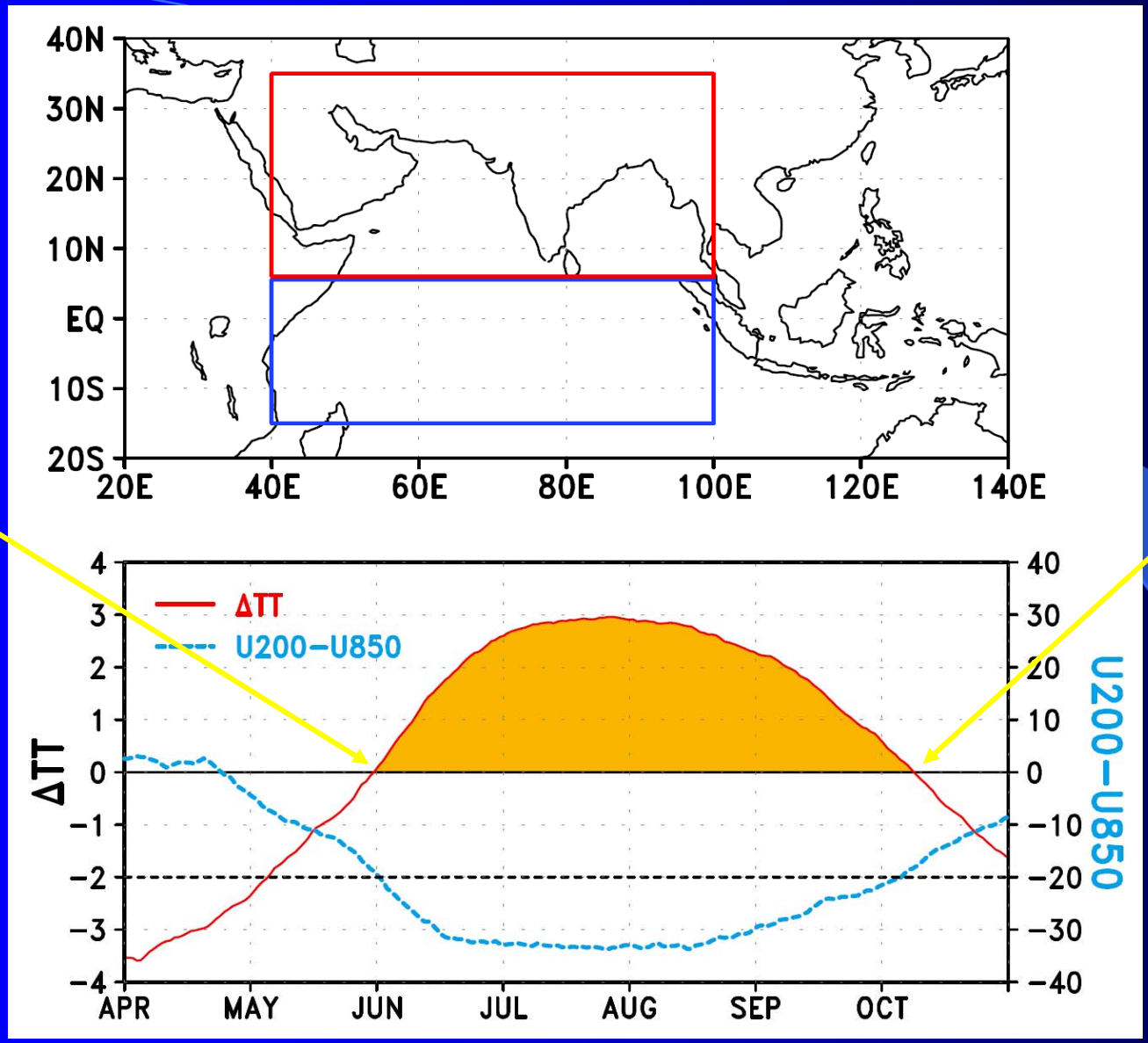
Quasi-stationary response to these heat sources leads to persistent negative (positive) TT anomaly over northern India /southern Eurasia during El Nino (La Nina)

Results in delayed Onset and early Withdrawal, reduced LRS during El Nino and opposite during La Nina!



(a)Normalized Time series of LRS and JJAS Nino4 SSTA

(b) 21-year sliding window correlation between LRS and JJAS Nino4 SST



Onset

Withdraw

A new large scale (thermodynamic) index of Indian summer monsoon (TISM)

TISM = Area under the positive ΔTT

TABLE 2. CORRELATIONS BETWEEN TISM, AIR FOR THE JJAS AND LRS PERIODS, AND LRS

	TISM	JJAS AIR	LRS AIR	LRS
TISM	1	0.67	0.75	0.73
JJAS AIR		1	0.94	0.49
LRS AIR			1	0.71
LRS				1

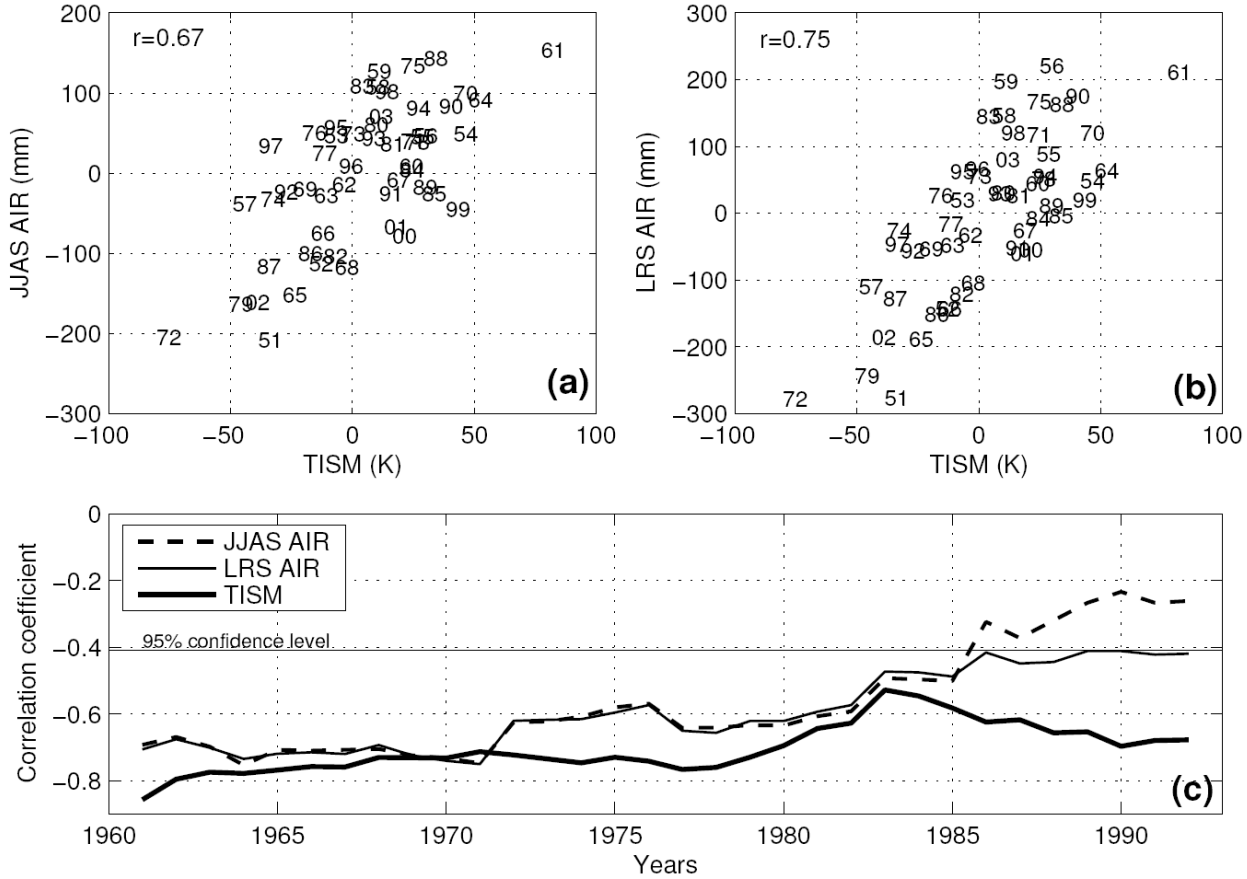
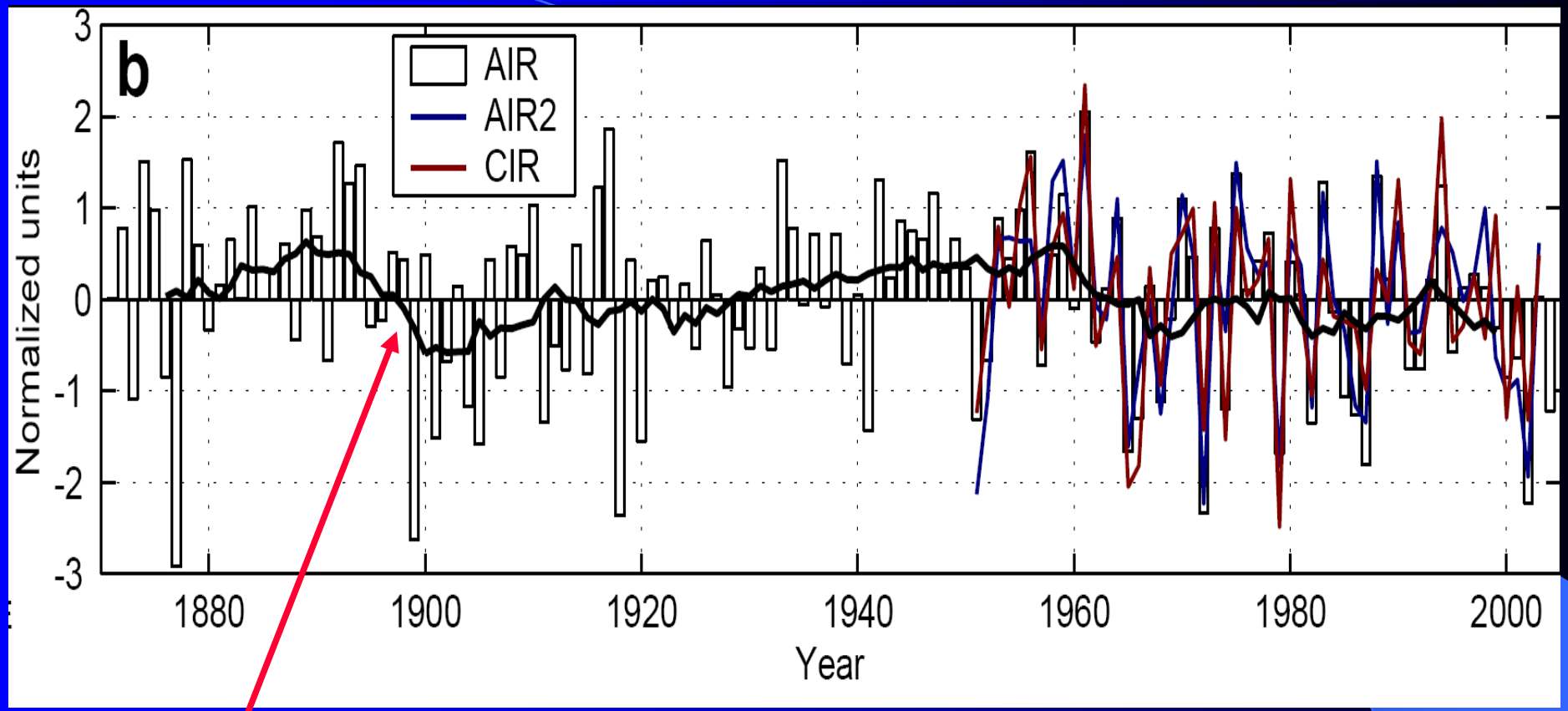


Figure 8. Scatter plot of TISM with (a) the anomalies of total AIR for JJAS season and (b) with the anomalies of total AIR for the LRS period. Points are represented with last two digits of the years. Correlations between the two are shown in the respective panels. (c) 21-year running window correlation between JJAS Niño3 SST anomalies and the anomalies of total AIR for JJAS season, anomalies of total AIR for the LRS period and TISM.

- Thus, in reality the ENSO-Monsoon connection has not weakened in recent times! The observed weakening of 'correlation' is essentially an artifact of defining monsoon season rainfall over a 'fixed' period.
- Our 'out-of-the-box' approach to define the rainy season led to the new 'thermodynamic index of Indian summer monsoon' (TISM) and provides a way of extracting the predictable component of the monsoon, a long standing need!
- Another spin off from our new approach. There are strong evidence that Indian monsoon and North Atlantic are strongly related in interdecadal, centennial and millennium time scales. Our work, for the first time provides a physical mechanism for this linkage.

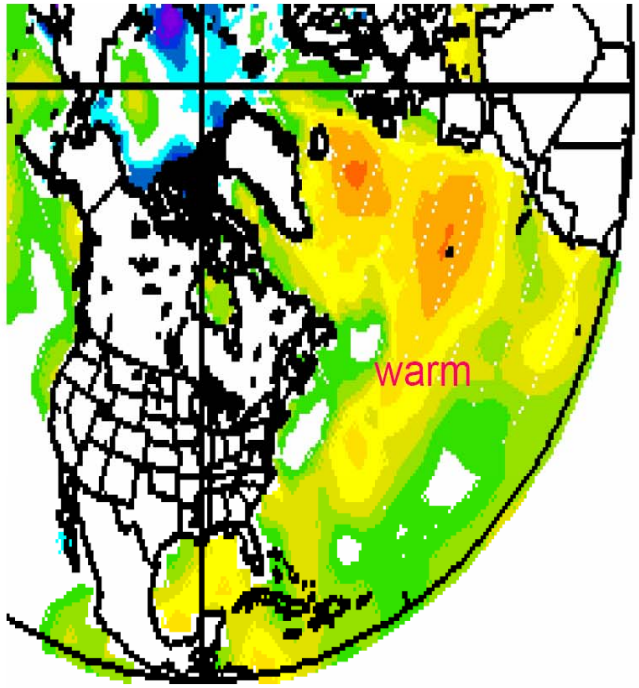


Interdecadal variations of Indian summer monsoon

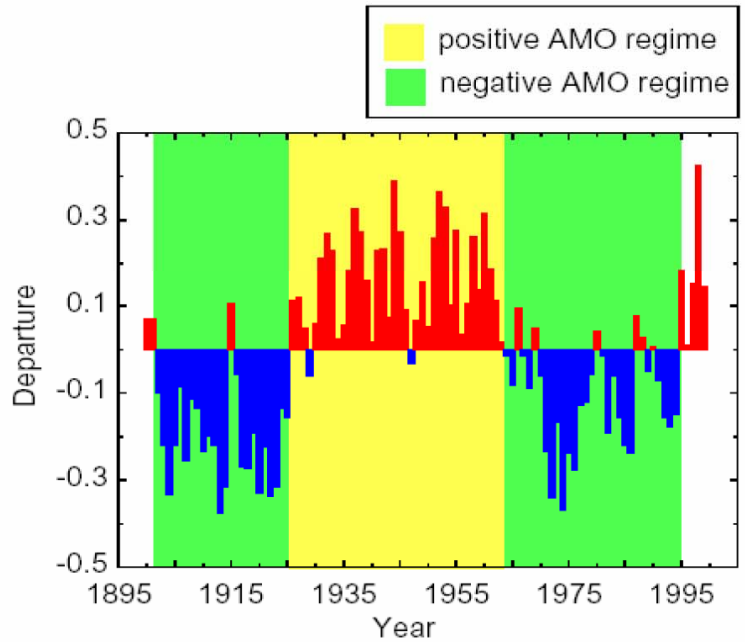
Atlantic Multi-Decadal Oscillation - AMO

Positive AMO Phase

Sea-surface Temperatures



AMO is an index of decadal variability in the North Atlantic Ocean.



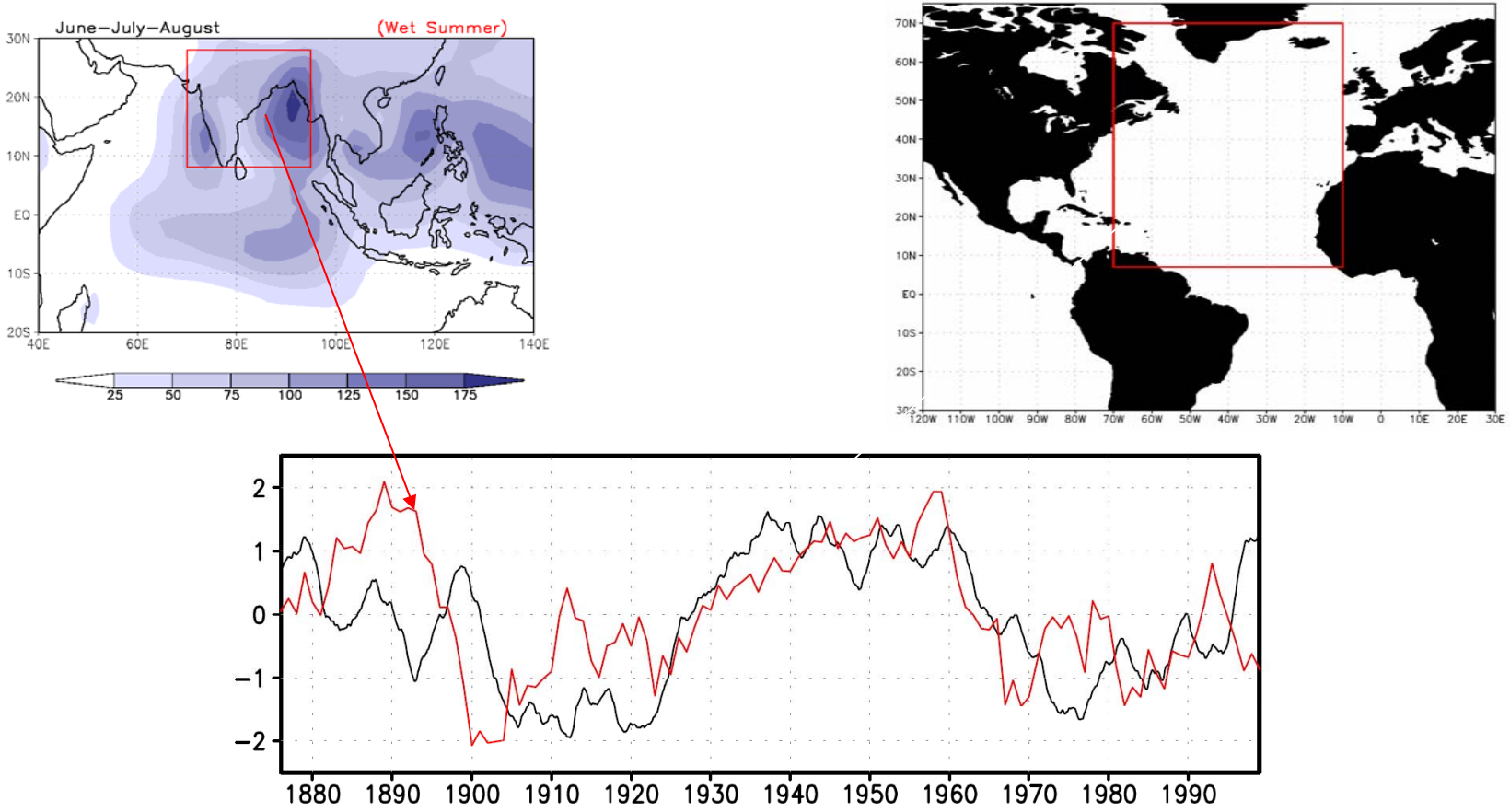


Figure 7: Multidecadal oscillation of AIR (red line, obtained from 11-yr running mean of JJAS mean all India rainfall) and Atlantic multidecadal oscillation (AMO, black line). AMO is based on 60-month running mean of monthly anomalies averaged over Atlantic north of Equator.

- Coupled model simulations (Delworth and Mann, 2000, Climate Dynamics, vol.16, 661-676) indicate that AMO may be a natural oscillation of the coupled ocean-atmosphere system.

- Close association between AMO and interdecadal monsoon variability indicates that the monsoon interdecadal variability is also due to the coupled oscillation.

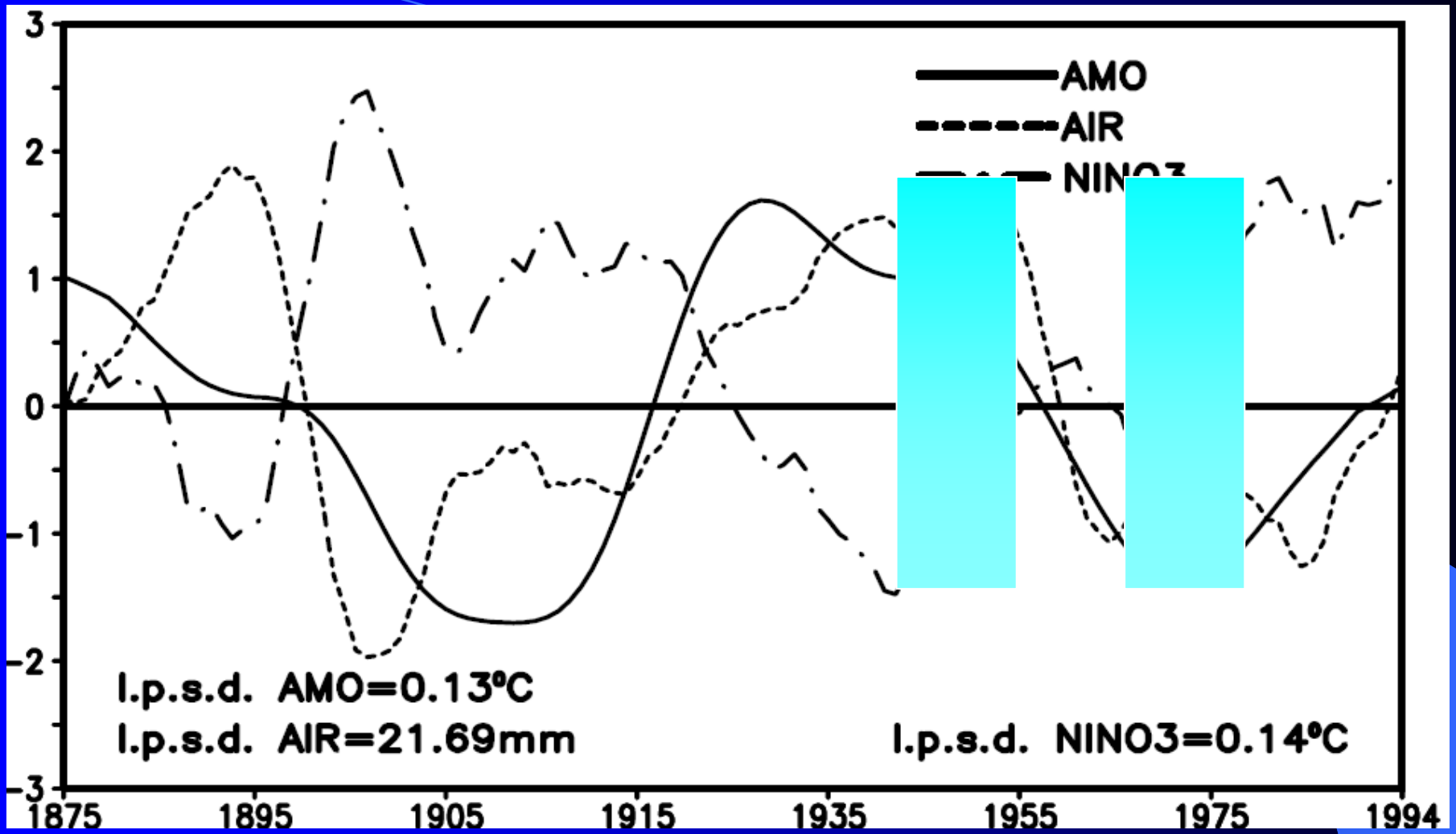
→ High potential predictability of the monsoon interdecadal swings

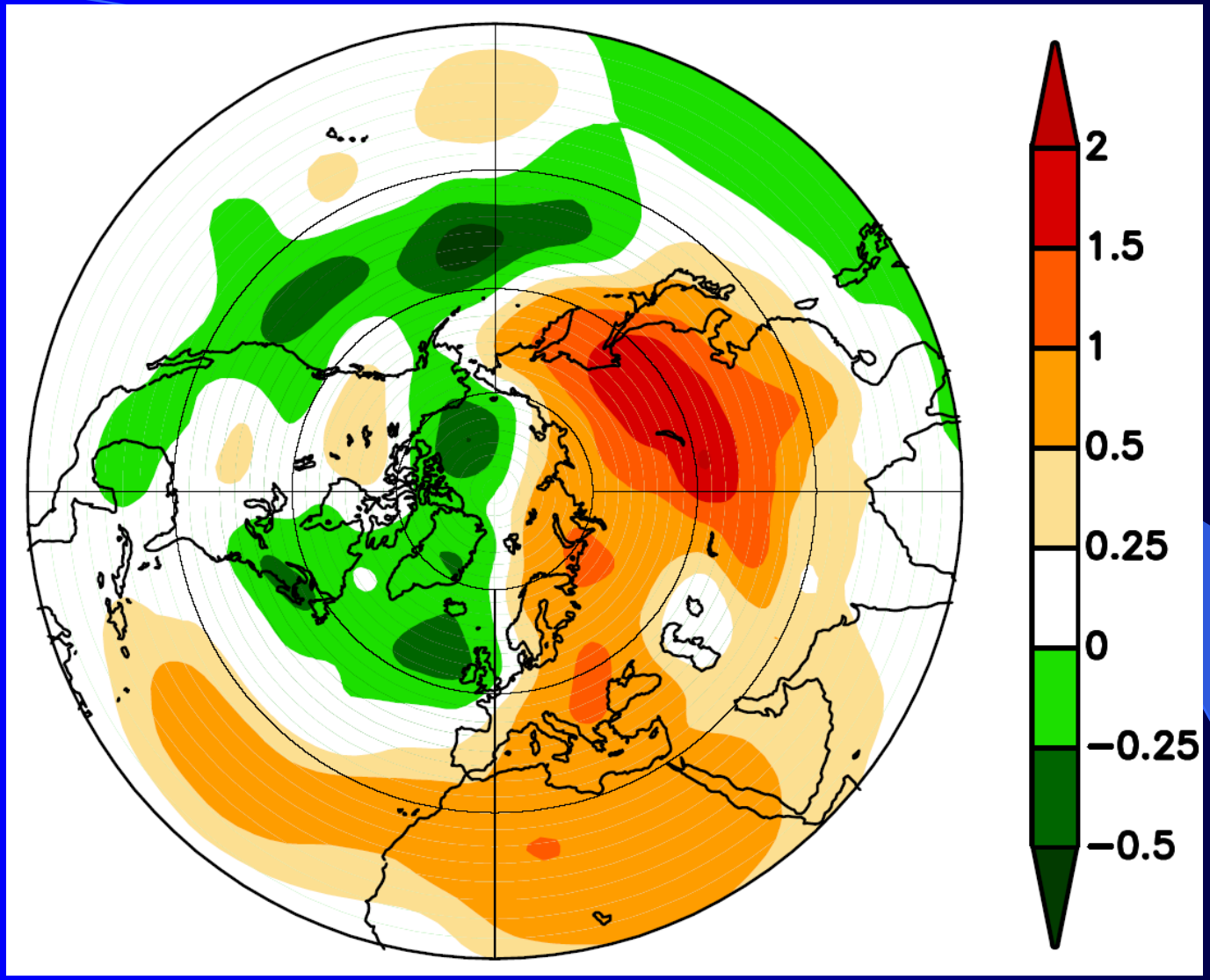
Question:

How does AMO influences Indian monsoon?

To understand this, we must look for an extra-tropical teleconnection mechanism between Atlantic and monsoon.

Could AMO influence monsoon by introducing persistent TT anomaly over Eurasia?


AMO
AIR
NINO3
l.p.s.d. AMO=0.13°C
l.p.s.d. AIR=21.69mm
l.p.s.d. NINO3=0.14°C
3
2
1
0
-1
-2
-3
1875
1895
1905
1915
1935
1955
1975
1994



Difference of JJAS TT between 11 warm AMO years and 11 cold AMO years between 1948 and 2003 using NCEP reanalysis.

+ (-) AMO induces persistent + (-) TT anomaly over Eurasia

→ Increase (decrease) Meridional gradient of TT

→ Strong (weak) Indian summer monsoon

Question:

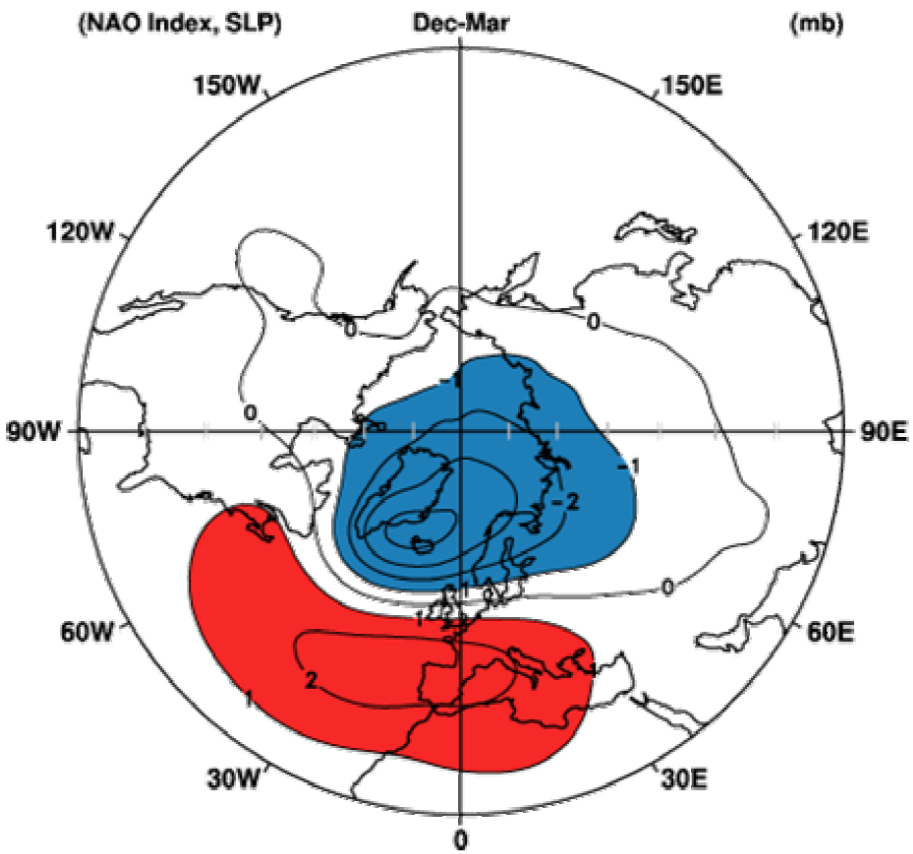
How does the AMO induces persistent TT anomalies over Eurasia

Hypothesis:

Through modulation of frequency of strong + (-) NAO events!

What is the North Atlantic Oscillation (NAO)?

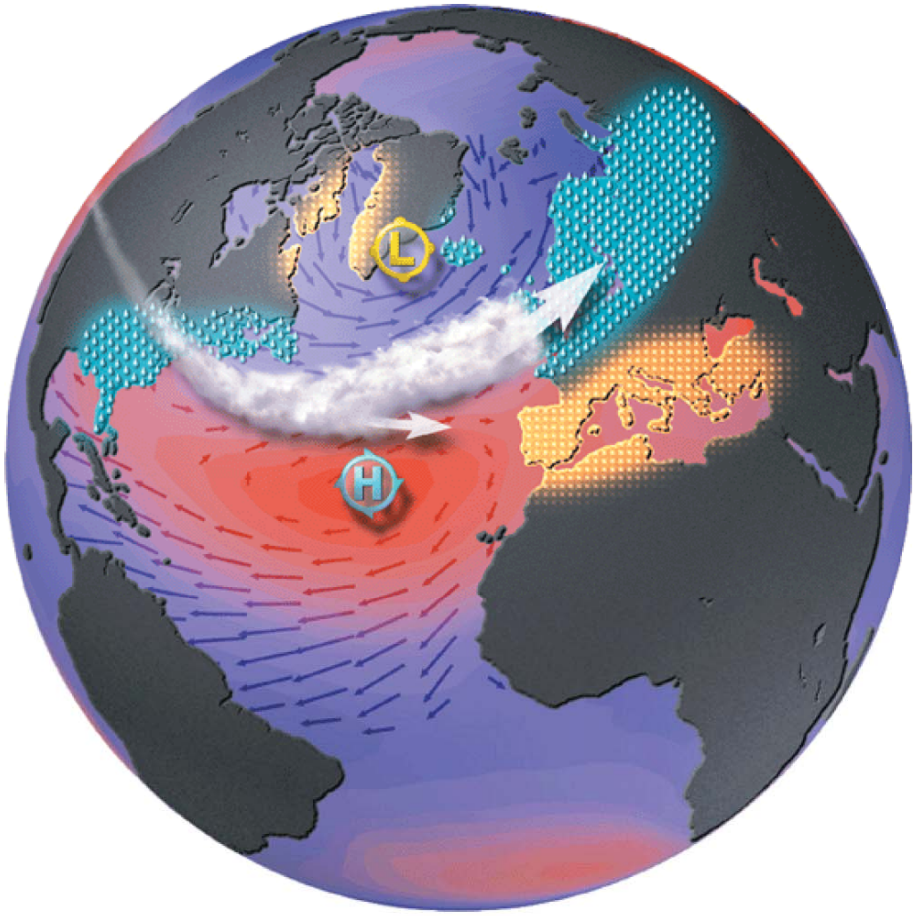
- Is a sea-saw of atmospheric mass which alternates between the polar and subtropical regions
- Is the most prominent and recurrent pattern of atmospheric variability over the middle and high latitudes of the Northern Hemisphere
- Is most noticeable during the winter seasons



©Hurrell

The positive NAO-Index phase

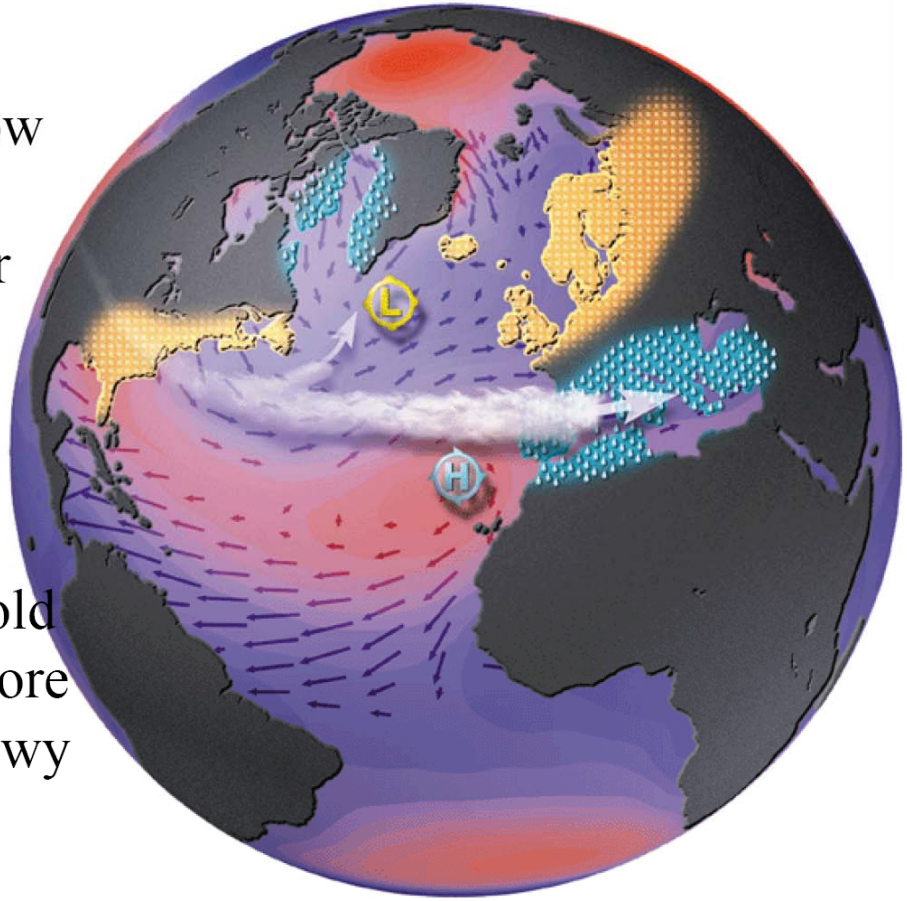
- Is characterized by a stronger subtropical high and a deeper Icelandic low than usual
- The increased pressure gradient results in more frequent and stronger winter storms crossing the Atlantic on a more northerly track
- This leads to warm and wet winters in Europe and cold and dry winters in Canada and Greenland



©Visbeck

The negative NAO-Index phase

- Is characterized by a weak subtropical high and Icelandic low
- The reduced pressure gradient leads to fewer and weaker winter storms crossing the Atlantic on a more west-east track
- The storms bring moist air into the Mediterranean
- Northern Europe experiences cold weather and the US east coast more cold air outbreaks and hence snowy conditions

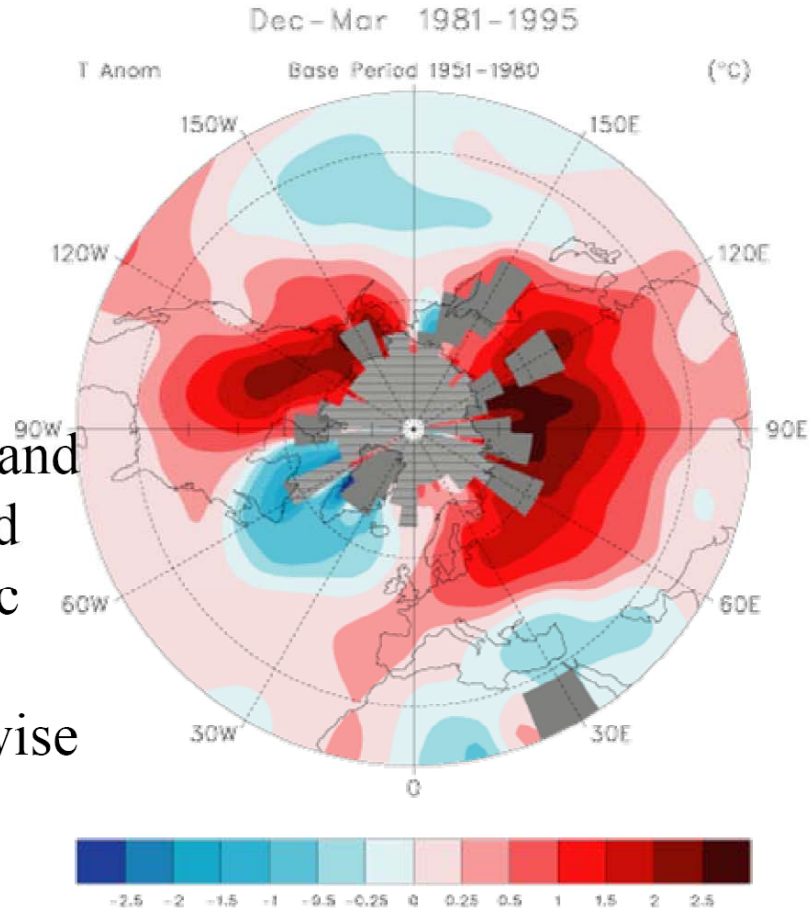


©Visbeck

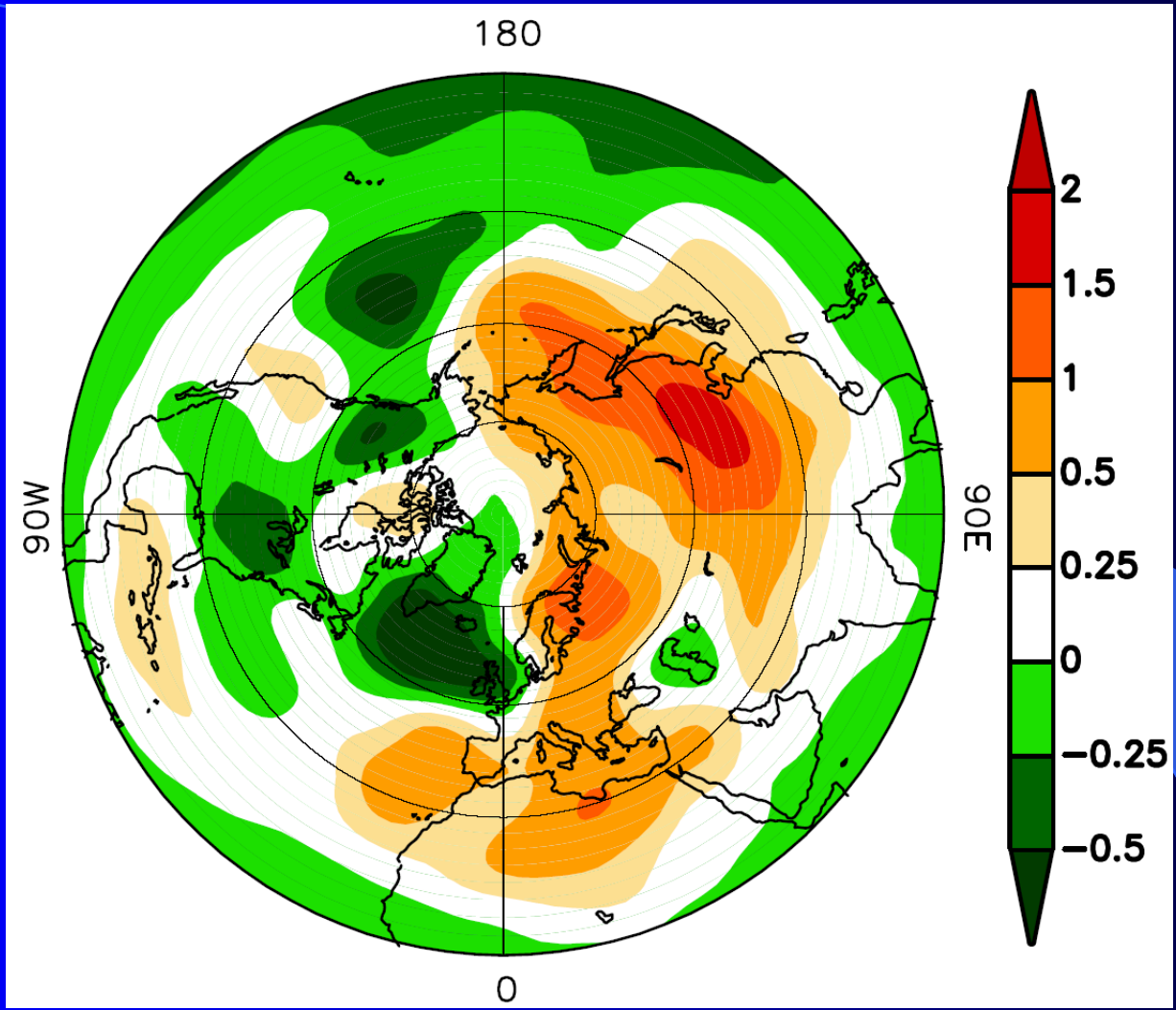
Impacts of the NAO: Temperature

Positive NAO index:

- Enhanced westerly winds move relatively warm maritime air over Eurasia
- Stronger northerly winds over north-eastern Canada and Greenland decrease the land temperature and SSTs over the north-west Atlantic
- Warming over North America associated with a stronger clockwise flow around the subtropical high

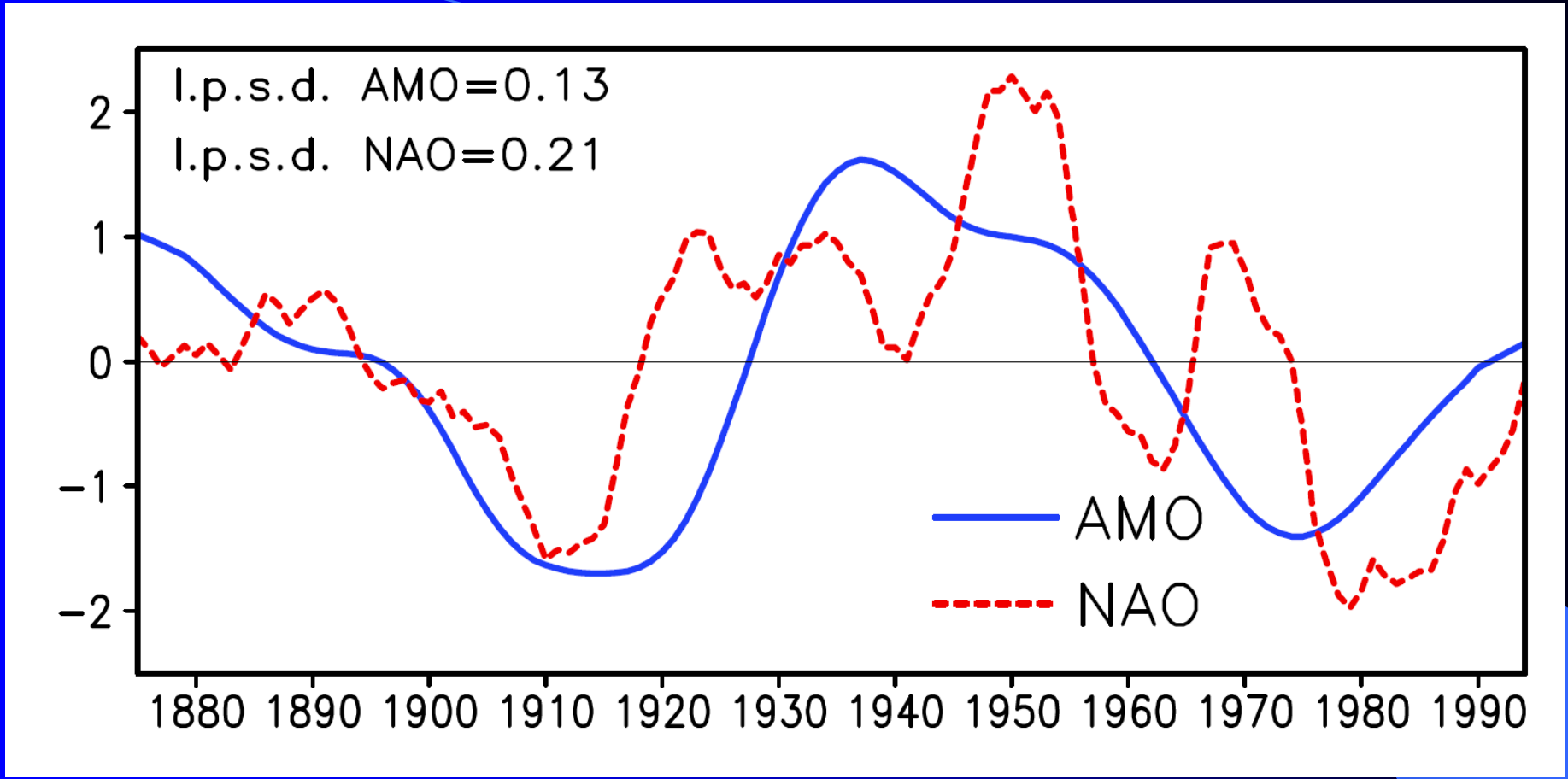


©Hurrell



Difference between strong +ve NAO and –ve NAO Composite July-Aug-Sept. TT.

>1.25 (<-1.25) normalized JJAS NAO used to define Strong +ve (-ve) NAO events



Low-pass filtered AMO and summer NAO Index. AMO indeed modulates the summer NAO.

+ (-) AMO phases of NA SST

Higher frequency of Strong + (-) NAO events

Changes in the Jet stream and storm tracks

Persistent + (-) TT anomaly over N. India and S. Eurasia

Persistent increase (decrease) Meridional gradient of TT over monsoon region.

Strong (weak) Indian summer monsoon

Paleo evidence of connection between NA and Indian monsoon

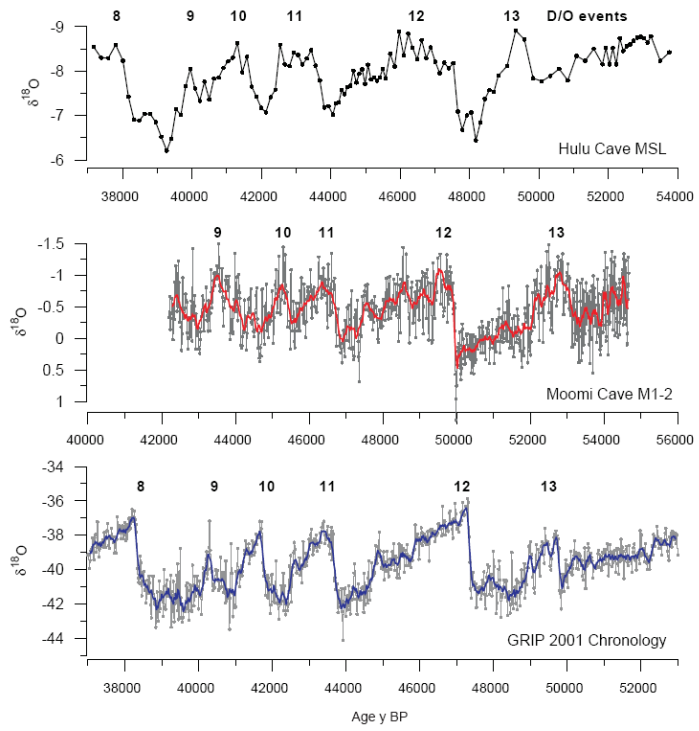
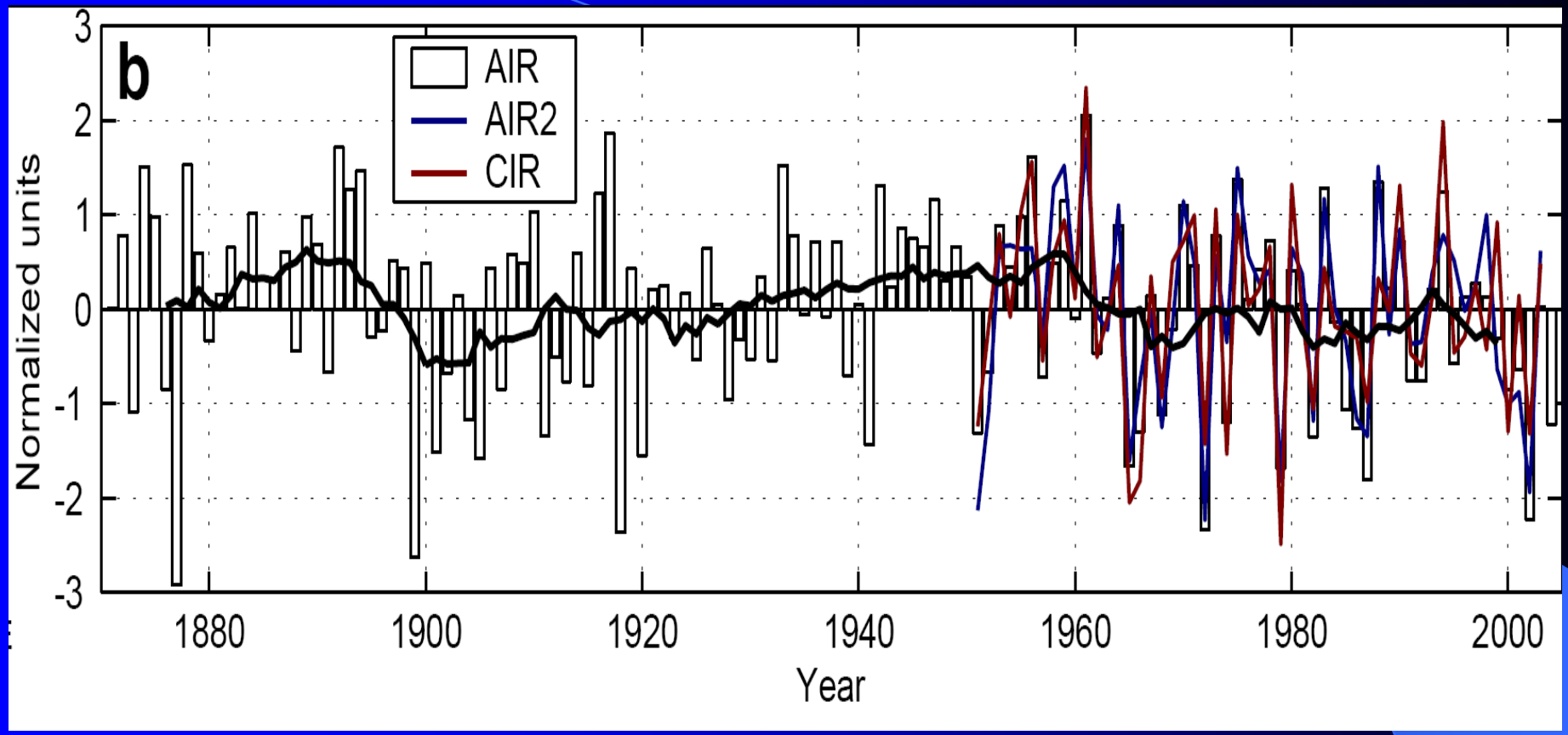
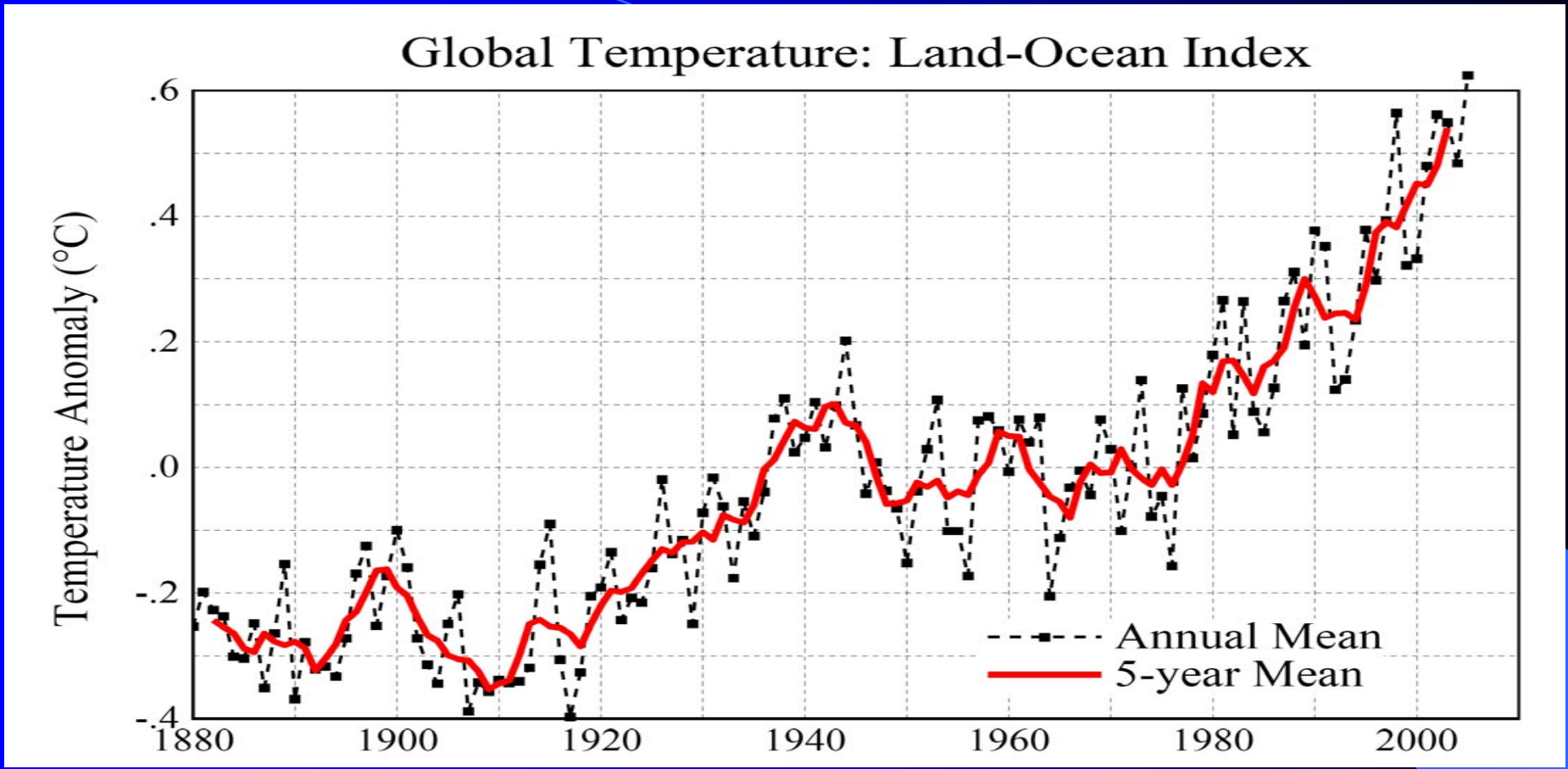


Figure 4: Comparison of the oxygen-isotope ratios of stalagmite M1-2 (at Socotra 54°E,12°,30'N) with oxygen isotope from the GRIP ice core (2)and the $\delta^{18}O$ record of a stalagmite from Hulu Cave in central China (4).The time scales are independent and shifted to give the best fit for D/O events.The oxygen isotopic scales for the stalagmite records are reversed.The locations of D/O events 9 through 13 as identified in each record are also shown.

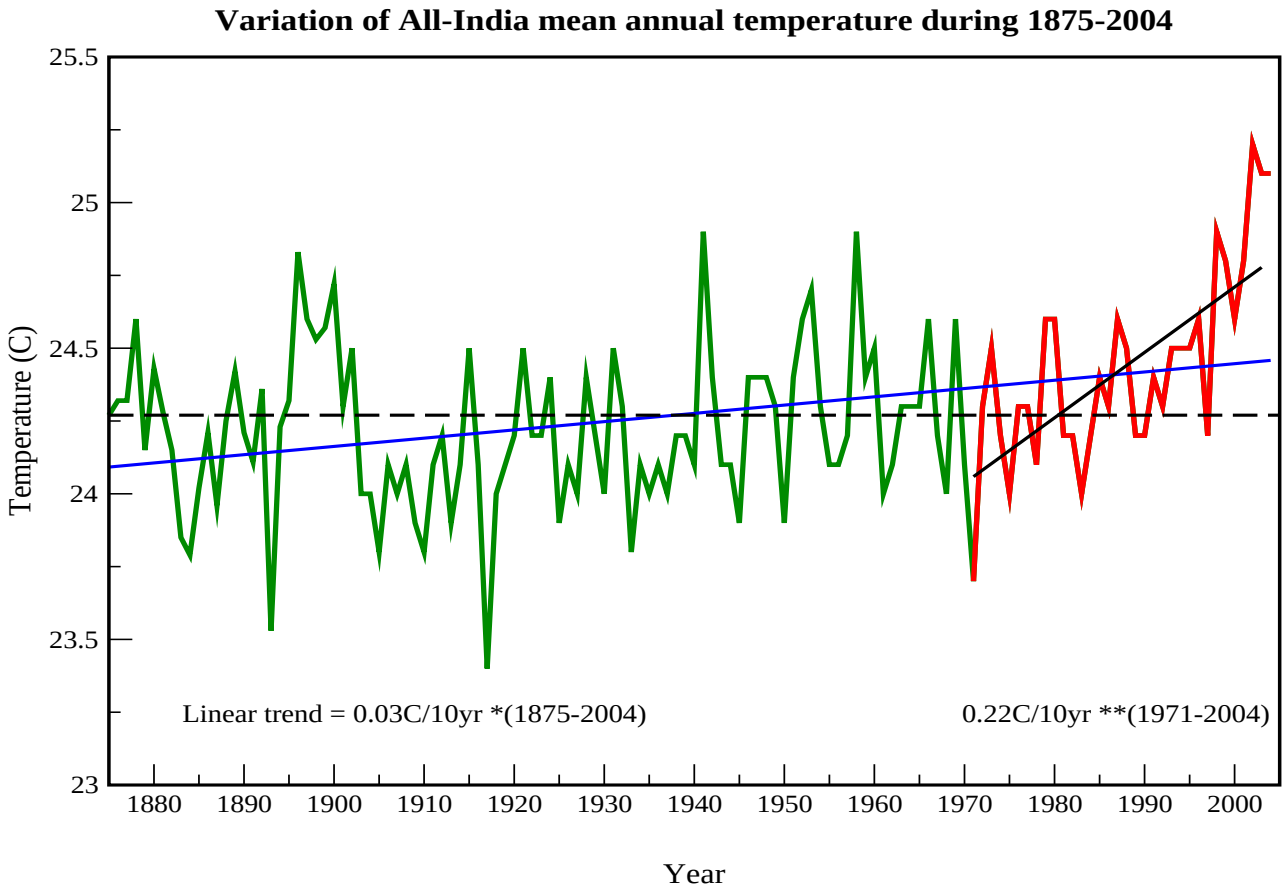
Burns et al. , 2003, Science, 301,1365-1368



Indian summer monsoon has remained stable in the backdrop of an warming environment with no increasing trend!



Updated from Hansen et al. 2001, JGR,106, 23947



Trend in temp. is similar to global temp. trend.
Much faster during past 50 years

Rise in air temperature → Increased moisture in atmos.

Increased moisture in the Atmosphere

↓

Convectively more unstable atmos.

Increased frequency of extreme events

↓

Increase in mean rainfall

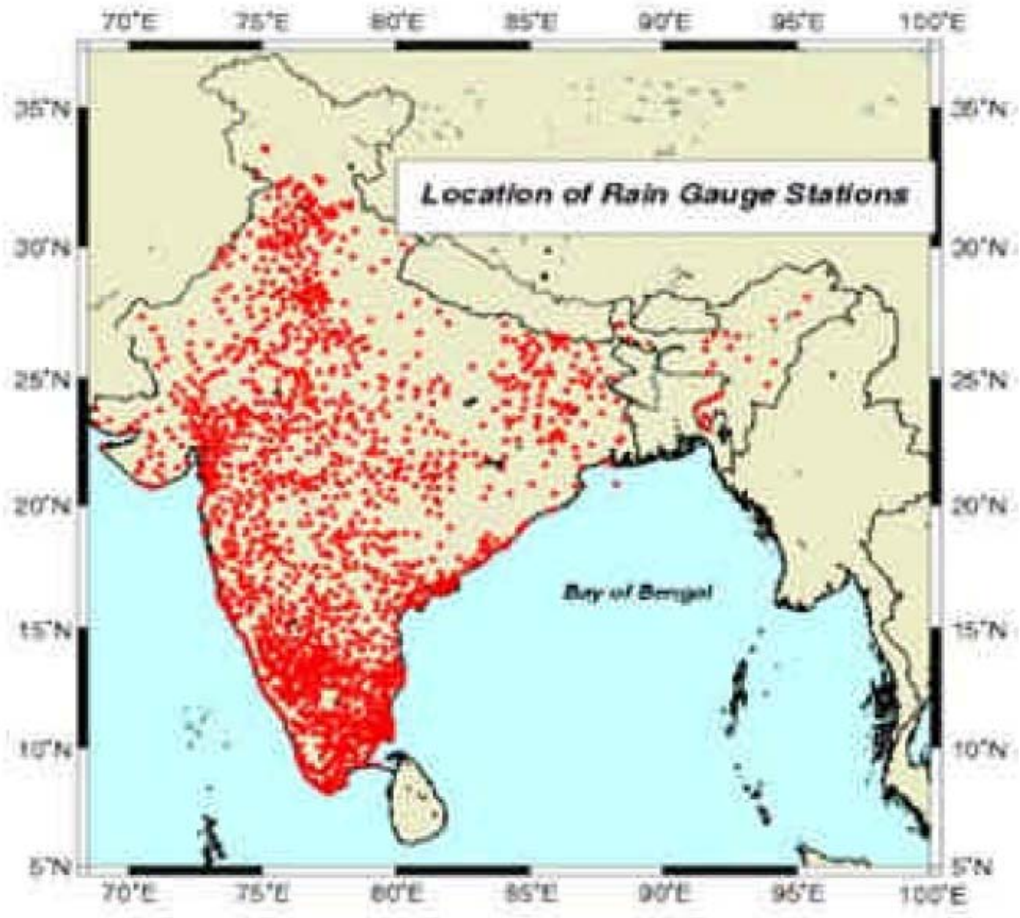


Figure 1. Location of 1803 rain gauge stations.

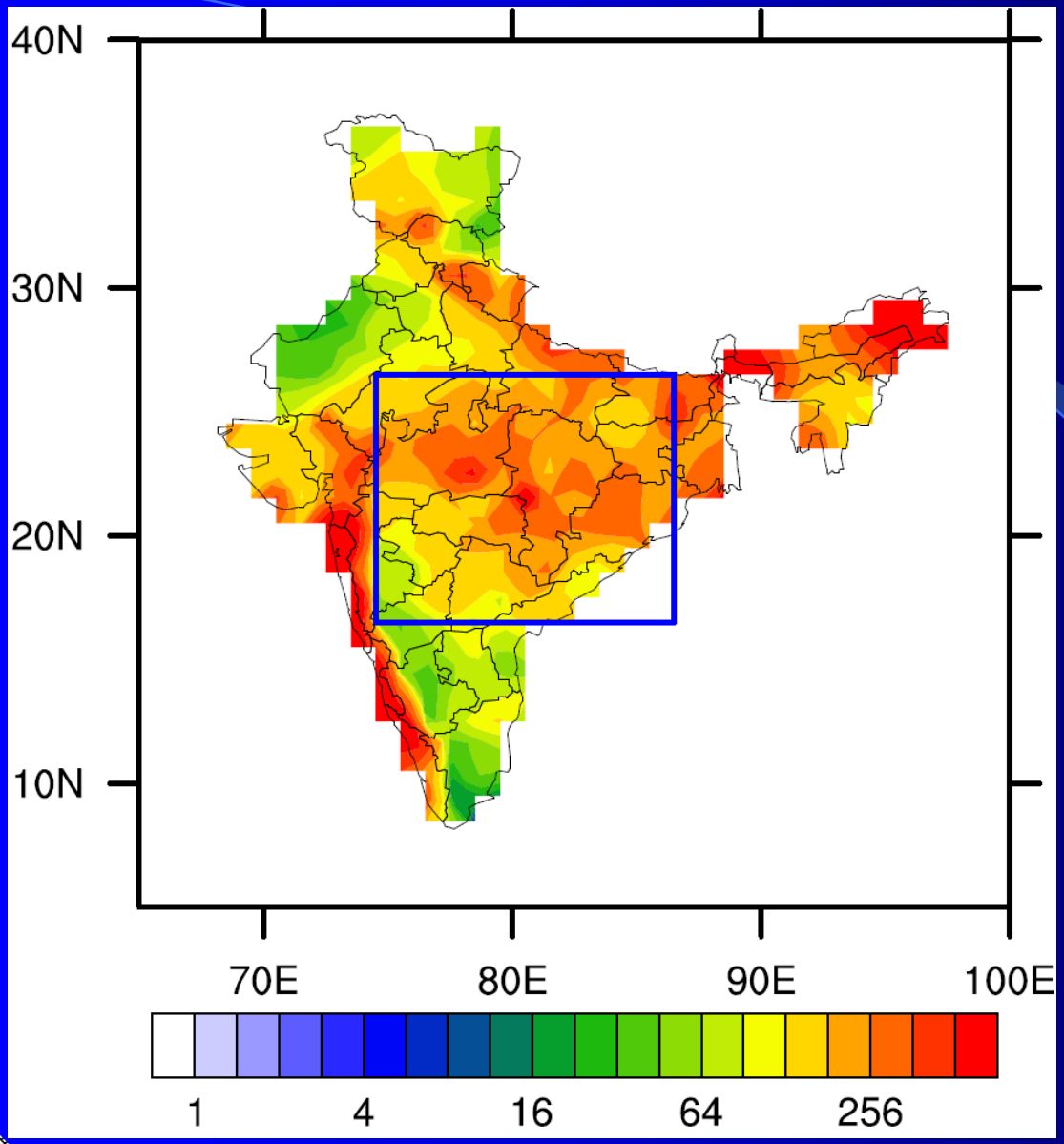
CURRENT SCIENCE, VOL. 91, NO. 3, 10 AUGUST 2006

High resolution daily rainfall

1803 stations used

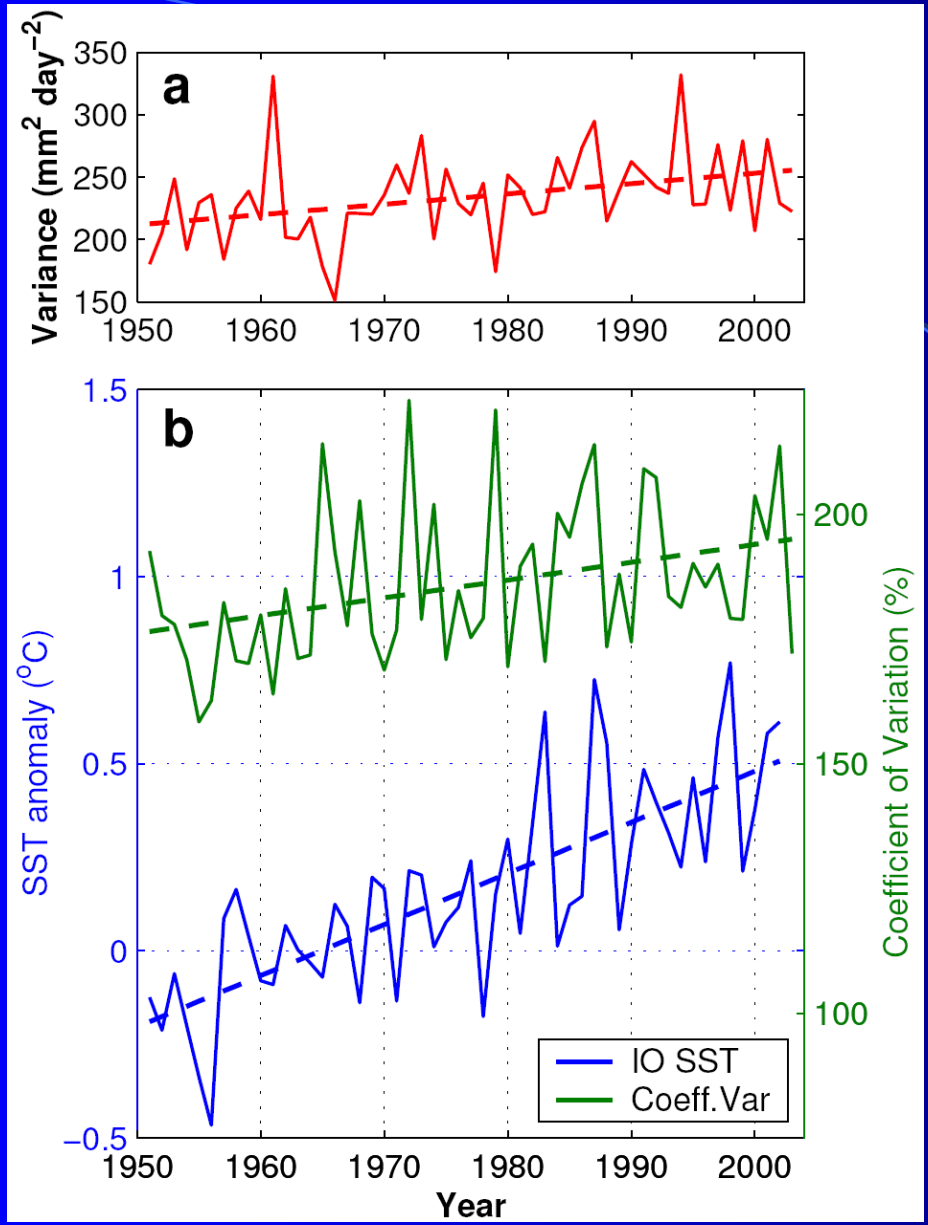
- Period : 1950-2003
- Daily
- Analysed into 1° X 1° boxes
- Quality Controlled

Rajeevan et al, 2006, Curr. Sci. 91,



Climatoological mean variance of daily rainfall during JJAS

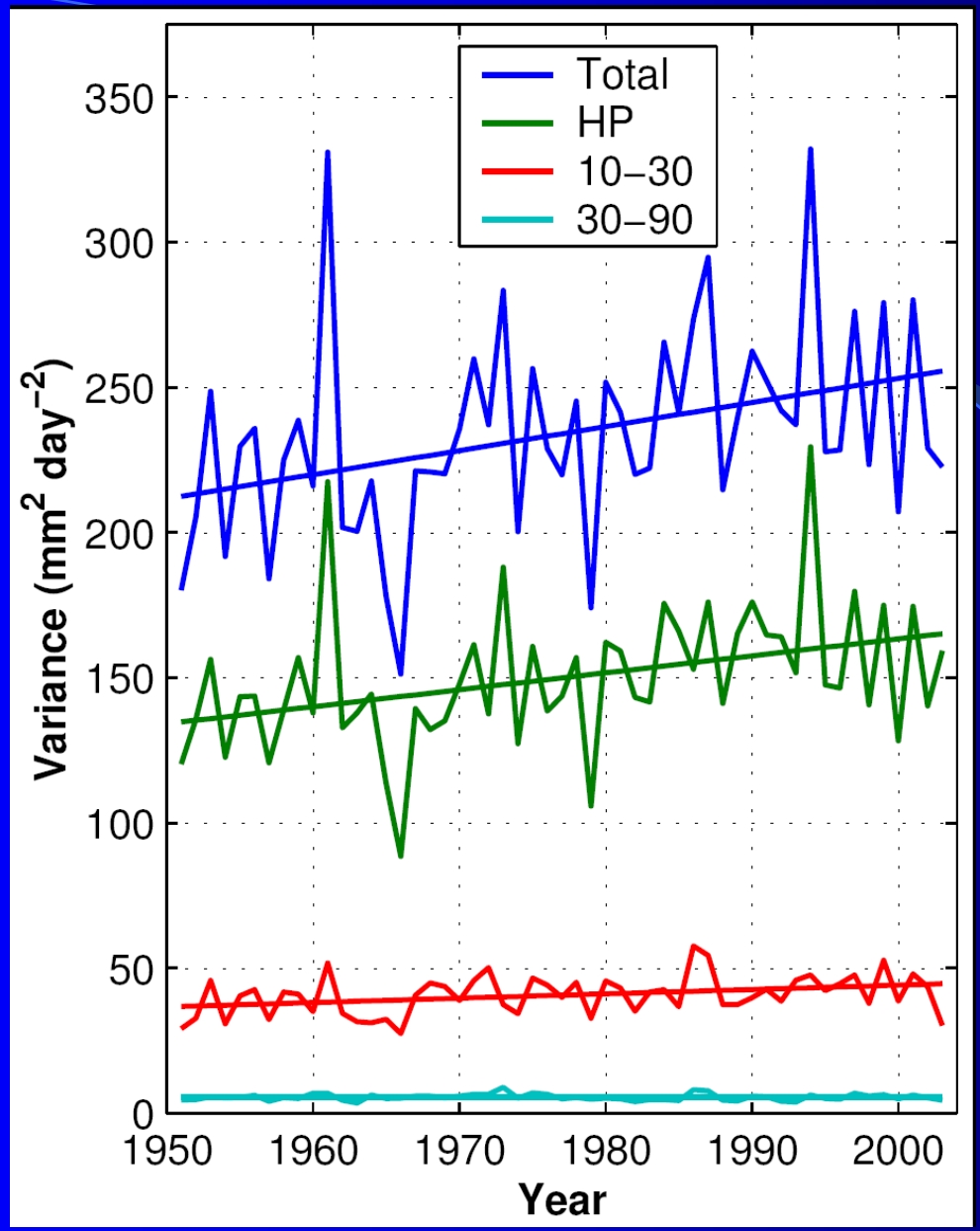
Goswami et al. 2006, Science



Variance of daily rainfall over CE during JJAS

CoV (S.D/mean) daily rainfall over CE, JJAS

SST anom during JJAS over tropical Indian Ocean (50E-100E,20S 20N)



- **Contributions of HP, 10-20 day mode , 30-60 day mode to the trend of total daily rainfall variance.**

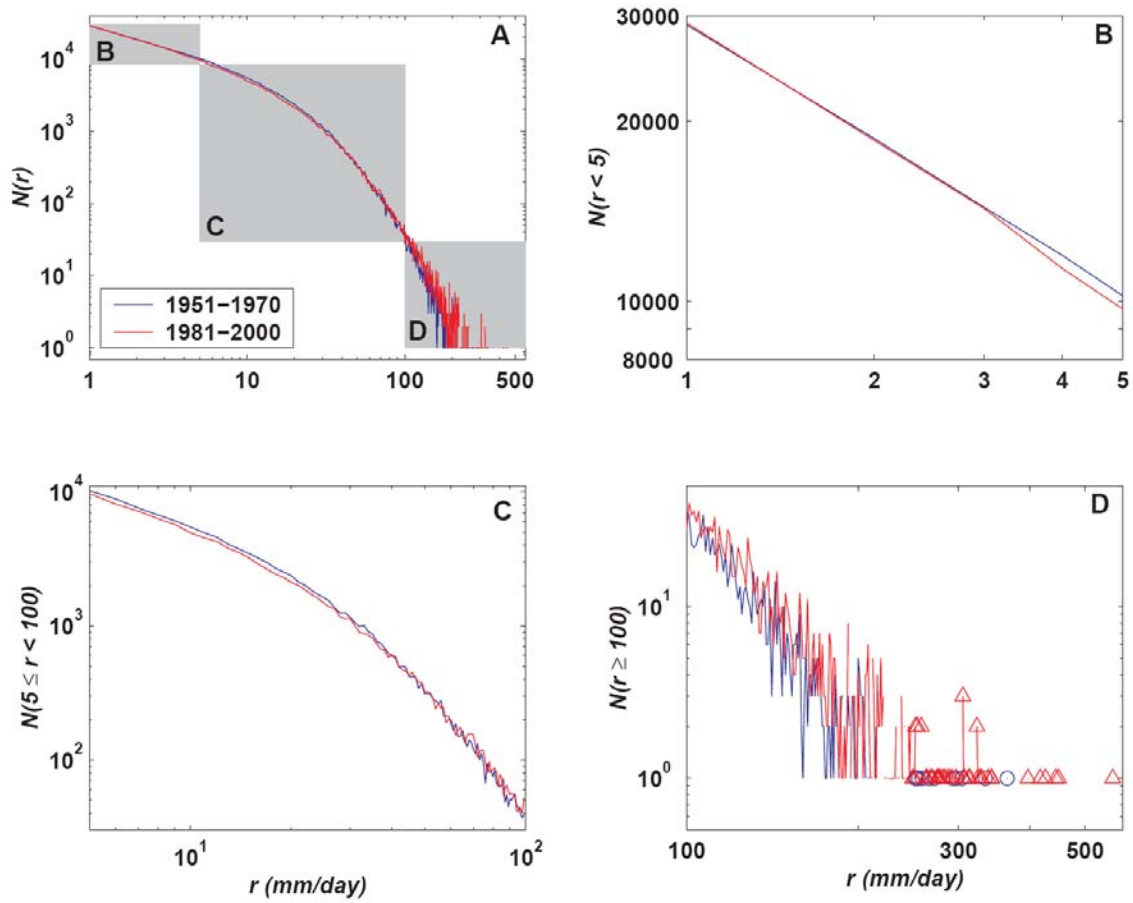
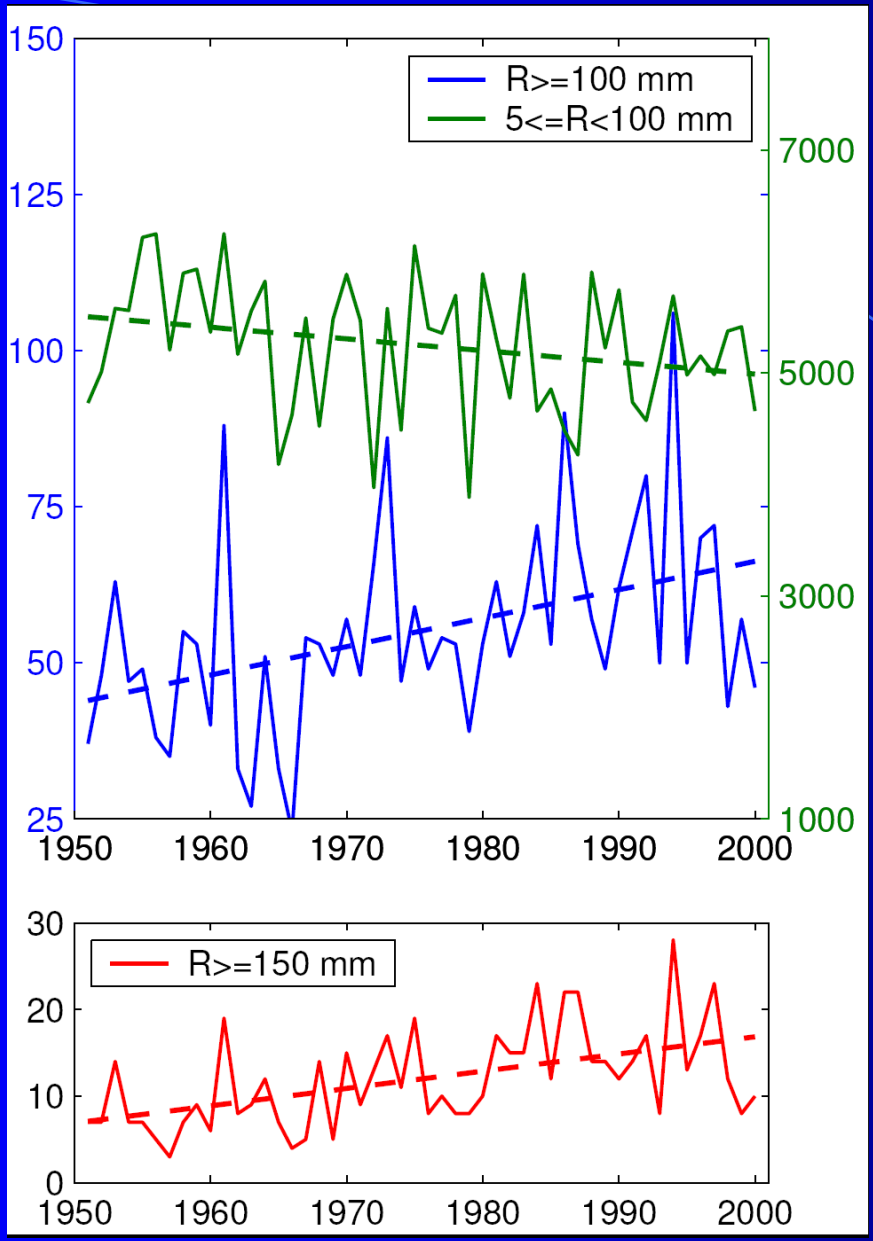


Fig. S2: (A) Frequency Histogram of daily rainfall over CI during summer monsoon for two periods, 1950-1970 and 1980-2000. The regions marked by the shaded rectangles in A are magnified in B, C, and D. For the sake of clarity, rain intensities larger than 250 mm/day have been shown by symbols (blue circles and red triangles) in panel (D).

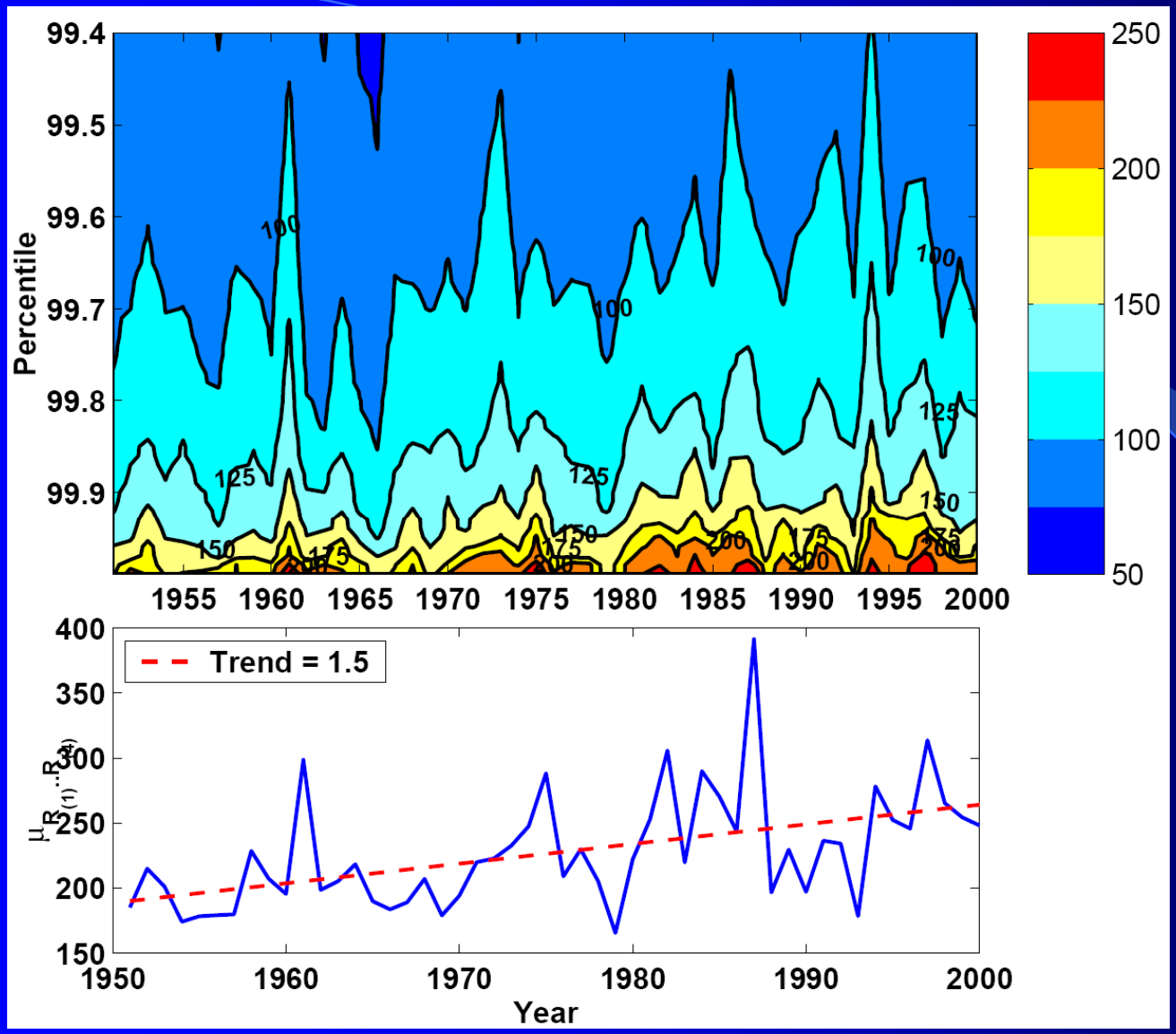
Time series of count over CI



Low & Moderate events

Heavy events (>10cm)

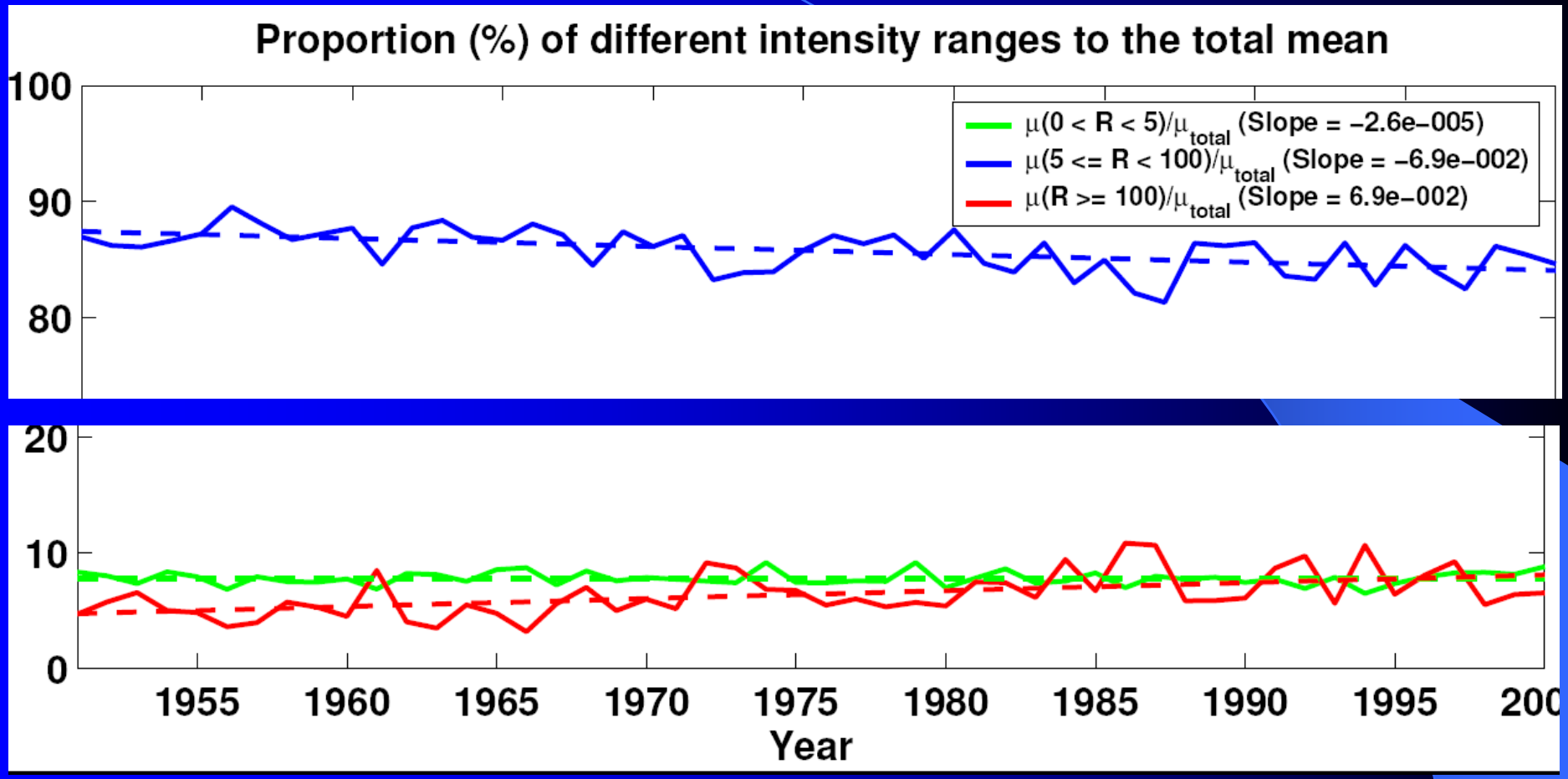
V. Heavy events (>15cm)



- **Increase in intensity of extreme events**

Time series of av. Intensity of four largest events in a year

Why no trend in the seasonal mean ?



- Frequency of occurrence as well as intensity of heavy and very-heavy rainfall events have highly significant increasing trends over Central India
- Low and moderate events have significant decreasing trend over CI
- The seasonal mean does not have a trend because decreasing contribution from low and moderate events are compensated by increasing contribution from heavy events.
- Thus, statistics of high-frequency component of rainfall variability modulates low frequency variability of monsoon (e.g. trend or interdecadal)

Goswami et al. 2006, *Science* (Dec. 1 issue),

Conclusion:

- An objective method is found to define the Indian summer monsoon (ISM) Season. ISM is driven by asymmetric tropospheric heat source, north of 5N. Thus, 'onset' and 'wthdrawal' of ISM may be defined when the north-south gradient of tropospheric heat source transits to positive or negative. Tropospheric temperature (TT) can be used as a proxi for tropospheric heat source.
- Helps discover a new extra-tropical teleconnection through which tropical Pacific SST as well as NA SST could influence Indian monsoon.
- Helps discover a new thermodynamic index of indian summer monsoon through which it has been possible to extract the predictable monsoon signal.

Based on :

Goswami B N and Prince Xavier, ***Geophys. Res. Lett.*** 30(18), 1966, doi:10.1029/2003GL017,810, 2003.

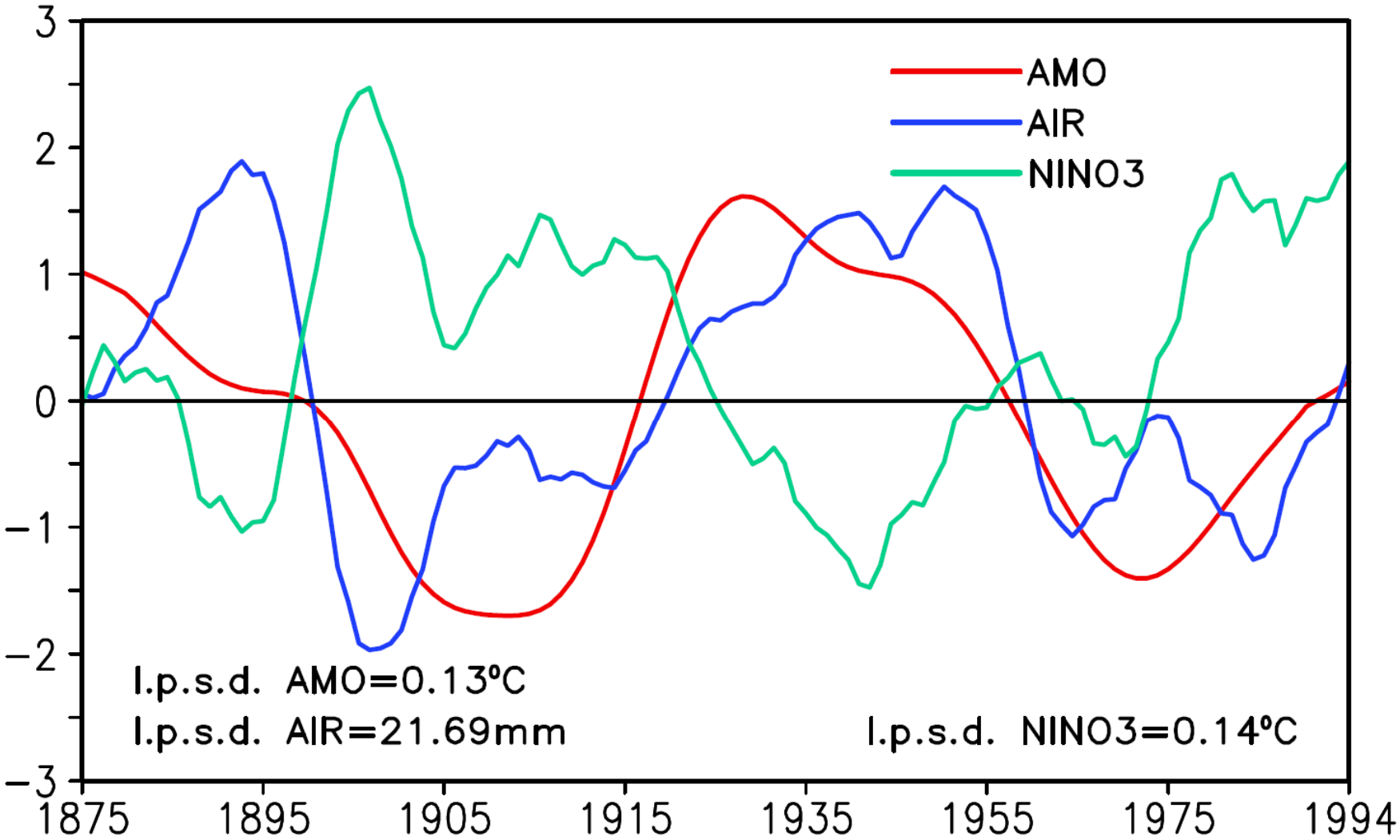
Xavier et al. ***Q. J. Meteorol. Soc.*** 133, 749-764, 2007

Goswami et al. , ***Geophys. Res. Lett***. , vol 33, L02706,doi:10.1029/2005GL026803, 2006

Krishnamurthy and Goswami, *J. Climate*, 2000

Goswami et al, 2006, Science

Thank you



Low-pass filtered JJAS AMO index, AIR and Nino3 SST

Multi-scale Interactions & variability of monsoon

Interdecadal

~60 years

Interannual Var
seasonal mean
2-4 yrs

Sub-seasonal

Active-break spells

15-d, 40-d

Weather

Lows & Depressions

5-d

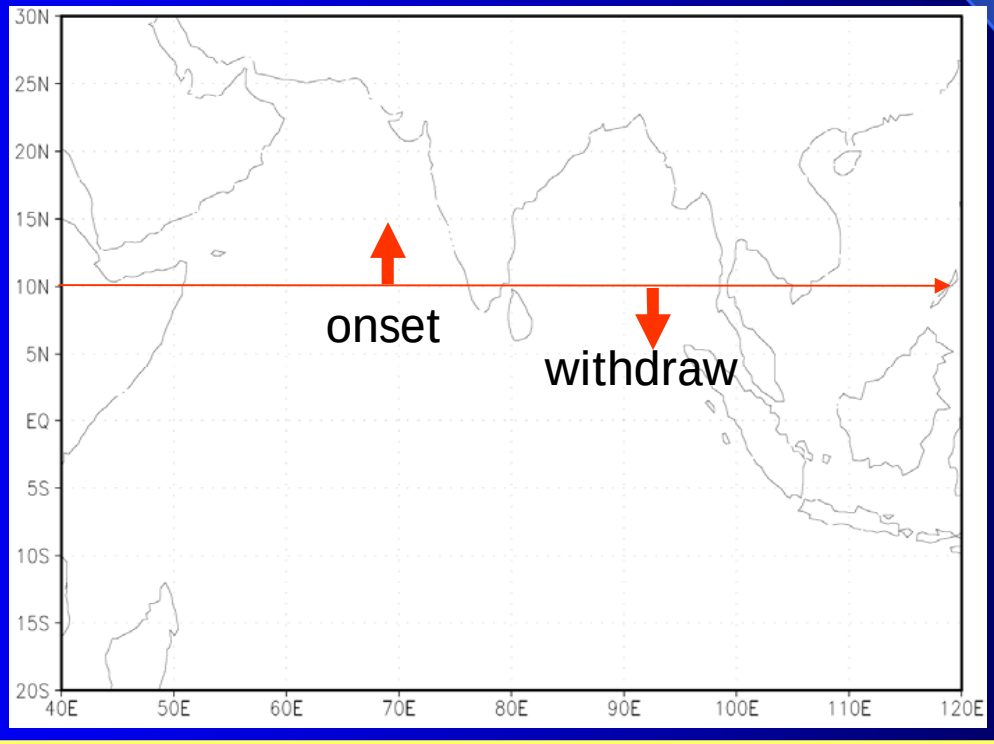
Short-rain events

Extreme events

1-3 hrs

Define Indian summer monsoon *rainy season*

- **What really delineates the Indian Summer Monsoon (rainy) Season?**
  - **Physically, the rainy season is delineated by large scale Monsoon *'Onset'* over Kerala and *'Withdrawal'* from the southern tip (say 10N).**



Background

- For over a century south-west monsoon season is assumed fixed between 1 June and 30 September!

- Operational Convenience, May be.

- Physical Basis ? Not known!

- South-west monsoon season is a part of the monsoon annual cycle (MAC). External forces that drive MAC has IAV and produces IAV of monsoon season.

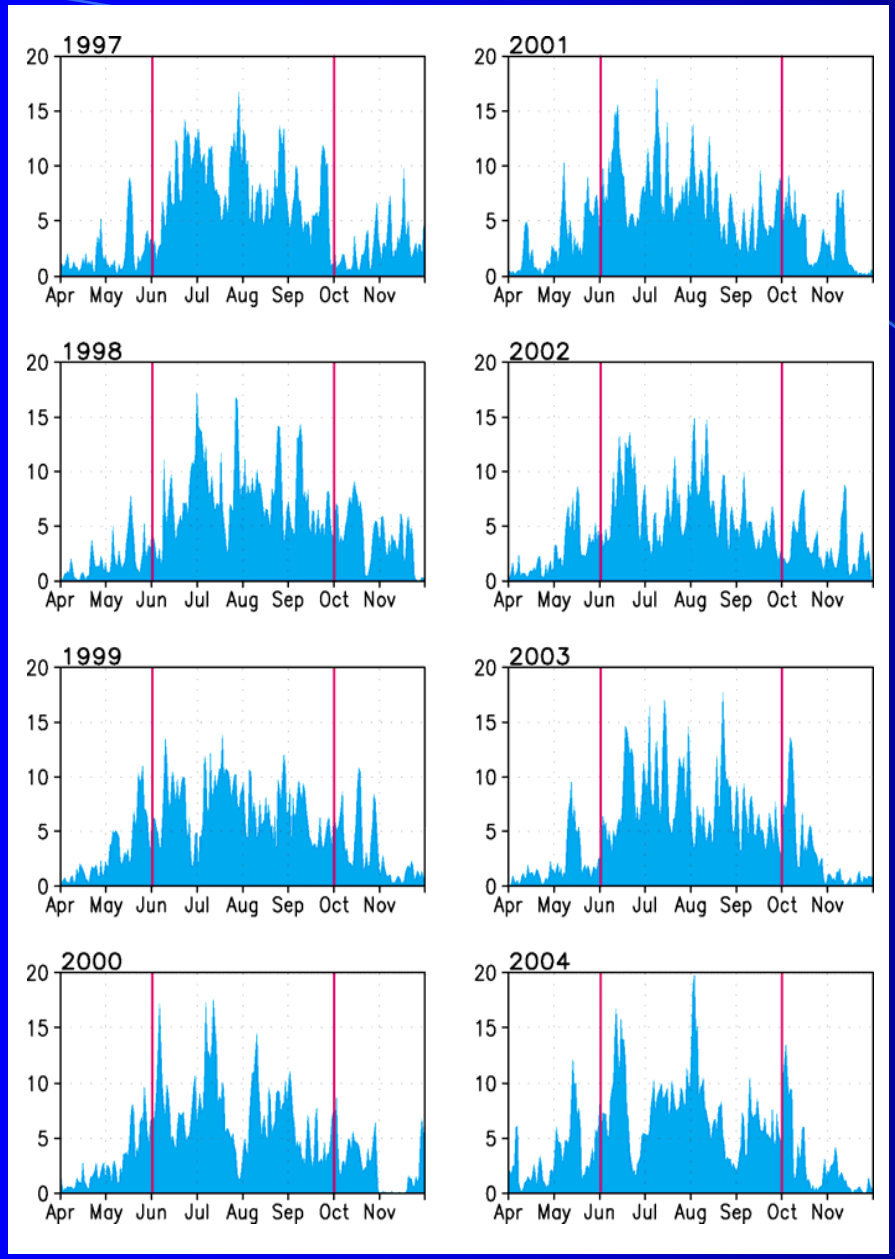
Danger

- Many monsoon *'Onset'* over Kerala (MOK) take place much before June 1 and *'Withdrawal'* from Kerala also takes place after September 30.

- Monsoon rain from spells before June 1 and after Sept. 30 are traditionally not included in the Seasonal mean (JJAS) rainfall!

- Could influence the interannual variability of Indian summer monsoon rainfall!

- Teleconnections studied so far with JJAS rainfall (e.g. ENSO-monsoon, monsoon-snow etc) may be completely misleading of physical relationships!



Daily all India rainfall for a few years

Objective:

- An objective method of delineating the Indian Summer Monsoon Rainy Season.

Spin-off:

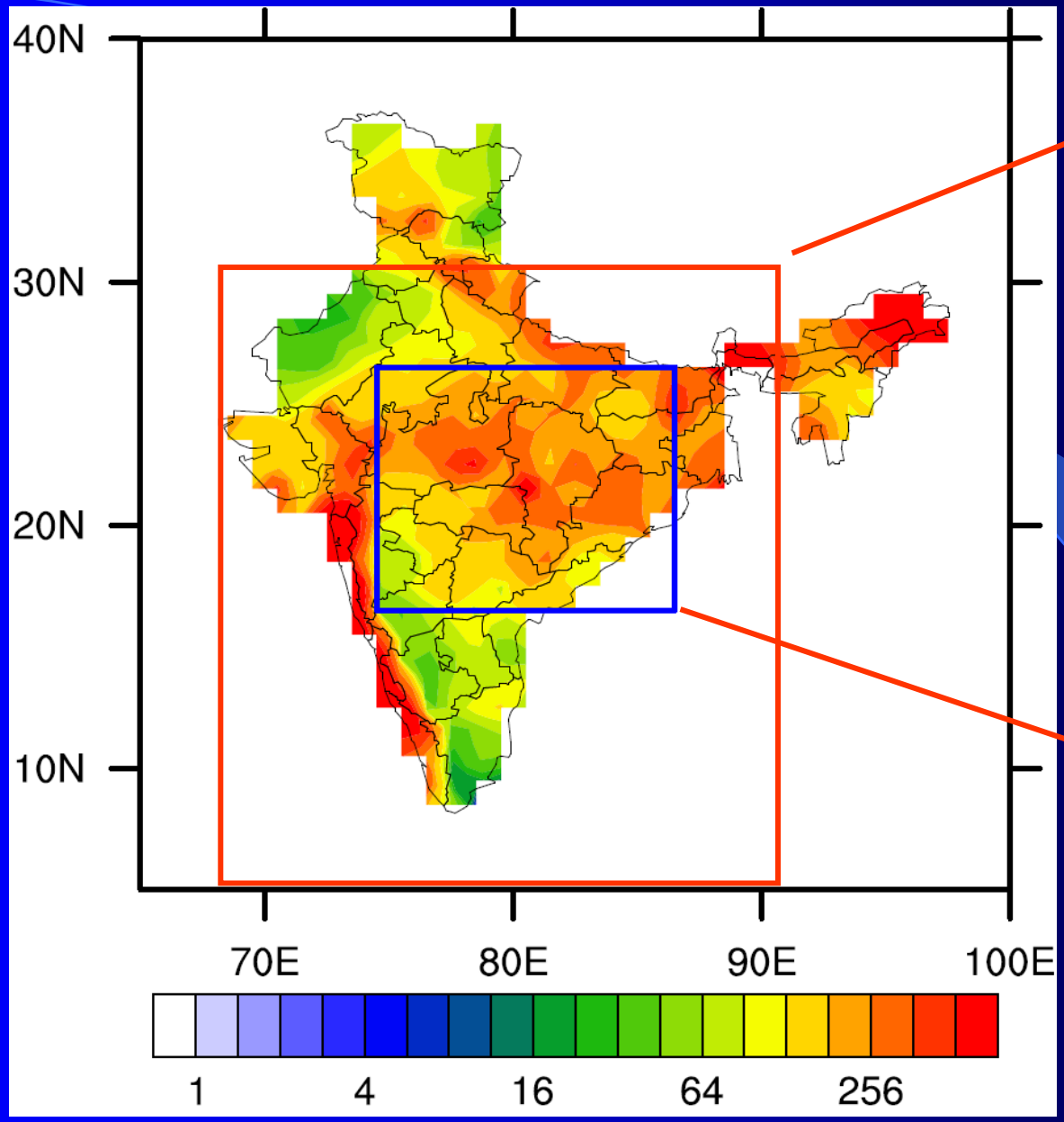
- A new teleconnection mechanism, not recognized so far, through which ENSO induces decreased precipitation over Indian monsoon region during northern summer.
- Provides physical basis for explaining several paleo connections between NA SST and Indian monsoon

Whatever controls the MOK and 'withdrawal' of Monsoon from southern tip of India (~5°N) , therefore, determines the length of the Indian summer monsoon season or the Length of the Raining Season (LRS).

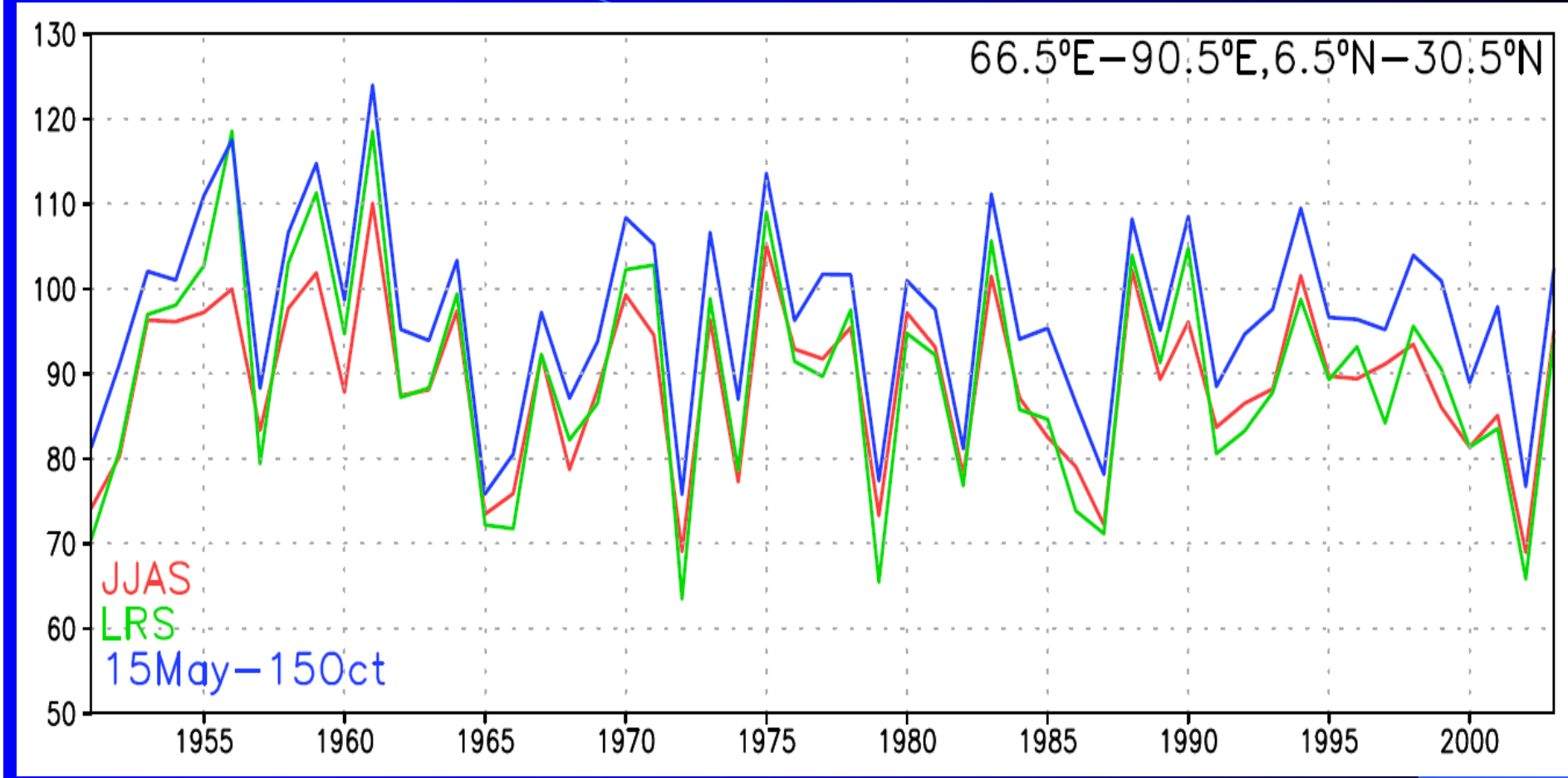
- **Can we use existing definitions of MOK and withdrawal for defining LRS?**

- **Almost all existing definitions of MOK or withdrawal are not physically based and require a 'magic' threshold on precipitation and/or low level wind shear! Unsatisfactory.**

- **To our knowledge, nobody has attempted to define the Monsoon Season objectively using the physical driving that determine the onset and withdrawal!**


40N
30N
20N
10N
70E
80E
90E
100E
1
4
16
64
256
AIR
CIR

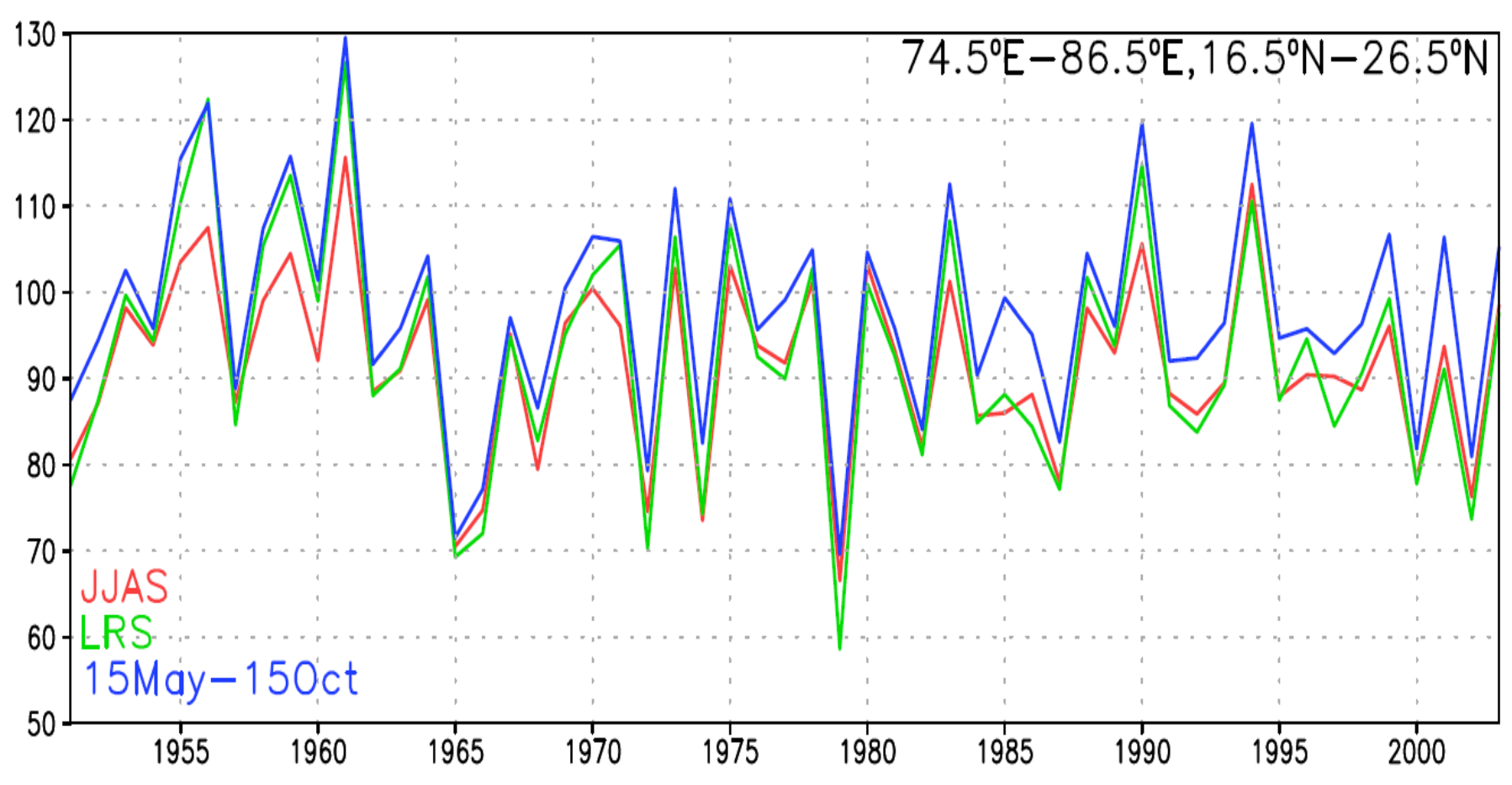
Interannual variation of AIR



JJAS → rainfall (cm) between 1 June – 30 September

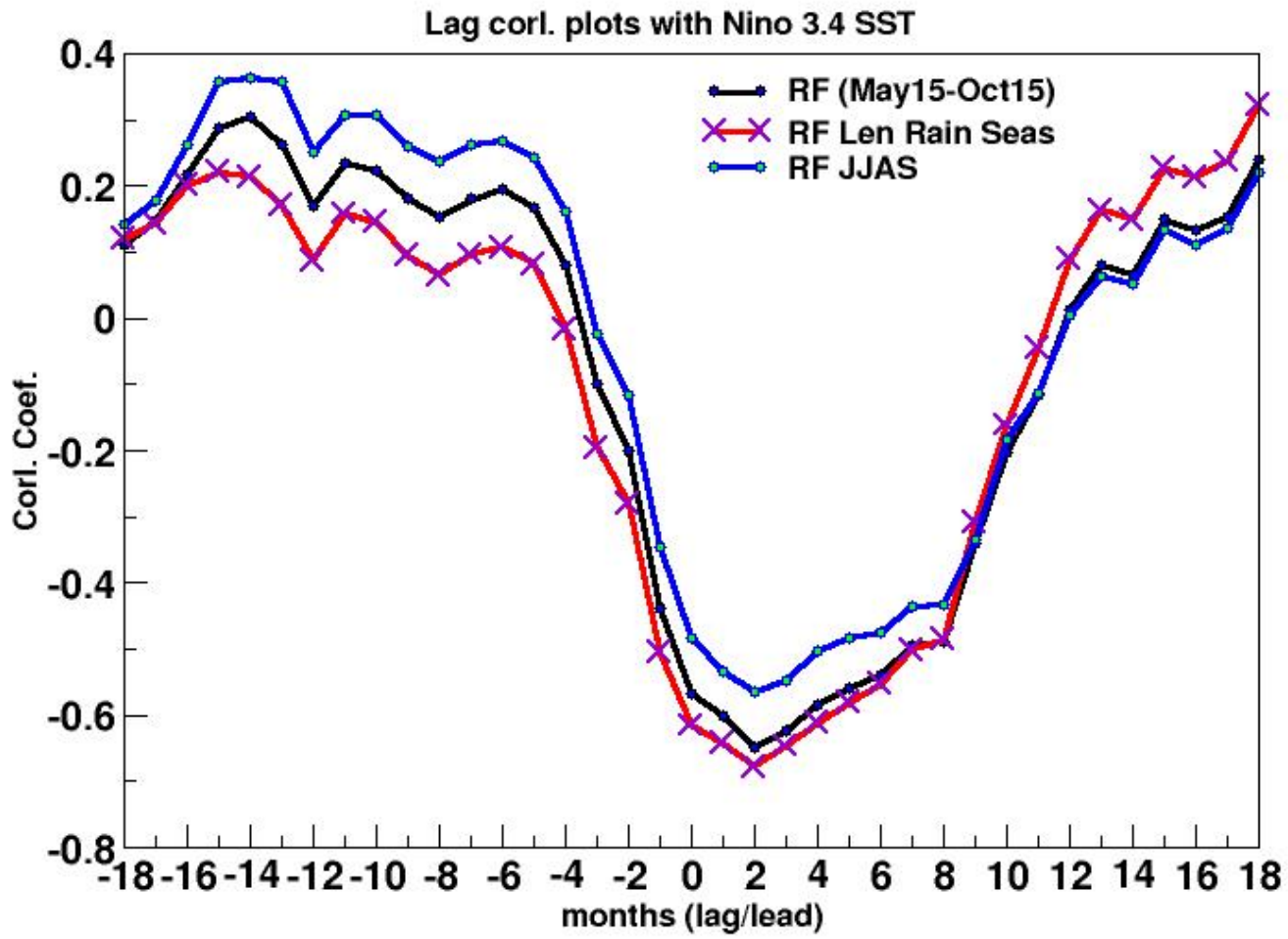
LRS → rainfall (cm) during LRS (OD and WD), variable

Interannual variation of CIR



JJAS → rainfall (cm) between 1 June – 30 September

LRS → rainfall (cm) during LRS (OD and WD), variable


Lag corl. plots with Nino 3.4 SST
RF (May15-Oct15)
RF Len Rain Seas
RF JJAS
Corl. Coef.
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18
months (lag/lead)

74.5°E – 86.5°E, 16.5°N – 26.5°N

Correlation

	JJAS	*15 May-15 Oct*	*LRS*
JJAS	1.0000		
15 May-15 Oct	0.9669	1.0000	
LRS	0.9679	0.9746	1.0000

	JJAS	*15 May-15 Oct*	*LRS*
Mean (cm)	91.6804	98.0692	92.8548
S.D. (cm)	10.5462	12.6129	13.6936

66.5°E – 90.5°E, 6.5°N – 30.5°N

Correlation

	JJAS	*15 May-15 Oct*	*LRS*
JJAS	1.0000		
15 May-15 Oct	0.9597	1.0000	
LRS	0.9554	0.9736	1.0000

	JJAS	*15 May-15 Oct*	*LRS*
Mean (cm)	89.0624	97.0436	89.9428
S.D. (cm)	9.6731	11.1495	12.8444
C.V. (%)	10.8610	11.4892	14.2806

Recall that the total seasonal rainfall is not only affected by LRS but it can also be influenced by the PDF of the rains spells. This part is governed by 'internal dynamics'.

Therefore, the total seasonal rainfall and ENSO SST can still have slightly different relationship that that with LRS and ENSO SST due to the contribution of 'internal dynamics'.

Conclusions:

- A physically based method has been described to define the Indian summer monsoon rainy reason.
- A robust mechanism through which ENSO influence Indian summer monsoon rainfall is discovered. El Nino (La Nina) reduce (increase) monsoon season rainfall by shrinking (expanding) the rainy season thus encompassing more or less rain spells.
- In contrast to JJAS AIR & Nino3 (or Nino4) SST relationship, the LRS & Nino3 (or Nino4) SST relationship has remained steady over the years.
- We believe that the primary mechanism through which ENSO influence Indian monsoon rainfall is through LRS which has remained strong. The apparent weakening ENSO-monsoon relationship based on JJAS AIR is largely due to 'internal dynamics' being relatively more important during the recent years.

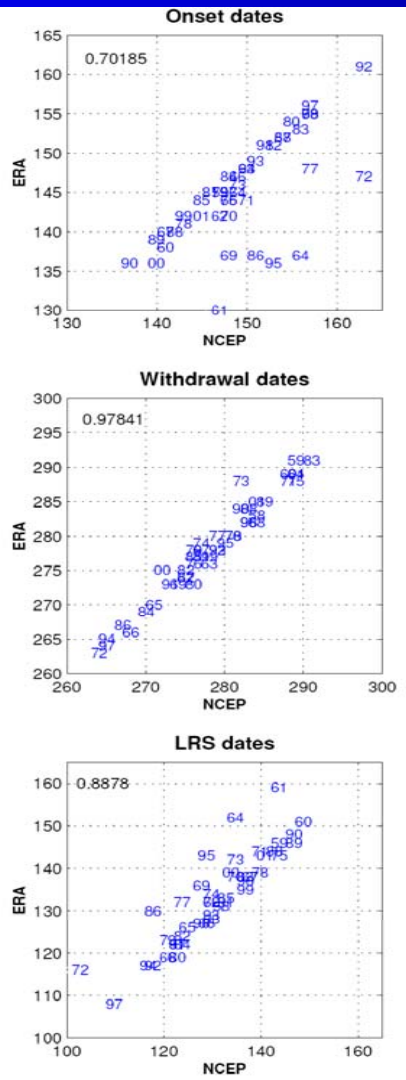


Figure 2: (Supplementary) The scatter plot of OD, WD and LRS dates from ERA and NC from 1958 to 2001. The correlation coefficient between ERA and NC are given in respective panels.

Comparison between Onset dates, withdrawal dates and LRS derived from NCEP reanalysis and ERA during the common period between 1958 and 2001