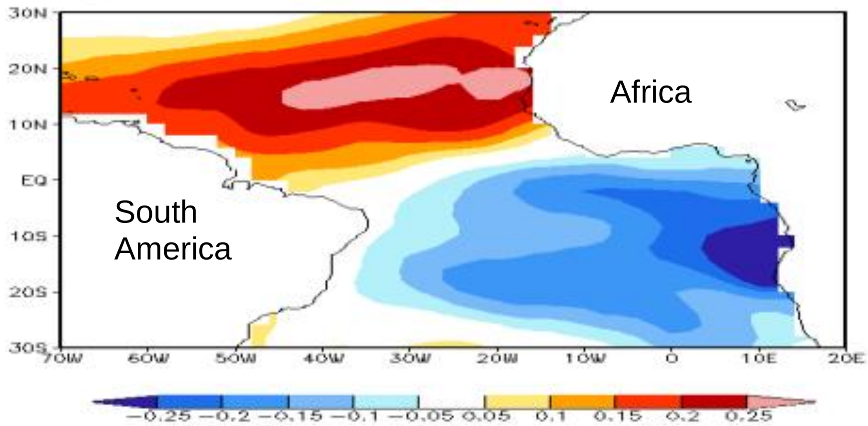
The Center for Research on the Changing Earth System
The First Decade: 2001-2011

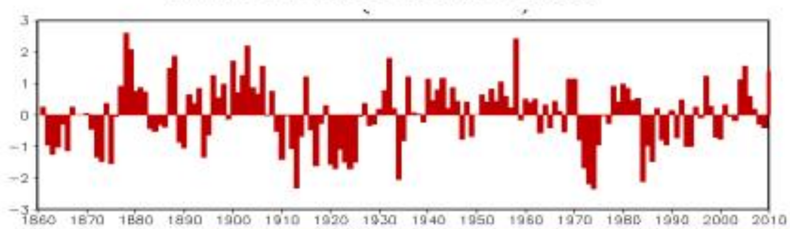
A Report

Vikram M. Mehta
The Center for Research on the Changing Earth System
Maryland, U.S.A.

Tropical Atlantic SST gradient oscillation at …



…decadal timescales…



…is one of the causes of decadal droughts in the Missouri River Basin.

Contents

Foreword

The Center for Research on the Changing Earth System (CRCES) was founded in late 2001 in Maryland as a non-profit, tax-exempt (Internal Revenue Service Code Section 501(c)(3)), scientific research organization. It formally opened an office in July 2002 in Columbia, Maryland. CRCES is governed by a Board of Directors consisting of Dr. Vikram M. Mehta (CRCES), Dr. Norman J. Rosenberg (CRCES), Dr. James J. O'Brien (Florida State University), and Dr. Amita V. Mehta (NASA-UMBC Joint Center for Earth System Technology); Ms. Chetana Neerchal (World Bank) also served as one of the Directors in the initial years. I am very happy to present to you a progress report as CRCES enters its tenth year.

Following my Ph.D. dissertation at the Florida State University in the late 1980s on modeling decadal climate variability (DCV) and subsequent continuation of this research in NASA-Goddard Space Flight Center in the 1990s, I wanted to focus my research not only on DCV and its predictability, but also on its impacts on societal sectors such as water, food, and public health. That was the reason for CRCES's founding. By the time CRCES was founded in 2001-02, DCV was emerging as an important research area and a sizable group of DCV researchers was developing.

In its first decade, CRCES's focus areas have been:

- DCV and its physics, including the possible roles of atmospheric and riverine freshwater fluxes in ocean-atmosphere dynamics;
- assessments and modeling of DCV impacts on water and agriculture, especially in the Missouri River Basin (MRB), a major "bread basket" of not only the U.S. but also the world;
- assessments of decadal climate and societal impacts information needs of stakeholders and policymakers in the MRB; and
- contributions to the evolution of DCV and societal impacts communities via workshops and other means.

This report summarizes CRCES's contributions in these areas.

CRCES's founding and much of its subsequent progress would not have been possible without the encouragement and support provided by Dr. Eric Lindstrom, Program Scientist, Physical Oceanography Program at NASA Headquarters, who has supported CRCES's DCV research, workshops, and the development of the Virtual Center for Decadal Climate Variability. Dr. Nancy Beller-Simms of the Sectoral Applications Research Program (now the Climate and Societal Interactions - Water Program), NOAA-Climate Program Office, has provided encouragement and support of CRCES's projects on DCV impacts on water and agriculture in the MRB. Dr. Jay Fein, Climate and Large-scale Dynamics Program, National Science Foundation; Dr. Anjuli Bamzai, Office of Biological and Energy Research, U.S. Department of Energy (now in Climate and Large-scale Dynamics Program, National Science Foundation); and Dr. James Todd, Climate Variability and Predictability Program, NOAA-Climate Program Office have supported workshops organized by CRCES. Recently, Dr. Louie Tupas (Global Climate Change Division, Institute of Bioenergy, Climate and Environment, National Institute of Food and Agriculture, U.S. Department of Energy) has provided major support for a new CRCES project on experimental decadal climate and societal impacts prediction in the MRB; and on experimental, climate-adaptive, water and agriculture management system for the MRB.

CRCES's progress in the first decade has been made possible by its people. CRCES has benefitted from Dr. O'Brien's and Dr. Rosenberg's guidance, and from Dr. A. Mehta's professional expertise and personal support. Ms. Janet Wood and Mr. David Wolff established and maintained administrative and information technology systems, respectively, in support of CRCES scientists. Ms. Susan Rapaport (Davis, Agnor, Rapaport & Skalny, L.L.C.) and Ms. Alice Weber (CBIZ) helped in legal and accounting matters, respectively, when CRCES was founded. Subsequently, Ms. Kathy Kahler (Kahler & Associates) and Mr. Chris Scholtes (C.E.A. Scholtes & Associates) have been responsible for accounting and auditing functions. I sincerely thank all the people who have helped CRCES, worked for it, or associated with it in some capacity. They have made CRCES successful in its first decade.

Vikram M. Mehta
Executive Director

1. Research

1.1 Decadal Climate Variability

1.1.1 Decadal variability of the Tropical Warm Pools and Its Association with Global Atmospheric Variability

One of the most important permanent features of the Earth system are the Tropical Warm Pools (TWPs), especially the Indo-Pacific Warm Pool (IPWP) and the west Atlantic Warm Pool (WAWP). The TWPs contain much of the warmest and freshest surface ocean water on the Earth. Annual-average sea-surface temperatures (SSTs) in the TWP regions usually exceed 28°C (Fig. 1).

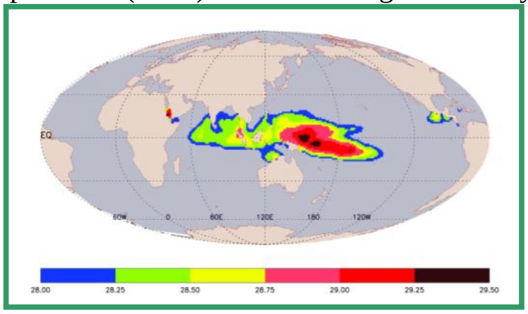


Figure 1: The Indo-Pacific Warm Pool as outlined by SSTs ≥ 28°C.

Since saturation vapor pressure is an exponential function of SST, there can be a dramatic increase in atmospheric convection over the TWPs when the SST exceeds a threshold, typically 28°C-28.5°C. Therefore, even small changes in the TWP SST can cause large changes in atmospheric convection locally. Such a change can significantly modify atmospheric boundary layer and convective processes locally, and substantially impact global atmospheric heating and planetary-scale wave activity. The annual, long-term average area of the IPWP on the eastern Indian Ocean side is approximately 6 million sq. km and on the western Pacific Ocean side is approximately 12 million sq. kms.. The surface area of the IPWP undergoes pronounced (50-100%) variability at decadal and longer timescales (Fig. 2; *Mehta and Mehta, 2004*).

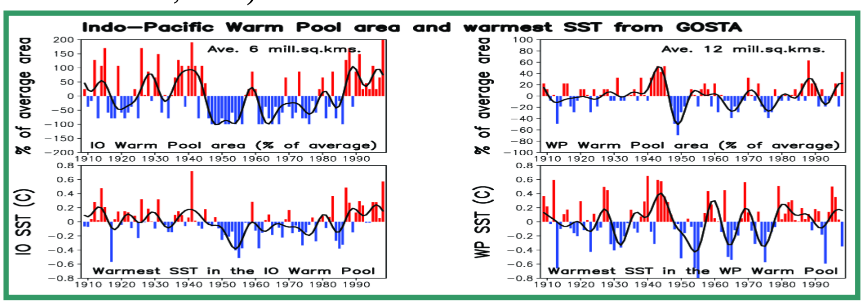


Figure 2: Changes in the Indo-Pacific Warm Pool surface area and warmest SST during 1909-2000.

Decadal variability of the IPWP SST and its association with atmospheric and oceanic circulations were investigated with observed 50-year (1952–2001) SST, and atmospheric and oceanic reanalysis data. It was found (*Wang and Mehta, 2008*) that two leading empirical patterns (EPs) well represent the IPWP SST decadal variations. Spatial evolution of EP1 is dominated by opposing changes in zonal and meridional dimensions and thus a strong deformation of the warm pool on decadal time scales; EP2 is dominated by changes in size and intensity of the warm pool. Analyses of ocean temperatures associated with the two SST EPs indicated that decadal changes in the IPWP can extend down to 300 m depth. Atmospheric circulations exhibited thermally direct responses to the two decadal IPWP SST EPs. Also associated with the two SST EPs and atmospheric circulation changes were rainfall anomalies over the United States (Fig. 3).

We also investigated (*Mehta and Wang, 2011a, 2011b*) interannual to decadal variability of the west Pacific Warm Pool (WPWP) and the west Atlantic Warm Pool (WAWP) sea-surface temperatures (SSTs) and its association with ocean surface variables are investigated with remote sensing based 27-yr (1982–2008) Optimal Interpolation SST; 15-yr (1993-2008) sea-surface height (SSH) from TOPEX/Poseidon, Jason-1, and ERS 1/2; 9-yr (1999-2008) surface wind stress (SWS) from QuikScat; and 15-yr (1992-2007) surface current (SC) from Ocean Surface Current Analyses-Real time (OSCAR) data sets. Data products from the 12-yr (1992-2004) Estimating the Circulation and Climate of the Ocean (ECCO) oceanic reanalysis system were also used in this study.

During the analysis period, dominant anomalous SST patterns evolved largely *in situ* in the WPWP region, and then move northeast into north Pacific from the WPWP, possibly transported by the surface branch of the northern sub-tropical cell or the subtropical gyre. SSH and SC variability was physically consistent with SST variability in some years. A thermally-direct atmospheric response to the WPWP SST anomalies was implied by anomalous SWS convergence over warmer than average SSTs; extra-tropical SWS anomalies were also associated with WPWP SST anomalies, possibly connected via the Hadley circulation and/or Rossby waves to anomalous atmospheric heating in the WPWP region associated with SST anomalies. It was also found that the WPWP in the warm phase extended to 150-200 m depth in western Pacific Ocean and eastern Indian Ocean, with relative cooling extending to 150m in the eastern Pacific. The SST variability was driven largely by net surface heat flux, especially latent heat flux, with a negligible role of advection terms. Mixed-layer temperature variability, however, was driven by anomalous zonal and meridional temperature advection, which showed the important role of ocean dynamics in determining mixed-layer temperature variability. Temperature variability in the 50 m layer below the mixed layer also, zonal advection process was found to be dominant.

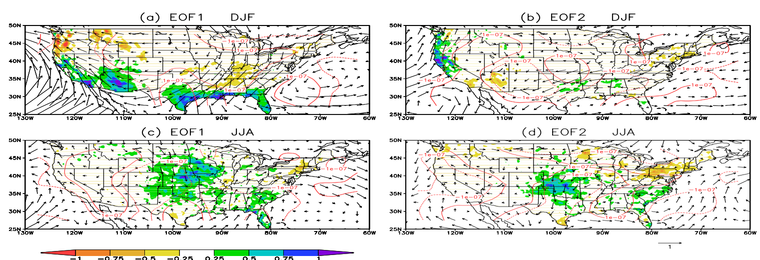


Figure 3: U.S. rainfall (Unit: mm day^{-1}, shadings), 850-hPa wind (Unit: m s^{-1}, vectors) and divergence (contours) anomalies. Contour value is 1x10^{-7} s^{-1} with negative dashed and zero contour omitted. (a),(b) DJF and (c),(d) JJA associated with two leading EOFs of the IPWP SST. The maps are linear regressions versus each EOF time series with a two standard deviation departure.

In the WAWP at interannual timescales, surface wind stress appears to respond in a thermally-direct manner such that there is anomalous convergence over warmer water. There is also a definite relationship between interannual variability in the WAWP, and eastern and central tropical Pacific. At the decadal time scale, variability of the Atlantic Meridional Overturning Cicrulation (AMOC) is associated with sea-surface height (SSH) variability in the tropical Atlantic, such that a bipolar pattern of SSH anomalies from the GECCO data set, with opposite signs on two sides of the equator, develops 1-2 years after AMOC strength reaches a maximum and persists for several years. The development of a bipolar SST anomaly pattern, however, was not evident in the GECCO data; however, substantial SST anomalies developed in the North Atlantic 1-2 years after the AMOC maximum and persisted for several years. Anomalous surface currents from OSCAR show an out-of-phase relationship with WAWP SST anomalies and surface wind stress from QuikScat, suggesting that ocean dynamics are involved in the WAWP SST variability. However, a detailed heat budget analysis using ECCO data shows that surface heat fluxes, especially latent heat flux, play the dominant role in interannual SST variability.

These results show that the quality of multi-decades long, independently-estimated, remote sensing based ocean surface variables is high enough that a coherent, physical picture of interannual WPWP and WAWP variability can emerge from analyses of these data sets. These results also imply that ocean dynamical processes, in addition to ocean-atmosphere interactions via surface heat flux, are also involved in interannual variability of the two warm pools.

1.1.2 Influences of Net Atmospheric Freshwater on the Pacific and Atlantic oceans in Decadal Ocean and Climate Variability

In addition to the observational results described above, modeling and observational results by other researchers show that the IPWP region is also a "fresh pool" because it receives copious amounts of rainfall and that this can influence IPWP temperature by modifying vertical heat mixing processes. These results strongly suggest that coupled atmosphere-ocean processes may be responsible for interannual-multidecadal variability of the IPWP, in which interactions between upper ocean and the atmosphere via the net atmospheric freshwater flux, defined as evaporation minus precipitation (EmP) at the surface, may be very important. Therefore, the response of the IPWP, and the Pacific and Atlantic oceans to EmP at interannual and longer timescales was studied with the MIT ocean general circulation model (OGCM). The OGCM was forced by observed, monthly EmP from 1988 to 2000, derived from evaporation estimates from the Goddard Satellite Surface Turbulent Fluxes and precipitation estimates from the Global Precipitation Climatology Project; and by climatological heat and momentum fluxes. Observed interannual variations of sea-surface salinity (SSS) in the west Pacific Warm Pool were simulated successfully (Fig. 4). Our simulations show (*Huang and Mehta*, *2004*) that the magnitude of interannual anomalies of salinity and temperature reaches about 0.7 psu and 0.4°C, respectively. The typical timescale of these interannual variabilities is about 3 – 5 years. The diagnosed budgets of salinity and temperature (heat) to estimate the role of advection and vertical mixing in response to the surface EmP forcing indicate that the salinity anomaly in the IPWP is largely due to vertical mixing, especially in the surface layer. The vertical mixing of salinity, in turn, is associated with the surface EmP anomaly. In contrast, the temperature anomaly above 300 m is primarily due to changes in advection forced by the EmP, which is associated with basin-wide changes in major ocean currents. Because of the strong effect of advection on the interannual variability of temperature, the temperature anomaly in the surface layer lags the salinity anomaly about 14 – 15 months.

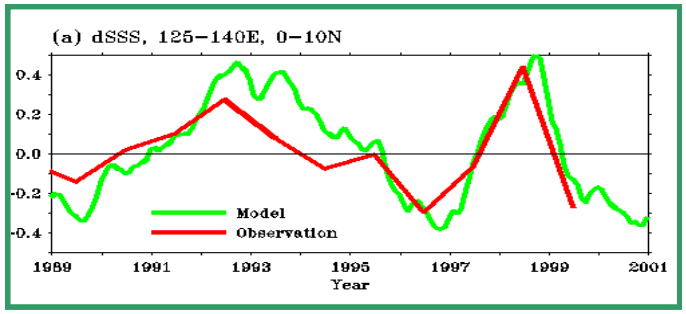


Figure 4: Observed and simulated sea-surface salinity anomalies in the West Pacific Warm Pool.

Model simulations also showed (*Huang and Mehta*, *2005*) that the spatial distribution of the average SSS changes during the 1988 – 2000 period in the Pacific and Atlantic oceans resembled that of average EmP changes, because SSS changes were primarily associated with anomalous vertical mixing forced by the anomalous EmP. The spatial distribution of average near-surface temperature anomalies, however, was different from those of average EmP and SSS anomalies. Analyses indicated that temperature changes in the subtropical North and South Pacific resulted from anomalous heat advection which, in turn, resulted from changes in the subtropical gyre circulations caused by anomalous EmP. Temperature changes in the Atlantic, however, were largely associated with vertical mixing changes due to anomalous EmP.

To further explore the magnitude of salinity and temperature anomalies and their generation processes in response to EmP anomalies, we studied the response of the Pacific Ocean to idealized EmP anomalies in the tropics and subtropics using the MIT OGCM. Simulations showed (*Huang et al.*, *2005*) that salinity anomalies generated by the anomalous EmP were spread throughout the Pacific basin by mean flow advection. This redistribution of salinity anomalies caused adjustments of basin-scale ocean currents, which further resulted in basin-scale temperature anomalies due to changes in heat advection caused by anomalous currents. The temperature anomalies propagated from the tropical Pacific to the subtropical North and South Pacific via equatorial divergent Ekman flows and poleward western boundary currents, and they propagated from the subtropical North and South Pacific to the western tropical Pacific via equatorward-propagating coastal Kelvin waves and to the eastern tropical Pacific via eastward-propagating equatorial Kelvin waves.

The slower response of ocean temperatures in these simulations due to changes in basin-scale heat advection suggests the possibility that ocean and, perhaps, climate variability at interannual and longer timescales can be generated by large-scale EmP forcing at seasonal and longer timescales.

1.1.3 Influences of Freshwater from Major Rivers on Ocean Circulation and Temperature

Many large dams on rivers have been built in the last 100 years or so to store the freshwater for societal uses and more large dams are in the offing as the world's thirst for freshwater continues to increase. Not much is known, however, about the possible consequences of blocking the river water flowing into the world's oceans. Therefore, we have started to study responses of global ocean circulation and temperature to freshwater runoff from major rivers. In the initial simulations, the runoff from several major rivers was selectively blocked in the MIT global ocean general circulation model. Runoff into the tropical Atlantic, the western North Pacific, and the Bay of Bengal and northern Arabian Sea were selectively blocked, using monthly river run-off data from the world's major rivers. The blocking of river runoff first resulted in a significant (2 psu) salinity increase near the river mouths (e.g., Fig. 5 for the Amazon River blocking).

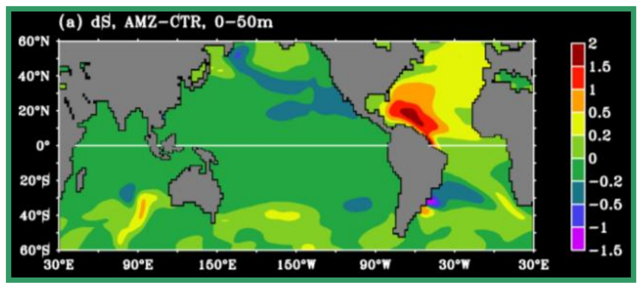


Figure 5: Salinity differences (psu) in the upper 50m between blocked and unblocked Amazon River experiments.

The saltier and, therefore, denser water was then transported to higher latitudes in the North Atlantic, North Pacific, and southern Indian Ocean by mean currents. The subsequent density contrasts between northern and southern hemispheric oceans resulted in changes in major ocean currents. These anomalous ocean currents lead to significant temperature changes (1-2ºC) by the resulting anomalous heat transports (e.g., Fig. 6 for the Amazon River blocking). The current and temperature anomalies created by the blocked river runoff propagated from one ocean basin to others via coastal and equatorial Kelvin waves.

This initial study (*Huang and Mehta, 2010*) suggests that river runoff may be playing an important role in oceanic salinity, temperature, and circulations; and that partially or fully blocking major rivers to divert freshwater for societal purposes might significantly change ocean salinity, circulations, temperature, and atmospheric climate.

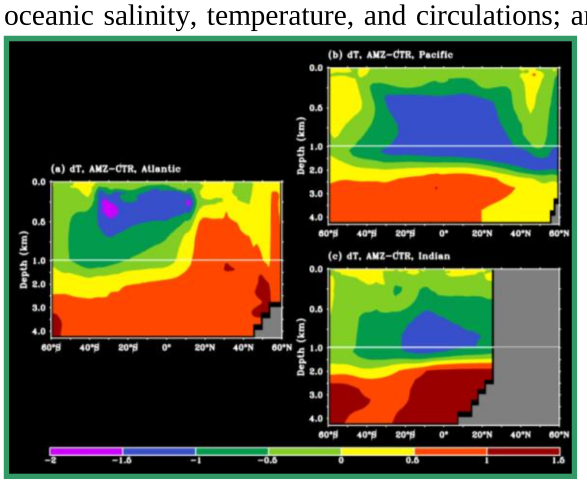


Figure 6: Zonally-averaged temperature differences (°C) in the Atlantic, Pacific, and Indiaon oceans between blocked and unblocked Amazon River experiments.

1.1.4 The Fundamental Global Water Cycle

The understanding and prediction of local, regional, and global water cycles are very important for understanding and prediction of societal impacts of water, especially water availability for domestic and industrial uses, and agriculture. There is substantial progress in understanding local and regional water cycles; but global water cycles, their variability, and changes are poorly quantified and understood. A major reason for this lack of progress is the non-availability of long-term observations of evaporation, precipitation, and water vapor transport, especially over the oceans. Among all global-scale water cycles, the most important one is the fundamental global water cycle (FGWC), defined as the annual cycle of evaporation, precipitation, and water vapor transport between the Northern and Southern Hemispheres.

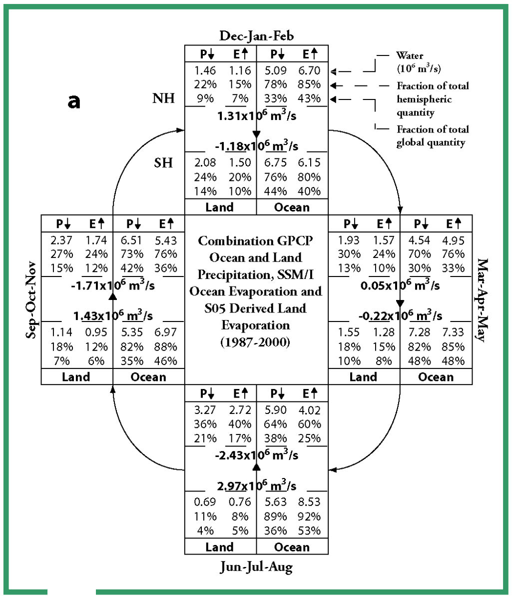


Figure 7: The FGWC based on precipitation, GSSTF2 over-ocean evaporation, and over-land evaporation based on combined S05 EmP and GPCP precipitation during 1988-2000. Arrows and numbers across the hemispheric interface denote the direction and amount of net moisture flux transport. All quantities are in units of 10^6 m^3/s.

We quantified the average FGWC over 13 years with remote-sensing-based precipitation estimates from the Global Precipitation Climatology Project (GPCP) Version 2 data sets and over-ocean evaporation estimates from the Goddard Satellite Surface Turbulent Fluxes Version 2 data set from 1988 to 2000. Over-land evaporation was estimated from the remote-sensing-based precipitation estimates combined with a global evaporation minus precipitation (EmP) data set.

Results show (*Mehta et al., 2005*) that 75% to 85% of the total global evaporation and approximately 70% of the total global precipitation occurs over the oceans in each season. In the GPCP-based FGWC estimate, there is a remarkable balance in the inter-hemispheric import-export of atmospheric moisture in December-January-February and June-July-August.

The dominant cross-equatorial atmospheric moisture transports in the atmospheric branch of the FGWC supply a significant amount of moisture to precipitation regions and are from the Northern Hemisphere to the Southern Hemisphere in December-January-February and the Southern Hemisphere to the Northern Hemisphere in June-July-August, with approximately $3x10^6$ m^3 s^{-1} net annual transport from the Southern Hemisphere to the Northern Hemisphere in the GPCP-based FGWC estimate (Fig. 7). These unique results show that evaporation, precipitation and atmospheric moisture transport over the oceans play a very important role in the FGWC and that they should be a significant component in national and international research programs on the global water cycle.

1.2 Societal Impacts of Decadal Climate Variability

1.2.1 <u>Decadal Climate Variability Impacts on Water and Crop Yields in the Missouri River Basin</u>

It is well-known that weather and climate variability cause substantial impacts on water resources and agriculture. With demands on water resources increasing and with the global food security precariously balanced and food demands increasing for several reasons, it is very important to understand and predict, if possible, weather and climate impacts on water availability and agricultural production. There have been several studies of impacts of ENSO and global warming on water resources and agricultural production in the U.S.A., but the study of impacts of decadal climate variability (DCV) on water and agriculture have been few and far between. Therefore, in 2006 we were motivated to begin a systematic program of study to assess DCV impacts on water and crop yields in major food-producing regions. We began with the Missouri River Basin (MRB) because it is the largest river basin in the U. S. A., is one of the most important crop and livestock-producing regions in the world, and experiences a pronounced decadal variability of droughts and wet periods (Fig. 8).

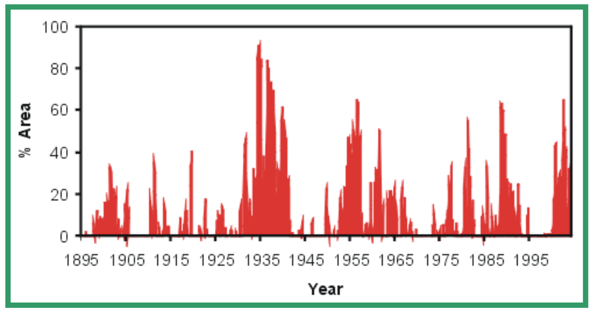


Figure 8: Percent of total Missouri River Basin area experiencing severe to extreme drought between January 1895 and March 2004. Based on data provided by the National Climatic Data Center, NOAA; Copyright 2004 National Drought Mitigation Center.

In a study of associations between DCV phenomena and hydro-meteorological (HM) variability in the MRB for Northern Hemisphere spring and summer, it was found that positive and negative phases of the Pacific Decadal Oscillation (PDO), the tropical Atlantic sea-surface temperature gradient variability (TAG), and the west Pacific Warm Pool temperature variability (WPWP) were significantly associated with decadal variability in precipitation and 2-meter air temperature in the MRB. with combinations of The various phases of these DCV phenomena , alone or in combinations involving two or more DCVs, are associated with drought, flood, or neutral hydro-meteorological conditions.

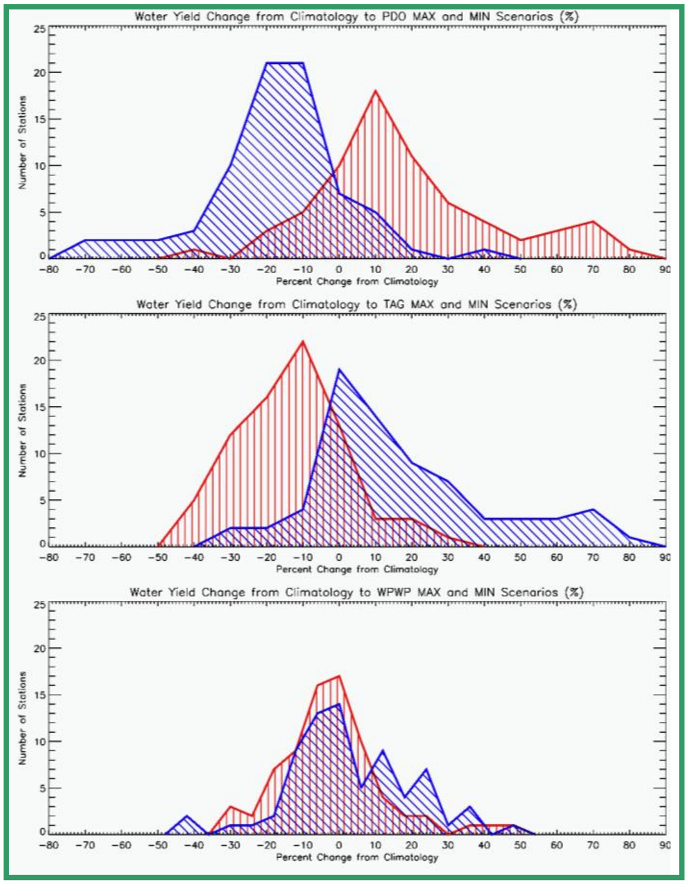


Figure 9: Aggregated water yield anomalies (%) in the MRB: (a) PDO$^+$ and PDO$^-$); (b) TAG$^+$ and TAG$^-$); and (c) WPWP$^+$ and WPWP$^-$). Blue line and hatching denote positive phase, and red line and hatching denote negative phase.

We developed and applied methodologies to assess whether the DCVs identified above directly affect the hydrology and crop yields in the MRB. The Hydrologic Unit Model of the United States (HUMUS) – Soil and Water Analysis Tool (SWAT) system, calibrated and validated for the MRB, was used to simulate water yields (in response to realistic values of the PDO, TAG and WPWP. HUMUS-SWAT. The models were applied to 75 widely-distributed, 8-digit hydrologic unit areas within the MRB. HUMUS-SWAT driven by HMV anomalies in both the positive and negative phases of the PDO and TAG resulted in major impacts on water yields--as much as ±20% of average water yield in some locations. Impacts of the WPWP were smaller. The distribution of water yield changes differed with phase (positive or negative) of the PDO and TAG. For all three DCV indices, the simulated impacts on water yield at the 75 study sites were more or less consistently distributed throughout the region. Aggregated water yield anomalies for the entire MRB in various phases of the three DCV phenomena are shown in Figure 9. The results of this study are described in *Mehta et al. (2011a).*

We also used the Erosion Productivity Impact Calculator (EPIC; also known as Environmental Policy Integrated Climate) model, calibrated and validated for the MRB, to simulate yields of dryland corn, winter and spring wheat, and soybean in response to HM anomalies associated with the aforementioned DCV phenomena. Realistic values of these DCV indices have major impacts on crop yields, as much as 50% of average yield in some locations in the MRB; however, our results also show that the impacts can be location-specific. Aggregated spring wheat yield anomalies for the entire MRB in various phases of the three DCV phenomena are shown in Figure 10. The results of this study are described in *Mehta et al. (2011b).*

Since the aforementioned three (and other) DCV phenomena can persist in one phase or another for several years to a decade or longer, and since the simultaneous correlation among these phenomena is negligibly small, their combined and cumulative positive/negative effects on the MRB water and crop yields can be dramatic, with consequences for transportation, recreation, fish and wildlife habitat, municipal and industrial water supplies, irrigation, food security, and the local, regional, and national economies.

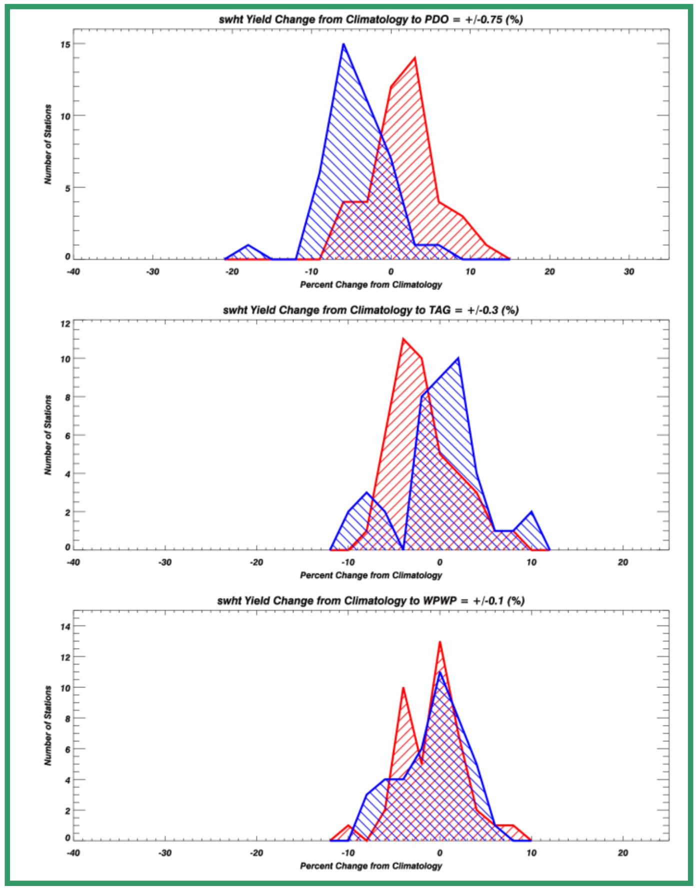


Figure 10: Aggregated spring wheat yield anomalies (%) in the MRB: (a) PDO^+ and PDO^-); (b) TAG^+ and TAG^-); and (c) $WPWP^+$ and $WPWP^-$). Blue line and hatching denote positive phase, and red line and hatching denote negative phase.

Since the MRB is a major American and global "bread basket", effects on irrigation and crop yields in particular can have implications for global food security as well. It may not be too far in the future that the evolution of major DCV phenomena and their associated HMVs will be effectively forecasted. If so, as the results of these exploratory and modest first tests demonstrate, it may become possible to prepare useful and reliable forecasts of multiyear to decadal water and crop yields in the MRB. The approach described here should also be applicable to other regions and other DCVs.

1.2.2 Assessments of Decadal Drought Information Needs of Stakeholders and Policymakers in the Missouri River Basin for Decision Support

As mentioned in the previous section, the MRB is the largest river basin in the U.S., and decadal droughts and wet periods in the MRB are correlated with various combinations of the three DCV phenomena mentioned in the previous section. With collaborators from the National Drought Mitigation Center (Univ. of Nebraska - Lincoln) and the Institute for Water Resources (US Army Corps of Engineers), we have been working on assessing impacts of and stakeholder information needs in the MRB for decision support with respect to decadal drought. This has been done through: (1) workshops involving stakeholders in the Basin; (2) development of retrospective drought and wet period scenarios using statistical modeling of DCV indices and their associations with hydro-meteorological variables in the Basin; and (3) development of sectoral impact evaluations through use of the HUMUS and EPIC models driven by the retrospective scenarios.

Approximately 100 stakeholders in the MRB, representing the water and agriculture sectors have helped define the problems and research approach we have developed. This has been accomplished by means of three dedicated workshops as well as interviews and discussions with well-placed individuals. The workshops were held in Kansas City; Helena, Montana; and Lincoln, Nebraska. There was a unanimous agreement among stakeholders that there are identifiable and quantifiable impacts, including economic impacts, of DCV on water, including urban water security, and agriculture. They made many important and specific suggestions to climate scientists for providing DCV information. Participants experienced DCV impacts on water and agriculture in the past and know that credible climate information can be useful in their work. The stakeholders are eager (e.g., Fig. 11) to use climate information, including decadal climate outlooks, as and when available. But there are obstacles to the effective use of such information by stakeholders: credibility of climate information must be established; institutional rules and regulations must be addressed and laws and legal precedents developed. The results of these assessment workshops and individual discussions are summarized in *Rosenberg et al. (2007)* and *Mehta et al. (2010a, 2010b, 2010c)*.

Figure 11: Honorable John Bohlinger, Lt. Governor of Montana, explaining the importance of this project to Workshop participants in Helena, Montana.

Our research activity on assessing impacts of DCV on water and agriculture in the MRB is now being expanded in two newly-awarded projects: One aims to develop an experimental decadal climate and impacts prediction system for the MRB, and to develop an experimental climate-adaptive water and agriculture management system for the region. The other aims to assess impacts of interannual to decadal climate variability on urban water security in the MRB.

2. A Leadership Role in Decadal Climate Variability and Societal Impacts Community Development

Beginning with its founding, CRCES has played a leadership role in the U.S. community or researchers stydying decadal climate variability and has contributed importantly to the development of a worldwide community of researchers on this topic. To date, CRCES has organized ten workshops on decadal climate variability and its societal impacts (please see Appendix 1 for details). These workshops were co-sponsored by NASA, NOAA, NSF, U.S. Geological Survey, and the U.S. Department of Energy. The number of participants in these workshops has varied from 40 to 125. Most of these workshops led to formulation of “white papers” with recommendations to U.S. funding agencies and climate research organizations about decadal climate variability research; some of these have been published in the peer-reviewed literature (e.g., *Mehta et al., 2006, 2011*). Thus, these workshops have played an important role in developing national and international research programs on decadal climate variability. CRCES has also contributed to community-wide “white papers” about decadal climate variability and predictability presented in international conferences such as OceanObs99 (*Mehta and Latif, 2001*) and World Climate Conference 3 (*Murphy et al., 2009*).

To further generate ideas and recommendations about assessment and possible prediction of impacts of decadal climate variability in the U.S. on water resources, agriculture, transportation, coastal preparedness, health, insurance industry, and economy, CRCES organized a special workshop to focus on societal impacts of decadal climate variability on the U.S. This workshop brought together a selected and unique group of climate scientists and societal impacts specialists. A “white paper” containing recommendations from this workshop was published by *Rosenberg et al. (2007)*. Under a grant from NOAA’s Sectoral Applications Research Program, two workshops were organized in 2009 and one in 2010 to assess decadal climate information needs of stakeholders and policymakers in the Missouri River Basin; the findings are available as reports by *Mehta et al. (2010a, 2010b, 2010c)*.

CRCES is also contributing significantly towards international development of climate and societal impacts research, education, and applications. For this purpose, CRCES and the Nirma University of Science and Technology in Ahmedabad, India, organized a workshop titled “The Workshop on Monsoon Climate Variability and Change, and Their Impacts on Water, Food, and Health in Western India” in February 2007. This workshop was co-sponsored by the U.S. National Science Foundation and the Indian Government Department of Science & Technology. This workshop brought together over 45 scientists from India, the U.S.A., Europe, and Japan. Conclusions and recommendations from this workshop led in August 2008 to the founding of the Indian Centre for Climate and Societal Impacts Research (ICCSIR) in Ahmedabad. Officers of CRCES are involved in the development of this Centre.

Figure 12: The entrance to the Virtual center for Decadal Climate Variability.

CRCES is also one of the pioneers of the application of contemporary information technology to climate research. The community of researchers interested in decadal climate variability and its societal impacts is worldwide. Because of the Internet and associated technologies, it is no longer necessary to physically co-locate researchers in one building in order to tackle the immense problems of understanding and prediction of decadal climate variability and its impacts. Therefore, with NASA sponsorship, CRCES created “the Virtual Center for Decadal Climate Variability” (www.DecVar.org; *Mehta et al., 2006*). The DecVar system uses the Internet to allow any participating scientist to do research as if he/she were physically located in a research center--to perform data analysis, communicate with other scientists, and access publications. Thus, the Virtual Center research “staff” consists of any scientist in the world who has access to a Web browser.

The accomplishments briefly described above have positioned CRCES as a leading institute in the global decadal climate and societal impacts research communities.

3. Publications

The research results described in this report have already been or are being published as peer-reviewed papers in frontline scientific journals such as *Journal of Geophysical Research - Oceans*, *Journal of Geophysical Research - Atmospheres*, *Journal of Climate*, *Journal of Physical Oceanography*, *Bulletin of the American Meteorological Society*, *Eos* – Transactions of the American Geophysical Union, *Advances in Atmospheric Sciences*, *Journal of the American Water Resources Association*, and *Agricultural and Forest Meteorology*. CRCES has also issued special reports aboutdescribing specific activities in which it has engaged. CRCES scientists have given invited and contributed seminars and presentations in various national and international conferences and workshops. The list of published papers, reports, and conference/workshop presentations is given in Appendix 2.

4. Grants, Personnel, and Collaborations

In its first decade, CRCES has obtained millions of dollars in grants from National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, National Science Foundation, U.S. Geological Survey, U.S. Department of Energy, and U.S. Department of Agriculture (see Appendix 3 for details). These grants were awarded for research on DCV analysis and modeling; global water cycle; assessments of DCV impacts on water resources and agriculture in the MRB; assessments of decadal drought information needs of stakeholders and policymakers in the MRB for decision support;

contributions towards a decision support system for reducing agricultural risks caused by climate variability in southeast U.S.; development of an experimental decadal climate and impacts prediction system and climate-adaptive water and agriculture management system for the MRB; and for organizing workshops on DCV and its societal impacts. These grants support senior scientists, research associates, research assistants, information technology specialists, and an administrative officer.

In view of the highly multi-disciplinary nature of CRCES's work, collaborations have been developed with distinguished scientists with complementary expertise in other organizations. These organizations are the National Drought Mitigation Center, University of Nebraska – Lincoln; Institute for Water Resources, the U.S. Army Corps of Engineers; Texas Agricultural and Mechanical University; and NASA-University of Maryland at Baltimore County – Joint Center for Earth System Technology.