Multi-decadal Variability and Mega-Droughts of the Indian Summer Monsoon

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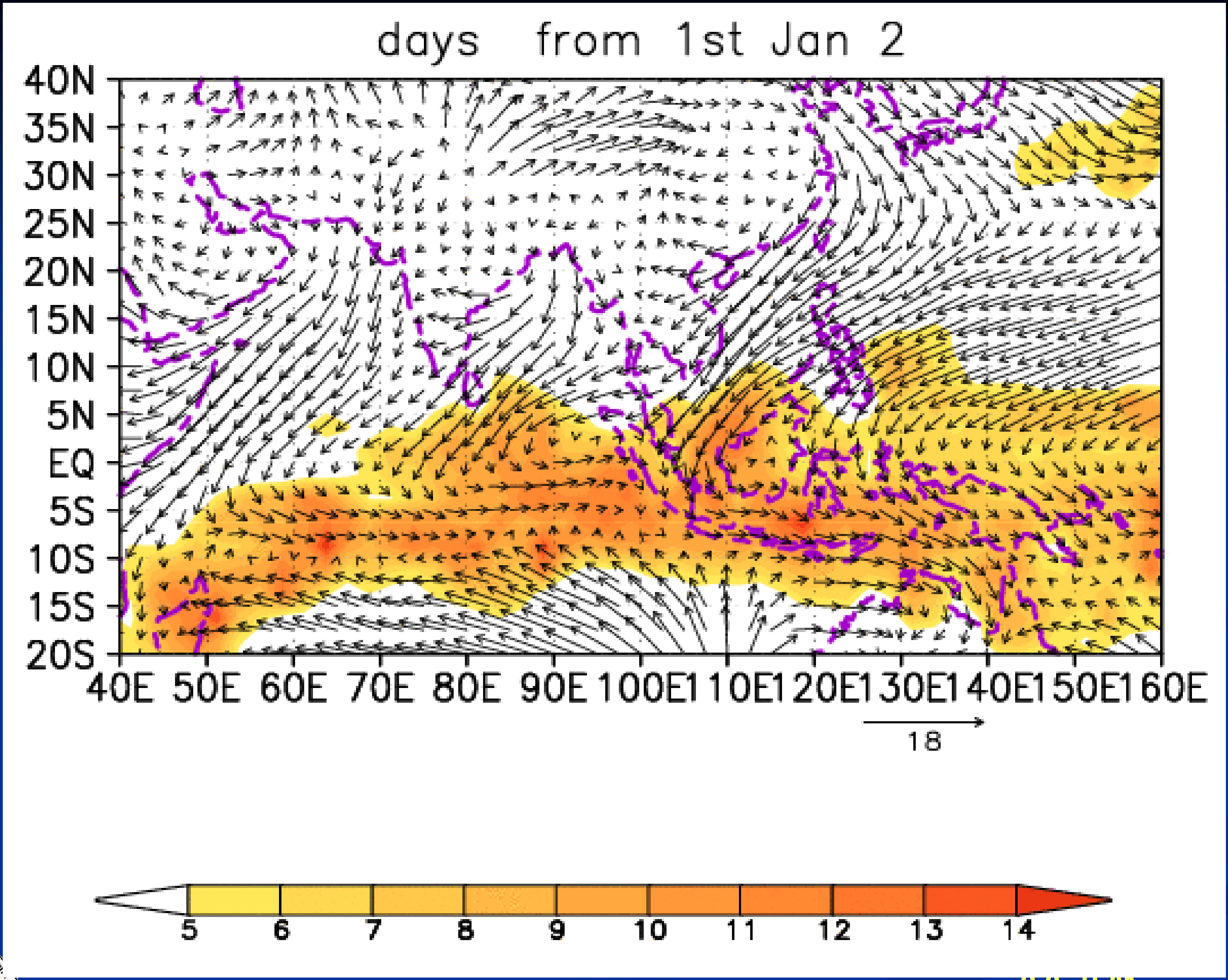
Outline

- Conceptual framework for understanding Indian Monsoon variability
- Multi-decadal variability and Mega-droughts of Indian Monsoon
- Multi-decadal variability of Monsoon→ a natural mode of variability: Examine linkages with ENSO and North Atlantic SST
- Is Indian Monsoon tipping towards a Mega-drought in recent decades?
- Robustness of multi-decadal variability of Indian Monsoon : Some proxy records

What is the Indian Summer Monsoon?

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

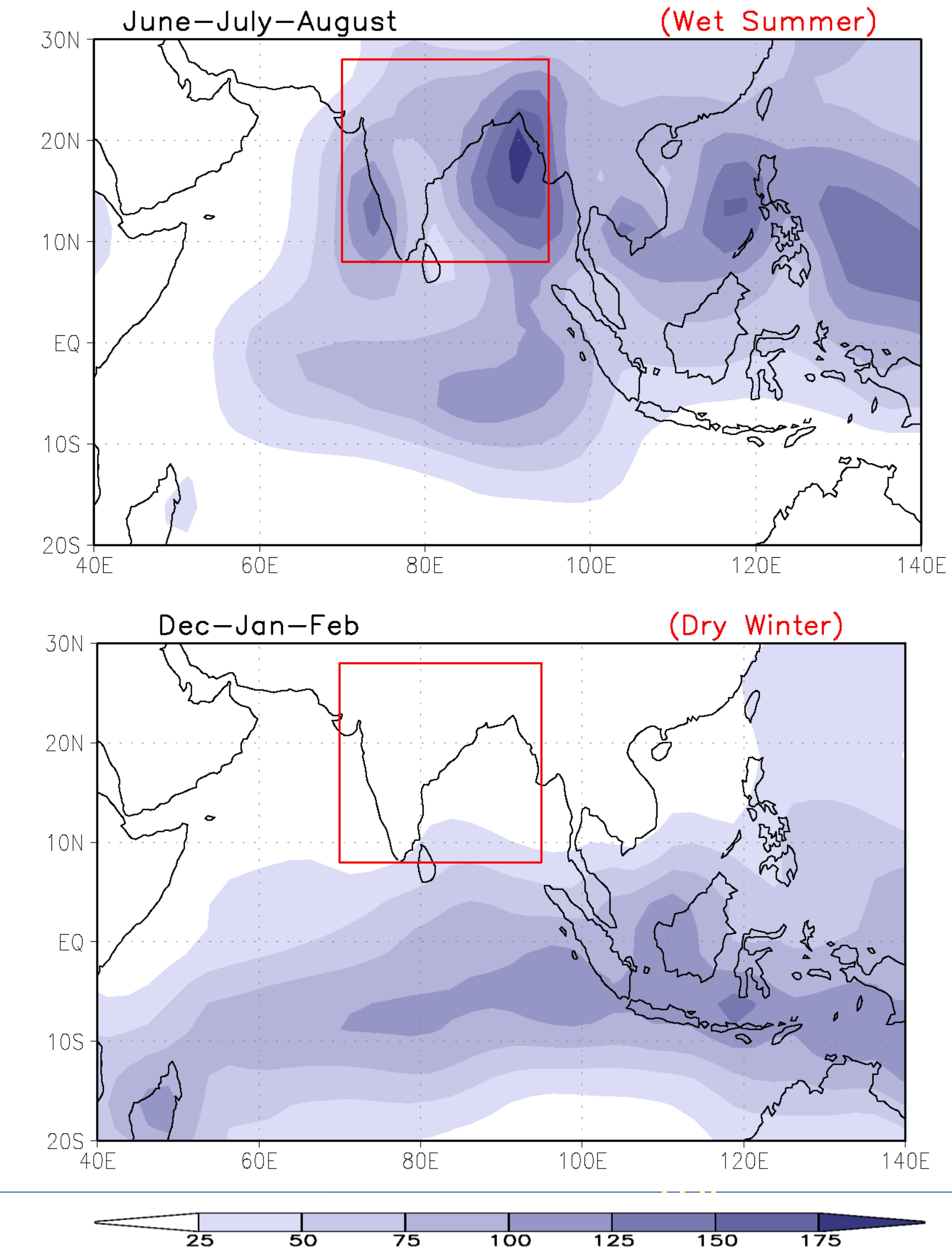


days from 1st Jan 2
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
40E 50E 60E 70E 80E 90E 100E110E120E130E140E150E160E
18
5 6 7 8 9 10 11 12 13 14

Long term mean

JJA precipitation and

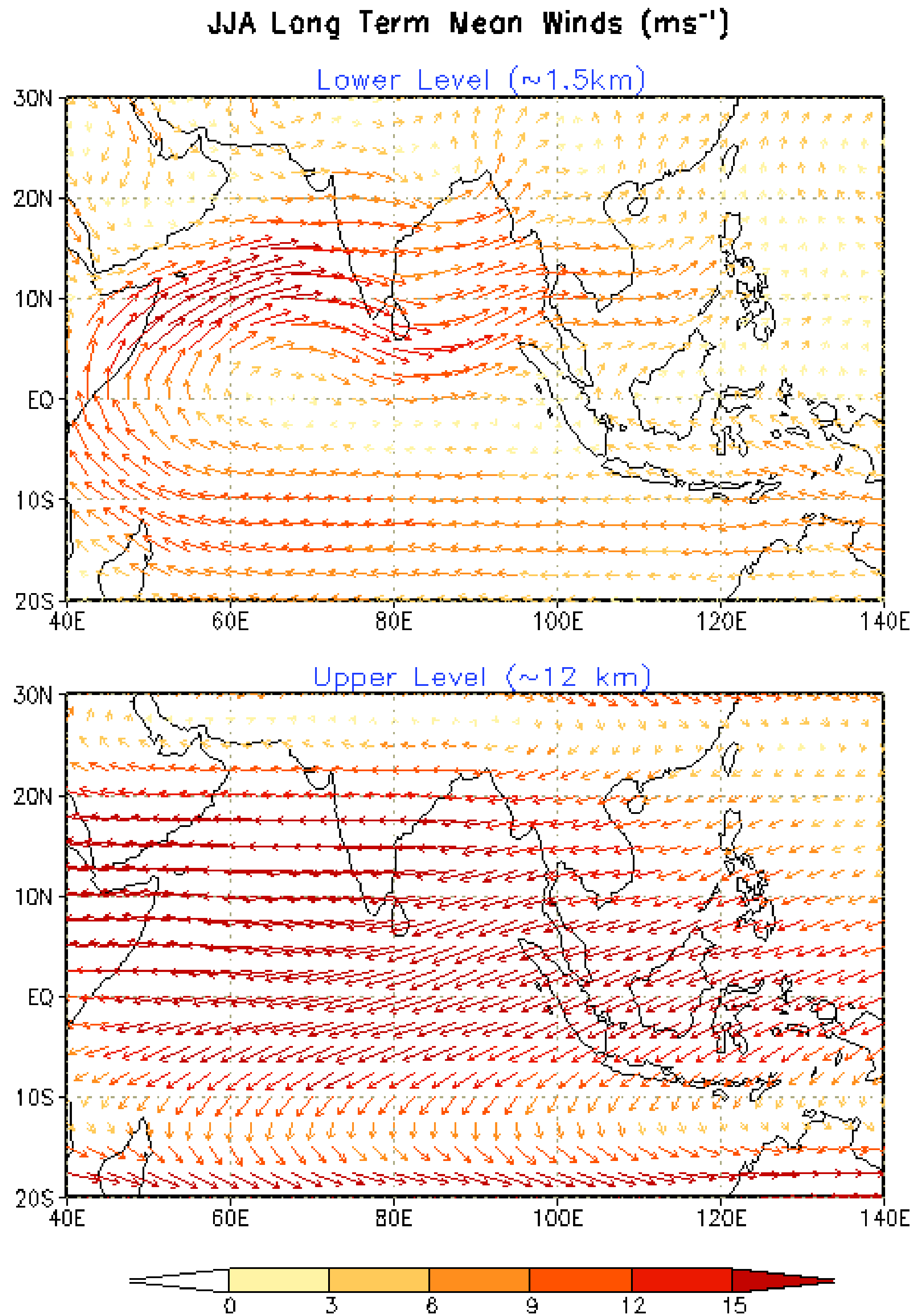
DJF precipitation



Monsoon ?

Wet- summer

Dry - winter

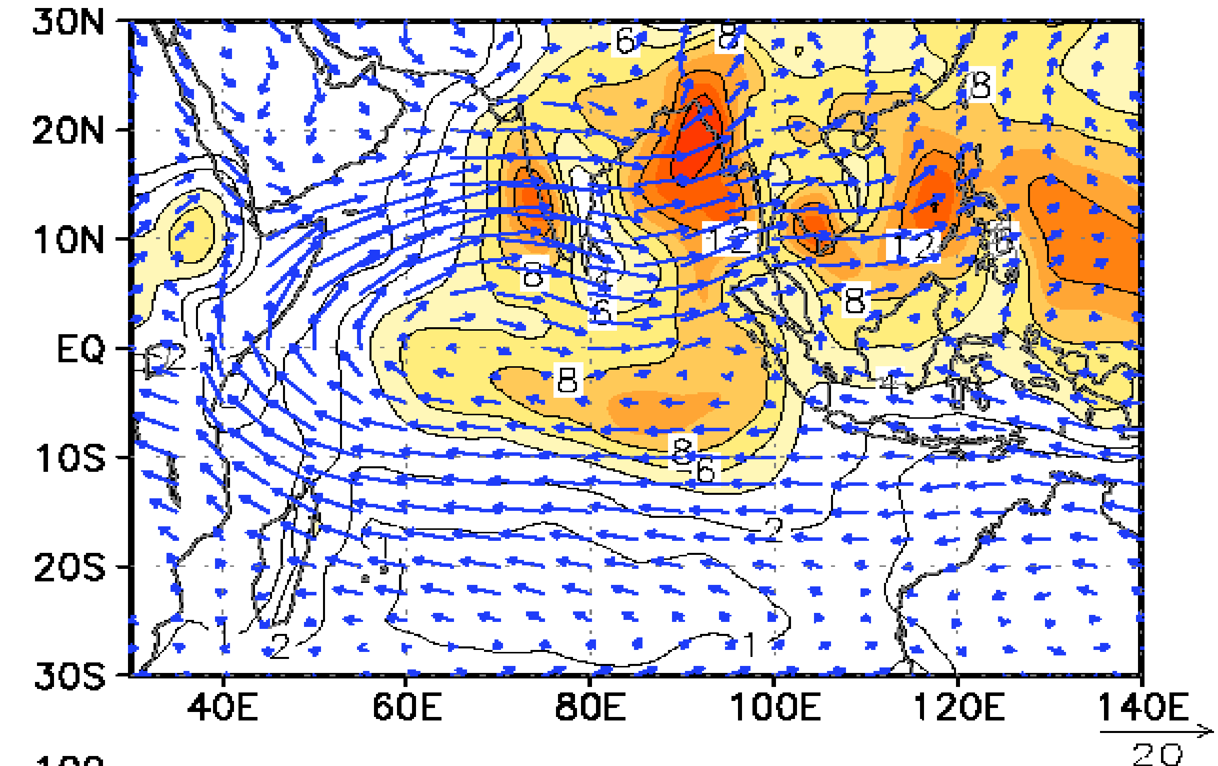


Characteristic features of summer monsoon circulation

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

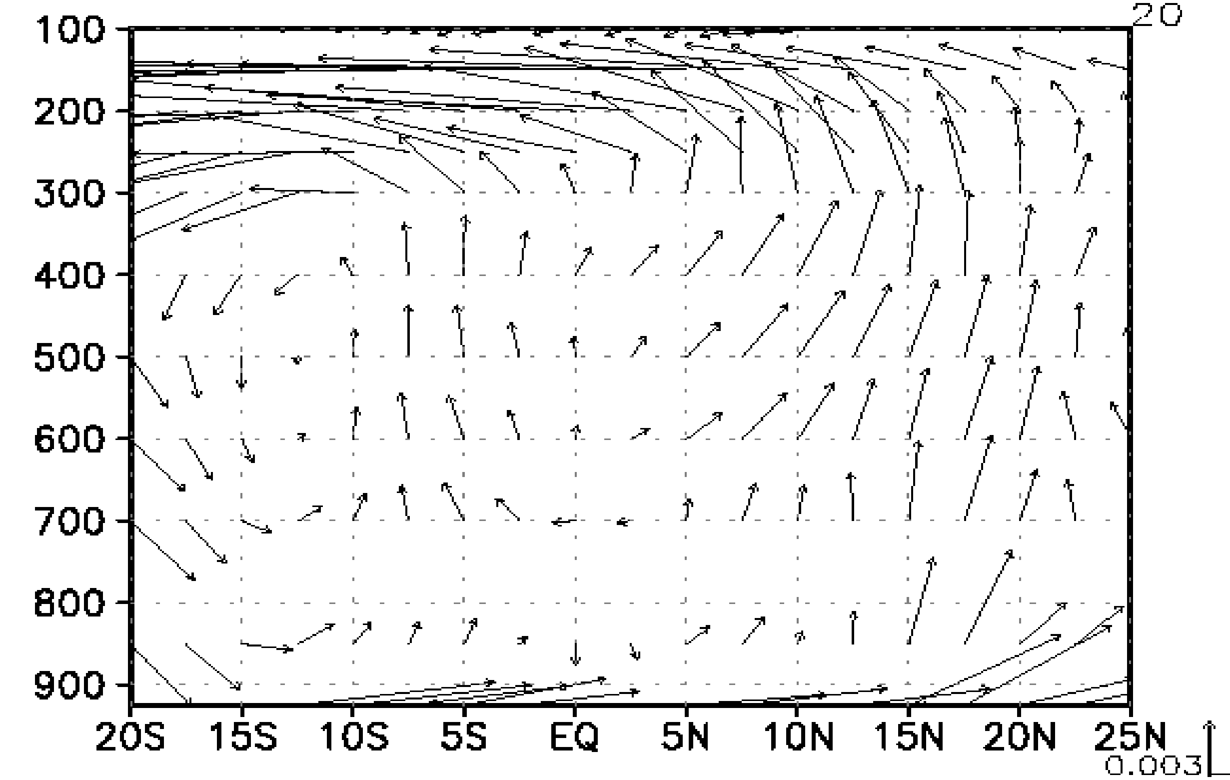
Upper level easterlies, Monsoon Easterly Jet

Climatological mean JJAS P and 850 hPa winds



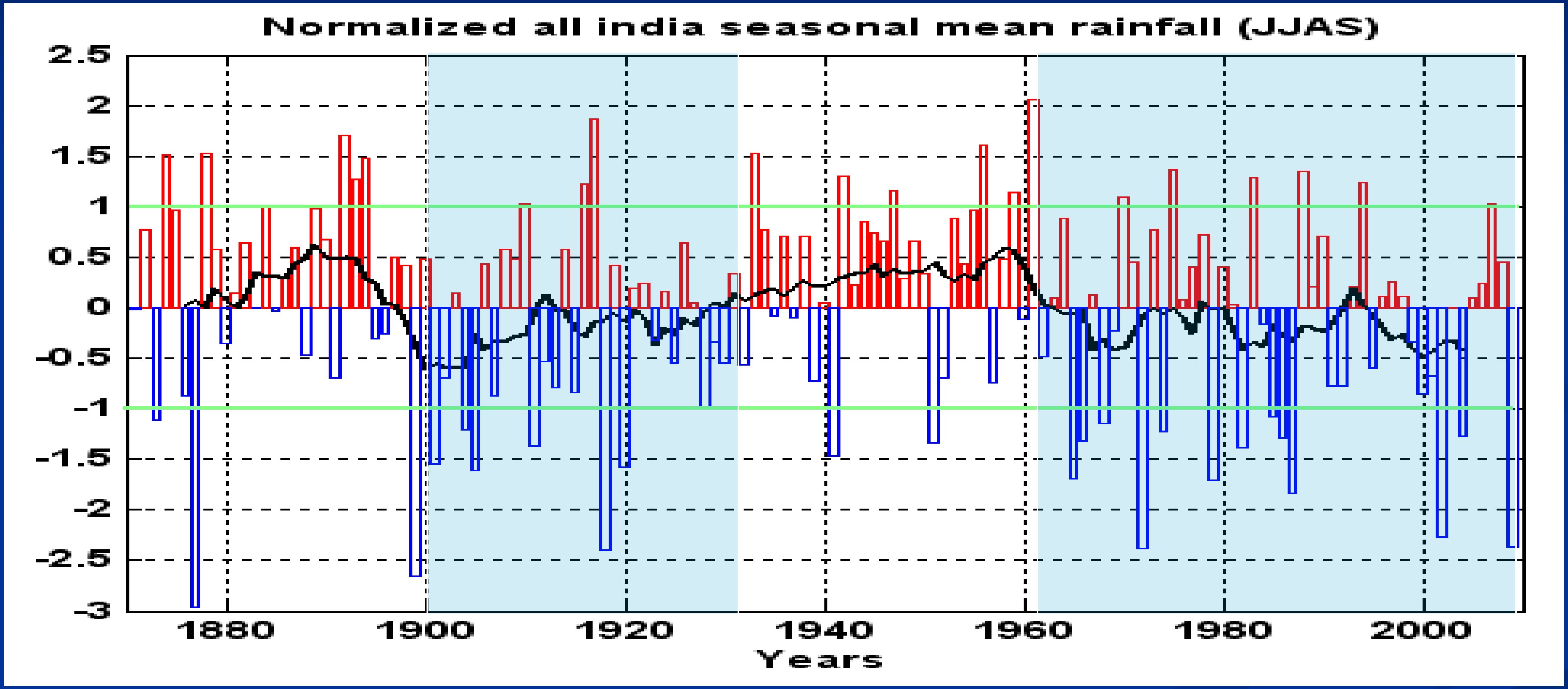
Mean monsoon Hadley circul.

70E-90E

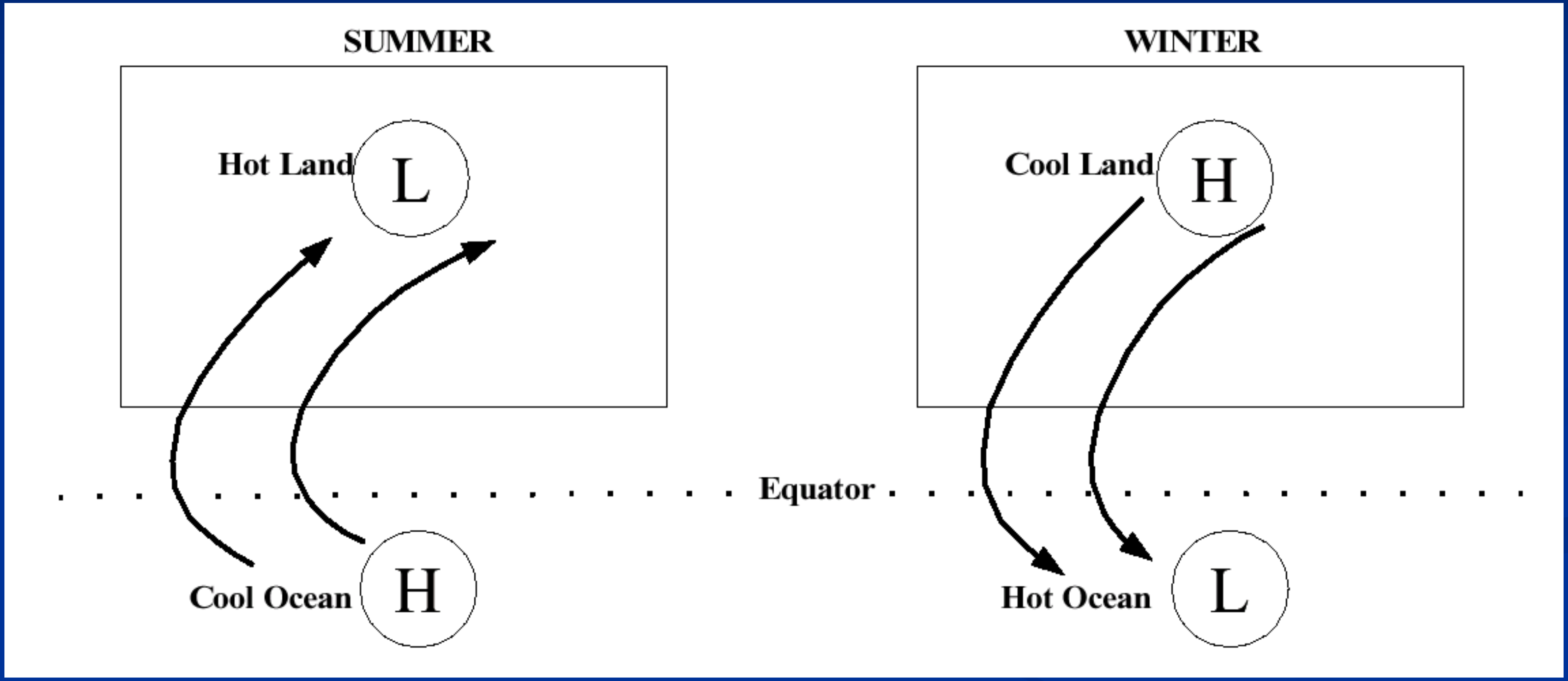


All India Rainfall (AIR): Interannual Variability

Mean : 86 cm; S.D. : 8.5 cm

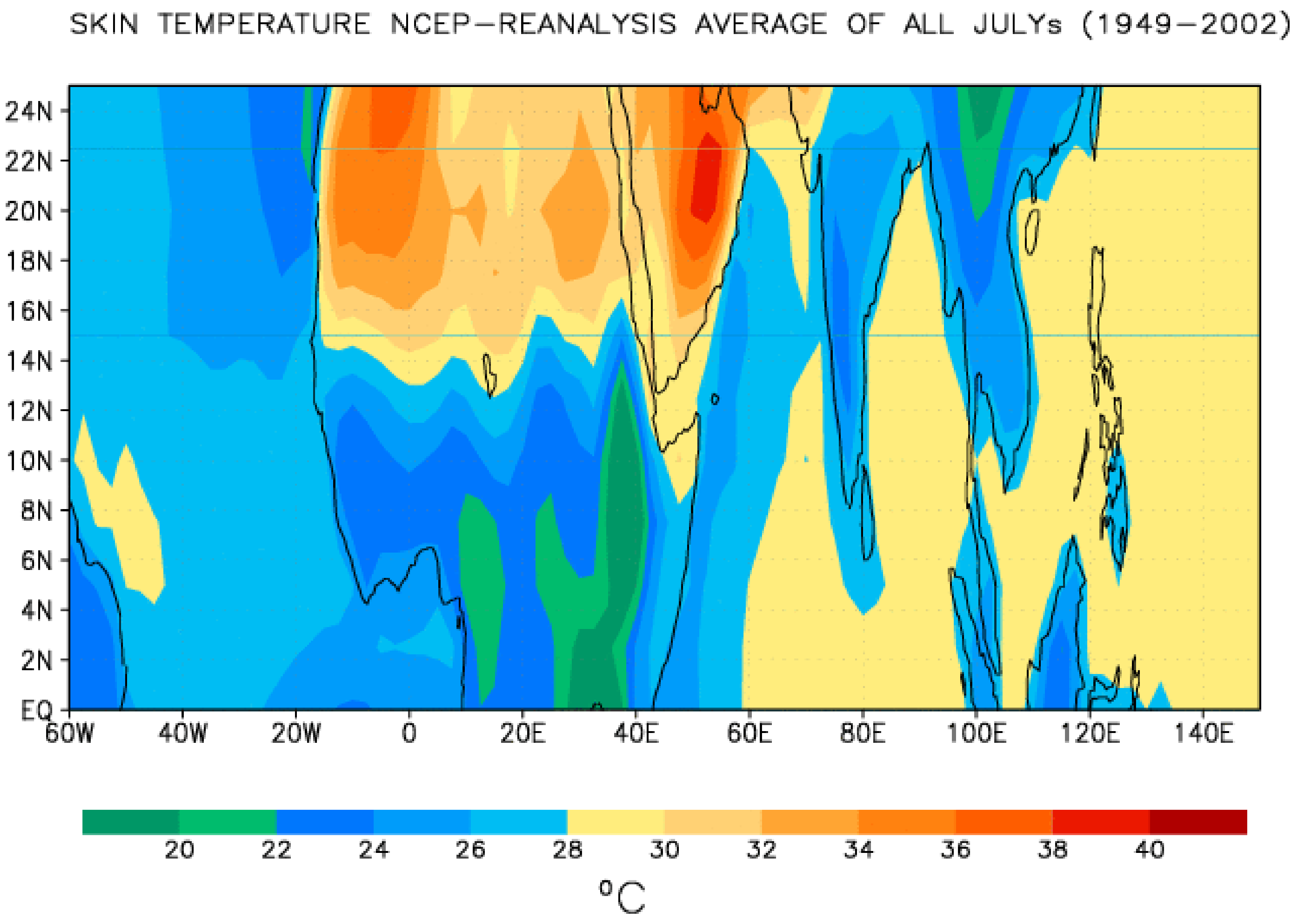


Classical model of monsoon: Large land-sea Breeze

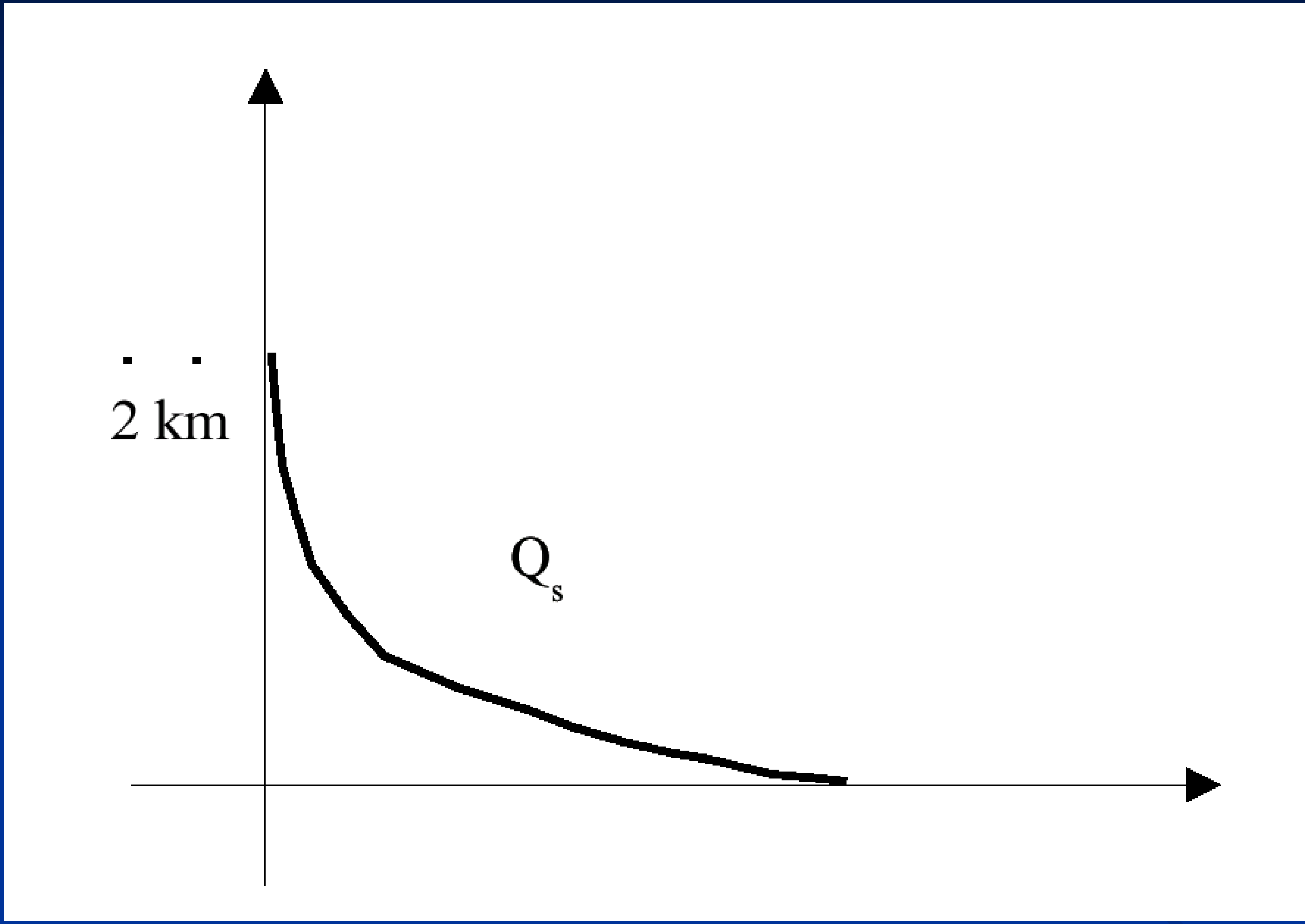


Cannot Explain:

- 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)
24N
22N
20N
18N
16N
14N
12N
10N
8N
6N
4N
2N
EQ
60W
40W
20W
0
20E
40E
60E
80E
100E
120E
140E
20
22
24
26
28
30
32
34
36
38
40
°C

Schematic of the vertical profile of surface heating



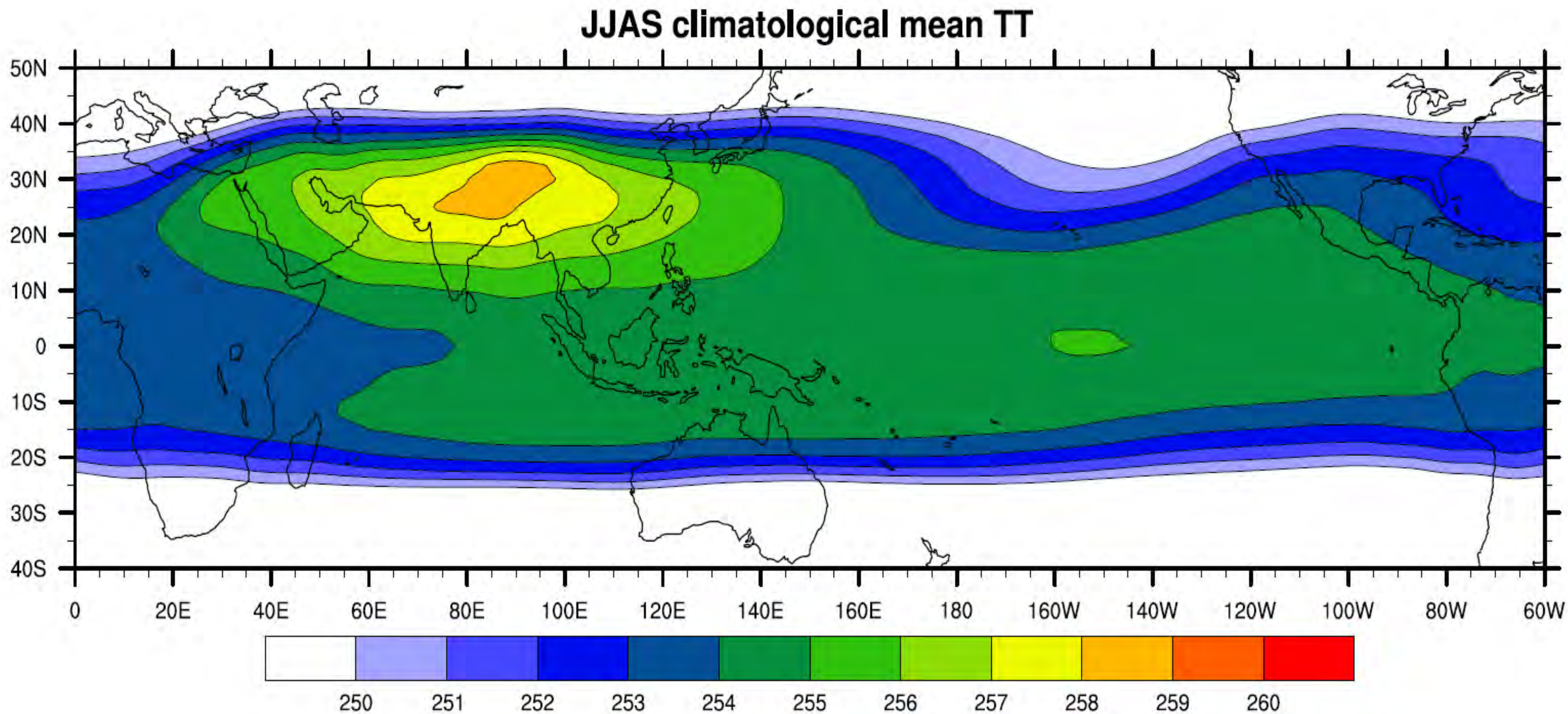
Another problem with the surface heating theory is that such a heating profile is confined to the lower layer as shown above and can not force deep vertical circulation as observed

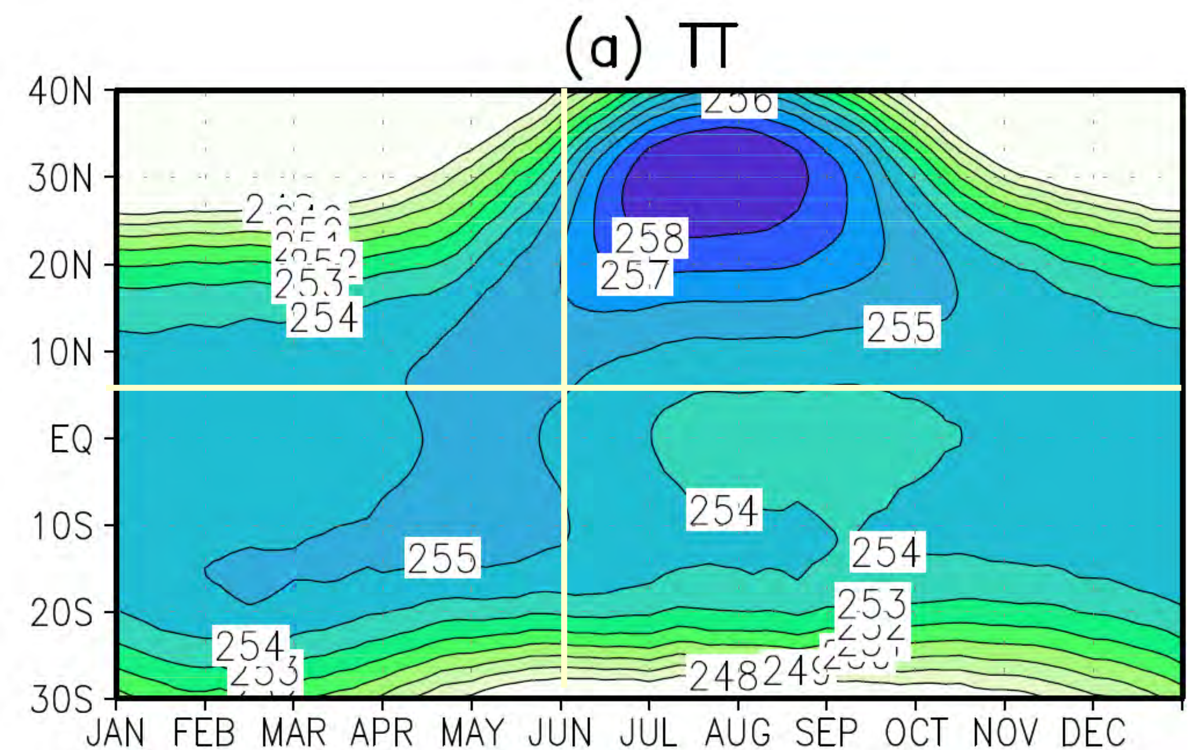
Thus, the classical concept of Indian monsoon being driven by north-south gradient of surface temperature is inadequate to explain maintenance of Indian monsoon!

So, what exactly dives the Indian monsoon?

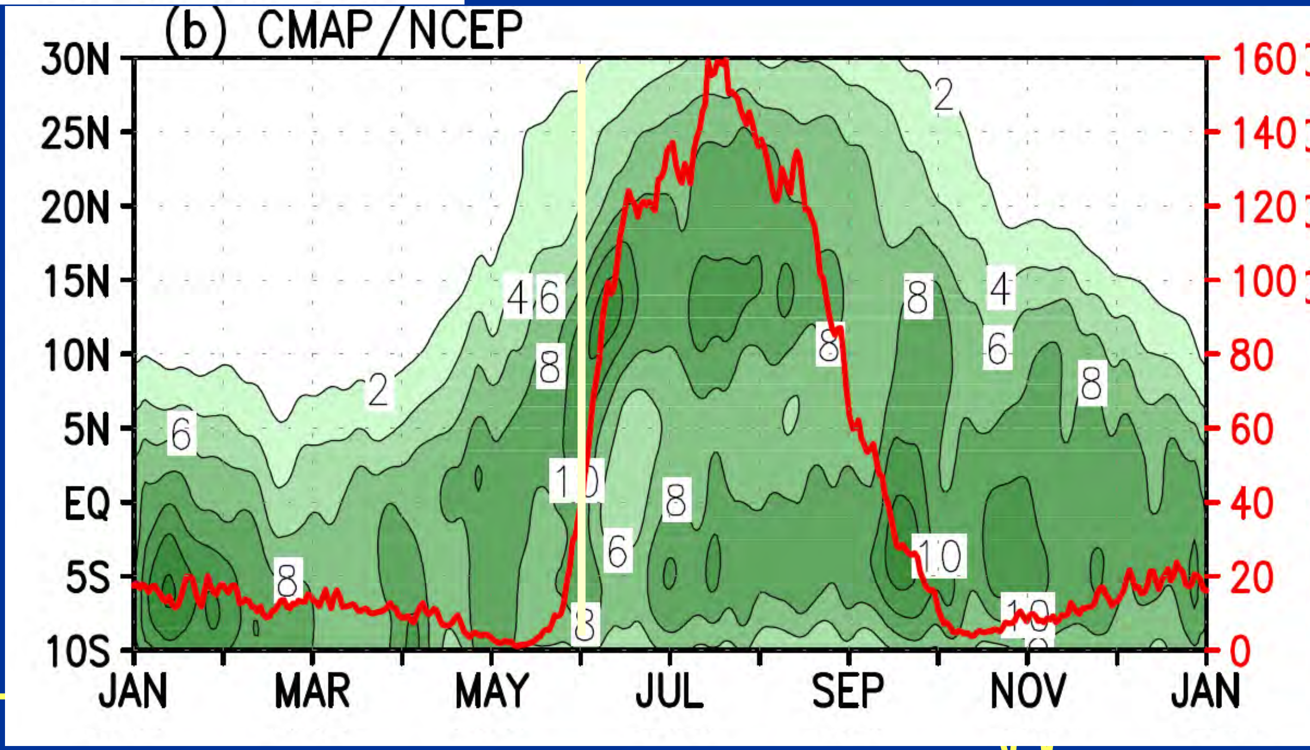
Meridional gradient of Tropospheric heating drives the monsoon circulation!

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


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

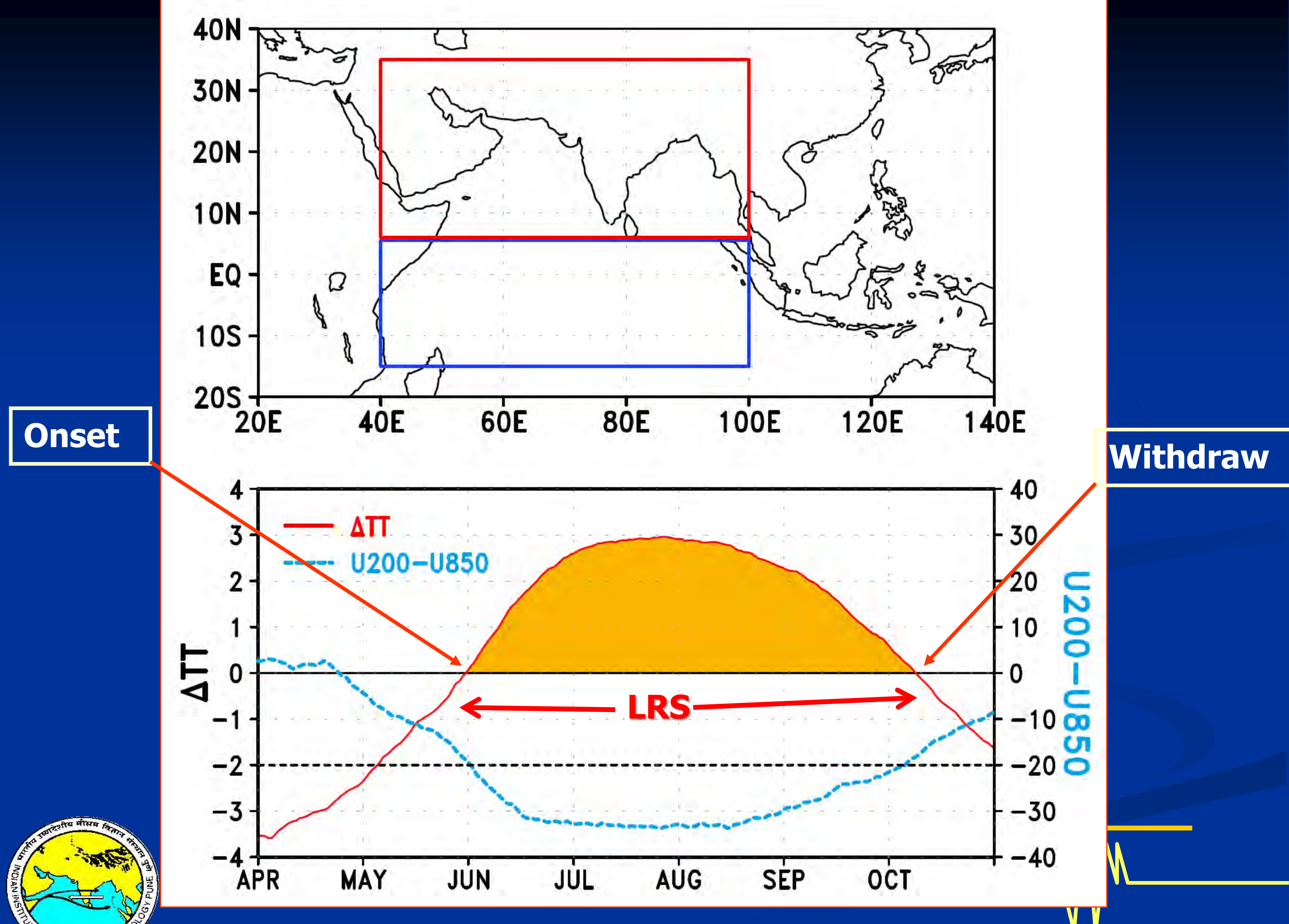


Tropospheric temperature averaged between 200 and 600 hPa (TT) averaged between 40E and 100E



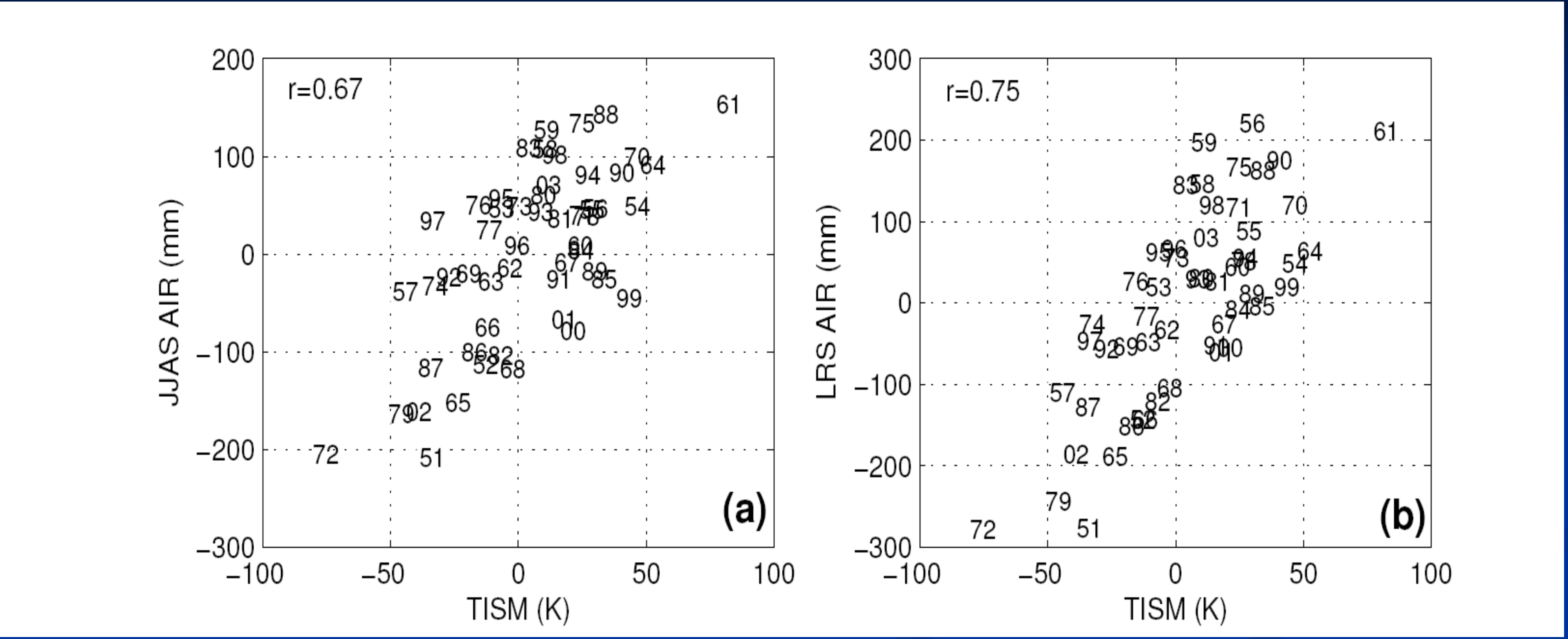
CMAP precipitation averaged between 70E and 90E (green) & K.E. at 850 hPa averaged over low level jet region (red line)

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



Onset
Withdraw
40N
30N
20N
10N
EQ
10S
20S
20E
40E
60E
80E
100E
120E
140E
ΔTT
U200–U850
LRS
APR
MAY
JUN
JUL
AUG
SEP
OCT

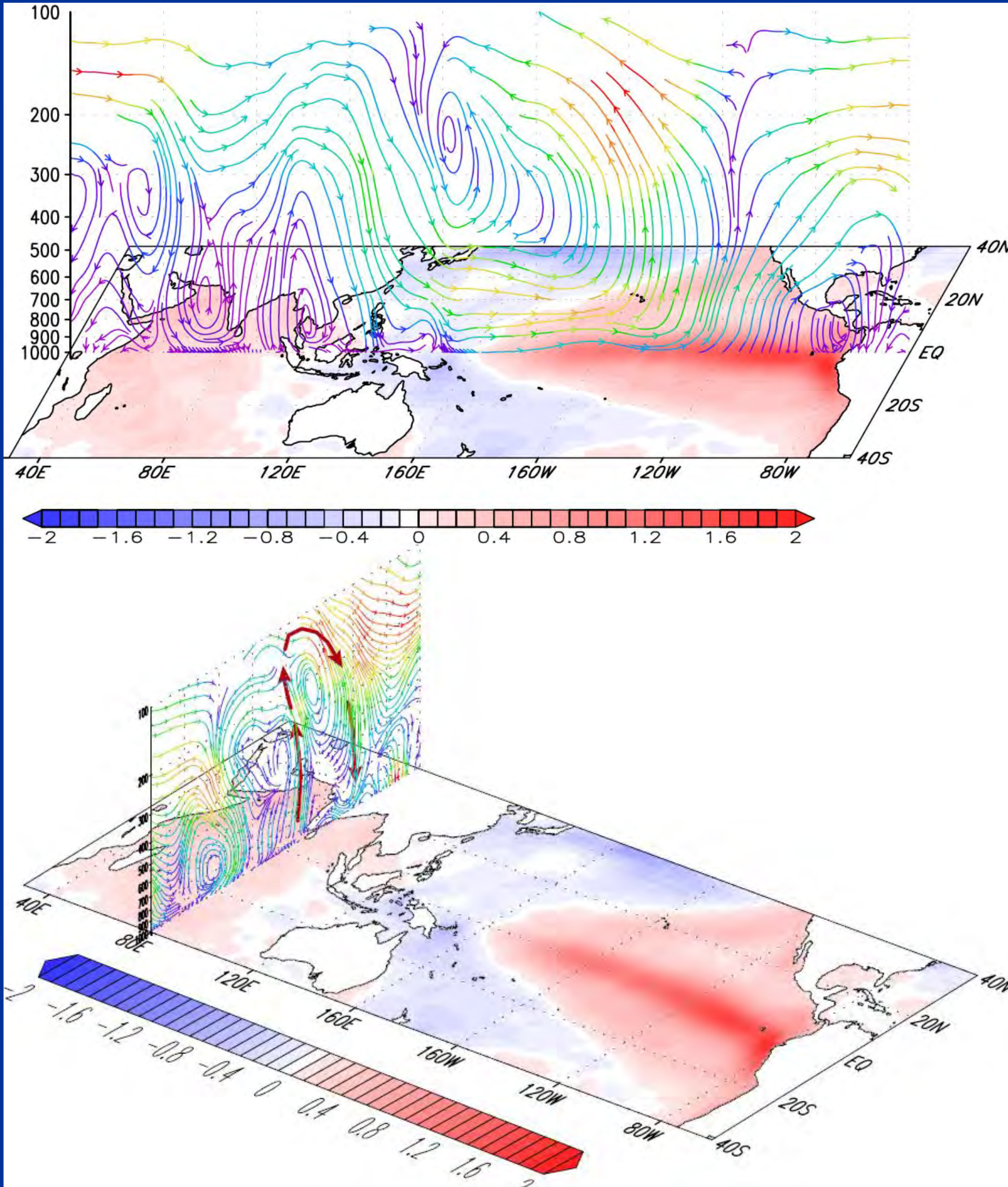
TISM : Integral of positive gradient of TT



Scatter plot of JJAS AIR and TISM (left) and LRS AIR and TISM (right). Correlation between the two are given in each panel

Xavier et al., 2007, QJRMS

Equatorial teleconnection with ENSO



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

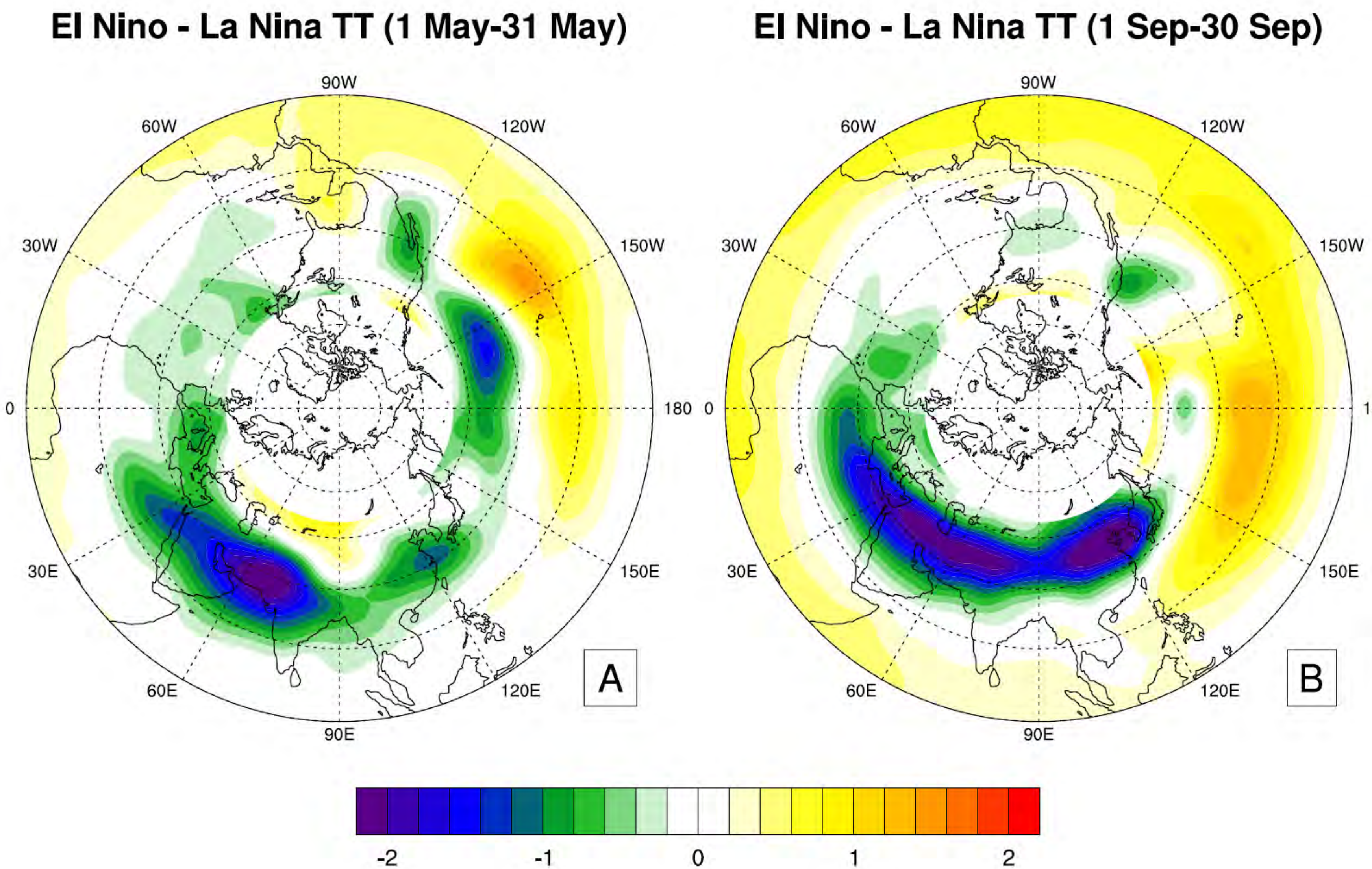
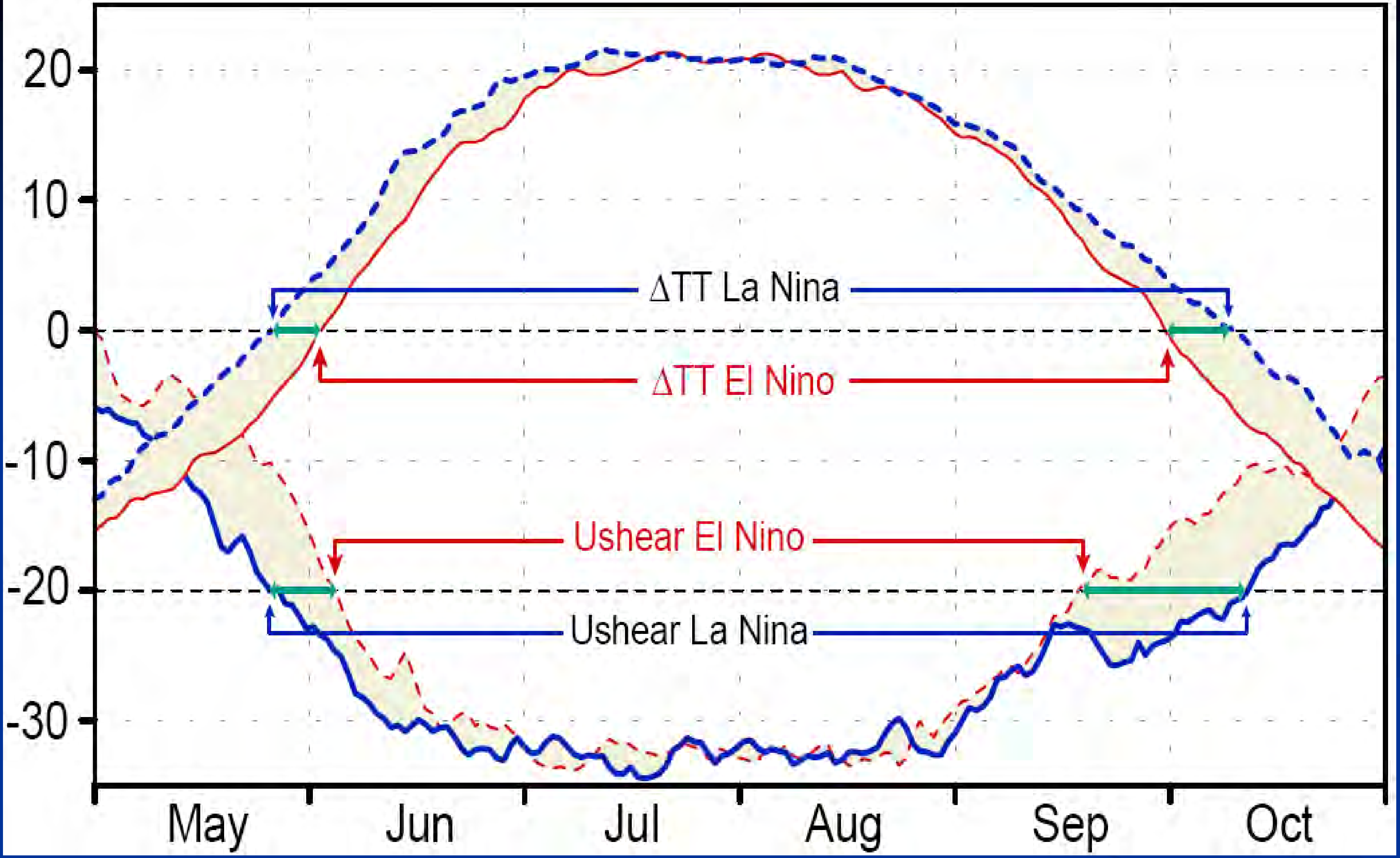


FIGURE 3.9: El Niño minus La Niña composites of TT (K) averaged between (A) 1 May and 31 May and (B) 1 September and 30 September. These are based on 11 El Niño (10 La Niña) years defined using normalized Niño3 SST anomalies being > 1 (< -1).

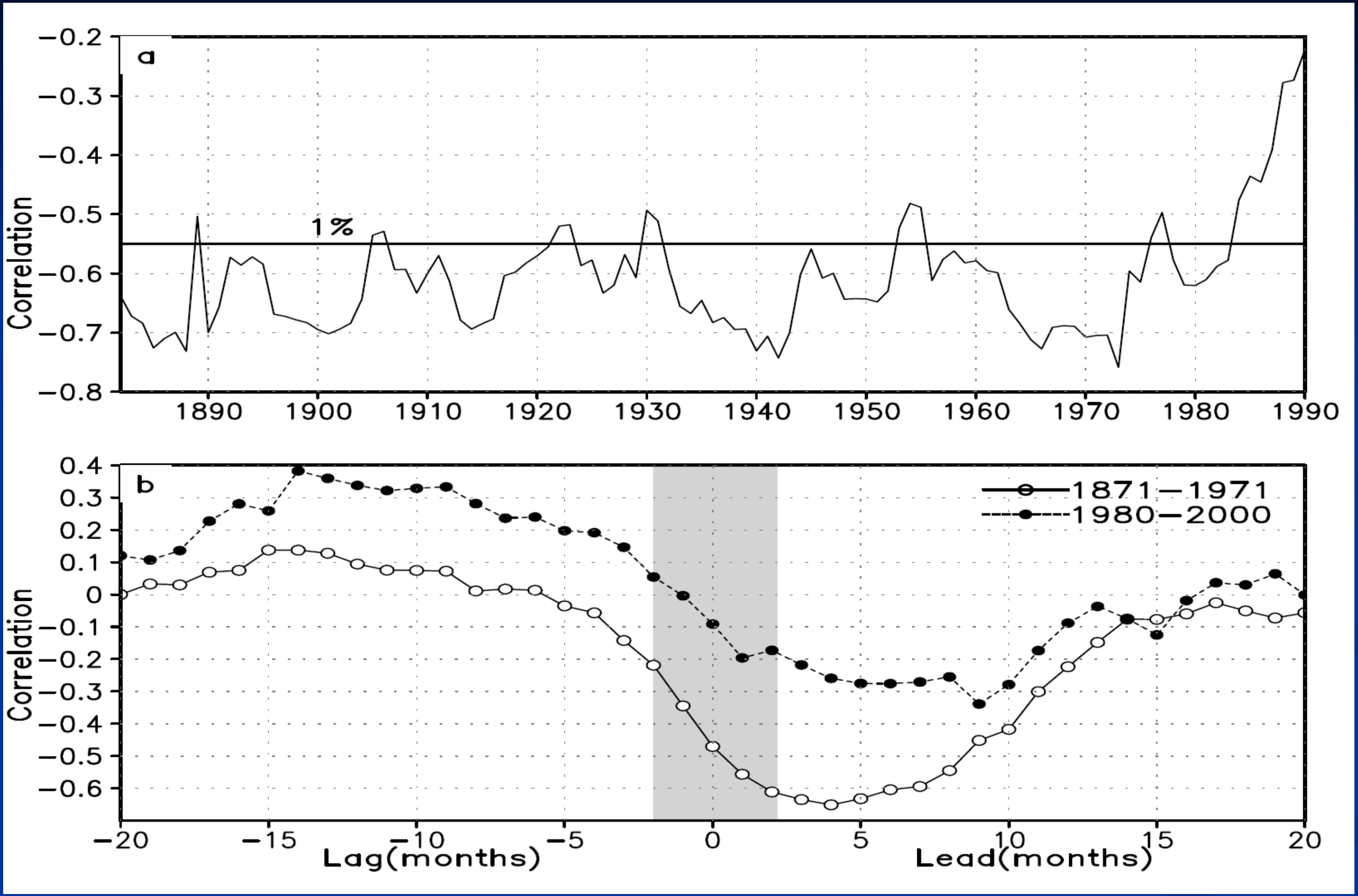
Extra-tropical Teleconnection with ENSO



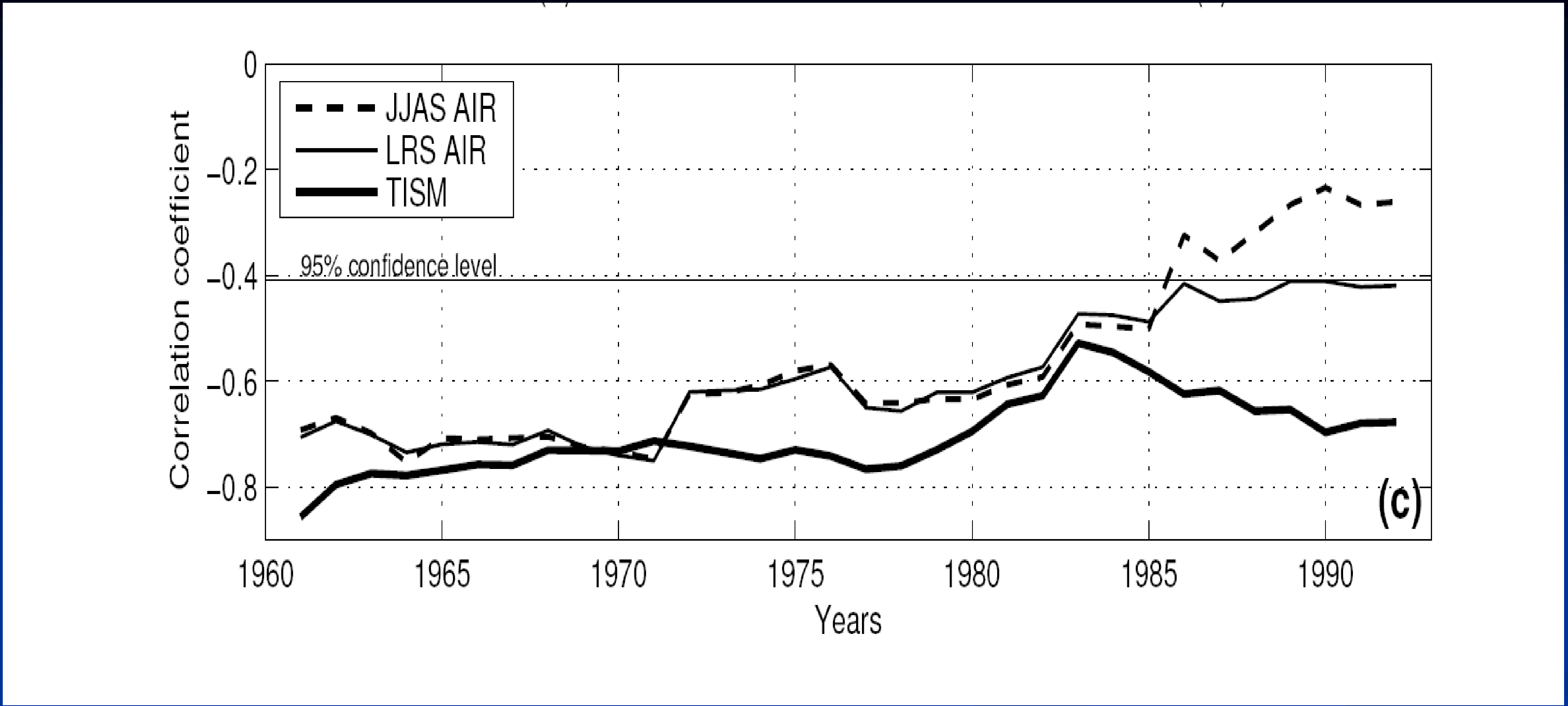
EL Nino and La Nina Composite of ΔTT and Ushear

Goswami and Xavier, 2005, GRL

ENSO-Monsoon Relationship: Interannual



(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.



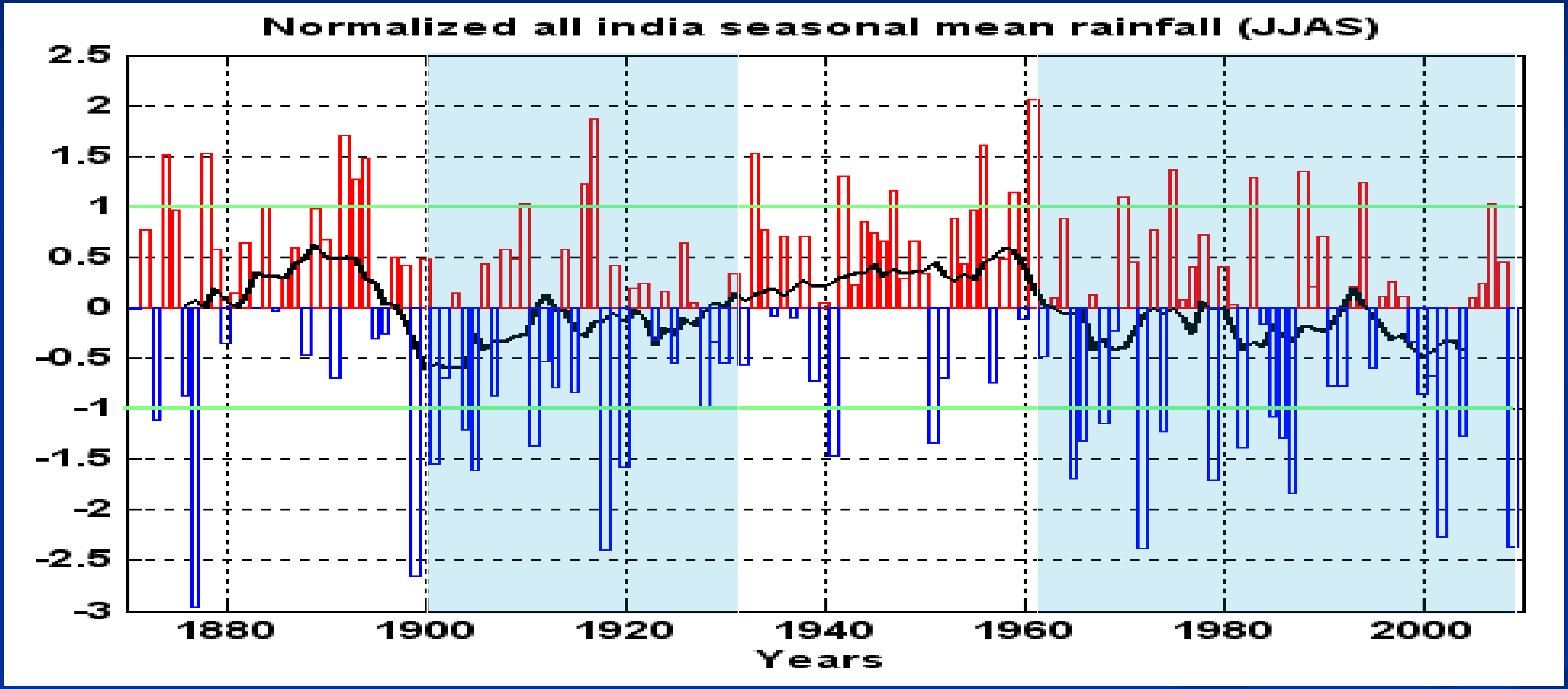
21-year running window correlation between Nino3 JJAS SST and JJAS AIR, LRS AIR and TISM

Xavier et al., 2007, QJRMS

Multi-decadal variability of the Indian Monsoon Rainfall and Mega-droughts

All India Rainfall (AIR): Interannual Variability

Mean : 86 cm; S.D. : 8.5 cm



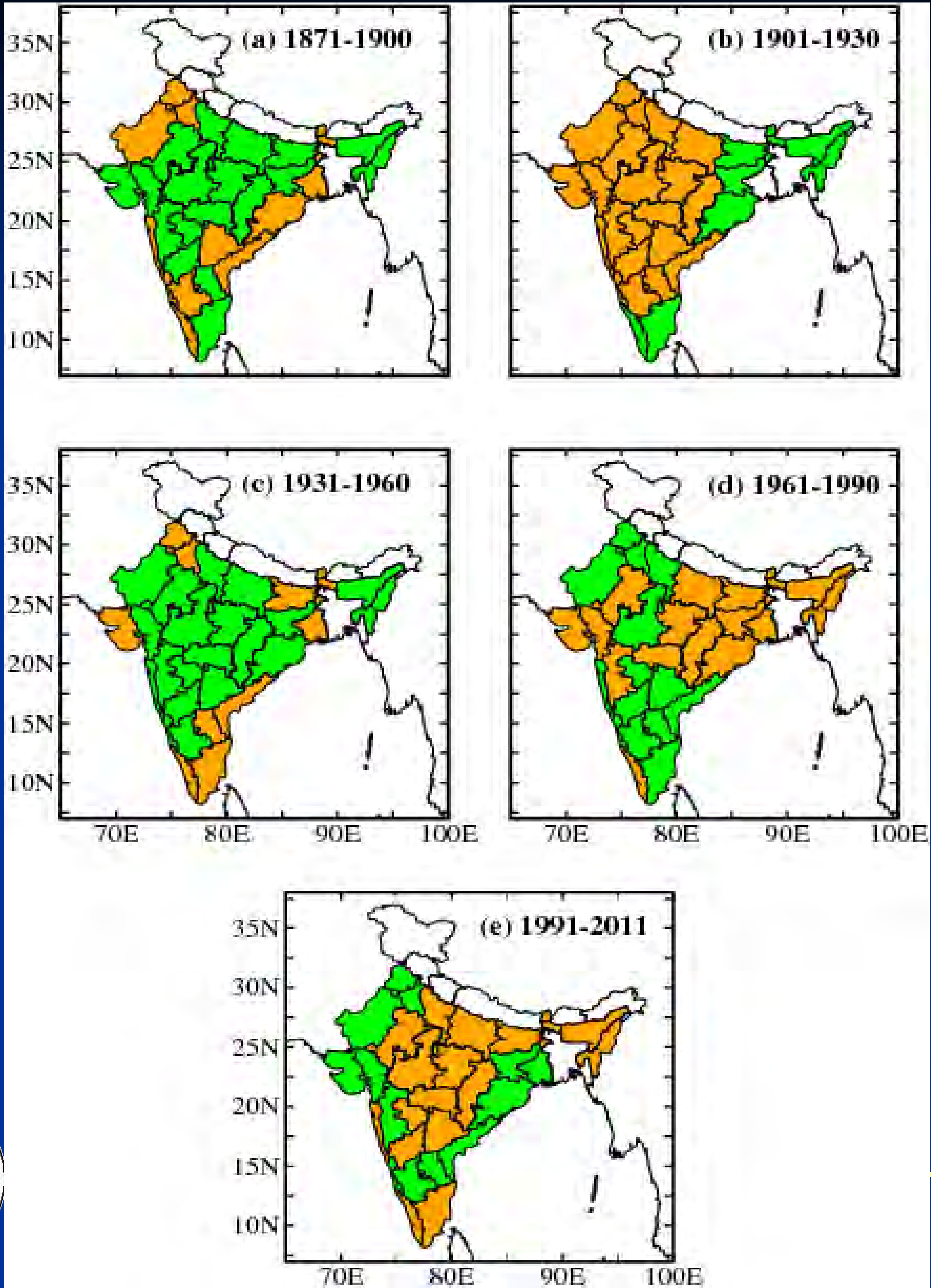
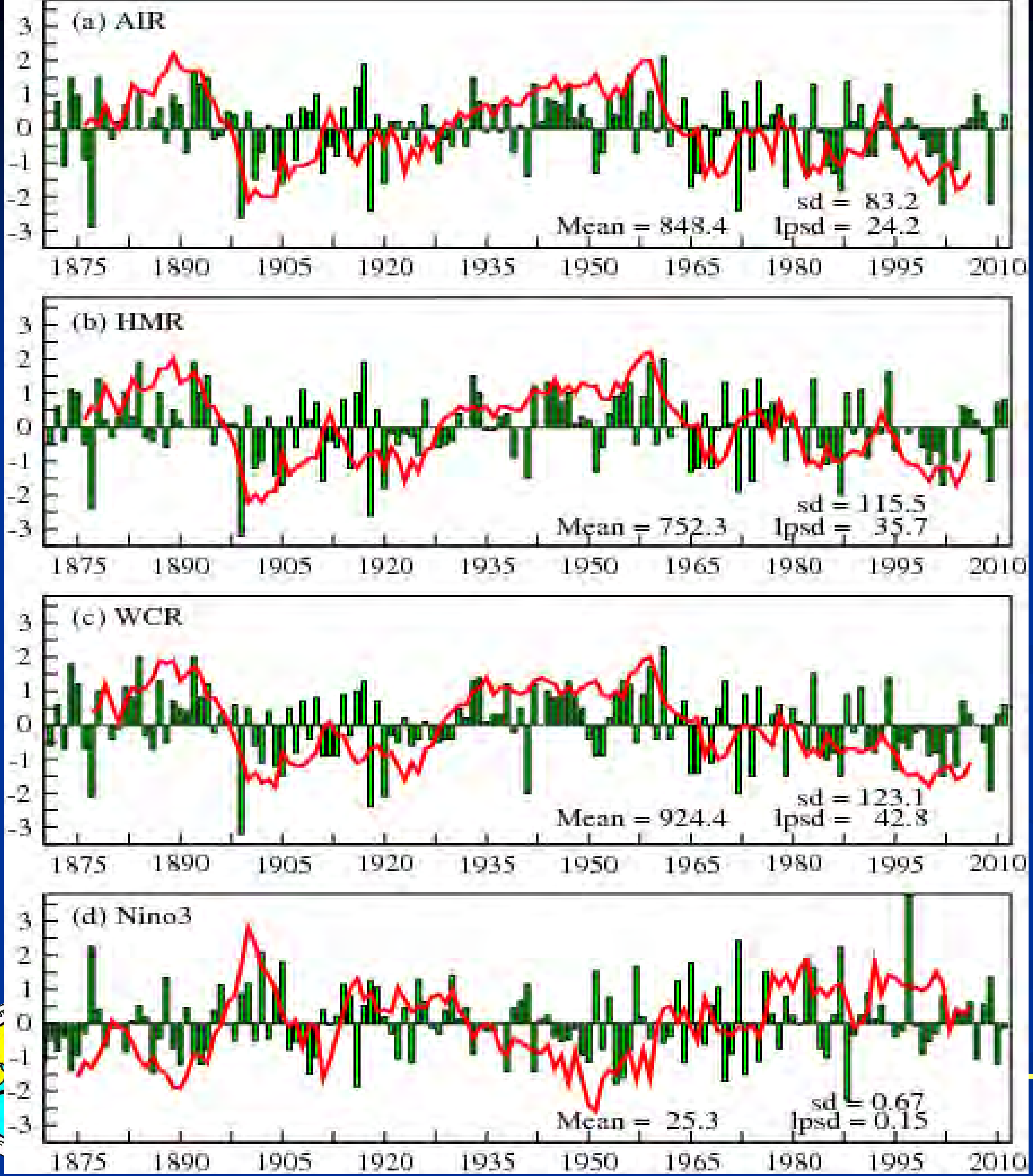


Fig. 2

Spatial distribution of rainfall

Anomalies based on

1871-2011



11 year running mean

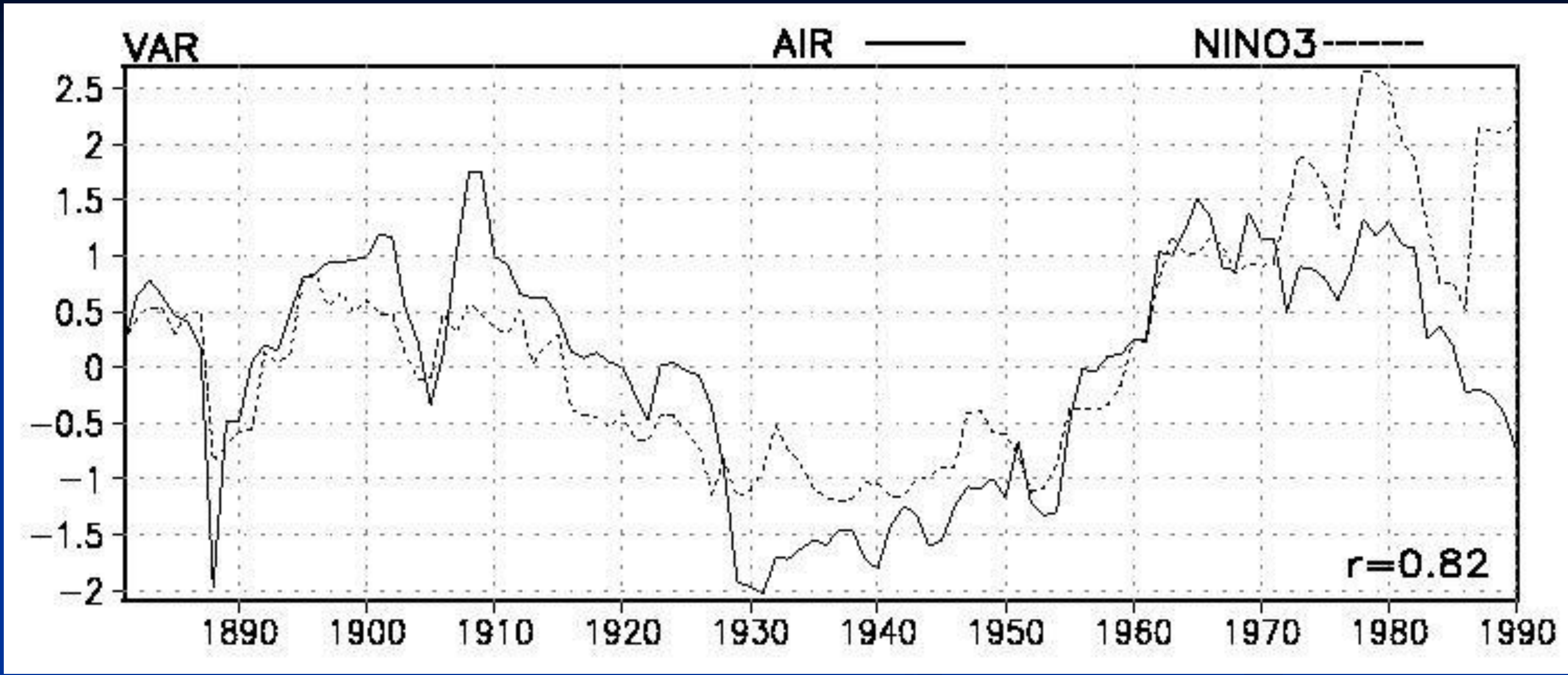
Fig. 1

Data Source

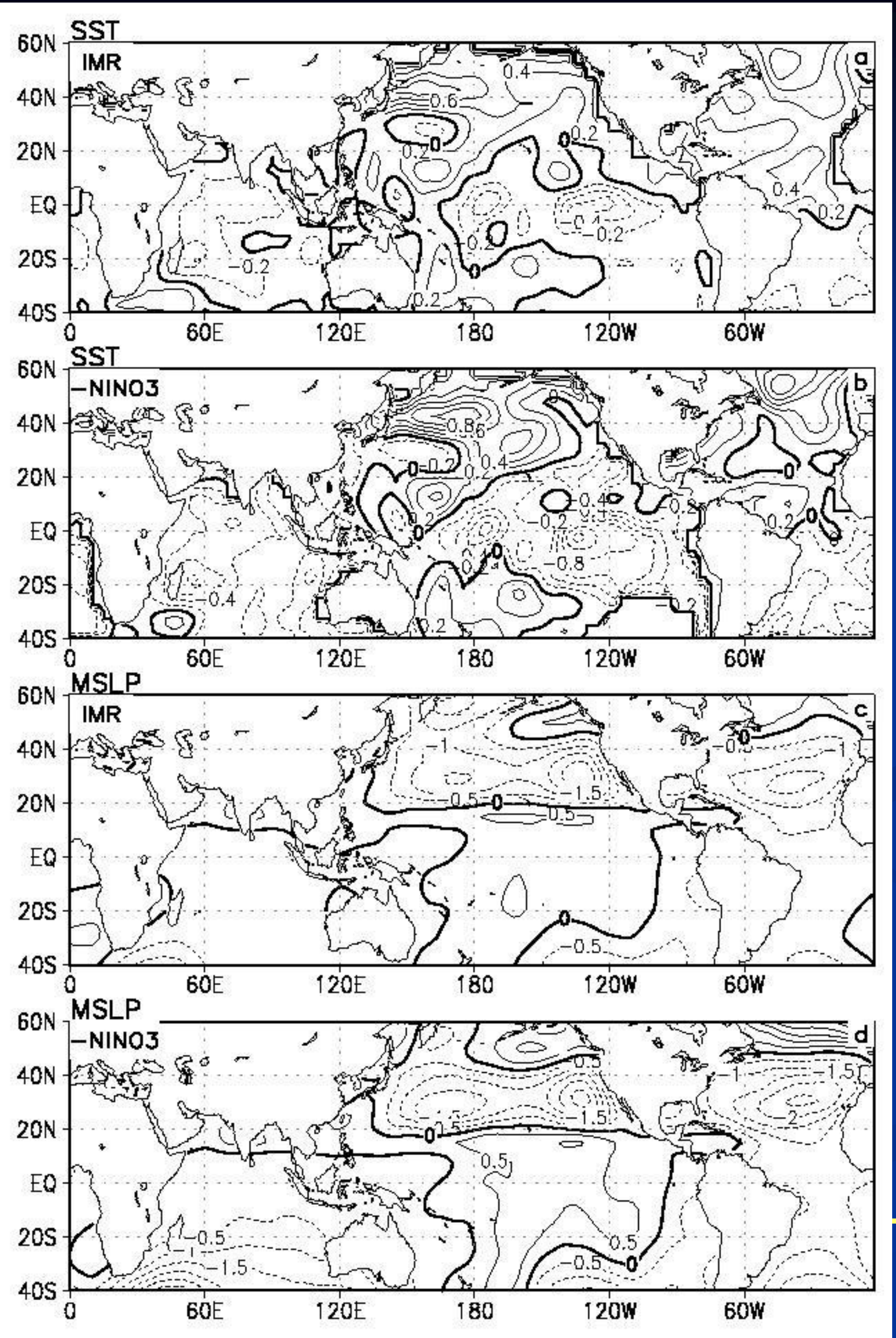
Rainfall : IITM

SST : HadISST

Indian monsoon rainfall and ENSO are linked on multidecadal time scale too



Interdecadal variability of interannual variance of normalized AIR (solid) and JJAS Nino3 SST(dotted) using a 15-year moving window. The correlation (r) between the two is shown.



Spatial pattern obtained by regressing global SST (top two panels) and global SLP (bottom two panels) on low pass filtered AIR and -Nino3 (shown in Fig.1) respectively. Negative contours are dashed and contour interval is 0.1 K per standard deviation for SST and 0.1 hPa for SLP respectively.

Krishnamurthy and Goswami, 2000

- **Mega Droughts in recent past**

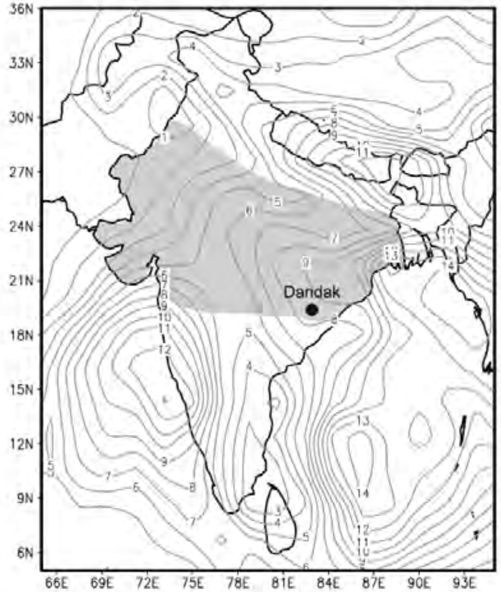
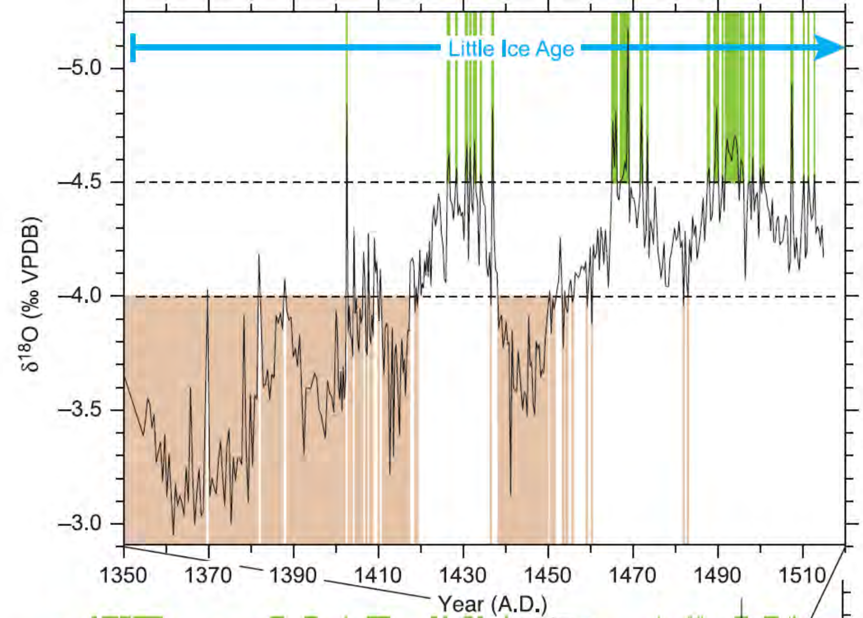


Figure 1. Location of Dandak Cave, Kanger Valley National Park, Chhattisgarh, India. Contours indicate Southwest Indian summer monsoon mean precipitation rate (mm/day) from NCEP/NCAR reanalysis dataset (June to September, 1948 to 2006). Shaded region represents the core monsoon zone of India.



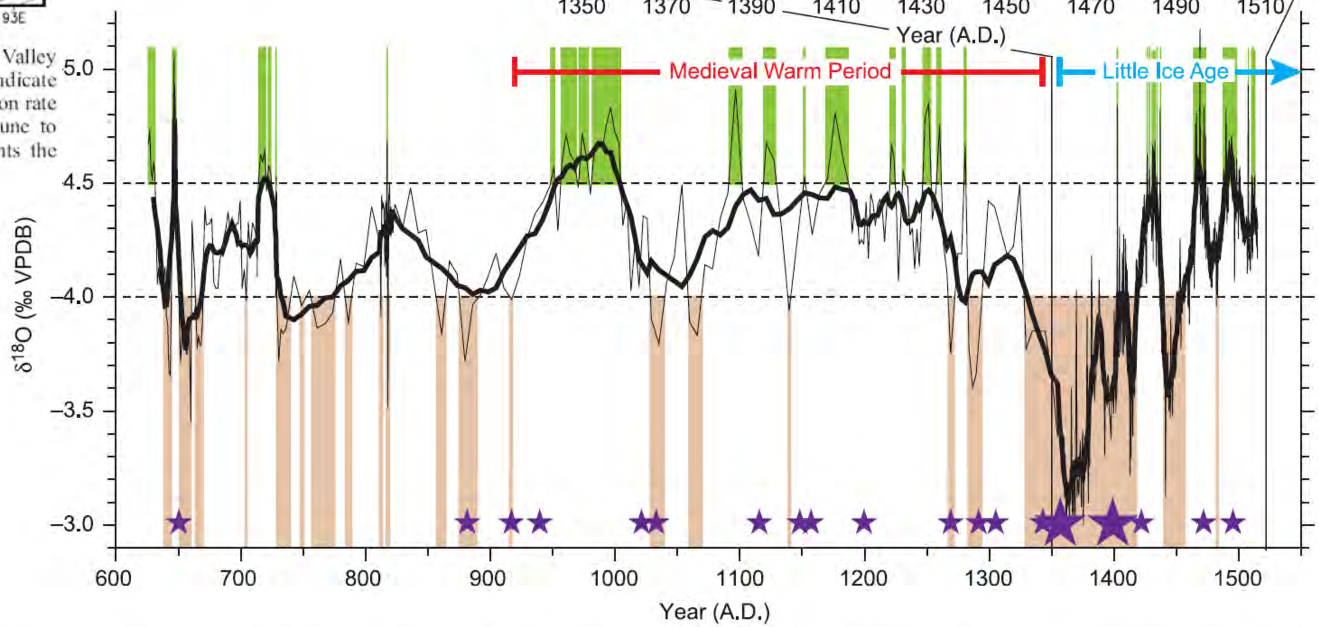


Figure 3. $\delta^{18}O$ record of Dandak Cave stalagmite. Thick line is 9-point running mean. Dashed lines indicate $\delta^{18}O$ range of calcite from Dandak Cave stalagmites deposited during the modern instrumental period. Intervals of inferred stronger monsoon shaded green and intervals of weaker monsoon shaded brown. Purple stars indicate timing of historical famines in India (two large stars indicate decadal length famines).

Sinha et al., 2007, GRL, vol. 34, L16707

- **Paleo-climatic evidence of mega-droughts of Indian monsoon and linkages between North Atlantic Temperature and Indian Monsoon**

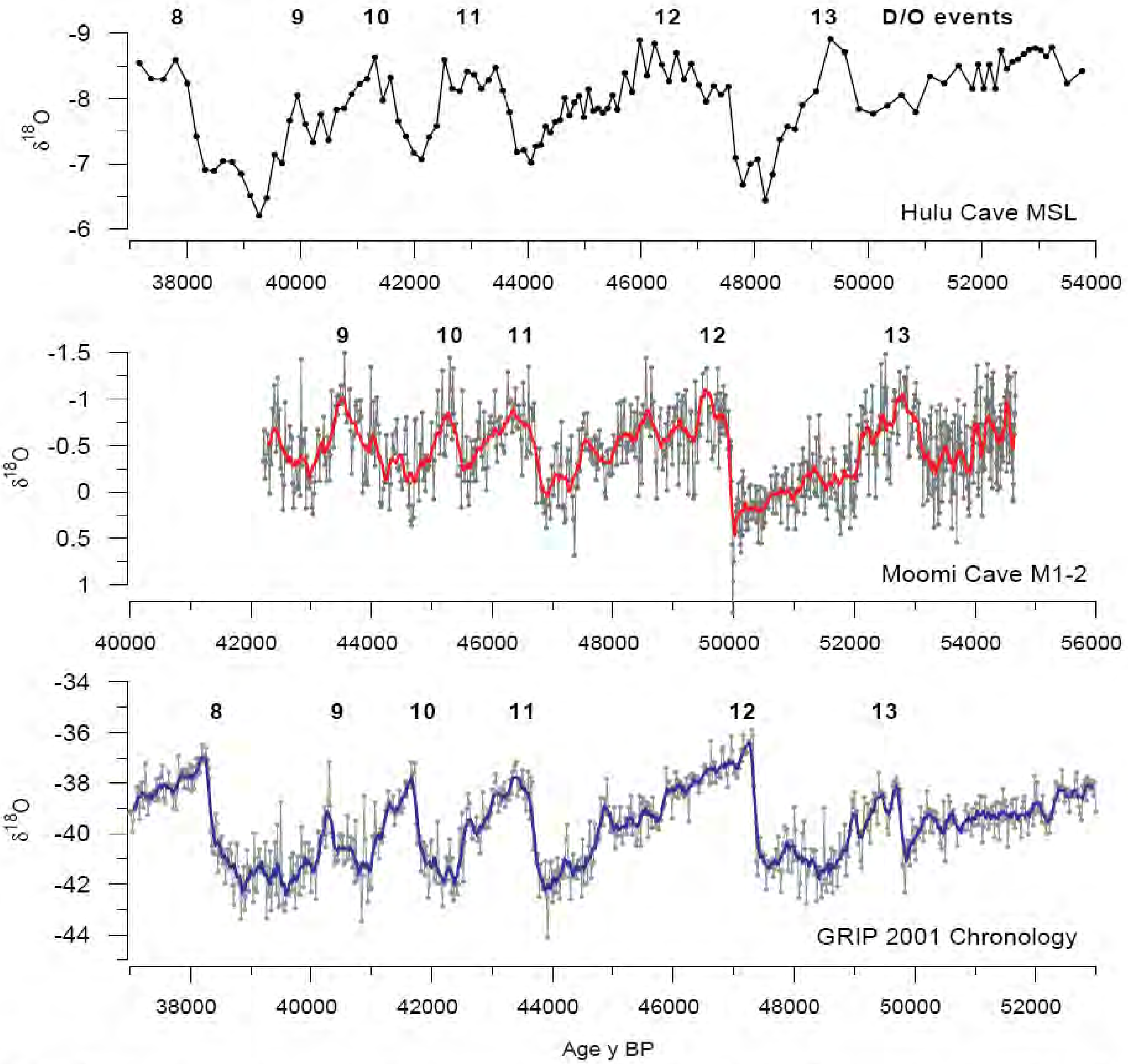


Fig. 2. Comparison of the oxygen-isotope ratios of stalagmite M1-2 with oxygen isotopes from the GRIP ice core (*2*) and the $\delta^{18}O$ record of a stalagmite from Hulu Cave in central China (*4*). The time scales are independent and shifted to give the best fit for D/O events. The oxygen isotopic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

NA Temp & Monsoon

Sacotra Is.

12°30'N,54E

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

NA Temperature & Indian Monsoon

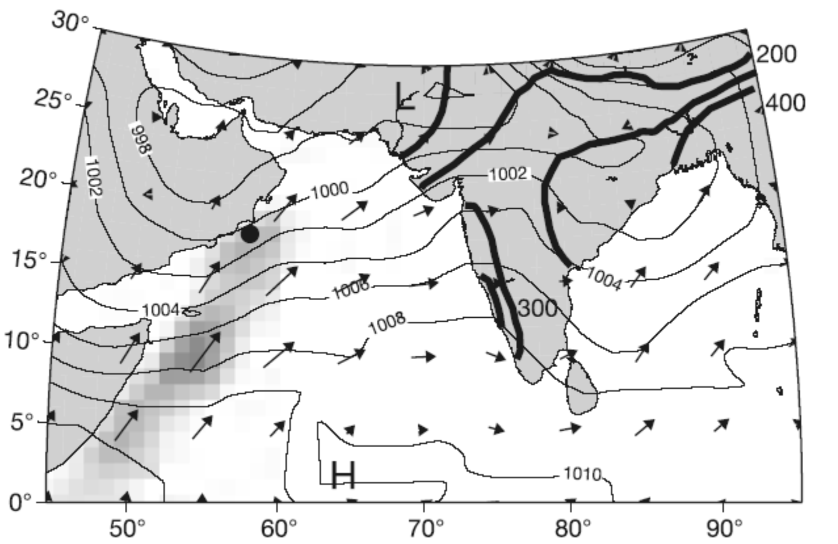


Figure 1 July sea-level pressure (mbar, thin contours), wind direction[27], cooling of the Arabian Sea due to upwelling[28], and precipitation over Asia[29] (mm month^{-1}, thick contours). Site 723 and box core RC2730 are located at 18° N, 58° E (circle). H, high pressure; L, low pressure.

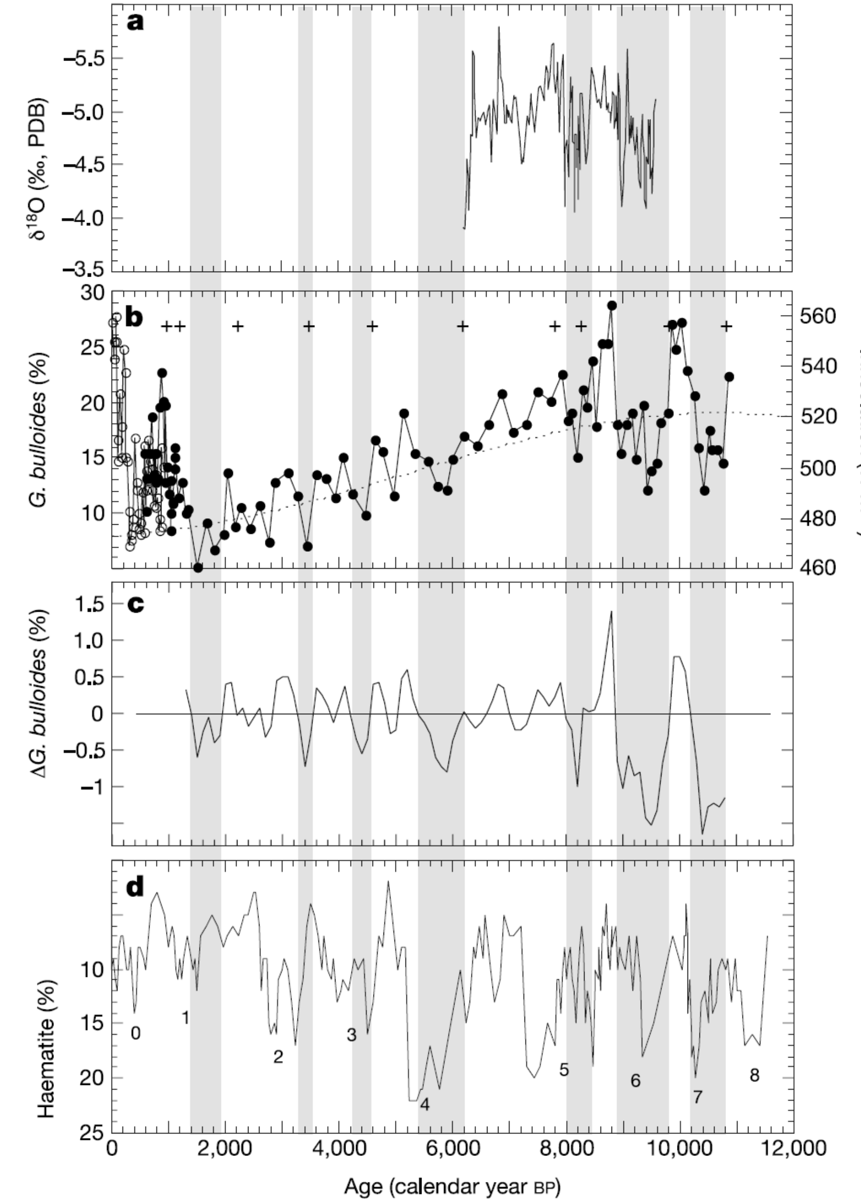
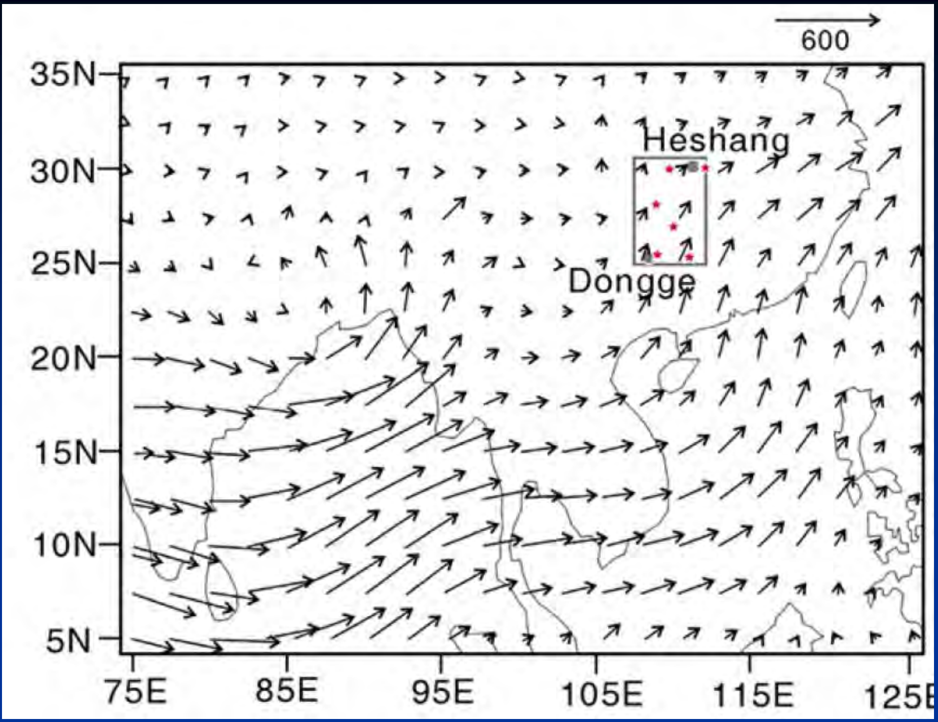
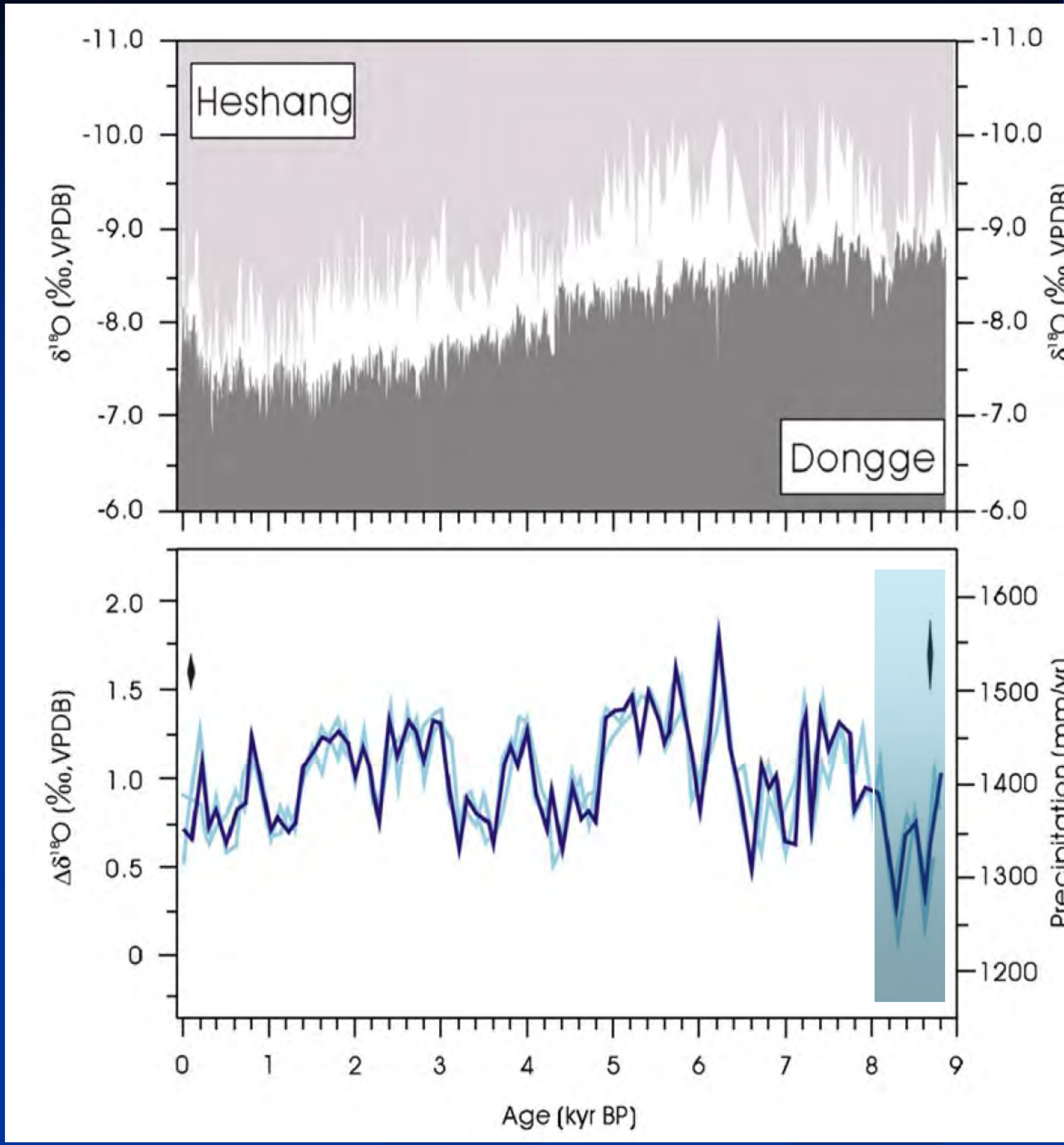


Figure 2 Southwest monsoon proxy record from the Arabian Sea Site 723A and box core RC2730 combined with Oman cave stalagmite δ^{18}O and North Atlantic haematite percentage. Time series of **a**, cave stalagmite δ^{18}O from ref. 16, **b**, *G. bulloides* percentage in Hole 723A (filled circles) and box core RC2730 (open circles) from the Arabian Sea (detail in Fig. 3), and July insolation at 65° N (ref. 18, shown by dotted line; radiocarbon-dated intervals shown by crosses), **c**, change in *G. bulloides* percentage (normalized by removing the trend related to insolation), and **d**, haematite percentage in core MC52 -VM29-191 from the North Atlantic, and events labelled 0–8 in ref. 4. The vertical grey bars indicate intervals of weak Asian SW monsoon.

Gupta, Anderson and Overpeck, 2003, Nature, 421, 354





Chaoyong Hu et al. , 2008, EPSL, **266**, 221-232

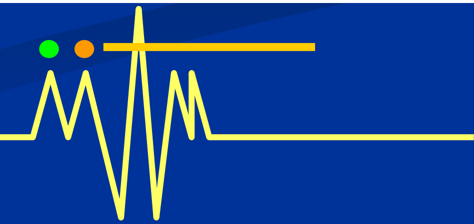
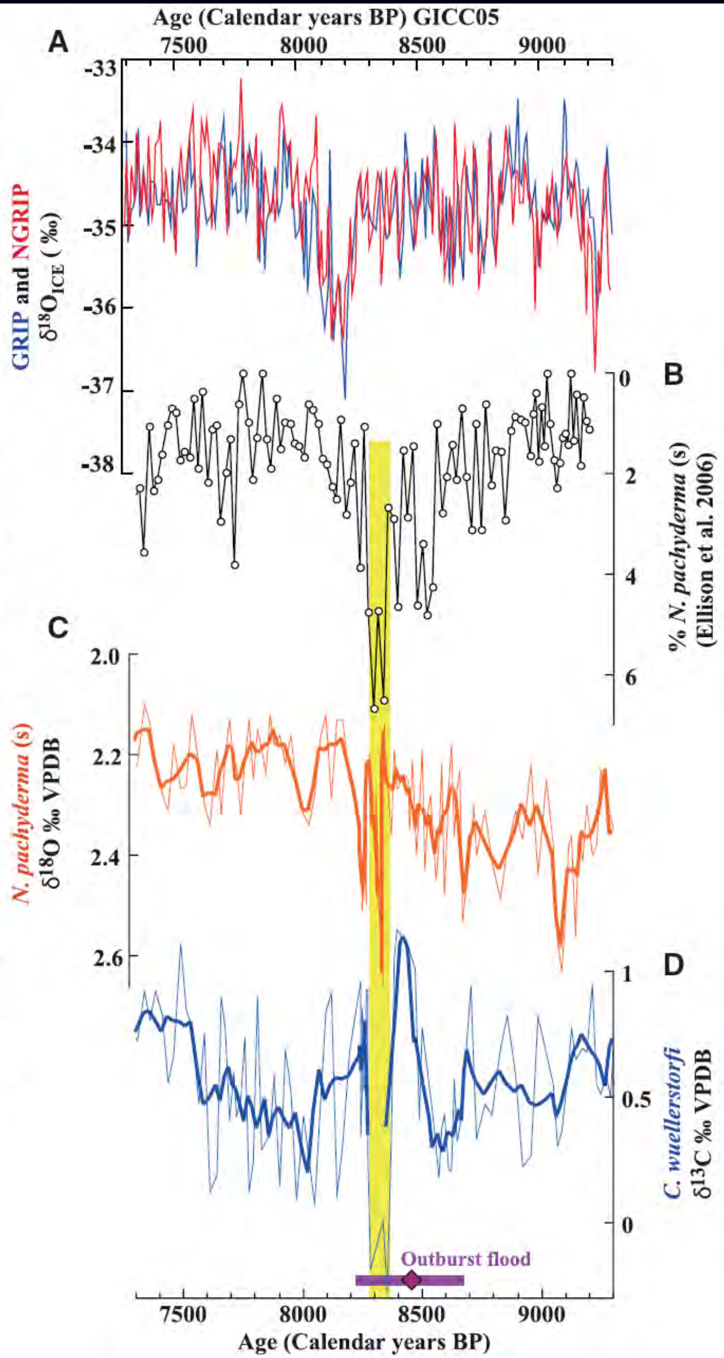


Fig. 4. Paleoceanographic records along core MD03-2665 compared with *Neogloboquadrina pachyderma* (sinistral coiling) percentage counts from core MD99-2251 and NGRIP and GRIP ice core data over the interval 7300 to 9300 calendar years B.P. **(A)** NGRIP and GRIP $\delta^{18}O_{ice}$‰ after (*37*) plotted on the ice core chronology of (*38*, *39*). **(B)** Percentage *Neogloboquadrina pachyderma* sinistral coiling after (*16*). **(C)** *Neogloboquadrina pachyderma* sinistral coiling $\delta^{18}O$‰ VPDB plotted with a 5-point running mean. **(D)** *Cibicidoides wuellerstorfi* $\delta^{13}C$‰ VPDB plotted with a 5-point running mean. The yellow vertical bar highlights the interval where LNADW influence is inferred to be absent at our site. Also shown is the age for the Lake Agassiz drainage event: 8470 years B.P. (*7*) (purple diamond), with its 1 SD uncertainties (8160 to 8740 years B.P.) denoted by a purple line. The age model used for (C) and (D) is described in the Supporting Online Material.



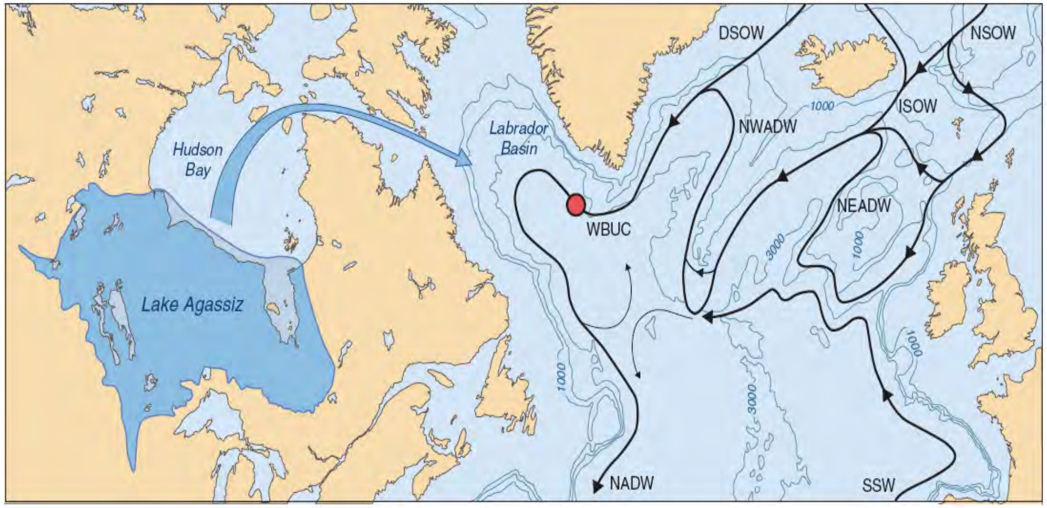


Fig. 1. Map of study area with the location of core MD03-2665 (57°26.56N, 48°36.60W; 3440-m water depth) marked with a red circle. The black arrows indicate the overflows and spreading pathways of deep and intermediate currents, after (*21*, *35*, *36*). The total area covered by Lake Agassiz is shaded, and the general routing of the overflow and outburst through the Hudson bay to the North Atlantic is marked with a blue arrow [modified after (*9*)].

Helga et al. 2008, Science, 319, 60-64

Atlantic mutlidecadal variability (AMO) and Indian monsoon

Goswami et al. 2006, GRL, vol.33, L02706

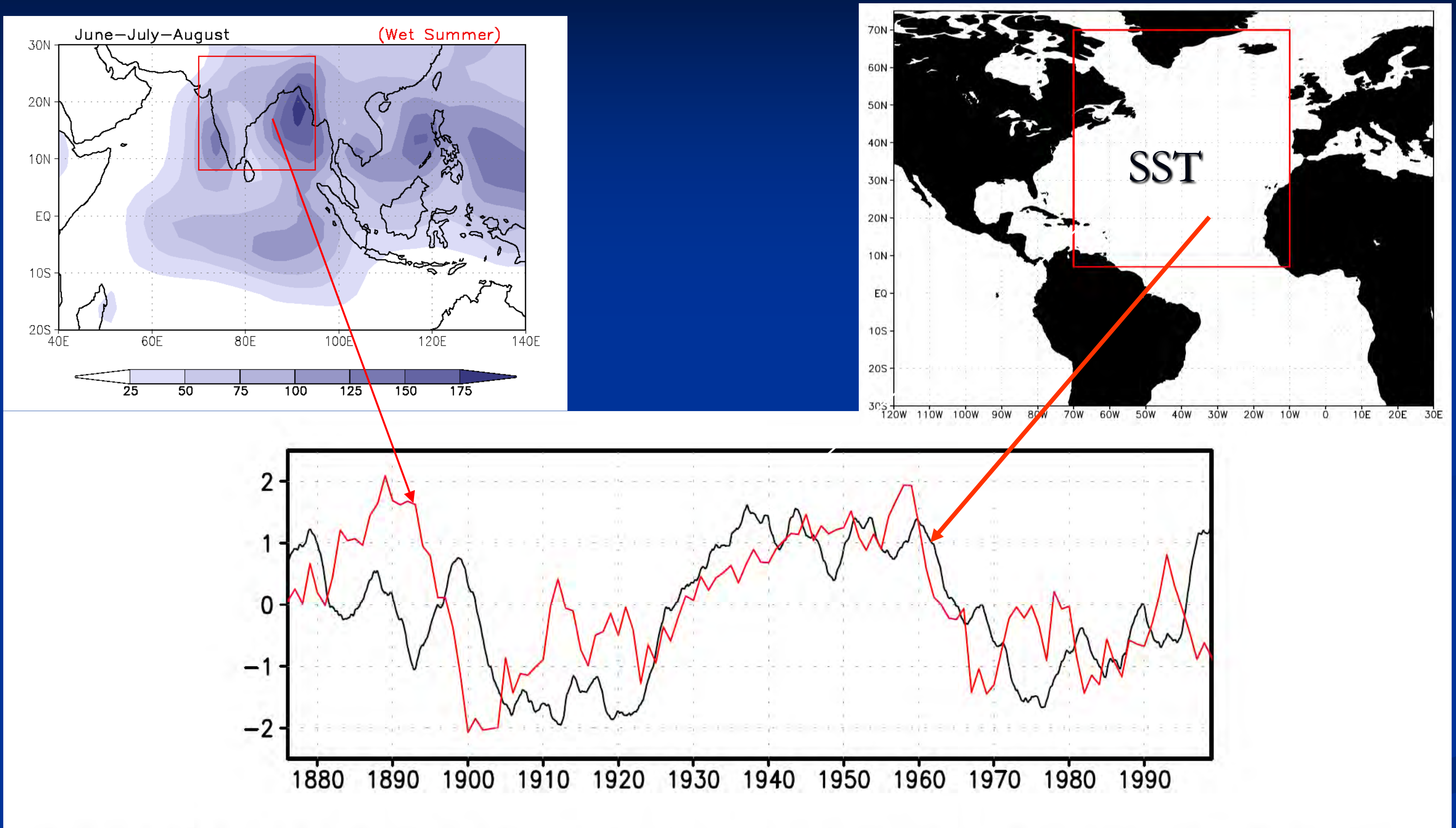
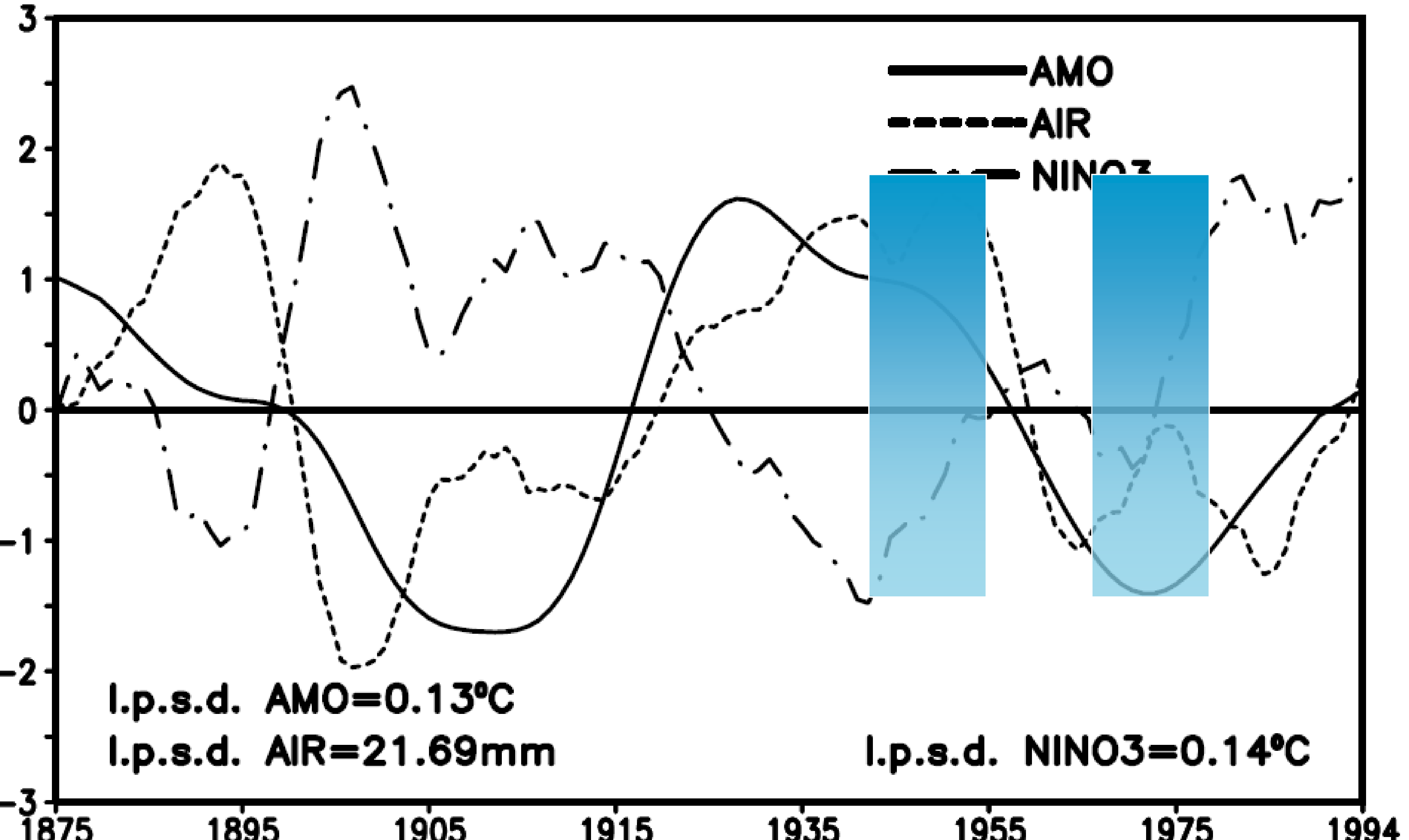
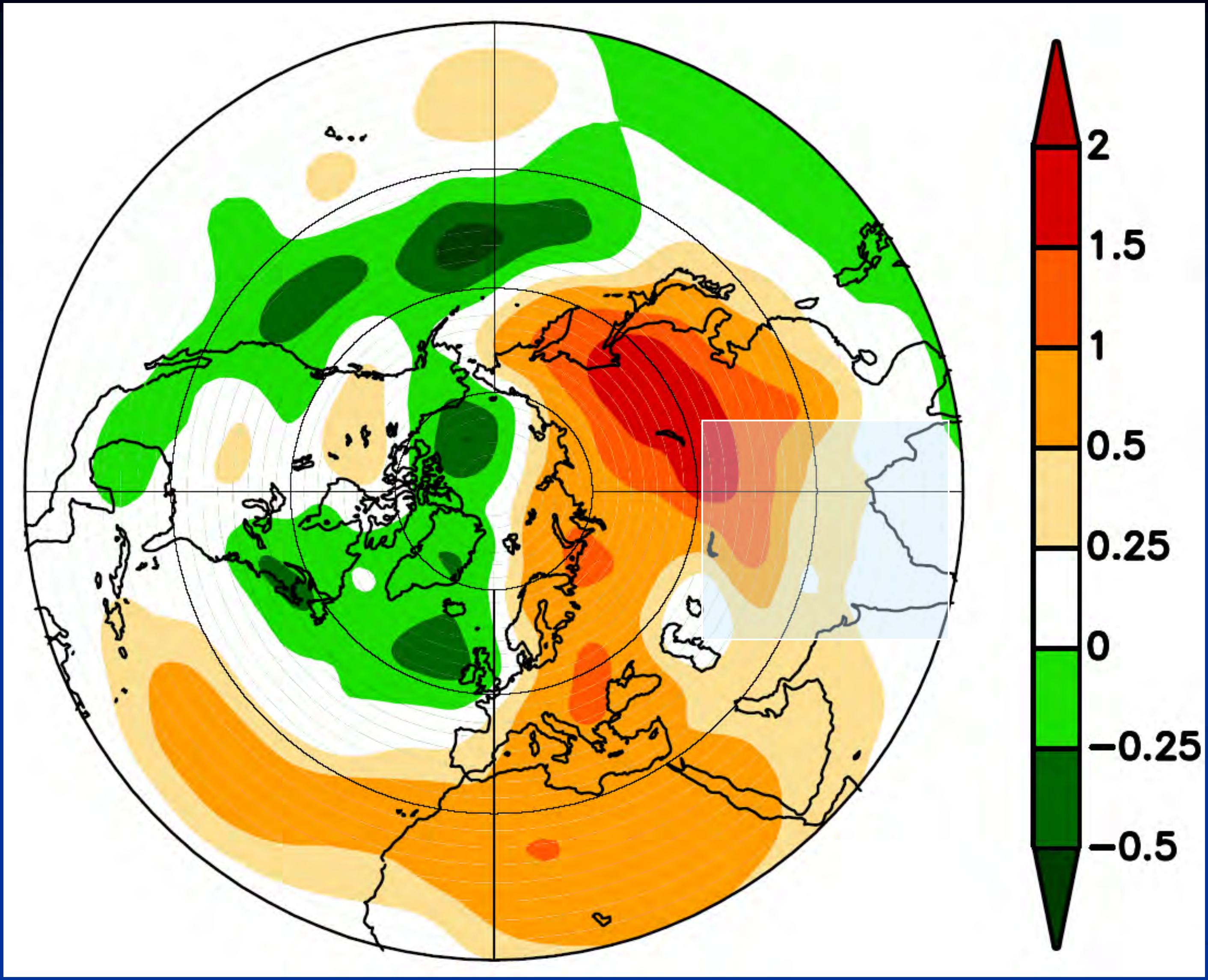


Figure 7: Multidecadal oscillation of AIR (red line, obtained from 11-yr running mean of JJAS mean all India rainfall) and Atlantic multidecadal oscillation (AMO, black line). AMO is based on 60-month running mean of monthly anomalies averaged over Atlantic north of Equator.


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



Goswami et al. 2006, GRL

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

INDIAN INSTITUTE OF TROPICAL METEOROLOGY PUNE

+ (-) 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

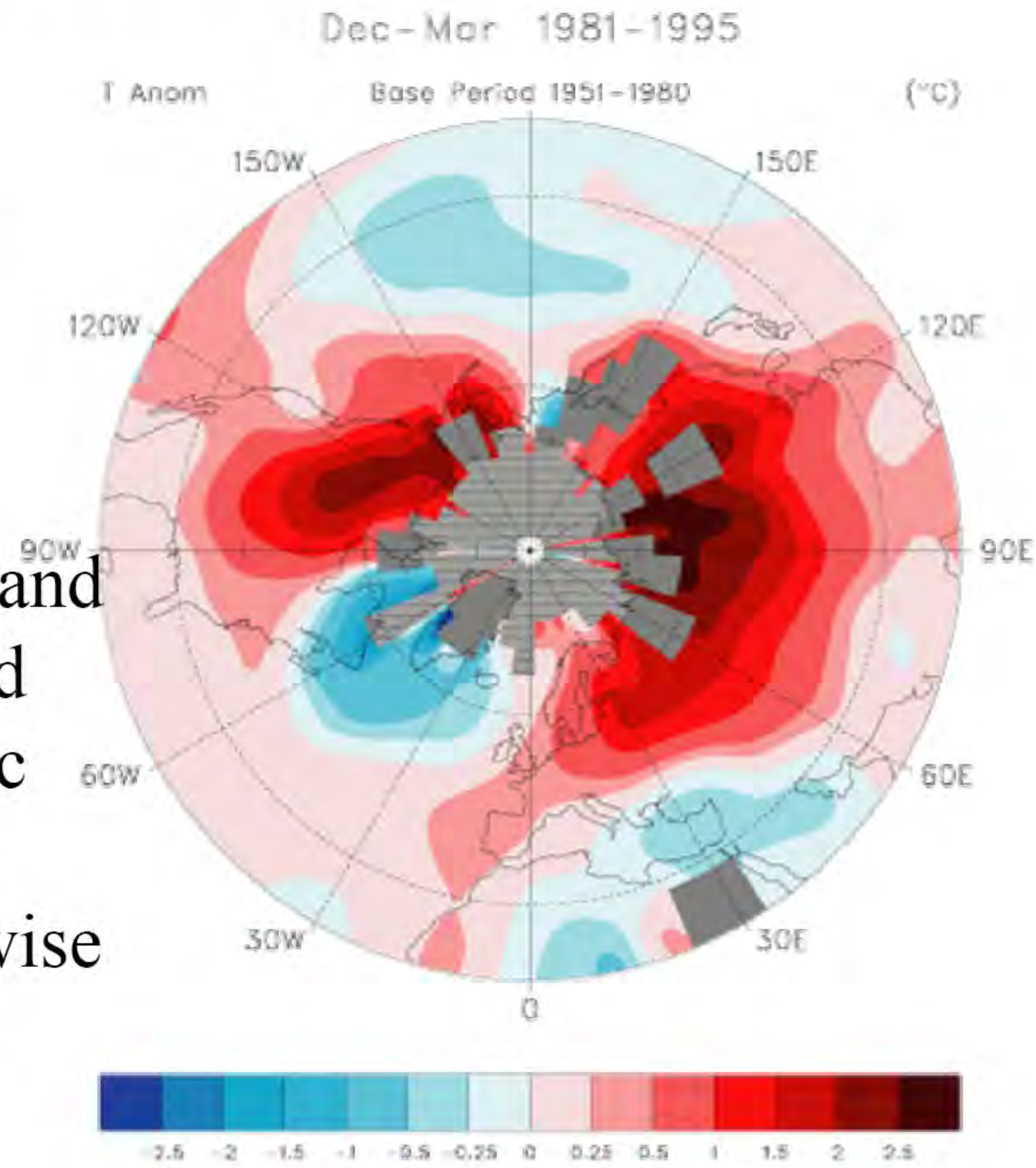
Hypothesis:

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

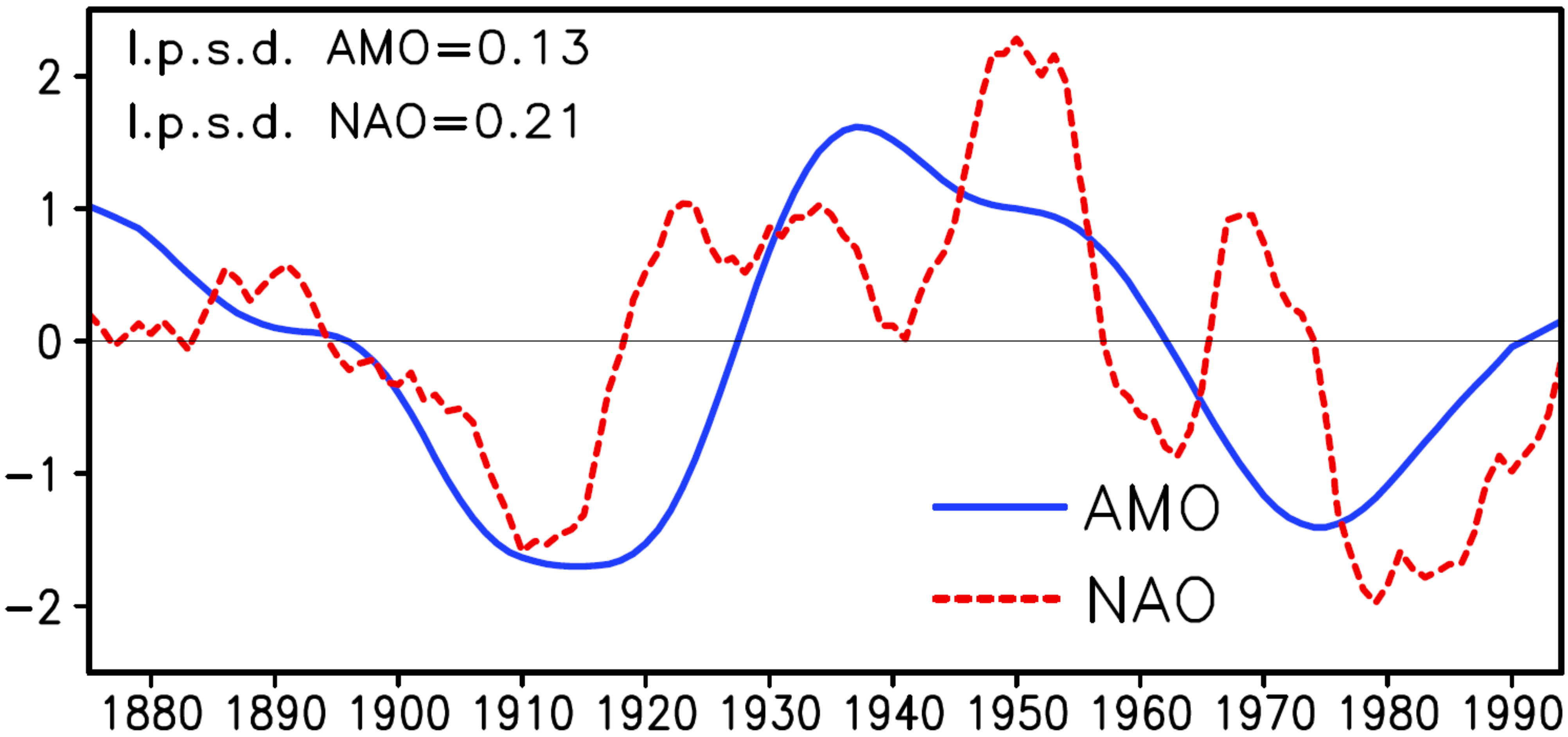
Impacts of the NAO: Temperature

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



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

+ (-) AMO phases of NA SST

Strong (weak) Indian summer monsoon

Higher frequency of Strong + (-) NAO events

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

Changes in the Jet stream and storm tracks

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

Question:

- **With the extra-tropical teleconnection between North Atlantic and Indian monsoon established, is it a reasonable question to ask whether Global Warming to take Indian monsoon to Mega-drought state?**

Conventional wisdom

Global Warming

More moisture

in Atmos.

Stronger
Hydrological
Cycle

Strong Monsoon.

More floods

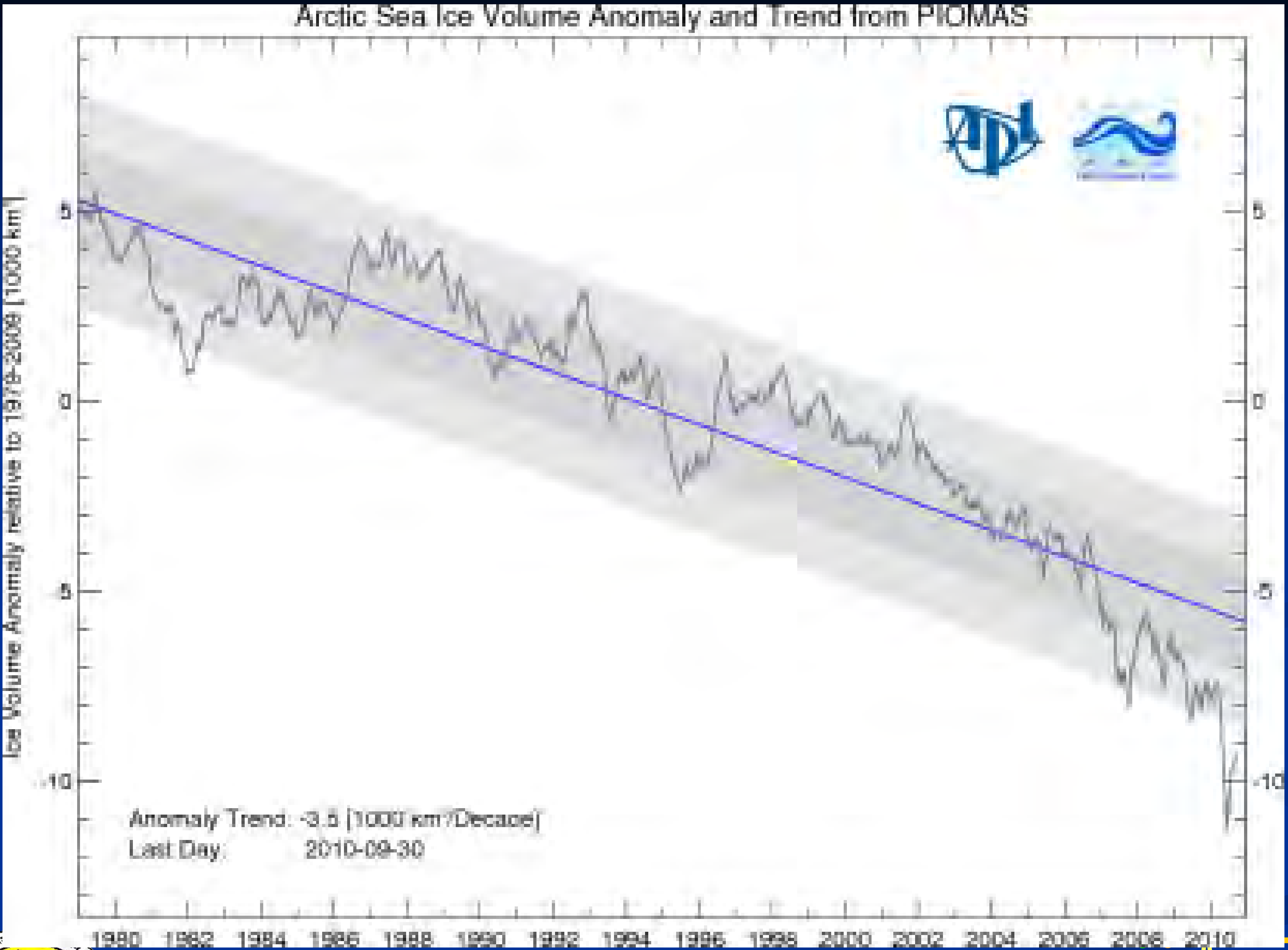
Another possibility!
(Through Internal Feedback of climate system)

Global Warming

Melting Arctic & Greenland Ice

Cooling of North Atlantic

Monsoon Mega Drought



Courtesy, Arctic Sea Ice Centre, University of Washington

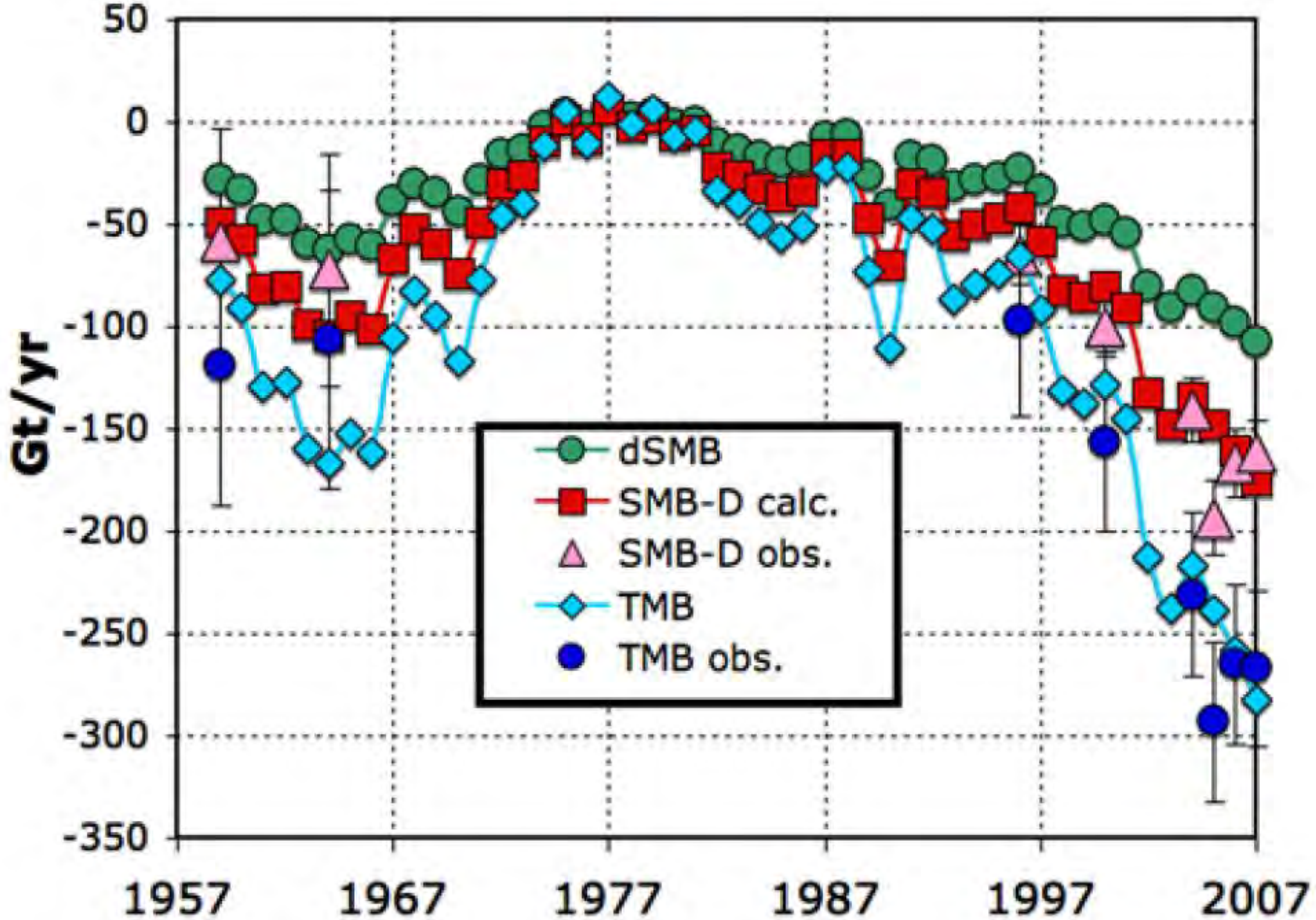


Figure 3. Interpolated (TMB, light blue diamonds) or observed (dark blue circles) total ice sheet mass balance for 1958–2007 combining anomalies in SMB (δSMB, green circles) and interpolated (SMB-D, red squares) or observed (pink triangles) anomalies in D. Vertical error bars for SMB-D are $\pm\sigma$; $\pm$45 Gt/yr for SMB and $\pm$60 Gt/yr for TMB.

Rignot et al. GRL, 2008

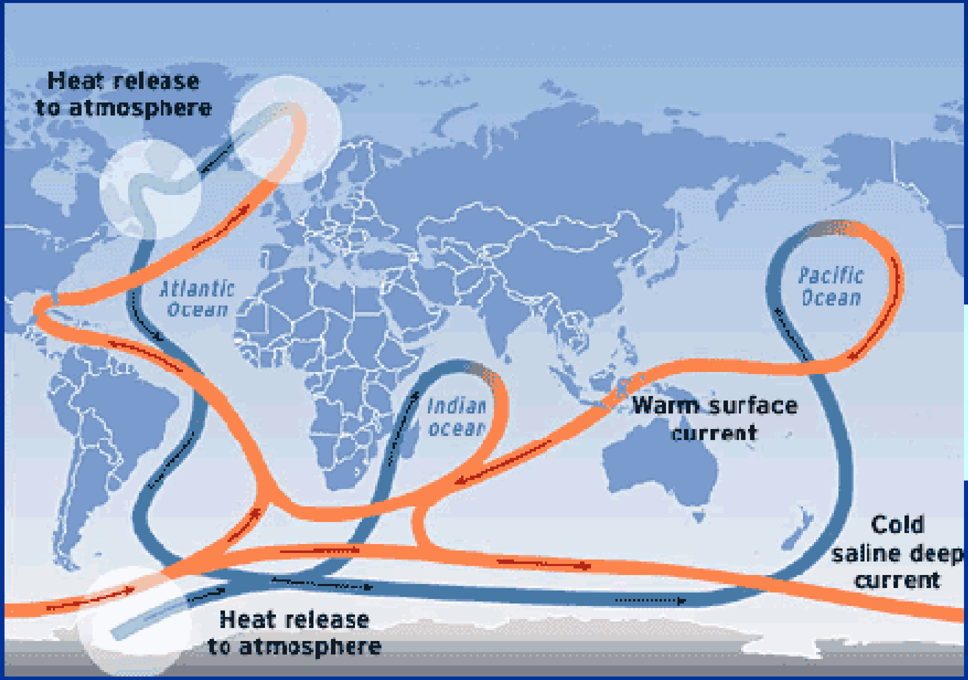
"In the last 11 years total mass deficit has tripled"

Hypothesis

Monsoon may tip to a persistent drought phase!

Global warming

Fresh water addition to North Atlantic Ocean



Weakening of Atlantic Thermohaline Circulation & Cool NA SST

Weak north-south Atmos. Temp. Gradient over Indian Longitudes

Persistent Weak Monsoon

Back

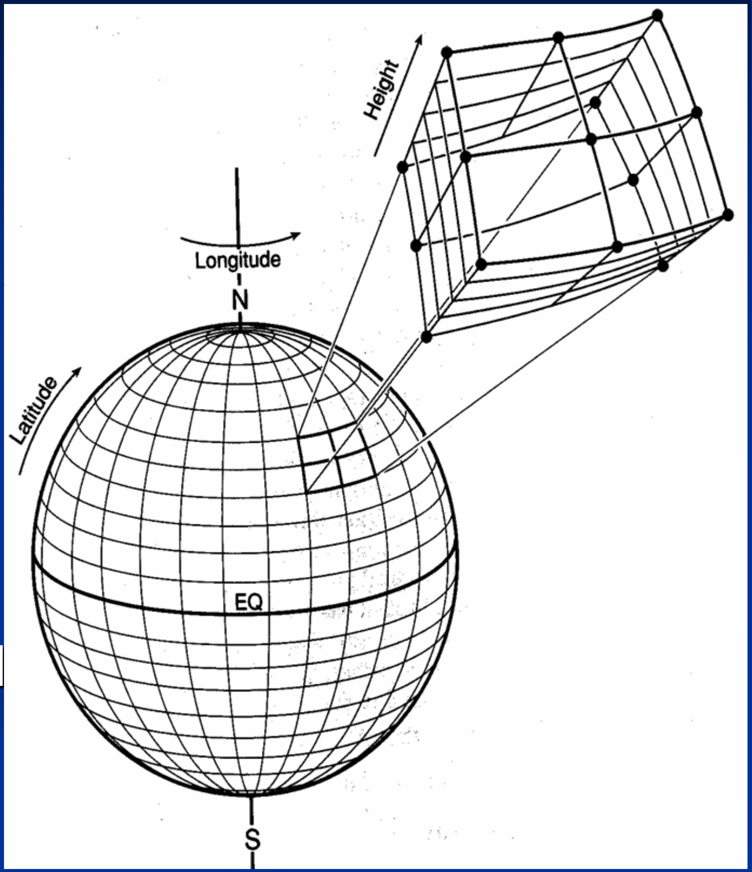
The Model : HadCM3 AOGCM

The Atmosphere :

- Hydrostatic, Primitive Equation
- Grid-point model, 2.5° x3.75° horizontal grid
- 19 Hybrid levels in vertical

The Ocean :

- Hydrostatic, Primitive Equation
- Grid-point model, 1.25° x 1.25° horizontal grid
- 20 levels in vertical, more layers near surface

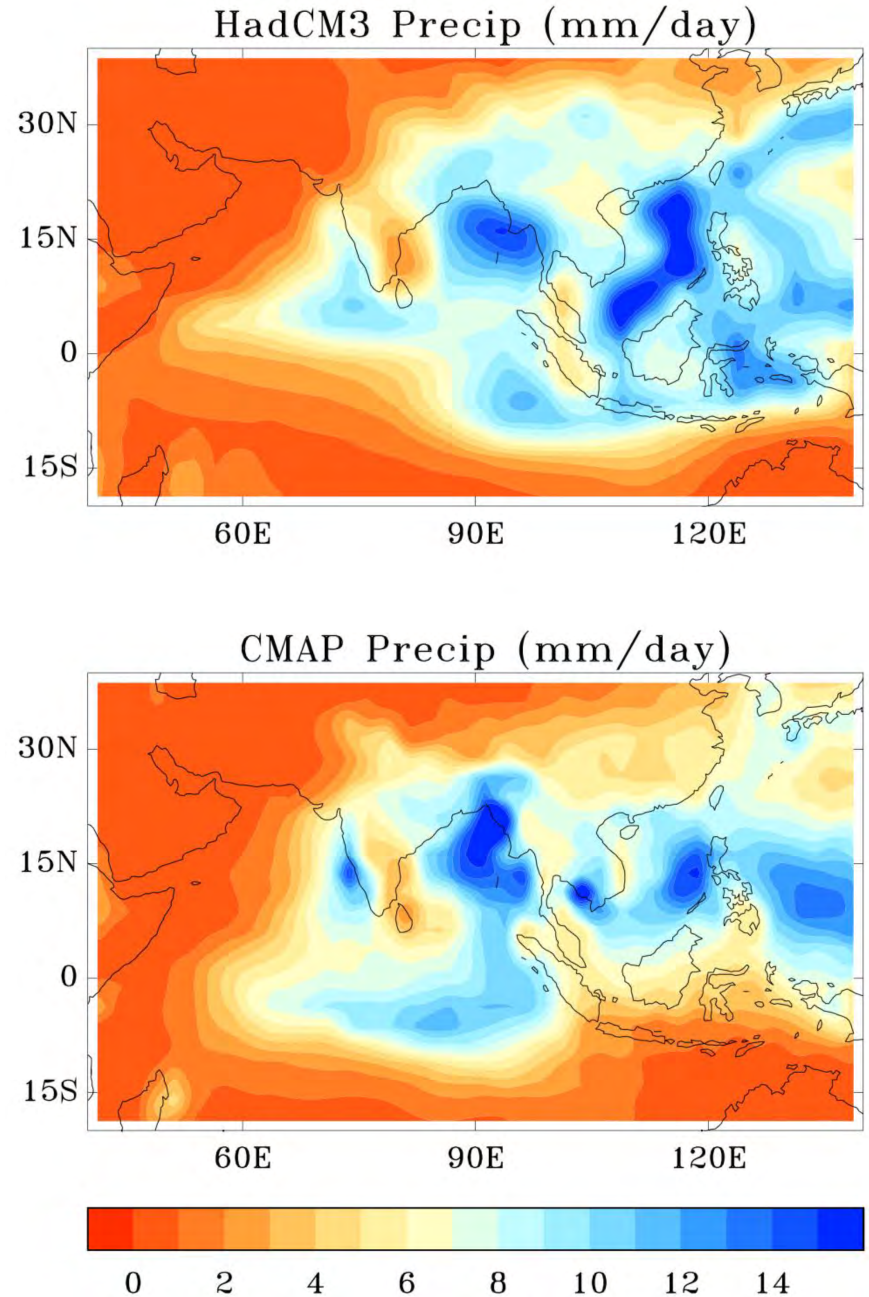


Coupling:

- Momentum and heat fluxes to the Ocean
- SST, evaporation, moisture flux to atmosphere
- Exchange information every 24 hours

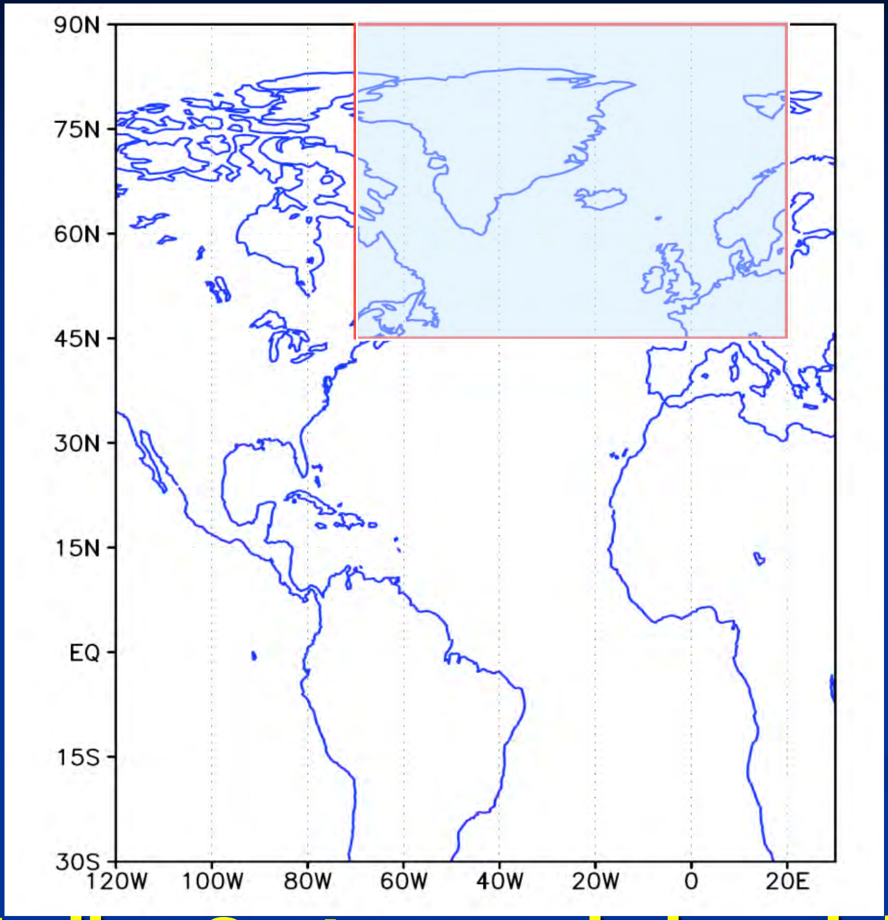
- **JJAS Mean Rainfall simulated by the model from a long simulation**

- **Observations, CMAP**



S1 : Climatological mean June-September rainfall in mm/day. Observed (top) and model simulation (bottom).

Fresh water flux Experiment with a Coupled Ocean-Atmosphere Model

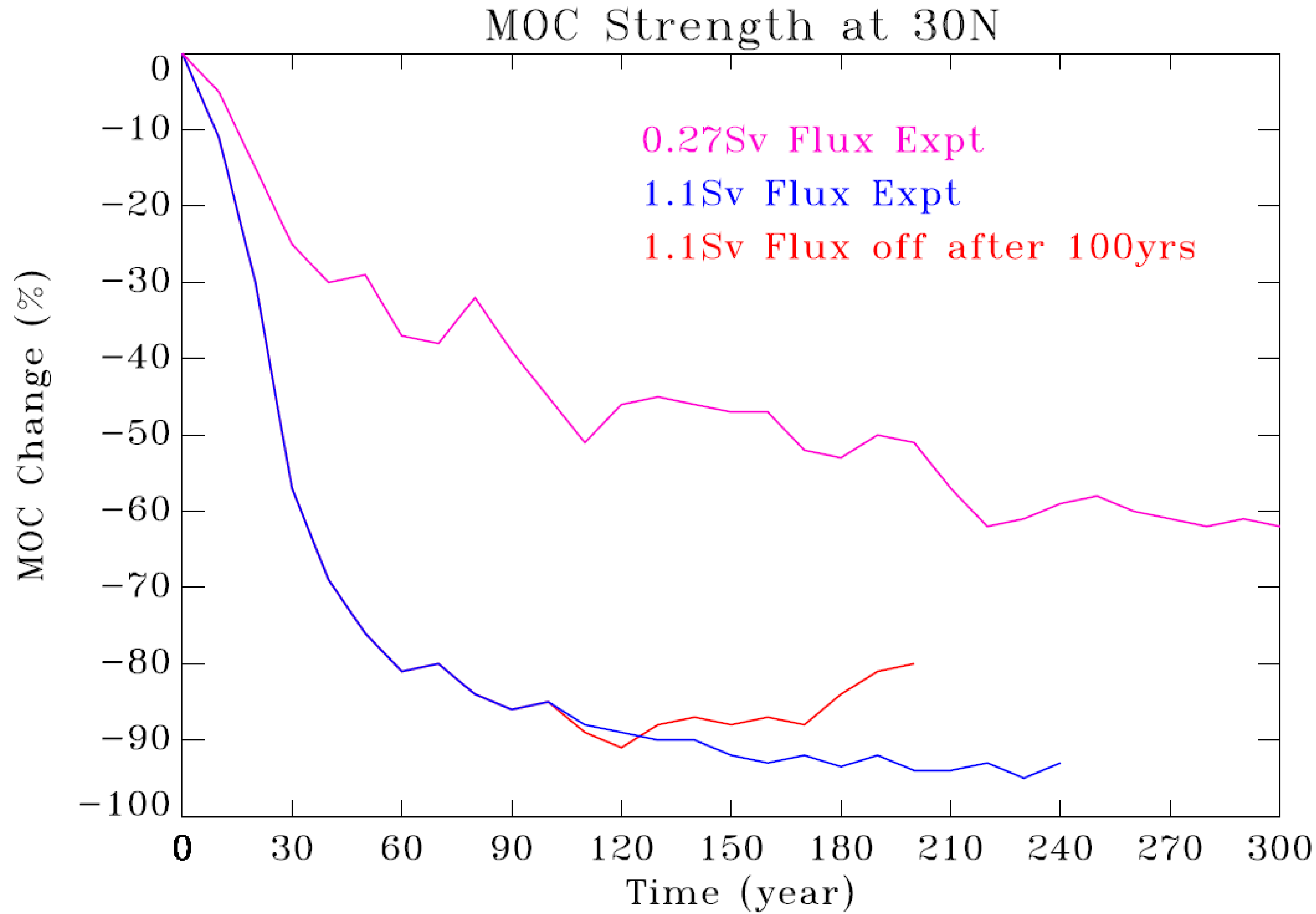


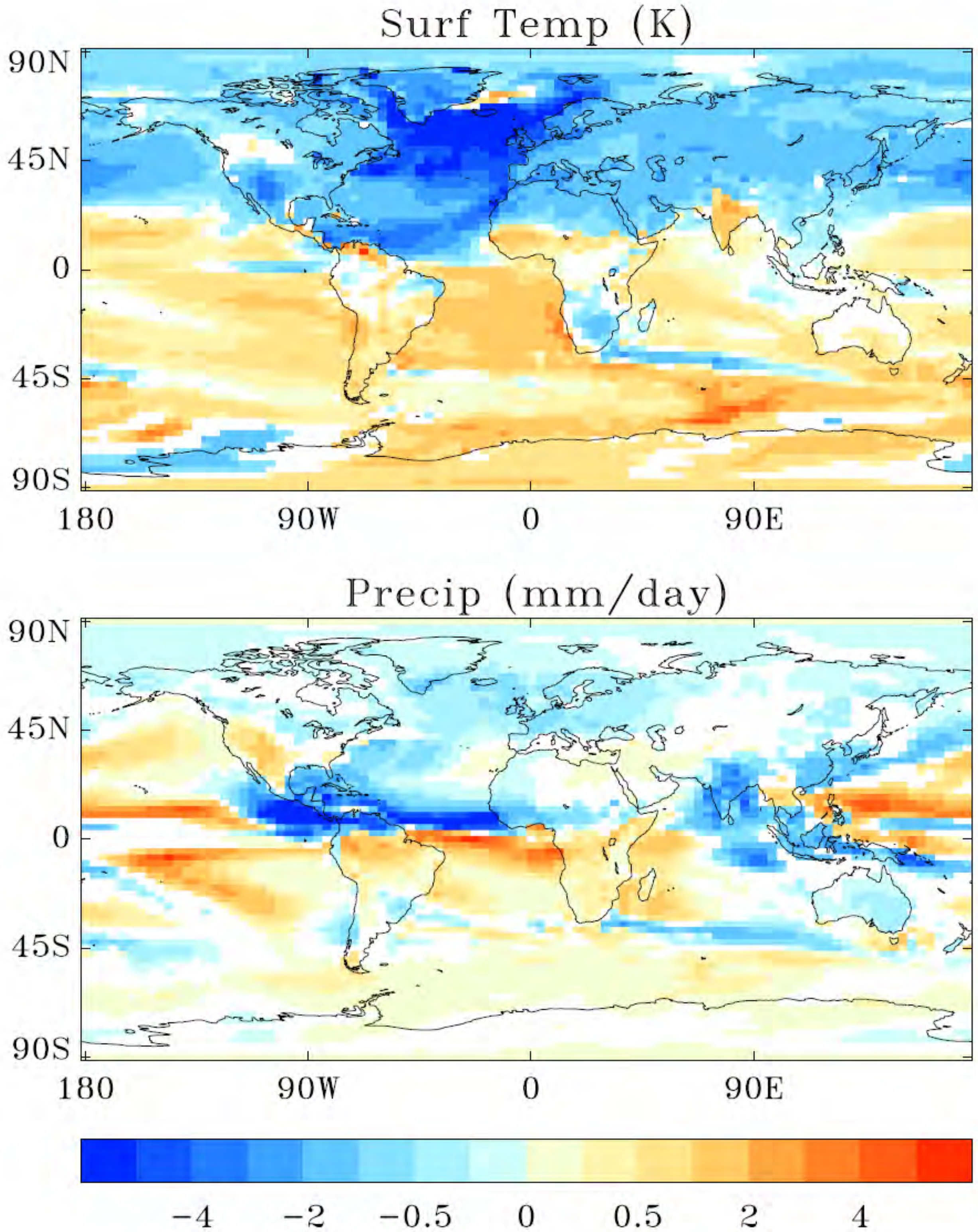
In collaboration with

Dr. B. Bhaskaran

Met. Office , Hadley Centre,UK

- **Model : Hadley Centre coupled model HadCM3**
- **100 Year simulation with 1.1 Sv and 0.27 freshwater flux in NA**
- **Fresh water flux switched off after 100 years and model is run for another 100 years**


MOC Strength at 30N
0.27Sv Flux Expt
1.1Sv Flux Expt
1.1Sv Flux off after 100yrs
MOC Change (%)
Time (year)
0
−10
−20
−30
−40
−50
−60
−70
−80
−90
−100
0
30
60
90
120
150
180
210
240
270
300

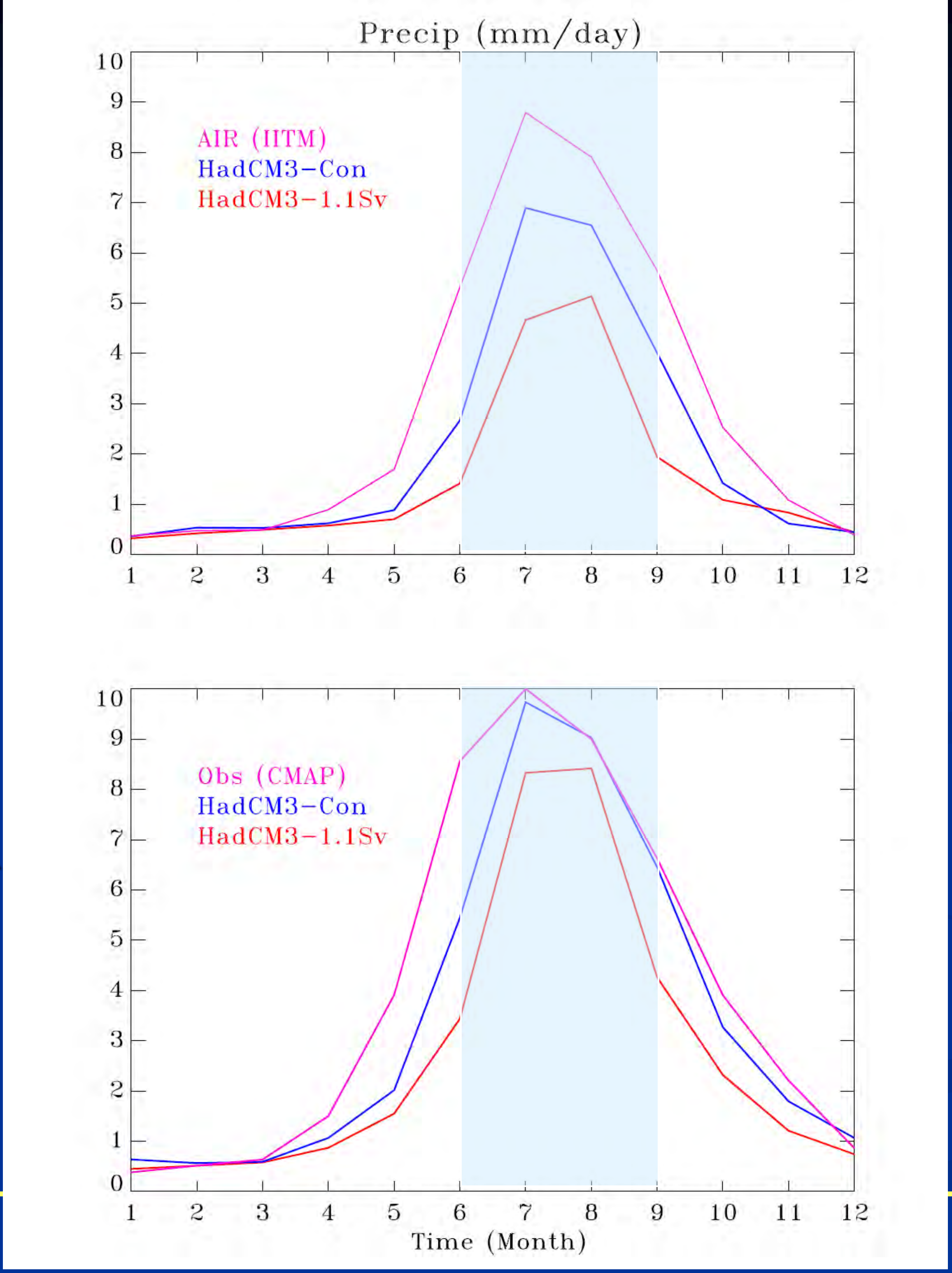


JJAS Mean

1.1Sv -Control

AIR

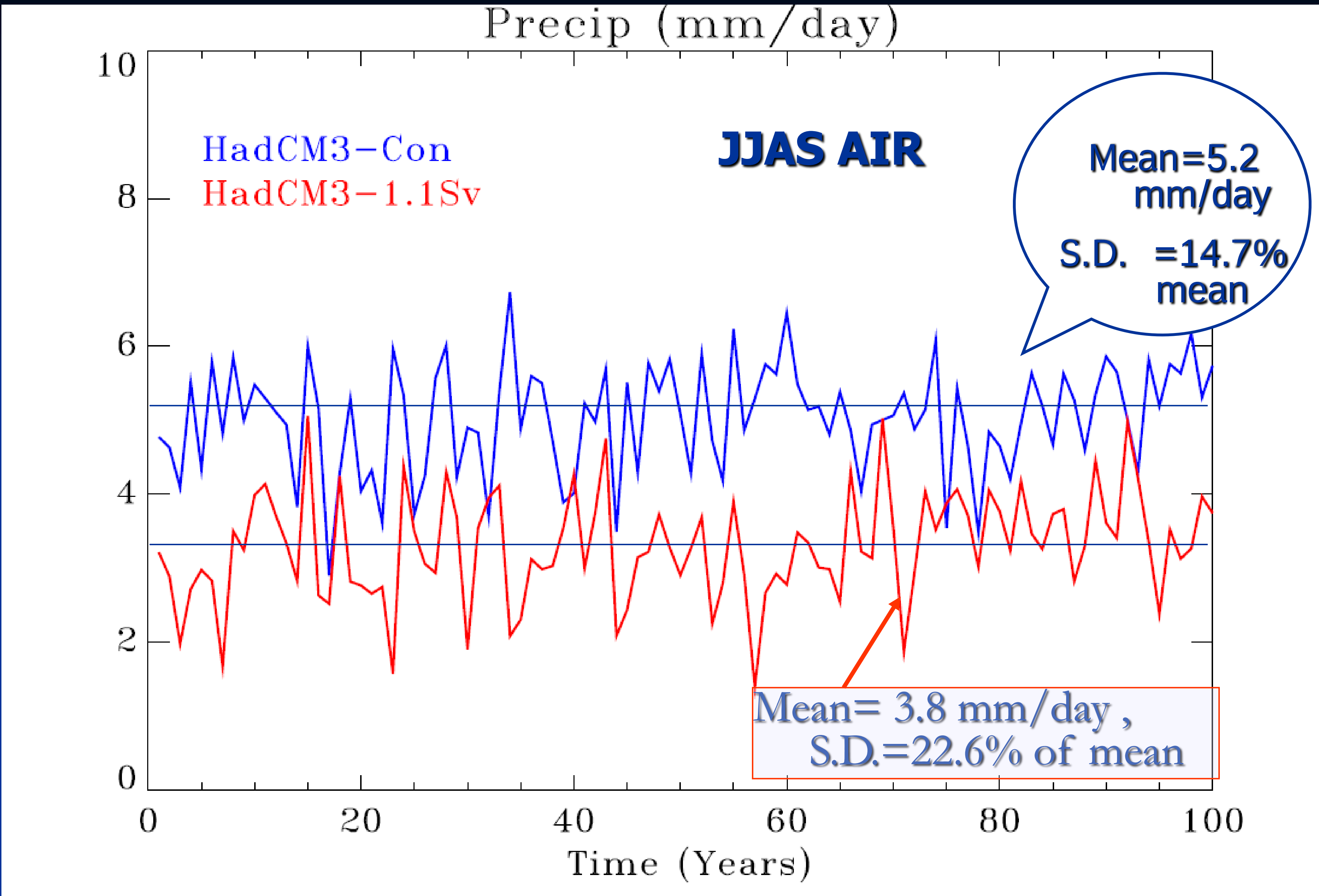
EIMR



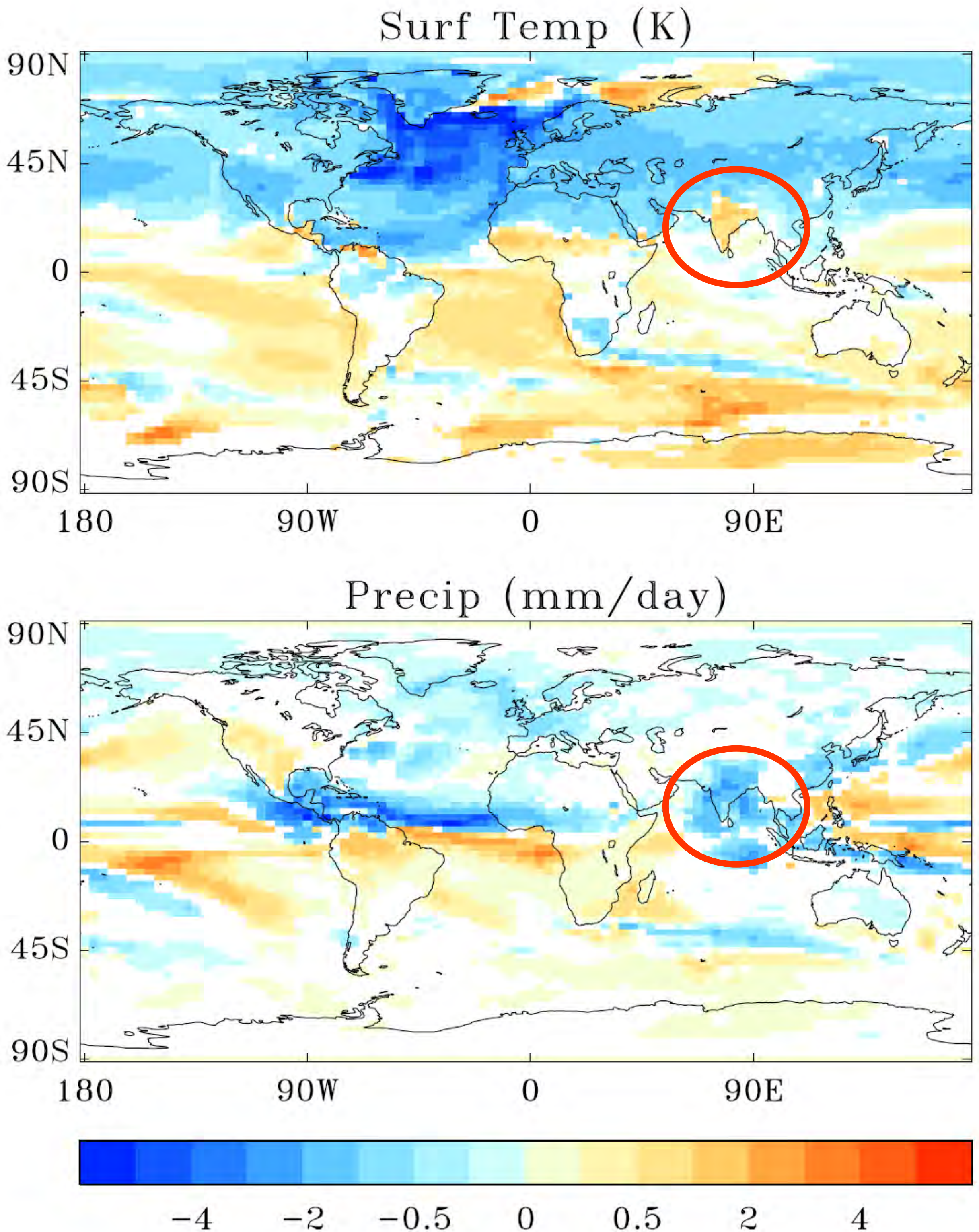
1.1Sv JJAS AIR 34.6% weaker than Control

1.1Sv JJAS EIMR 20.2% weaker than Control

Goswami et al. 1999. QJRMS

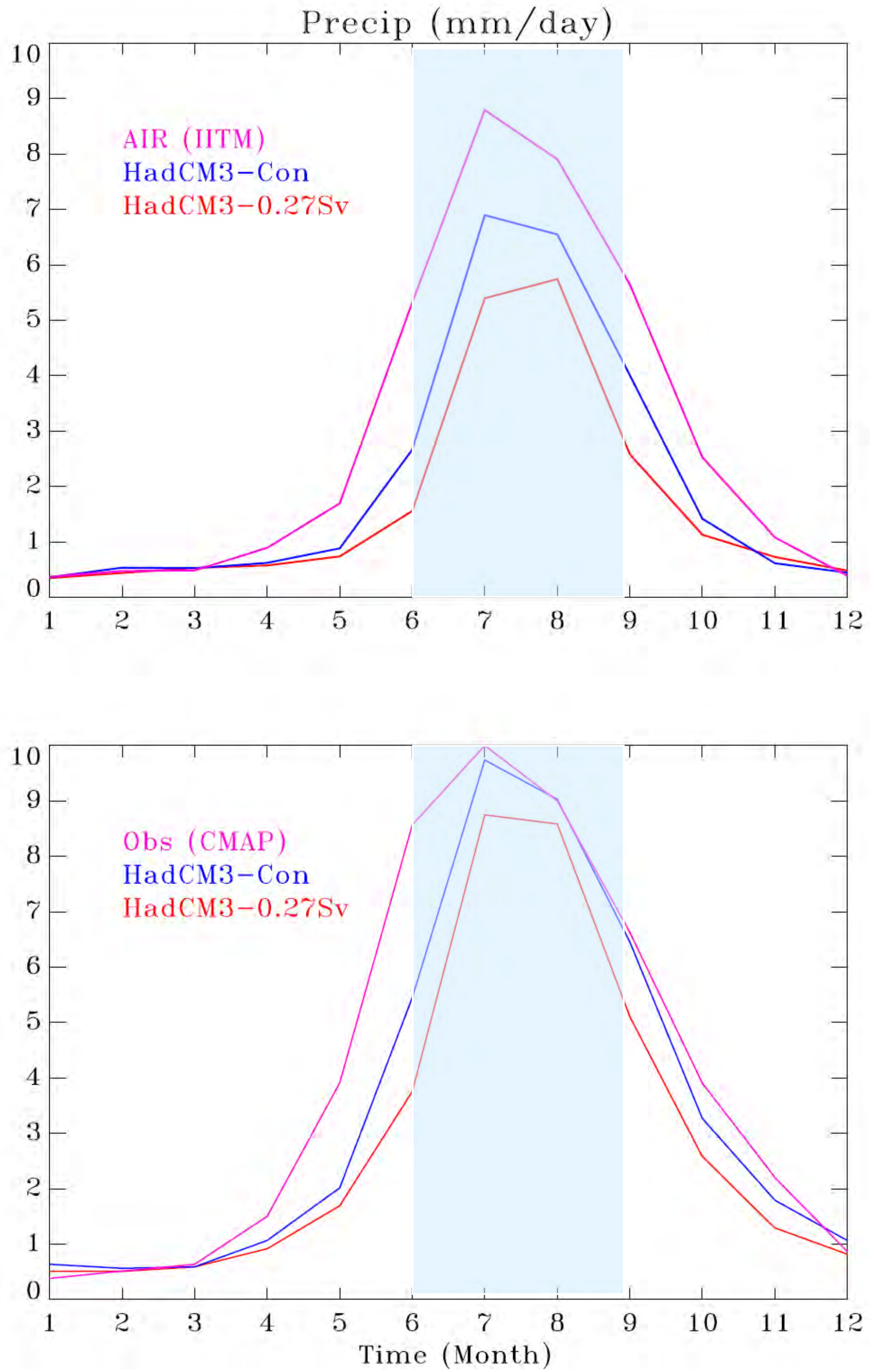


Precip (mm/day)
JJAS AIR
HadCM3−Con
HadCM3−1.1Sv
Mean=5.2 mm/day
S.D. =14.7% mean
Mean= 3.8 mm/day ,
S.D.=22.6% of mean
0
2
4
6
8
10
0
20
40
60
80
100
Time (Years)



JJAS Mean

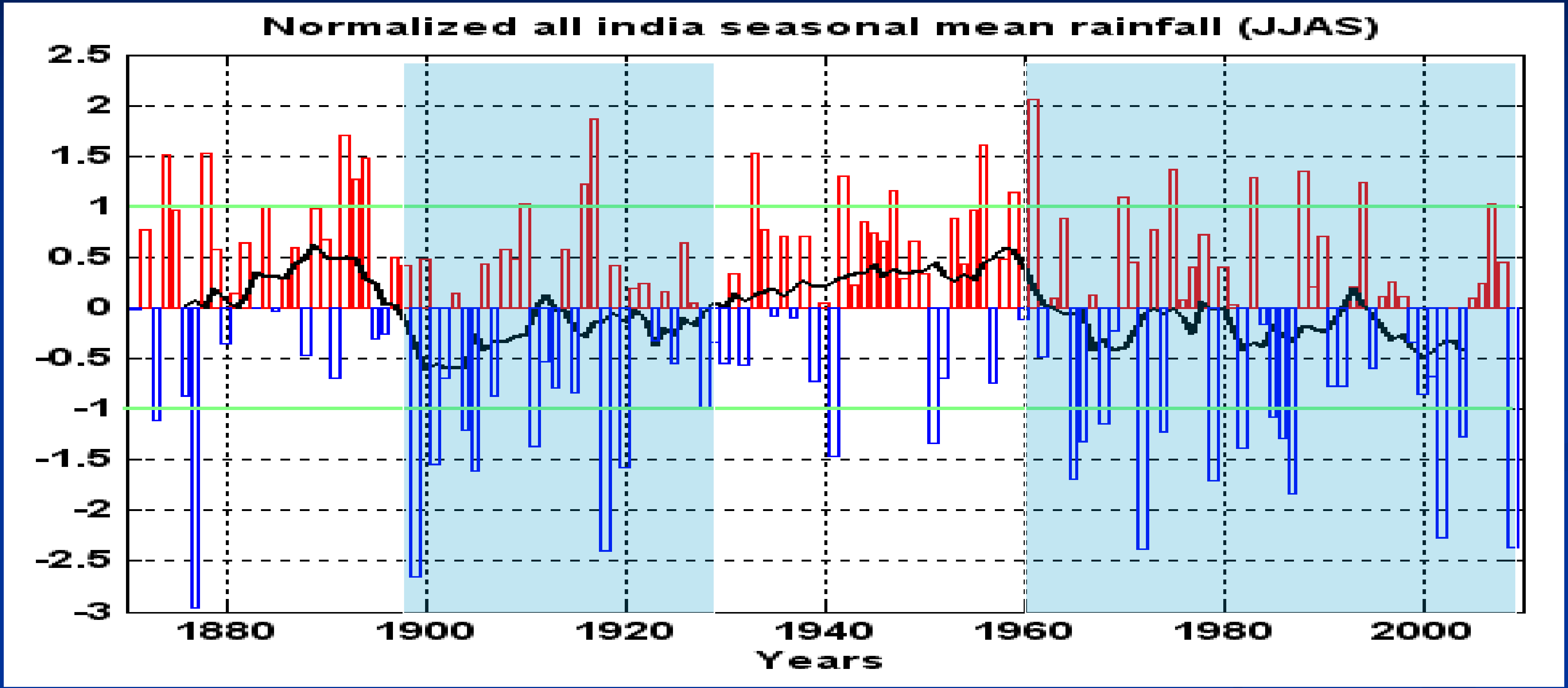
0.27Sv -Control



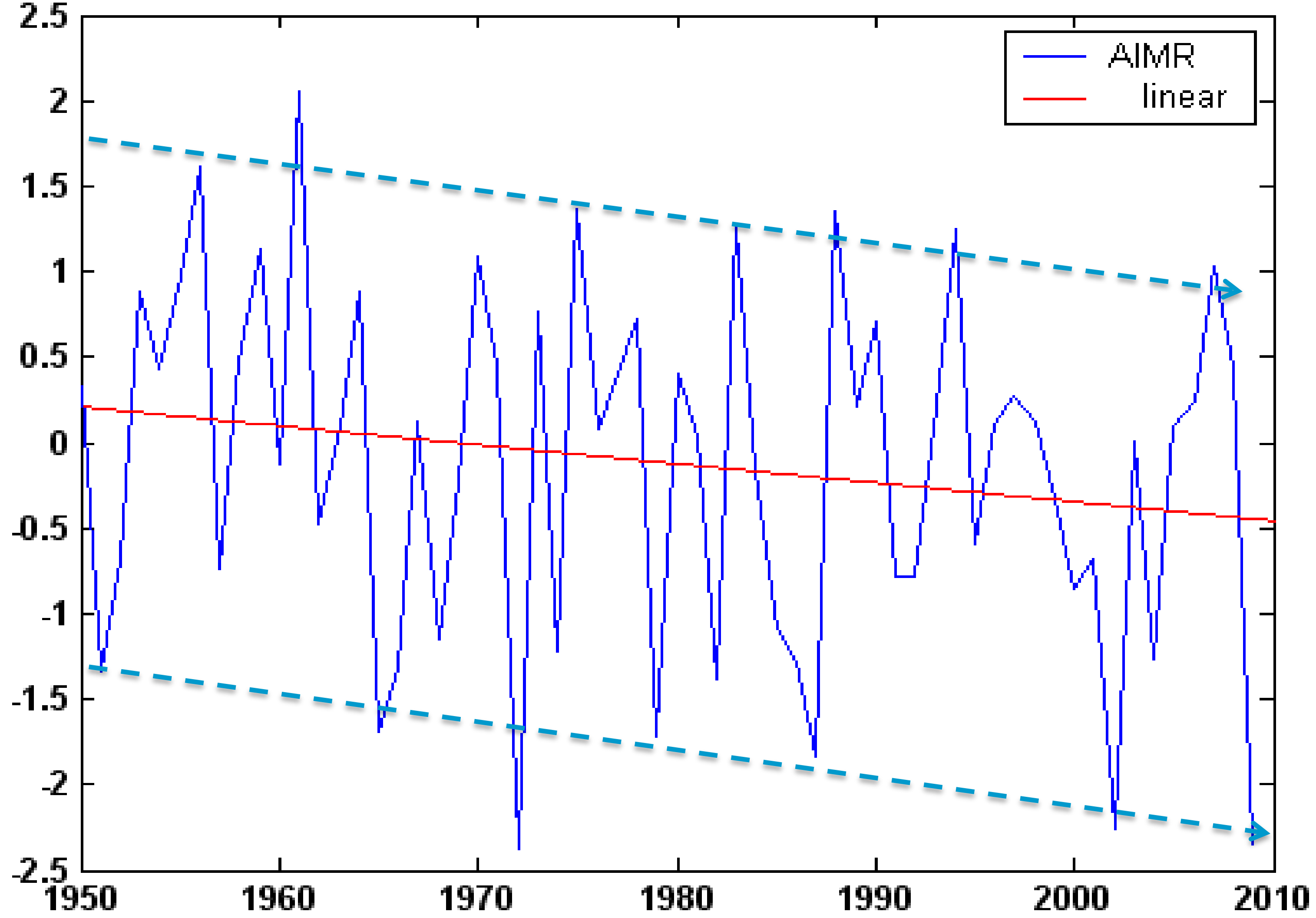
0.27Sv JJAS AIR 24.1% weaker than Control

0.27Sv JJAS EIMR 14.6% weaker than Control

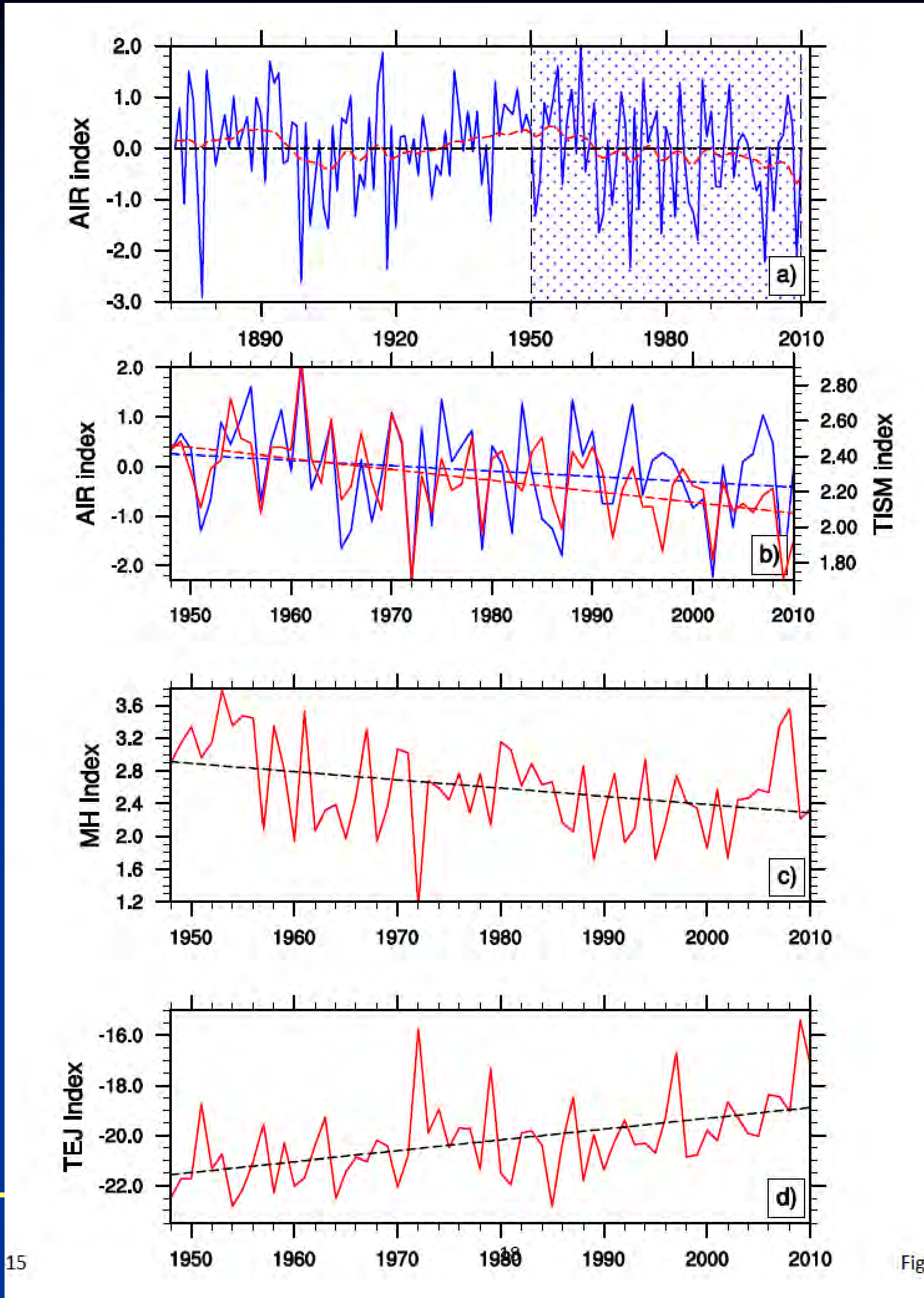
Has the Indian Monsoon tipped to Mega Drought state?



Normalized all india seasonal mean rainfall (JJAS)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
1880
1900
1920
1940
1960
1980
2000
Years



Standardized AIMR from 1950 to 2009. Red line is linear trend



AIR :

All India JJAS rainfall averaged over land points

TISM :

Thermodynamic Index of Indian Monsoon , integral of positive TT gradient

MH :

Monsoon Hadley Index, vertical shear of meridional winds averaged over Indian monsoon region

TEJ:

Tropical Easterly Jet at 200 hPa averaged around the centre

Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon

Massimo A. Bollasina,[1] Yi Ming,[2*] V. Ramaswamy[2]

Science, 2011

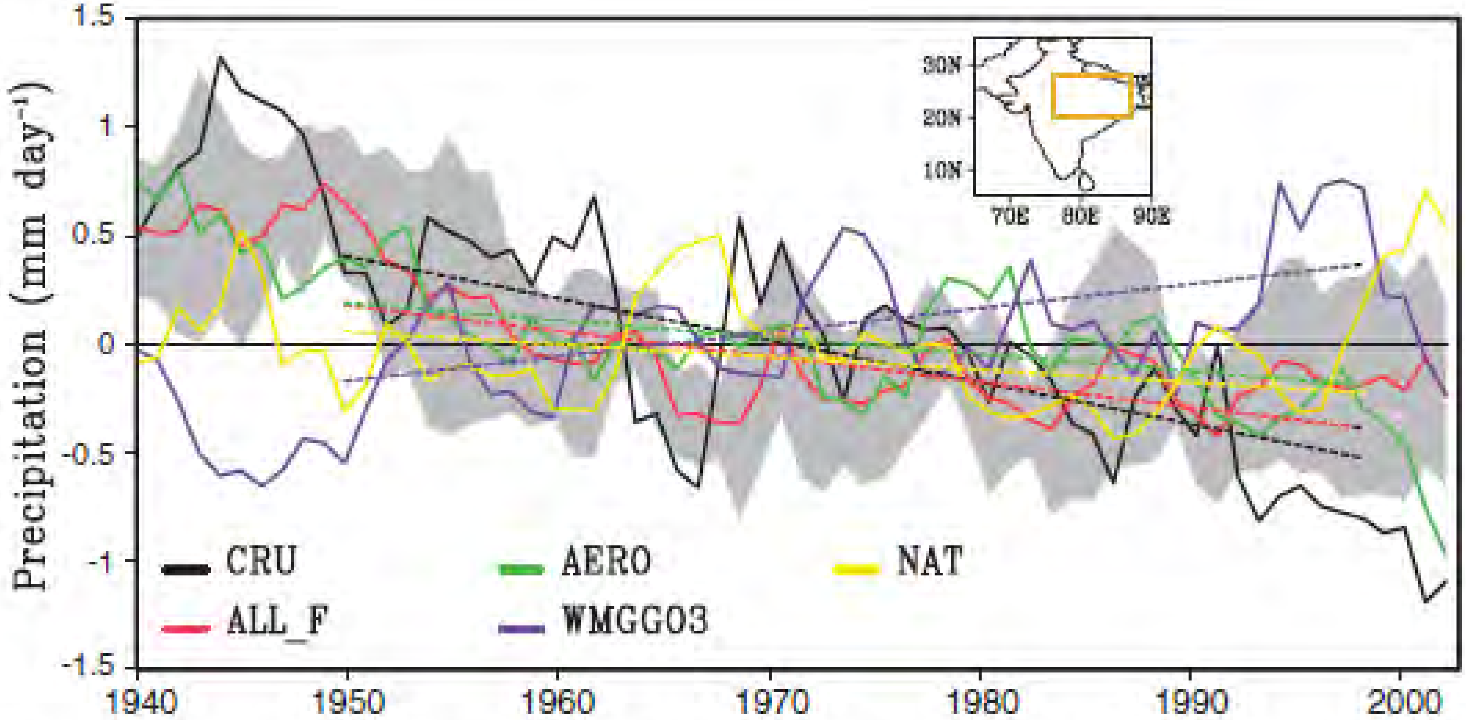
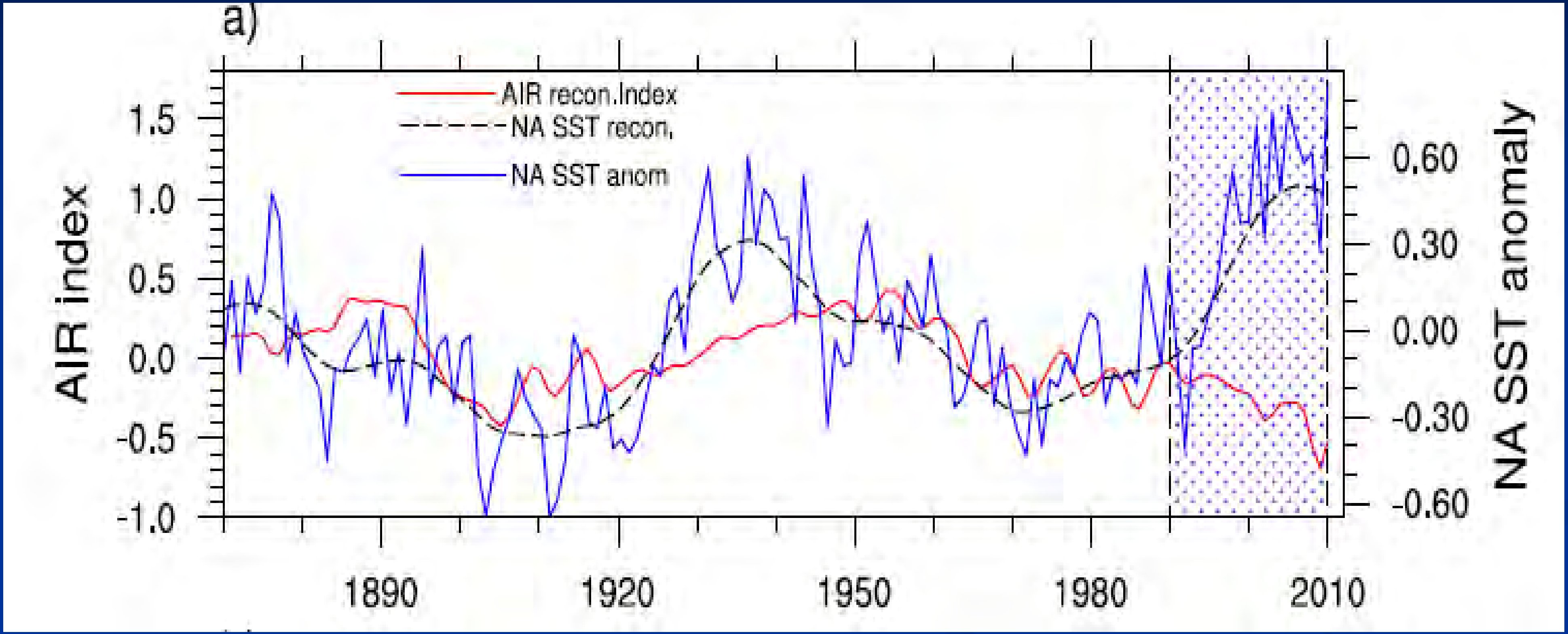


Fig. 1. Five-year running mean June-September average precipitation anomalies over central-northern India (76° to 87°E, 20° to 28°N; see the orange box in the inset map). Anomalies are calculated as deviations from the 1940–2005 climatology. The black line is based on the CRU TS 3.0 observational data set. The red, green, blue, and yellow lines are for the ensemble-mean all-forcing (ALL_F), aerosol-only (AERO), greenhouse gases and ozone-only (WMGGO3), and natural forcing-only (NAT) CM3 historical integrations, respectively. The gray shading represents the standard deviation of the five-member all-forcing ensemble. The least-squares linear trends during 1950–1999 are plotted as dashed lines in the respective colors. The trend [mm day^{-1} (50 years)$^{-1}$] and its *P* value based on the two-tailed Student's *t* test (*32*) (in parentheses) are as follows: −0.95 ($P = 0.04$) for CRU, −0.58 ($P = 0.01$) for ALL_F, −0.39 ($P = 0.09$) for AERO, 0.55 ($P = 0.07$) for WMGGO3, and −0.29 ($P = 0.17$) for NAT. The 50-year trends from the other three observational data sets, which are not plotted to avoid overcrowding the figure, are −0.20 ($P = 0.70$) for IMR, −0.79 ($P = 0.10$) for UDEL, and −0.76 ($P = 0.10$) for PREC/L.

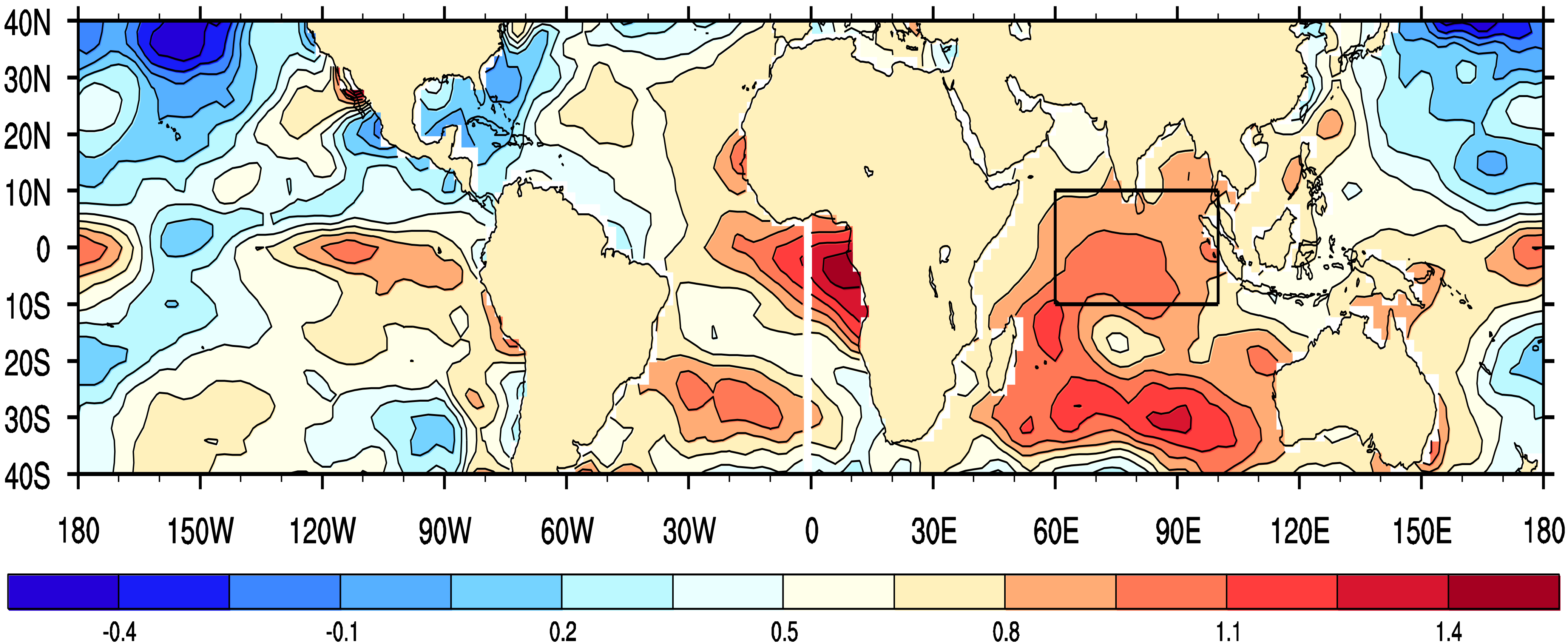
Could the decreasing trend be driven by NA SST ?



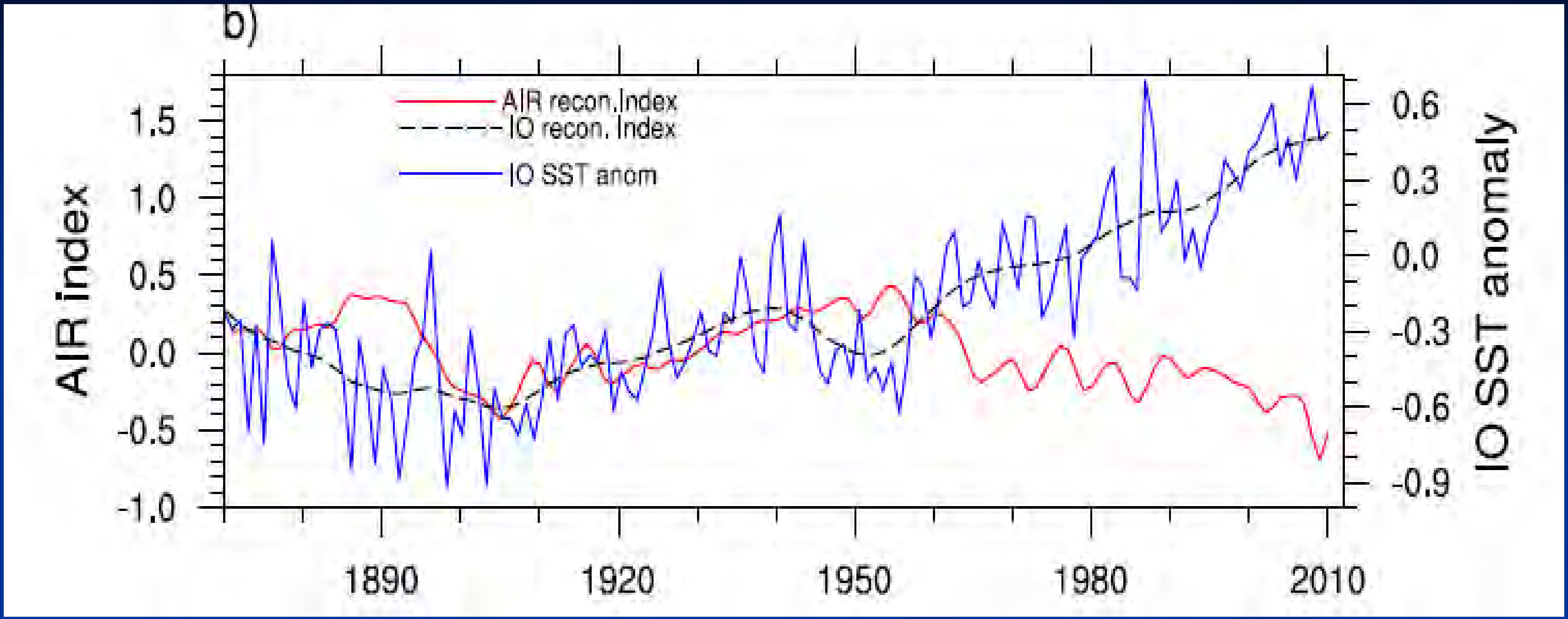
- Multi-decadal modes extracted using SSA for AIR and NA SST do not correlated well in recent decades.

- If NA SST is not driving the recent decreasing trend, what is?

Could it be driven by the Indian Ocean SST?



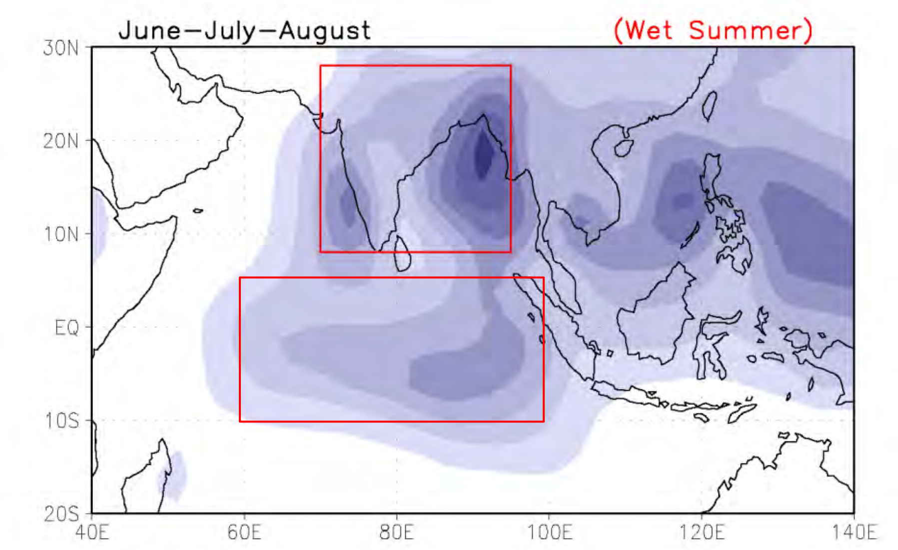
The linear trend of seasonal mean SST is calculated at each grid point for the period1950 to 2010 and the difference between 2010 season and that of 1950 is shown (Unit °C/61 years). Equatorial Indian Ocean domain is highlighted with black solid line.

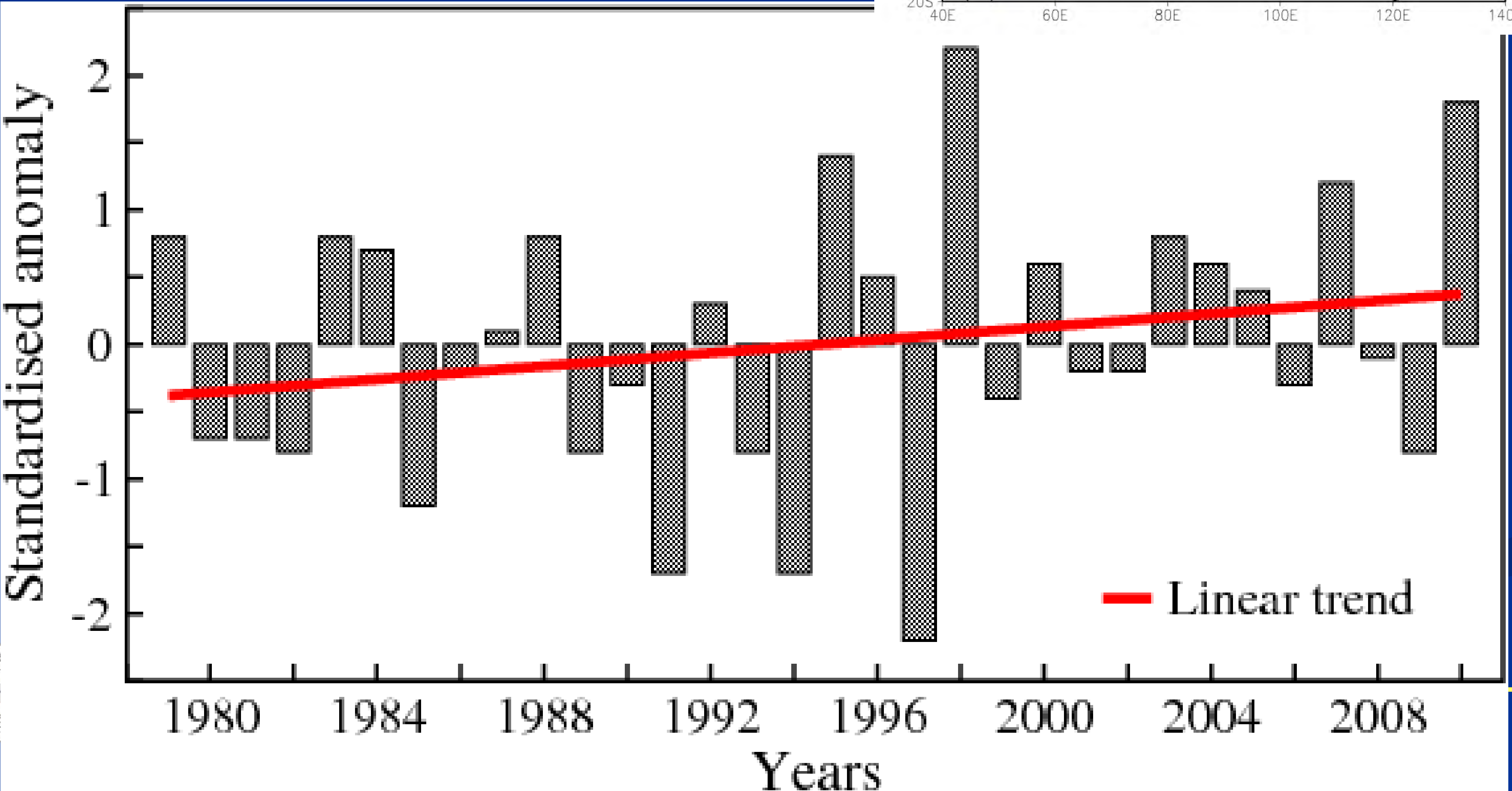


- Multi-decadal modes of AIR and EQIO SST extracted by SSA indicate strong opposing trends after 1950s.

- May be the increasing trend of EQIO SST is driving the decreasing trend of AIR during recent decades. How does EQIO SST does this?

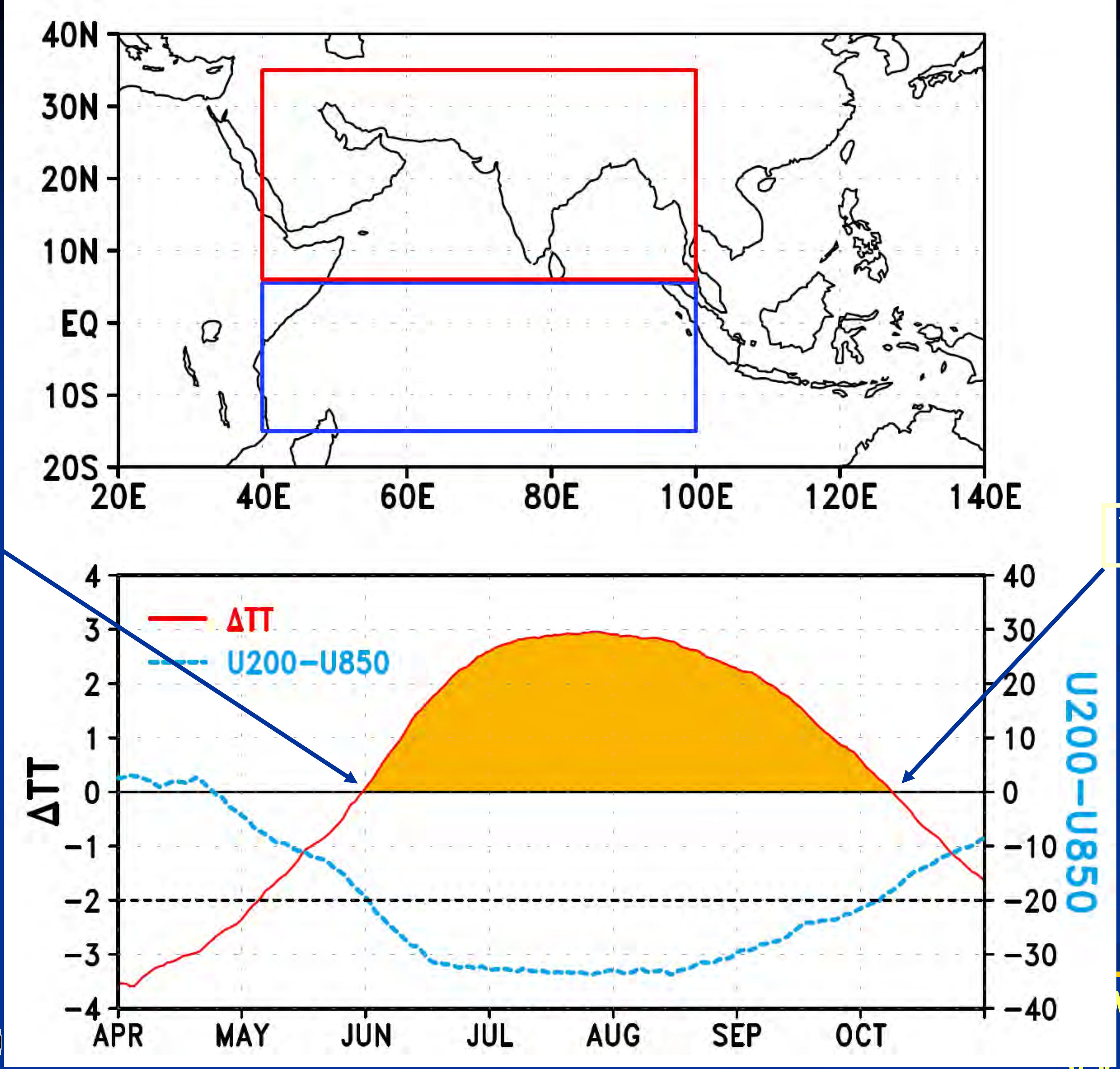
Summer monsoon (JJAS) rainfall over Indian Ocean (60ºE-100ºE; 10ºS-5ºN)





Onset

Withdraw



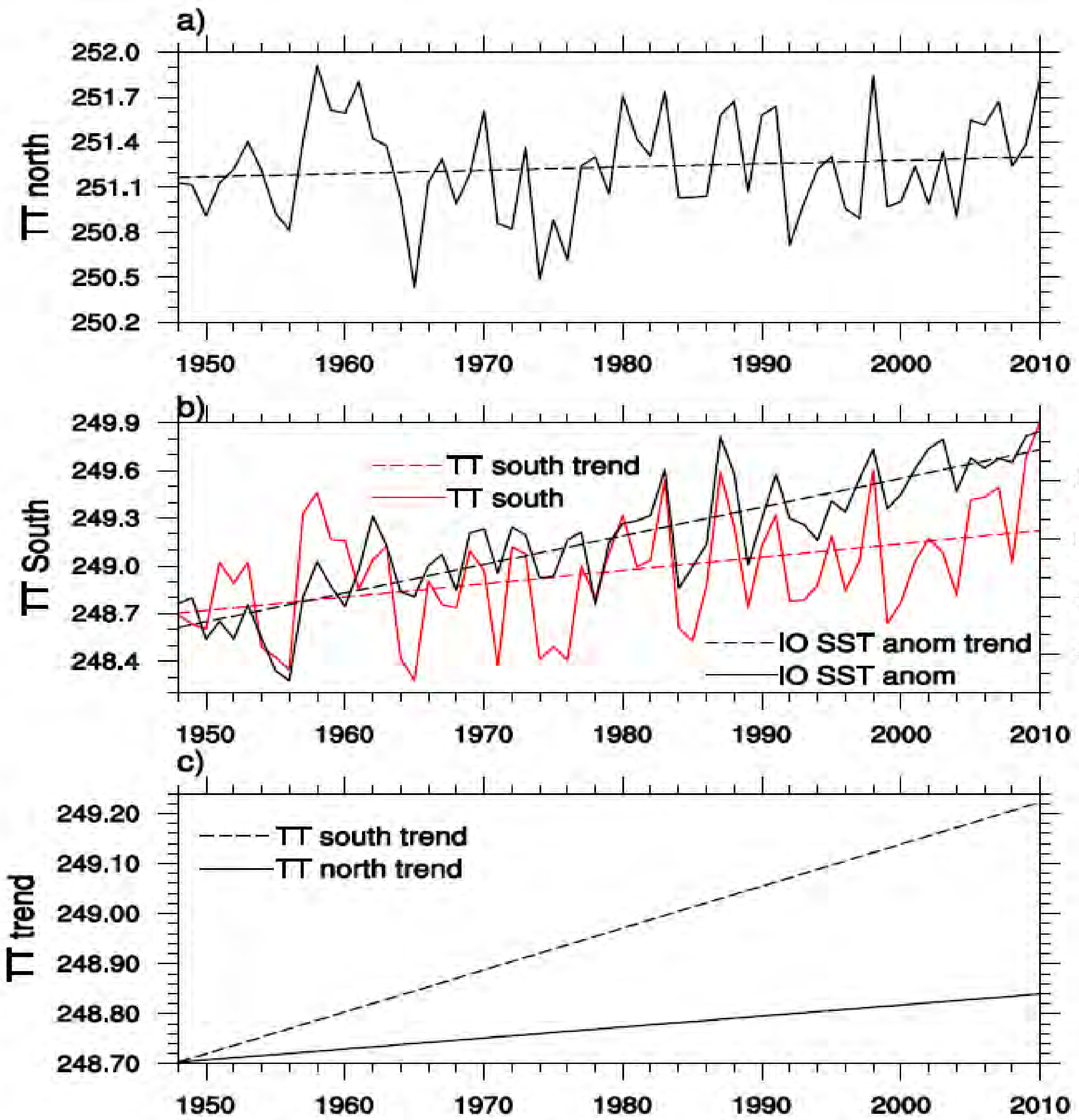
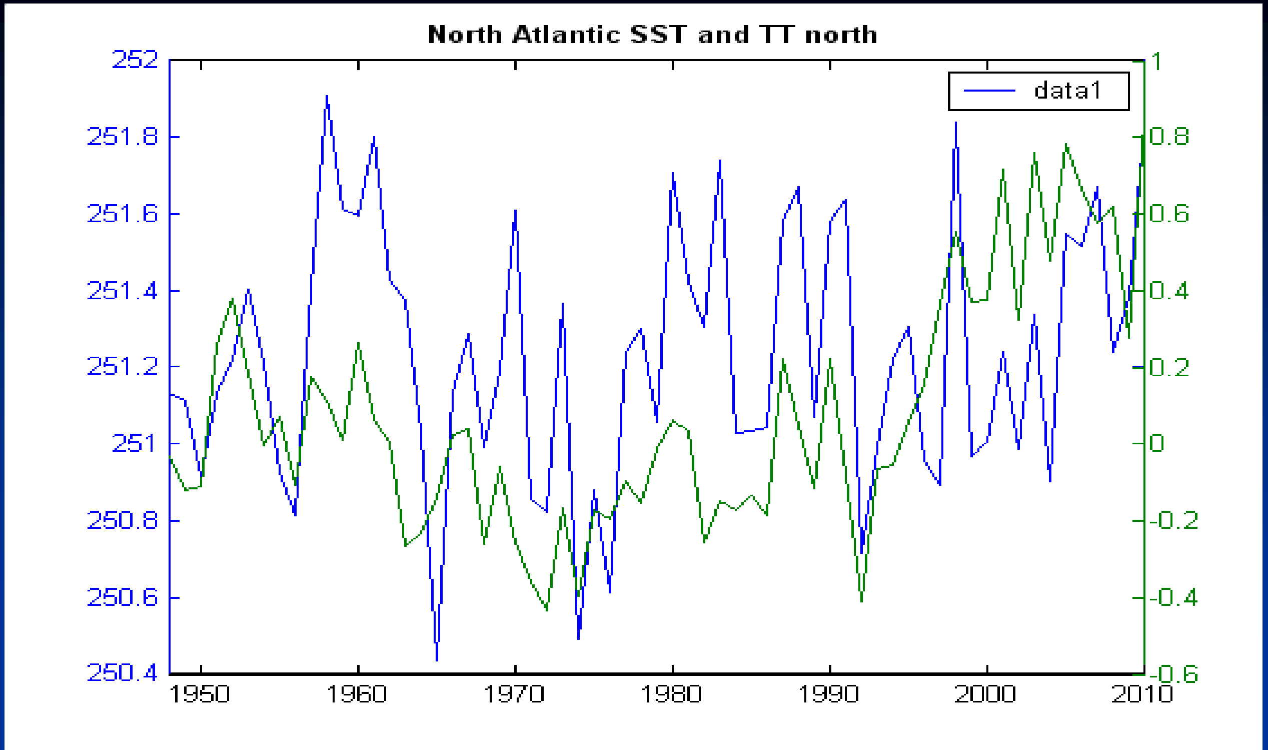
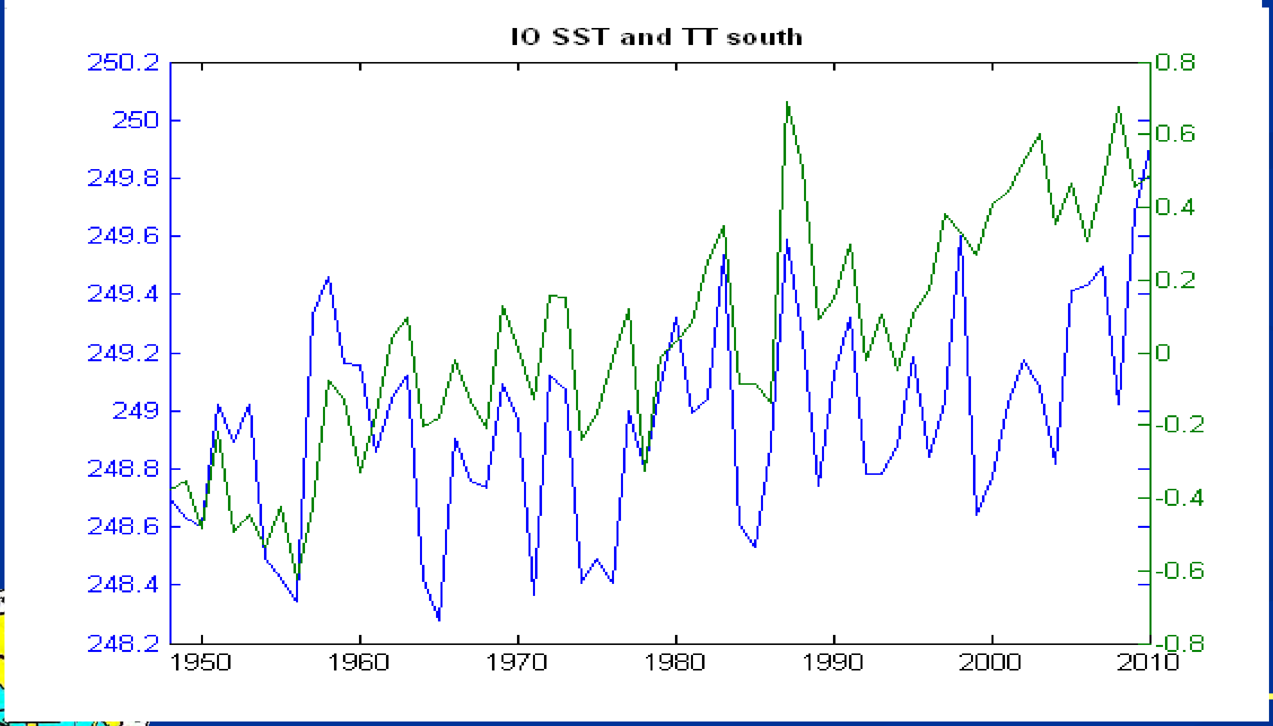


Fig. 3: Inter-annual variability of vertically averaged (200-600hPa) seasonal mean tropospheric temperature (TT, in °K) calculated over the north box (5°N-35°N, 40°E-100°E) and the south box (15°S-5°N, 40°E-100°E). a) IAV of TT north (black solid) and its linear trend (black dashed). b) IAV of TT south (black solid line) and its linear trend (black dashed line) compared with those of IO SST anomaly (red





NA SST correlates with TT-North, but drives only a weak trend

EQIO SST correlates with TT-South, and drives a stronger trend

- Is there a preferred periodicity of the Multi-decadal Variability of the Indian Monsoon?

- If there is, is it stationary?

India Tree-ring : (A.D. 1481-2003); Palaeo-3, Borgaonkar et al. 2010

Thailand Tree-ring (A. D. 1558-2005); Clim.Dyn, Buckley et al. 2007

Speleothem $\delta\ ^{18}$O: (A.D. 652-2007); GRL, Sinha et al, 2011 (Dandak and Jhumar caves)

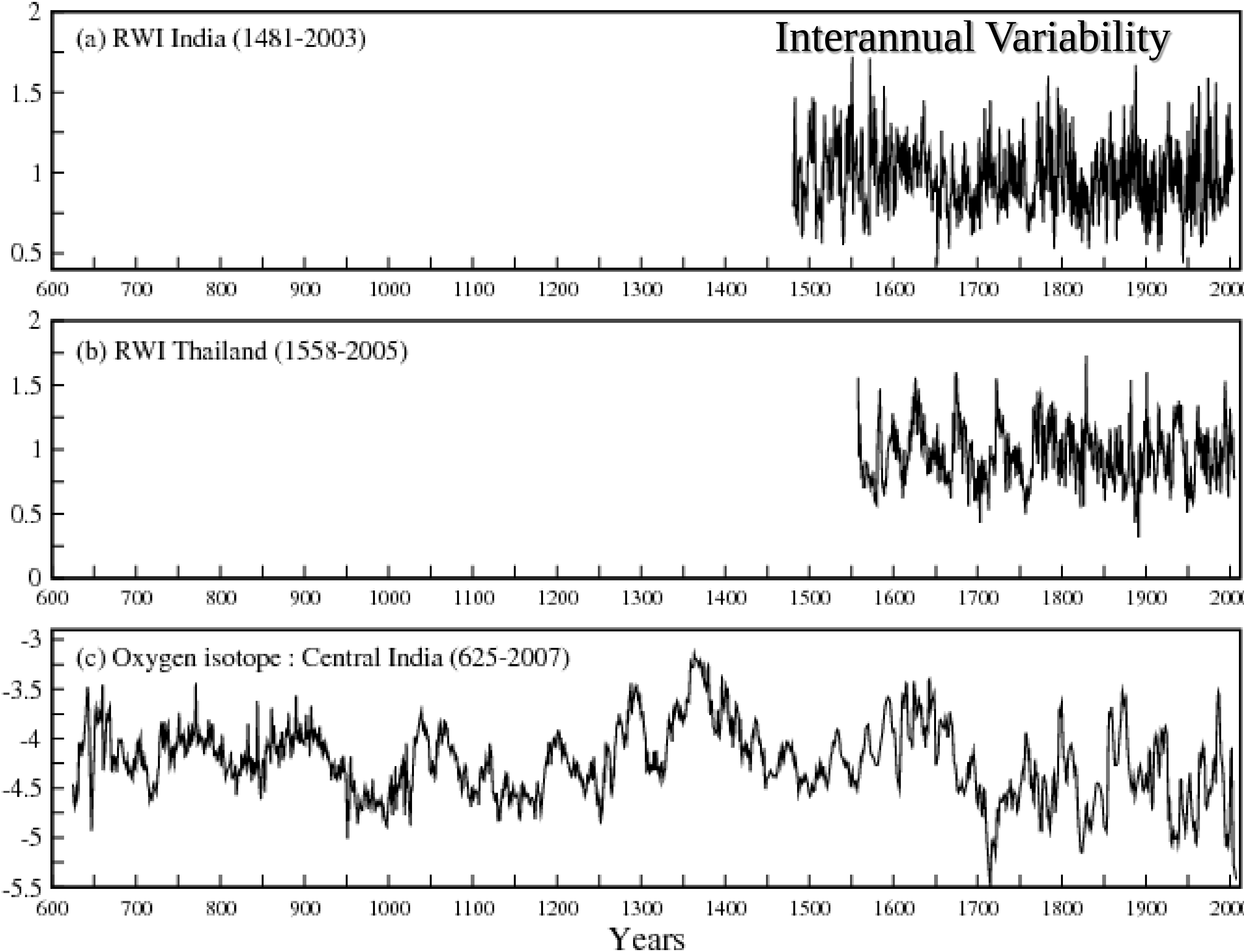
References

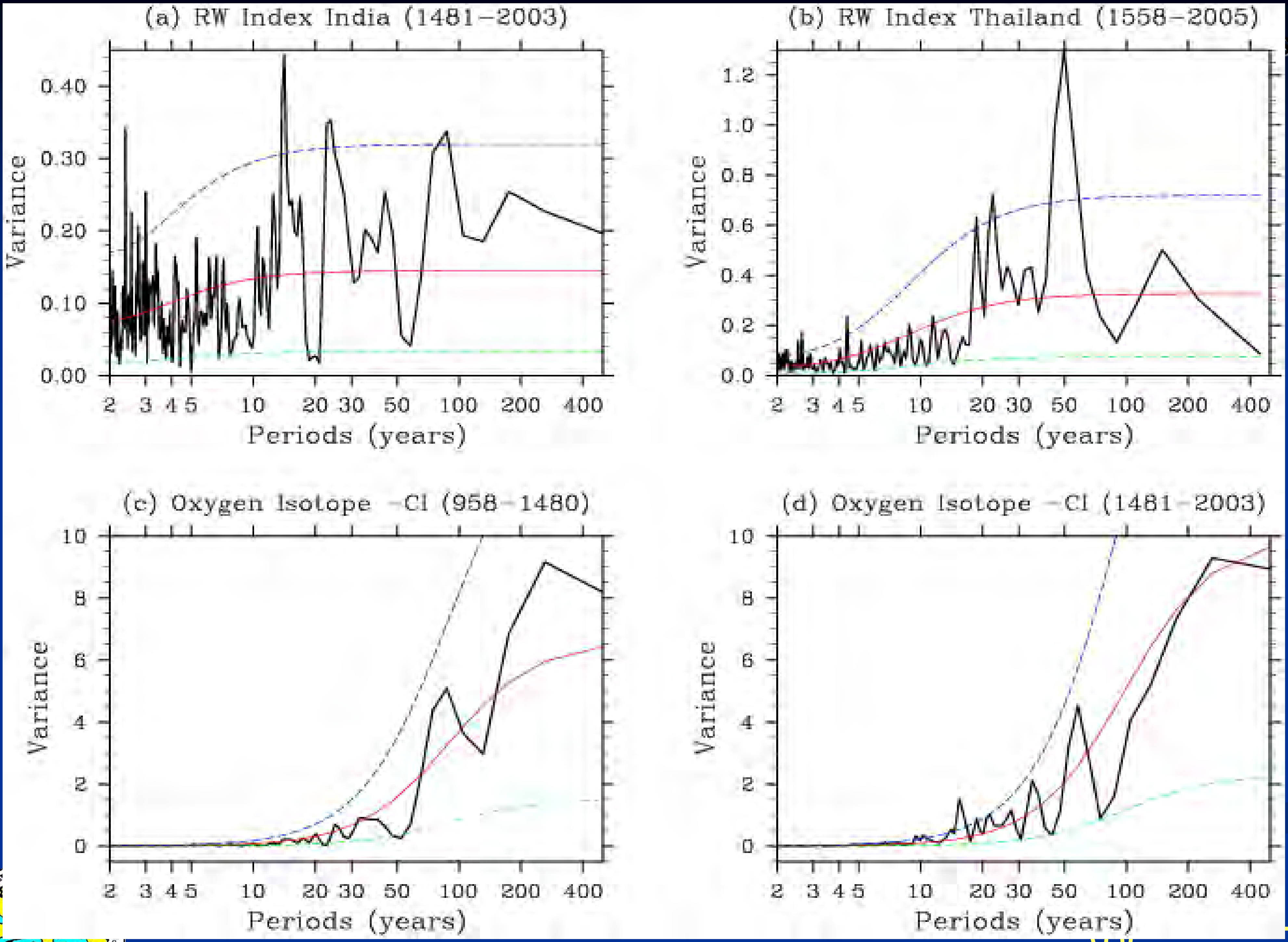
Borgaonkar, H.P., Sikdera, A.B., Rama, S., Panta, G.B., 2010. El Niño and related monsoon drought signals in 523-year-long ring width records of teak (Tectona grandis L.F.) trees from south India. Palaeogeogr. Palaeoclimatol. Palaeoecol. 285, 74-84.

Buckley, B.M., Palakit, K., Duangsathaporn, K., Sanguantham, P., Prasomsin, P., 2007. Decadal scale droughts over northwestern Thailand over the past 448 years: links to the tropical Pacific and Indian Ocean sectors. Clim. Dyn. 29, 63-71.

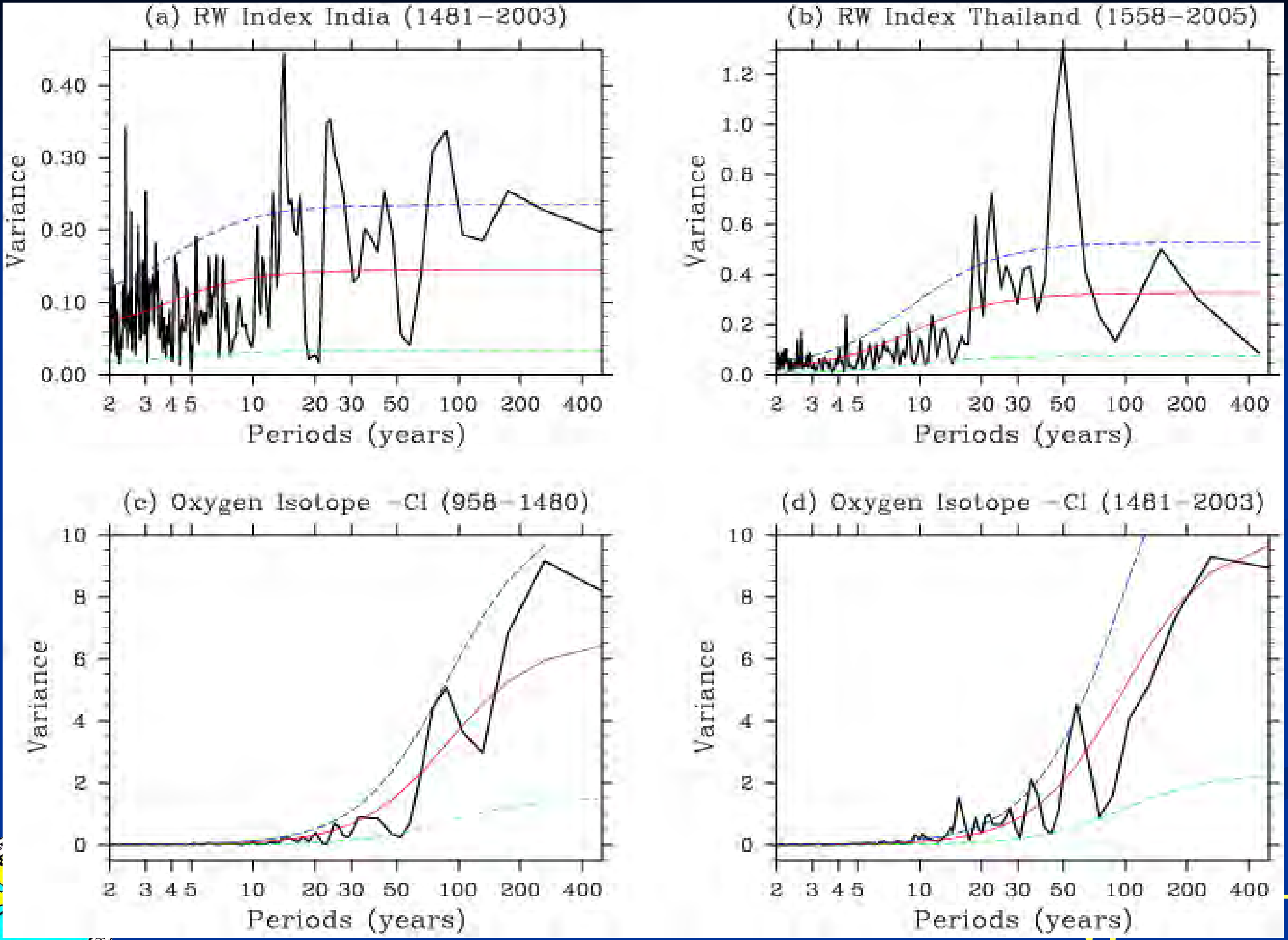
Ashish Sinha, Max Berkelhammer, Lowell Stott, Manfred Mudelsee, Hai Cheng, and Jayant Biswas, 2011. The leading mode of Indian Summer Monsoon precipitation variability during the last millennium Geop. Res. Lett, olL. 38, L15703, doi:10.1029/2011GL047713, 2011

Interannual Variability





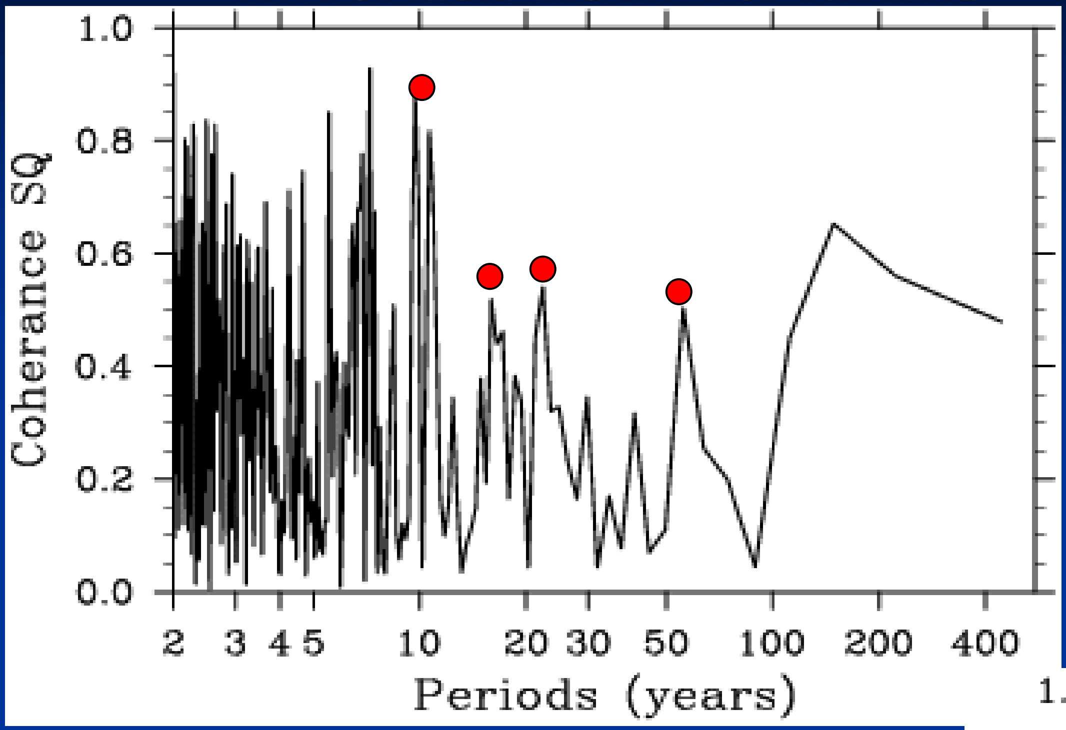
Blue dashed line : Significance at 95 % CL



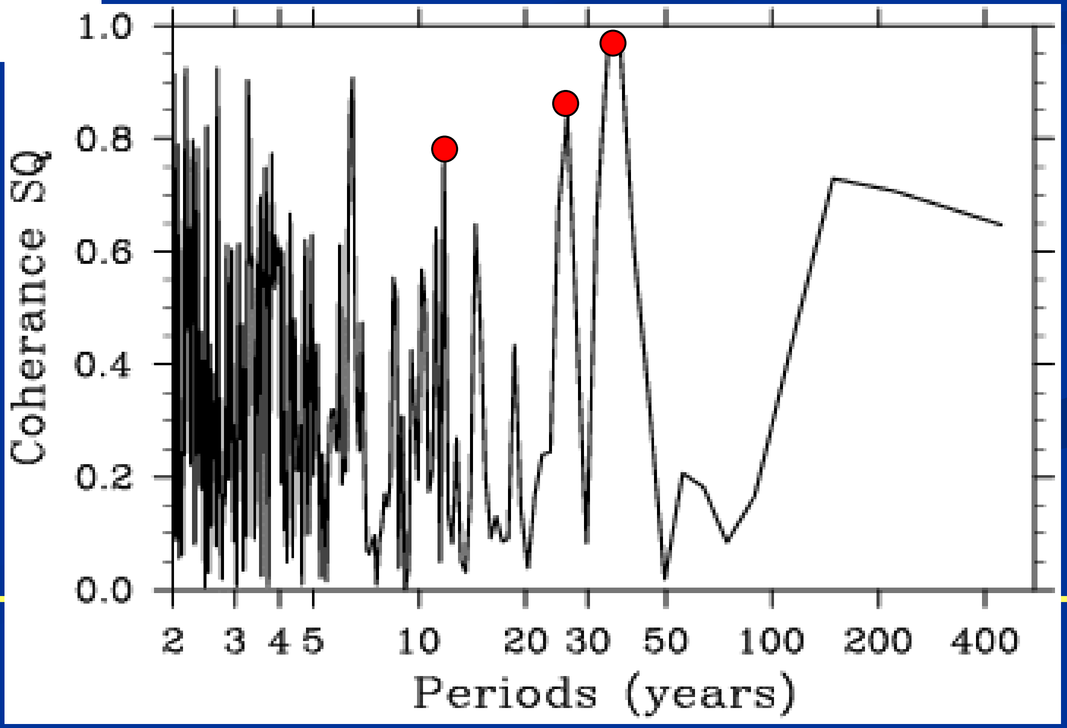
Blue dashed line : Significance at 85 % CL

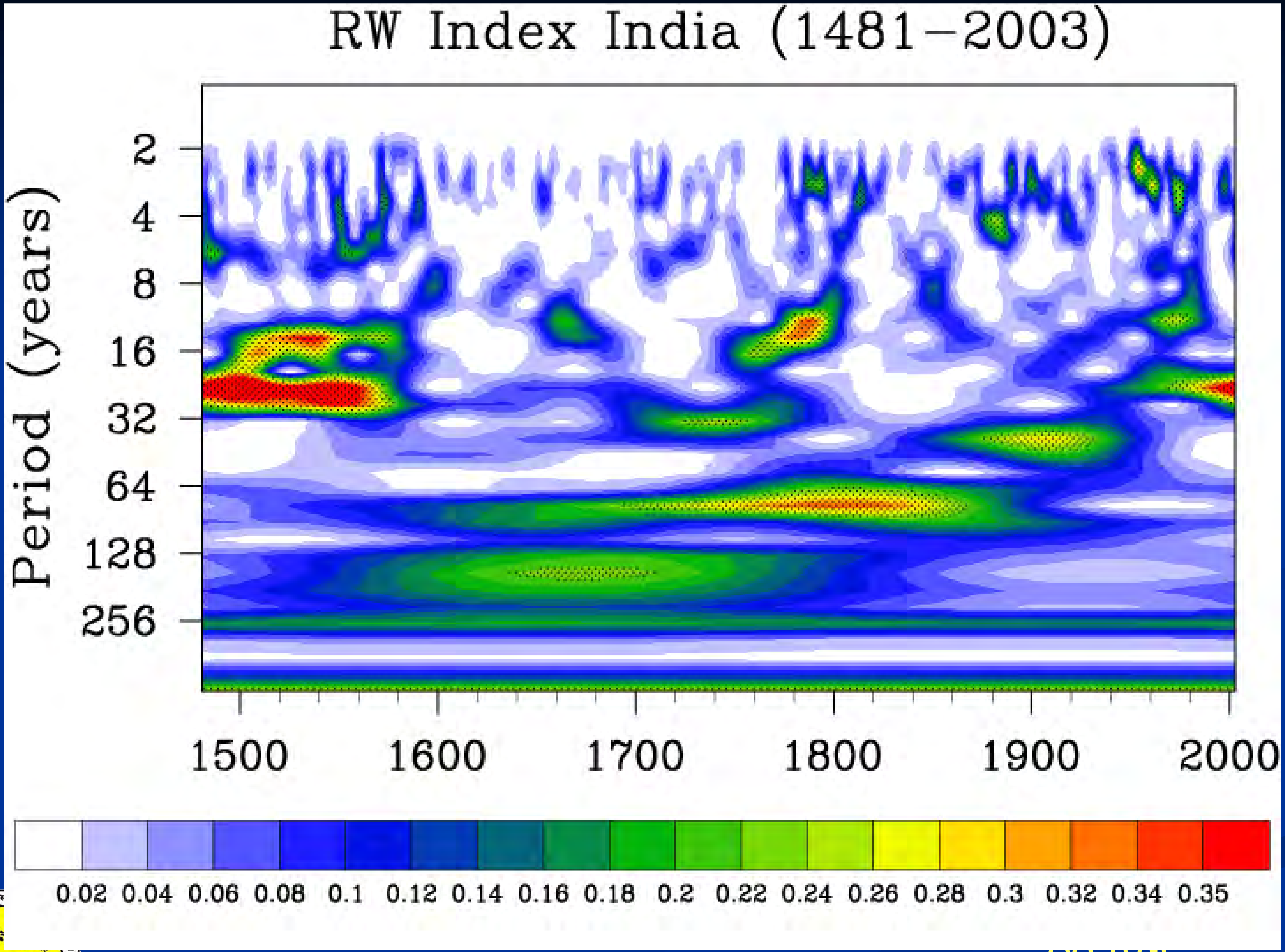
Coherence Spectra

RWI of India and RWI of Thailand

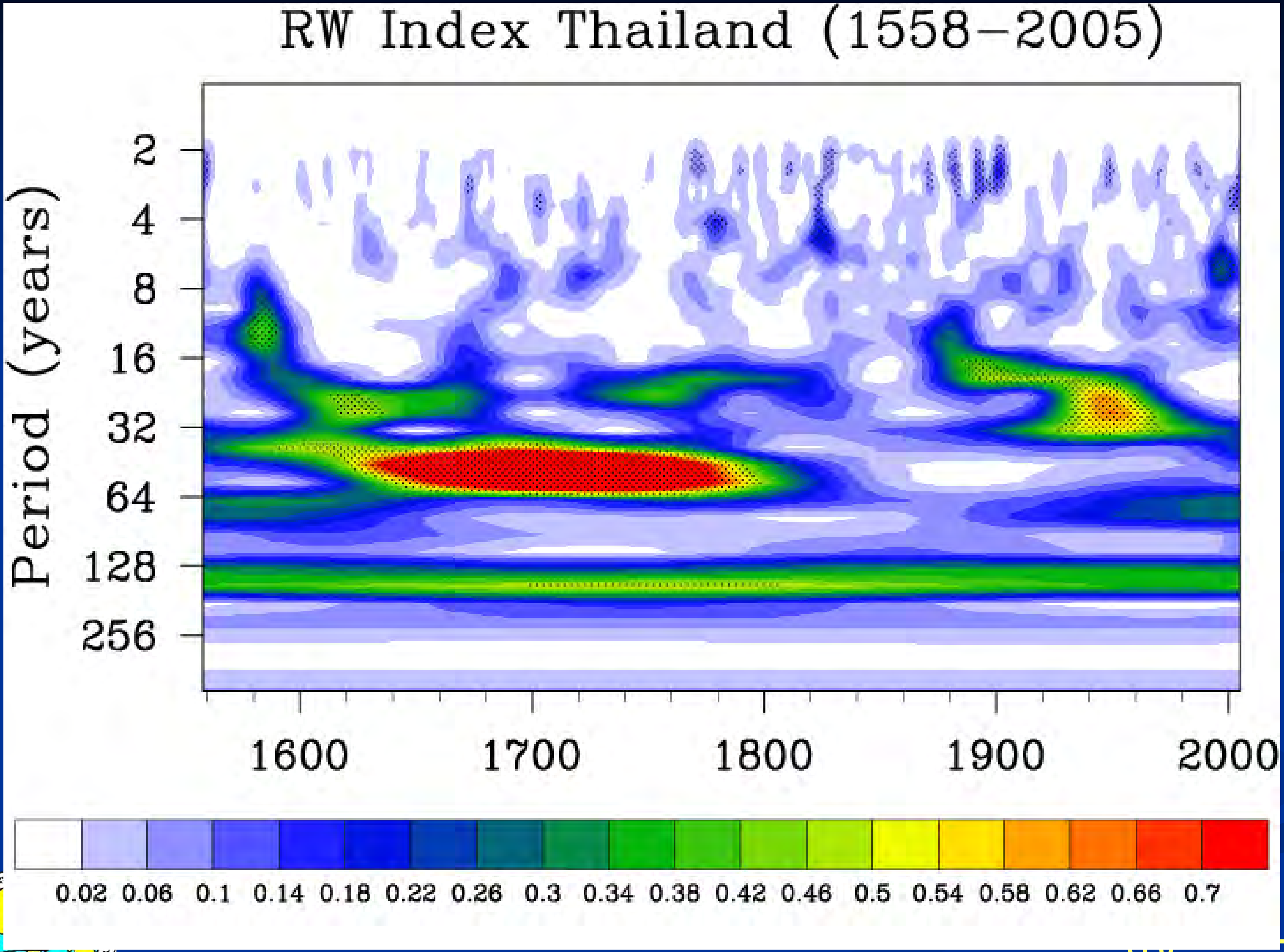


RWI of India and Oxygen Isotope of CI

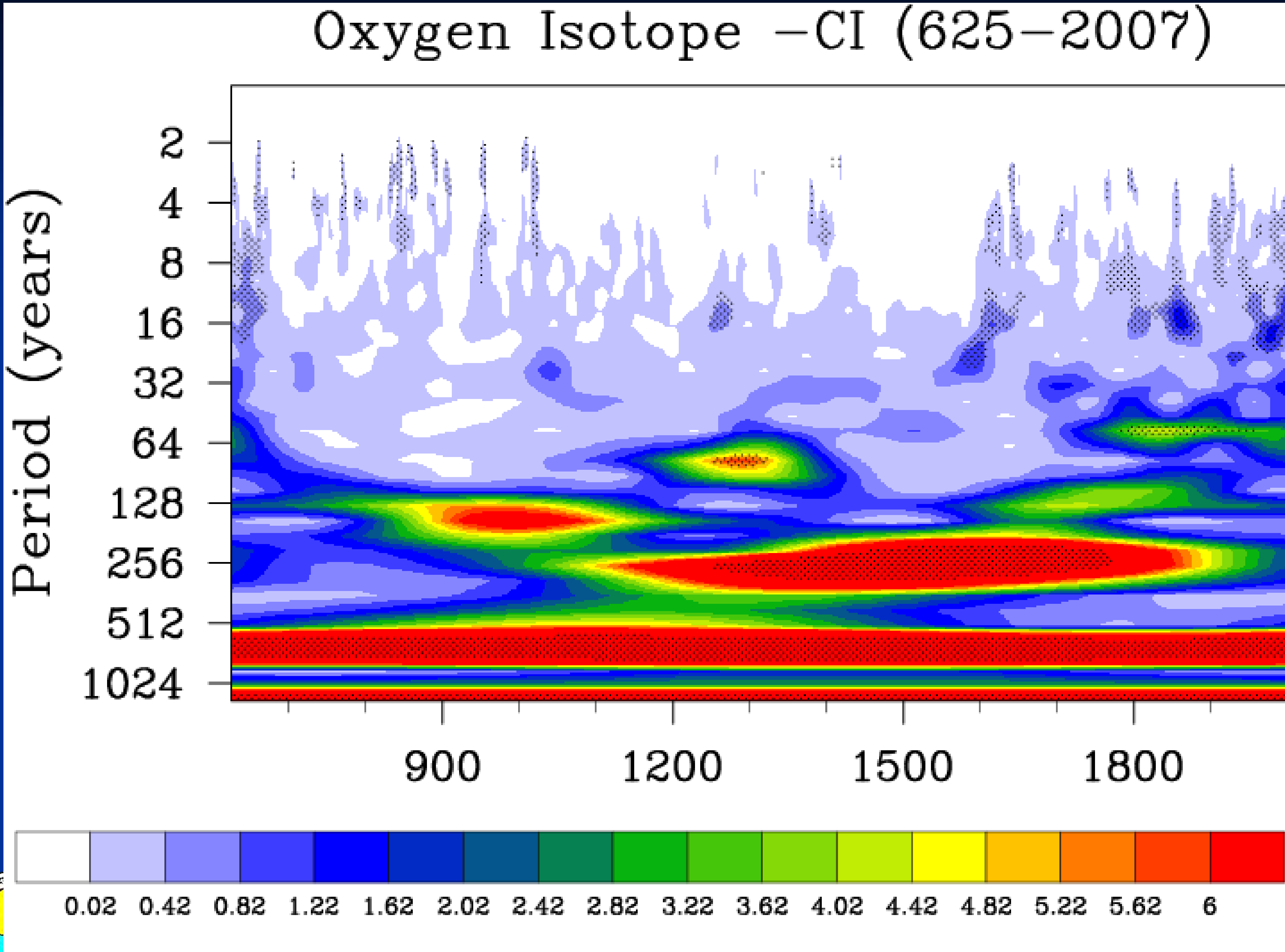




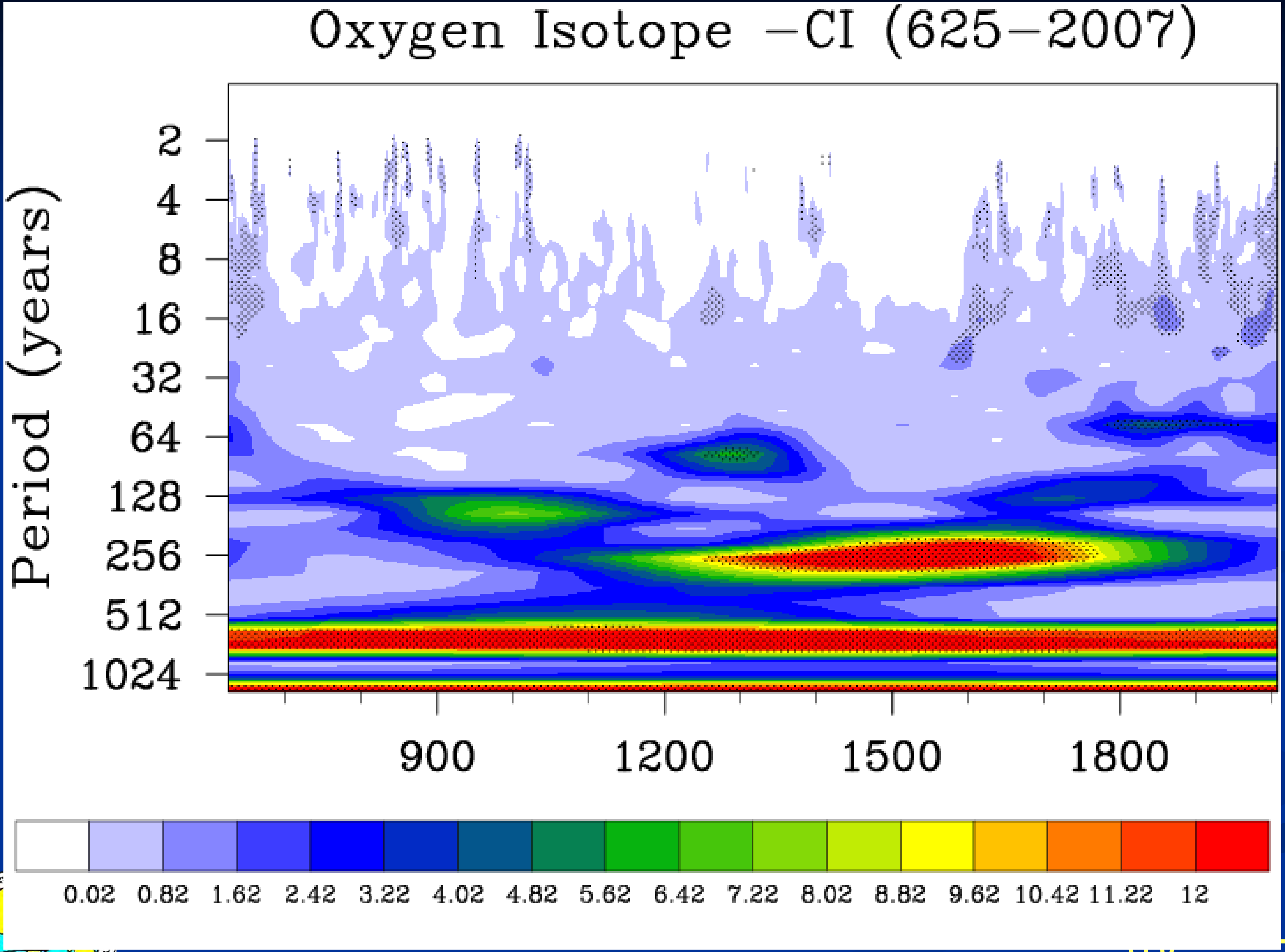
Black dots : Significance at 95 % CL



Black dots : Significance at 95 % CL



Black dots : Significance at 95 % CL



Black dots : Significance at 95 % CL

Conclusion

- Multi-decadal variability responsible for Mega-droughts over monsoon region appear to be a natural variability of the coupled ocean atmosphere system as evidenced by connection with ENSO and NA SST.

- However, the connections with ENSO and NA SST do not seem to be very strong as seen in the recent anomalous case of decreasing trend of monsoon rainfall that seems to be governed by IO SST rather than Pacific or Atlantic SST.

- There is significant coherence in the time scale between 50-80 years amongst different proxies of rainfall over India and Thailand, again indicating that this may be a natural mode of variability.

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Ms. Preethi Bhaskar , IITM, Pune

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Thank You !