Drivers' of the Indian Summer Monsoon: ENSO and NA-SST Teleconnections

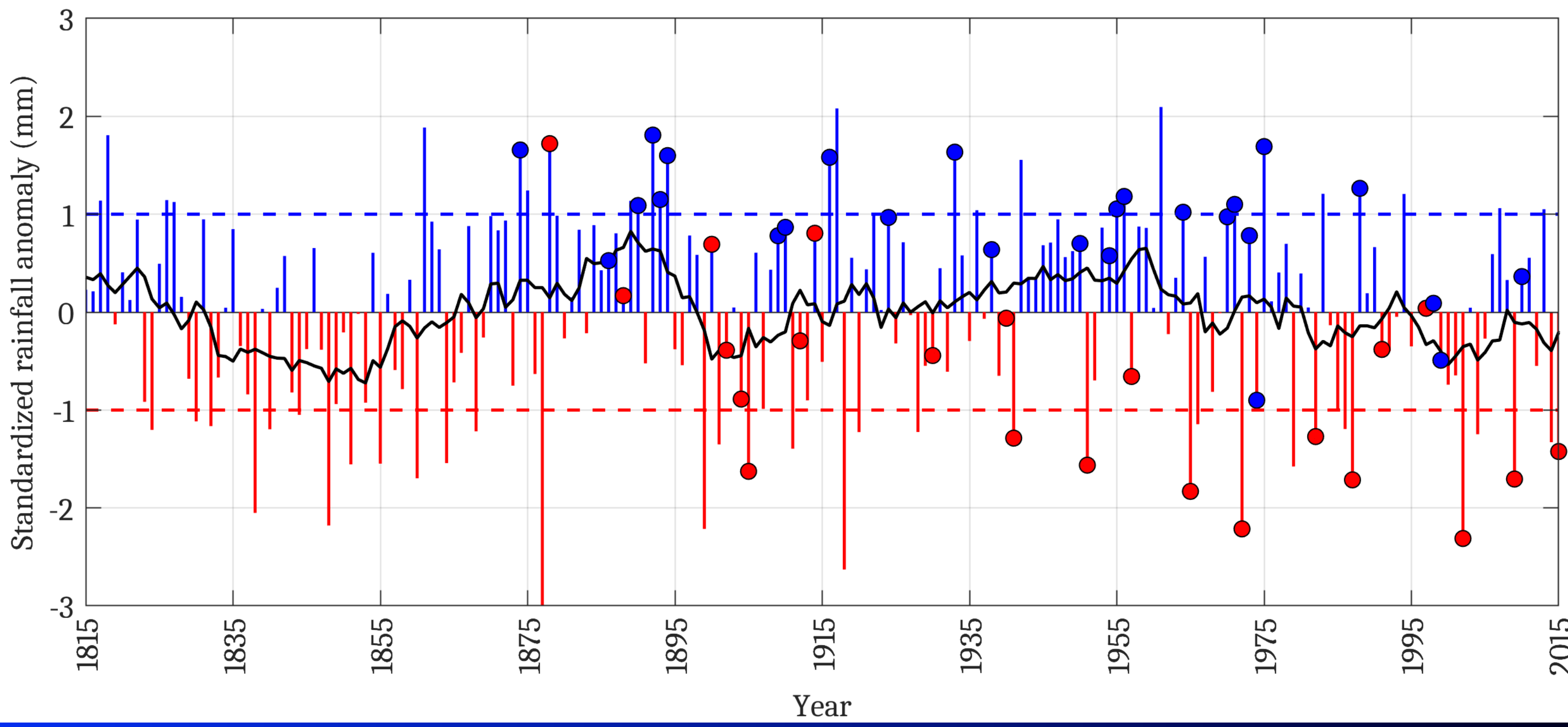
Lecture-9

B. N. Goswami

SERB Distinguished Fellow, Cotton University, Guwahati

28 May, 2022

What Drives the year-to-year Variability of ISMR?



- A strong ENSO-ISMR negative relationship
- But plenty of non-El Nino droughts & non-La Nina Floods
- A clear multi-decadal variability

- Normalized seasonal mean ISMR anomaly (normalized by its own s.d)
- Red dots→ El Nino years
- Blue dots→La Nina years

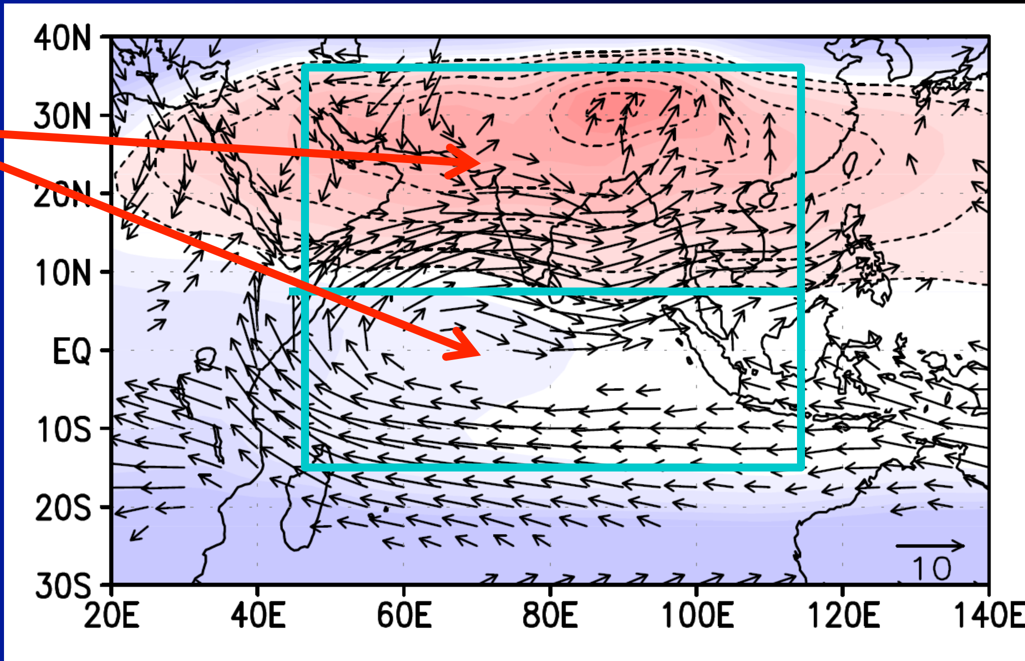
A Framework for Exploring Potential Drivers of Indian monsoon Variability

Traditionally, 'drivers' of Indian monsoon have been explored through associations (correlations) between ISMR (monsoon index) and climate variables that could potentially influence global-scale 'circulation', ex.

- Sea surface temperature (SST) → evaporation → Clouds → Atmospheric heating → Circulation
- Mean Sea Level Pressure (MSLP) → Large-scale surface pressure gradients → winds → Circulation
- Snow cover → Radiation balance → N-S gradient Atmospheric temperature → N-S pressure gradient → circulation

A Framework for Drivers of Indian monsoon Variability

With the ΔTT ($TT_n - TT_s$) framework for the 'mean' monsoon, a potential driver could influence monsoon by either:



➔Influencing TT_n like the ENSO and NA SST (AMO)

Or by

➔Influencing TT_s like the Indian Ocean SST in general and IOD as a special case

Potential 'External' and 'Internal' Drivers

External :

- Strong association with any remote slowly varying climate modes could be considered as a '*potential* External driver' of ISMR. These associations often manifest in linear correlations between drivers and ISMR. That is how they are discovered.

  - ENSO-ISMR, AMO-ISMR, PDO-ISMR, At-Nino-ISMR, relationships are such examples

    → Importance of these associations:

  - If the 'External' drivers are 'slowly varying' compared to the annual cycle of ISMR, they are predictable at one season or longer lead. Therefore, such drivers are sources of **'potential predictability'** for ISMR.

Potential ‘External’ and ‘Internal’ Drivers

Internal :

ISMR in years when it is not related to any of the known ‘external’ drivers can be considered to arise from ‘Internal’ ISMR variability. But how such ‘Internal’ ISMR variability arise from? ‘Internal’ here refers to arising from within the regional Indian monsoon system.

Some possibilities:

- Local Ocean- atmosphere interaction like Indian Ocean Dipole Mode (IOD). So IOD may be a potentially predictable ‘Internal’ driver’
- Land-atmosphere feedback
- Interaction between Higher frequency sub-seasonal fluctuations and Seasonal mean (Complexity)

Exploration for Search for 'External' Drivers has a Long History..

1875- IMD was Established, with Blanford, H. F., FRS

Meteorological Reporter-Govt. India,

Blanford, H.F. (1884). "On the Connexion of the Himalaya Snowfall with Dry Winds and Seasons of Drought in India". Proceedings of the Royal Society of London. 37: 3–22. doi: 10.1098/rspl.1884.0003

Sir Gilbert Walker, FRS

Director General, IMD during 1904-1924

Walker G, 1924: Correlations in seasonal variations of weather, IX, Mem. India Meteor. Dept., 24, 333-345 (Discovered SO and association with monsoon)

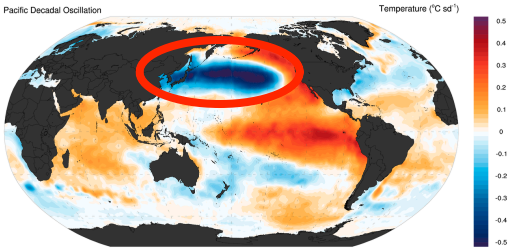
The search for 'Predictors' of Indian summer monsoon rainfall (ISMR) over the past over 150 years led to discovery of some notable associations between ISMR and other 'climate modes'. Two most prominent are,

➔**ISMR and El Nino and Southern Oscillation (ENSO)** (Tropical Pacific SST) connection (Walker, 1924, Pant and Parthasarathy, 1981, Rasmusson and Carpenter, 1983, Webster and Yang, 1992, Krishnamurthy and Goswami, 2000, Xavier et al., 2007, Kumar et al, 1999, Lau and Nath, 2000)

➔**ISMR and NA-SST** (North Atlantic SST) connection (Burns et al, 2003, Gupta et al. 2003, Goswami et al., 2006, Zhang and Delworth, 2006, Krishnamurthy and Krishnamurthy, 2016, Borah et al., 2020, Rajesh and Goswami, 2020)

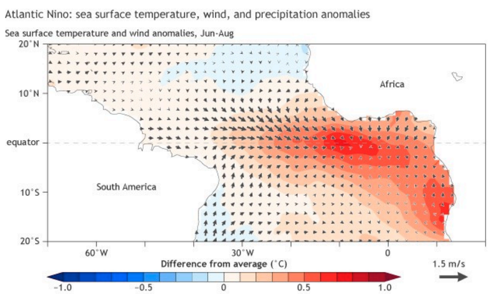
Comment: The list of references for ENSO-ISMR relationship is only indicative and not exhaustive. A whole bunch of work is available for ENSO-ISMR relationship but relatively small volume of work on AMO-ISMR relationship.

In addtion to the ENSO and the NA-SST association between ISMR and other climate modes are also found. Ex.



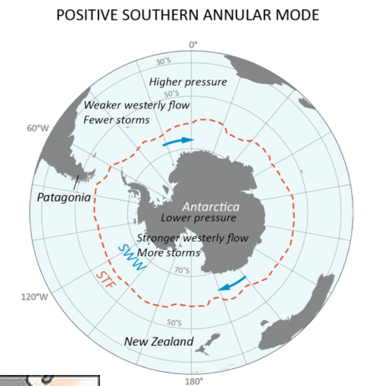
Pacific Decadal Oscillation (PDO)

Krishnan and Sugi, 2003, Krishnamurthy and Krishnamurthy, 2014



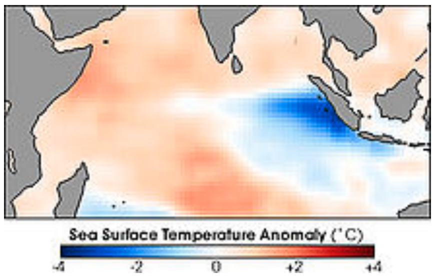
Atlantic Nino (At-Nino)

Yadav R. et al, 2018, npj:CAS; Kucharski et a., 2008 GRL



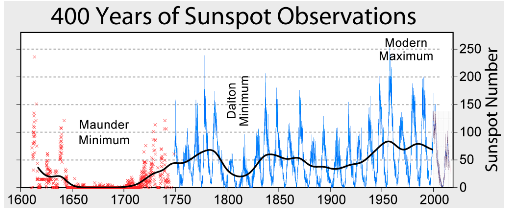
Southern Annular Mode

Parbhu et al., 2016, 2017, Dou et al., 2017



Indian Ocean Dipole Mode

Saji, Goswami et al., 1999, Webster et al., 1999, Ashok et al, 2001



Sunspot Cycle (11-year)

Hirenath and Mandi, 2004, Bhattacharya & Narasimha, 2005, Agnihorti et al.,2002

Apart from the ENSO and the NA-SST association between ISMR and other climate modes are also found.

And

European snow cover

Han and Shukla, 1976, Bamzai and Shukla 1999, Kripalani and Kulkarni, 1999, Fasullo, 2004, Saha et al., 2013

➔Although European Snow cover may not be an independent climate mode but gets contributions from many of them.

Comment:

These associations are important as they could 'potentially' enhance predictability of ISMR. Robust estimate of their contribution to ISMR variability required.

The 'linear' correlations between them and ISMR are smaller than the best ENSO-ISMR correlations. However, with ENSO-ISMR relation weakening in recent years, they may be important.

As illustration, in this lecture, I shall limit to ENSO and NA-SST (AMV) associations

ISMR , ENSO and AMV Indices for Interannual variability studies: ENSO

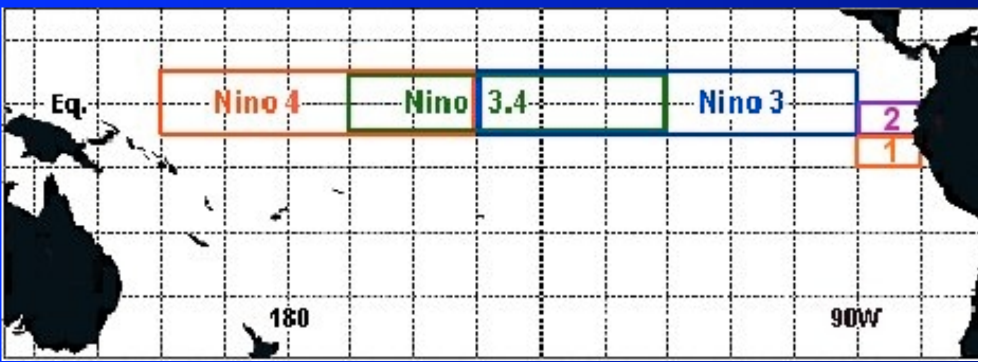
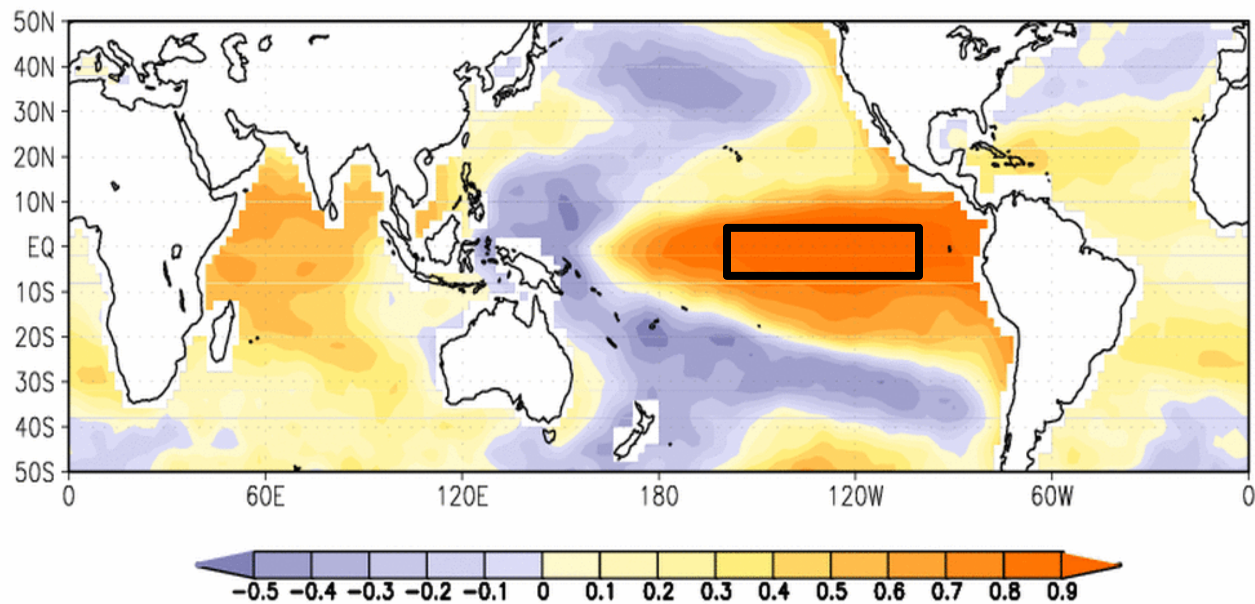


TABLE 1. The lat and lon ranges defining area averages for SST indices. SOI is calculated using pressure differences between Tahiti (17.5°S, 149.6°W) and Darwin (12.4°S, 130.9°E).

Index	Lat range	Lon range
Niño-1+2	0°–10°S	90°–80°W
Niño-3	5°N–5°S	150°–90°W
Niño-3.4	5°N–5°S	170°–120°W
Niño-4	5°N–5°S	160°E–150°W
JMA	4°N–4°S	150°–90°W
TNI	Niño-1+2 and Niño-4	Niño-1+2 and Niño-4

ENSO SST indices are constructed by averaging monthly SST anomaly over the boxes shown.

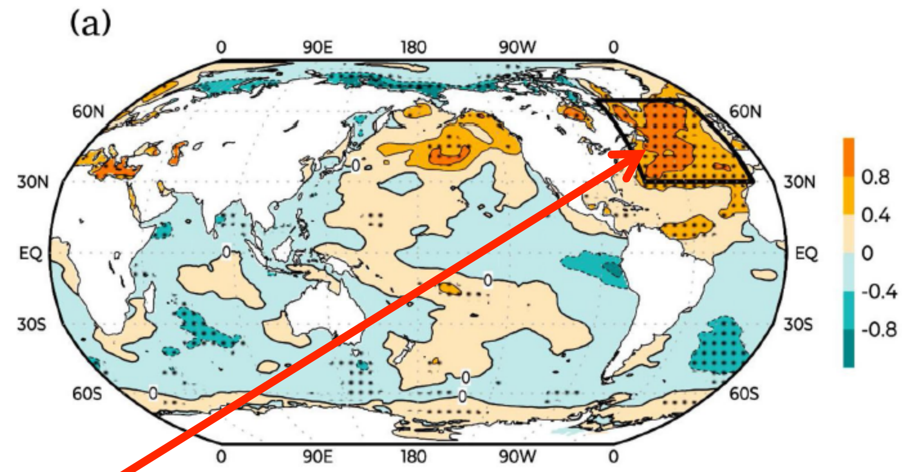
Correlation between Nino3 anomalies and SST at all points

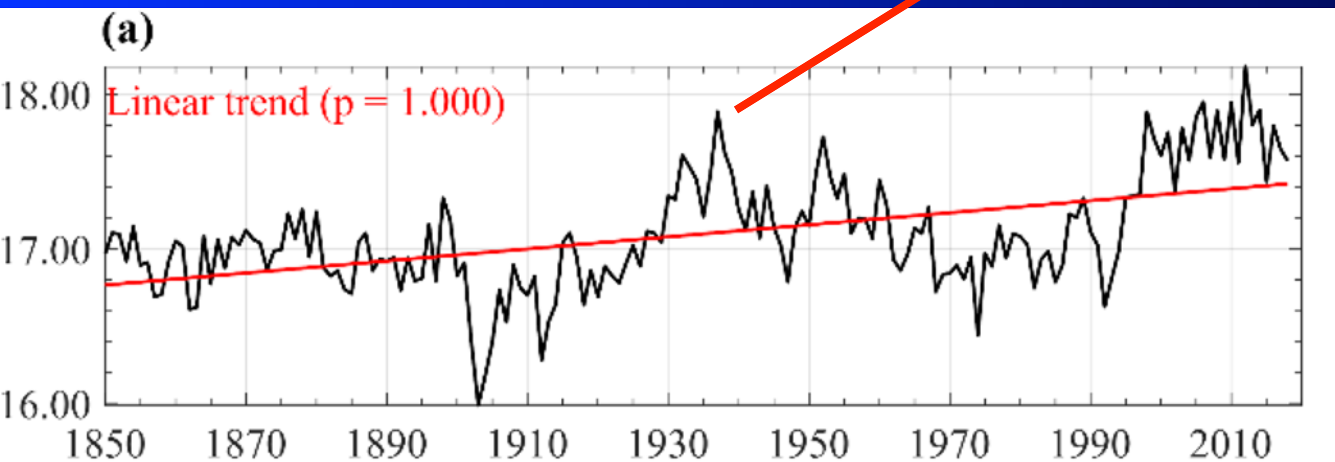


ISMR , ENSO and NA-SST Indices for Interannual variability studies: NA-SST

Global pattern of JJAS SST associated with NA JJAS SST over the box shown

Fig. 10 **a** Regression of JJAS SST with NA box SST IMF-5 and **b** regression of JJAS SST with AMOC index IMF-5. The black dotted region represent the values significant above 95% confidence level. Units are in K K^{-1} and K Sv^{-1} respectively. The pattern correlation between **a** and **b** is 0.89





Time series of JJAS SST over the NA box.

Note dominance of a multi-decadal mode often refered to as AMO

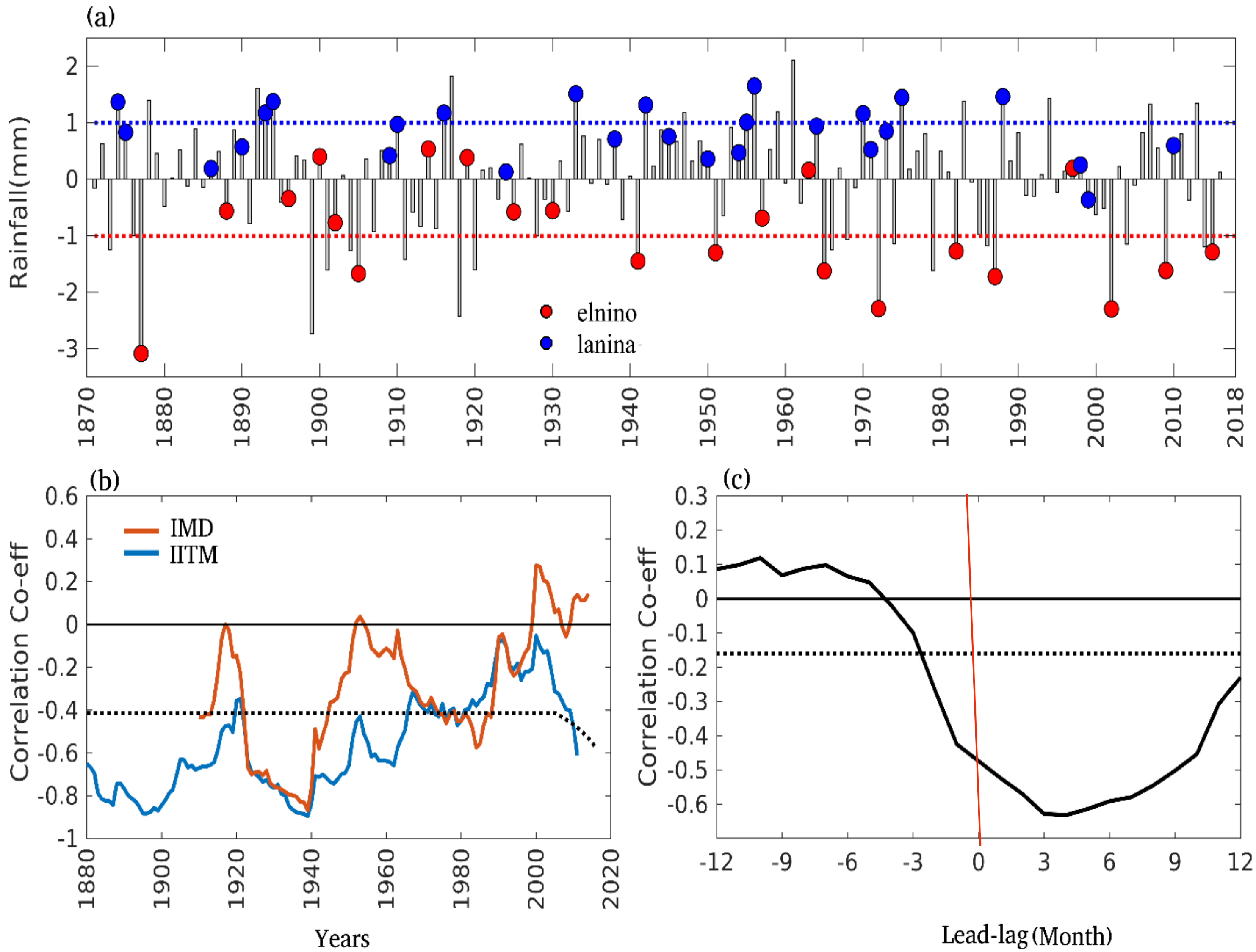
How do we quantify the ENSO-ISMR relationship?

Moving Correlations and lead-lag correlations

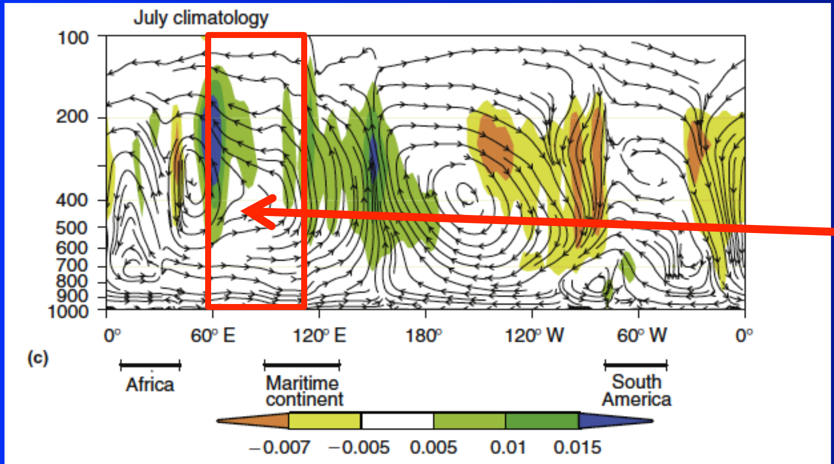
(a) Normalized ISMR with El Nino/La Nina

(b) 21-year moving corr. ISMR-Nino3.4

(c) Lead-lag corr. Between ISMR and Nino3.4 SST



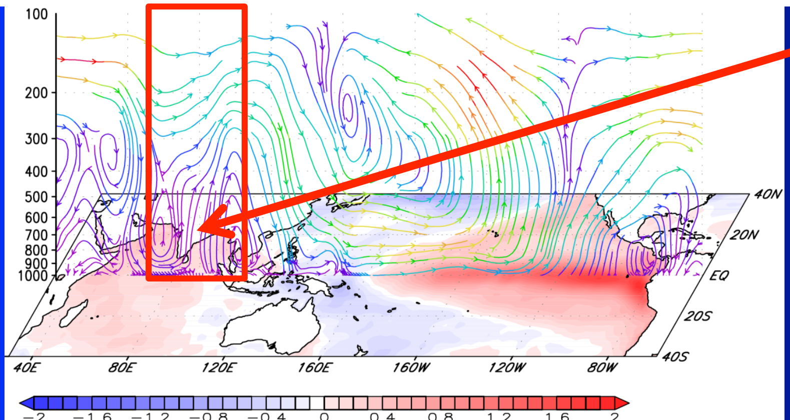
ENSO-ISMR Teleconnection : Tropical connection



Climatological mean Walker Circulation during July

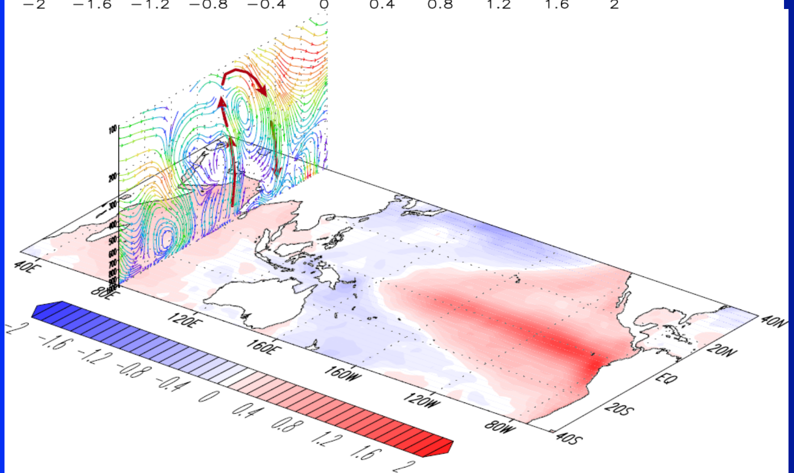
Weak Ascent

Strong Ascent



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

A sub-tropical pathway of connecting ENSO with ISMR through TT gradient.

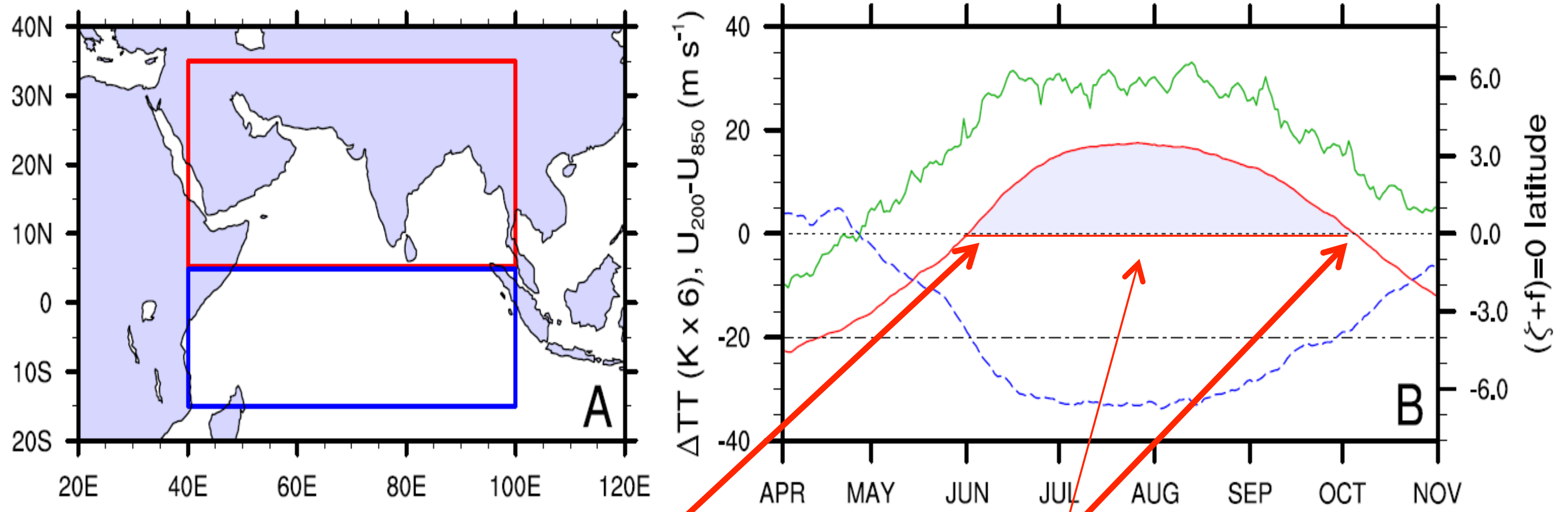


FIGURE 3.3: (A) The area used to define ΔTT. (B) Shows the evolution of climatological values of ΔTT (K×6, solid red line, scale to the left) and the climatological mean vertical shear of zonal winds (U_{200} - U_{850}) averaged over 50°-95°E, 0°-15°N (m s^{-1}, dashed blue line, scale to the left). 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).

Red → Meridional gradient of TT (ΔTT = TT_n –TT_s)

Onset Withdrawal LRS

Correlation between LRS (i) days, i =1, N years with JJAS SST (i), i =1, N years over the Indo-Pacific. Note similarity of corr. Pattern with that with ENSO pattern

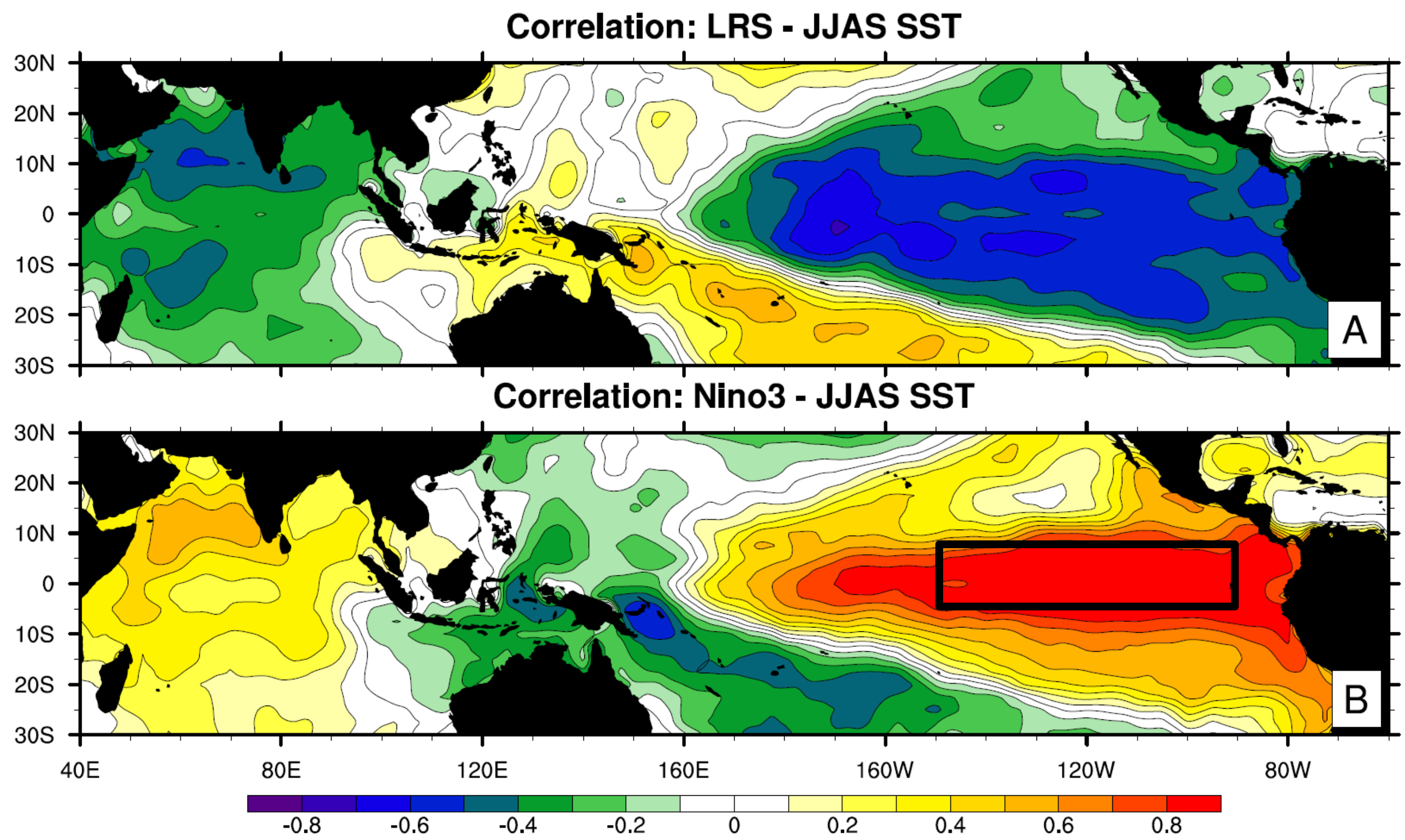
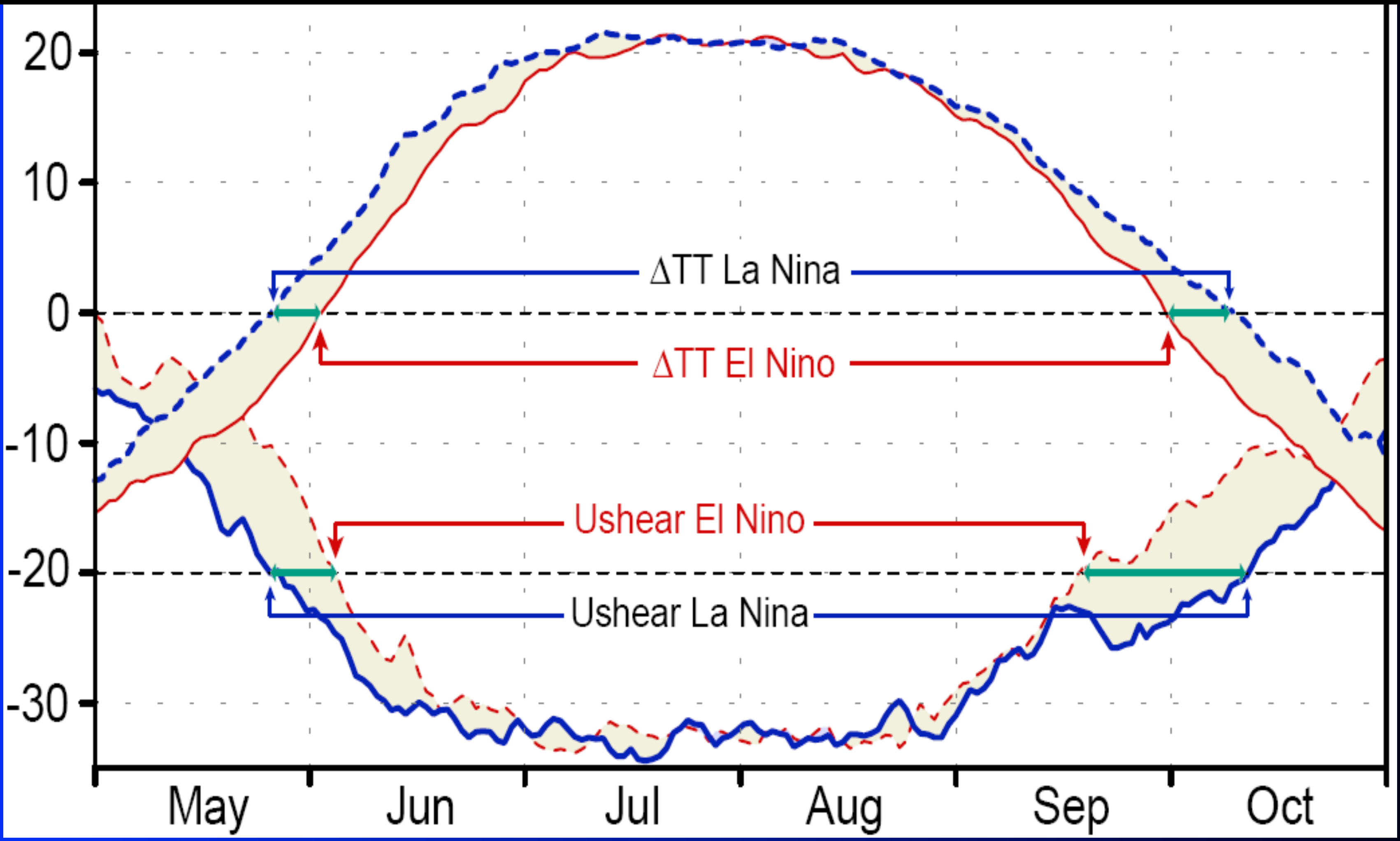


FIGURE 3.8: Correlation coefficient of June-September SST anomalies at every grid box with (A) LRS and (B) with Niño 3 SST anomalies, based on data between 1950 and 2003.

→Strong association between LRS of Indian monsoon & ENSO

How does the association come about?

El Nino 'contracts' LRS while La Nina 'expands' it!



EL Nino and La Nina Composite of ΔTT and Ushear

Goswami and Xavier, 2005, GRL

How does the ENSO influence the ΔTT ?

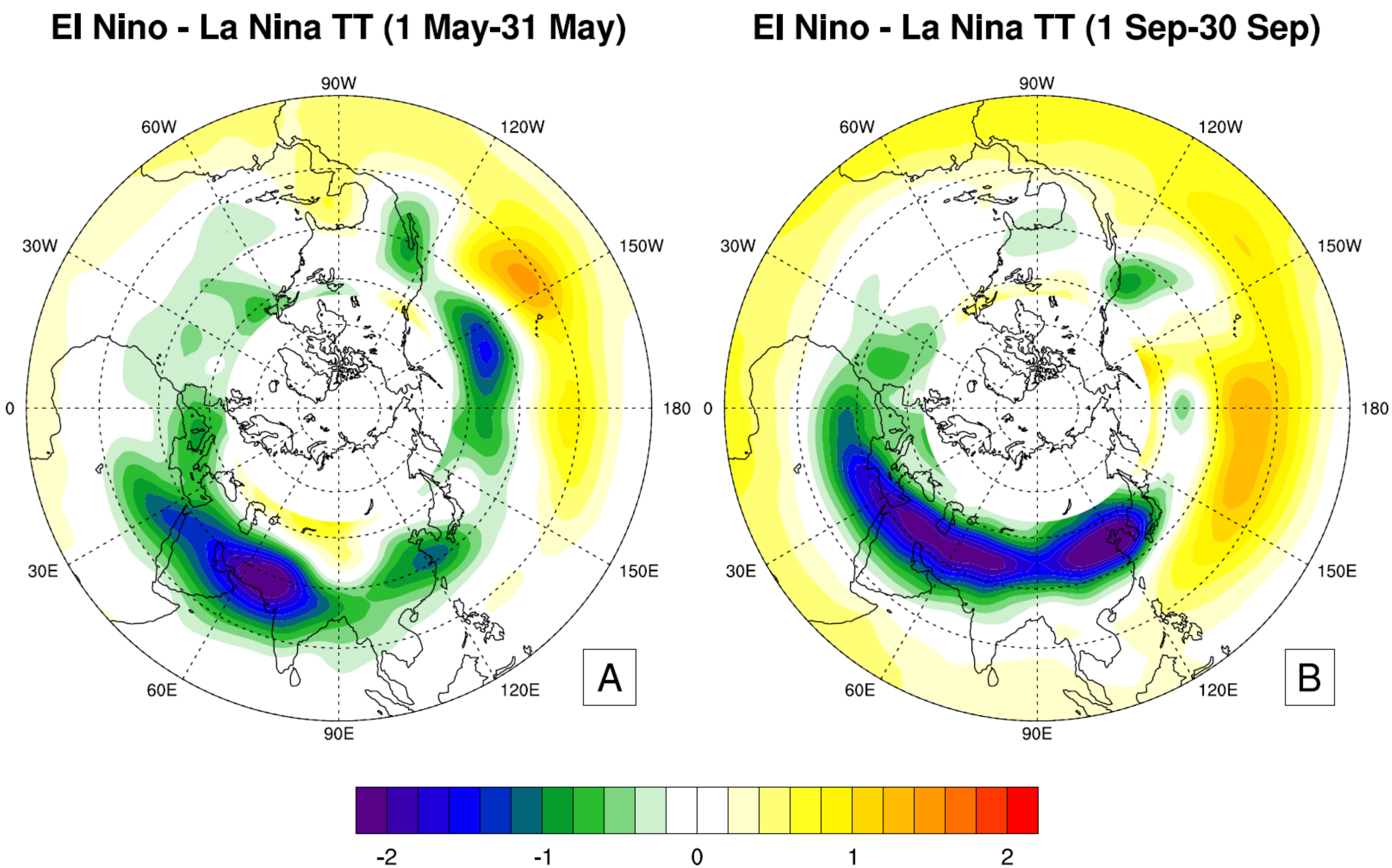
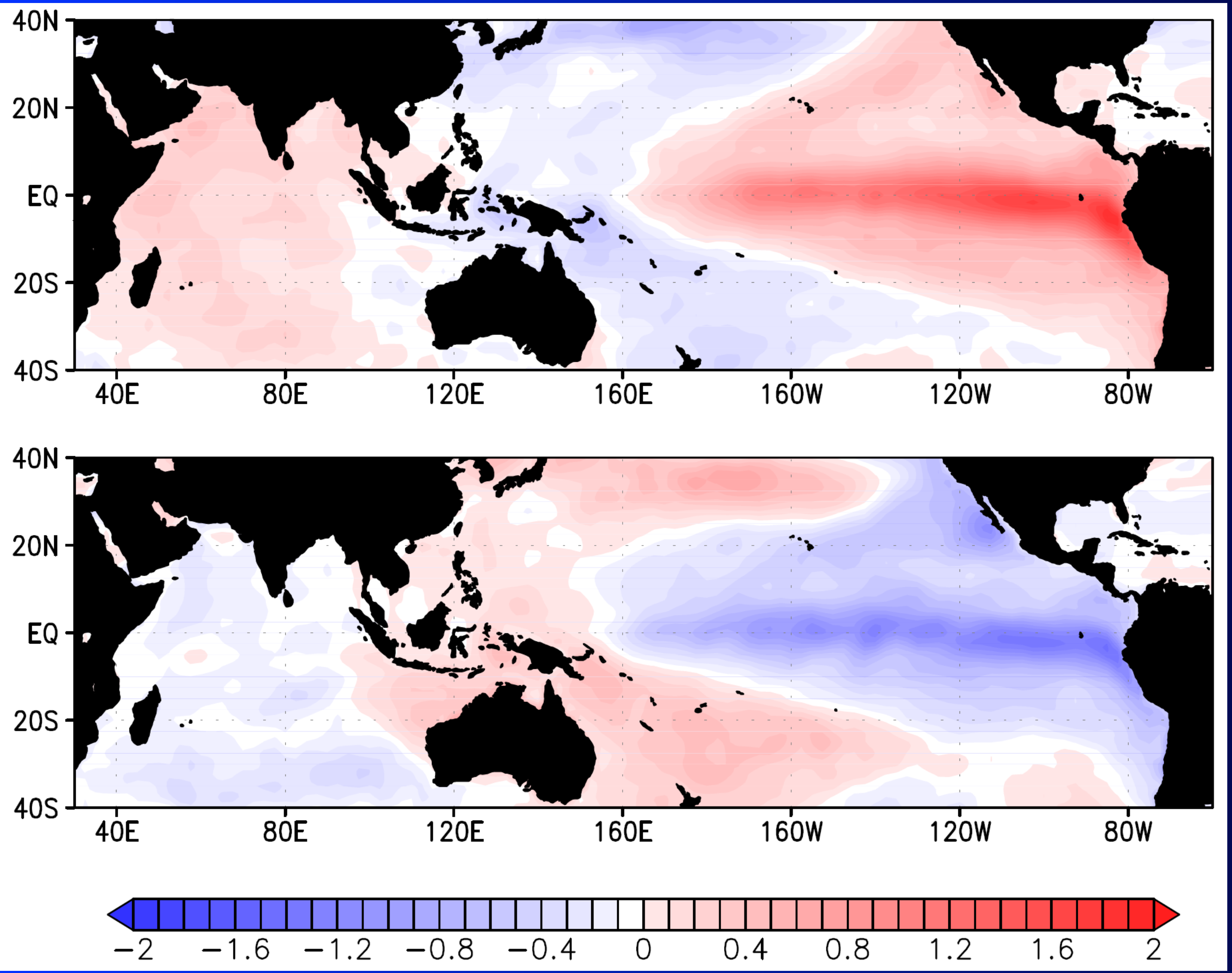


FIGURE 3.9: El Niño minus La Niña composites of TT (K) averaged between (A) 1 May and 31 May and (B) 1 September and 30 September. These are based on 11 El Niño (10 La Niña) years defined using normalized Niño3 SST anomalies being > 1 (< -1).

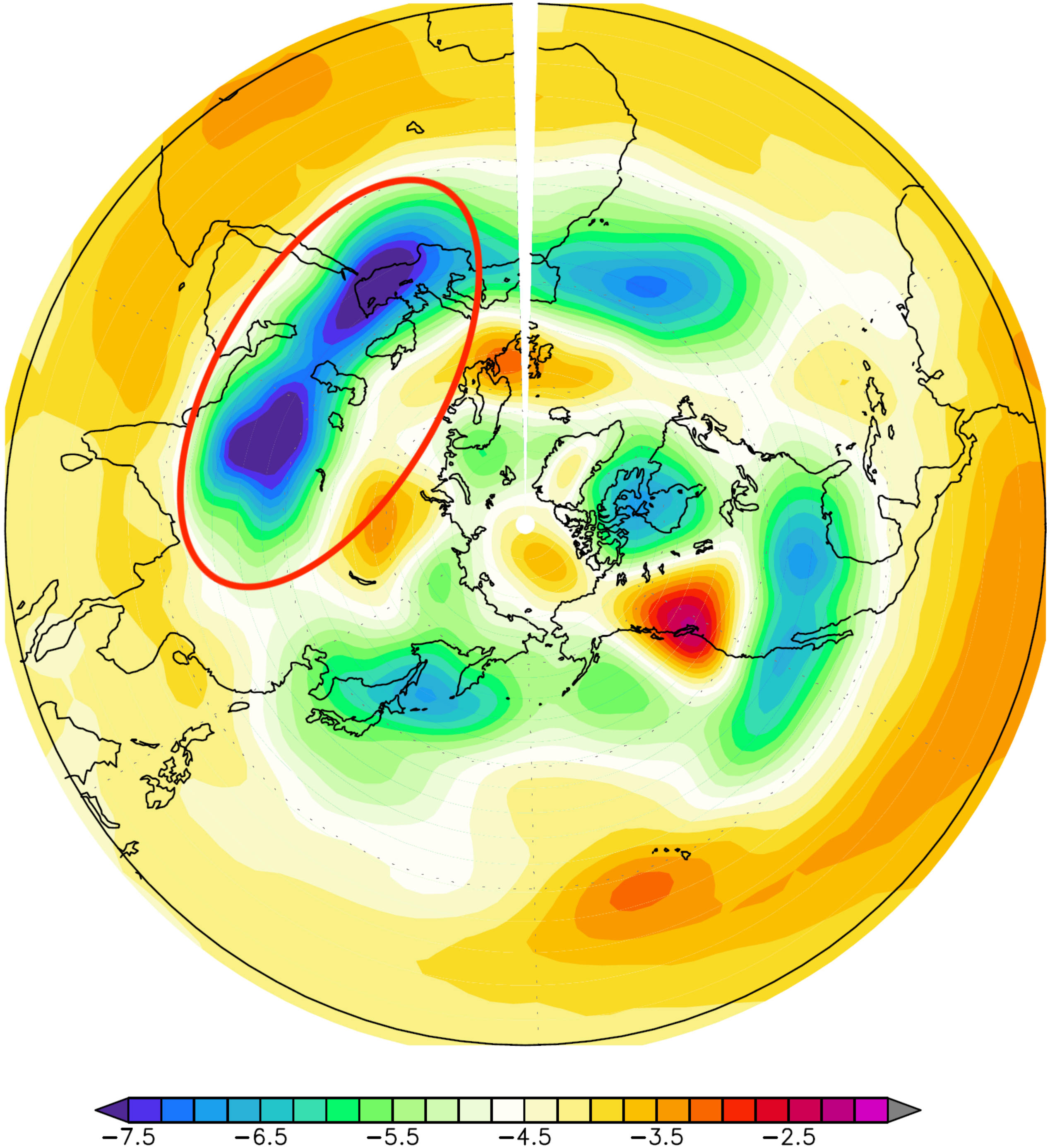
To test the hypothesis that ENSO SST anomalies drive the TT anomalies over Indian region, we carry our experiments with a AGCM forced by El Nino and La Nina SST anomalies.



El Nino

Composite SST anomalies (JJAS)

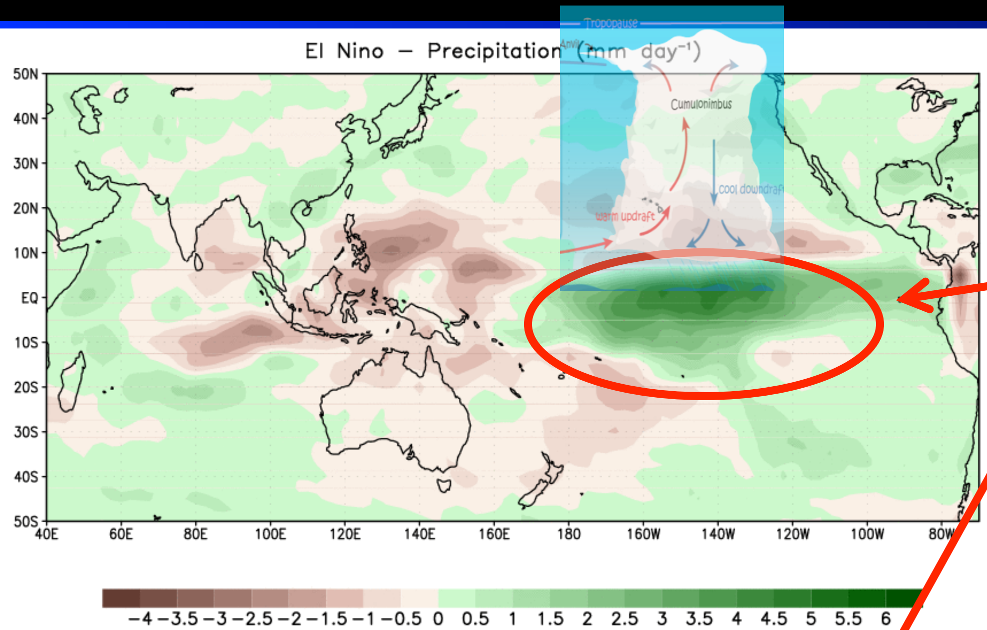
La Nina

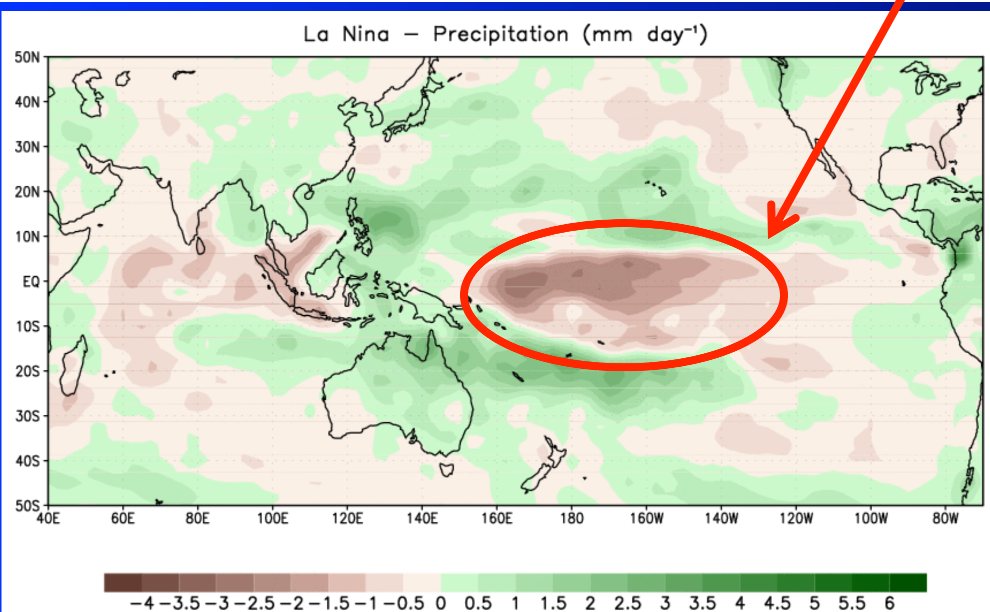


AGCM simulation to understand the extra-tropical teleconnection rout for ENSO-monsoon connection

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 ENSO SST forces the TT anomaly over Eurasia?





Increased (decreased) persistent atmospheric heating during El Nino (La Nina) over equatorial Central Pacific.

- Sets up a stationary Rossby wave pattern with –ve (+ve) TT anomaly over southern Eurasia during El Nino (La Nina)

How does the ENSO SST controls the LRS?

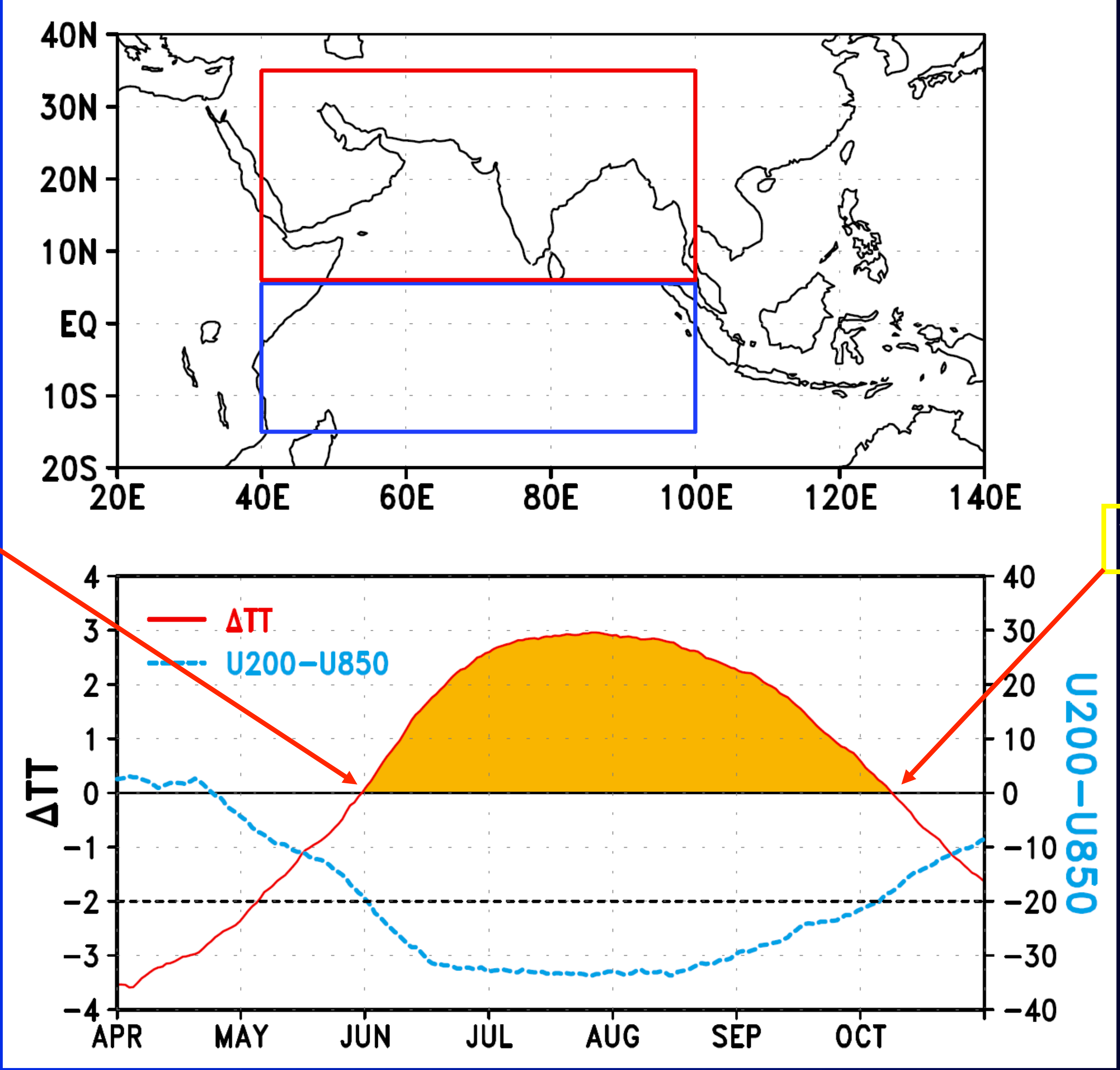
During positive ENSO phase (El Nino), SST results in positive P anom over central and eastern Pacific and negative P anom over western Pacific and maritime continent.

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!

Onset

Withdraw



Recall, ISMR or AIR→ An rainfall index of Indian monsoon, JJAS rainfall over land points

Alternatively, We can define 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

Moving correlation between Nino3 and TISM

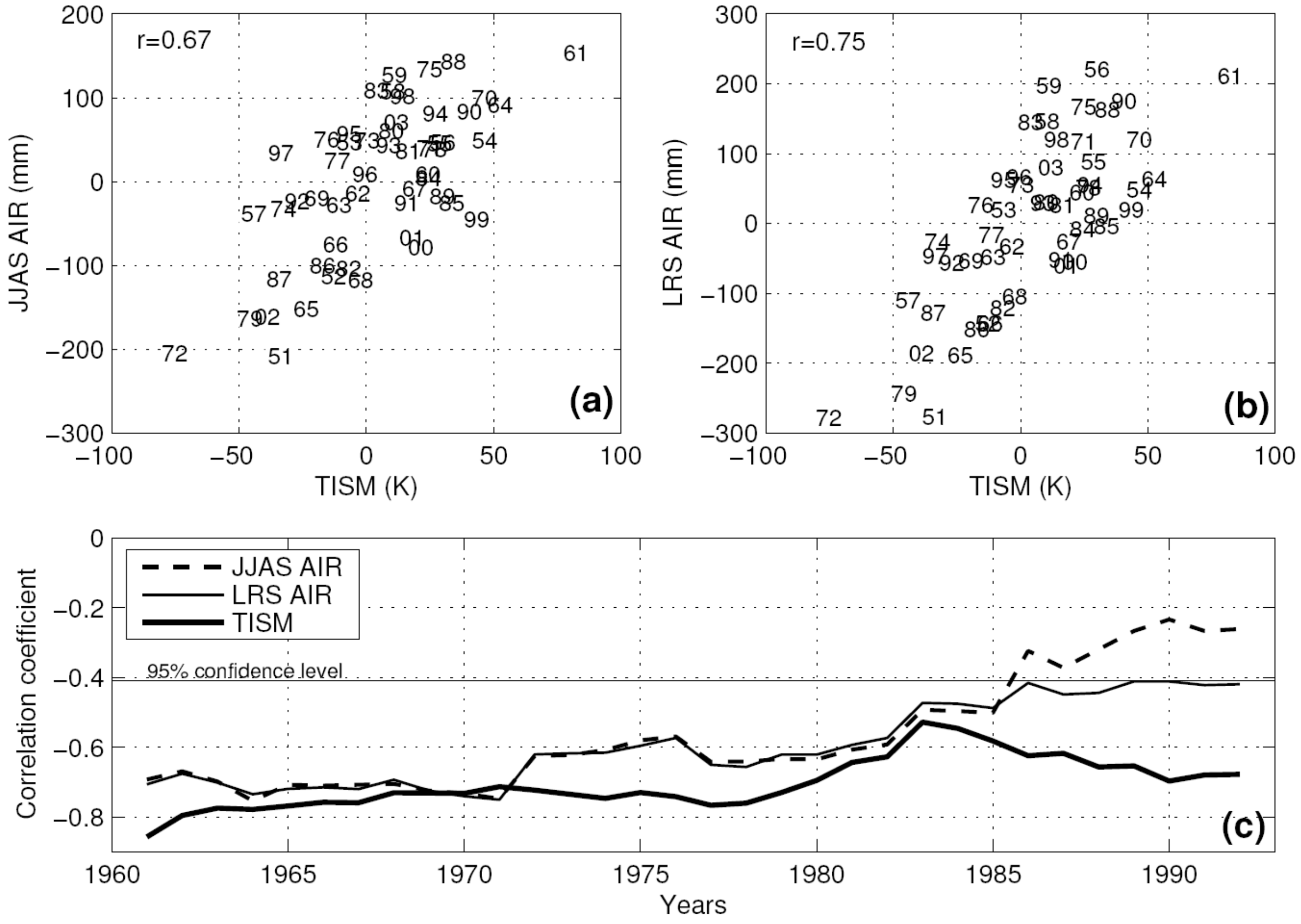
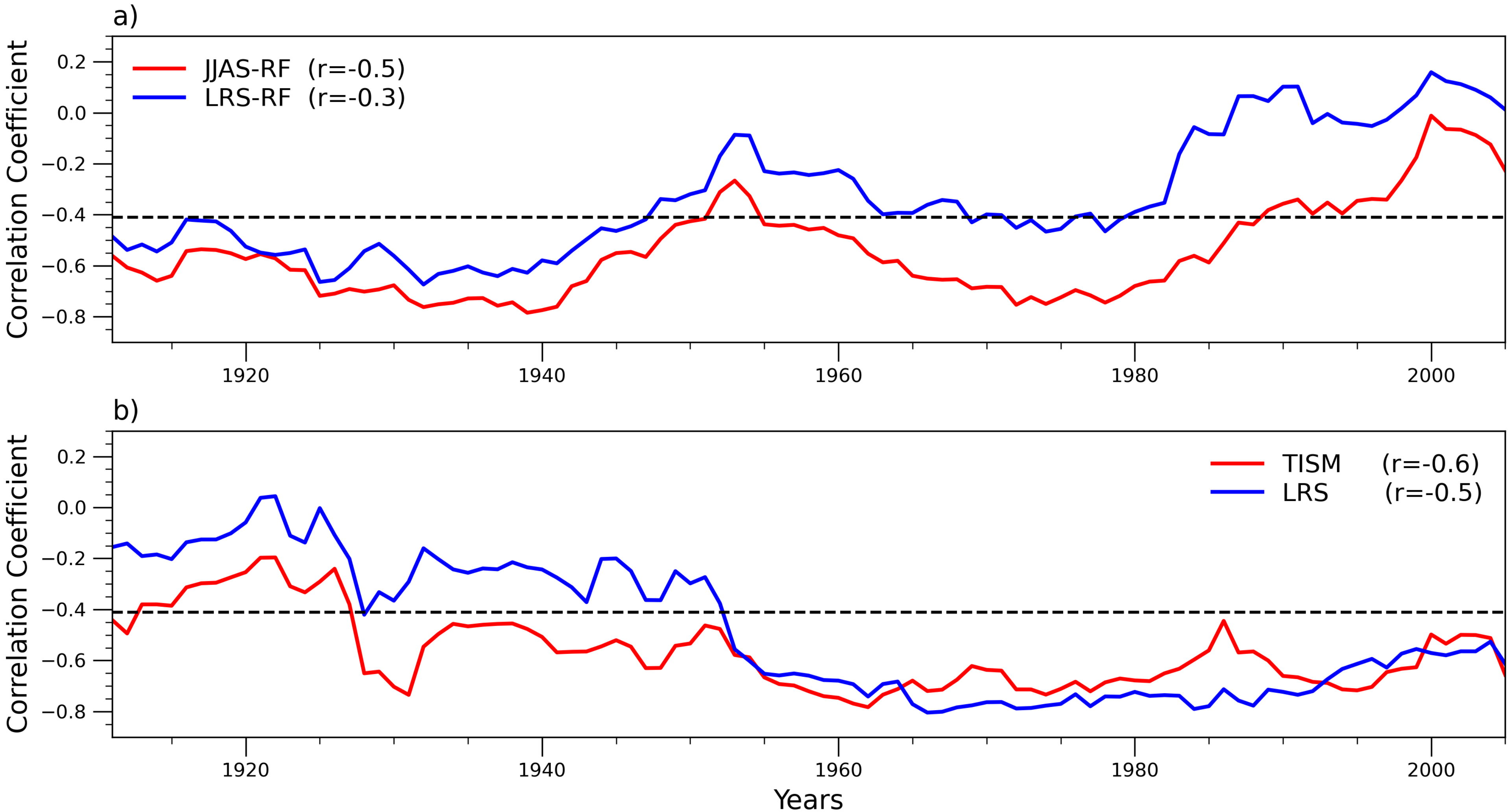


Figure 8. Scatter plot of TISM with (a) the anomalies of total AIR for JJAS season and (b) with the anomalies of total AIR for the LRS period. Points are represented with last two digits of the years. Correlations between the two are shown in the respective panels. (c) 21-year running window correlation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

Xavier et al., 2007, QJRMS

Updating the changing ENSO-ISMR relationship up to 2020



21-year moving correlations between (a) JJAS-RF,LRS-RF and Nino3.4, (b)TISM and LRS days and Nino3.4

- **Thus, it appears that in reality the ENSO-Monsoon connection has not weakened in recent times! The observed weakening of ‘correlation’ is essentially related to defining monsoon season with a rainfall index.**

- **The seasonal mean rainfall has a component coming from ‘chaotic’ internal variability. It seems, global warming increases the ‘internal’ stochastic contribution to the seasonal mean rainfall increasing decorrelation with SST.**

- **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!**

Need to look beyond ENSO and TOGA!

North-Atlantic SST has emerged as a Potential Source!

- There has been paleo evidence that North Atlantic cooling is associated with mega-droughts of the Indian monsoon (Burns et al, 2003, Gupta et al. 2003) on centennial time scale.
- Over the past 15 years, we have investigated the robustness connection between NA-SST or AMO and ISMR and its independence from ENSO-ISMR connection on interannual and multi-decadal time scales. (Goswami et al., 2006, Borah et al., 2020, Rajesh and Goswami, 2020, Chattopadhyaya et al., 2014, Rajesh and Goswami. 2022).
- The teleconnection through which the NA SST influence ISMR on interannual time scales has also become clearer (Krishnamurthy and Krishnamurthy, 2016, Borah et al., 2020, Rajesh and Goswami, 2020)

ISMR-North Atlantic SST connection on Millennium time scales

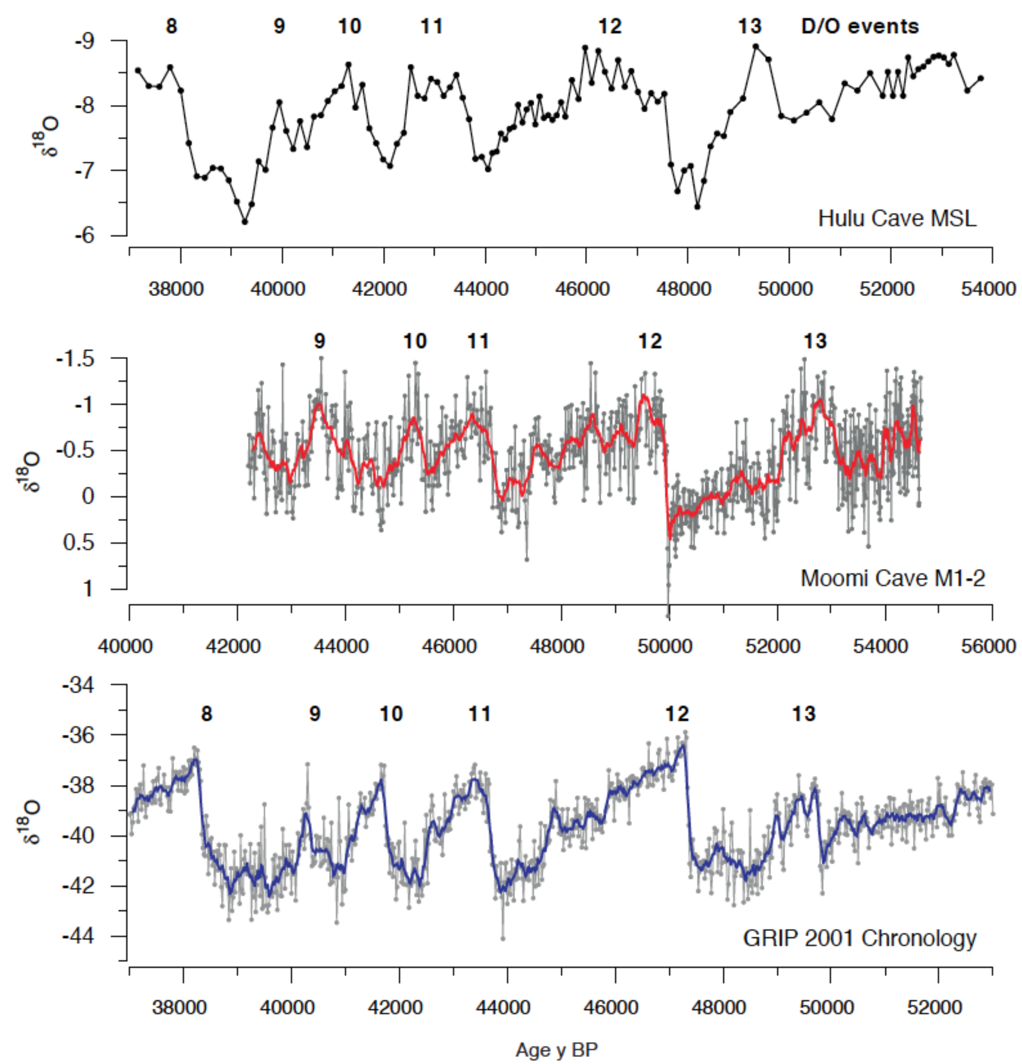


Fig. 2. Comparison of the oxygen-isotope ratios of stalagmite M1-2 with oxygen isotopes from the GRIP ice core (2) and the $\delta^{18}O$ record of a stalagmite from Hulu Cave in central China (4). The time scales are independent and shifted to give the best fit for D/O events. The oxygen isotopic scales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

Oxygen isotope ratio from stalegmites in Hulu cave, China, Close to Nanjing (32°30′ N,119°10′ E)

Oxygen isotope ratio from stalegmites in Moomi Cave in Arabian Sea, Socotra Island

Oxygen isotope ratio from GRIP Ice core.

Note: the y-scale for stalegmites are reversed

Burnes et al., 2003, Science,301

ISMR-North Atlantic SST connection on Centennial time scales

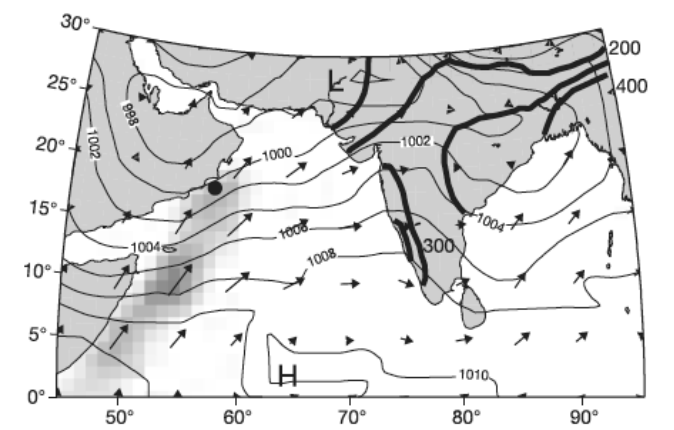


Figure 1 July sea-level pressure (mbar, thin contours), wind direction[27], cooling of the Arabian Sea due to upwelling[28], and precipitation over Asia[29] (mm month^{-1}, thick contours). Site 723 and box core RC2730 are located at 18° N, 58° E (circle). H, high pressure; L, low pressure.

Gupta et al., 2003, Narure

- G-Bulloide abundance reflects strength of monsoon winds over oman coast.
- Hematite abundance is sensitive to temperature in North Atlantic (NA)
- Many cold episodes over the NA are related to low abundances of Bulloides over Arabian Sea

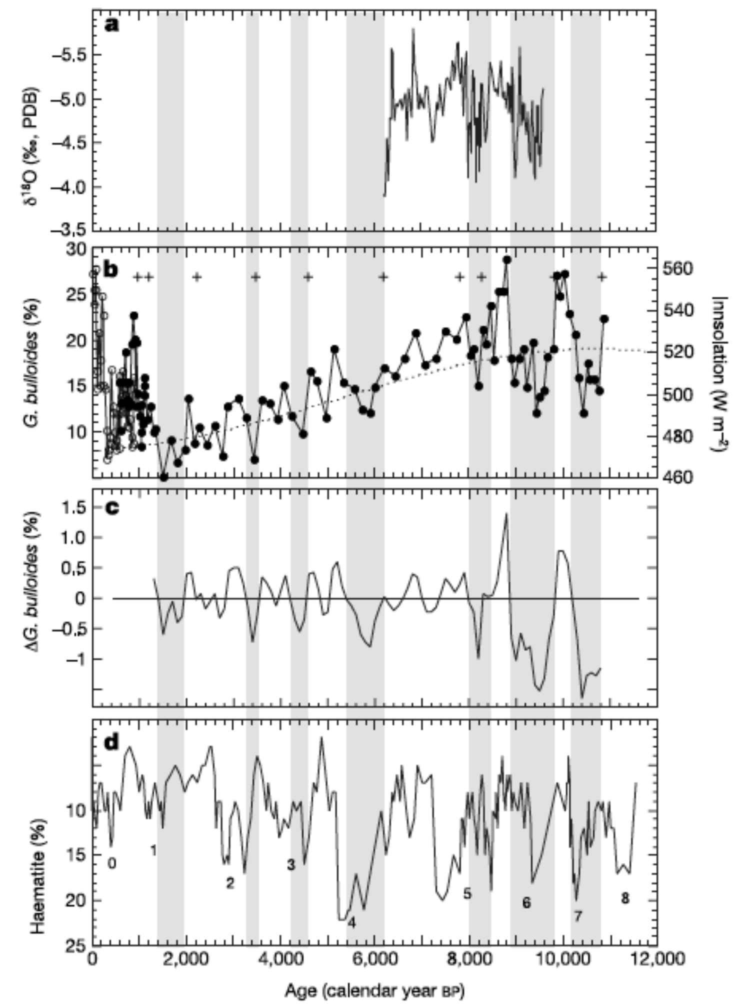
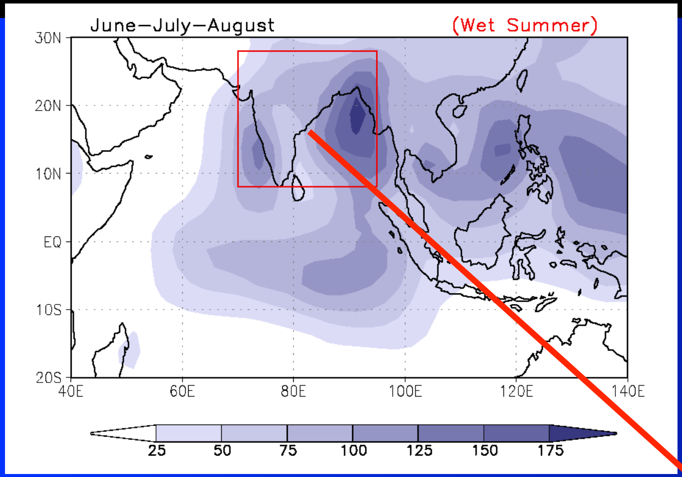
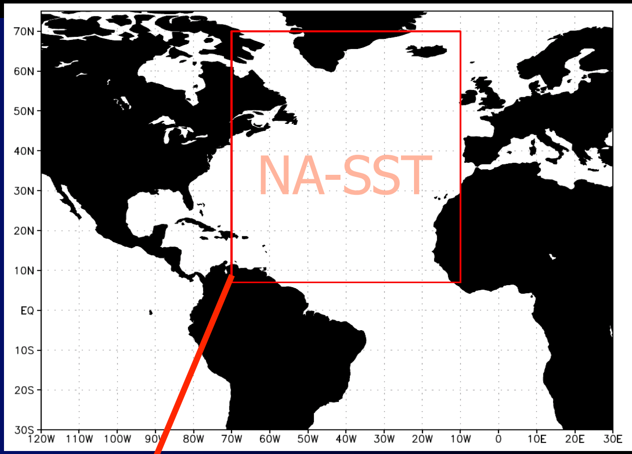
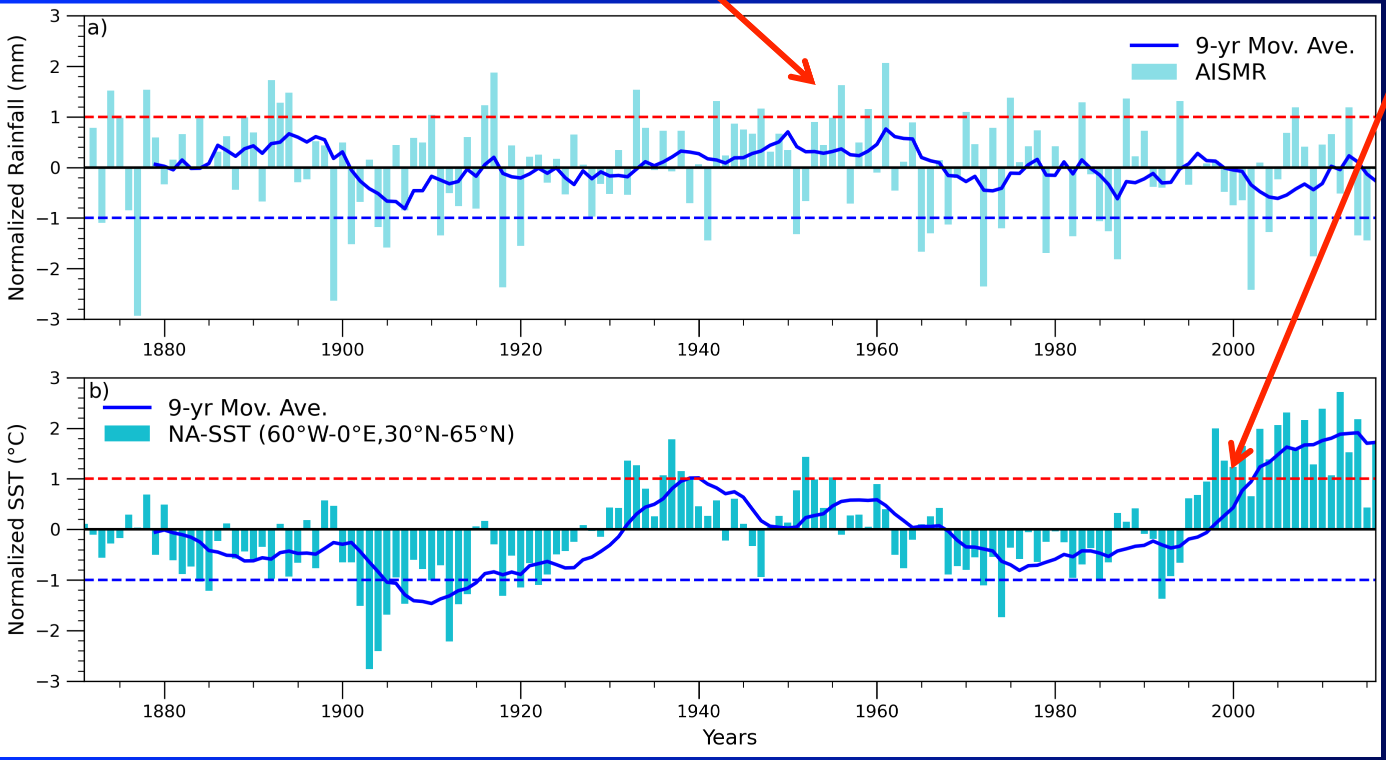


Figure 2 Southwest monsoon proxy record from the Arabian Sea Site 723A and box core RC2730 combined with Oman cave stalagmite $\delta^{18}O$ and North Atlantic haematite percentage. Time series of **a**, cave stalagmite $\delta^{18}O$ from ref. 16, **b**, *G. bulloides* percentage in Hole 723A (filled 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.

However, the NA-SST and ISMR relationship is intrinsically nonlinear



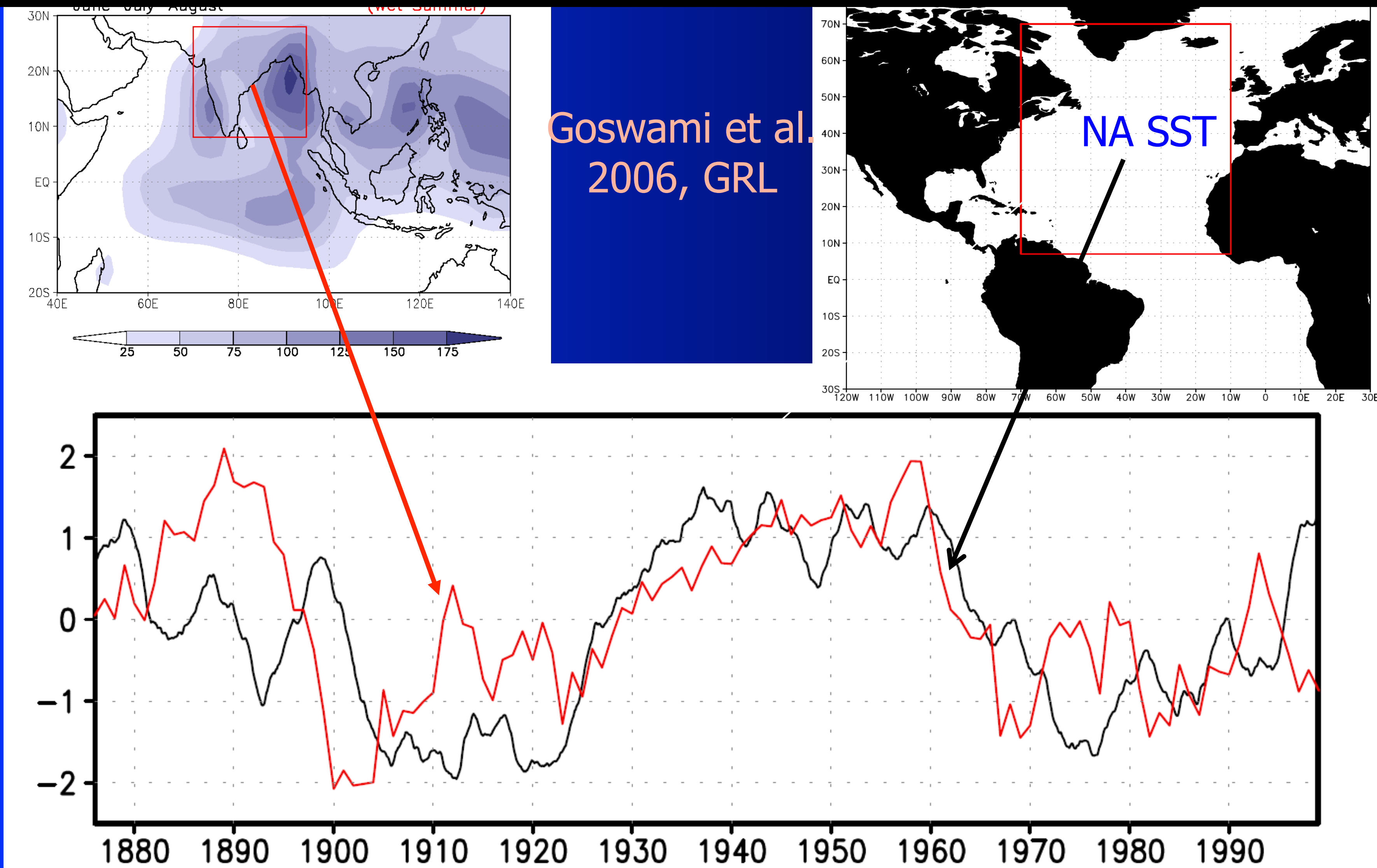




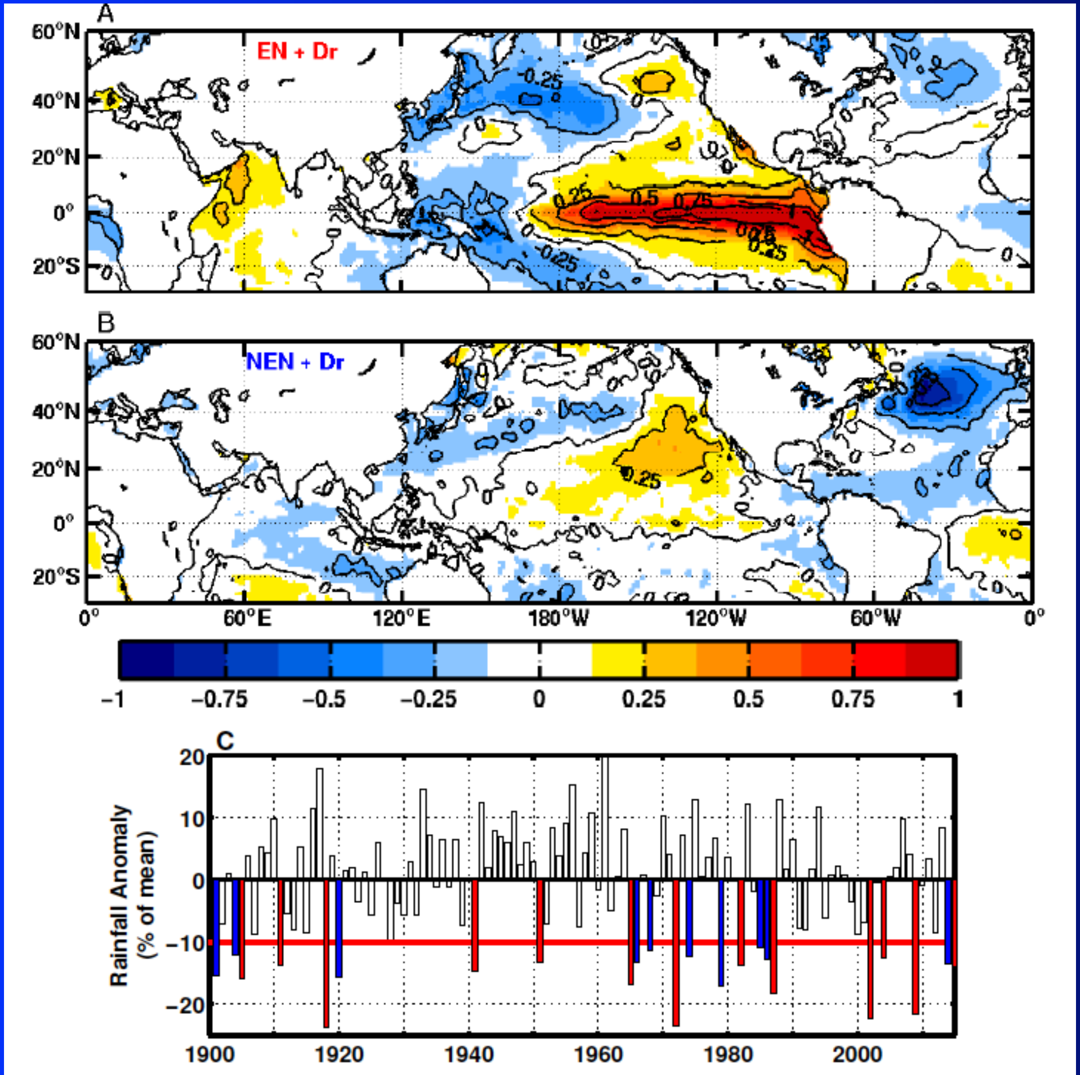
1. Dominant T~ 2.5yrs
2. Weak multi-decadal
3. Weak trend

- Weak biennial
- Strong multi-decadal
- Strong trend

Some time back, we found that NA SST and IMR are closely associated on multi-decadal time scale and showed that it modulates ISMR through the troposhperic Temperature gradient.



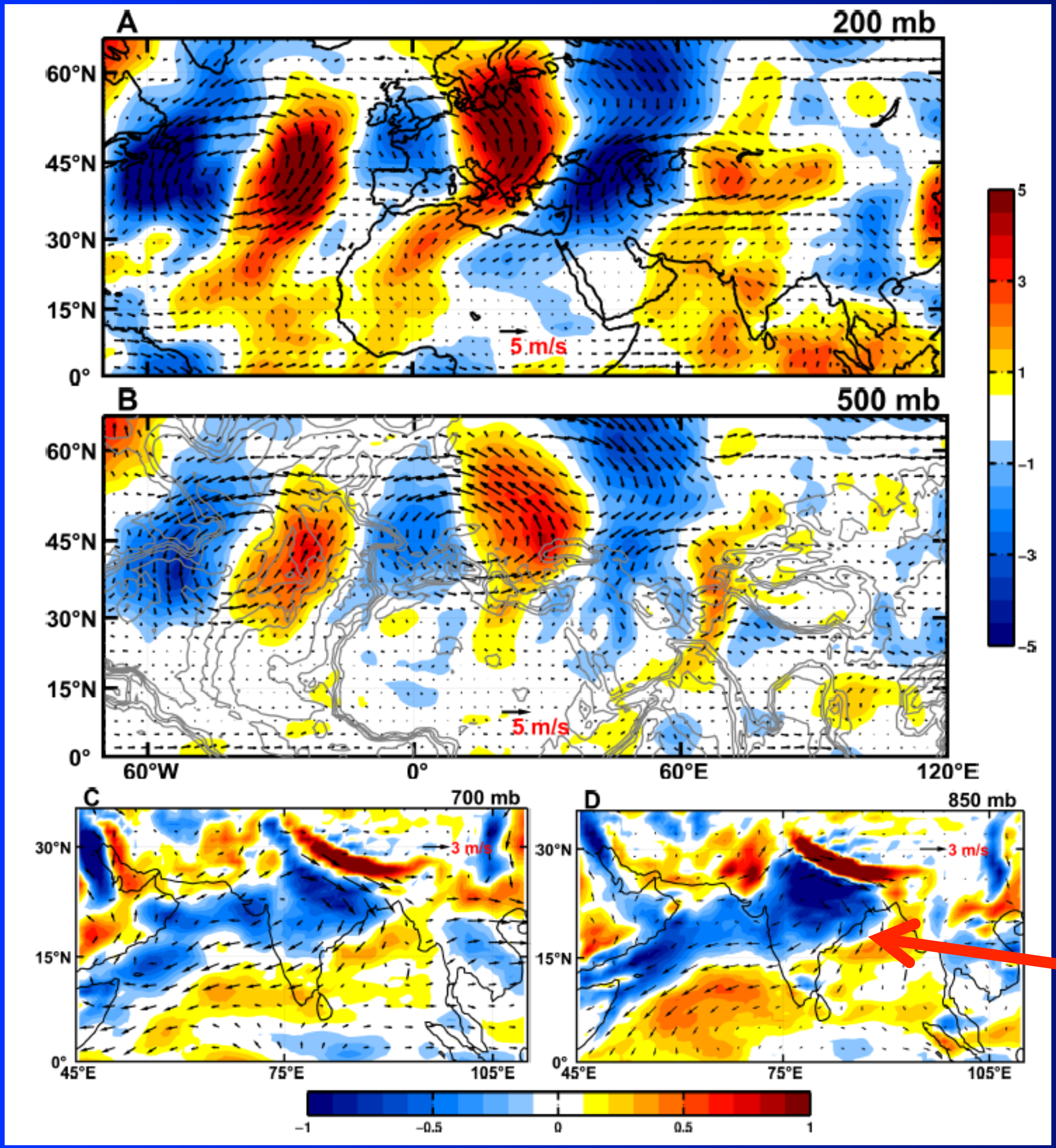
Even on interannual time scale,
Evidences Extra-tropical SST Influence on Indian Monsoon is mounting…



Borah, Venugopal, Sukhatme, Muddebihal & Goswami , **Science**, 2020, 11 December issue

- All Non-ENSO droughts are linked to NA cooling (AMO) & no ENSO signal in equatorial region!
- Thus, all Indian monsoon droughts are predictable, either with ENSO or with AMO!
- Out of 23, 13 are ENSO and 10 are non-ENSO droughts

How does far away NA SST influence the ISMR?



Borah et al, Science, 2020

- Associated with a Barotropic Rossby wave train emanating from NA
- Episodic, persisting for three weeks to a month during NH summer.
- This wave, train leads to a persisting cyclonic vorticity at 200 hPa and anticyclonic vorticity at 850 hPa over Indian monsoon region.

NA-SST seems to impact ISMR only when equatorial SST anomaly is near neutral..

- Borah et al (2020) show that NA-SST causes ISMR drought when ENSO is neutral in tropics from observations.
- Chattopadhyaya et al. (2015) also show using AGCM experiments that NA-SST influences simulation of ISMR when ENSO passing through transitions.

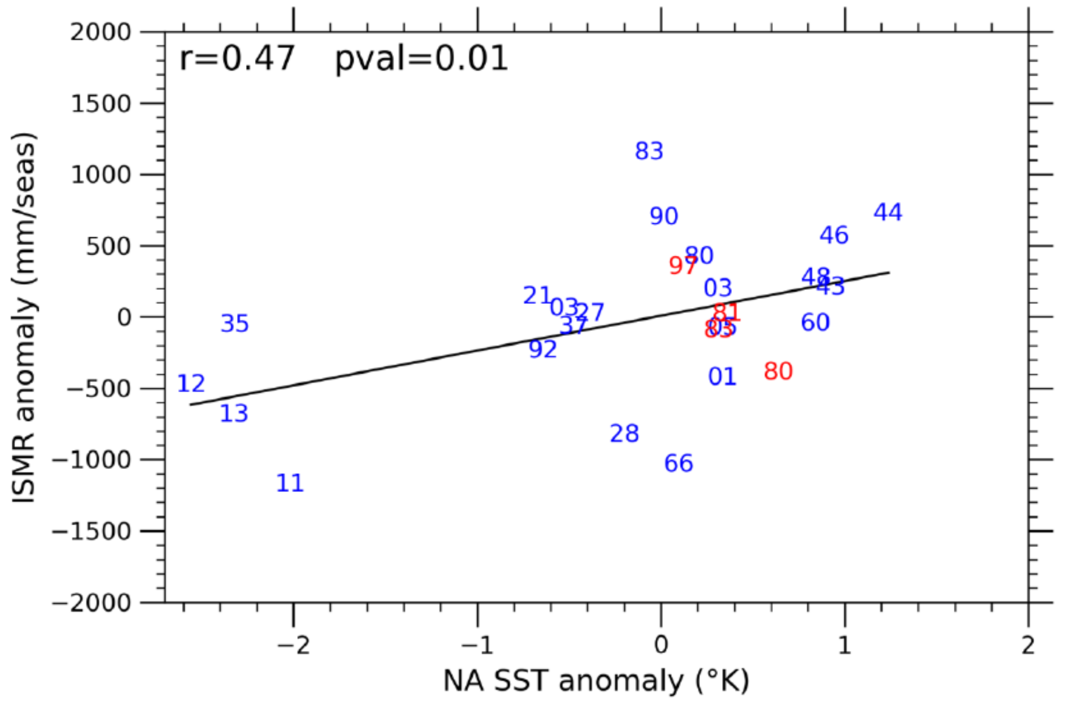
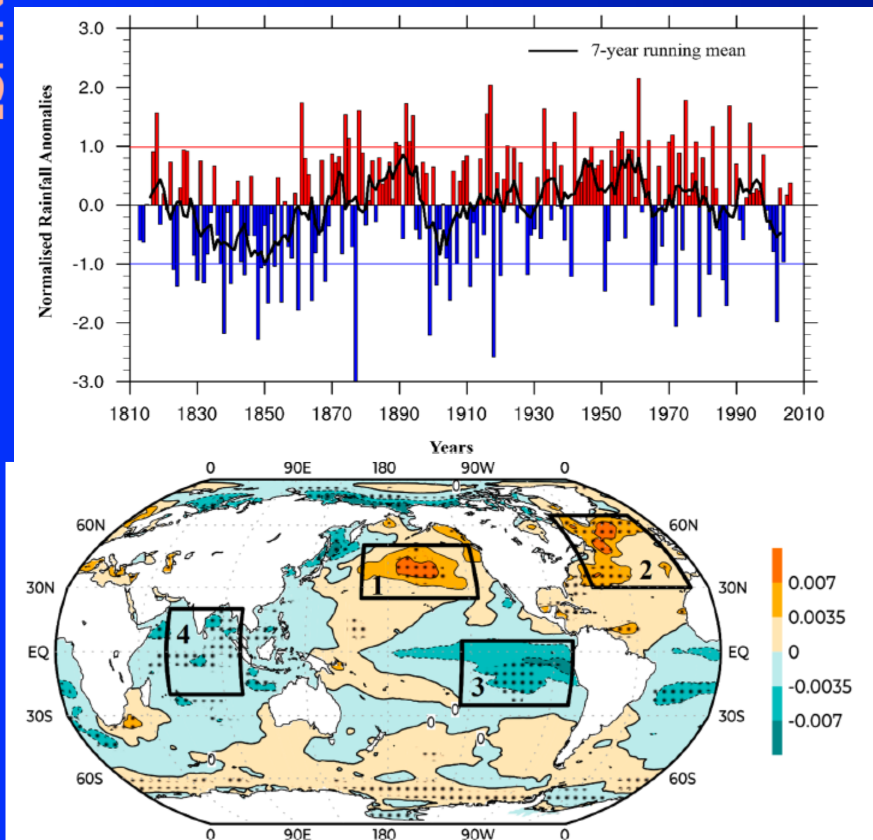


Fig S10. Relationship between JJAS accumulated rainfall and mean NA SST anomaly for weak ENSO years. Where weak ENSO years are defined by JJAS Nino3.4 between + or – 0.25 s.d.. The numbers (red: before 1901 and blue: from 1901) represents year from 1870-2016.

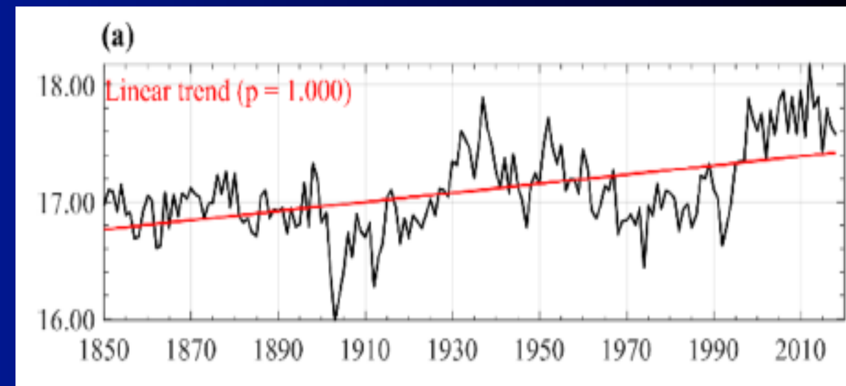
From inter-annual to multi-decadal time scales…

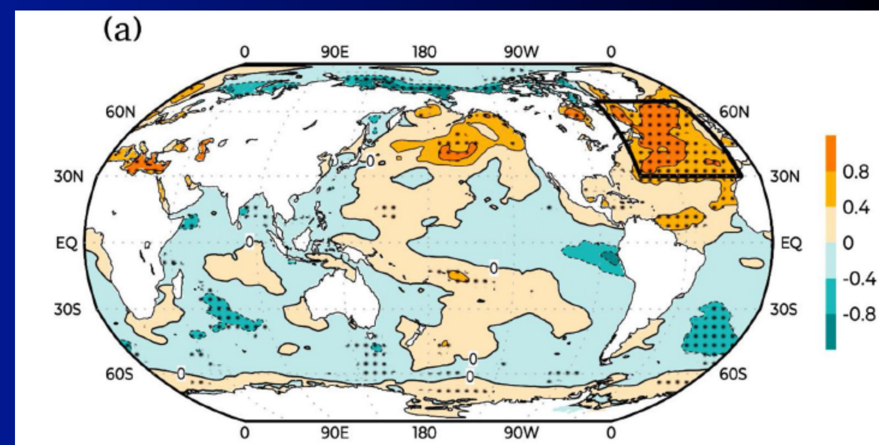
The global JJAS SST pattern associated with the ISMR multi-decadal mode and that associated with NA SST multi-decadal mode are strongly correlated.

ISMR



NA SST



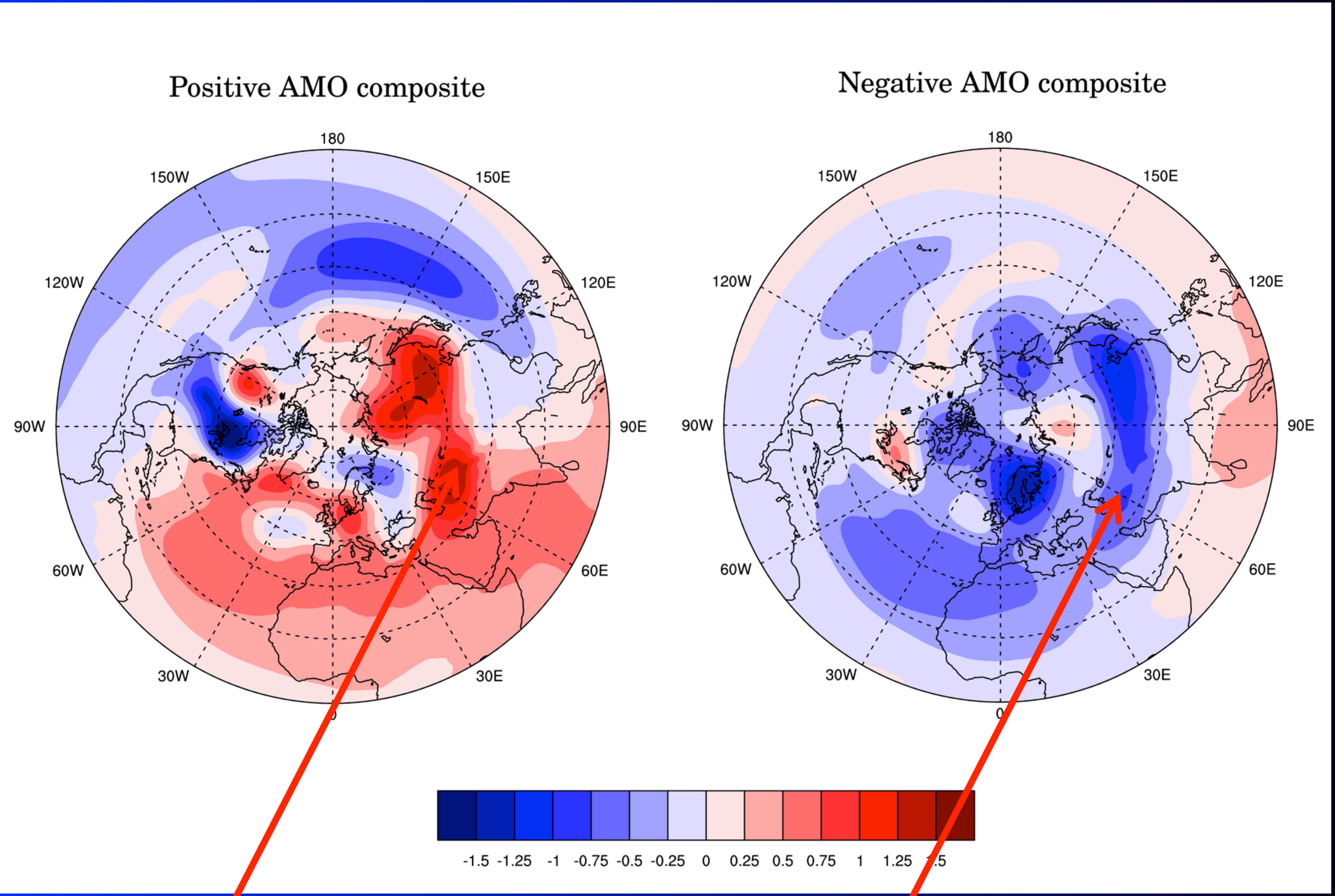


Global JJAS SST pattern associated with ISMR MDM

Global JJAS SST pattern associated with NA SST MDM

Indicates that the NA SST MDM has strong association with the ISMR MDM.

How does the multi-decadal varaition of NA-SST influence through TT?

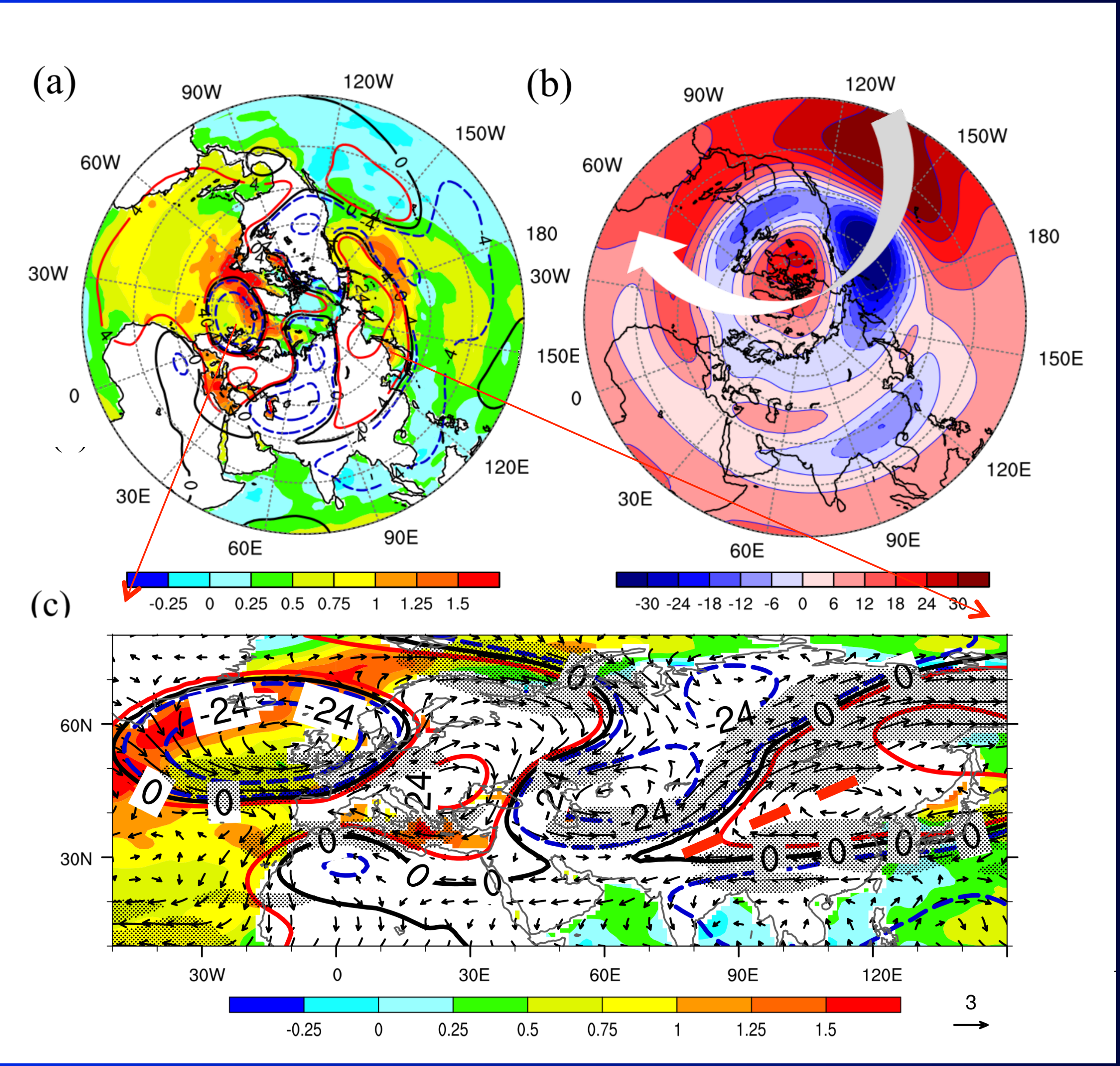


Composite of two 20-year periods in positive phases of AMO

Composite of two 20-year periods in negative phases of AMO

Rossby wave train associated with NA SST multi-decadal mode in contrast to that associated with the summer ENSO mode

NA-SST (AMO)



ENSO

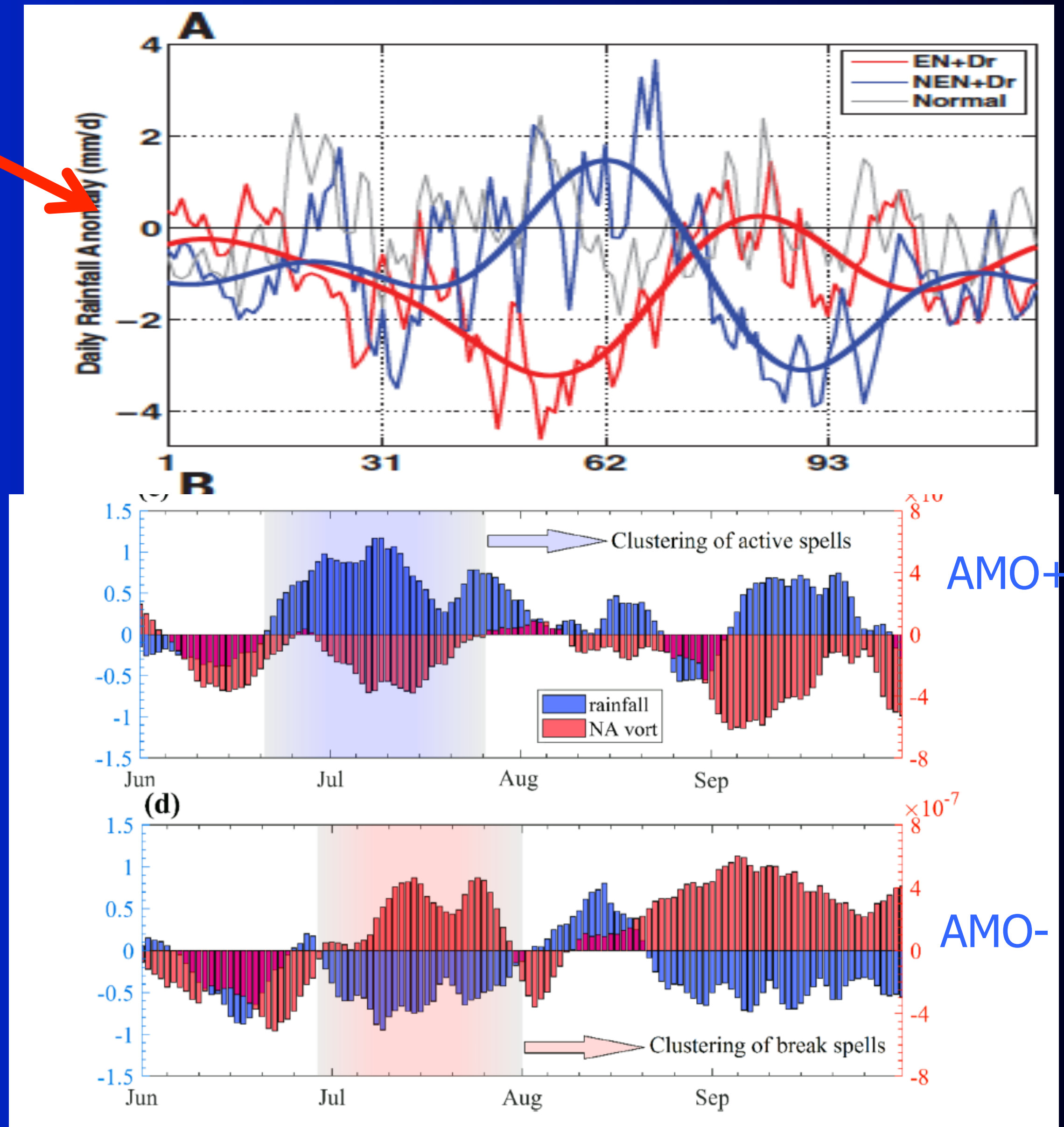
The Wave train leads to seasonally phase-locked long 'Active' or long 'Break' spells & thereby strengthen (weaken) ISMR

Borah et al., 2020 Science

Composite of seasonal mean ISMR anomaly during a +ve phase and a –ve phase of AMV

Composite of 5-day running mean ISMR daily anomaly & NA vorticity during a +ve AMV

Composite of 5-day running mean ISMR daily anomaly & NA vorticity during a -ve AMV



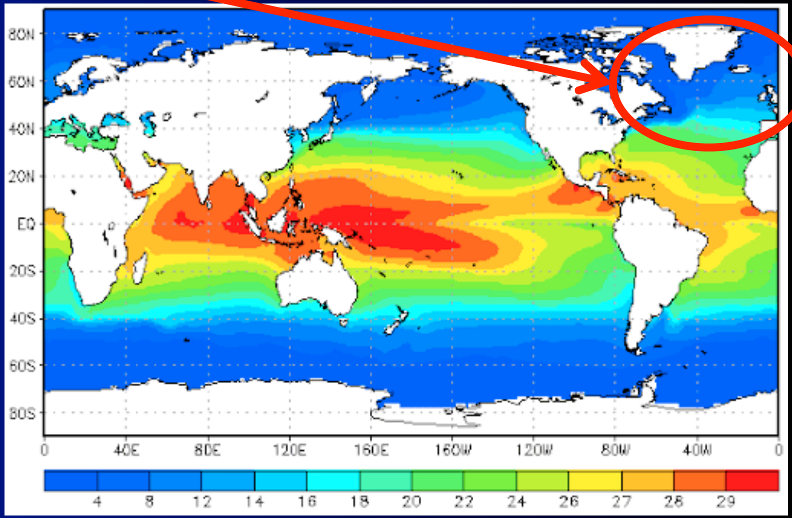
Rajesh et al, 2020, Climate Dynamics

However, there were some concerns..

- Colder mean SST in extra-tropics can not influence convection and influence atmospheric circulation.

- Then, how would the SST produce needed atmospheric circulation changes & teleconnection to the Tropics?

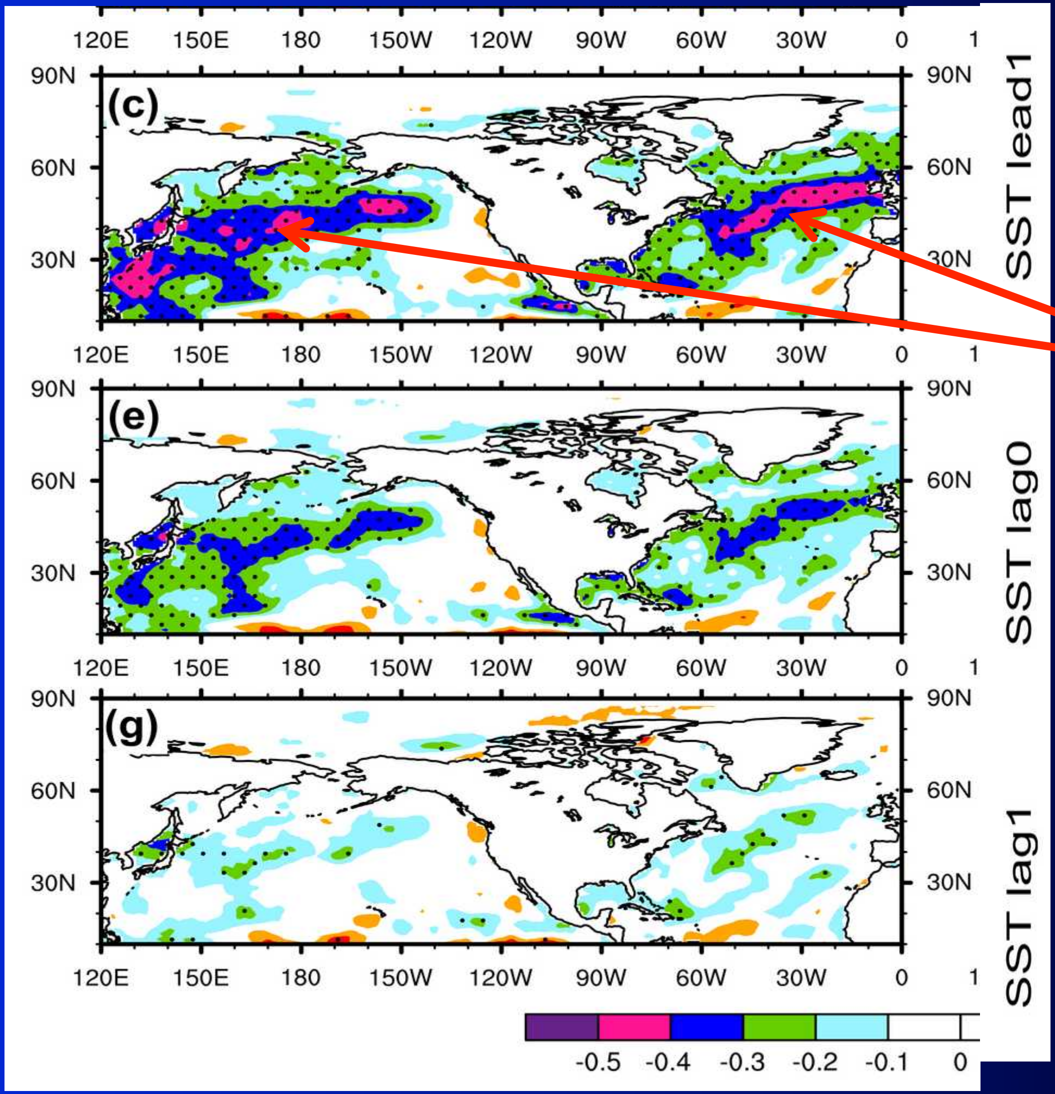
- Conventional thinking is that over the extra-tropics, atmospheric fluxes drive the SST rather than SST driving circulation!



In what follows, I present evidence that SST could influence circulation in the extratropics on super-synoptic time scales. We shall also establish the **Causality** between the AMO and ISMR.

Does the SST drive the barotropic vorticity or is it a response of the atmospheric circulation and fluxes?

Correlation between weekly SST and weekly barotropic vorticity from two different reanalysis. Note, high correlation at SST leading by 1-week.



Significant negative correlations ➔ +ve SST associated with anticyclonic barotropic vorticity

Goswami et al., 2022 (under review)

Causal Inferences…

- While the physical mechanism of teleconnection is rather compelling, the ***cause and effect*** is still not well established.
- This is because, so far all associations are **linear** while the functional relationships are quite **nonlinear.**
- Also conditional independence with other drivers (e.g. ENSO, PDO, IOD and Atlantic Nino) is not established.
- Even the Causality between ENSO and ISMR has not been established after 100 years of finding the association!
- Advanced Causal Inference techniques are now available and provides opportunity to establish causal relationship between AMO ←→ ISMR and ENSO ←→ ISMR.

Causal Inferences---Techniques

Granger Causality (Granger, 1969, *Econometrica*, *37*(3), 424. https://doi.org/10.2307/1912791)

- Introduced originally by Ganger in 1969, the algorithm is now used extensively in all AI

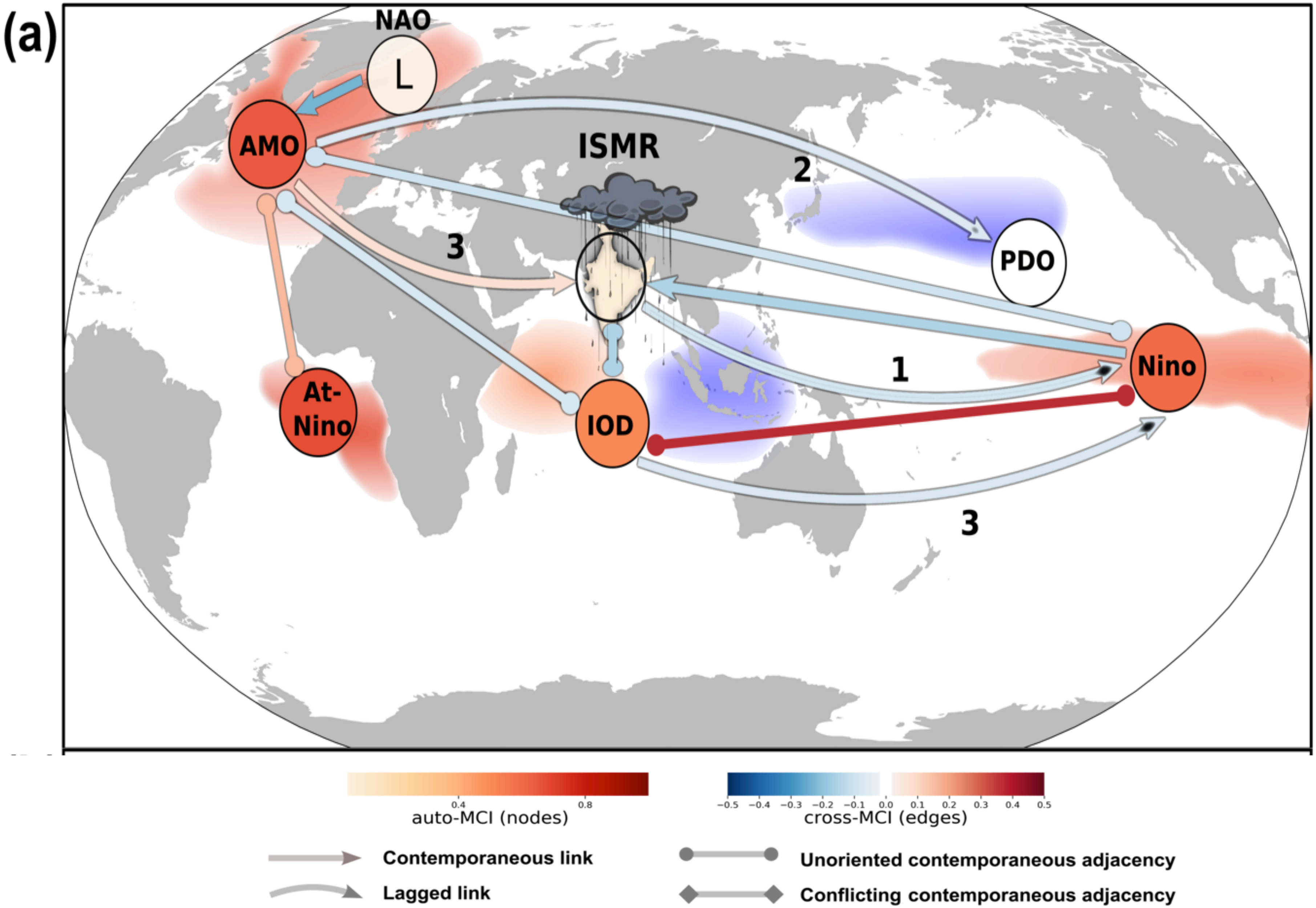
- Estimates time-lagged causal associations using an autoregressive model framework implemented using standard regression techniques but taking into account the memory of the data.

PCMCI (Peter & Clark Momentary Conditional Independence) (Runge et al., 2017, 2018, 2019, 2020)

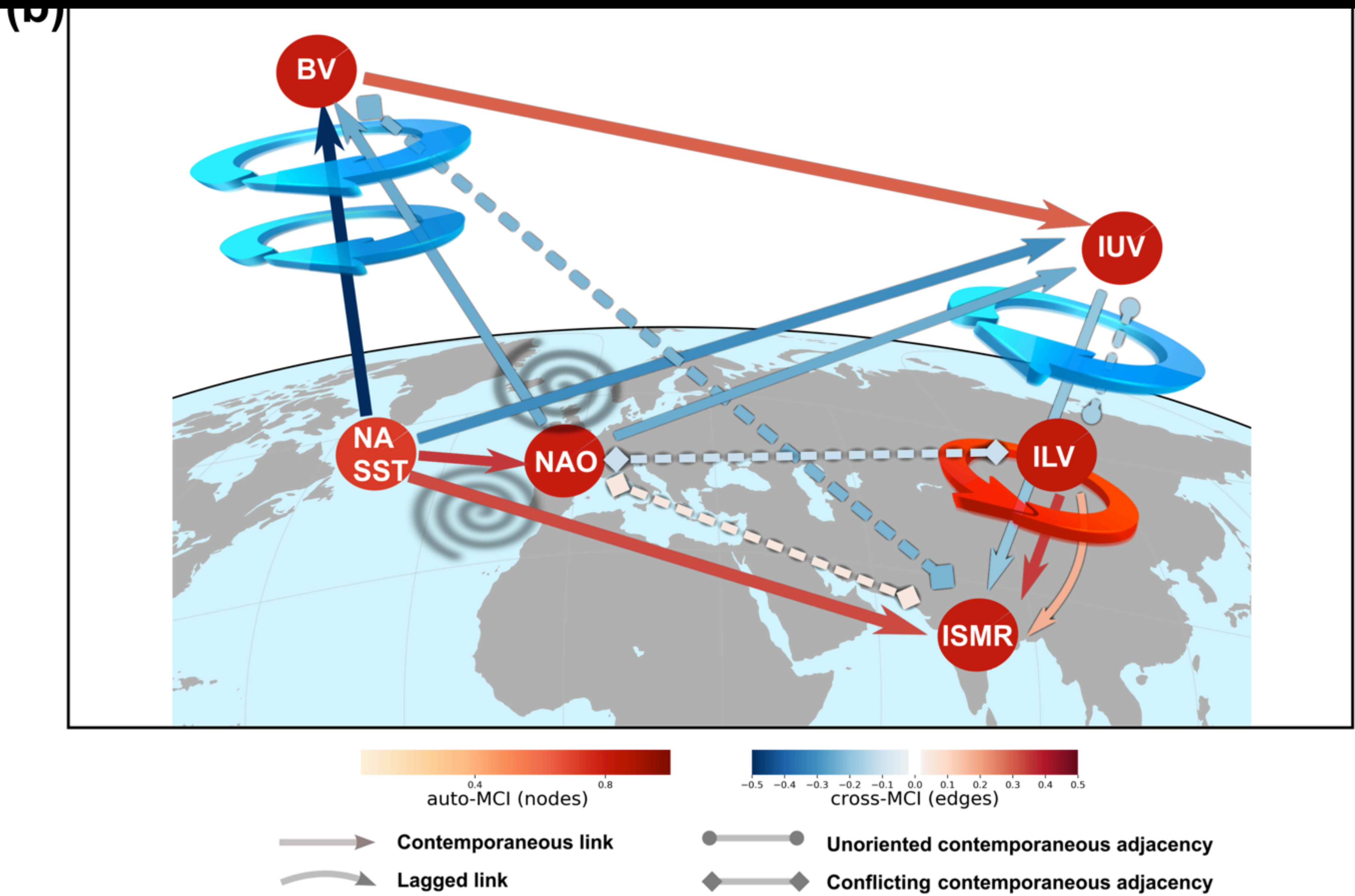
- PCMCI is similar to Granger but with a slightly different set of assumptions.

- PCMCI+ can identify the full, lagged and contemporaneous causal graph under the standard assumptions of causal sufficiency, and the Markov condition (Runge, 2020).

The AMO and the ENSO are only independent drivers of ISMR of comparable strength!



How does Causality on Seasonal scale arise from Sub-Seasonal Causality between NA SST and ISMR?



New knowledge gained from the Causal Inference…

- As expected, the ENSO is an independent driver of ISMR inter-annual variability. However, ISMR can also drive the ENSO!
- The NA SST (AMO) is another independent driver of the ISMR inter-annual variability and there is no feedback from ISMR to AMO. Strength of AMO→ ISMR is comparable to ENSO→ISMR!
- There is no direct link between IMSR and PDO and Atlantic Nino. Their association with ISMR are not independent of ENSO-ISMR or AMO-ISMR associations.
- The IOD-ISMR association found in some studies appears to be fragile. A direct link between IOD to ISMR is seen only with Granger and only for a particular SST data set. Thus, it is sensitive to method used and SST data set used.

Predictability of ISMR beyond TOGA

- For over 100 years the ENSO remained as the primary source of predictability of ISMR
- However, now the causality of NA-SST driving ISMR is established together with a physical teleconnection mechanism.
- When ENSO is strong (El Nino and La Nina), ENSO dominates the teleconnection to ISMR. NA-SST influences ISMR when ENSO near neutral or passing through transitions.
- Thus, NA-SST is complementary to ENSO and adds additional potential predictability to ISMR
- It is time to include extratropical SST in the framework of ISMR predictability

Acknowledgements:

- I thank Science and Engineering Research Board (SERB), Govt. of India for a Fellowship and Research Grant.

- The work presented here is based on collaborations with several Colleagues and Students at IISc, Bangalore, IITM Pune and Cotton University, Guwahati over the past two decades.

Thank you