Multi-decadal Variability of The Indian Summer Monsoon and Concluding Thoughts

Lecture-13

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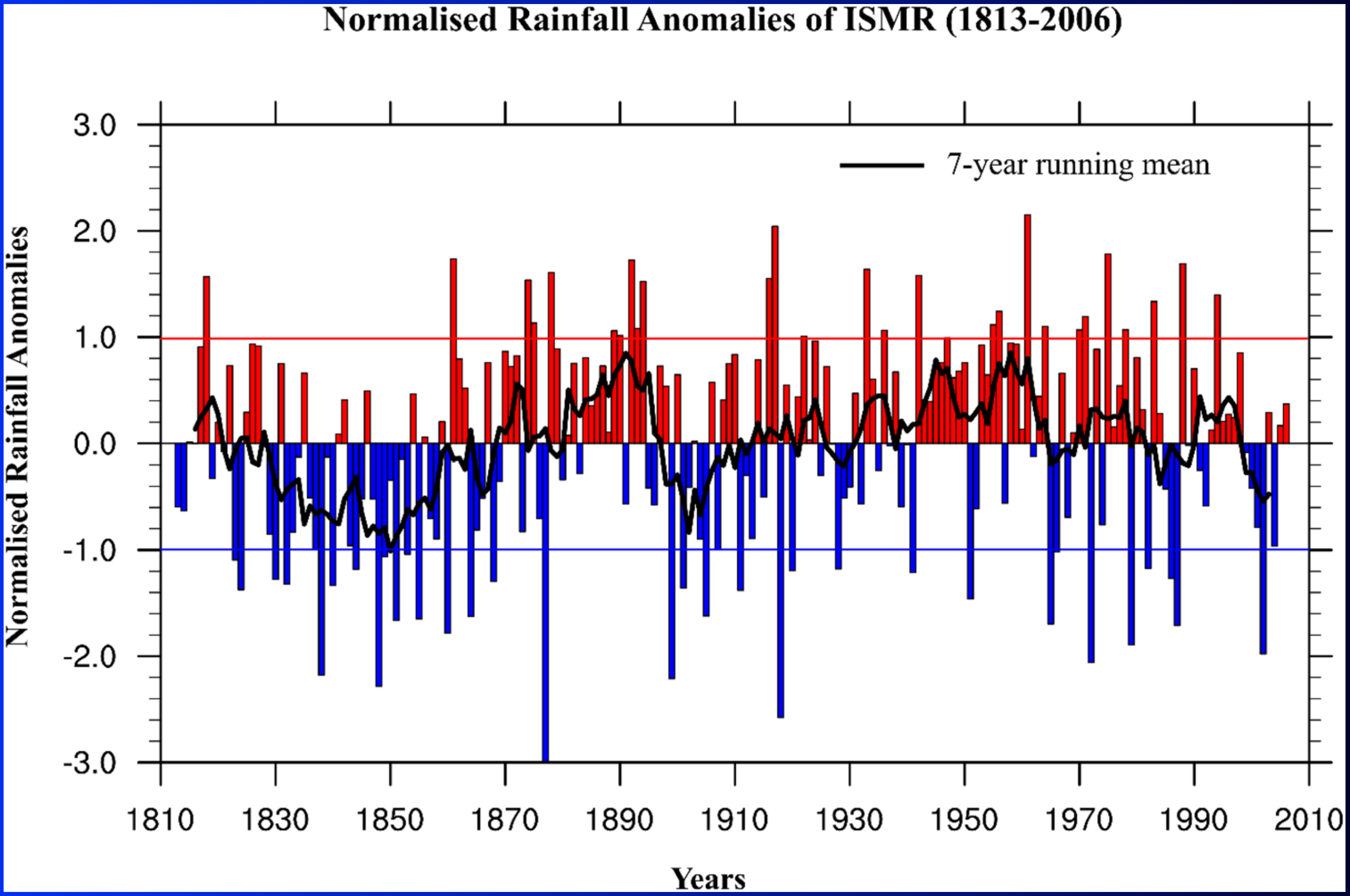
The Multi-decadal Mode of ISMR:



Interdecadal variations of Indian summer monsoon

The EEMD method decomposes a time series into a small set of oscillatory modes and a residual trend explaining the total variance of the time series. The oscillatory modes are also called Intrinsic Mode Functions (IMFs)

- Quasi-biennial has largest variance ~65%
- Quasi-biennial and multi-decadal T~65 yrs are only two statistically significant

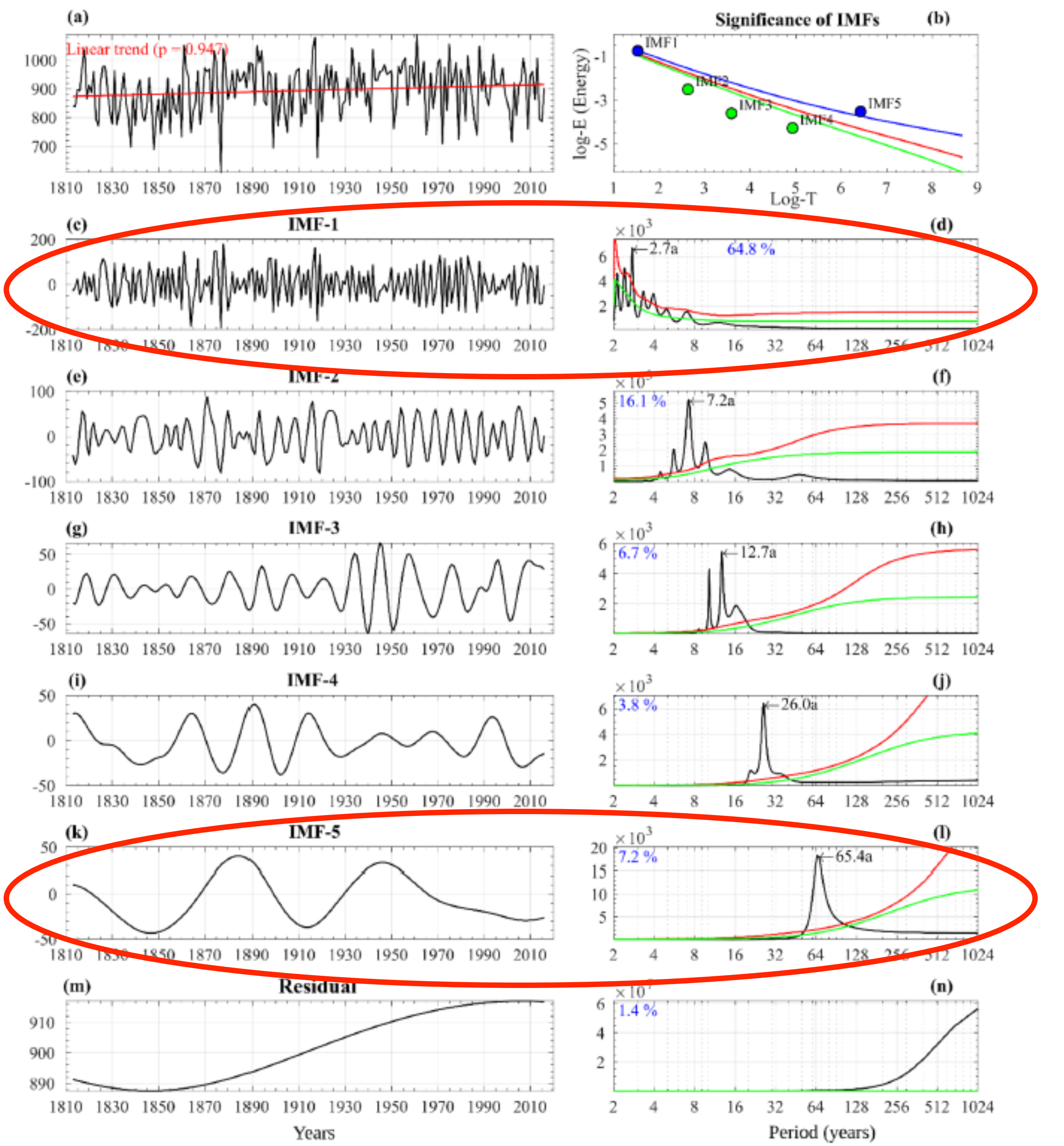


Fig. 3 **a** ISMR time series with linear trend (redline) for a period from 1813–2016 and **b** the statistical significance of the IMFs, where blue, red and green line shows 99%, 95% and 90% CI. **c**, **e**, **g**, **i**, **k**, **m** Six IMF components of ISMR and **d**, **f**, **h**, **j**, **l**, **n** their respective power spectrums. Red lines in the power spectrums show the red-noise at 99% CI using Monte-Carlo algorithm and green lines are th mean spectrum of red-noise modeling. Dominant periodicity (value pointed with arrow) and percentage of variance explained by eacl mode (blue font) is given in the right panels. Units are in mm

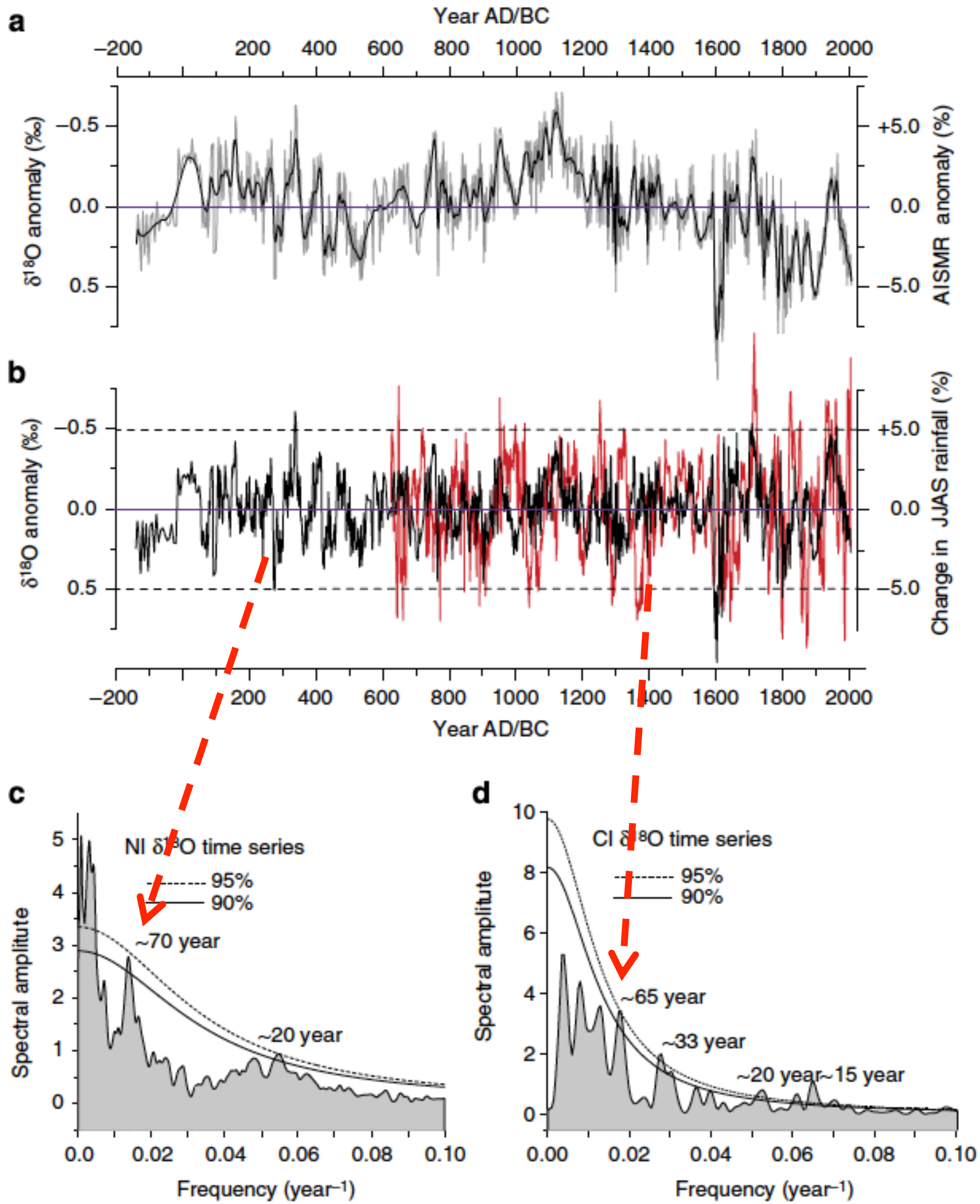


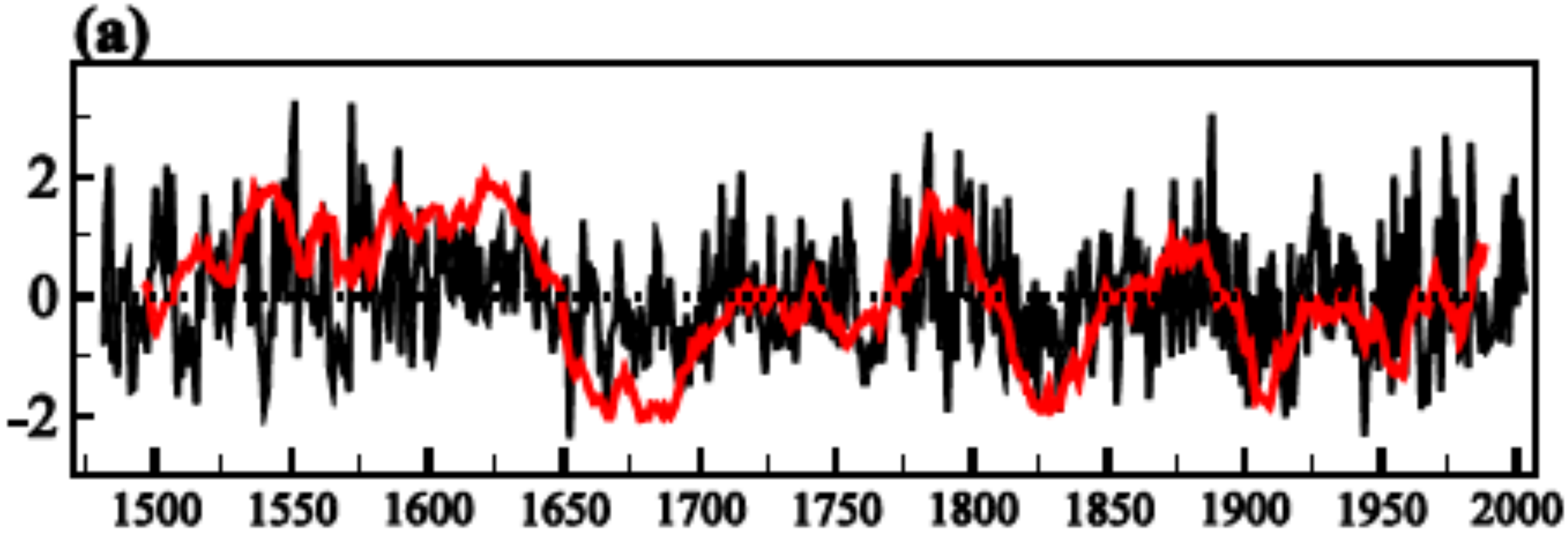
Figure 3 | Time series analysis of the NI and CI $\delta^{18}O$ records. (**a**) The NI speleothem record shown as $\delta^{18}O$ anomalies (relative to the mean of the time series). The $\delta^{18}O$ anomalies are shown both as raw data (grey) and smoothed (11-year running mean) (black) along with the regressed AISMR anomalies (%). (**b**) The comparison between the SSA[44] detrended NI (black) and CI[14-16] (red) speleothem records shown as $\delta^{18}O$ anomalies (raw data). The long-term non-stationary trends in both time series are removed by subtracting the first reconstructed component indicated by SSA of the raw data. The two dashed horizontal lines delineate a 10% change in monsoon rainfall amounts, highlighting the magnitude of multi-decadal variability inferred from our NI $\delta^{18}O$ record. (**c**) Power spectrum of the composite NI and (**d**) CI SSA-detrended $\delta^{18}O$ time series obtained using REDFIT[31] software. A varying number of Welch overlaps were used to optimize bias/variance properties. Spectral band significant above the 90% level are labelled with their period.

NI➔Sahiya Cave ((30360N, 77520E, B1,190m above sea level (m.a.s.l.))

CI➔ Jhumar Cave (18° 52′ N, 81° 52′ E; 600 masl)

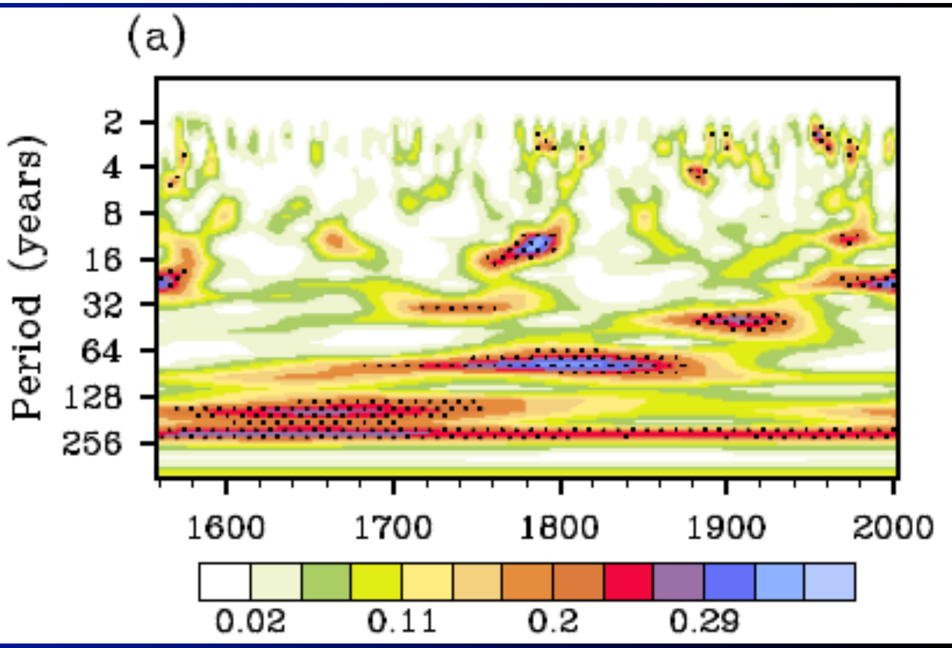
Sinha et al., 2011, Nat. Comm

Ring Width Index (RWI) from tree rings of ~523 year old Teak tree in Kerela. The RWI primarily depends on rainfall over here.



Goswami,Borgaonkar et.al. (2015). Climate Change : Multi-decadal and beyond, Chap. 21, C.P Chang etal. Eds

Wavelet spectrum of RWI over southern India



Why need to study multi-decadal variability of ISMR?

- It has significant amplitude, explains ~7% ISMR variance
- Can modulate interannual variability and predictability of seasonal mean

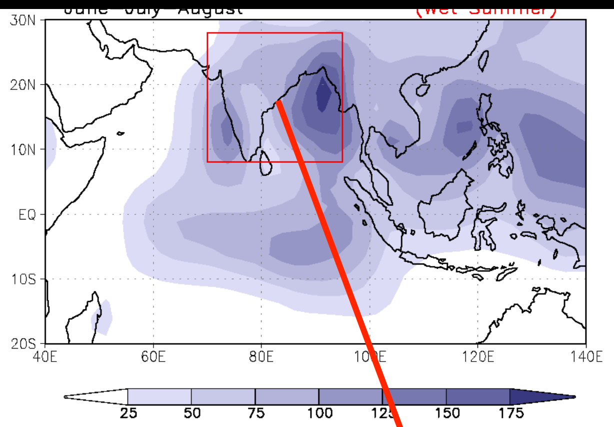
Table 1 Frequency of occurrence of floods (normalized ISMR index > +1) and droughts (normalized ISMR index < −1) during approximate different epochs of multi-decadal variability

Period	Epoch of multi-decadal mode	Floods	Droughts
1820–1870	Negative	2	**14**
1870–1900	Positive	**9**	1
1900–1930	Negative	3	**7**
1930–1965	Positive	**8**	3
1965–2006	Negative	7	**8**

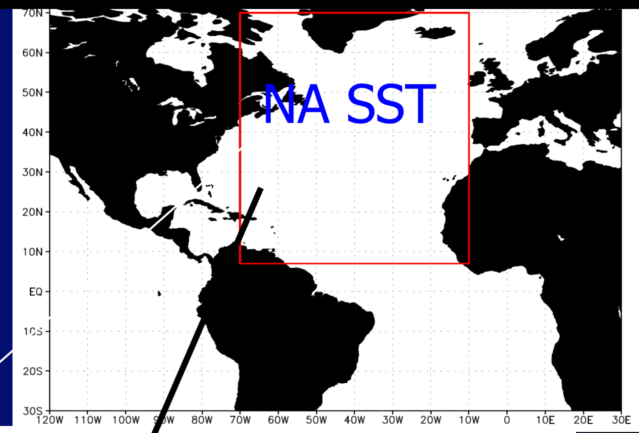
Rajesh and Goswami, 2020, Climate Dynamics

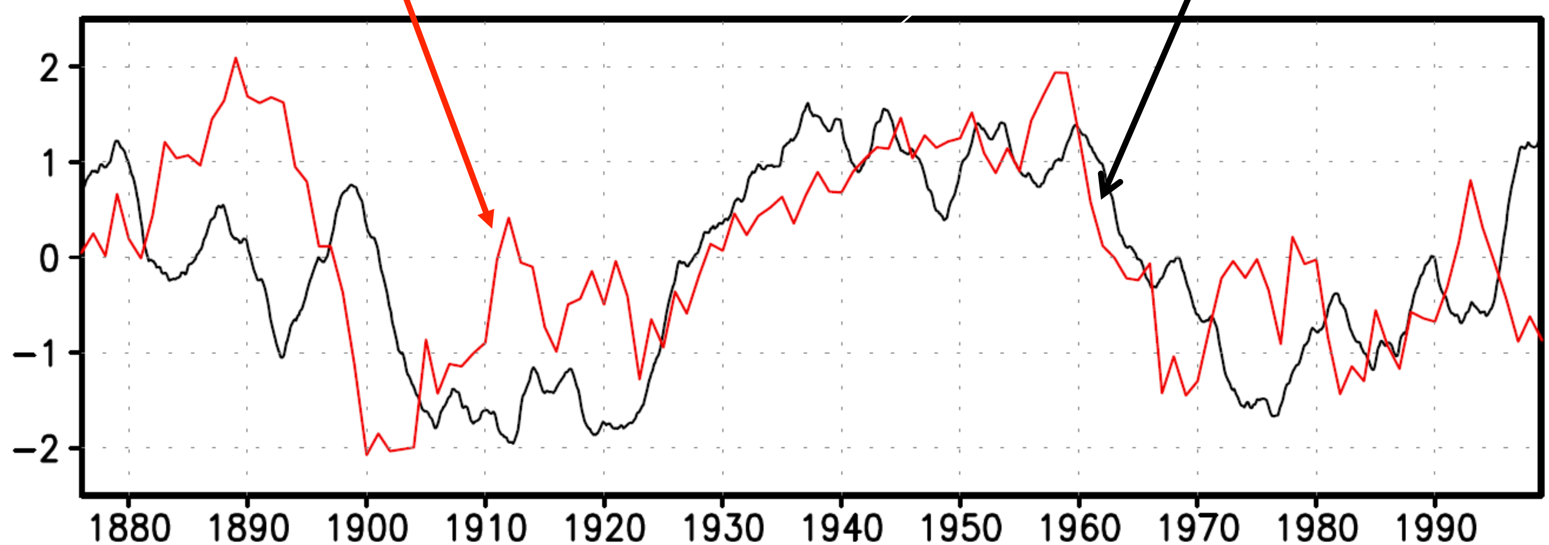
What Drives the Multi-decadal Variability of ISMR?

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.

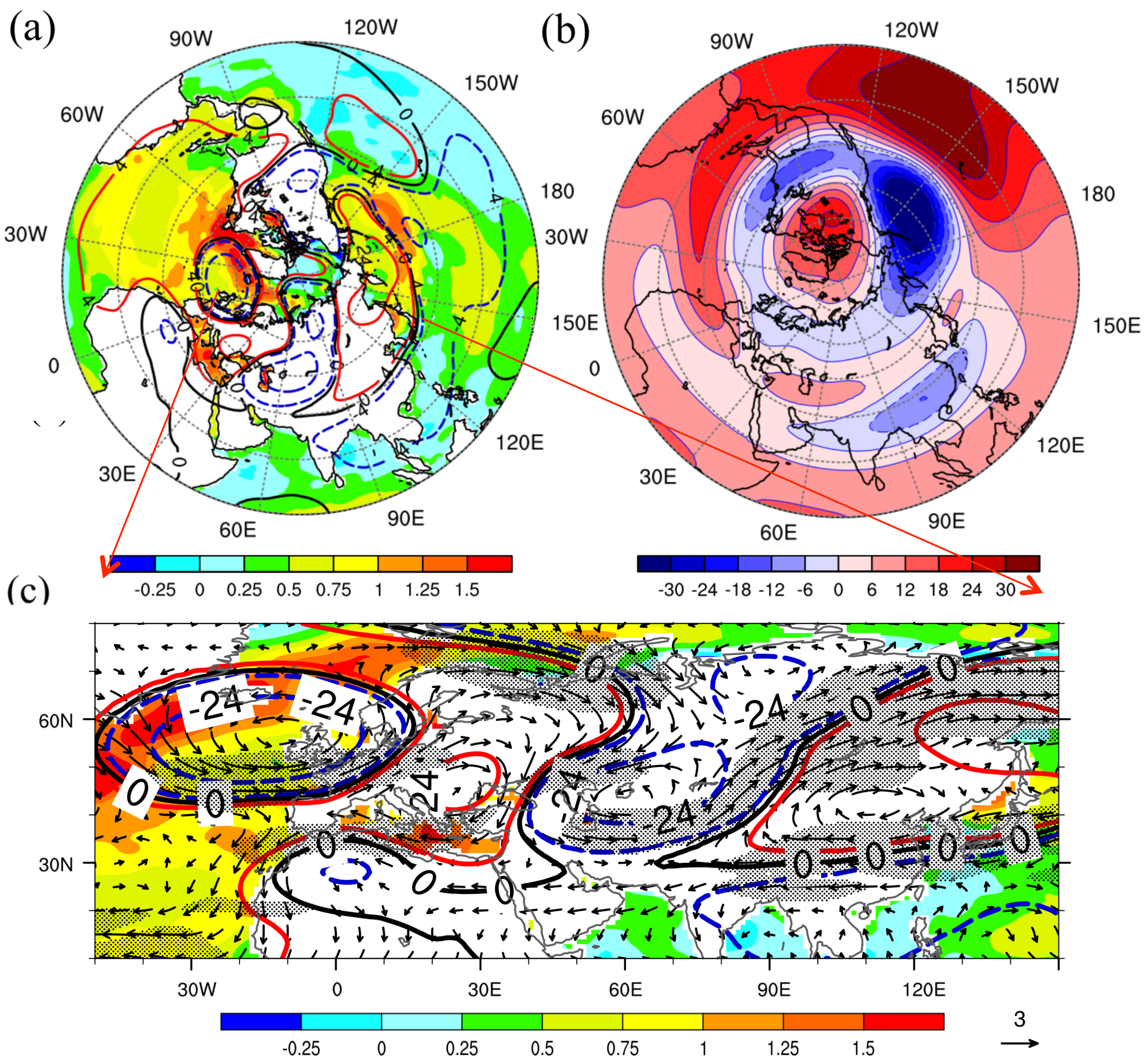


Goswami et al. 2006, GRL





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

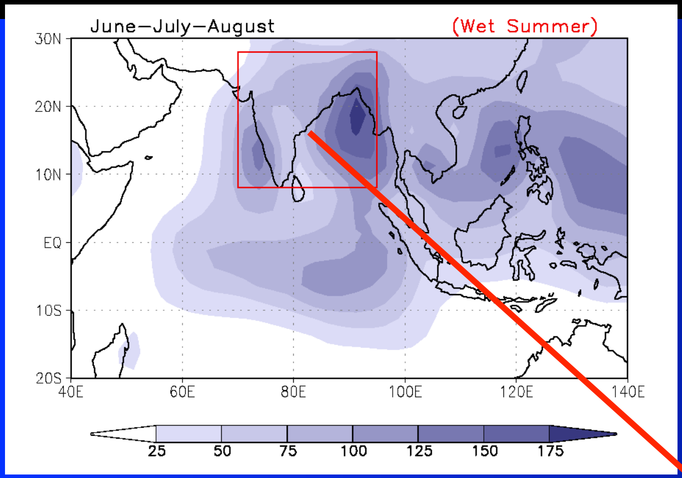


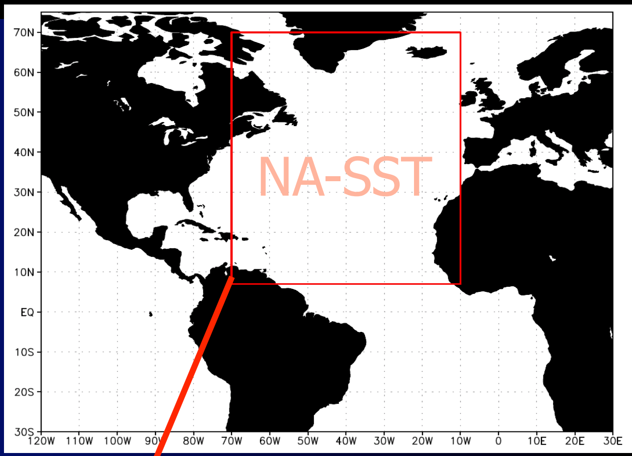
ENSO

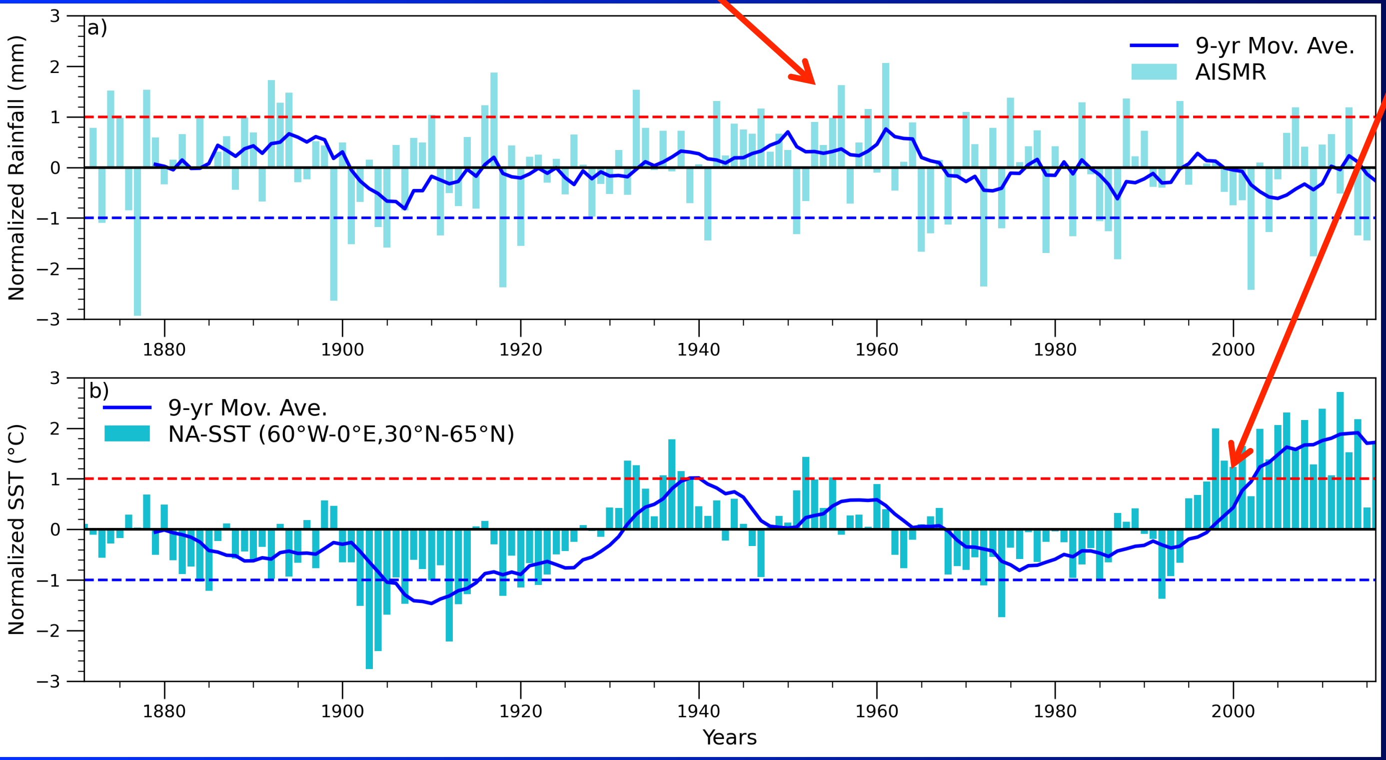
Goswami et al., 2022, npj Climate and Atmospheric Science

NA-SST (AMO)

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





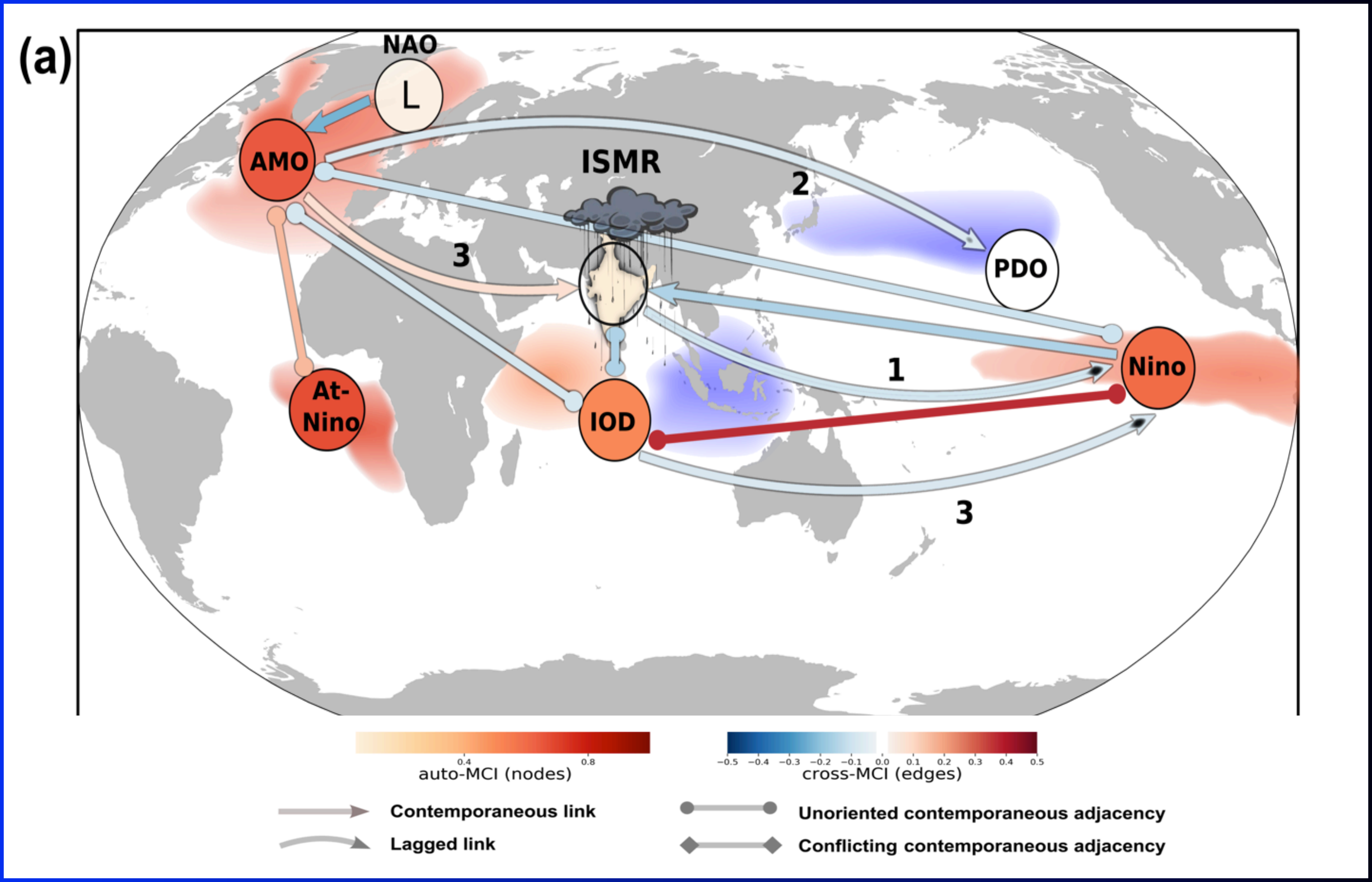


1. Dominant T~ 2.5yrs
2. Weak multi-decadal
3. Weak trend

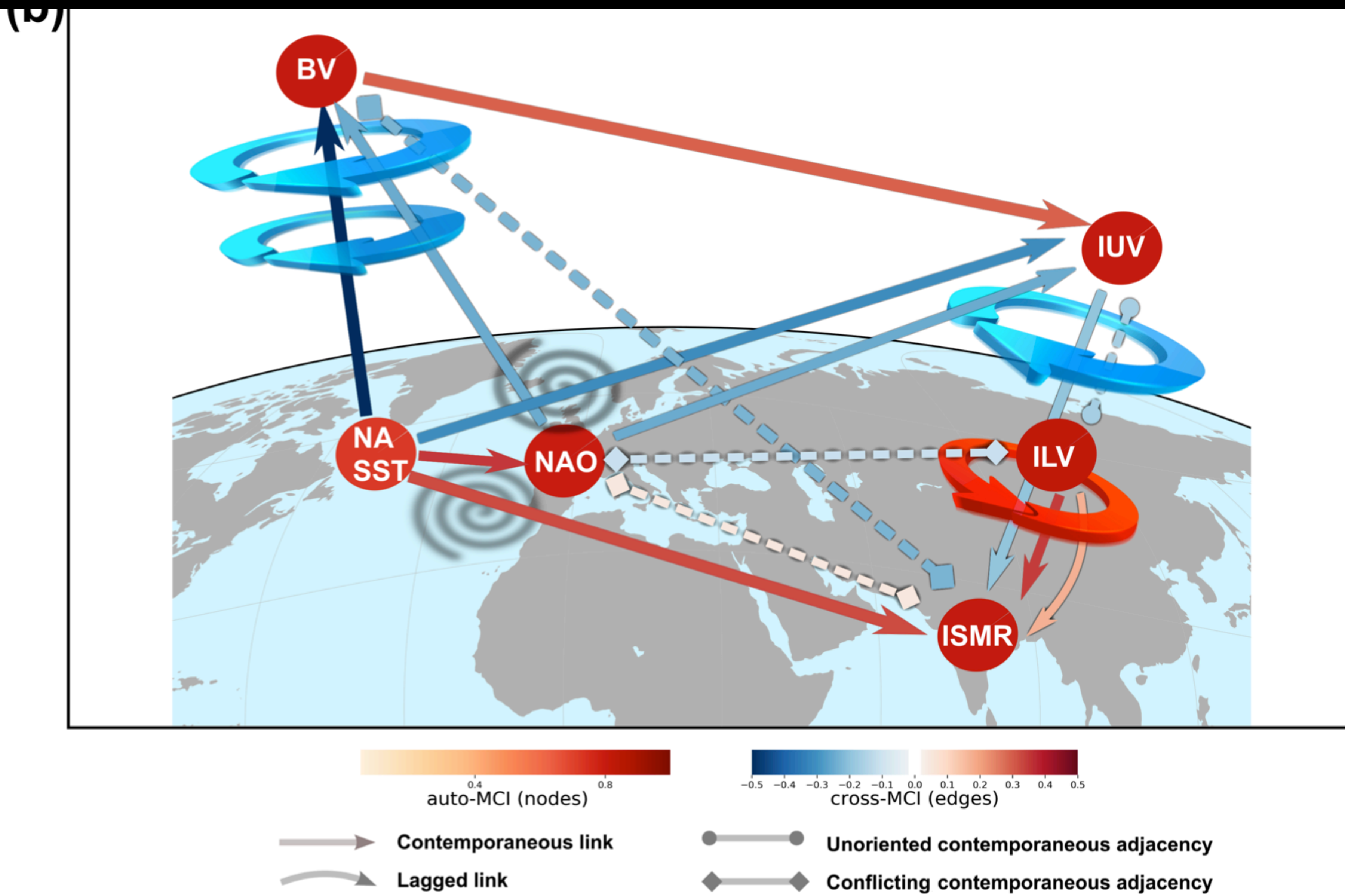
- Weak biennial
- Strong multi-decadal
- Strong trend

Causal Inference using PCMCI+

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

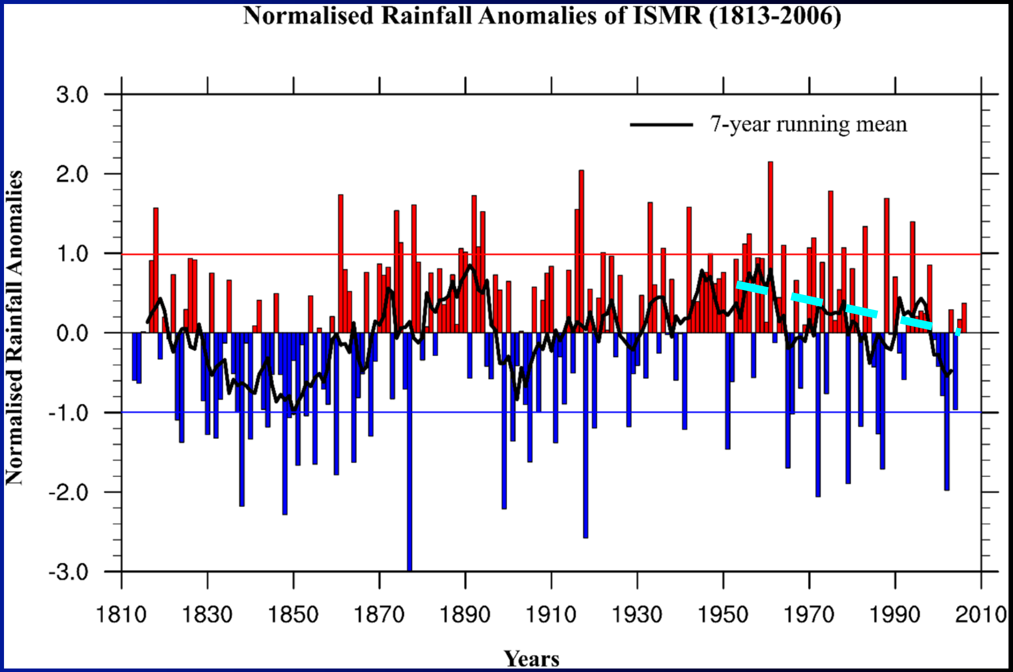


How does Causality on Seasonal scale arise from Sub-Seasonal Causality between NA SST and ISMR?



Remaining question: What is the role of local air-sea interaction in modifying the ISMR multi-decadal mode?

If we look at ISMR between 1950 and 2000, there is prominent decreasing trend.



The cause of this 'decreasing' trend of ISMR has been investigated in several studies.

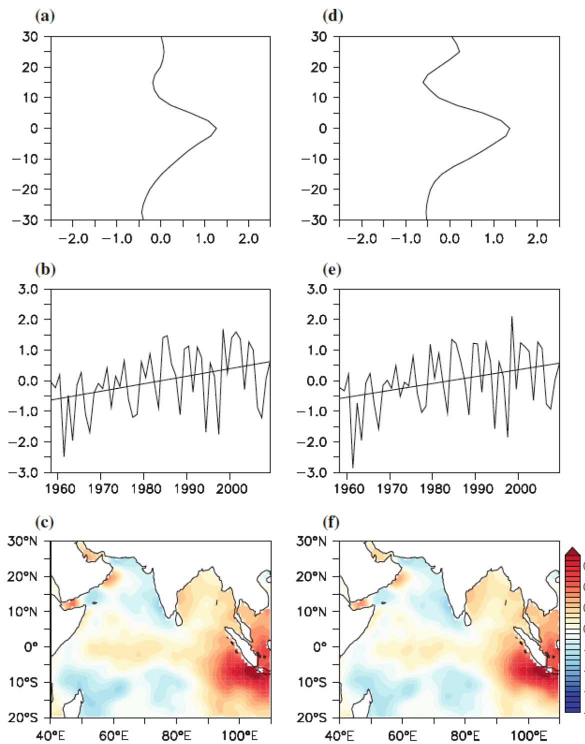
➔One such study by M. Bollasina et al. (2011) uses the GFDL GCM with active aerosol chemical model and indicate that direct and indirect effect of aerosols cool the surface over land, weaken the N-S temperature gradient and weaken the monsoon.

What is the role of local air-sea interaction in modifying the ISMR multi-decadal mode?

Another interesting study by Swapna, Krishnan & Wallace, 2014 argue that the decreasing trend of ISMR during the period is due to air-sea interaction driven by increasing trend of SST in the equatorial IO.

1. Bjerknes feedback...

Fig. 3 *Upper panels* show the leading EOF of the meridional profile of ERA zonal wind anomalies averaged from 70°E to 90°E along a section extending from 30°S to 30°N for the JJAS season **a** surface, **d** 850 hPa. *Middle panels* show time series of the corresponding PC. *Lower panels* show the anomaly patterns obtained by regressing SST upon the PC1 of winds for the summer monsoon season for 1958–2011. The trends of the linear regression best-fit lines in (**b**, **e**) exceed the 95 % confidence level. Units of regression pattern are (°C) (ms^{-1})$^{-1}$



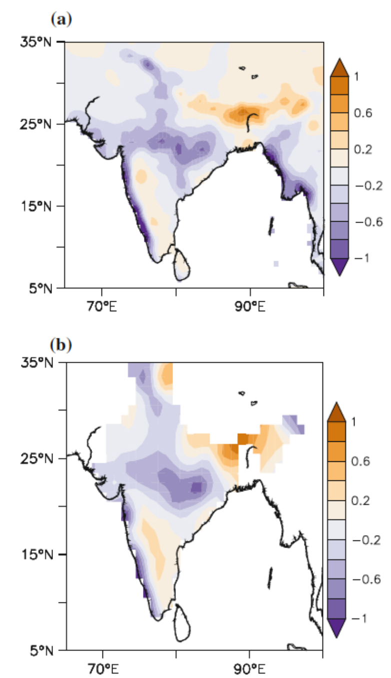


Fig. 4 Anomaly patterns generated by regressing the rainfall upon the first PC of the 850 hPa zonal wind profile averaged from 70°E to 90°E from ERA **a** APHRODITE rainfall **b** IMD gridded rainfall. Units of regression pattern are (mm day^{-1}) (ms^{-1})$^{-1}$

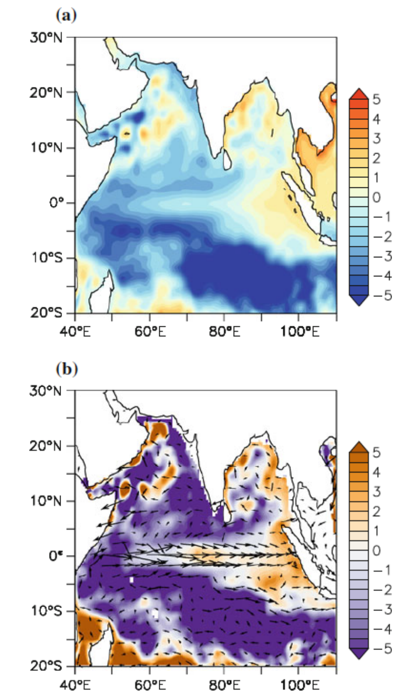


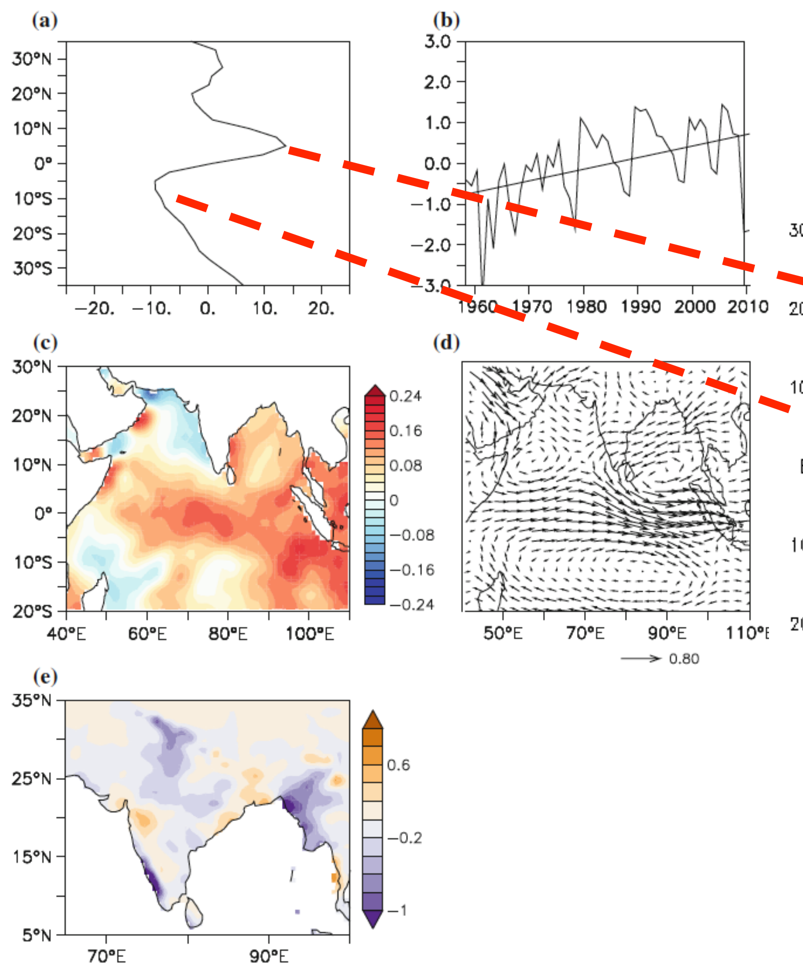
Fig. 5 **a** Trends in (a) sea level (m per 50 years) from 1958 to 2007 during the JJAS summer monsoon season based on the SODA reanalysis. **b** As in (a) except for thermocline depth (D20 in m per 50 years, *shaded*) and surface currents (m s^{-1} per 50 years, vectors)

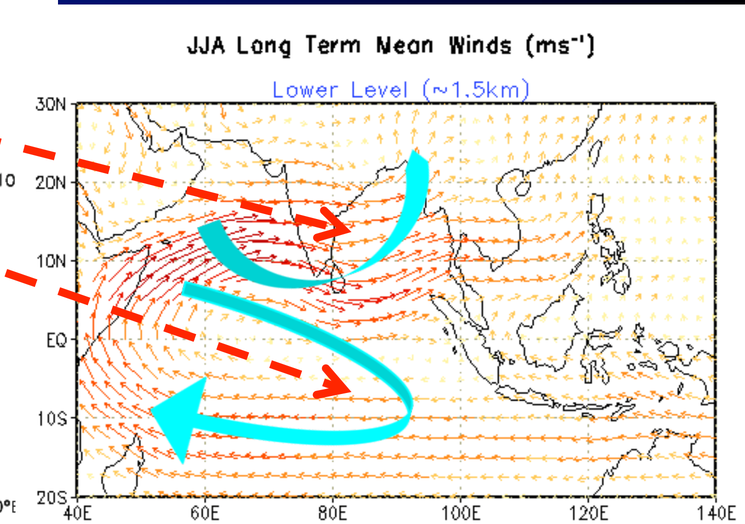
What is the role of local air-sea interaction in modifying the ISMR multi-decadal mode?

Swapna, Krishnan & Wallace, 2014

2. Large-scale vorticity feedback…

Fig. 9 **a** The leading EOF of the meridional profile of (−du/dy) anomalies from ERA reanalysis averaged from 70°E to 90°E along a section extending from 35°S to 35°N for the summer season. **b** The time series of the corresponding PC. The trend of the linear regression best-fit line exceeds the 95 % confidence level **c** Patterns of SST anomalies obtained by regressing SST upon PC1 of (−du/dy) for the summer monsoon season for 1958–2011. Units are (°C) (s). **d** Same as (c) except for 850 hPa winds. Units are (ms^{-1}) (s). **e** Same as (c) except for rainfall. Units are ($mm\ day^{-1}$) (s)





However, there is a problem

We note that during 1901- 1955, ISMR→ increasing trend, SST→also has increasing trend.

P1= 1901-1957

P2= 1958-2007

Are two Phases of ISMR Multi-decadal mode

Dhruba J Goswami, K. Ashok & B.N.Goswami, 2022, Climate Dynamics (accepted)

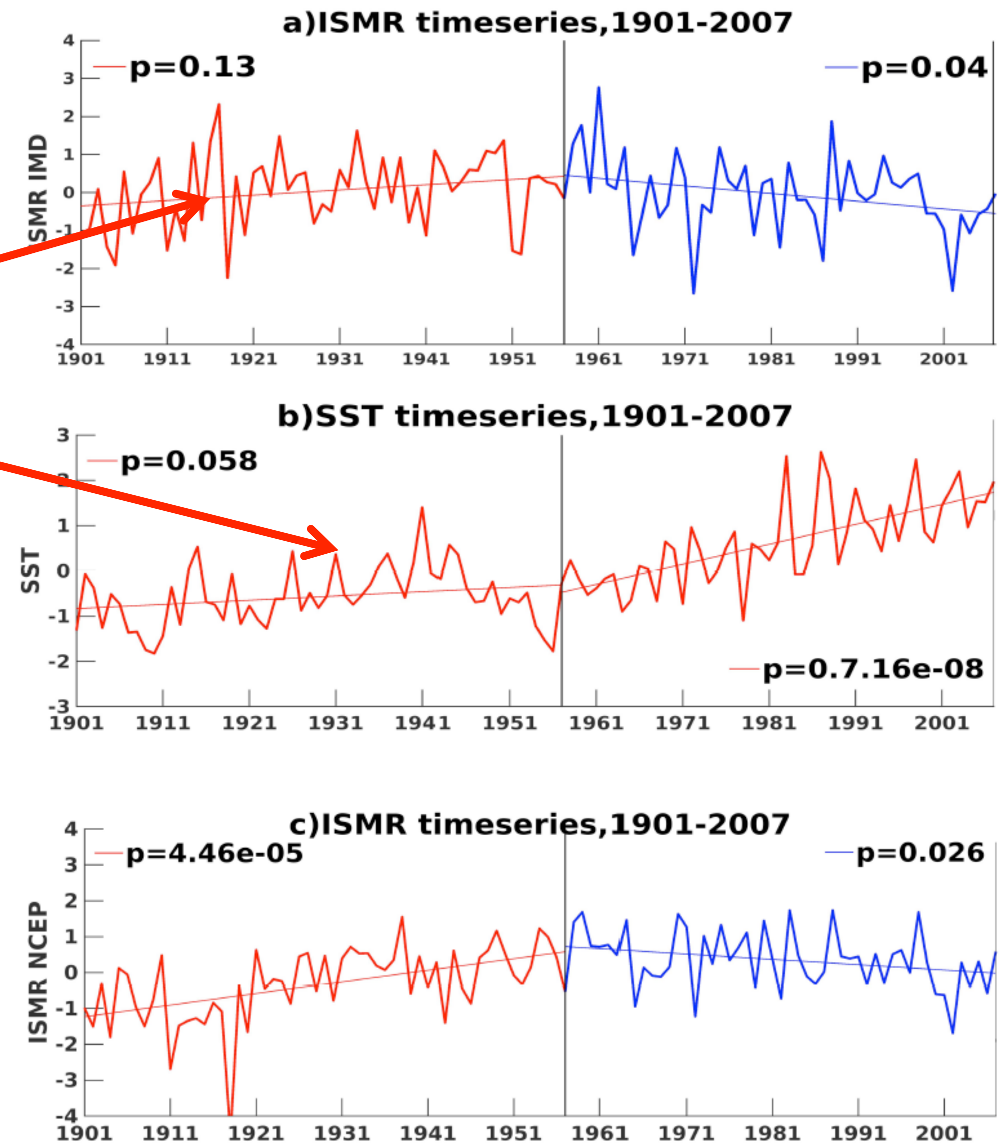


Fig. 1 (a) Indian summer monsoon rainfall (ISMR) using Rajeevan et al. (2006) rainfall data normalized by its own inter-annual standard deviation during 1901 to 2007. The linear trends for the periods 1901 to 1957 (P1) and 1958 to 2007 (P2) are shown. (b) Sea surface temperature averaged over (50°E-100°E, 20°S-20°N) during June-September for the period 1901 to 2007 normalized by its own standard deviation. (c) Normalized ISMR similar to (a) but from NCEPv3.

Do the ‘Bjerknes’ feedback and ‘Large-scale vorticity’ feedback work similarly in both phases of the ISMR MDV?

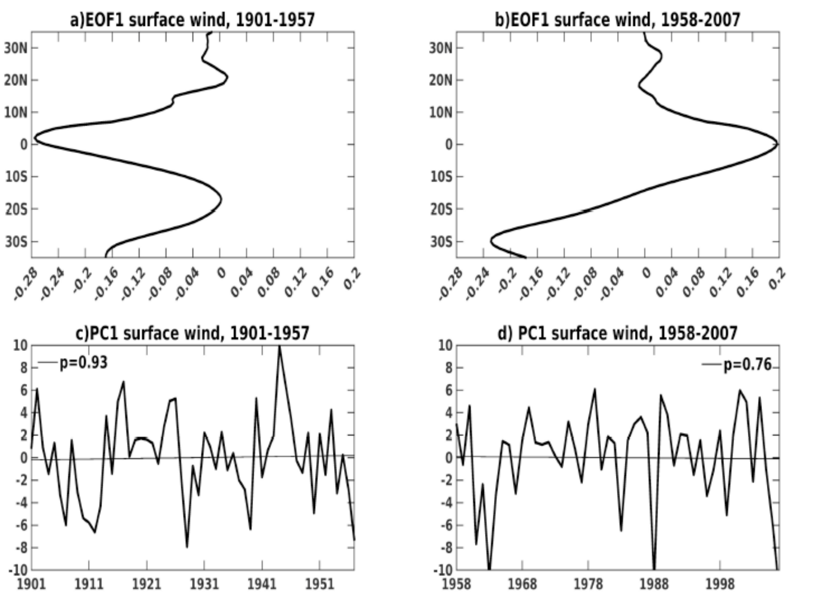


Fig. 2 (a) Latitude dependence of the dominant EOF (EOF1) of zonal wind zonally averaged between 70°E and 90°E for the period P1, (b) Same as (a) but for the period P2, (c) Time series of principal component (PC1) corresponding to EOF1 for the period P1, (d) Same as (c) but for the period P2. The linear trends of the PCs shown by straight lines are statistically insignificant (see p-values).

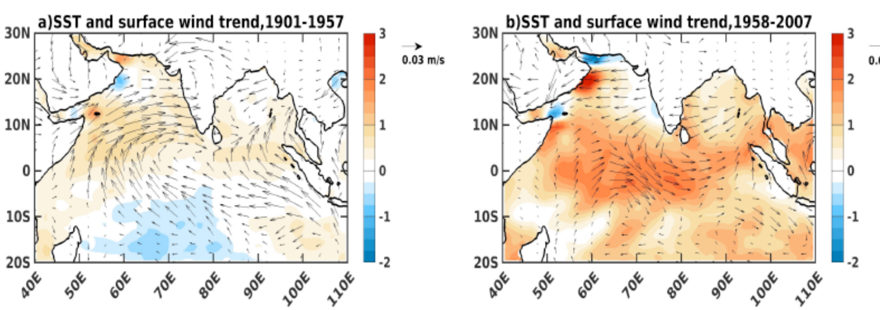


Fig. 3 (a) Trends in sea surface temperature (SST in °C/57- years) and NCEPv3 surface winds (m s $^{-1}$ / 57-years) in the tropical Indian Ocean (IO) for the summer monsoon season for period P1. (b) Same as (a) but for period P2. (SST values at each grid points are multiplied by 100 for better representation of the colour bar)

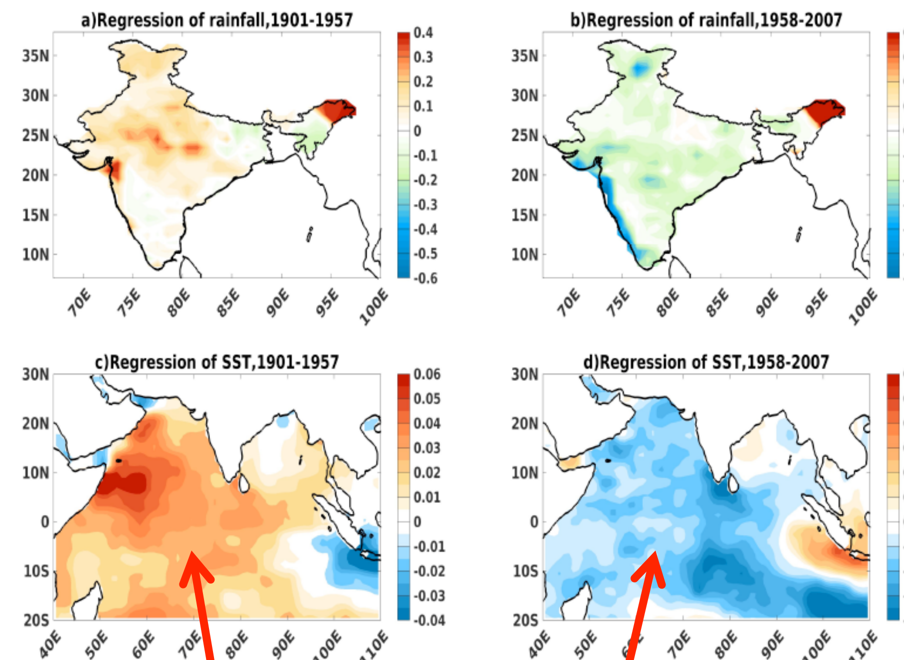


Fig. 4 (a) Regressed anomaly pattern of seasonal mean rainfall with PC1 of surface zonal wind averaged between 70°E and 90°E during P1. (IMD rainfall data and wind from NCEP v3), (b) Same as (a) but during P2. (IMD rainfall data and wind from NCEPv3) Units: (mm day^{-1})(ms^{-1})$^{-1}$. (c) Regressed anomaly pattern of seasonal mean SST with PC1 of surface zonal wind averaged between 70°E and 90°E during P1. (d) Same as (c) but during P2. Units (°C)(ms $^{-1}$)$^{-1}$.

Bjerknes feedback→

- Increasing trend of SST in P1
- Decreasing trend of SST in P2

However, Bjerknes feedback + Vorticity feedback can not explain the strong increasing trend of SST during P2 (1958-2014). Need to include contribution of 'heat fluxes' in the Indian Ocean.

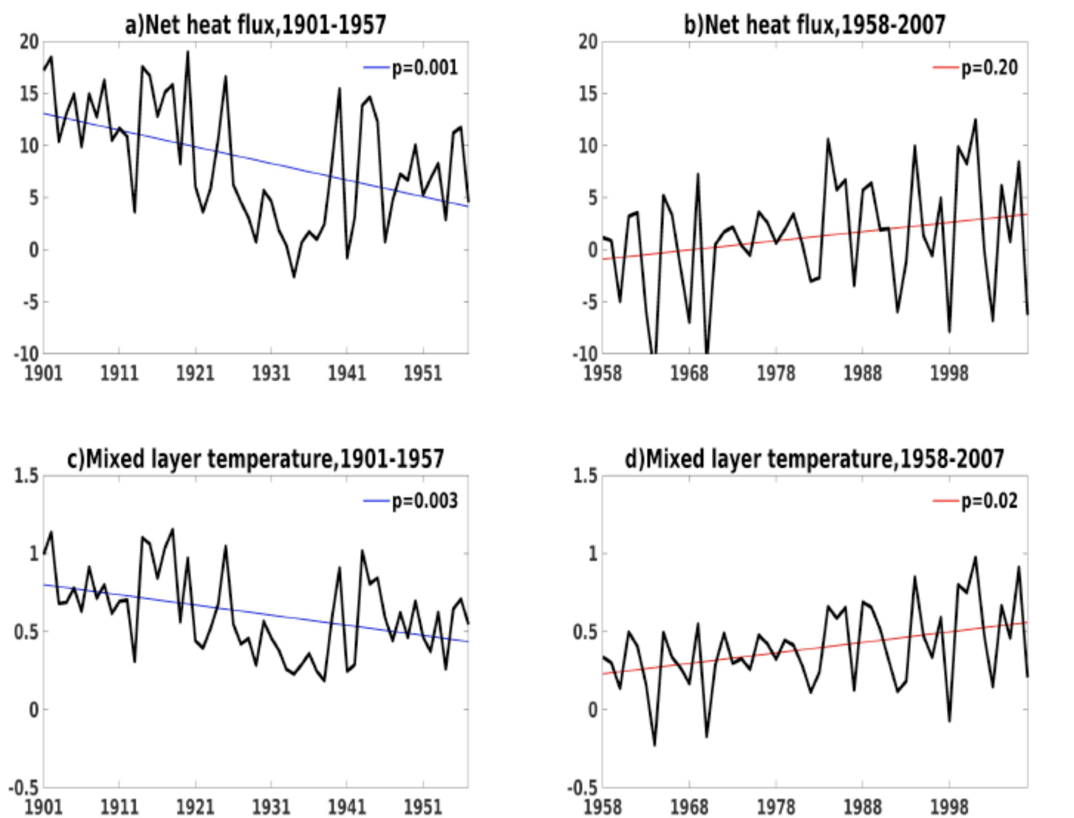


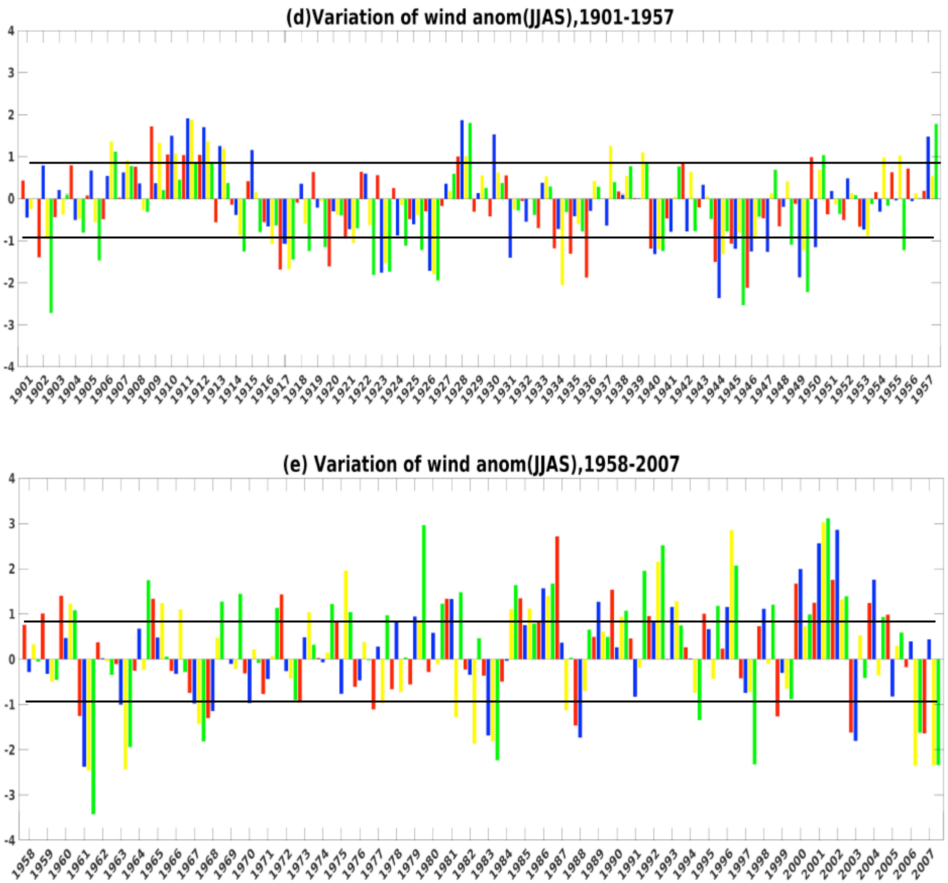
Fig. 9 (a) Time series of JJAS mean Q_{net} from NCEPv.3 averaged over (50°E-100°E, 20°S-20°N) for P1 together with its linear decreasing trend (blue line). (b) Same as (a) but for P2. Unit:($W.m^{-2}$). The red line shows linear increasing trend. (c) Time series of mixed layer temperature during the JJAS season forced by Q_{net} during P1. The decreasing linear trend is shown by blue line. (d) Same as (c) but during P2. The red line shows the increasing linear trend. Unit: (°C. day^{-1}). The p-values for statistical significance of the linear trends are shown.

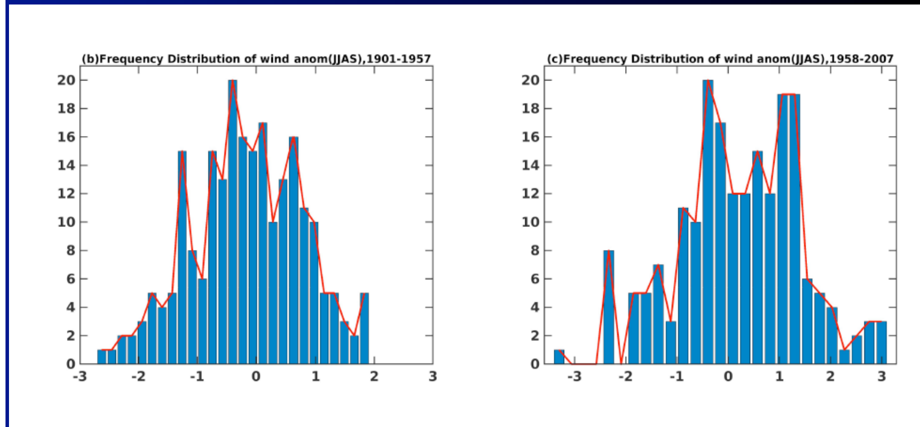
$$hC\rho\,(\delta/\delta t\ SST) = Q_{net}\ ,$$

Where,

Q_{net} = NetSW – NetLW – LHF - SHF

The key to the differences in air-sea interaction for Bjerknes & vorticity feedbacks during P1 and P2 are the changes in Equatorial Indian Ocean zonal winds in the two periods.





P1➔higher propensity of 'Eq. Easterlies➔ Higher frequency +ve IOD

P2➔higher propensity of 'Eq. westerlies➔ Higher frequency -ve IOD

Fig. S1 (a) Time series of equatorial JJAS mean zonal wind anomaly over the century (1901- 2007) averaged over the region between 70°E to 90°E and 5°S to 5°N. Unit: $m.s^{-1}$. Frequency distribution of wind anomaly for JJAS months over the box 2°S-2°N and 70°E-90°E for the periods (b) 1901-1957 and (c) 1958-2007 respectively. Variation of monthly wind anomaly for JJAS months over the box 2°S-2 °N and 70°E-90 °E for the periods (d) 1901-1957 and (e) 1958-2007 respectively. Unit: $m.s^{-1}$ (Red:June, Blue:July, Yellow: August, Green: September)

In Conclusion of the Lecture series:

Thoughts on two issues…

1. What does India need to improve the current Weather and Climate Prediction capability and how the Academic Community could contribute to this National need?

2. Identify a few broader outstanding science questions on Weather and Climate in general and Indian monsoon in particular, where collaboration between the country’s Academic Community and Weather and Climate scientists could lead to new Advances in Weather and Climate Science

What India needs…

- What India needs, for that matter what any country needs, is skillful and reliable prediction of Weather as well as Climate (seasonal mean). Because that is what Users and Policymakers need and demand.

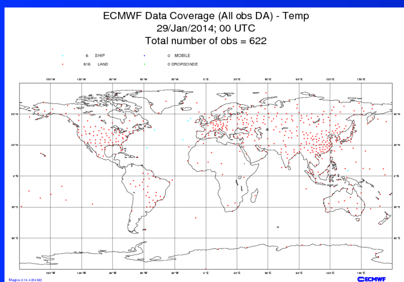
- The ‘Excellent skill’ of Weather Forecasts today is largely contributed by Fundamental research in atmospheric and oceanic Processes that led to significant improvement of the Forecast Models.

- We continue to search for new phenomena and variability and persevere to understand them, hoping that the understanding will eventually lead to improvement of Forecast Models and Forecast skill.

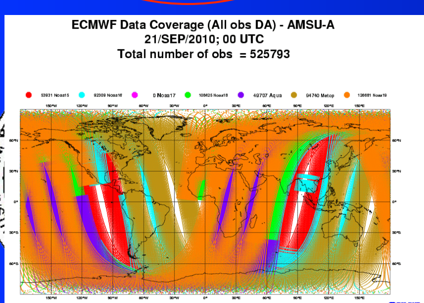
In order to understand What is needed to improve skill of Forecasts, we need to start with getting a feel of, **What is a Forecast System?**

A Weather Prediction System

Initial Conditions:

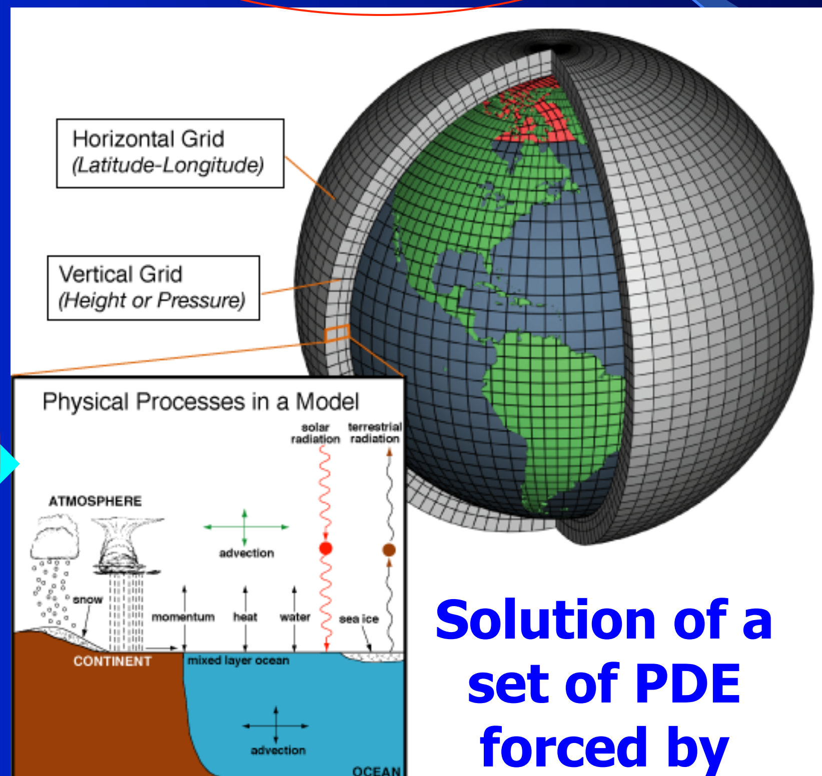


Analysis of conventional and satellite Obs. & Data Assimilation



U V W T Q P etc

Forecast Model



Solution of a set of PDE forced by Heat Balance

Forecasts

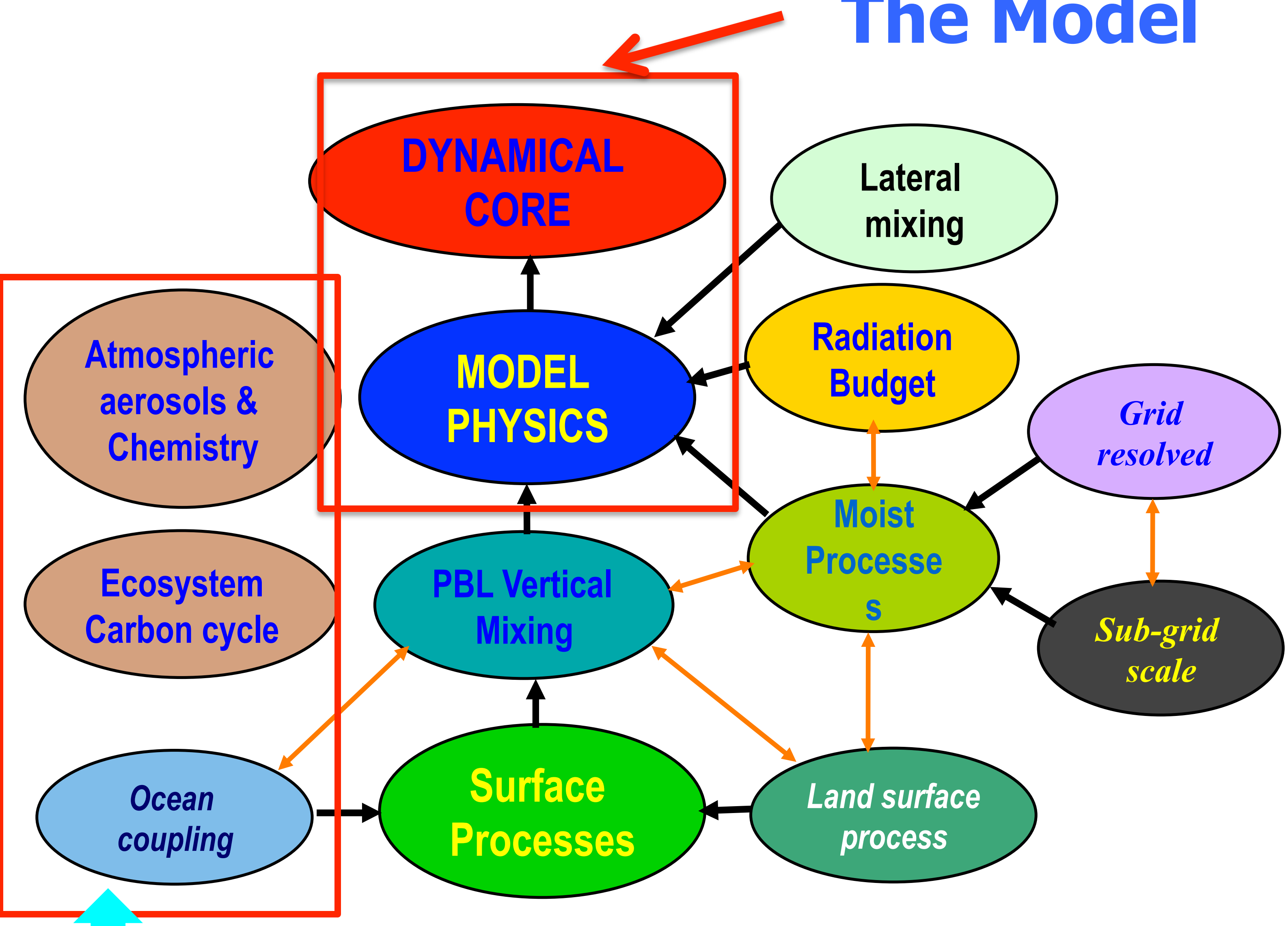
Time Marching

U V W T Q P etc

Met. Parameters

Therefore, The Forecast Model is the key instrument with which Forecasts are made. What does a Forecast Model Look Like?

The Model



Model ‘Complexicity’ needed for Climate prediction

Dynamical Core is nothing but solution of the basic equations…

Equations of motion (ECWMF model)

$$\frac{\partial U}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial \lambda} + v\cos\theta\frac{\partial U}{\partial \theta}\right\} + \dot{\eta}\frac{\partial U}{\partial \eta}$$

$$(-fv) + \frac{1}{a}\left\{\frac{\partial \phi}{\partial \lambda} + R_{\mathrm{dry}}T_{\mathrm{v}}\frac{\partial}{\partial \lambda}(\ln p)\right\} = \underline{P_U + K_U}$$

East-west wind

$$\frac{\partial V}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda} + V\cos\theta\frac{\partial V}{\partial \theta} + \sin\theta(U^2 + V^2)\right\} + \dot{\eta}\frac{\partial V}{\partial \eta}$$

$$+fU + \frac{\cos\theta}{a}\left\{\frac{\partial \phi}{\partial \theta} + R_{\mathrm{dry}}T_{\mathrm{v}}\frac{\partial}{\partial \theta}(\ln p)\right\} = \underline{P_V + K_V}$$

North-south wind

$$\frac{\partial T}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \theta} + V\cos\theta\frac{\partial T}{\partial \theta}\right\} + \dot{\eta}\frac{\partial T}{\partial \eta} - \frac{\kappa T_{\mathrm{v}}\omega}{(1 + (\delta - 1)q)p} = \underline{P_T + K_T}$$

Temperature

$$\frac{\partial q}{\partial t} = \frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda} + V\cos\theta\frac{\partial q}{\partial \theta}\right\} = \eta\frac{\partial q}{\partial \eta} = \underline{P_q + K_q}$$

Humidity

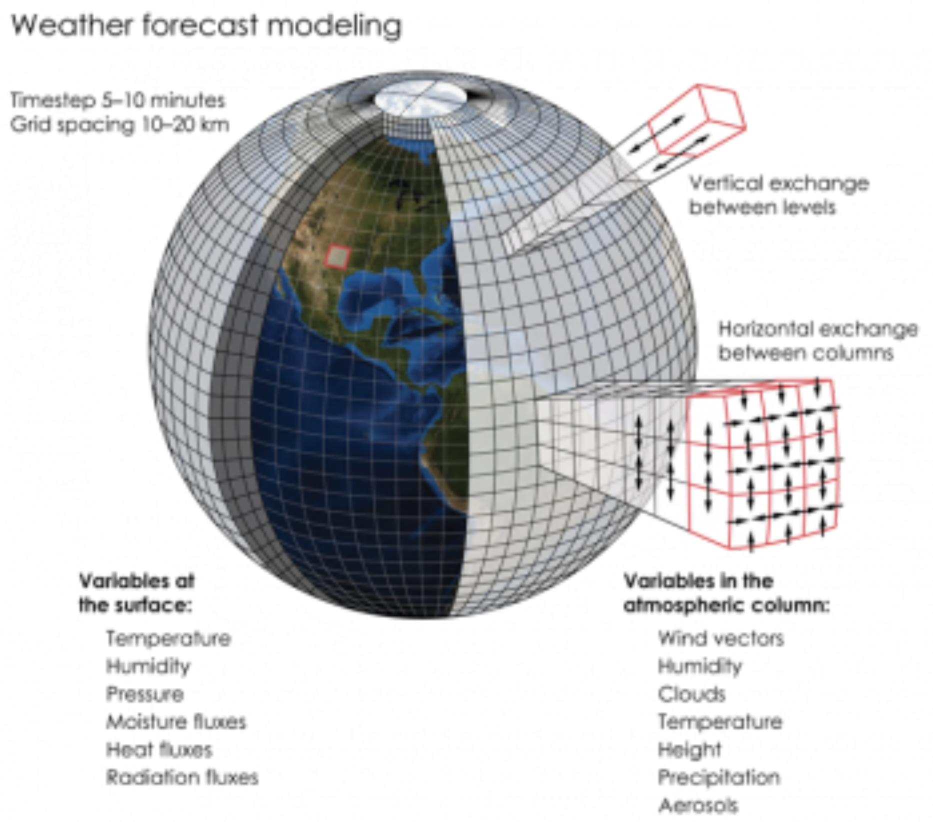
$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) + \nabla.\left(\mathbf{v}_{\mathrm{H}}\frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) = 0$$

Continuity of mass

$$\frac{\partial p_{\mathrm{surf}}}{\partial t} = -\int_0^1 \nabla.\left(\mathbf{v}_{\mathrm{H}}\frac{\partial p}{\partial \eta}\right)d\eta$$

Surface pressure

Challenges in Accurate Numerical Solution of Equations for Weather Forests..

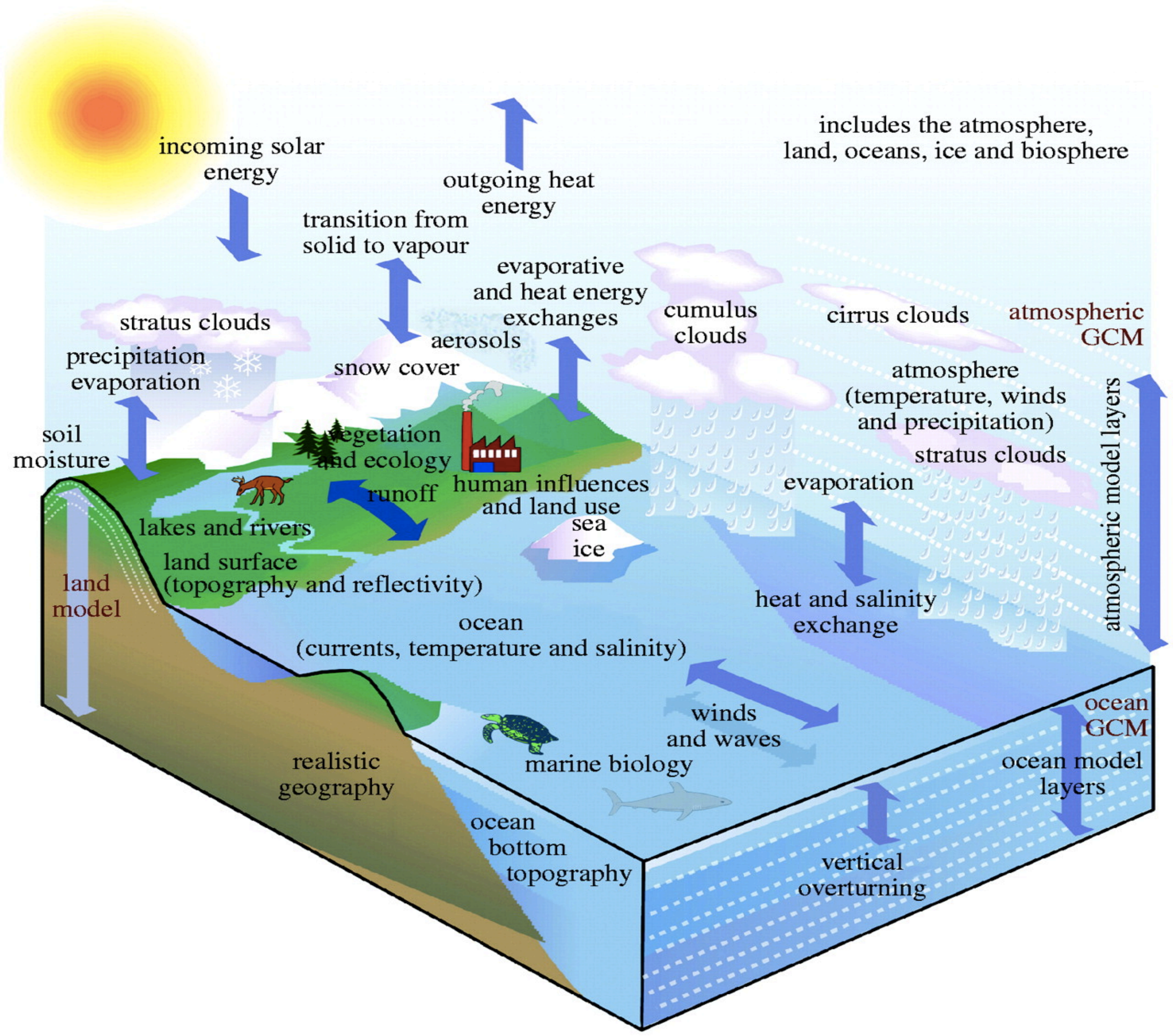


- **Equations to be solved in each grid box**
- **Ex. 100 km x100 km, 60 levels in vertical,**
  - **3.8 x 10^6 grid points!**
- **Accuracy of the finite difference solutions increase with higher resolution**
- **Ex. 20 km x 20 km x 60 levels**
  - **98 x 10^6 grid points!!**

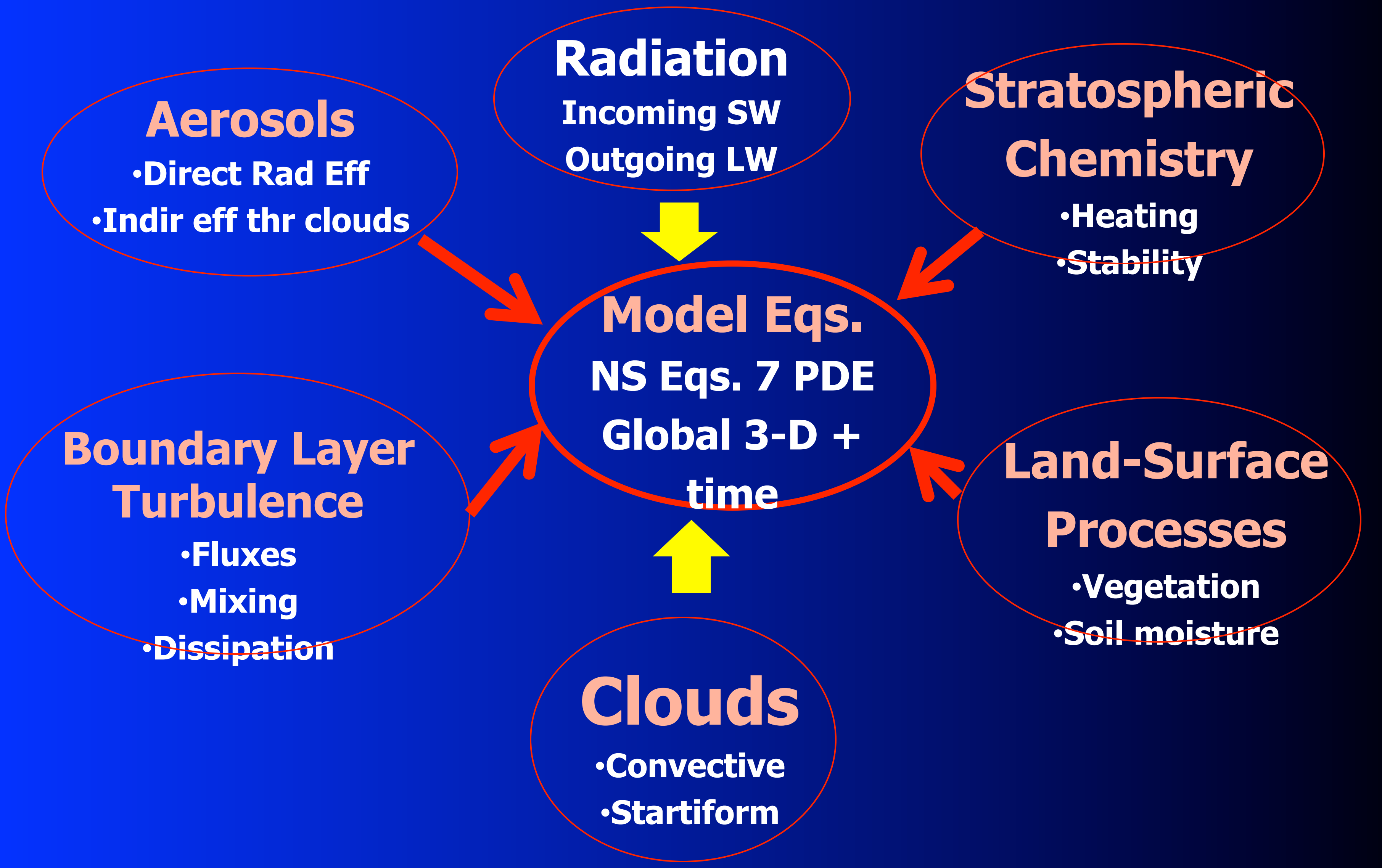
Then there is the problem of Numerical stability. For stability of the solutions, when one decreases $\triangle$ X and $\triangle$ Y, you also have to reduce the time step of integration $\triangle$ T !!→ requires more time to reach same Forecast Lead time

- **Thus if you increase the number of grid points N, cost of computation goes as N^3 not N^2 !!**

A Schematic of the Physical Processes Weather and Climate



How do the Physics contribute to Heat Balance?



Challenges in calculating the contribution of the Physical Processes to the heat balance…

- Physical processes leading to heat balance work on Small Scales not resolved in a large scale global model.

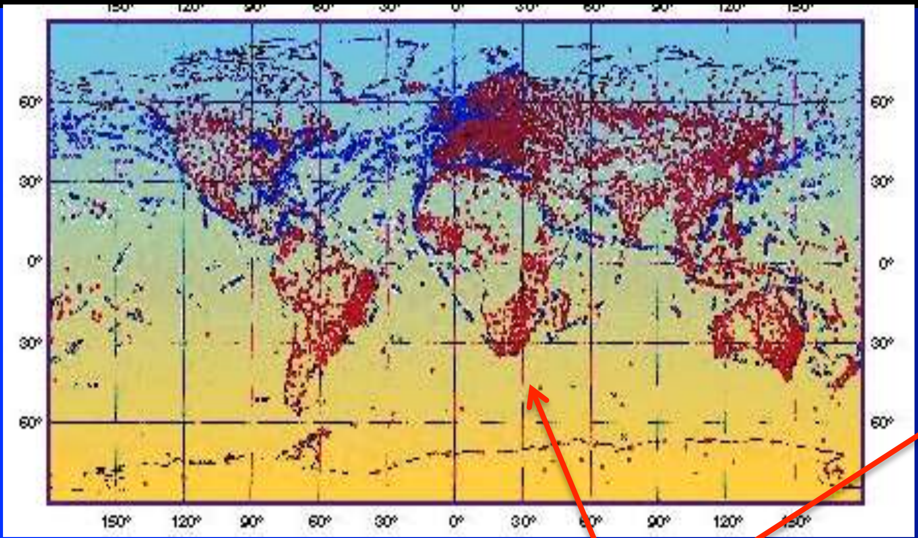
- Ex. Scale of individual clouds is 1-10 km, while a typical grid size of global model may be 50km x 50 km . Clouds could not be explicitly resolved. We need a mechanism, so that given the large scale meteorological fields, we could formulate the contribution of unresolved small scales.

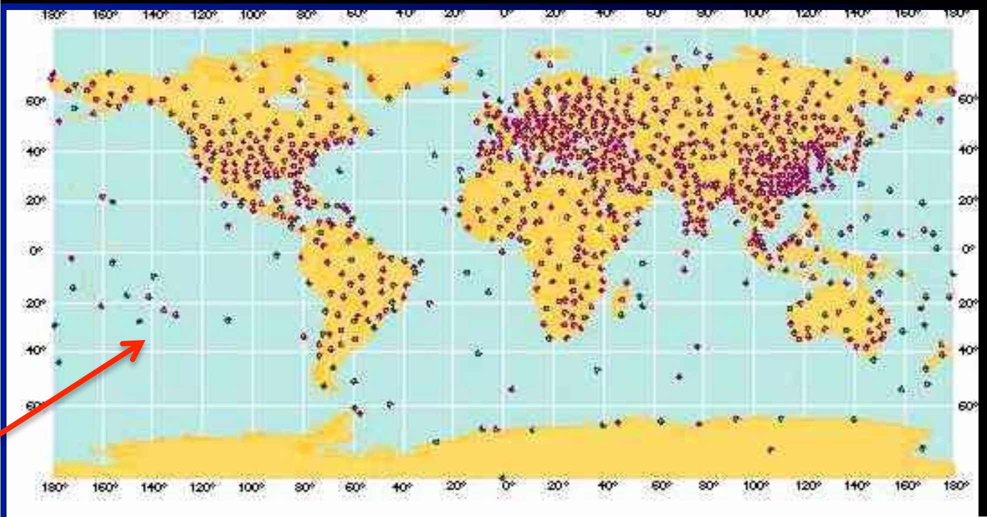
→ **PARAMETERIZATIONS**

- Need Parameterization, for clouds and convection, Radiation, Boundary Layer turbulent mixing, Land Surface Processes, Stratospheric Chemistry, aerosols etc

- Parameterizations are major sources 'errors' in a Forecast Model that improves to some extent going from 'simple' to 'complex' (more accurate) parameterizations.

Preparation of Initial Condition for the model Forecasts…



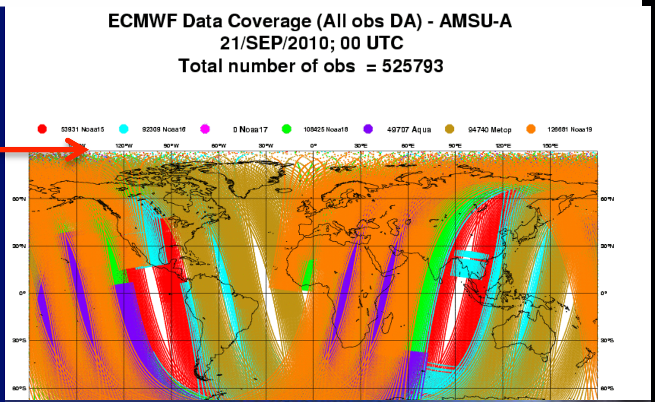


- Initial Conditions come from Observations, conventional and space and ground based remote sensed,

- Irregular in space and time , but the Forecast model in Regular grid points!

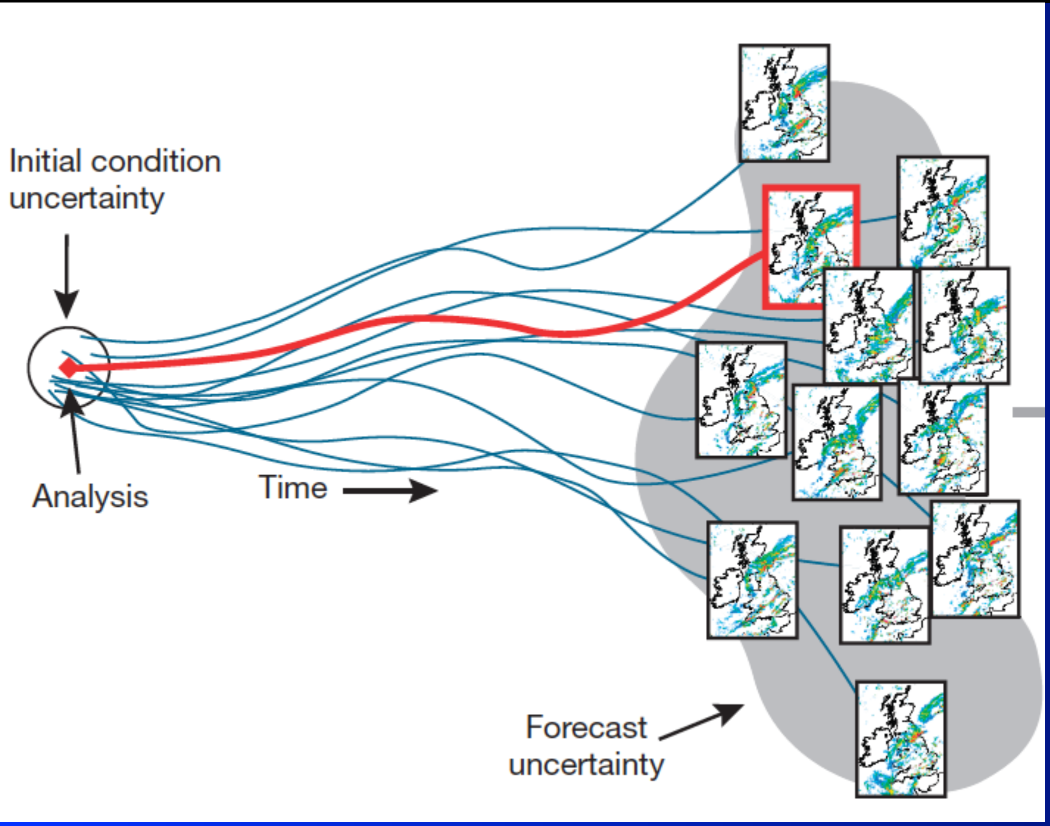
- Needs to be Interpolated to Regular grid points…

→ ANALYSIS



→ This also introduces some error in the

Unlike some systems like the Tides and Planetary Positions, which could be predicted indefinitely in advance, Weather cannot be predicted indefinitely in advance!! To improve the skill of Weather Forecasts, we need to understand why weather forecasts deteriorates with Forecast lead times?



- **Atmospheric Dynamics is a Deterministic Chaos**
- **Highly Sensitive to initial conditions**
- **Small error in initial condition grows rapidly with time of integration making the trajectories to diverge!**

→Reduce/Minimize initial error

→Ensemble forecasting, to reduce initial condition uncertainty

Two sources of errors in a Weather Forecasting System

Errors | **What Needs to be done to reduce/ minimize**

1. Initial Error

- Improve Analysis adding as much observations as possible, satellite data
- Reduce imbalance between Analysis and Model at t=0 through better/ improved **Data Assimilation**

2. Model Error

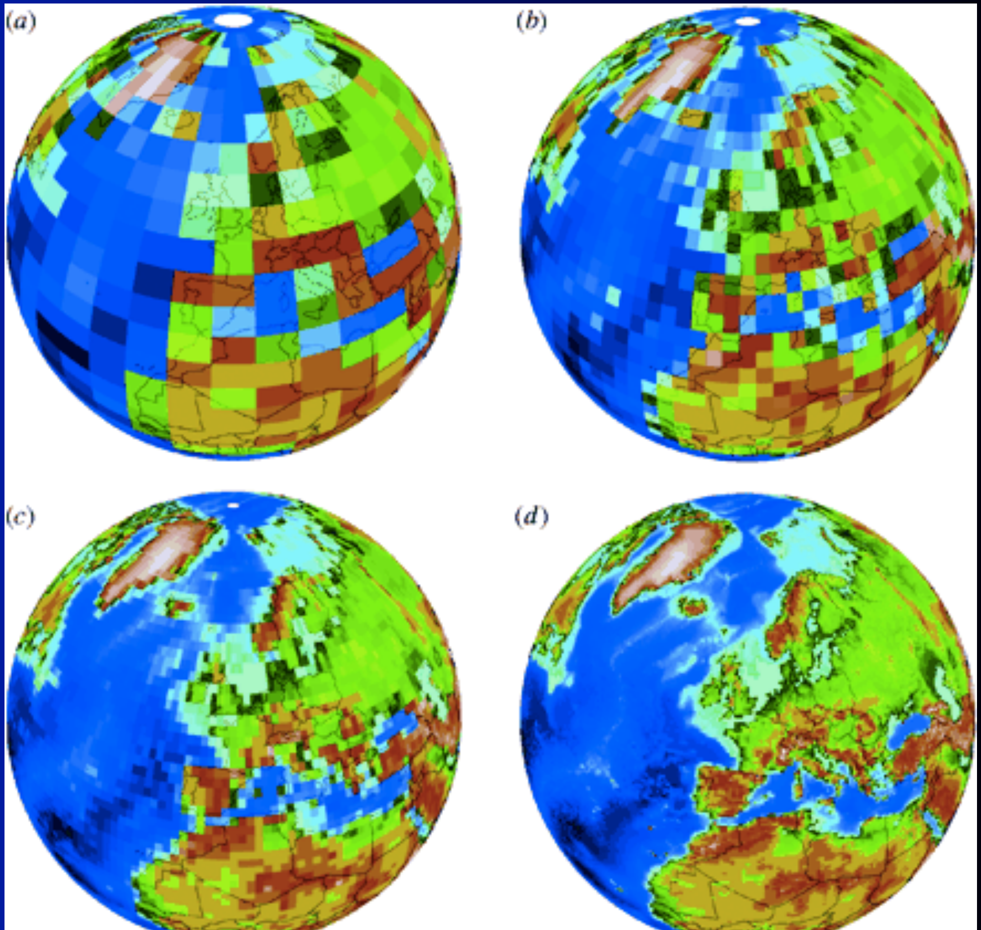
- Physics error, **parameterization**.
  - Improve all parameterizations persistently!
- **Resolutions** of the Model. Improve Resolutions, both horizontal and vertical

Model resolutions improve the accuracy of Simulations in TWO ways…

1. First, error due to finite difference representation of the PDEs reduce with increasing resolutions

2. Second, due to improved representation of Orography, improved simulation of Precipitation and gravity wave drag

Horizontal resolution of the contemporary atmospheric and ocean climate model components. An approximate resolution of (a) 500km, (b) 300km, (c) 150km and (d) 75 km.



Improvements in Forecasts are largely due to

1.

Better observations, specially space based observations providing obs over ocean, reducing errors in the initial condition.

2.

Great improvements in Models, in resolutions and complexity as well as in improving the formulation of the physical processes.

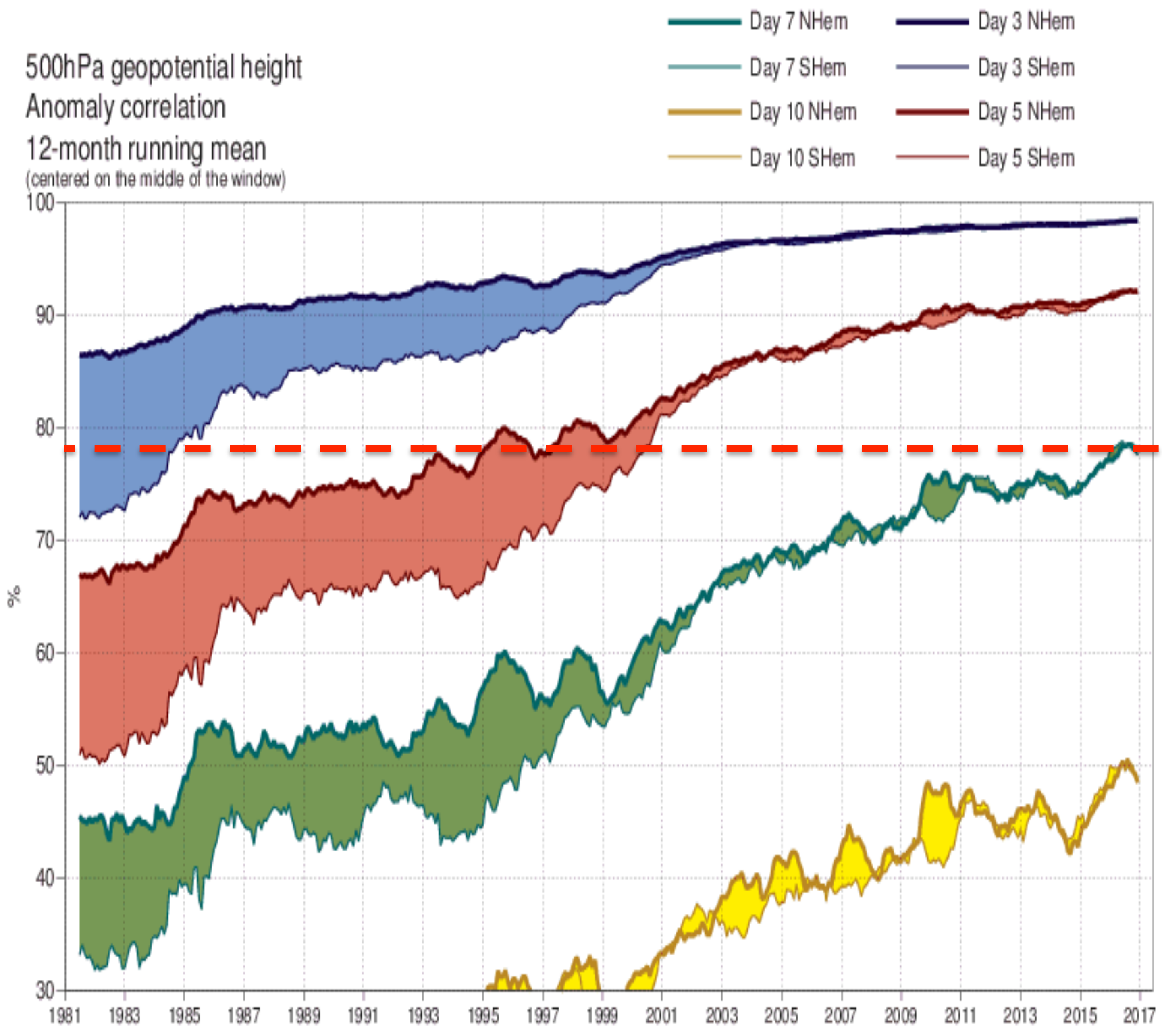
3.

Availability of much higher capacity HPC!

Aaditya at IITM

Pratyush at IITM

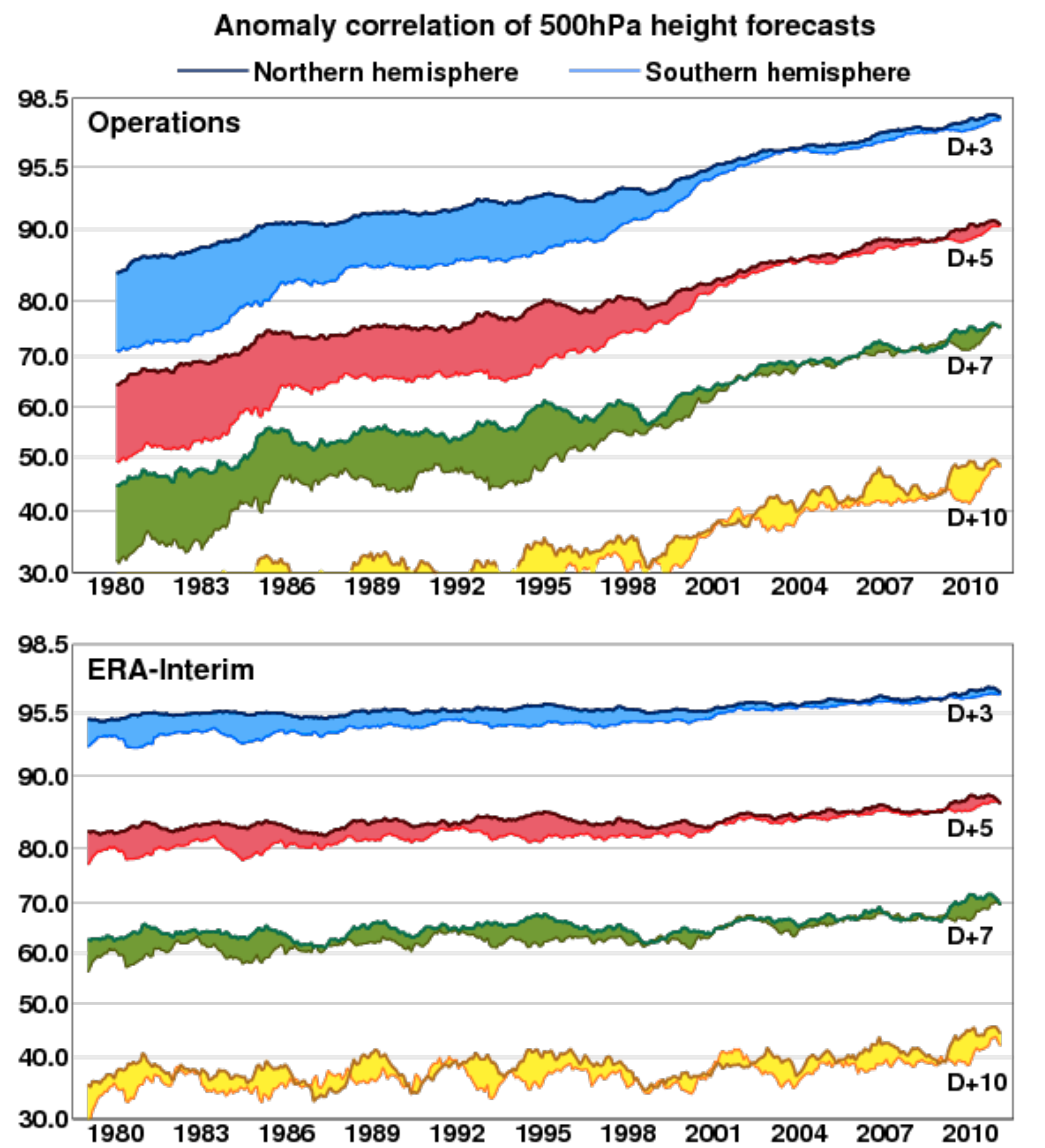
Improvement of skill of Extra-tropical Weather forecasts by the ECMWF from 1981 to 2017!



Power of improved Observational data, Ex

SH extra-tropical forecasts!

Role of Improved Forecast Model and Assimilation on Forecast Skill



Evolution of skill in ECMWF operational forecasts (top panel) and in re-forecasts produced by the ERA-Interim system (bottom panel). Colored plumes show anomaly correlations for 3-day, 5-day,7-day and 10-day forecasts of 500hPa geopotential height, averaged for the northern and southern hemispheres. Comparing the top and the bottom panels helps separate the effect of changes in the observing system. Figure produced by Adrian Simmons. (Contributed by D. Dee)

Important Lesson Learned from this experience:

- **For improving the 'initial condition' and reduce 'initial error', observational data is Important. More importantly, better 'data' assimilation is required to reduce the 'initial shock' and 'initial error.**

- **But improvement of the 'Forecast Model' seems to be far more important in improving the skill of forecasts. This makes sense as 'model error' keeps on contributing to the 'forecast errors' on every time step of generating the forecasts.**

Improvement of Forecast Skill

- Any Country's Forecast System, whether Weather Forecast or Seasonal Forecast System is operated by the Operation Weather Service, the IMD in our case.
- Therefore, improvement skill of forecasts can come only by improvement of the **Operational Forecast Models!**
- Each Weather Prediction Model or Climate Prediction Model is 'different' as they use a different set of 'Physics modules' . 'Parameterizations' of different 'Physics Modules' are interdependent to some extent. Hence, a 'Parameterization' that works in one Model may not work equally well in Another model.
- Model development must be done in the country on the Operational Model!

Forecast model development strategy…

- Normally, the Operationally Agency has a Model Research and Development group in-house that is supported by a few dedicated Government Research Labs. For example, NCEP in USA is supported by NOAA through GFDL, Princeton University and NCAR.
- In India, IITM was set in 1962 to do basic research and help IMD in all aspects including Model development.
- However, for various reasons, IITM and IMD drifted apart over the years with little or no synergy in Forecast model developments in the country. Little capacity in modeling.
- So, when I joined IITM in 2006
  - We were doing deterministic weather prediction with a T80 (~150 km resolution) atmospheric model
  - No dynamical coupled model for seasonal forecasts or extended range forecasts.

What was the reason behind India lagging behind?

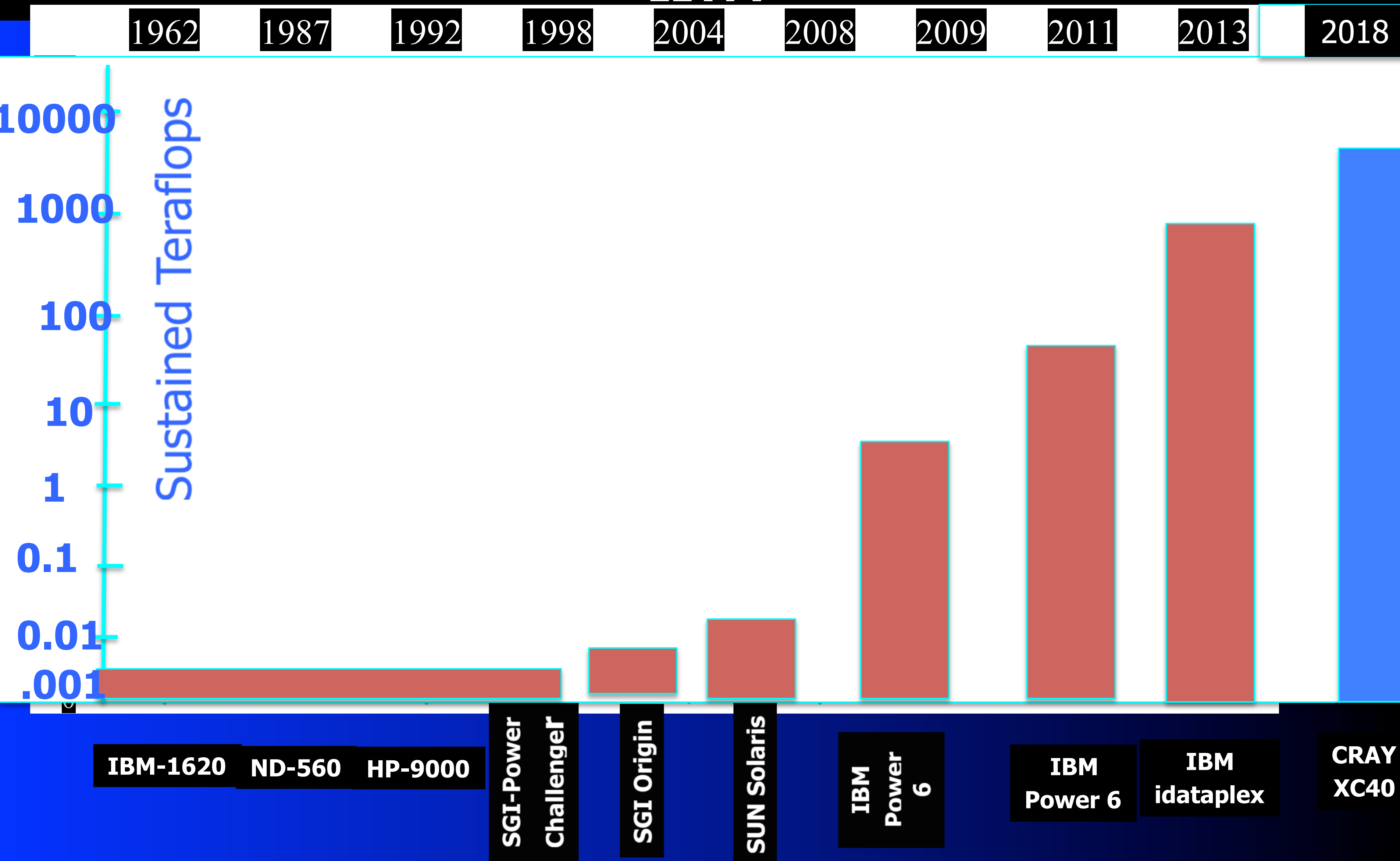
- Elsewhere in the world, advances in Weather and Climate Forecasts were aided by rapidly advancing Supercomputing capabilities.
- However, in India trying to develop our own Supercomputer, we seriously lagged behind in supercomputing capacity. In 2006, the combined computing capability under MoES was < 1 Terrafloops while the major Forecasting and Research Centers it was ~ 1 Petafloops!
- The lack of recognition from senior monsoon scientists and IMD that for improving forecasts, improvement of the Forecast model is more important than observational input!
- As a result, there was a vacuum in capacity in global Ocean, Atmosphere modeling in the country!

2006 Also opened up new Opportunities….

- **MoES was born!** I consider it as major historic event
- Synergy between IITM, IMD, NCMRWF and INCOIS was created by MoES
- Under the **Monsoon Mission** a major plan for capacity building in Modeling was put in and
- An ambitious long-term plan supercomputing capacity building was put in place

➔The success of the Monsoon Mission Project owes to strong support of Secretary MoES Dr. Shailesh Nayak who convinced policy makers the importance of the Project and generated necessary resources.

History of Supercomputing in Indian Met. Organizations, IITM



While there is considerable scope for improvement, today IMD Prediction Systems can be called 'State-of-the-Art'. Today IMD Operationally runs…

1. NCEP GFS based global model with ~12 km horizontal resolution and 64 levels in vertical together with Ensemble Kalman filter GDAS data assimilation, deterministic weather forecasts
2. A Ensemble Prediction System (EPS) with GFS T512 resolution (~35 km) for probabilistic weather forecasts.
3. A high resolution Regional Model (WRF) is run over weather active regions for detailed update
4. A Seasonal Prediction System with coupled CFS (GFS – Atmos, MOM4-Ocean)
5. An Extended Range Prediction System with versions of CFS for active/break spells

- By 2014, All these Prediction Systems were Operationalized at IMD
- Between 2006 and 2014, IITM developed, tested their prediction skill and transferred All **Four Global Prediction Systems** to IMD ready to be Operationalized!
- People who know what is involved in doing these things would say that this is a highly non-trivial achievement for MoES!
- During this period IITM, IMD, NCMRWF, INCOIS worked as one Unit.
- It is good to see that that synergy with mutual respect between IITM and IMD is continuing.

IMD's Tropical Cyclone Prediction Model

- In addition to the regional weather prediction model , IMD has developed a Tropical Cyclone Prediction system over the years through in-house development and through some input from academic Institutions like IIT/D (Prof. U. C. Mohanty).
- The improvement of skill of the TC forecasts by IMD in recent years is quite impressive.
- With the implementation of of the higher resolution and better physics Monsoon Mission global models providing improved large scale boundary condition for the TC forecast Models, its skill TC forecasts has further improved in recent years.

Developments on Improving the Monsoon Mission Model

- Implementation of a newly developed 6-layer Snow-model (Dr. S. K. Saha et al.,)
- Implementation of newly developed cloud microphysics scheme (Dr. Anupam Hazra et al.,)

IITM also worked and tested several other potential improvements

- Implementation of a different cloud microphysics parameterization (Dr. P. Mukhopadhya et al.)
- Implementation of A Stochastic Cloud model (Dr. P. Mukhopadhyay, Dr. B. B. Goswami et al.)

- It may be noted that each of these are major projects. With all that work, we were able to push skill of seasonal prediction of ISMR from 0.5 to 0.7 during the Monsoon Mission Phase-I!

Does it mean that we can seat back, relax and be Complacent?

- Absolutely not! It is Only the Beginning ..
- While the Operationalized Prediction Systems have shown reasonable skill, there are still significant biases of the GFS/CFS Forecast Models in simulating the global climate and ISMR
- There is considerable scope in improving these biases leading to further improvement of weather and climate forecasts. Two examples of developments at IITM mentioned earlier demonstrated improvement of seasonal prediction skill,

What should be our strategy for Model Development?

- As we have chosen the GFS/CFS model system and invested considerable resources to improve it to an extent, we MUST concentrate future developments ONLY on this modeling system!
- Two important improvements required for the GFS/CFS system
  1. Currently, GSF/CSF is a 'Hydrostatic Model'. Make it a 'Non-Hydrostatic model'. This is required to transform the system to a 'Unified Model Framework' for 'extreme events to climate change'.
  2. The current Ocean model has large biases in SST simulation over IO. Improve the physics of mixing of the model or replace it by a new Ocean Model.

How could the Academic Community in the Country contribute to this effort?

- Through focused development of the GFS/CFS modeling system through MoES/IITM collaboration
- The following may be required by them
  - Developing Ocean-Atmosphere Coupled data Assimilation
  - Improved Parameterizations of
    - Stochastic Cloud model, moist convection and microphysics
    - Boundary Layer turbulence
    - Ocean Vertical mixing in regions of fresh water
    - Ocean Model development

I envisage two potential roadblock for success of such collaboration

- These model development problems are challenging but only makes incremental improvement of the models. The Academic community do not feel compelled to invest the time and effort that may take long time to get a publication. Ex.
- While I do feel that such collaboration is key for making further progress in improving Coupled Models in India, the present leadership at MoES/ IITM must be convinced that investing the required resources would be worthwhile.
- Could some brainstorming dialogue between interested parties start such a collaboration?

Outstanding Climate Science Questions on which collaboration between Academic Community and Climate Community is possible

1. **‘Complexity in Climate Science’**
   1. Over the past 70 years, we have built ‘simple models’ for most climate phenomena such as ENSO, Indian monsoon etc.
   2. But each of these phenomena have event-to-event variability or ‘Complexity’ that limits their predictability.
   3. What is responsible for the ‘Complexity’ or ‘Nonlinearity’?
   4. Is there some ‘order’ or ‘pattern’ to this low-dimensional chaos?

Outstanding Climate Science Questions on which collaboration between Academic Community and Climate Community is possible

2. AI/ML for Improving ISMR Prediction

- Linear empirical models for prediction of ISMR are limited by ‘over fitting’ issue and inability to model the ‘nonlinearity’ or event-to-event variability
- The skill of Coupled GCMs is limited by their biases in simulating the climate modes & teleconnections.
- As AI/ML model the ‘nonlinear’ dependence and minimize the over fitting, physically based use of AI/ML has the potential for improving the skill of ISMR prediction at short as well as long leads
- What is the nonlinear dependence of the initial state of the predictor at different leads (e.g. 3,6,9,12,15,18, months) to the predicted state of the ISMR?

Outstanding Climate Science Questions on which collaboration between Academic Community and Climate Community is possible

RESEARCH LETTER

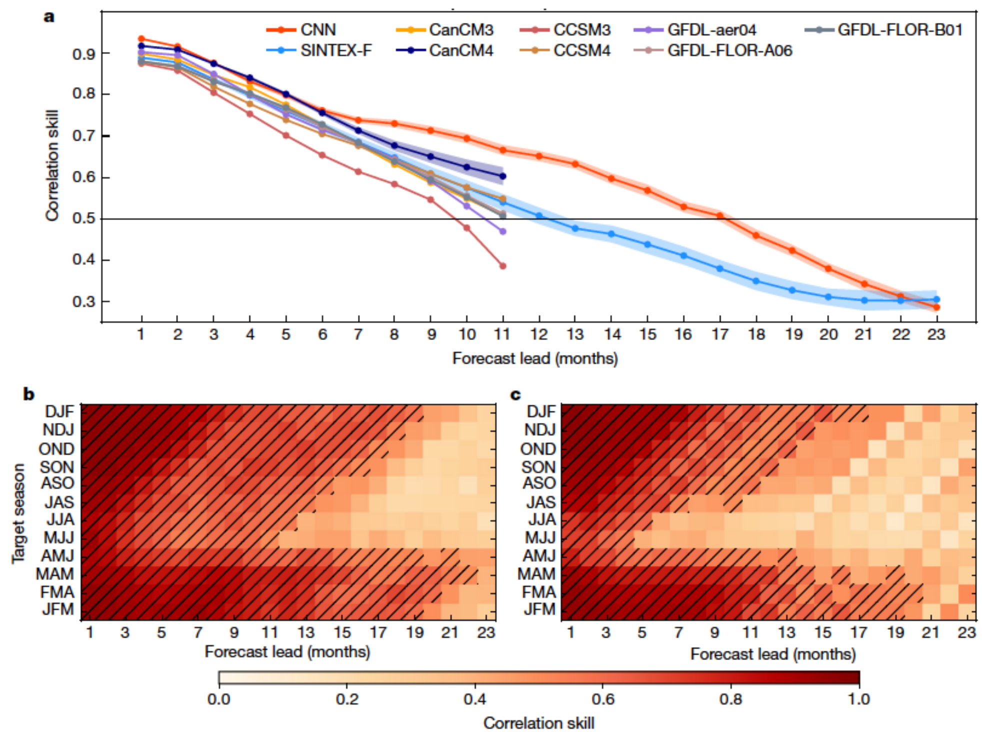


Fig. 2 | ENSO correlation skill in the CNN model. a, The all-season correlation skill of the three-month-moving-averaged Nino3.4 index as a function of the forecast lead month in the CNN model (red), SINTEX-F dynamical forecast system (blue), and dynamical forecast systems included in the North American Multi-Model Ensemble (NMME) project (the other colours). The validation period is between 1984 and 2017. The shading around the lines for CNN, CanCM4 and SINTEX-F denotes the 95% confidence interval, based on the bootstrap method. **b**, **c**, The correlation skill of the Nino3.4 index targeted to each calendar month in the CNN model (**b**) and the SINTEX-F dynamical forecast system (**c**). Hatching highlights the forecasts with correlation skill exceeding 0.5.

This was demonstrated for ENSO prediction recently, (Ham et al. 2019: Nature, https://doi.org/10.1038/s41586-019-1559-7

Outstanding Climate Science Questions on which collaboration between Academic Community and Climate Community is possible

3. Finding ‘Signal’ from a sea of ‘Noise’

- Most ‘signals’ of climate variability are buried in a lot of atmospheric and oceanic ‘noise’. Bringing out the ‘signal’ is an outstanding issue in climate science.
- For example, separating anthropogenic ‘externally’ forced Climate Change signal from a sea of ‘natural variability’ is still an outstanding issue
- This situation is parallel in Physics, be it “God” particle in Hadron Collider or Gravitational wave in LIGO, Physicists have experience in bringing out ‘small signal’ from ‘noise’. I think, we can learn from these experiences and knowledge

Outstanding Climate Science Questions on which collaboration between Academic Community and Climate Community is possible

4. From Weather prediction to Decadal Prediction.

- Decades of 70's and 80's belonged to development of Weather Prediction capability
- Decades of 90's and 2000's belonged to development of Seasonal Prediction capability
- Decades of 2010's and 2020's belong to development of Decadal Prediction capability

➔During the last 100 years, we were obsessed by trying to understand interannual variability for seasonal prediction. It is time to invest in understanding decadal/ multidecadal variability for Decadal Prediction.

Thank you