

Final Report for Period: 08/2007 - 07/2008**Submitted on:** 09/09/2010**Principal Investigator:** Cullen, Heidi M.**Award ID:** 0233563**Organization:** GA Tech Res Corp - GIT**Submitted By:**

Cullen, Heidi - Principal Investigator

Title:

Collaborative Research: WCR: Hydrology of Central and Southwest Asia: Connections Between Regional Atmospheric Circulation and Large-scale Climate Variability

Project Participants**Senior Personnel****Name:** Cullen, Heidi**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Barlow, Matthew**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Tippet, M**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Kaplan, A**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Salstein, D**Worked for more than 160 Hours:** Yes**Contribution to Project:****Post-doc****Graduate Student****Name:** Heoll, A**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Saini, R**Worked for more than 160 Hours:** Yes**Contribution to Project:****Undergraduate Student****Technician, Programmer**

Other Participant**Research Experience for Undergraduates****Organizational Partners**

Columbia University Lamont Doherty Earth Observatory

Other Collaborators or Contacts

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Activities and Findings**Research and Education Activities: (See PDF version submitted by PI at the end of the report)**

This summary reflects the efforts of all collaborators over the full period of the project.

Motivation and Objectives

The motivation for this project was an initial analysis of the exceptionally-severe 1999-2001 drought in Central-Southwest Asia, which suggested that regional and large-scale climate variability played an important and perhaps predictable role in the drought. The initial analysis highlighted the ongoing La Nina episode during the drought, enhanced tropical convection in the eastern Indian Ocean and Maritime Continent, and changes in upper-level wind consistent with a

Gill-like response in forcing the drought, although the exact dynamical mechanisms were not clear. The objectives of the proposed work were to investigate these relationships through observational analyses of: (1) regional-scale fluctuations in river flows, (2) the links between these fluctuations and key features of the regional atmospheric circulation, and (3) the influence of large-scale climate variability on the regional circulation. An overall goal, in light of the high human and environmental cost of the drought, was to identify and develop the societal relevance of the results, especially the feasibility of seasonal forecasts.

Research Activities

To accomplish these objectives, we carried out the following main activities:

?Observational analysis to determine recurrent regional patterns of cold season precipitation and the associated connections to tropical SSTs and convection, and development of a prediction scheme from the results,

?Observational analysis of daily data to examine the links between the tropical forcing and regional synoptic storm variability, which eventually included analysis of the influence of the Madden-Julian Oscillation (MJO) due to its importance in modulating tropical convection in the eastern Indian Ocean,

?Observational analysis of changes to the thermodynamic balance during periods of enhanced or suppressed regional precipitation, to investigate the dynamics of the tropical influence,

?Observational analysis of moisture transport and links to regional and large-scale variability, to investigate the dynamics of the tropical influence,

?Modeling simulations with enhanced convection in the eastern Indian Ocean, to test the isolated influence of that region and establish cause-and-effect,

?Reconstruction of precipitation, temperature, and river flows, based on regional patterns of variability,

?Observational analysis of regional patterns of river flow variability and their connections to regional and global-scale climate variability, and development of a prediction scheme based

on the results,

?Analysis comparing droughts as defined by the hydroclimatological data with droughts as defined by the occurrence of recorded drought disasters.

Education Activities

This project had four main education activities

1. Convened workshop on regional research and data issues (including travel funding for a graduate student from Uzbekistan), including both researchers and representatives of famine and drought monitoring and mitigation organizations
2. Research experience for two graduate students at the University of Massachusetts Lowell
3. Use of results in public presentations (one to a summer program aimed at high school students from underrepresented groups, one to an adult continued education program)
4. Compilation of contact list for regional researchers and decision-makers, which we will use to start an email listserv

Findings: (See PDF version submitted by PI at the end of the report)

The three collaborating institutions produced 11 papers and 1 report as part of this project. The major findings are:

?We confirmed the direct influence of tropical convection in the eastern Indian Ocean and Maritime Continent on Central-Southwest Asia in three distinct ways: through further observational analysis, through modified GCM simulations, and through successful forecasts.

?We advanced and tested, both observationally and with modeling, a hypothesis for the dynamical mechanism underlying the tropical influence, based on Rodwell-Hoskins-type thermodynamics.

?We identified a potential new dynamical pathway for tropical influence on the region, via *eastward* ducting of the midlatitude response to the tropical convection along the global westerly wave guide, and subsequent modification of moisture transport into the region.

?We demonstrated that regional-scale climate variability as observed even in the sparse available data can accurately capture the behavior of the mountain snowpack, and can be used for skillful forecasting of individual river flows, including several with small drainage basins.

?We identified a relationship between MJO events and synoptic storms and flooding in the region, with possible application to short and medium-range forecasting.

?We demonstrated a correspondence between hydroclimatic measures of drought and actual recorded drought disasters -- confirming that the drought variability being analyzed is of considerable societal importance, that data scarcity issues are not overwhelming the validity of the results, and that drought disasters in the region are driven in large part by climate variations (as opposed to politically-generated famines or biased reporting).

Our findings have also identified several key questions that have motivated our ongoing and future research plans, especially: 1) the dynamics of the apparent upstream influence from the tropics, 2) the potential role of the monsoon onset in determining the end of the wet season, 2) the links between hydrology and vegetation in the region, 3) the influence of warming trends on the timing of snowmelt and the links between snowpack and regional variability, and 4) the relevance of the dynamics and techniques considered for Central-Southwest Asia to other regions, especially the potential for representing local variability with regional patterns in data-sparse mountain regions.

Training and Development:

At the University of Massachusetts Lowell, two graduate students, Andy Hoell and Roop Saini, received training and development as part of this project. Both students have drafted manuscripts as first author for this project, with expected submission by the end of this year, and one of the students (Hoell) is a second author on a published paper for this project.

A workshop on research and data issues for the region was convened as part of this project, including travel support for a graduate student from

Uzbekistan.

Outreach Activities:

The results of this project were used as part of discussions with local media, seminars to the public, and presentations to high school and adult education students. This study also motivated and informed the PI's participation in the writing team for the 2008 AMS Water Resources Statement.

Journal Publications

Barlow, M. Wheeler, B. Lyon, and H. Cullen, "Modulation of daily precipitation over Southwest Asia by the Madden-Julian Oscillation.", *Monthly Weather Review*, p. , vol. , (). Submitted,

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

The findings and activities of this project have led to the following five primary contributions in the principal disciplines of climate and hydrology:

- 1) Considerably increased understanding of the regional and large-scale climate variability linked to the hydroclimate of CSW Asia, a very climate-sensitive and understudied region of the world, including identification of key drought and flood patterns and underlying dynamical mechanisms;
- 2) Showed that the Rodwell-Hoskins Dessert Monsoon hypothesis can apply more generally, including to tropical convection in some cases;
- 3) Demonstrated that regional-scale patterns of climate variability can contain a large amount of information about variability at individual locations, even in data-sparse regions, and, particularly, can capture snowpack variability in mountainous regions;
- 4) Developed seasonal forecast tools for both precipitation and river flows in Central-Southwest Asia; and
- 5) Began development of a new modeling tool allowing investigation of response to tropical forcing in a full GCM;

The tools, data, and ideas developed for this project (see also findings section) have additionally provided the primary foundation for much of the PI's current and planned research program, including two additional NSF projects, one NOAA project, two pending proposals (one that applies the regional-pattern approach to western US snowpack and river prediction), and several planned proposals.

Contributions to Other Disciplines:

The main contributions of the project outside the primary disciplines of climate and hydrology were the preliminary analysis of vegetation and the analysis of the societal impacts of drought.

Contributions to Human Resource Development:

Several project activities contributed to the development of human resources, including the workshop and regional networking, graduate student training, and inclusion of some of the results in outreach to a summer program for disadvantaged high school students.

Contributions to Resources for Research and Education:

Several research and education resources were produced or are in development as a result of this project:

??The NCAR CAM atmospheric model was installed and made available to department faculty and students

??A new modeling tool based on a modified version of the CAM was developed and is available to the community (already in-use by another group)

??Development of several simple models (e.g., Gill-Matsuno) was begun as part of this effort and is being finalized for classroom use.

Contributions Beyond Science and Engineering:

One of the overall goals of this project was to identify and develop the societal relevance of the results, especially the feasibility of seasonal forecasts. We devoted considerable attention to this aspect of the project, including: 1) developing separate forecasting schemes for precipitation and river flows (both now in regular use); 2) producing an analysis of drought disasters as a chapter in a World Bank analysis on risk assessment and mitigation, which we identified as a useful avenue for bringing our results to the attention of policy makers; 3) convening a workshop on research and data issues which included several groups active in both research and drought mitigation for the region; and 4) corresponding with numerous national and local experts and decision makers in the region, which will be the basis a listserv focusing on disseminating forecasts, research results, and data.

Conference Proceedings

Categories for which nothing is reported:

Any Book

Any Web/Internet Site

Any Product

Any Conference

Publications and products

Journal Articles

- Tippett, M. K., Barlow, M. and Lyon, B., 2003. Statistical correction of Central Southwest Asia winter precipitation simulations, *Int. J. Climatol.*, 23, 1421-1433.
- Barlow, M., and M. Tippett, 2004: Predicting Central Asia river flows from regional precipitation and wind patterns during the preceding cold season. *IAHS Red Book, Regional Hydrologic Impacts of Climate Variability.*
- Tippett, M. K., Goddard, L. and Barnston, A. G., 2005. Statistical-Dynamical Seasonal Forecasts of Central Southwest Asia winter precipitation, *J. Climate*, 18, 1831-1843.
- Barlow, M., D. Salstein, and H. Cullen, 2005: Hydrologic extremes in Central-Southwest Asia. *Eos*, 86, 218.
- Barlow, M., M. Wheeler, B. Lyon, and H. Cullen, 2005: Modulation of daily precipitation over Southwest Asia by the Madden-Julian Oscillation. *Mon. Wea. Rev.*, 133, 3579-3594.
- Anchukaitis, K. J., M. N. Evans, A. Kaplan, E. A. Vaganov, M. K. Hughes, H. D. Grissino-Mayer and M. A. Cane, 2006: Forward modeling of regional scale tree-ring patterns in the southeastern United States and the recent influence of summer drought. *Geophysical Research Letters*, 33(4): L04705, doi:10.1029/2005GL025050.
- Shaman, J., M. Cane and A. Kaplan, 2005: The relationship between tibetan snow depth, ENSO, river discharge and the monsoons of Bangladesh. *International Journal of Remote Sensing*, 26(17): 3735-3748.
- Gorodetskaya, I. V., M. A. Cane, L. B. Tremblay and A. Kaplan, 2006: The effects of sea-ice and land-snow concentrations on planetary albedo from the earth radiation budget experiment. *Atmosphere-Ocean*, 44(2): 195-205.
- Cohen, J., M. Barlow, P. Kushner, and K. Saito, 2007: Stratosphere-troposphere coupling and links to Eurasian land-surface variability. *J. Climate*, in press.
- Barlow, M., A. Hoell, and F. Colby, 2007: Examining the wintertime response to tropical convection over the eastern Indian Ocean by modifying atmospheric heating in a global atmospheric model. *Geophys. Res. Lett.*, 34, L19702, doi:10.1029/2007GL030043.
- Barlow, M., and M. Tippett, 2008: Variability and predictability of Central Asia river flows: antecedent winter precipitation and large-scale teleconnections. *J. Hydrometeorol.*, in press.

Book Chapters

- M. Barlow, H. Cullen, B. Lyon, and O. Wilhelmi, 2006: Drought disaster in Asia. In "Natural Disaster Hotspots Case Studies," *World Bank Disaster Risk Management Series* No. 6. Edited by J. Arnold, R. Chen, U. Deichmann, M. Dilley, A Lerner-Lam, R. Pullen, and Z. Trohanis.

Products

- Forecast tool for cold season precipitation in Central-Southwest Asia
- Forecast tool for warm season river flows in Central Asia

Activities for Year 1

Collaborative Research: Hydrology of Central and Southwest Asia: Connections between regional atmospheric circulation and large-scale climate variability
M. Barlow, H. Cullen, A. Kaplan, M. Tippett, D. Salstein

The objectives of the project (from page 10 of the proposal) are:

1. Assembly of a regional hydro-climatic dataset, from monthly precipitation, temperature, and river flows for 1938-present; and multivariate reconstructions based on this dataset, using reduced-space estimation techniques to fill data gaps.
2. Identification of recurrent patterns and severe events in regional-scale hydrology, including consideration of seasonality and relationships among the hydro-climatic variables.
3. Documentation of links between the hydrologic variations and atmospheric circulation features that affect moisture transport into the region.
4. Examination of the influence of large-scale modes of climate variability (NAO and ENSO-related variability) on the atmospheric circulation features.
5. Assessment of potential predictability of regional-scale variations in hydrology due to the seasonal hydrologic cycle and links with the large-scale climate, and construction of statistical forecast tool to produce hydrologic forecasts from current seasonal forecast models.

Progress was made on all five objectives in the first year of effort. For the first objective, we substantially added to our station precipitation holdings and tested our reconstruction methodology, with a focused effort on reconstruction planned for the second year of the project. For the second and third objectives, we have considered links between intraseasonal variability of the local precipitation, including flooding events, and the convective maximum in the eastern Indian Ocean, and we have also considered patterns of covariability between cold season precipitation and subsequent warm season river flow. For the fourth objective, we examined the effects of changes in ENSO pattern on the teleconnections to the jet level winds over Asia. And for the fifth objective, we constructed a cross-validated forecasting tool for river flows, based on operationally available data.

A detailed list of activities follows:

1. Examined the influence of the Madden-Julian Oscillation (MJO) on daily precipitation of the region, including flooding events.

The MJO, the dominant mode of tropical intraseasonal variability, has time scales of roughly 30-60 days and is accompanied by wind anomalies that extend into the midlatitudes. The MJO is most vigorous in the eastern Indian Ocean, when its wind anomalies extend over Southwest Asia. Using observational data, we examined the

influence of the MJO on the wintertime daily precipitation of the region, using both Outgoing Longwave Radiation (OLR) and station records as precipitation estimates. Changes in both daily mean values and extreme events (flooding) were considered, as was the influence of the MJO on storm evolution. The underlying dynamics of the connection between the MJO winds and Southwest Asia precipitation was investigated with respect to the thermodynamic forcing of vertical motion by the interaction of the midlatitude MJO circulation and the westerlies.

2. Examined the relationship between warm season (peak) river flows, regional precipitation during the preceding cold season, and large-scale climate variability; assessed related predictability.

River flows in Central Asia are largely determined by snow melt, with peak flows occurring in spring and summer as the snow pack in the high mountains melts. Accurate knowledge of the snow pack present at the end of winter within a given river basin, therefore, would give a significant amount of advance information about the magnitude of river flow. While accurate, high-resolution estimates of snow pack are difficult to obtain, even coarse-resolution precipitation estimates may provide relevant information in cases when regional-scale patterns of variability are important. The degree to which regional-scale variability is important was examined using 35 years of river flow data for 25 stations. The regional-scale wind patterns and teleconnections to Pacific sea surface temperatures were investigated. Canonical Correlation Analysis (CCA) was used to assess cross-validated forecast skill based on operationally available precipitation and wind data using non-overlapping seasons—predicting Apr-Aug (peak) river flows from Nov-Mar data.

3. Investigated links between oceanic precipitation, the west Pacific structure of the El Nino -- Southern Oscillation (ENSO), and changes in jet-level winds over Asia.

A synthesis of several recent studies, which encompass a diverse array of analytic approaches, suggests that two recurrent patterns of ENSO variability may be distinguished in both observational and model data. In the Pacific, variations in the longitudinal extent and east-west asymmetry of the sea surface temperature (SST) anomalies are related to the longitudinal position and on/off equatorial character of the associated precipitation anomalies. These variations in Pacific pattern are associated with markedly different teleconnections (in winds and precipitation) both to the west, over the Indian Ocean and Asia, and to the east, over the US. A newly available dataset of reconstructed oceanic precipitation allows consideration of the tropical Pacific SST – precipitation relationship prior to the satellite era. The reconstructed precipitation, ensemble averages of General Circulation Model (GCM) precipitation forced by observed SSTs, and NCEP/NCAR reanalysis winds were used to examine the patterns in oceanic precipitation for 1950-2000.

4. Tested the methodology of hydroclimatic analyses and climate field reconstruction.

To test our methodology of hydroclimatic analyses and climate field reconstruction we have analyzed the Bangladesh monsoon using the following data: River Data: Monthly river discharge data was from the Bahadurabad Transit station site (SW46.9L) on the Brahmaputra River for 1979-1987. Data for June 1983 was missing. Monthly anomalies were calculated, and the June monthly anomalies were used. ENSO Data: NINO3 (5N-5S, 150W-90W) was the index of ENSO used for this study (Kaplan et al. 1998). A time series of JJAS seasonal anomalies were used. Rainfall Data: Two time series measuring Bangladesh monsoon rainfall (BMR) were employed. 1) We averaged monthly rainfall data from all NCDC Global Historical Climatology Network (GHCN) stations between 21N-26N and 87E to 93E for 1900 through 2000. Monthly and seasonal anomalies were then constructed based on this record. 2) Our trial version of optimally interpolated (OI) monthly rainfall was also used. These data were constructed by reduced space optimal interpolation of the raw GHCN station data. The method is similar to the sea level pressured analysis presented in Kaplan et al. (2000). The OI data were gridded at 4x4 degree resolution. Monthly and seasonal anomalies for 1900-2000 from the grid box centered at 24N and 90E were employed for this study. The increased variability was evident in the GHCN record during last decade, due to changes in the number and location of stations in operation, is reduced by the optimal interpolation. For purposes of comparison we also employed the All-India Monthly Rainfall data of the Indian Institute of Tropical Meteorology (Parthasarathy et al. 1995) and compiled these data for JJAS, 1900-2000 as seasonal anomalies. Four of the 29 subdivision employed in the construction of this index lie partially or wholly within the domain of the GHCN BMR.

5. Continued to acquire precipitation data.

Additional, high-quality station precipitation for Iran was acquired, both monthly (12 stations, 1951-1995) and daily (28 stations, 1991-2000). Additional daily station precipitation for the Former Soviet Union countries within the domain was also acquired, from the newly available Global Daily Climatology Network (GDCN) dataset.

6. Two presentations were made, and one more is scheduled by 1 August 2004.

Barlow, M., M. Tippett, and D. Salstein, 2003: Dynamics in the West/Central Pacific and variations in ENSO structure. Presented by M. Barlow at The International Union of Geodesy and Geophysics (IUGG) in Sapporo, Japan, June 30-July 11, 2003.

Barlow, M., and M. Tippett, 2004: Predictability of Central Asia River Flow: Antecedent Winter Precipitation and Large-Scale Teleconnections. Presented by M. Barlow as an IRI seminar on April 07, 2004.

Barlow, M., and M. Tippett, 2004: The use of large-scale climate information to predict Central Asia river flows at one and two season leads. To be presented as a poster at the First International CLIVAR Conference, June 21-25, 2004 in Baltimore, Maryland.

Findings for Year 1

Collaborative Research: Hydrology of Central and Southwest Asia: Connections between regional atmospheric circulation and large-scale climate variability
M. Barlow, H. Cullen, A. Kaplan, M. Tippett, D. Salstein

Findings

1. Influence of the Madden-Julian Oscillation (MJO) on daily precipitation of the region, including flooding events. This work has been submitted as a journal article and is in revision.

This analysis of daily observations showed that wintertime (Nov-Apr) precipitation over Southwest Asia is modulated by Madden-Julian Oscillation (MJO) activity in the eastern Indian Ocean, with strength comparable to the interannual variability. In the station data, for the average of all available stations, there is a 55% increase in daily precipitation when the phase of the MJO is negative (suppressed tropical convection in the eastern Indian Ocean). The distribution of extremes is also affected such that the 10 wettest days all occur during the negative MJO phase. The longer record of OLR data indicates that the effect of the MJO is quite consistent from year to year, with the anomalies averaged over Southwest Asia more negative (indicating more rain) for the negative phase of the MJO for each of the 22 years in the record. Additionally, in 9 of the 22 years the average influence of the MJO is larger than the interannual variability (e.g., the relationship results in anomalously wet periods even in dry years and vice versa). Examination of the thermodynamic balance shows that the thermal interaction of the MJO wind anomalies with the westerlies results in subsidence over Southwest Asia, consistent with the observed modulation of synoptic precipitation. A simple persistence scheme for forecasting the sign of the MJO suggests that the modulation of Southwest Asia precipitation may be forecastable for three-week periods. Finally, analysis of changes in storm evolution due to MJO influence shows a large difference in strength as the storms move over Afghanistan, with apparent relevance to severe flooding on April 12-13, 2002.

2. The relationship between warm season (peak) river flows, regional precipitation during the preceding cold season, and large-scale climate variability. This work is being finalized and prepared as a journal article.

Linear correlation analysis was used to examine the relationship between warm season (Apr-Aug) river flows and antecedent cold season (Nov-Mar) precipitation and winds for 36 years (1950-1985). The Apr-Aug flow comprises the bulk of the yearly flow for most of the stations considered. The high degree of spatial coherence in observed river flow variability makes the station-averaged normalized river flow a simple but representative index of seasonal river flow in the region. Computing the correlation of this index with gridded observed Nov-Mar precipitation data indicates that river flow

variability is related to spatially-coherent, regional-scale precipitation variability with correlations exceeding 0.8 in some places. Although river flows are expected to be tied to precipitation along with temperature and drainage basin characteristics, the extent to which this relationship is captured by the data is remarkable given the spatial paucity of precipitation measurements, especially in regions with exceptionally mountainous terrain. This indicates that relatively large spatial scales of variability play a dominant role in the hydrology of the region. These results are supported by Canonical Correlation Analysis (CCA), a pattern based multiple linear regression method which considers the different river flow stations rather than their normalized average.

Because the seasons chosen for precipitation and river flow do not overlap, the CCA analysis can also be used to construct a scheme to predict season forecast river flows from the preceding cold season's precipitation. First the CCA method uses historical data to identify the cold season precipitation patterns that are most highly correlated with warm season river flow. The sign and strength of the forecast warm season river flow anomaly is determined by the projecting current precipitation anomalies onto these patterns. The skill of the river flow forecast model is estimated using cross-validation. A season of data is omitted from the calculation of the prediction model which is then used to predict the observed anomaly for the withheld season. Withholding each season in turn gives 36 forecasts for independent data, which are used to compute skill. Observed precipitation data is not available in real-time, i.e., sufficiently soon after the end of the cold season. Therefore precipitation and upper-level zonal wind from NCEP/NCAR reanalysis were used as the predictor. The NCEP/NCAR reanalysis, available operationally, is a model-based combination of in situ and satellite observations. Zonal winds were used as a predictor since regression of the observed precipitation pattern time-series showed changes in the intensity of the local westerly flow that impinges on the mountains of the region, consistent with the precipitation anomalies. Even with this simple approach and operationally-available data, cross-validated correlations were greater than 0.5 for 10 of the 24 stations, with a maximum correlation greater than 0.7. These changes in regional winds and precipitation are, in turn, associated with SST anomalies in the equatorial Pacific Ocean. The SST anomalies are similar to the El Nino pattern, but with greater strength in the central Pacific relative to the eastern Pacific--an SST pattern previously shown to affect the region.

3. Links between oceanic precipitation, the west Pacific structure of the El Nino -- Southern Oscillation (ENSO), and changes in jet-level winds over Asia. This work is in progress.

Analysis of the relationship between the reconstructed tropical ocean precipitation and upper-level winds validates the reconstructed precipitation product in the pre-1979 period. Using this data in combination with the SST and wind, we have shown that there are important variations in the West/Central structure of ENSO that may be characterized either by West Pacific SSTs or West/Central Pacific precipitation and that these variations are robust in both the 1950-1976 and 1977-2000 periods. Atmospheric

models have some local skill in reproducing variations despite deficiencies in climatology. The strength of the West/Central precipitation anomalies is closely related to the contrast between warmer West Pacific SSTs and colder Central Pacific SSTs. The variations in the pattern of warm (El Niño) and cold (La Niña) phases are not completely symmetric, due to the positive-definite nature of precipitation and the low mean values in the eastern Pacific (total precipitation can increase considerably in that region from the near-zero mean values but cannot decrease much.) For El Niño, changes in the strength of West/Central precipitation anomalies are associated with Pacific-wide shifts in precipitation anomalies for very warm events (1982-1983, 1997-1998) when precipitation can extend into east Pacific. For La Niña, changes in the strength of West/Central precipitation anomalies result in notable differences in jet anomalies over Asia and, apparently, the US. The differences from the standard La Niña pattern can dominate entire events (1970-71, 1999-2001), both in terms of SST pattern and teleconnections.

4. The Relationship between Tibetan snow depth, ENSO, river discharge and the monsoons of Bangladesh.

We examined the interannual variability of the monsoon rains of Bangladesh, an area greatly affected by land surface hydrologic processes including Himalayan snow pack size, snowmelt river flooding, and Bay of Bengal storm surge. For the 20th century, we find Bangladesh monsoon rainfall (BMR) to be uncorrelated with the All-Indian Monsoon Index. This result is consistent with previous findings for shorter time records. We next use a 9-year record of satellite estimates of April snow depth for the Himalayan region and concurrent seasonal El Niño-Southern Oscillation (ENSO) conditions in the equatorial Pacific to develop an empirical model that explains a high percentage of BMR interannual variability. Inclusion of late spring river discharge levels further improves empirical model representation of BMR for June-September. These results, though for a limited record length, suggest that BMR interannual variability is constrained by concurrent ENSO conditions, spring Himalayan snow pack size and land surface flooding. The 20th century analysis indicates that BMR should be considered independently of Indian monsoon rainfall. This study demonstrated the usability of our trial reconstruction of precipitation fields.