FINAL PROJECT REPORT RCN CONTRACT NO. 216554

INDIA-CLIM: Decadal to multi-decadal variability in the Indian Monsoon Rainfall and teleconnection with Atlantic Multidecadal Oscillation

- a joint study of observed and modelled variations in climate in India.

in response to INDNOR/NORKLIMA call "***Climate change – research collaboration with India***"

Project Leader;
Prof. Ola M. Johannessen, *Nansen Environmental and Remote Sensing Center (NERSC), Bergen, Norway*
Project manager:
Research leader Lasse Pettersson, *NERSC, Bergen, Norway*
Co-Principal Investigators;
Prof. P.V. Joseph, *Cochin University of Science and Technology (CUSAT), Kochi, India* and *Nansen Environmental Research Centre-India (NERCI), Kochi, India* and
Prof. Dr. Yongqi Gao, *NERSC, Norway*
Investigators;
PhD candidate Lea Svendsen, *NERSC, Norway*
Dr. K. Ajith Joseph, Dr. Syam Sankar, Dr. G. Bindu, Dr. B. Abish, Dr. K. Shadananan Nair, Ph.D students Archana Nair and S. Wilson, *NERCI, Kochi, India*
Prof. A.N. Balchand, *CUSAT, Cochin, India*
Dr. R. Vidhya, *Institute of Remote Sensing, Anna University, Chennai, India*

1 Background and Objectives

Much of the earth's population, including the Indian subcontinent, lives in regions with climate dominated by Asian monsoons. Here seasonally reversing circulations characterized by alternating wet and dry seasons has large impact on the availability of water resources and hydrological system. The basic economic livelihood of those regions influenced by monsoons often depends on the amount of available rainfall during the wet-season.

In the IndiaClim project we have analysed comprehensive data sets of climate variables in India including the Indian Ocean as well as output from available IPCC/CMIP5 coupled climate model and available newly-developed Earth System model simulations used in the IPCC AR5 in order to investigate the variability of the Indian Monsoon with special focus on the wet season of the Indian Summer Monsoon (ISM). The project has focused on decadal and multi-decadal scales and has explored the climate teleconnection between the Indian Monsoon system and the Atlantic Multidecadal Oscillation (AMO).

The overall objective: To explore decadal to multi-decadal variations in Indian Monsoon in the last 600 years and to identify the remote causes from Atlantic Multi-decadal Oscillation on variations in temperature and precipitation patterns affecting water availability in India in order to contribute to better prediction of Indian Monsoon Rainfall.

Specific objectives:

- To analyse, correlate and synthesis available long-time series of reconstructed and historical data over last 600 years and instrumental climate parameters for India (Asian Monsoon Drought Index, AMDI) and the Atlantic Ocean Multidecadal Oscillation (AMO or AMV).
- To validate model output from the available IPCC/CMIP5 including the new Earth System Model simulations (including BCM and NorESM) against reconstructed, historical, instrumental and re-analysis data in order to select a few realistic models out of more than 40 available models for further analysis

- To analyze the selected multi-model ensembles output simulations in order to identify decadal to multi-decadal variations and identify and understand potential teleconnection mechanism between AMO and AMDI in order to contribute to better prediction of IMR.
- To foster and strengthen the partnership in climate research between Norway and India.

2 Implementation and Results

Climate data records and proxy data analysis

IndiaClim have studies the decadal to multi-decadal variability and change in Indian Summer Monsoon from the observed and historical data records.

Proxy data records have been analyzed in order to assess the multi-decadal variability over centuries, allowing analysis beyond the time period of instrumental measurements, which started in 1844. Svendsen et al (2014) have extend the record of Atlantic multi-decadal variability (AMV) 90 years past the instrumental record using principle component analysis of five marine-based proxy records to identify the leading mode of variability. The first principal component is consistent with the observed AMV, and multi-decadal variability seems to persist prior to the instrumental record. Thus, we demonstrate that reconstructions of past Atlantic low-frequency variability can be improved by combining marine-based proxies.

Sankar et al (submitted to Tellus, 2016) are studying several proxy data records for both Indian and Atlantic oceans for a period from 1481 to present in order to investigate multi-decadal variability in the ISMR, AMV and the teleconnection between them prior to the instrumental period. They conclude that multi-decadal variability in the ISMR is persistent, but the link between ISMR and AMV is not persistent. The correlation between the two regions is weak and even negative during some periods. However, the correlation is significant during the instrumental data records period from 1844 (≈ 0.43), but has weakened during the last decade, suggesting that the AMV-ISMR link is not steady.

Joseph et al (submitted to Current Science, 2016) have studied the impact of the upper tropospheric cooling trend over central Asia on the Indian summer monsoon rainfall and tracks of cyclones in the Bay of Bengal. The Indian summer monsoon rainfall had alternating three decade long DRY and WET epochs during the 150 years from 1840 to 1989. The DRY epochs had frequent drought monsoons affecting agriculture, power generation and the overall Indian economy. A high percentage of severe cyclones of the Bay of Bengal moved northwards in the DRY epochs causing disasters in Bangladesh, Myanmar and in Indian states of Orissa and West Bengal. These DRY epochs have been shown to be associated with the cold phase of the Atlantic Multi-decadal Oscillation in sea surface temperature. Using the available tropospheric temperature (re-analysis) data since 1948, the recent DRY epoch 1960-89, which included ten monsoon drought years, it was found to have cold upper tropospheric temperature anomaly over central Asia. This cold anomaly region has also experienced a long term cooling trend.

Modeled climate variability

Luo et al (to be submitted to GRL, 2016) have studied the relationship between the Atlantic Multi-decadal Variability (AMV) and the Indian Summer Monsoon (ISM) using instrumental records, and five models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) that reasonably simulate both the AMV and the ISM, for the period 1870 to 2005. The significant relation in observational data is not reproduced by any of the models in the in Pre-industrial control simulations with fixed external forcing, but is reproduced by one model (GFDL-CM3) in historical simulations with all external forcing. Regression analyses reveal that external forcing is linked to a mid-to-upper tropospheric temperature pattern with a strengthened land-ocean thermal gradient in Southern Asia consistent with an enhanced ISM. External forcing also leads to a concurrent evolution of AMV. Thus, the significant relationship found in observations after the onset of the industrial revolution may be associated with the external forcing, instead of resulting from internal climate dynamics. Since the teleconnection between the ISME and the AMV is not steady we have also investigated other teleconnection pattern, namely between ISMR and NAO/AO.

Cui et al. (2014) used reconstructed data and multi-centennial model integrations performed with the Bergen Climate Model to further investigate the impact of natural external forcing factors on the Indian summer monsoon (ISM) rainfall, the winter North Atlantic Oscillation (NAO), and the potential relationship between the ISM rainfall and the winter NAO on decadal to inter-decadal timescales. The model simulations include a 600-year control integration (CTL600) and a 600-year integration with time-varied natural external forcing factors from 1400 to 1999 (EXT600). Both reconstructed data and the model simulation showed increased ISM rainfall 2–3 years after strong volcanic eruptions. Strong volcanic eruptions decrease the sea surface temperature (SST) in the Indian Ocean, which increases the strength of the southwesterly winds over the Arabian Sea. With negative externally-forced radiative anomaly, the lower stratospheric pole-to-equator winter temperature gradient is enhanced, leading to a positive winter NAO anomaly with a time lag of one year. There is no significant correlation between the winter NAO and ISM rainfall in CTL600. However, the ISM rainfall is significantly positively correlated with the winter NAO in EXT600 simulations, with the NAO leading by 2–4 years, which is consistent with the NAO–ISM rainfall relationship in the reconstructed data. We suggest that natural external forcing factors regulate the inter-decadal variability of both the winter NAO and the ISM rainfall and thus likely lead to an increased statistical, but not causal relationship between them on the inter-decadal timescale over the past centuries.

Scientifically related to studies of the Indian Ocean monsoon (but not targeting the main scope of IndiaClim) and with contributions from scientists in IndiaClim, Gong et al (2013) have analyzed the interannual relationship between the Arctic Oscillation (AO)/North Atlantic Oscillation (NAO) and the tropical Indian Ocean (TIO) precipitation in boreal winter for the period 1979–2009. A significant simultaneous teleconnection between them is found. After removing the El Ninõ/ Southern Oscillation and Indian Ocean dipole signals, the AO/NAO and the TIO precipitation (0°–10°S, 60°–80°E) yield a correlation of +0.56, which is also consistent with the AO/NAO-outgoing longwave radiation correlation of -0.61. The atmospheric and oceanic features in association with the AO/NAO-precipitation links are investigated. During positive AO/NAO winter, the Rossby wave guided by westerlies tends to trigger persistent positive geopotential heights in upper troposphere over about 20°–30°N and 55°–70°E, which is accompanied by a stronger Middle East jet stream. Meanwhile, there are anomalous downward air motions, strengthening the air pressure in mid-lower troposphere. The enhanced Arabian High brings anomalous northern winds over the northern Indian Ocean. As a result the anomalous crossing-equator airflow enhances the intertropical convergence zone (ITCZ). On the other hand, the anomalous Ekman transport convergence by the wind stress curl over the central TIO deepens the thermocline. Both the enhanced ITCZ and the anomalous upper ocean heat content favor in situ precipitation in the central TIO. The AO/NAO-TIO precipitation co-variations in the IPCC AR4 historical climate simulation (1850–1999) of Bergen Climate Model (v2) were investigated. The Indian Ocean precipitation anomalies (particularly the convective precipitation along the ITCZ), in conjunction with the corresponding surface winds and 200 hPa anticyclonic atmospheric circulation and upper ocean heat contents were well reproduced in simulation. The similarity between the observation and simulation support the physical robustness of the AO/NAO-TIO precipitation links.

The research cooperation within IndiaClim project have been triggered further Indo-Norwegian and Indo-European cooperation, through the FP7 INCOLAB IndoMareClim project and through Nansen Fellowship stipend for an Indian doctoral candidate funded by the Nansen Scientific Society. This cooperation has addressed other aspects of the Indian Ocean monsoon variability, complementary to the scientific objectives of IndiaClim.

Two publications by Abish et al (2013 and 2015) addressed the tropical and sub-tropical jet steam variability during the resent 60 years. Abish et al (submitted to Climate Dynamics, 2016[1]) have investigated the Indian Ocean (IO) warming and its relation with El Niño Southern Oscillation (ENSO) using available ocean and atmospheric reanalysis datasets. By comparing the events before and after 1976, the results indicate that the IO had experienced a distinct change in the warming pattern since 1976.

The interannual variability of the Variability of Summer Monsoon Rainfall in India has been analyzed Joseph et al (2013). A season of deficient June to September monsoon rainfall in India is followed by warm sea surface temperature (SST) anomalies over the tropical Indian Ocean and cold SST anomalies over the western Pacific Ocean. These anomalies persist until the following monsoon, which yields normal or excessive rainfall. Monsoon rainfall in India has shown decadal variability in the form of 30 year epochs of alternately occurring frequent and infrequent drought monsoons since 1841, when rainfall measurements began in India.

Nansen Fellowship candidate Wilson et al (submitted to Climate Dynamics, 2016) have analyzed the intra-seasonal, inter-annual and decadal scale variability of the Low Level Jetstream (LLJ) using 850 hPa wind data for monsoon seasons June to September of the years 1950 to 2010. Some of the main findings are: (a) During drought monsoons the westerly winds of LLJ extend eastwards to longitude 180˚E and positive deep convection anomaly develops in west Pacific Ocean. (b) The westerly wind anomaly and the positive convection anomaly over west Pacific Ocean have persistence from the previous winter season. (c) The positive wind and convection anomalies of the monsoon season are generated during the weak / break monsoon phase on the intra-seasonal time scale. (d) On the inter-annual and decadal time scales, the linear correlation coefficients among many of the LLJ parameters and between these parameters and ISMR / El Nino index are large and statistically significant.

Synthesis and assessment

The main hypothesis for the IndiaClim project is that the AMO is an intrinsic oceanic mode and that the associated SST anomalies in Atlantic Ocean can impact the Indian Summer Monsoon through teleconnection.

However, the data studies in IndiaClim have shown that there is a non-steady teleconnection between the variability observed in the Atlantic Ocean and the Indian Ocean Summer Monsoon. The correlation is significant during the period of observational data (≈0.43) and is less pronounced and even lacking during the period of analysis of proxy data. According to Syam et al (submitted to Tellus, 2016) the instrumental records of both ISMR and North Atlantic SSTs have multidecadal variability with a period close to 60 years, where periods of warm (cold) North Atlantic SSTs are accompanied by periods of wetter (dryer) ISMR and lower (higher) frequencies of drought years. We find that multidecadal variability in the ISMR is persistent, but the link between ISMR and AMV is not that pronounced. The correlation between the two regions is weak and even negative in some periods. The observed correlation between AMV and ISMR has also weakened in the last decade, further suggesting that the AMV-ISMR link is not steady. However, ISM rainfall is significantly positively correlated with the winter NAO model simulations, with the NAO leading by 2–4 years. This is consistent with the NAO–ISM rainfall relationship in the reconstructed data. However, the natural external forcing factors regulating the inter-decadal variability of both the winter NAO and the ISM rainfall likely lead to an increased statistical relationship. It has not been possible to identify a causal relationship between NAO and the ISM rainfall on the inter-decadal timescale over the past centuries.

[1] Abish, B., Cherchi, A., Ratna, S.B., Masina, S (submitted, 2016): ENSO and the basin wide warming of the Indian Ocean. Submitted to Climate Dynamics January 2016. (related to IndiaClim and monsoon research, but not funded by the project).

The Indian summer monsoon rainfall had alternating three decade long DRY and WET epochs during the 150 years from 1840 to 1989. The DRY epochs had frequent drought monsoons affecting agriculture, power generation and the overall Indian economy. A high percentage of severe cyclones of the Bay of Bengal moved northwards in the DRY epochs causing disasters in Bangladesh, Myanmar and in Indian states of Orissa and West Bengal. These DRY epochs have been shown to be associated with the cold phase of the Atlantic Multi-decadal Oscillation in Sea Surface Temperature.

The Indian Ocean precipitation anomalies, the corresponding surface winds and 200 hPa anticyclonic atmospheric circulation, as well as upper ocean heat contents, was well reproduced in the Bergen Climate Model simulations. The similarity between the observation and simulations support the physical robustness of the AO/NAO-TIO precipitation relationship.

The significant relation between observational data is not reproduced by any of the CMIP5 models during the in pre-industrial control simulations with fixed external forcing, but is reproduced by one model (the US NOAA GFDL-CM3) in historical simulations with all external forcing. A significant relationship however found in observations after the onset of the industrial revolution may be associated with the external forcing, instead of resulting from internal climate variability, which partly supports the hypothesis of the IndiaClim project.

Societal benefits and Relevance

The ability to improve the understanding and predictability of the Indian Monsoon system is of great importance to over a billion people living in the region. Frequent occurrence of droughts in the seasonal monsoon rainfall in epochs of duration of about 30 years had adverse impact on agriculture, power generation and the overall Indian economy (Joseph et al, 2013). In 1998–1999 the monsoon rains caused the water level to increase by more than 4 meter in some places, and 20,000 hectares of land flooded. A million people lost their homes, and 300 died in India alone. Research leading to improved understanding of the monsoon variability is accordingly critical for the livelihood of the Indian population.

IndiaClim has also strengthened the bilateral Indo-Norwegian cooperation in climate research as well as higher university (PhD) education. One Norwegian PhD candidate, Mrs. Lea Svendsen, NERSC/Geophysical Institute, University of Bergen has been fully funded by the Indo-MareClim project and she is due for dissertation in June 2016. Her PhD dissertation comprises two published papers and two manuscripts under preparation and due for submission in 2016. During her PhD studies she has extensively cooperated with Indian scientists and students, including several longer research stays at NERCI in India (Funded by the EU FP7 INDO-MARECLIM project – GA295092). In addition, one Indian PhD candidate - Mrs. Shinu Wilson - at NERCI and Cochin University of Science and Technology (CUSAT), is currently being funded for 3 years by the Nansen Scientific Society working on climate variability of the Indian monsoon. These two doctoral candidates as well as other scientists involved in IndiaClima have worked together on publications through extensive research exchange visits both to Norway and India.

Dissemination

The INDNOR/NORKLIMA IndiaClim project has capitalized on the cooperation with the European FP7 **INDO-European Research Facilities for Studies on MARine Ecosystem and CLIMate in India (INDO-MARECLIM)** – an EU FP7 Inco-Lab project fostering Indo-European research cooperation within climate and marine research. Particularly the INDO-MARECLIM activities focusing on *Monsoon and ocean variability, climate change and sea level variations* (Indo-MareClim WP3.1) are scientifically complementary to the Norwegian NORKLIMA IndiaClim project activities. In this respect the scientific results and exposure to students and future scientific recruitment have capitalized from joint hosting of a workshop and a summer school i.e.:

- **India-EU Workshop on Monsoon and Ocean variability, climate change and sea level variations** - November 11-13, 2013 at Cochin: Participation 69 scientists, including some PhD students.
- **INDO-MARECLIM Winter School On Climate Change And Variability, Marine Ecosystems And Coastal Zone Management** - November 2^{nd} -7^{th}, 2013 in Cochin. Participation 70 scientists and students.

An extensive network towards young and established Indian scientists and research institutions have been developed and will be utilized for maintaining a bilateral and European cooperation with India in climate and environmental research and higher education. The research results have been share with the several institutes under the Ministry of Earth Sciences, Government of India, in order to found a basis for future cooperation, including scientific recruitment and hosting of research schools. Direct cooperation is established with Indian Institute of Tropical Meteorology (IITM) in Pune and National Oceanographic Institute (NIO) in Goa. The partnership and research cooperation with and between the three Indian partners in IndiaClim have been strengthened including expansion of one Indian PhD. candidate due for dissertation in 2016. The European Indian Research cooperation has also been strengthened through the cooperation with the Italian climate research institute *Centro Euromediterraneo per i Cambiamenti Climatici (CMCC)*, Italy, both through joint publications and scientific exchange visits.

Nine scientific papers have been published under the IndiaClim project. Lea Svendsen has submitted her doctoral thesis *Impacts of Atlantic multi-decadal variability on the Indo-Pacific and Northern Hemisphere* climate to Geophysical Institute, University of Bergen for evaluation. The dissertation is scheduled for June 3. 2016. The results have been communicated at several (30) scientific conferences, as well as contributions to the World Climate Research regional program through meetings under CORDEX program for southern-Asia. In addition three journal papers are under final preparation and will be submitted in 2016.

Popular summary

In order to understand the observed relation between the Atlantic multi-decadal Oscillation/Variability (AMO/AMV) and multi-decadal variability in the Indian summer monsoon (ISM) rainfall, we have analyzed observational data (Abish et al, 2013, 2015, Joseph et al, 2013) proxy reconstructions (Svendsen et al, 2014 and Sankar, submitted to Tellus, 2016) and several coupled model simulations (Cui et al, 2014, Gong et al, 2014, Svendsen et al, 2013 and Luo et al, in prep. to GRL).

To assess the persistency of this relation a new multi-proxy reconstruction of the AMV was made (Svendsen et al. 2014). The short observational data do not significantly resolve multidecadal variability, and the existing AMV proxy reconstructions are all heavily based on land records, such as tree rings. Since AMV is an ocean signal, we have extended the AMV record past the instrumental record with five marine-based proxy records using principle component analysis to identify the leading mode of variability. We find that multidecadal variability in the Atlantic seems to persist prior to the instrumental record.

This marine-based AMV reconstruction together with previously published AMV reconstructions, were then compared with several ISM proxy reconstructions (Sankar et al., submitted to Tellus, 2016). We find that multidecadal variability in the ISM is persistent as in Atlantic SSTs, but the link between ISM and AMV is not. The correlation between the two regions is weak and even negative in some periods. The observed correlation between AMV and the ISM has also weakened in the last decade, further suggesting that the AMV-ISM link is not steady. However there are not many reconstructions for the ISM that are available, and a similar analysis should be repeated when more reconstructions for the ISM have been published.

The analysis of the proxy reconstructions in Sankar et al. (submitted to Tellus, 2016) showed that the AMV-ISM relation have been weaker prior to the instrumental era. This hypothesis is further investigated in Luo et al. (in prep.). Here we analysed 12 models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), selected based on how well they simulate both the AMV and the ISM. We analysed both pre-industrial control simulations with constant forcing, and historical (1850-2000) simulation with prescribed external forcings including the greenhouse gasses. We found that none of the models simulated the observed AMV-ISM relation in the pre-industrial control simulations, but 3 models were able to simulate the correlation in the historical simulations. The significant correlation between AMV and ISM in these three models is due to external forcing phasing both the AMV and ISM independently, and not due to internal climate variability.

In addition to the possible impact from the AMV on to the ISM on multidecadal timescales, the AMV could also impact the ISM though modulating interannual variability in the tropics. In Svendsen et al., (2013) we use a so-called freshwater hosing experiment with the Bergen Climate model, where freshwater is artificially added to the North Atlantic resulting in a weakening of the thermohaline circulation and a colder North Atlantic comparable to a negative AMV phase. We find that when the Atlantic cools there is a synchronization of interannual variability in the tropical Atlantic and Pacific, with the Atlantic leading the Pacific with half a year. The ENSO variability shifts also to higher frequencies during this period. From earlier studies on the ENSO-ISM relation we expect this to impact the ISM as well.

Published papers

1. Abish, B., P. V. Joseph, and O. M. Johannessen, (2015): Climate change in the subtropical jetstream during 1950– 2009. Adv. Atmos. Sci., 32(1), 140–148, doi: 10.1007/s00376-014-4156-6.
2. Abish, B., P.V. Joseph and O.M. Johannessen, (2013): Weakening Trend of the Tropical Easterly Jetstream of the Boreal Summer Monsoon season 1950 - 2009, Journal of Climate. http://dx.doi.org/10.1175/JCLI-D-13-00440.1
3. Cui, X.D., Gao, Y.Q., Sun, J.Q. (2014): The response of the East Asian summer monsoon to strong tropical volcanic eruptions. Adv. Atmos. Sci., 31(6), 1245-1255, doi: 10.1007/s00376-014-3239-8
4. Cui, X.D., Gao, Y.Q., Sun, J.Q., Guo, D., Li, S.L., Johannessen, O.M. (2014): Role of external forcing factors in modulating the Indian summer monsoon rainfall, the North Atlantic Oscillation and their relationship on inter-decadal timescale Climate Dynamics, 43, 2283-2295, DOI: 10.1007/s00382-014-2053-4
5. Gong, D.Y., Gao, Y.Q., Guo, D., Mao, R., Yang, J., Hu, M., Gao, M.N., (2013): Interannual linkage between Arctic/North Atlantic Oscillation and tropical Indian Ocean precipitation during boreal winter. Climate Dynamics, 42, 1007-1027, DOI 10.1007/s00382-013-1681-4
6. Joseph, P.V., G. Bindu and N. Preethi, (in press, 2016): Impact of the upper tropospheric cooling trend over the central Asian on the Indian summer monsoon rainfall and the Bay of Bengal cyclone tracks. Current Science. J. of the Indian Academy of Sciences.
7. Joseph, P.V., G. Bindu, A. Nair, S. Wilson, 2013: Variability of summer monsoon rainfall in India on in- ter-annual and decadal time scales, Atmos. Oceanic Sci. Lett., 6, 398–403, doi:10.3878/j.issn.1674-2834.13.0044.
8. Svendsen, L., S. Hetzinger, N. Keenlyside, and Y. Gao (2014): Marine-based multiproxy reconstruction of Atlantic multidecadal variability, Geophysical Research Letters, 41, doi:10.1002/2013GL059076.
9. Svendsen, Lea, Nils Gunnar Kvamstø, and Noel Keenlyside (2013): Weakening AMOC connects Equatorial Atlantic and Pacific interannual variability, Climate Dynamics, doi:10.1007/s00382-013-1904-8

Publications under preparation (results sited in the report)

10. Luo, Feifei, Yongqi Gao, Lea Svendsen, Noel Keenlyside, Shuanglin L. and Tore Furevik (in prep. 2016): External forcing synchronizes the Atlantic Multidecadal Variability and the Indian Summer Monsoon. To be submitted to Geophys. Research Letters.
11. Sankar, Syam, Lea Svendsen, Bindu G., and P. V. Joseph, and Ola M. Johannessen (in prep.): Teleconnections of Indian Summer Monsoon Rainfall with Atlantic Multidecadal Variability from 1400 to present. In preparation to be submitted to Tellus.
12. Wilson, Shinu Sheela, Joseph P.V, K. Mohanakumar, and Ola M. Johannessen, 2016: Temporal and Spatial Variability of the Low Level Jetstream of Asian Summer Monsoon. Submitted to Climate Dynamics.