Rivers, Oceans and Monsoons: A Study with an Earth System Model

Ravi S. Nanjundiah, Jahfer Sharif and P N Vinayachandran
CAOS, IISc

Global Hydrological Cycle

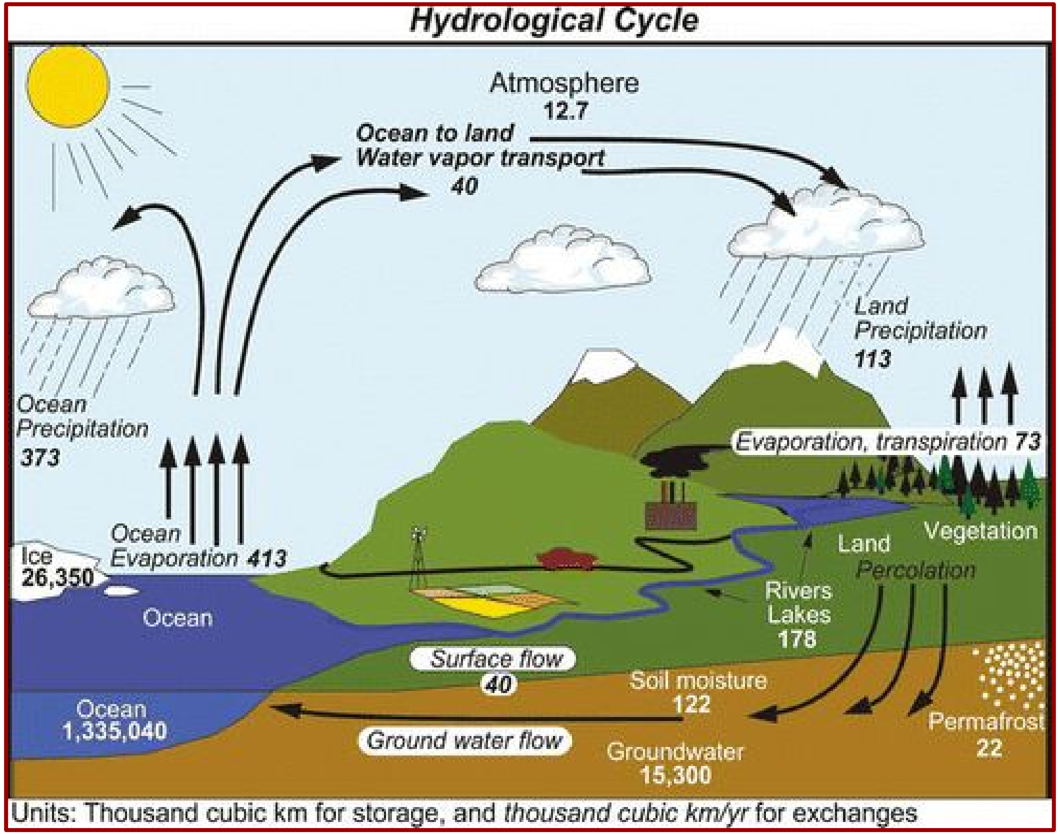


Fig: Schematic of freshwater exchanges involved in global hydrological cycle (from Trenberth2007)

- ★ In hydrological cycle, Evap, Prec & Runoff are balanced in long-term. Runoff = 40,000 km^3/yr = ~10% of overall FW influx.
- ★ Climatic roles of river runoff are largely unknown. Most of the climate modeling studies did not even consider the role of runoff.
- ★ **Objective: Account for climatic role of runoff using a fully coupled earth system model.**

Freshwater discharge to global Ocean

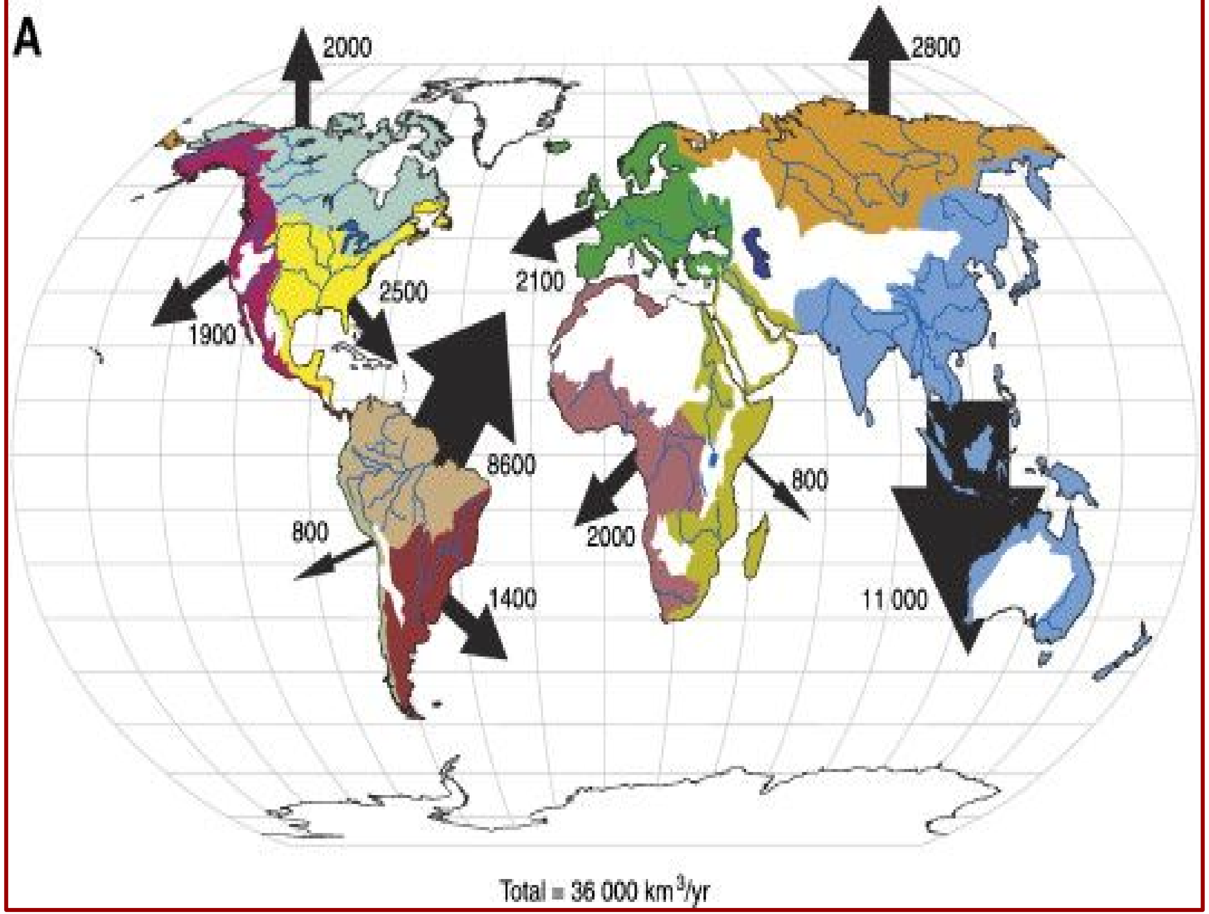
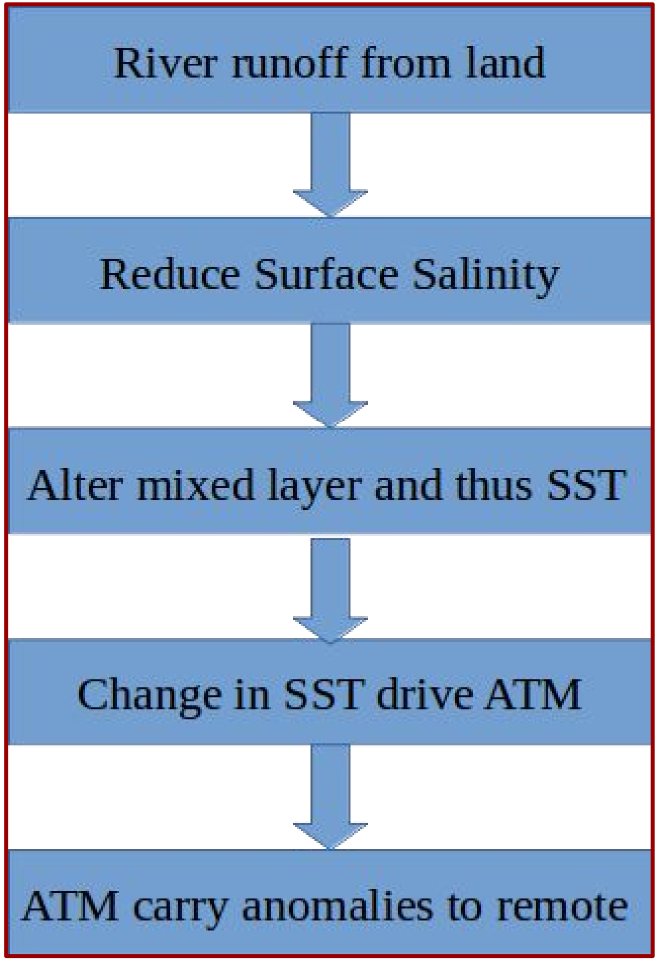


Fig: Schematic of global runoff into ocean (km³/yr). From [Milliman 2011]()

★ Global = 36,000 km³/yr
★ Arrow thickness represent magnitude of discharge
★ Tropical ocean receives maximum runoff
★ **Impacts of runoff into the ocean?**

How much we know about the role of river runoff?



- ★ Transport sediments, alter seawater composition & lower Surface salinity (Roden 1967).
- ★ Regulate ocean stratification and form a source of momentum and buoyancy (Kourafalou 1996)
- ★ Salinity changes in ocean due to runoff induce changes in ocean circulation and heat transfer (Fedorov 2004)
- ★ Alter SST through its effect on mixed layer dynamics by controlling stratification (Montegut 2007)
- ★ Climatic impacts of runoff was first addressed by Vinayachandran 2015 using a coupled climate model.

Motivation

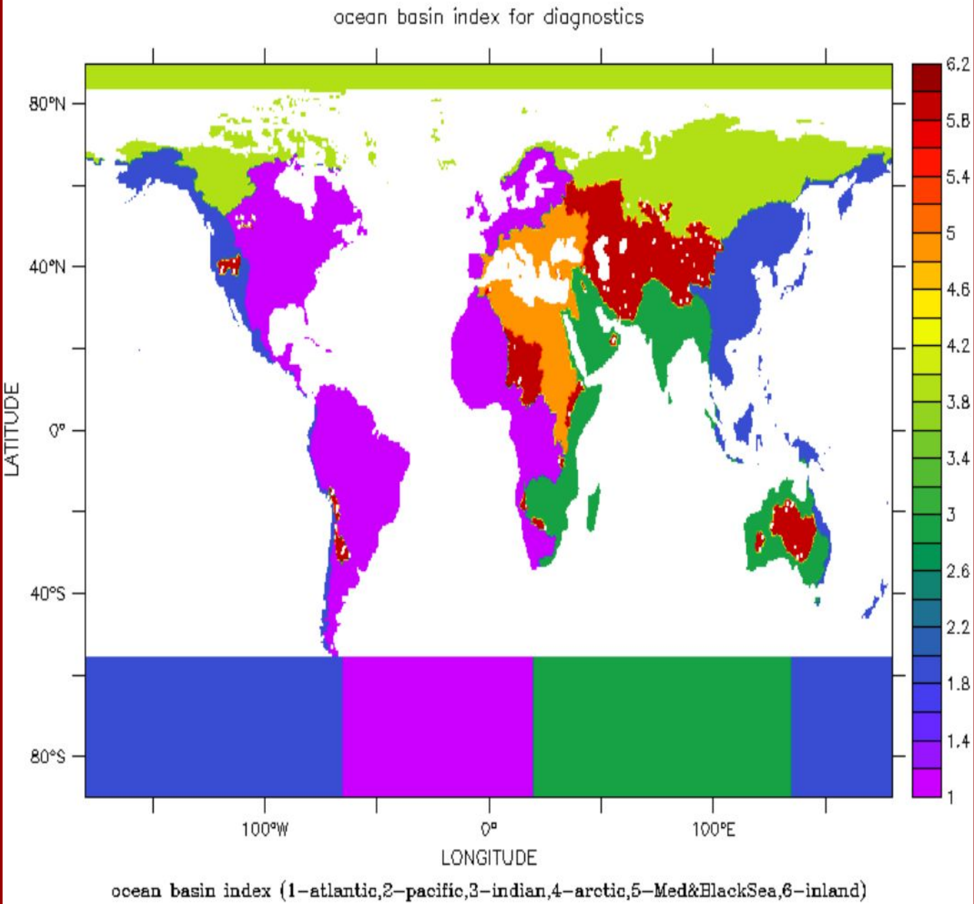


Fig: Drainage areas for oceans (index 1-6). Inland diversion/blocking by dams on large-scale considerably lower runoff

- ★ Large fluctuations in runoff due to recent warming scenario
- ★ Extensive usage of inland water resources for irrigation/industry and household
- ★ Large scale diversion of rivers due to interlinking and dams
- ★ All the above processes affect the quantity river runoff into the ocean, **the impact (feedback) of which on climate is completely unknown**

How to project the climatic impacts of large-scale fluctuations in runoff?

★ Fluctuations in runoff due to climate variability and anthropogenic activities

★ Since the interactions in earth system are highly nonlinear and complex, it is hard to foresee the feedbacks of this runoff variations on climate, with some degree of accuracy.

★ Climate models are representation of earth system components on grid that can simulate processes & its interactions in each components, namely Atmosphere, Ocean, Land, & Ice coupled together using a Coupler.

★ **Sensitivity model experiments that accounts for future changes in runoff can give some insights to possible effects of river runoff changes on climate.**

Freshwater effect of Bay of Bengal

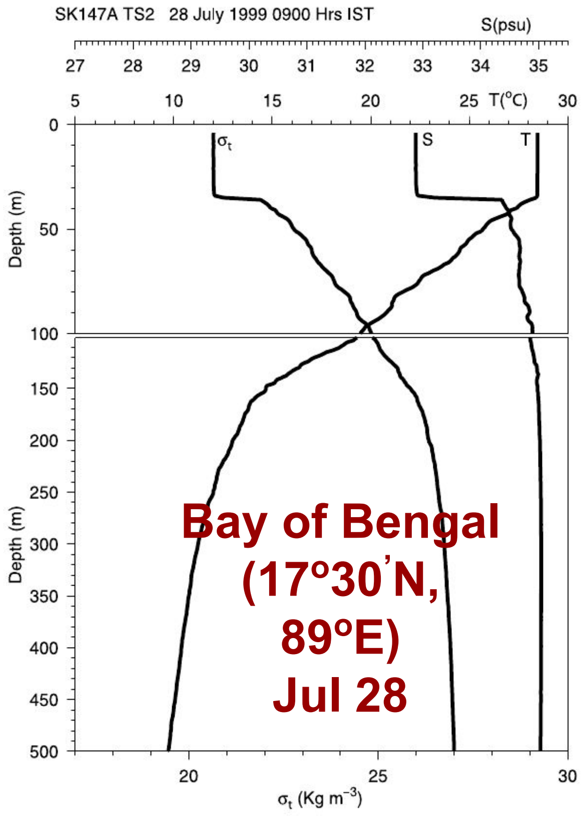


Figure 4. Vertical profiles of temperature, salinity and density on 28 July at 0900 hours IST.

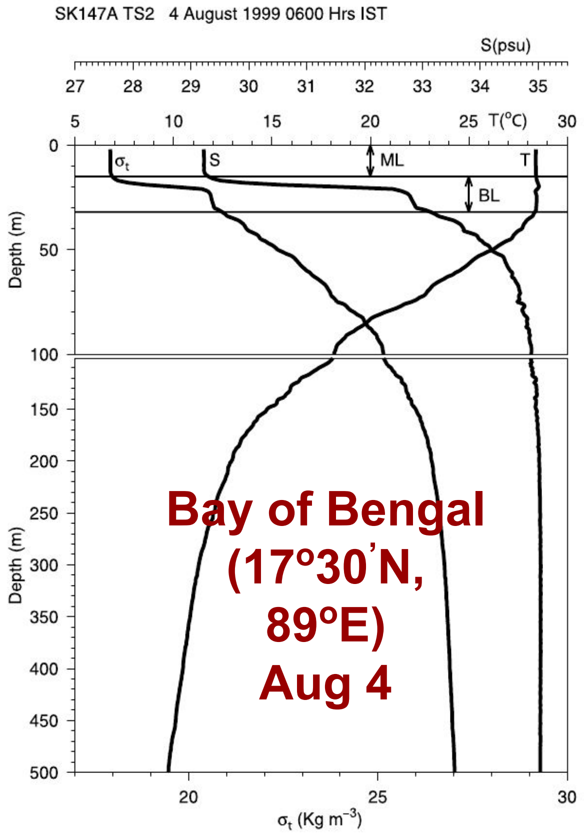


Figure 5. Vertical profiles of temperature, salinity and density on 04 August 1500 at 0600 hours IST. ML and BL indicates mixed layer and barrier layer respectively.

Vertical profiles of temperature, salinity and density From Vinayachandran 2002

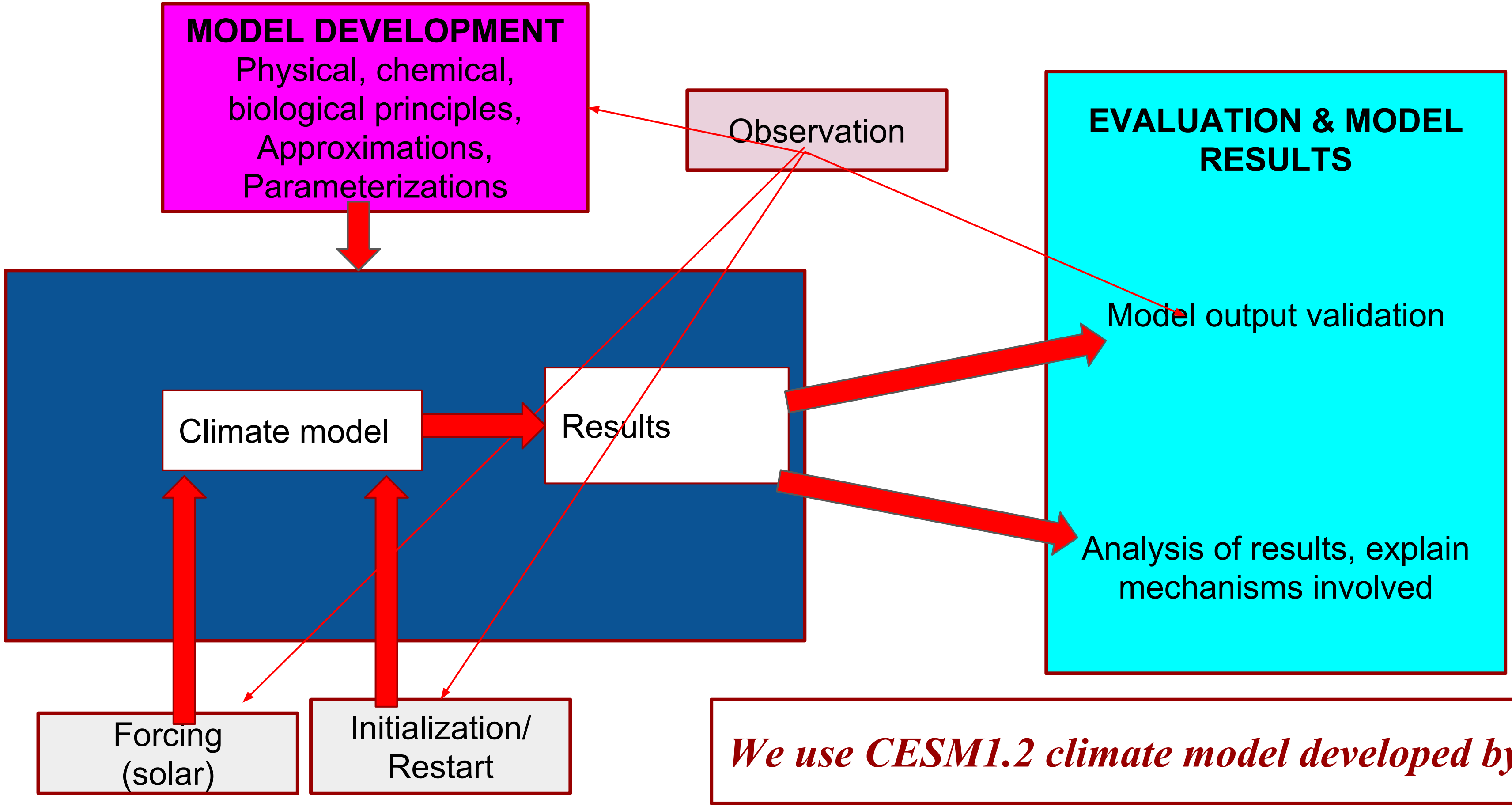
> When the FW influence is minimal (left panel), halocline, & thermocline resembled MLD.

> With the advent of FW (right panel), the thermocline remained largely unaffected but ***SSS reduced by >3 psu*** in top 10m altering the pycnocline. As a result a Barrier Layer (BL) is formed.

> In presence of BL mixing of surface waters with subsurface is inhibited.

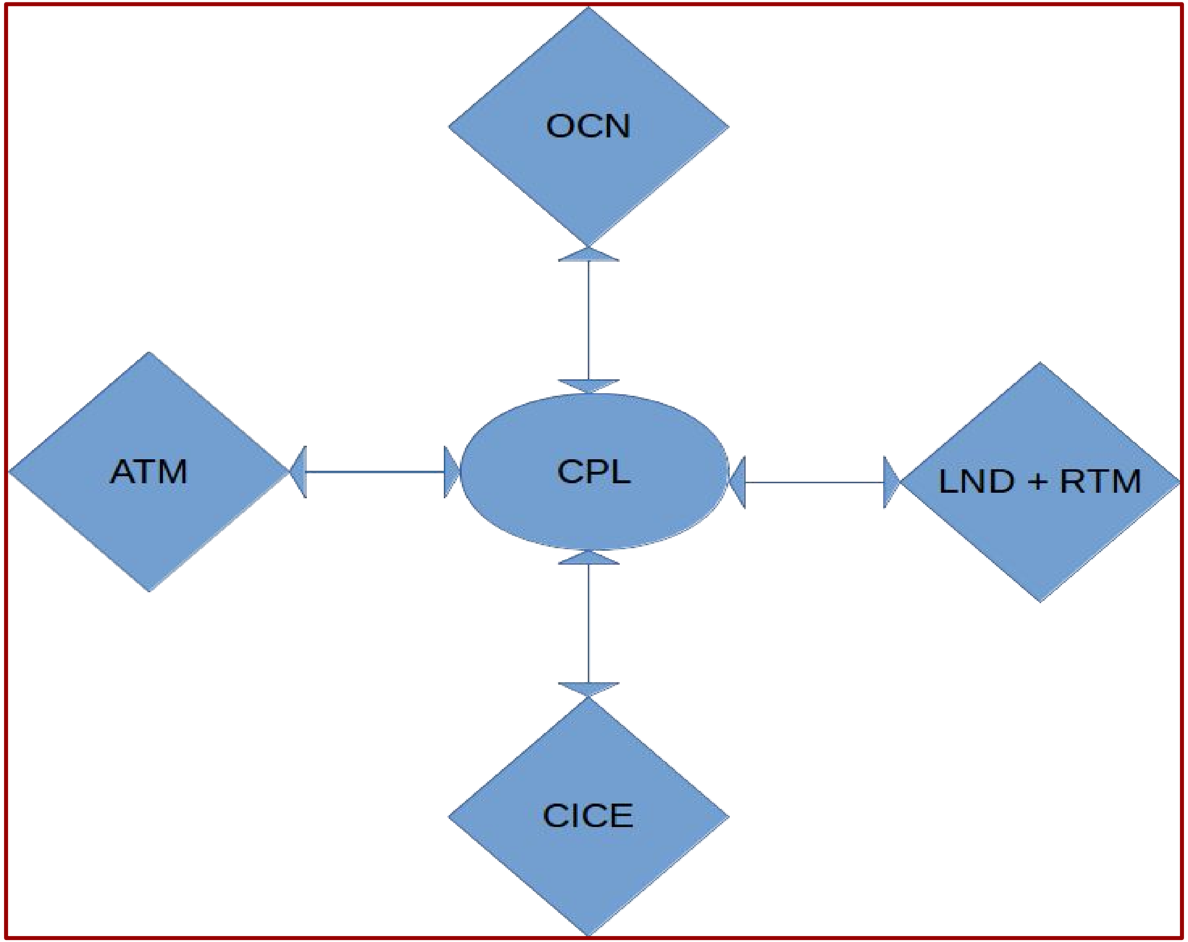
> Presence of low saline water creates a thinner Mixed layer, enhancing the air-sea interactions in the freshwater dominant regions like river mouths.

Climate model workflow



We use CESM1.2 climate model developed by NCAR

CESM1.2 model configuration: I



- ★ ***Figure: Schematic of geophysical components of CESM climate model***
- ★ Ocean (POP2), Atmosphere (CAM5), Land (CLM2), Sea-ice (CICE) and river model (RTM) interact via central coupler (CPL)
- ★ Components interact 48 times per day (½ an hour coupling frequency)

CESM1.2 model configuration: II

- Horizontal grid
  - ATM/LND: 0.9°x1.25° (192x288 lat/lon), FV dynamical core (dycore)
  - OCN/ICE: ~1° dipole grid (384x320)
- Vertical grid
  - ATM: 30 levels, hybrid coordinate
  - OCN: 60 levels, z-coordinate
- CAM5 physics in ATM
  - Full aerosol indirect effects within stratus
  - New shallow convection scheme that accurately simulates spatial distribution of shallow convective activity
  - Allows for aerosol-cumulus interactions
  - Revised cloud macrophysics scheme
  - Radiation scheme has been updated to the Rapid Radiative Transfer Method for GCMs (RRTMG)
- OCN has displaced dipole grid to avoid singularity at the poles.
- CN (Carbon-Nitrogen) cycle enabled in Land Model
- River runoff is computed in the River Transport Model (RTM)
- Overflows in the land is directed to the river route based on steepest slope and carried to Ocean
- Open source; more than 5 lakh lines of code mostly written in Fortran 90 standards

Major processes included in Earth System Model

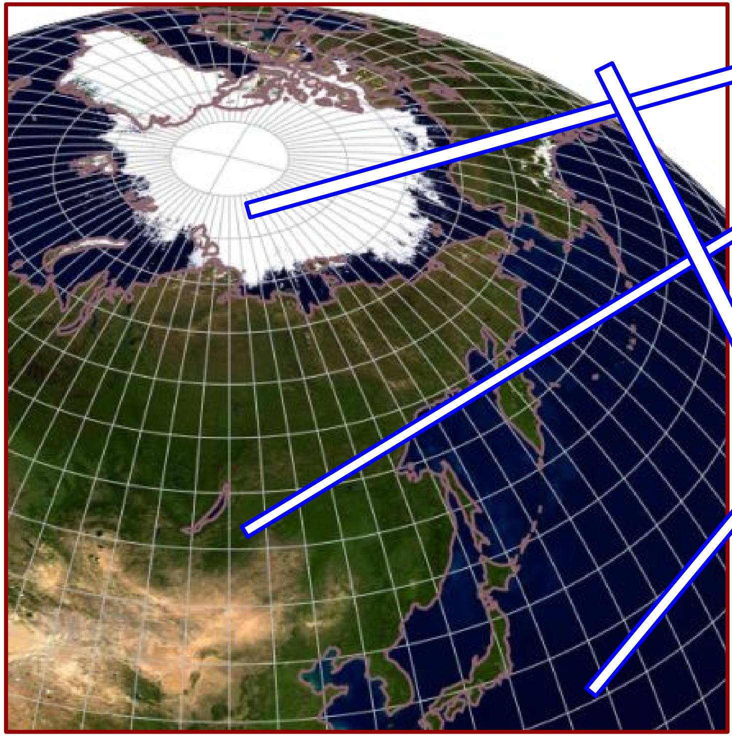


Fig: Image recreated from Earth Map using GDAL

CICE: Growth/decay of ice. Heat balance at surface. Transport. Interaction with atmosphere, ocean & land etc.

CLM: Evaporation, precipitation, evapotranspiration. Heat/moisture exchange b/w soil layers & atmosphere. Biogeochemistry. Carbon-Nitrogen cycle.

POP: Heat & moisture exchange with atmosphere, Surface & subsurface circulation, horizontal & vertical mixing & diffusion. Interaction with sea-ice, atmosphere & run off. Biogeochemistry is not included in our model.

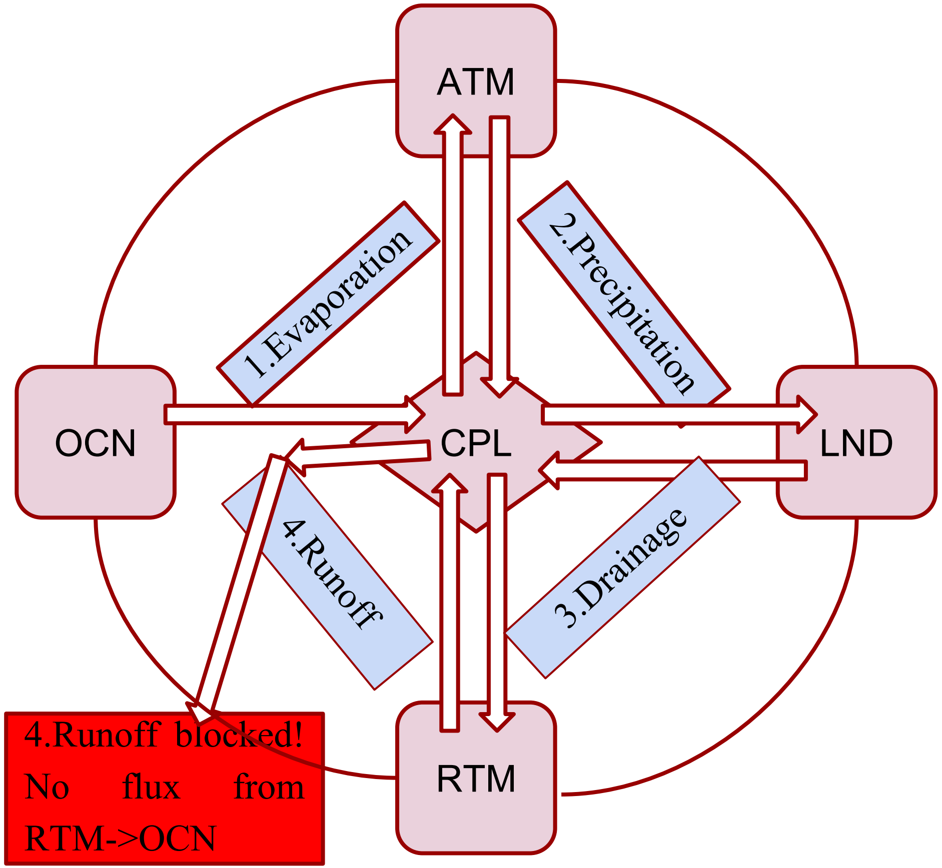
CAM: Radiative forcing. Cloud and convective processes. Aerosol interaction. Winds and circulation. Interaction with land, ocean, ice etc.

RTM: Surface/subsurface drainage, river routing, directing to ocean.

Experimental Details

- ★ Pre-industrial (1850 condition with fixed 287 ppmv CO2)
- ★ Control run (CR) is the reference run which simulate pre-industrial climate with the above mentioned configuration for a spin-up period of 600 years
- ★ CR validated with observation and sensitivity experiment (NoRiv) is branched from CR at 600th year
- ★ NoRiv is exactly similar to the CR except that global runoff into the ocean is blocked.
- ★ I.e., NoRiv ocean is devoid of river runoff. **The anomalies between NoRiv and CR is due to the impact of river runoff.**

Methodology



★ CPL do the grid interpolations for runoff from the RTM and transfer to the ocean

★ ***In NoRiv, river runoff flux from CPL->OCN ocean is intercepted globally***

★ *NoRiv is run for 200 years branched from CR.*

★ *CR run for the same period serve as the reference run and NoRiv, the sensitivity run.*

Modules & Compilers

- ★ Successfully run CESM1.2 CR and NoRiv simulations for a model period of 200 years on SahasraT CRAY XC40

- ★ Specific Modules used:
  - PrgEnv-intel/5.2.40
  - netcdf/4.3.0
  - cray-mpich/7.0.5
  - cray-parallel-netcdf/1.4.1
  - cray-hdf5/1.8.13
- ★ Compilers
  - Ifort
  - Icc
  - icpc

CESM load balancing

Runs	ATM pes	OCN pes	LND pes	CICE pes	RTM pes	CPL pes	TOTAL pes	Yrs/day
Case1	1080	1080	1080	1080	1080	1080	1080	9.2
Case2	720	1080	480	480	240	480	1080	11.2
Case3	720	1080	480	480	240	720	1080	12.5

- ★ ***Table: Processor layout distribution for various cases (1-3) to find optimum no: of processors for each components to even out execution times among component models***
- ★ Load balancing is needed since the computational intensity & grid resolution varies among component models. The most expensive component is determined from the timing file and is allocated with highest number of processors.
- ★ **Case3** performance improved (maximum throughput) with better distribution of processors
- ★ Threading option turned off, since it didn't improve the performance.

Comparison with Yellowstone

Machine	ATM pes	OCN pes	LND pes	CICE pes	CPL pes	Total pes	Years/day
SahasraT	720	1080	480	480	720	1080	12.5
Yellowstone	1200	600	420	780	1200	1200	10.60

- ★ ***Table:** Model performance comparison of Yellowstone and SahasraT for CESM1.2 (fully active = B1850C5CN compset, ~1º resolution = f09_g16 grid).*
- ★ Performance comparison of Cray XC40 SahasraT with NCAR's Yellowstone HPC cluster (from CESM1.2-timing-table provided by NCAR).
- ★ Yellowstone is NCAR's 1.5-petaflops high-performance IBM iDataPlex cluster, featuring 72,576 Intel Sandy Bridge processors and 144.6 TB of memory.
- ★ 16 pes/node in Yellowstone compared to 24 pes/node in SahasraT

Model Output Files

File types	ATM (GB)	OCN (GB)	CICE (GB)	LND (GB)	Files/yr	Size/yr (GB)	Size/run (200 yrs*size/yr)	Total (4 expts)
History	0.3	1.1	0.07	0.084	12	~19	3.8 TB	15.2 TB
Restart	1.3	0.6	0.15	0.48	1	~3	0.6 TB	2.4 TB

★ ***Table: Various output files generated and corresponding storage requirements***

★ Comprised of history (monthly) and restart (yearly) files

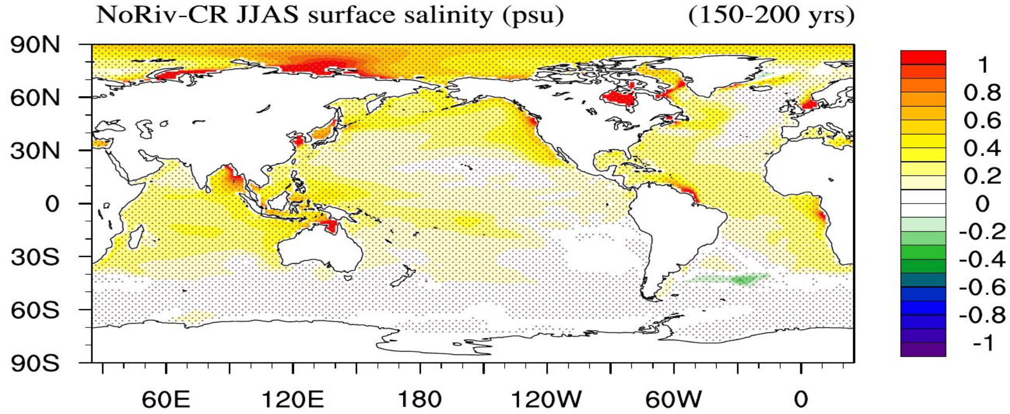
★ 3 out of 4 runs of 200 year simulations are finished

★ Total size of output files (4 runs) = 17.6 TB (Table)

★ Transferring of these huge files from SahasraT to local machine via "**rsync**" facility**.**

★ Data transfer at an average rate of 10MB/s. More than a week to transfer.

Results: Oceanic Response



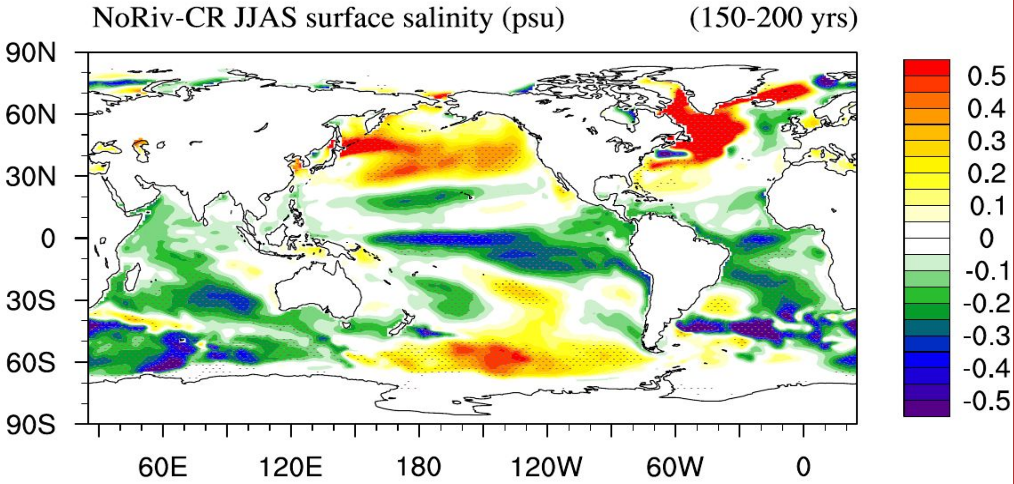


Fig: NoRiv-CR JJAS ocean surface salinity (top) and temperature (bottom)

- ★ Direct effect of runoff is on surface salinity
- ★ Northern hemispheric ocean are most sensitive (runoff to N.H. > S.H.)
- ★ Ocean surface temperature response is complex. Though no local runoff, cooling in the central Pacific is noteworthy.
- ★ Central Pacific cooling effect El Nino Southern Oscillation (ENSO) and therefore can have global impact.

Results: Atmospheric response

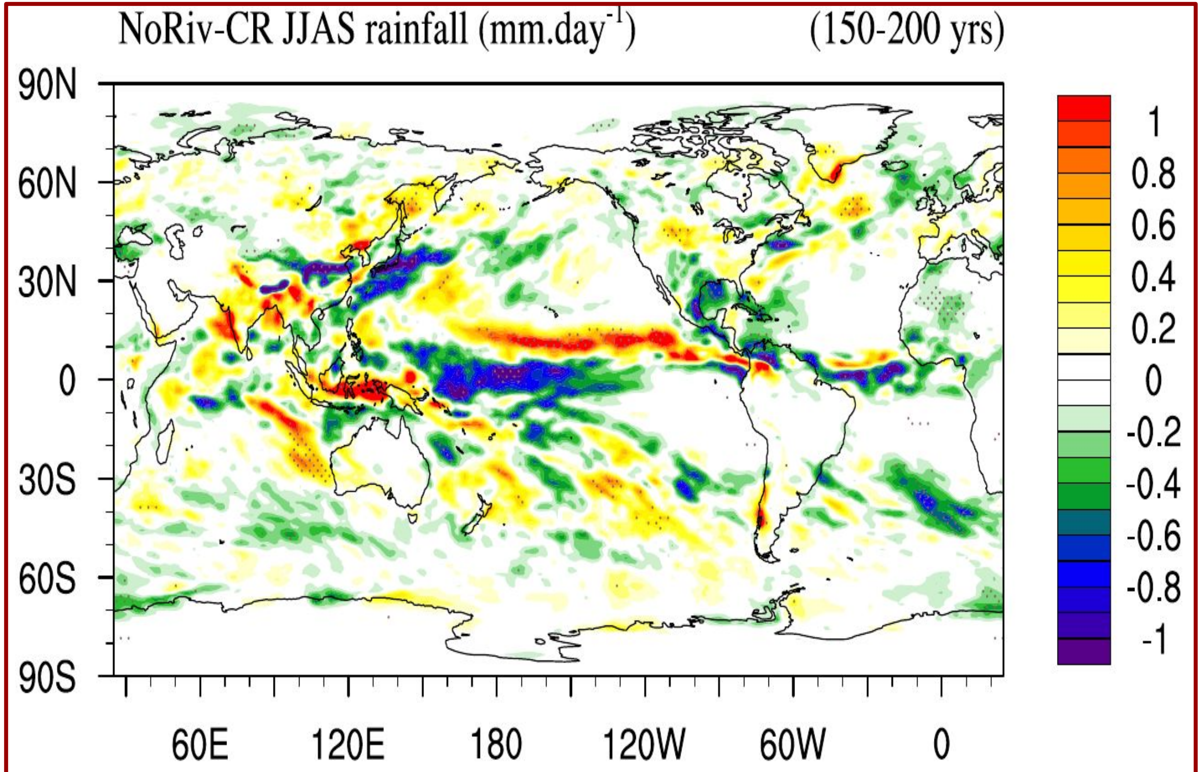


Fig: NoRiv-CR mean JJAS rainfall for 150-200 years.

- ★ Rainfall response to runoff perturbation is complex
- ★ SST anomalies trigger atmospheric anomalies via pressure variations & winds
- ★ Increase in Indian Summer Monsoon Rainfall (ISMR)
- ★ **Mechanism linking ISMR and runoff?**

Mechanism

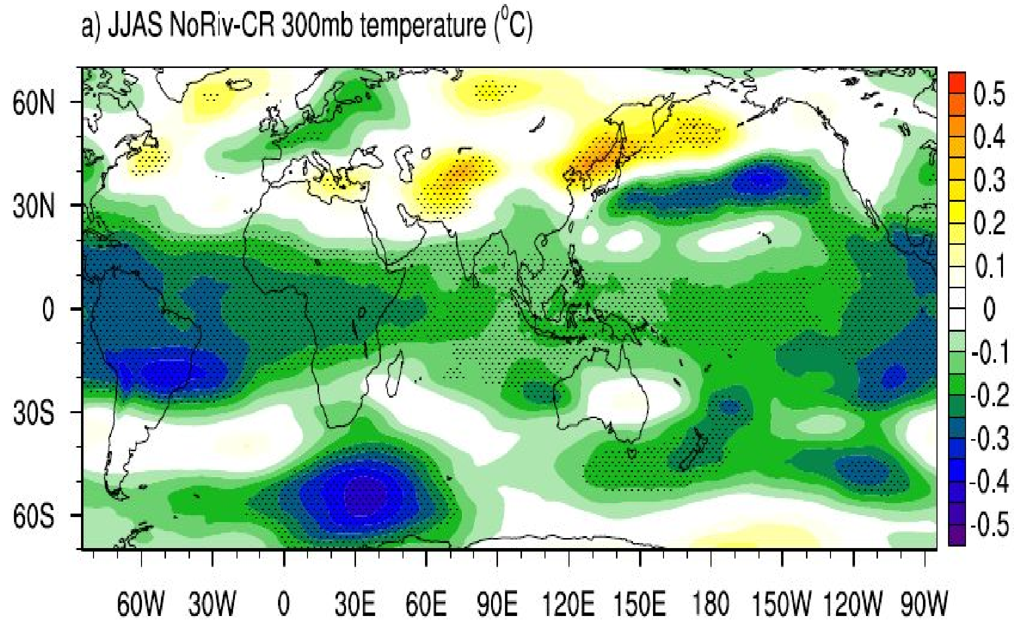


Fig: NoRiv-CR 300mb a) Temperature. Gradient b/w Asian landmass & Equatorial Indian Ocean increased.

★ Cooler equatorial Pacific favors strengthening of meridional temperature gradients between Asian landmass and eq. Indian Ocean.

★ This strong gradient increases intraseasonal activity over the Indian region which leads to a stronger summer monsoon (Jiang 2004)

Mechanism ….

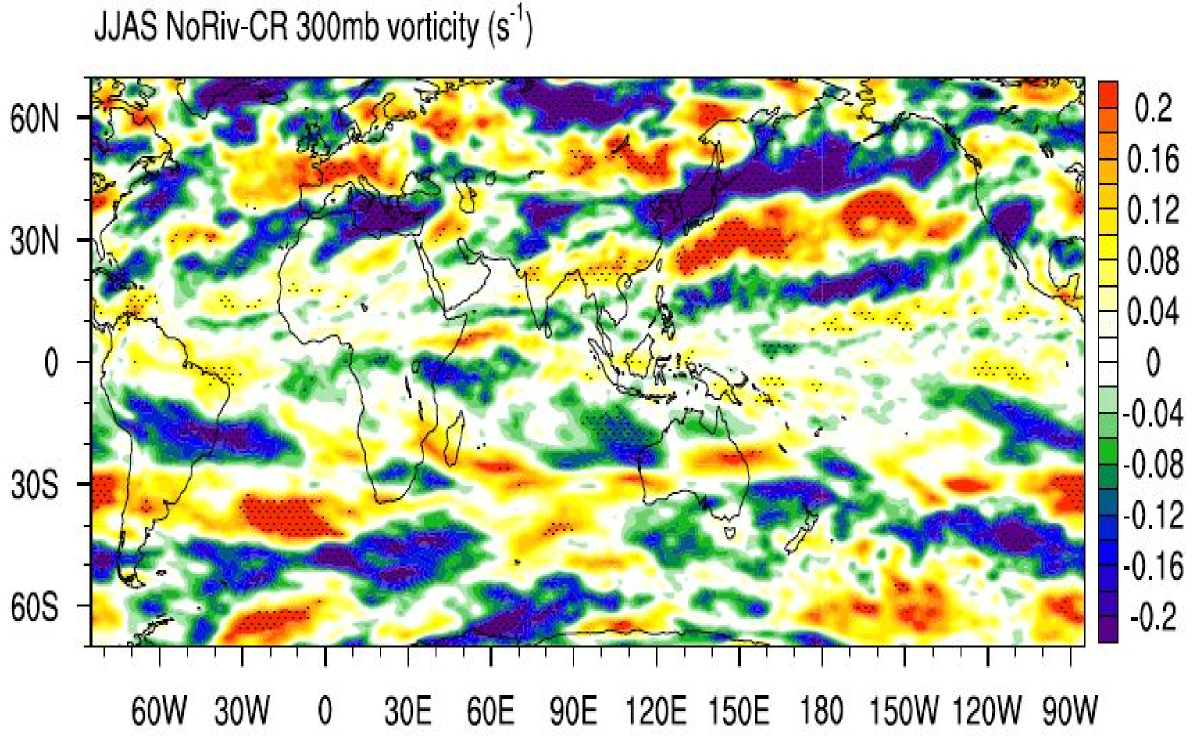
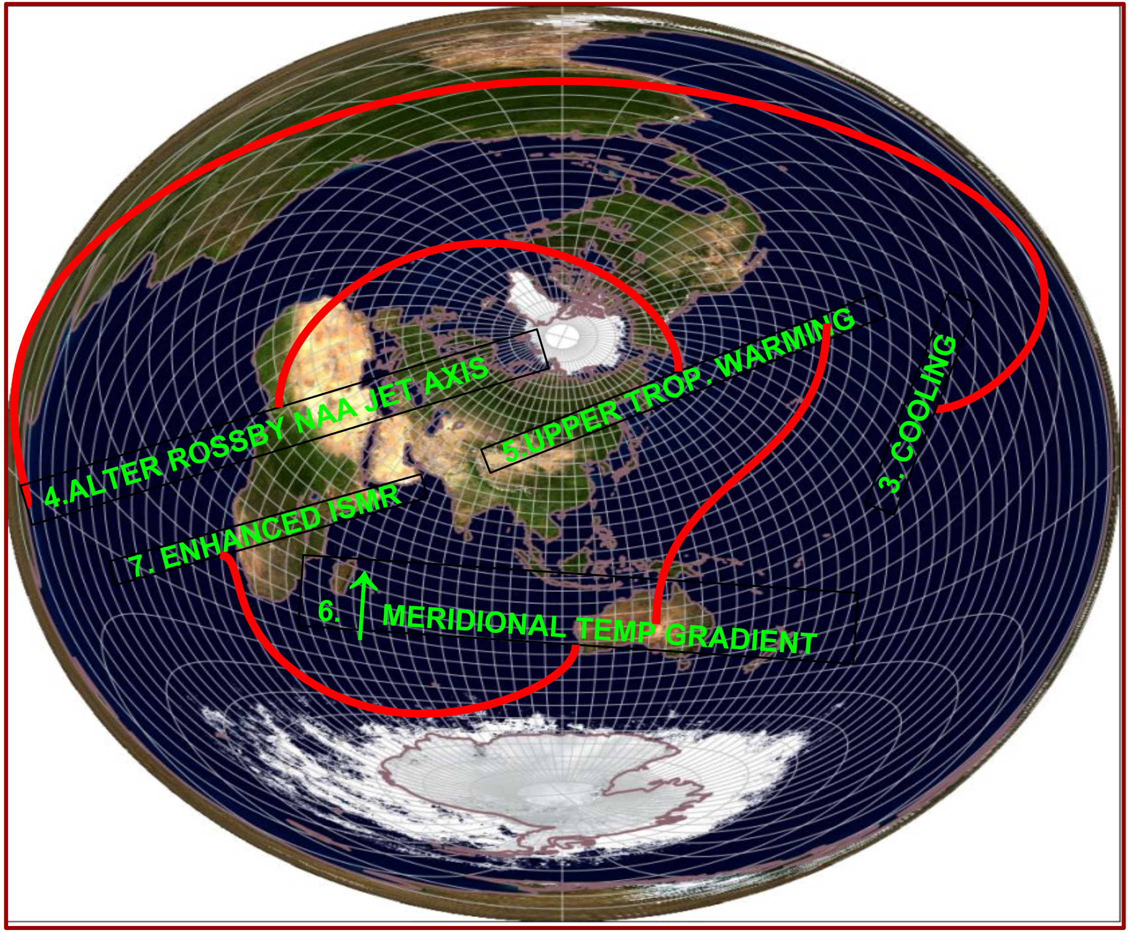


Fig: NoRiv-CR 300mb JJAS vorticity. NAA strength strengthened.

- ★ Negative convective anomalies during La Nina leading to convergence and westward propagating vorticity anomalies along the North African–Asian jet (Shaman 2007).

- ★ Negative vorticity anomalies lead to warm temperature anomalies in the upper troposphere over the Asian land mass.

Results Summary



1.Lack of runoff => SSS increase

2.SST changes due to changes in air-sea interaction.

3.Cooling in Pacific due to stronger trades & upwelling

4.Alters Rossby wave propagation in the NAA Jet axis

5.Warming in upper troposphere over Asian land mass.

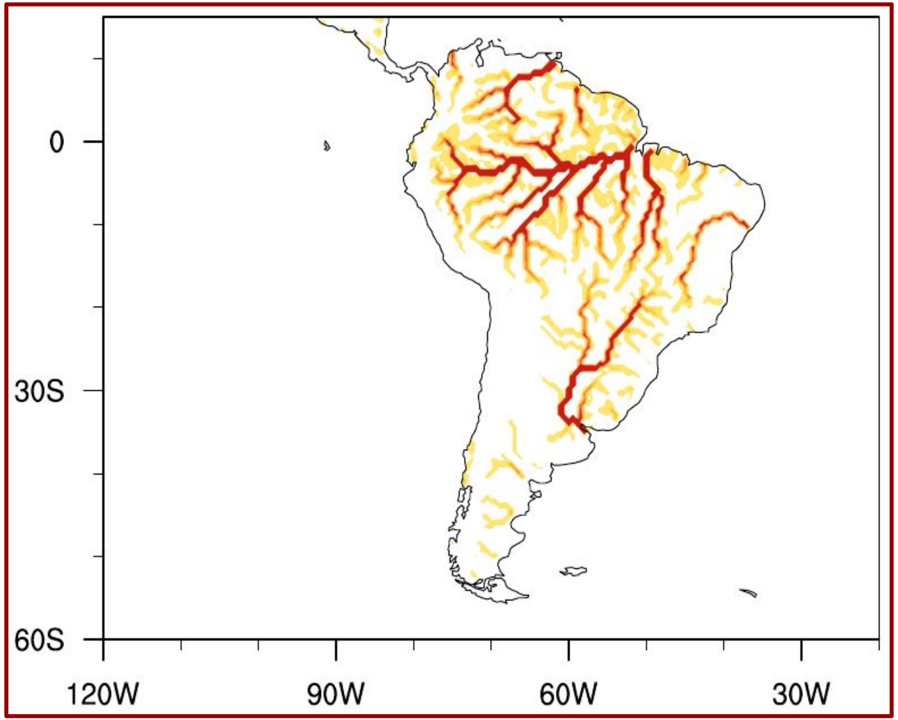
6.Strengthening of upper trop. meridional temp gradient.

7.Strengthening of ISMR

Discussion

- ★ Larger response in the northern hemispheric ocean due to asymmetry in runoff (larger runoff in NH).
- ★ Cooling the equatorial Atlantic and Pacific ocean shifts the maximum rainfall band to further north of equator
- ★ Without global freshwater flux into the ocean, equatorial Pacific exhibits a La nina-like climate.
- ★ Indian Summer Monsoon increased due to strengthening of upper tropospheric meridional temperature gradient.
- ★ Impact of individual rivers and river system need to be studied to distinguish local and remote impacts.
- ★ Amazon runoff experiment is in progress. Preliminary results are shown in next few slides.

Amazon Runoff Experiment



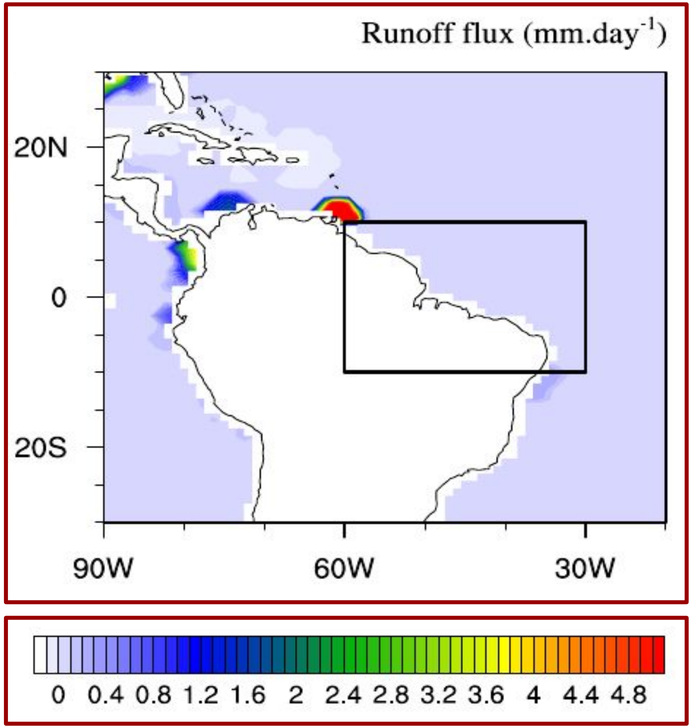


Fig: a) Amazon river network in CESM RTM model. & b) Map of river runoff in Amazon (AMZ) experiment. Box encloses the area over which river runoff into the ocean is intercepted.

Preliminary results: Oceanic Response to Amazon runoff

- ★ Change in salinity in the Atlantic.
- ★ Highly turbulent surface waters and the presence of western boundary currents could play a significant role in modulating the salinity anomalies in Atlantic.
- ★ Changes in Indian Ocean salinity
- ★ Changes in the Pacific SST due to interception of Amazon runoff!
- ★ Mechanisms responsible for these changes are yet to be investigated.
- ★ So far, 150 years of AMZ experiment is over. 50 more to go.

Future work

- ★ In the future work we would like to address the climatic role of Bay of Bengal river runoff
  - ○ How does major rivers like Ganga-Brahmaputra, Mahanadi, Godavari etc. control the upper ocean vertical structure.
  - ○ How does the runoff into Bay modulate the air-sea interactions?
  - ○ Does it have any control over the Monsoon rainfall over India?
  - ○ If Bay rivers can alter the monsoon rainfall, What will be the impact of over-exploitation of river water (by construction of Dams and inland diversion of rivers) on rainfall?

Acknowledgements:

- ★ Sincere thanks to SERC for making available this computational facility, without which the present experiments would be impossible.

- ★ Assistance from Dr J Lakshmi , Mr. Vinod, Mr. Anoop in setting up the CESM1.2 model and sorting out build-time issues.

- ★ Dell visualisation servers helped a great deal in post processing, visualisation and model validation. Thanks Mr. Vinod for installing climate data visualisation packages.
- ★ Work Partially supported by INCOIS-MoES under HOOFS programme

References

- ★ Trenberth K E, Smith L, Qian T, Dai A and Fasullo J 2007 Estimates of the global water budget and its annual cycle using observational and model data J. Hydrometeorol. 8758–69.
- ★ Roden, G. I., 1967: On river discharge into the Northeastern Pacific Ocean and the Bering Sea. Journal of Geophysical Research, 72(22), 5613–5629.
- ★ Kourafalou, V. H., L. Y. Oey, J. D. Wang, and T. N. Lee, 1996: The fate of river discharge on the continental shelf 1: Modeling the river plume and the inner shelf coastal current. Geophysical Research Letters, 101, 3415–3434.
- ★ Fedorov, A., M. Barreiro, G. Boccaletti, R. Pacanowski, and S. G. Philander, 2007: The freshening of surface waters in high latitudes: Effects on the thermohaline and wind-driven circulations. Journal of Physical Oceanography, 37, 896–907, doi: 10.1175/JPO3033.1.
- ★ Montegut, C., J. Mignot, A. Lazar, and S. Cravatte, 2007: Control of salinity on the mixed layer depth in the world ocean: 1. General description. Journal of Geophysical Research, 112, C06 011, doi:10.1029/2006JC003953.
- ★ Vinayachandran, P. N., Jahfer, S. And Nanjundiah, R.S. (2015).Impact of river runoff into the ocean on Indian summer monsoon, Environ. Res. Lett. 10, doi:10.1088/1748-9326/10/5/054008.
- ★ Jiang X, Li T and Wang B 2004 Structures and mechanisms of the northward propagating boreal summer intraseasonal oscillation J. Clim. 17 1022–39
- ★ Shaman J and Tziperman E 2007 Summertime ENSO-North African-Asian Jet teleconnection and implications for the Indian monsoons Geophysical Research Letters 34 L11702
- ★ Milliman, J. D. and K. L. Farnsworth, 2011: River discharge to the coastal ocean: A global synthesis. Cambridge university press, Cambridge, United Kingdom, first edition.
- ★ Vinayachandran, P. N., V. S. N. Murty, and V. Ramesh Babu, Observations of barrier layer formation in the Bay of Bengal during summer monsoon, J. Geophys. Res., 107(C12), 8018, doi:10.1029/2001JC000831, 2002.

THANK YOU