Decadal Drought Risk Assessment and Scenario Development for Food and Bio-fuels Agriculture in Four Sub-basins in the Missouri River Basin*

Final Report

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Summary

Scientific objectives of this project were: (1) to define decadal drought information needs of agricultural stakeholders in four selected sub-basins of the Missouri River Basin (MRB); and (2) to conduct a scenario-planning exercise for coping with decadal droughts in the four sub-basins selected for study. Data analysis and modeling results prove conclusively that there are decadal hydrologic cycles (DHCs), with multiyear dry and wet parts, in the selected sub-basins – the James in North and South Dakota, the Central Platte in Nebraska, the Lower Grand in Missouri and Iowa, and the Marias in Montana. The results also strongly support the hypothesis that natural decadal climate variability phenomena are substantially associated with these DHCs. Interactions with representative stakeholders confirmed the occurrences of DHCs and their impacts on food, feed, and bio-fuels crop yields. They also provided important information about impacts on water resources for municipal and agricultural uses. Stakeholders clearly articulated their information needs to cope with dry and wet epochs, and outlined ways in which the information can be used if provided at the spatial resolution and format needed, and if provided well in advance of the onset of such epochs. A large degree of similarity of impacts, experiences, and coping actions strongly suggests that the results of this project are generalizable across the four sub-basins despite differences in crop types, sources and uses of water, importance of various sectors. Data analysis and modeling results, and stakeholder experiences also show that availability of irrigation for agriculture is not sufficient to protect against vagaries of climate variability, especially DHCs, because crops are under the influences of naturally-occurring precipitation as well as varying temperatures. Also, availability of groundwater is not an insurance against impacts of multiyear droughts on crop yields and productions.

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1. Introduction and Objectives

Multiyear to decadal hydrologic cycles (DHCs), with dry and wet epochs, affect infrastructure, electricity generation, river navigation, recreation, urban water systems, crop production, pasture and range conditions, livestock production and health, ecological integrity, and regional and national economies (see, for example, Mehta et al., 2013a). Recognition by decision-makers of the increasing societal consequences of DHCs has prompted legislation at the local, state and national levels encouraging water management and use efficiency. Floods cause loss of life and property in coastal regions and low-lying lands, and cause public health hazards that threaten the lives of survivors. The effects of multiyear to decadal droughts, however, are particularly dramatic, resulting in billions of dollars in crop losses around the world annually. Droughts affect more people worldwide than any other natural hazard (Wilhite, 2000). Shortages of water for drinking and irrigation, consequent reductions in food production, and other stresses due to drought contribute to social and political strife, civil wars, and international conflicts (see, for example, Gleick, 1993; Cooley et al., 2013). The negative consequences of long-duration droughts will intensify as growing numbers of humans and domesticated animals increase demands on available water supplies. The Final Declaration[1] of the recent United Nations sponsored High-level Meeting on National Drought Policy recognizes the need for and provision of drought information to affected countries and regions, and to help in the development of national drought policies. In addition to the need for information in times of immediate drought emergency, planning for water, food, energy, and urban infrastructure development would benefit greatly from reliable information on prospects for wet and dry periods in the next two or three decades.

Similarly, in the U.S., the goal of NOAA's National Integrated Drought Information System (NIDIS) is to improve the nation's capacity to proactively manage drought-related risks, by providing those affected with the best available information and tools to assess the potential impacts of drought, and to better prepare for and mitigate the effects of drought. NIDIS is especially focusing efforts on Drought Early Warning System (DEWS) regions, such as the Missouri River Basin (MRB), to provide a mechanism for the nation to prototype various approaches for developing early warning and information for proactive drought risk reduction. The goal of the DEWS is to explore and demonstrate a variety of early warning and drought risk reduction strategies that incorporate drought monitoring and prediction information in partnership with stakeholders and federal, state, regional, and local agencies[2].

To assist NIDIS in these efforts, this project aimed to develop an understanding of the needs of agriculture and water sector stakeholders in four sub-basins in the MRB for decadal drought information, and to develop scenarios of possible future decadal droughts and their impacts on agriculture and water in these sub-basins for use in decision support systems. The sub-basins chosen for study were: the James (North and South Dakota), the Central Platte (Nebraska), the Lower Grand (Iowa and Missouri), and the Marias (Montana). Our prior research demonstrated that strong linkages exist in the MRB between decadal variability of temperature and precipitation, the hydrologic cycle, drought severity and duration, water availability, and crop yields (Mehta et al., 2011, 2012, 2013, 2016; Mehta, 2017). These impacts can, in turn, affect allocation of land to cropping or livestock, stocking rates, investments in and management of irrigation, and availability of water for non-agricultural uses. These impacts substantially affect the regional economy as per our preliminary estimates (Fernandez et al., 2016) and

[1] Available from www.hmndp.org.
[2] https://www.drought.gov/drought/regions/dews

probably affect the national economy as well. Throughout this research and stakeholder engagement, we learned that DCV information can be of value to farmers and other agricultural sector decision makers in the MRB (Mehta et al., 2013). Our prior research, however, indicated that DCV impacts on MRB agriculture are highly crop- and region-dependent and, therefore, decadal climate and impacts information should be assessed and tailored for each affected region/sub-basin separately. It was also evident that scenarios of decadal droughts and their impacts should be developed and provided at regional/sub-basin spatial scales.

As stakeholder opinions, modeling, and quantitative data analyses in our previous projects showed, MRB-wide DCV-related dry and wet periods can substantially impact water availability and agriculture. It is also clear that decisions by farmers, water managers, and other stakeholders are made at the sub-basin (10 to 20 counties) to the individual county and smaller spatial scales. Therefore, climate information, including climate predictions, and scenarios of future decadal climate and potential impacts for use in stakeholders' decision support systems should be developed or generated at these spatial scales. However, this is a grand challenge for multidisciplinary climate impacts science because (1) unpredictable climate and weather noise increases with decreasing spatial scale; (2) identification of DCV-related climate signals becomes more difficult; (3) such noise in nature and prediction models makes it more difficult to predict decadal climate accurately at smaller than at larger spatial scales (e.g., state or MRB); and (4) impacts prediction at smaller scales is even more difficult because of the heterogeneity of agricultural conditions, types of crops planted, etc. All of the above combine to make the development or generation of future decadal climate and impacts scenarios more difficult at smaller spatial scales. Nevertheless, in view of the importance of decadal climate information and future climate and impacts scenarios to stakeholders, this grand challenge must be addressed. We addressed the grand challenge in this project and went from the MRB-wide scale of much of our previous research to the sub-basin and even the county scale. The scientific objectives of this project were: (1) to define decadal drought information needs of agricultural stakeholders in four selected sub-basins of the MRB; and (2) to conduct a scenario-planning exercise for coping with decadal droughts in the four sub-basins selected for study.

After this brief Introduction, roles of the project team, stakeholders, and interactions with them are described in Section 2; the importance of the MRB and each selected sub-basin is described in Section 3; natural decadal climate variability phenomena are introduced in Section 4; and results obtained towards Objectives 1 and 2 are described in Sections 5 and 6, respectively. Outcomes of the project and ideas for future work are summarized in Section 7. Names and affiliations of stakeholder advisory team (SAT) members are given in Appendices 1, 2, and 3.

2. Stakeholder Advisory Teams and Interactions

Stakeholders were an integral part of this project. Upon inception of this project, an SAT was recruited in each sub-basin to continually provide input into the research and evaluate the products developed. In three of the sub-basins, the SAT was comprised of 10 to 15 knowledgeable stakeholders representing agriculture, including farmers of corn for bio-fuels; water; and other appropriate sectors; and policymakers from appropriate federal, state, tribal, and local government agencies, as well as the private sector. Names and affiliations of members of these three SATs are given in Appendices 1, 2, and 3. In Montana, we interacted with officials in the State of Montana Department of Natural Resources and Conservation, Office of Water Resources. The state had recently been engaged with stakeholders as part of several planning

activities, and were concerned about stakeholder burnout. Therefore, they opted to meet with the research team rather than a full-fledged SAT.

A variety of stakeholder engagement methods was used to facilitate dialogue and information flow between the investigators and the SATs. These included webinars and individual discussions via email and phone to bring the partners together at critical times during the research process. Our existing website dedicated to MRB research was also made accessible to all SAT members. In order to solicit the SATs' inputs into this research project, we interacted with the SATs primarily via webinars and emails. One series of webinars was conducted to address each objective. A typical webinar began by the project team outlining the background of the project and its objectives. This was followed by an introduction to DCV and its impacts in the MRB. Then, results of analyses of observed hydro-meteorological, river flow, and crop yield data were shown and discussed. Hypothetical scenarios of future dry and wet epochs, and their potential impacts simulated by a land use-hydrology-crop model were also shown and discussed. After this presentation by the project team, outreach specialists on the project team moderated a discussion period with the SAT members by posing questions to the stakeholders; other members of the project team followed up with SAT members to clarify/add to details. Results of one round were discussed in the next round with the corresponding SAT to confirm outcomes.

3. Importance of the Missouri River Basin and selected sub-basins

The MRB (Fig. 1) occupies more than 500,000 square miles (~1,280,000 square km) covering part or all of 10 states, and two Canadian provinces. It is home to 28 Native American tribes. Inhabitants of the Basin depend on the Missouri River and its tributaries for drinking water, irrigation and industrial needs; hydro-electricity; recreation; navigation; and fish and wildlife habitat. The MRB contains some of the country's most sparsely-populated agrarian counties as well as large metropolitan areas such as Omaha, Kansas City, and Denver. The MRB is a very important agricultural region. It produces approximately 46% of U.S. wheat, 22% of its corn, and 34% of its cattle. About 117 million acres (~47.35 million ha) are in cropland with 12 million acres (~4.86 million ha) under irrigation[3]. Thus, almost 90% of the MRB's cropland is entirely dependent on precipitation and is, therefore, greatly affected by climate variability and change.

3.2 Selected Sub-basins

We used the following criteria to select sub-basins for this project: (1) availability of multidecadal time series of hydro-meteorological and crop data; (2) substantial decadal variability in variables such as precipitation, temperature, the Palmer Drought Severity Index, and stream flow; (3) association between sub-basin hydro-meteorological variability and DCV phenomena; (4) importance of the sub-basin in MRB agriculture, including present and future bio-fuels crops; (5) association of variability in yields of major crops with DCV and hydro-meteorological variability; (6) differences in crop types and practices (e.g., irrigation) among sub-basins to allow investigation of DCV impacts on a variety of agricultural conditions; and (7) interest of sub-basin stakeholder groups in working with us. Based on these criteria, we selected

[3] The distribution of irrigated acreage among the states is uneven; in Nebraska 33% of the arable land is irrigated; in Montana 11%; in Kansas 9%, and in South and North Dakota about 2% and slightly less than 1%, respectively.

the following four sub-basins for the proposed research. General locations of the sub-basins are marked in Figure 1.

3.2.1 The James River Sub-basin in North and South Dakota

The James River is a tributary of the Missouri River in North and South Dakota. The primary crops in this sub-basin are spring and winter wheat, corn, soybeans, and sunflower. Alfalfa and fodder grasses are also important for supporting beef cattle production. Both North and South Dakota are major corn-based ethanol producers. Twice as much land is cropped to grains as fodder and range. Significant decadal hydrologic cycles, comprising of multiyear dry and wet periods, occur in the James River sub-basin. Other related problems include diminishing wildlife habitat, soil erosion, and water quality degraded by runoff from crop and livestock production. Glacial lakes and wetlands support waterfowl, hunting, and fishing and the tourism they encourage. The Sand Lake National Wildlife Refuge also contributes to tourism in this sub-basin.

3.2.2 The Central Platte River Sub-basin in Nebraska

The Platte River is considered to be one of the most endangered waterways in the U.S. The Central Platte River extends approximately 90 miles from Lexington to Chapman, Nebraska, and is managed primarily by the Central Platte Natural Resources District (NRD). According to the Central Platte NRD Master Plan (2011), agricultural land use in the Central Platte NRD includes cropland (48.5%), pasture and rangeland (38.5%), and some woodland and other minor land cover. Major crops in the Central Platte sub-basin include corn, soybeans, alfalfa and wild hay. Much of the cropland (estimated at 90%) is irrigated row crop. Approximately 10% of irrigation uses surface water, mostly from the Platte River, and the balance between surface and ground water uses is very carefully maintained. Nebraska is also a major corn-based ethanol producer. Livestock production is also prominent, featuring cattle, hog, and turkey operations along with some dairy cattle and sheep. The central Platte River also provides critical migration habitat for the endangered whooping crane, spring staging habitat for 80% of the world's Sandhill crane population, breeding habitat for the threatened piping plover and endangered least tern, and migrational and wintering habitat for millions of waterfowl. Over 300 bird species have been observed along the Platte River, and over 140 species are known to nest along the river (U.S. Fish and Wildlife Service, 2001). Management priorities in the Central Platte sub-basin are most often related to water management issues. High priority items include efforts to manage Platte River flows so that the interests of irrigated agriculture producers may coexist with endangered species recovery and urban interests during drought periods, and floodwater management to prevent property damage and limitations to agriculture production during wet years (Natural Resources Conservation Service, 2013).

3.2.3 The Lower Grand Sub-basin in Iowa and Missouri

Grasslands occupy 53% and row crops 32% of the agricultural land in the Lower Grand sub-basin straddling the Iowa–Missouri border. Forests occupy approximately 14% of the remaining non-urban land. The principal crops in this sub-basin are dryland corn, soybeans, and wheat, with a substantial fraction of corn used in producing ethanol. Wildlife habitat and the recreation sector make heavy (but non-consumptive) use of the sub-basin's water supplies. According to the Missouri Department of Natural Resources (DNR), the sub-basin is in an area of the state where drought conditions can threaten the drinking water supply for many communities. Because of the concern for drought, other water management issues, and stakeholder interests, the Missouri DNR selected this sub-basin to initiate its "Our Missouri

Waters Initiative"[4], an effort to move towards watershed-based management. The project's goal is to develop infrastructure, policies, and procedures to move the entire state to watershed-based management.

3.2.4 The Marias – Musselshell – Poplar Sub-basin in Montana

The Marias sub-basin in Montana is a very important agricultural region, with a mix of dryland and irrigated crops -- winter wheat, malting barley, and alfalfa most important among them. Fisheries and wildlife/conservation sectors are also important. There is a substantial interest and support from stakeholder groups, including a strong State of Montana interest in seeking climate information for water planning. Contiguous to and downstream from the Marias sub-basin on the Missouri River is the Musselshell sub-basin that has very active watershed groups and agricultural community. Downstream of the Musselshell is the Poplar sub-basin that produces a large fraction of the durum wheat grown in the U.S. In this project, these three sub-basins were treated as one ("the Marias sub-basin") due to their geographical contiguity, dependence on the Missouri River, and overlapping interest and support of stakeholder groups in the three sub-basins.

4. An Introduction to Natural Decadal Climate Variability

The study of natural decadal climate variability (DCV) and its societal impacts has a multi-century history. The phrase DCV is due to the association of climate variability with 11-year and 22-year sunspot cycles. In the last 30 years, analyses of observations and simulations with climate models have shown that natural DCV can occur due to ocean-atmosphere interactions, land-atmosphere interactions, and changes in atmospheric aerosols due to volcanic eruptions and human-induced industrial and other activities. Eleven- and 22-year cycles of solar radiation are also believed to be important in natural DCV.

Several DCV phenomena have been identified in observed data on sea-surface temperatures (SSTs), precipitation, and atmospheric winds and temperatures. Two major DCV phenomena are briefly described here. The Pacific Decadal Oscillation (PDO) occurs primarily due to interactions between the Pacific Ocean and the atmosphere. In the positive or warm phase of the PDO, SSTs in the tropical-subtropical Pacific are warmer than average and those in the midlatitude Pacific are cooler than average as shown in Figure 2a. In the negative or cool phase, the SST anomaly pattern is opposite to that in the positive phase. The so-called PDO index (Fig. 2b) shows the variability of this pattern since early 20th century. Figure 2a shows the change in SST anomaly for every unit change in the PDO index. As Figure 2b shows, the PDO persists in one phase for years to decades. As the SST anomalies associated with the PDO influence global atmospheric circulations and water vapor transport, the PDO influences worldwide climate at multiyear to multidecadal timescales.

Another major DCV phenomenon is the variability of cross-equatorial SST gradient in the Atlantic Ocean. The spatial pattern of this tropical Atlantic SST gradient (TAG) variability is shown in Figure 3a. As the figure shows, the gradient points from south to north in the positive TAG phase when SST anomalies north of the equator are warmer than those south of the equator. In the negative TAG phase, the gradient points southward across the equator. The TAG index (Fig. 3b) undergoes multiyear to decadal and longer term variability. The TAG pattern substantially influences climate on both the eastern and western sides of the Atlantic Ocean, Europe, and Asia to some extent.

[4] www.dnr.mo.gov/omwi.htm

Impacts of global-scale DCV phenomena on the climate of the U.S. are reasonably well-documented and quantified by analyses of large-scale climate observations. There are indications that large-scale climate forcings by the PDO (e.g., Ting and Wang, 1997; Mehta et al., 2011), the TAG variability (e.g., Schubert et al., 2004; Mehta et al., 2011), and the WPWP variability (e.g., Wang and Mehta, 2008; Mehta et al., 2011) influence precipitation variability in the MRB. Interannual El Niño – Southern Oscillation (ENSO) variability explains less than 20% of the MRB total precipitation, runoff, and streamflow variance while decadal (>7 years) timescale variability explains approximately 40-50% (Cayan et al., 1999; Guetter and Georgakakos, 1993; Lins, 1997). The DCV influences in the MRB are also reflected in the percentage of its area under severe to extreme drought conditions (Mehta et al., 2013). Portions of the MRB also experienced a multiyear to near-decadal drought during the first decade of the 21st century. The Basin has also experienced multiyear to decadal wet epochs, such as that in the 1990s.

5. Objective 1

To define decadal drought information needs of agricultural stakeholders in four selected sub-basins of the MRB.

In discussions with the SATs on Objective 1, tasks of the project team were: (1) to introduce natural DCV phenomena or cycles; (2) to show there are substantial associations between these climate cycles, and dry/wet cycles, crop yields and productions in each selected sub-basin; and (3) to provide past and possible future scenarios of dry/wet cycles, water availability, crop yields to stakeholders. The SAT members' tasks were: (1) to provide detailed and quantitative information about agriculture and water resources in each sub-basin; and about present and future use of corn and other crops to produce bio-fuels; (2) to describe perceptions of these dry/wet cycles and impacts on water and crops; (3) to discuss how they might have used this information if provided as forecasts; (4) to suggest best methods to convey such information to users of climate and impacts information; and (5) to disseminate information about this project and its results to other stakeholders.

We began by showing and discussing highlights of our previous research on DCV impacts on hydro-meteorology, river flows, and crop yields in the entire MRB (Section 5.1). Then, initial questions given in Section 5.2 were posed to the SATs. Analysis results for each sub-basin and our discussions with each SAT to address Objective 1 are described in Section 5.3.

5.1 Hydro-meteorological, River flow, and Crop Yield Variability

In our past research, we isolated precipitation and temperature patterns associated with the PDO, the TAG variability, and other DCV phenomena. As an example, Figure 4 shows precipitation and daily maximum temperature anomaly patterns associated with positive and negative phases of the PDO. These patterns were derived with regression analyses of observed precipitation and PDO index data from 1961 to 2010 (Mehta et al., 2016).

Figures 4a and 4c show that in the positive or warm phase of the PDO, almost the entire MRB is wetter and cooler than average; the climate is drier and warmer in the northern part of the Basin in this PDO phase. In the negative or cold PDO phase, much of the MRB is drier and warmer than average (Figs. 4b and 4d), with the northern part wetter and cooler than average. In general, physical agreement with these PDO-associated precipitation and temperature anomalies, USGS-observed streamflow anomalies in a specific warm PDO period (1982-1986) (Fig. 5a, left column) are positive in almost the entire MRB, implying above average flows. In a specific cold PDO period (1987-1990), streamflow anomalies were negative in almost the entire MRB (Fig. 5a, right column); that is, streamflows were below average in this period. We simulated

streamflows during these two PDO periods with a land use-hydrology-crop model, the Soil and Water Assessment Tool, forced by observed precipitation, temperature, and other hydro-meteorological anomalies in these two periods (Mehta et al., 2016). Figures 5b (left and right columns) show the simulated streamflow anomalies in these two periods, which are very similar to the USGS-observed streamflow anomalies. Thus, observed hydro-meteorological and streamflow data, and simulated streamflows show substantial impacts of the PDO in the MRB. The TAG variability and other DCV phenomena make smaller but significant impacts on the MRB as well (Mehta et al., 2016).

To further quantify associations between DCV phenomena and hydro-meteorological anomalies in each selected sub-basin, we calculated probabilities of precipitation and daily maximum temperature being above or below average in each phase of each DCV phenomenon, using very high resolution (7 km x 7 km) data from 1961 to 2015. Probabilities of above or below average streamflows were also calculated similarly wherever observed USGS data are available within each sub-basin. Then, using crop yield data estimated by the USDA-National Agricultural Statistics Service for approximately 55 years from 1961, we calculated probabilities of above or below average yields in each phase of each DCV phenomenon. Some of the results of these calculations are shown in Section 5.3.

5.2 Questions Posed to SATs

The following questions were posed to SATs during the first webinar. Section 5.3 describes the analysis conducted for each sub-basin followed by SAT responses to the questions.

- Please tell us about agriculture and water resources in your sub-basin, and the type of water resource (surface, groundwater) used in irrigation, if any.
- What are your perceptions of dry/wet cycles and their impacts?
- What are typical agricultural management practices in your sub-basin? Crop rotations?
- Please tell us about present and future use of corn and other crops to produce bio-fuels.
- Is run-off from farms and other sources contaminating water resources?
- Is there a competition for water among food production and other uses?
- Would it help stakeholders in your sub-basin if we can predict dry/wet cycles, streamflows, and crop yields one or more years in advance?

5.3 Interactions with Stakeholders

5.3.1 The James River Sub-basin in North and South Dakota

The rationale for selecting the James River sub-basin for this study is outlined in Section 3.2.1. A map of the James River sub-basin is shown in Figure 6. The James River sub-basin is within the overall MRB, with the James River flowing generally parallel to the Missouri River in North and South Dakota until their confluence near Yankton near the South Dakota-Nebraska border.

As mentioned in Section 5.1, we estimated probabilities (in percent) of above- and below-average precipitation and daily maximum temperature for positive and negative phases of the PDO, the TAG variability, and other DCV phenomena, using all available hydro-meteorological data in each county of the James River sub-basin. Then, differences between the above- and below-average probabilities were calculated for each DCV phenomenon and phase, and are shown in Figure 7 as county averages; only the results for PDO phases is shown as an example. Figure 7 shows that, in the positive or warm PDO phase, conditions are more likely to be generally wet in the south and dry in the center and the north by as much as 20-25%, and

generally warm except in the center part of the sub-basin. In the negative or cold PDO phase, conditions are more likely to be dry in the south and wet in the center and the north, and generally cool except in the southern part of the sub-basin. The differences between probabilities of above- and below-average streamflows are in physical agreement with the hydro-meteorological results as Table 1 shows for the locations where the USGS measures streamflows. In the positive or warm phase of the PDO, the probabilities of below-average streamflows is much higher than above-average streamflows as can be expected from generally less precipitation and warmer temperatures.

As mentioned in Section 3.2.1, major crops in the James River sub-basin are spring and winter wheat, corn, soybeans, and hay. We analyzed NASS crop yields estimates to calculate probabilities of above- and below-average yields associated with DCV phenomena and phases. As in Figure 7 and Table 1, differences in probabilities were calculated and are shown in Figure 8 for PDO phases. Actual years of data are also shown in Figure 8. In the positive or warm phase of the PDO in almost all counties, probabilities of above-average soybean and hay yields are substantially higher than below-average yields, whereas probabilities of below-average wheat and corn yields are much higher. The behavior of crop yields is generally opposite in the negative or cold phase of the PDO. The higher probabilities of below-average corn and wheat yields in the warm PDO phase is generally consistent with drier and warmer conditions over most of the sub-basin. Apparently, soybeans and grass prefer such hydro-meteorological conditions and that is why the probabilities of above-average yields are higher for these two crops.

As described briefly in this Section, DCV phenomena make substantial impacts on hydro-meteorology, river flows, and crop yields in the James River sub-basin. These results were shown and explained to the James River SAT. These explanations were followed by a discussion on specific topics with the SAT members. A summary of this discussion is provided here.

Agriculture and water resources in the James River sub-basin, and the type of water resource (surface, groundwater) used in irrigation

In South Dakota, both surface and groundwater are used, with surface water allocated out of the James River by the Water Management Board which places a limit on the amount of diversions allowed. Groundwater is withdrawn from aquifers throughout the length of the basin, with the withdrawals restricted by the requirement that the average annual use cannot exceed average annual recharge. Both surface and groundwater are used for irrigation, especially in the northern part of the sub-basin where groundwater aquifers are fully appropriated. Corn, soybeans, wheat, and potatoes are main crops in the sub-basin. Corn and soybeans are the most frequently irrigated crops, needing water later in the growing season.

Perceptions of dry/wet cycles and their impacts

There are 7-12 year and 22-25 year wet/dry cycles in the sub-basin, with the combination of cold phase of the PDO and La Niña resulting in wet epochs. Precipitation in eastern North Dakota undergoes pronounced decadal variability.

Potential usefulness of prediction of dry/wet cycles, streamflows, and crop yields one or more years in advance

Such predictions can catch the attention of urban and agricultural communities. In North Dakota, there is a lack of understanding of community vulnerabilities to droughts and how to cope with them. On the state level, there is a drought committee but local and tribal levels need more guidance. Even the initial information/results from this project can be useful for increasing understanding and awareness.

In the agriculture sector, this project can help to decide which crops/varieties to use. Many farmers would probably use the information to put safeguards in place, such as using specific hybrids if the prediction is for going into dry or wet epoch. Genetic research in the last several decades has resulted in new varieties of seeds that can withstand droughts or wet conditions better. Using these varieties of seeds, farmers might plant more drought-resistant seeds of the same crop (for example, corn) rather than change to another type of crop if DCV prediction points to a drier epoch in the next several years. In general, farmers would change crop varieties before they would change crop types if a dry or wet epoch is predicted. There may also be other adaptation actions such as planting a type of crop that may need water in spring if a wetter spring and drier summer/autumn are predicted rather than crops which require water in summer/autumn. A change in land tilling practices may also be used. For example, if a dry epoch is predicted, farmers might not till their lands or use a tilling practice that conserves soil moisture. If a wet epoch is predicted and if there is already substantial moisture in the soil, farmers might till the land to expose moisture and dry their fields. The SAT members also noted that some people may not trust the predicted information unless there is a track record of trustworthiness of information. Overall, the members said that predictions would be a useful tool for them.

Present and future use of corn and other crops to produce bio-fuels

Since this project includes bio-fuel crops such as corn and soybeans, there was a substantial discussion about present and future bio-fuels production in the James River sub-basin. The SAT members said that since the first bio-fuels plant was built in the sub-basin in 2007, a substantial fraction of the corn production is used to make ethanol. In addition, to process the sub-basin's soybeans production (just one county produces more soybeans than the entire state of Alabama), a new plant is being built which will process 20-25% of the sub-basin's production to produce vegetable oil, bio-diesel, and animal feed. The sub-basin's soybean production is impacted by DCV phenomena, so future climate variability will influence oil and bio-diesel productions.

5.3.2 The Central Platte River Sub-basin in Nebraska

A Central Platte River sub-basin map is shown in Figure 9. As the map shows, the Platte River flows across Nebraska from west to east. We estimated probabilities (in percent) of above- and below-average precipitation and daily maximum temperature for positive and negative phases of the PDO, the TAG variability, and other DCV phenomena, using all available hydro-meteorological data in each county of the Central Platte River sub-basin. Then, differences between the above- and below-average probabilities were calculated for each DCV phenomenon and phase, and are shown in Figure 10 as county averages; only the results for PDO phases is shown as an example. Figure 10 shows that, in the positive or warm PDO phase, conditions are more likely to be generally wet, except for two counties in the center, and warm everywhere in the sub-basin. In the negative or cold PDO phase, conditions are more likely to be dry almost everywhere, and generally cool or slightly warm.

The differences between probabilities of above- and below-average streamflows are in physical agreement with the hydro-meteorological results as Table 2 shows for the locations where the USGS measures streamflows. In the negative or cold phase of the PDO, the probabilities of below-average streamflows is much higher than above-average streamflows as can be expected from generally less precipitation and warmer temperatures.

Major crops in the Central Platte sub-basin include corn, soybeans, alfalfa and hay. Much of the cropland (estimated at 90%) is irrigated row crop. We analyzed NASS crop yields estimates to calculate probabilities of above- and below-average yields associated with DCV phenomena and phases. As in Figure 10 and Table 2, differences in probabilities were calculated and are shown in Figure 11 for PDO phases. Actual years of data are also shown in Figure 11. In the positive or warm phase of the PDO, there are wetter and warmer conditions in almost all counties. There are higher probabilities of below-average soybean; and above-average wheat, corn, and hay yields in almost all counties as Figure 11 shows. The behavior of crop yields is generally opposite in the negative or cold phase of the PDO. The higher probabilities of below-average soybean yields in the warm PDO phase is generally consistent with wetter and warmer conditions over most of the Central Platte sub-basin. Apparently, soybeans dislike such hydro-meteorological conditions and that is why the probabilities of below-average yields are higher for soybeans.

These results were shown and explained to the Central Platte River SAT. These explanations were followed by a discussion on specific topics with the SAT members. A summary of this discussion is provided here.

Agriculture and water resources in the Central Platte River sub-basin, and the type of water resource (surface, groundwater) used in irrigation

Irrigated agriculture is expanding in the last 30 years or so, with approximately 75% of the irrigated agricultural land in the MRB located in Nebraska. Agricultural irrigation has the highest priority of water rights in the Central Platte sub-basin, followed by recreation, fish and wildlife habitat, groundwater recharge, and hydro-electricity generation. Water released from reservoirs primarily for agricultural irrigation is also used for hydro-electricity generation. Groundwater is the dominant source of irrigated agriculture in Nebraska. In the Central Platte sub-basin, Lake McConaughy is the main source of reservoir water in addition to surface water from rivers and streams. Irrigation water is used to grow soybeans and corn, whereas wheat is grown on non-irrigated land.

Crops irrigated by surface water are the first to suffer during a drought. Groundwater irrigation would suffer in a multiyear to decadal drought. A SAT member's personal observation is that since 75% of the farms in the Central Platte sub-basin have wells to draw on groundwater, these farms can switch from surface water to groundwater irrigation during periods of lower precipitation, so there may not be a substantial change in crop yields due to droughts for such farms. As we see in empirical estimates of crop yields (Fig. 11), however, county-aggregated yields do show impacts of precipitation and temperature variability associated with the PDO (and other DCV phenomena).

Perceptions of dry/wet cycles and their impacts

SAT members opined that agriculture in the Central Platte sub-basin can withstand an average of 3 years of drought; perhaps, some farmers with accessible groundwater and other resources can withstand 5 years of drought.

Potential usefulness of prediction of dry/wet cycles, streamflows, and crop yields one or more years in advance

The SAT members indicated that such predictions would be useful, especially if predictions can be made at several times during the crop cycle, such as late winter-early spring, and late fall after harvest. A prediction of the Rocky Mountain winter snow pack – which supplies water to Lake McConaughy and rivers in the Central Platte sub-basin – would also be very useful for the following crop cycle. The late fall-winter prediction would help decisions regarding which crop and how much to plant in the following crop cycle; for example, whether to plant soybeans (likes drier conditions) or sorghum (likes wetter conditions) in non-irrigated fields. The members also suggested that the predicted conditions should be classified as very dry, dry, wet, and very wet for maximum usefulness in decision making. Such predictions would also help inform the usual corn-soybeans rotations which have two years of corn and one year of soybeans; if predictions favor one or the other crop, farmers can change the rotation accordingly.

Present and future use of corn and other crops to produce bio-fuels

Most of the grains produced in the Central Platte sub-basin are for bio-fuel and food for various livestock and poultry. Approximately 40-45% of Nebraska corn is grown for bio-fuels in this sub-basin, with a small fraction of total soybeans production used in bio-diesel production. Therefore, the DCV impacts on corn and soybeans production would make a sizeable impact on bio-fuels production in the Central Platte sub-basin.

Thus, as described briefly in this Section, DCV phenomena make substantial impacts on hydro-meteorology, river flows, and crop yields in the Central Platte River sub-basin.

5.3.3 The Lower Grand Sub-basin in Iowa and Missouri

Figure 12 shows a map of the States of Iowa and Missouri, with the Lower Grand sub-basin outlined in yellow/orange. We estimated probabilities (in percent) of above- and below-average precipitation and daily maximum temperature for positive and negative phases of the PDO, the TAG variability, and other DCV phenomena, using all available hydro-meteorological data in each county of the Lower Grand River sub-basin. Then, differences between the above- and below-average probabilities were calculated for each DCV phenomenon and phase, and are shown in Figure 13 as county averages; only the results for PDO phases is shown as an example.

Figure 13 shows that, in the positive or warm PDO phase, conditions are more likely to be generally wet, except for one county in the southeast and one in the extreme north, and cool everywhere in the sub-basin except in the northern-most county. In the negative or cold PDO phase, conditions are more likely to be dry and warm everywhere in the Lower Grand sub-basin.

The differences between probabilities of above- and below-average streamflows are in physical agreement with the hydro-meteorological results as Table 3 shows for the locations where the USGS measures streamflows. In the negative or cold phase of the PDO, the probabilities of below-average streamflows is much higher than above-average streamflows as can be expected from generally less precipitation and warmer temperatures.

Major crops in this sub-basin are dryland (non-irrigated) corn, soybeans, and wheat, with a substantial fraction of corn production used to produce ethanol. We analyzed NASS crop yields estimates to calculate probabilities of above- and below-average yields associated with DCV phenomena and phases. As in Figure 13 and Table 3, differences in probabilities of crop yields were calculated and are shown in Figure 14 for PDO phases. Actual years of data are also

shown in Figure 14. In the positive or warm phase of the PDO, there are wetter and cooler conditions in almost all counties. There are higher probabilities of above-average soybean yields in all counties; and slightly above- or below-average corn yields in almost all counties; and above-average wheat yields in all except two counties as Figure 14 shows. The behavior of crop yields is generally opposite in the negative or cold phase of the PDO.

These results were shown and explained to the Lower Grand River SAT. These explanations were followed by a discussion on specific topics with the SAT members. A summary of this discussion is provided here.

Agriculture and water resources in the Lower Grand River sub-basin, and the type of water resource (surface, groundwater) used in irrigation

Agricultural irrigation is fed largely by groundwater sources in the two southern-most counties of the sub-basin and by surface water sources, including the Grand River and privately-owned lakes, in the northern part of the sub-basin. The middle part of the sub-basin – Putnam, Grundy, and Sullivan Counties – contains non-irrigated agriculture. Water for domestic use is mostly from surface water sources and wells, some cities along Grand River use water from the River and wells along it.

Water quality is a major problem in the Lower Grand sub-basin. There are many impaired streams with E. Coli bacteria, sediment, and nutrient loading. The sediment loading is due to erosion caused by channeling of streams and the nutrient loading is from row crops, pastures, and water treatment facilities. In some areas, water quality is also affected by a layer of clay under the top soil. When there is substantial erosion, clay adheres to water molecules making brackish water of poor quality.

Perceptions of dry/wet cycles and their impacts

SAT members had observed dry and wet epochs in the 1970s and 1980s, and their impacts on crop yields including quality of grains, corn and soybeans prices, and cattle production. They had also observed that stronger water flows during wet epochs increased soil erosion and resulted in water pollution. Some ranchers noted that adaptation of cattle-grazing to dry and wet epochs was essential; those who did not have to downsize their herds.

Potential usefulness of prediction of dry/wet cycles, streamflows, and crop yields one or more years in advance

SAT members expressed several opinions about the potential usefulness of prediction. They focused mainly on droughts. Some members opined that skillful predictions can help them when choosing more drought-tolerant crops or varieties within a particular crop. Examples of potential choices mentioned were soybeans or corn, or sorghum or corn. Skillful predictions can also inform decisions about selling or retaining cattle and/or which age group of cattle to sell or retain. One member opined that sometimes it is better not to know what is going to happen, then there is no stress and stakeholders would just have to adjust to whatever happens.

Present and future use of corn and other crops to produce bio-fuels

There is not much bio-fuel production in the Lower Grand sub-basin due to market conditions - such as low cost of fossil fuels and the cost to transport bio-fuel crops to a processing facility.

5.3.4 The Marias Sub-basin in Montana

The prevailing drought and the fear of stakeholder burnout, the project team was only able to discuss the project with two state advisors in the DNRC water office. They provided the following information.

The information about DCV and its impacts in Montana would be most suitable for dryland farmers. Future efforts could be made outside of drought periods in discussing with the Montana grain growers' association, and by working in the future with the Department of Agriculture. Beyond the use of scenario planning, the two advisors said that drought in 2017 was an agricultural drought. The producers that had access to irrigation did quite well in 2017, while the dryland farmers suffered. Also, through additional discussion there may be a use of this information for irrigated crop land farmers, especially if there was reliable predictability. One advisor stated that active planning in the watershed groups and municipalities in terms of water supply could possibly use this information. The Upper Missouri Basin Water Basin Group might also be a group to include in future studies, along with any State of Montana drought planning efforts.

5.3.5 Drought Information Needs

To provide information to the SATs about the lengths and severities of past droughts in the selected sub-basins, we categorized severities and durations of dry and wet epochs in each sub-basin, using the Palmer Drought Severity Index (PDSI) data from 1915 to 2014. The data showed pronounced dry-wet cycles in each sub-basin such that a cycle evolved from very dry (wet) to very wet (dry) and back to very dry (wet) in several years to a decade. We found that the sub-basins experienced 10 to 14 dry events of low severity, each of which lasted 4 to 7 seasons; 2 to 5 dry events of low severity, each of which lasted 8 to 11 seasons; and 1 to 2 dry events of low severity, each of which lasted more than 12 seasons. There were 5 to 8 dry events of medium severity, each of which lasted 4 to 7 seasons; and up to 3 dry events of medium severity, each of which lasted 8 to 11 seasons or longer. Depending on the sub-basin, there were 2 to 7 dry events of high severity, each of which lasted for 4 to 7 seasons. These statistics showed that the selected sub-basins have been prone to droughts of various severities lasting up to 2 to 3 years. Then, in response to the SATs interest in the possibility of predicting such dry (and wet) events 1 to 2 seasons before the planting seasons, we estimated the potential predictability of PDSI anomalies by estimating time-delay correlations between DCV indices and PDSI anomalies. Results showed that there appears to be a potential to predict at least the sign of the PDSI anomaly 2 to 3 seasons in advance; for example, using the PDO and TAG indices in the September-October-November season as predictors to predict PDSI in the following 3 seasons and to use the indices in the December-January-February season to predict PDSI in the following 3 seasons.

SAT members were excited by these results and responded that such multi-season outlooks can be very useful to farmers, livestock producers, and for state emergency preparedness if it can be provided routinely. If the reliability of such information can be shown and if the information can be made available widely and publicly, it can also help in stabilizing market prices of commodities. If a decision support tool is developed and made available, users can see possible impacts of the DCV phenomena and ENSO on their geographical area and sector over the next several seasons.

5.3.6 Summary of Initial Interactions with the SATs

In initial interactions with the SATs of the James, Central Platte, and Lower Grand sub-basins, we found that surface and ground water are used for irrigation to various extents in the

three sub-basins; Central Platte is perhaps the most irrigated sub-basin among the three. It was also found that SAT members have experienced multiyear to decadal dry and wet epochs or cycles to various degrees. They also articulated a positive need of multiyear to decadal prediction for water resources management, agricultural infrastructure planning, crop/variety choice, disaster management; and stressed the potential usefulness of skillful predictions. It was also found that many of the SAT members were very responsive and keen to work with the project team.

6. Objective 2

To conduct a scenario-planning exercise for coping with decadal droughts in the four sub-basins selected for study.

In discussions with the SATs on Objective 2, the project team introduced two types of scenarios: (1) Scenarios based on observed data in the last 10 years; and (2) scenarios based on simulations with a land use-hydrology-crop model. In type-2 scenarios, simulations were carried out to estimate responses of river flows and crop yields to average climatic conditions and to extreme climatic conditions. Both types of scenarios were shown to the SAT members.

We began by showing and discussing possible scenarios on hydro-meteorology and crop yields in each sub-basin. Then, the following questions were posed to each SAT as the basis for detailed discussions about how they and other stakeholders might cope with the hypothetical scenarios.

・If these scenarios were provided to you before/while transitioning from wet to dry or dry to wet, how would you use this information to make decisions if you were a farmer, rancher, water manager, local-county-state official, or extension service provider?

・Would there be any difference(s) in coping with dry and wet epochs?

・Would the precipitation anomaly be more important or the temperature anomaly?

・What would you like in the predicted outlook of these epochs to take action and when would you like the information?

Highlights of the scenarios and SAT members' responses are described here.

6.1 The James Sub-basin

PDSI data showed that the James sub-basin experienced a wet epoch from 2007 to 2011 and a dry epoch from 2012 to 2014-15. River flow data in the sub-basin showed physically consistent above- and below-average flows in these two epochs, respectively. Corn, soybean, hay alfalfa, sunflower, and winter wheat yields were consistent with the hydro-meteorological data. These two recent epochs were selected to make composite scenarios of observed precipitation, temperature, and crop yields. Precipitation and temperature composites in the wet epoch showed that this was not only a wet epoch but was also a cool epoch. The dry epoch had above-average temperature anomalies, so it was a dry and warm epoch. Composite crop yield scenarios in the wet and dry epochs are shown in Figure 15. Generally larger crop yields (positive crop yield anomalies), especially of corn and soybean, in the wet epoch are seen in Figure 15.

SAT members observed that the observations-based wet and dry epochs were very consistent with disaster declarations by the Federal Government, thus linking empirical data to government decisions. They also noted that there was a multiyear dry epoch from 2000 to 2007, which was also represented in the PDSI data, then the 2007 to 2011 wet epoch occurred,

followed by the 2012 to 2014-15 dry epoch. Thus, the 2000 to 2015 hydrologic cycle lasting 15 years was represented both in empirical data and in stakeholders' experience. The wet epoch required installation of many mobile stream gauges in North Dakota and South Dakota to monitor potential local flooding. Due to above-average river flows, especially in the Red River, in this wet epoch, reservoirs were full and golf courses were flooded. In some autumns of this wet epoch, crops were too wet to harvest until they dried out in the following spring. It was opined that the larger corn yields in the wet epoch may be due to two corn harvests in some years.

If such dry/wet epochs occurred again and if stakeholders were provided appropriate information in advance, farmers would cope by changing land management practices such as tilling/not tilling fields, planting/not planting cover crops, and adjustments to crop rotation. If a dry epoch was predicted, land would not be tilled to preserve moisture in the soil, but if a wet epoch was predicted, land would be tilled to expose moisture and allow soil to dry in anticipation of more wetness. They would use different seeds, chemicals, fertilizers, and equipment, depending on whether a wet or a dry epoch was predicted. The SAT opined that local, tribal, and state mitigation and emergency planning could use this information to understand how the hydrological situation in the sub-basin is evolving, and update their plans to cope with the evolving situation. SAT members also stated that if a multiyear hydrologic outlook were provided to stakeholders in the autumn, farmers can benefit by scheduling equipment and seed purchases before the end of the tax year. Ranchers may choose to wean calves earlier than usual or cull their herd with this information. In general, stakeholders would like to see a reliable 2 to 3 season forecast, and a 2 to 3 year outlook.

6.2 The Central Platte Sub-basin

PDSI data showed that the Central Platte sub-basin experienced a wet epoch from 2007 to 2010 and a dry epoch from 2011 to 2015. These two epochs almost overlapped with corresponding epochs in the James sub-basin. River flow data in the sub-basin showed physically consistent above- and below-average flows in these two epochs, respectively. Corn, soybean, hay alfalfa, and winter wheat yields were consistent with the hydro-meteorological data. So, these two recent epochs were selected to make composite scenarios of observed precipitation, temperature, and crop yields. Precipitation and temperature composites in the wet epoch showed that this was not only a wet epoch but was also a cool epoch. The dry epoch had above-average temperature anomalies, so it was a dry and warm epoch. Composite crop yield scenarios in the wet and dry epochs are shown in Figure 16. Generally larger crop yields (positive crop yield anomalies), especially of corn and winter wheat, in the wet epoch are seen in Figure 16.

As mentioned in Section 3.2.2, almost all agriculture in the Central Platte sub-basin is irrigated with surface or ground water, with the latter from the Ogallala aquifer providing most of the irrigation water. Despite the dominance of irrigation, wet and cool epochs can make an adverse impact on crop yields and production due to too much water and/or too cool temperatures. Dry and warm epochs can make an adverse impact if farmers do not have access to sufficient irrigation water. Some SAT members mentioned that in some of the dry epoch years, especially 2012, irrigated acres were reduced. Groundwater depletion in multiyear to decadal dry epochs also makes an adverse impact on agriculture in the Central Platte sub-basin. Therefore, even in spite of irrigation, crop yields can be affected by climate variability as we can see clearly in the case of winter wheat in Figure 16.

The Central Platte SAT members were of the opinion that farmers can cope with dry epochs if multiseason to multiyear hydro-meteorological predictions were available. If reliable, such predictions would be used to lease irrigation equipment and purchase water before the dry epoch sets in. Such predictions would also be used to reduce the acreage to be planted or change to a more drought-resilient or hybrid crop. If a wet epoch was predicted, water infrastructure can be developed or augmented to store excess water to be used when needed in a dry epoch. It was mentioned that constructions of underground water storage facilities near the Platte River are being considered. As opined by the James sub-basin SAT, the Central Platte SAT members would also like to see multiseason predictions made in the autumn, preferably by 1 October.

6.3 The Lower Grand Sub-basin

PDSI data showed that the Lower Grand sub-basin experienced a wet epoch from 2008 to 2010 and a dry epoch from 2011 to 2014. These two epochs almost overlapped with corresponding epochs in the James and Central Platte sub-basins. River flow data in the Lower Grand sub-basin showed physically consistent above- and below-average flows in these two epochs, respectively. Corn, soybean, and winter wheat yields were consistent with the hydro-meteorological data. So, these two recent epochs were selected to make composite scenarios of observed precipitation, temperature, and crop yields. Precipitation and temperature composites in the wet epoch showed that this was not only a wet epoch but was also a cool epoch. The dry epoch had above-average temperature anomalies, so it was a dry and warm epoch. Thus, in all three sub-basins, there were wet and cool, or dry and warm epochs in nearly the same time periods. Composite crop yield scenarios in the wet and dry epochs are shown in Figure 17. Generally larger crop yields (positive crop yield anomalies), especially of corn and soybean, in the wet epoch are seen in Figure 17.

The SAT members confirmed the wet-cool and dry-warm epochs with their personal experiences. In some years of the dry epoch, especially 2012, livestock producers had to sell their cattle because of lack of water and less forage availability. The dry epoch also caused nitrate poisoning of corn plants due to accumulation of nitrogen fertilizer and also caused growth of alpha toxin, a fungus, which is fatal to cattle fetuses. Thus, the dry epoch caused impacts not only on crop yields but also on other aspects of food and feed productions.

SAT members felt overwhelmingly that multiseason to multiyear climate and hydro-meteorological outlooks would be valuable, especially if provided before the end of December and at county or sub-county resolution. If livestock producers knew at least six months ahead of going into a dry epoch, they could cope with it by restricting the number of cattle from June onwards because they would know that the carrying capacity of pastures would be reduced. Farmers would plant more wheat, grain sorghum, and milo, and less corn. Water managers would reduce evaporation loss on lakes used for irrigation by applying a cover chemical. They would also conserve the available water. If city commissioners knew about an approaching dry epoch for 3-4 years, they would focus on more bridge repairs. If farmers knew at least six months before a wet epoch, they would not have to plan for irrigation. Also, they can cope by planting crops adaptable to more water. During wet epochs, the biggest problem for livestock producers is to keep hay dry. They can store the hay in plastic wrap while bailing. If they knew it would be wet, then they could plan to get necessary equipment for wrapping the harvested hay. If the outlook is for a wet epoch for 3-4 years, city commissioners would spend more money on road maintenance and not on water infrastructure.

7. Conclusions and future work

The project team not only achieved the two objectives of this project, but also produced information consistent with our previous SARP-funded and other projects in the MRB, and uncovered more fundamental as well as more applications-oriented problems and suggestions. The data analysis and modeling results prove conclusively that there are decadal hydrologic cycles (DHCs), with multiyear dry and wet parts, in the selected sub-basins. The results also strongly support the hypothesis that DCV phenomena are substantially associated with these DHCs. Interactions with representative stakeholders confirmed the occurrences of DHCs and their impacts on food, feed, and bio-fuels crop yields. They also provided important information about impacts on water resources for municipal and agricultural uses. Stakeholders clearly articulated their information needs to cope with dry and wet epochs, and outlined ways in which the information can be used if provided at the spatial resolution and format needed, and if provided well in advance of the onset of such epochs. A large degree of similarity of impacts, experiences, and coping actions strongly suggests that the results of this project are generalizable despite differences in crop types, sources and uses of water, importance of various sectors. Data analysis and modeling results, and stakeholder experiences also show that availability of irrigation for agriculture is not sufficient to protect against vagaries of climate variability, especially DHCs, because crops are under the influences of naturally-occurring precipitation as well as varying temperatures. Also, availability of groundwater is not an insurance against impacts of multiyear droughts on crop yields and productions.

Three major recommendations for future work emerged from this project.

1. More detailed research is still needed, especially at sub-county resolutions, to understand and predict DHCs and their impacts.

2. A continuity of interactions with stakeholders in large numbers is required to understand their problems, gain their trust, and develop the data and information they need.

3. A web-based decision support tool is required to make data and information on DHCs and their impacts available to individual farmers, water managers, and other stakeholders in a consistent and timely manner to help them make proactive decisions.

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Appendix 1: Stakeholder Advisory Team for the James River Sub-basin in North and South Dakota.

Adnan Akyuz	North Dakota State Climatologist
Dave Bartel	James River Water Development District Manager
Gregory Delzer	USGS Dakota Water Science Center
Kathleen Donahue	North Dakota Department of Emergency Services
Dan Driscoll	USGS Dakota Water Science Center
Paul DuBourt	USDA/NRCS
Laura Edwards	South Dakota State Climatologist
Doug Goehring	North Dakota Department of Agriculture Commissioner
Kelsey Kolars	USGS Dakota Water Science Center
Kendall Nichols	North Dakota Soybean Council
Mark Rath	South Dakota Department of Environment and Natural Resources
Jim Ristau	South Dakota Corn
Karen Ryberg	USGS Dakota Water Science Center
Allen Schlag	NOAA Weather Forecast Office, Bismarck
Doug Sombke	South Dakota Farmers Union

Appendix 2: Stakeholder Advisory Team for the Central Platte River Sub-basin in Nebraska.

Brian Barels	North Platte Public Power District
Jeff Shafer	North Platte Public Power District
Cory Steinke	Central Nebraska Public Power and Irrigation District
Marcia Trompke	Central Nebraska Public Power and Irrigation District
Duane Woodward	Central Platte Natural Resources District
Jim Bendfeldt	Central Platte Natural Resources District, also a retired irrigation farmer and serves on the State Natural Resources District board
Lyndon Vogt	Manager, Central Platte Natural Resources District

Appendix 3: Stakeholder Advisory Team for the Lower Grand River Sub-basin in Missouri and Iowa.

Tracy Marlo Daugherty	Regional Community Development Specialist – Univ. Missouri Extension
Valerie Tate	Local Rancher/Plant Sciences Specialist – Univ. Missouri Extension
Kurt Boeckmann	Agriculture Liason – Missouri DNR
Dave Johnson	District Conservationist with NRCS for Linn, Livingston, Carroll Counties
Terri Bruner	District Conservationist with NRCS for Putnam, Sullivan, Adair, Schuyler Counties
Dennis McDonald	Local Rancher
Nelson Heil	Presiding County Commissioner for Carroll County
Bill Boelsen	Associate Commissioner for Carroll County
Bob Miller	Land Learning Foundation
Mike Ledbetter	Land Owner in Linn County
Mary Culler	Regional Office Watershed Co-ordinator DNR

Table 1: The Pacific Decadal Oscillation (PDO), and difference between probabilities of above- and below-average streamflow, precipitation, and daily maximum temperature at USGS stream gauge locations in the James River sub-basin.

Location (County)	PDO State	Streamflow (%)	Precipitation (%)	Daily Max. Temperature (%)
Sheyenne River Above Harvey, ND (Wells)	Warm/Cold	-23/10	-23/17	8/-17
Sheyenne River Warwick, ND (Eddy)	Warm/Cold	-39/38	-8/3	8/-17
James River Jamestown, ND (Stutsman)	Warm/Cold	-39/10	-8/-10	8/-3
James River La Moure, ND (La Moure)	Warm/Cold	-46/3	-8/3	0/-24
James River Columbia, SD (Brown)	Warm/Cold	-46/10	-23/-3	0/3
Maple River ND-SD State Line (Dickey)	Warm/Cold	-39/-10	-15/10	23/-10
Elm River Westport, SD (Brown)	Warm/Cold	-31/-17	-23/-3	0/3
James River Ashton, SD (Spink)	Warm/Cold	-46/10	0/10	0/-3
James River Huron, SD (Beadle)	Warm/Cold	-39/17	0/-17	0/-17
James River Forestburg, SD (Sanborn)	Warm/Cold	-46/10	0/-24	0/3

Table 2: The Pacific Decadal Oscillation (PDO), and difference between probabilities of above- and below-average streamflow, precipitation, and daily maximum temperature at USGS stream gauge locations in the Central Platte River sub-basin.

Location (County)	PDO State	Probability Difference of Above/Below Average Streamflow (%)	Probability Difference of Above/Below Average Precipitation (%)	Probability Difference of Above/Below Average Daily Max. Temperature (%)
Platte River near Grand Island, NE (Hall)	Warm/Cold	-15/-45	15/-3	8/3
South Loup River near St. Michael, NE (Buffalo)	Warm/Cold	-8/-59	8/-10	8/3
Platte River near Overton, NE (Dawson)	Warm/Cold	-8/-59	-8/-17	8/-3
Platte River near Duncan, NE (Platte)	Warm/Cold	-23/3	8/-24	8/3

Table 3: The Pacific Decadal Oscillation (PDO), and difference between probabilities of above- and below-average streamflow, precipitation, and daily maximum temperature at USGS stream gauge locations in the Lower Grand River sub-basin.

Location (County)	PDO State	Probability Difference of Above/Below Average Streamflow (%)	Probability Difference of Above/Below Average Precipitation (%)	Probability Difference of Above/Below Average Daily Max. Temperature (%)
Grundy (Thompson River at Trenton)	Warm/Cold	-8/-17	23/-38	0/24
Livingston (Grand River near Sumner)	Warm/Cold	0/-38	8/-24	-15/24
Chariton (Chariton River near Prairie Hill)	Warm/Cold	0/-24	-8/-17	-8/24

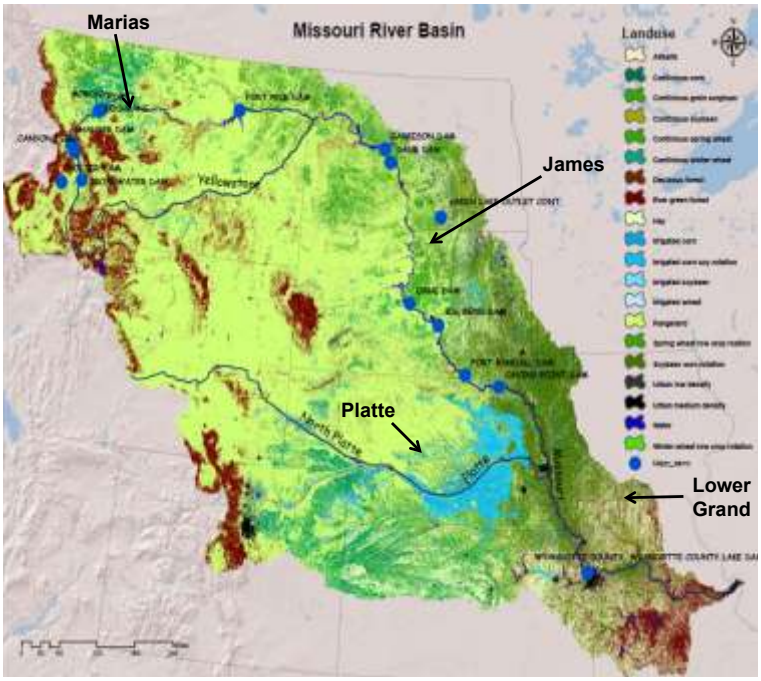

Figure 1: Locations of the Marias, James, Platte, and Lower Grand Sub-basins in the Missouri River Basin. Legend shows Land Use Classes.

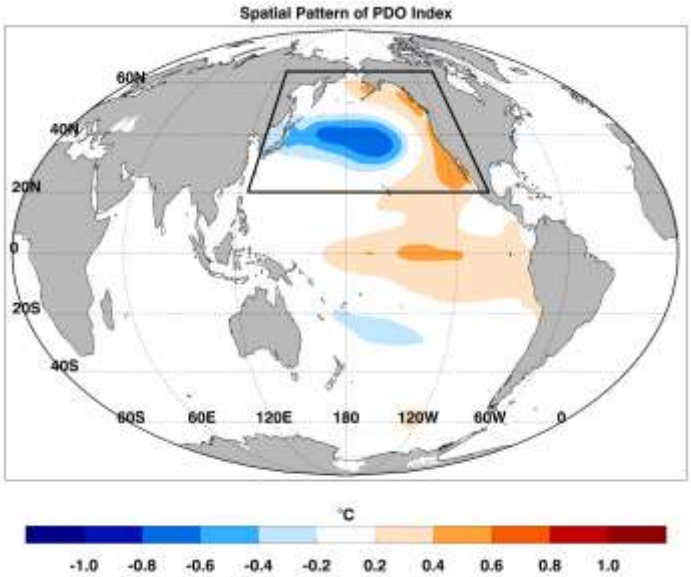

Figure 2a: Regression coefficient (°C/unit index) of the Pacific Decadal Oscillation index regressed on seasonal-average sea-surface temperature anomalies. (c) June–July–August, and (d) September–October–November. Color bar shows regression coefficient scale.

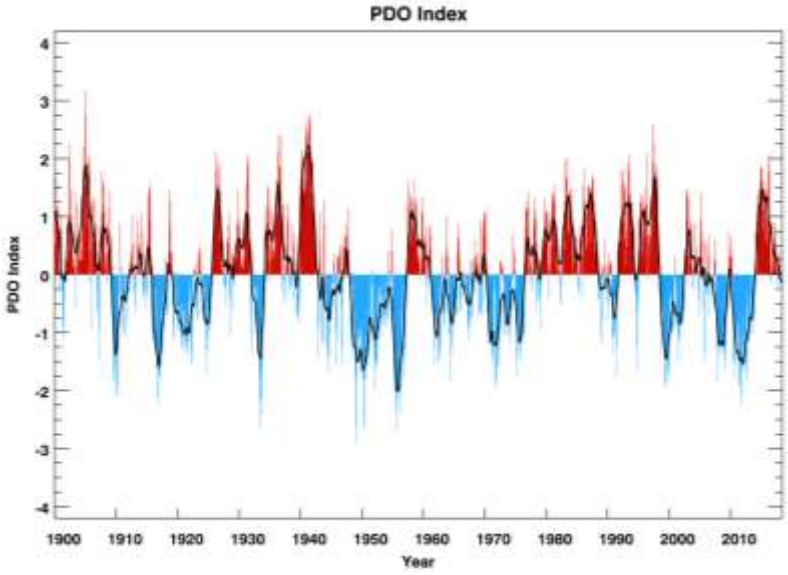

Figure 2b: The Pacific Decadal Oscillation Index (bars) from January 1900 to December 2015 and its 12-month running-average smoothed version (black line).

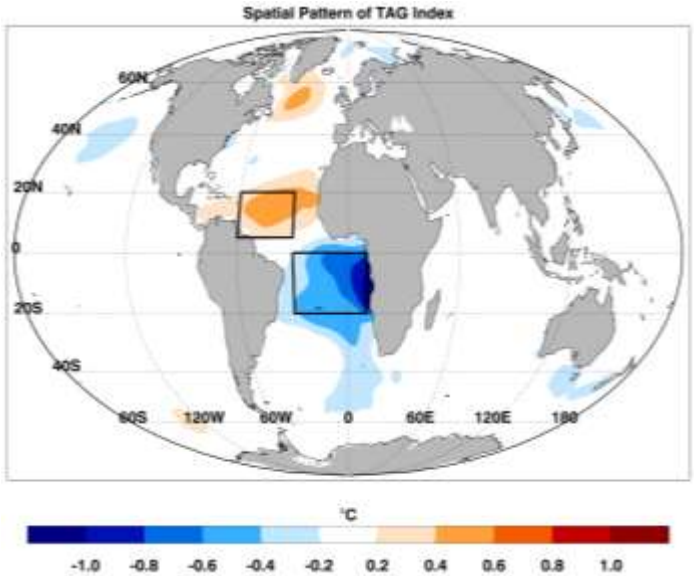

Figure 3a: Regression coefficient (°C/unit index) of the tropical Atlantic sea-surface temperature gradient (TAG) index regressed on seasonal-average sea-surface temperature anomalies. (c) June–July–August, and (d) September–October–November. Color bar shows regression coefficient scale.

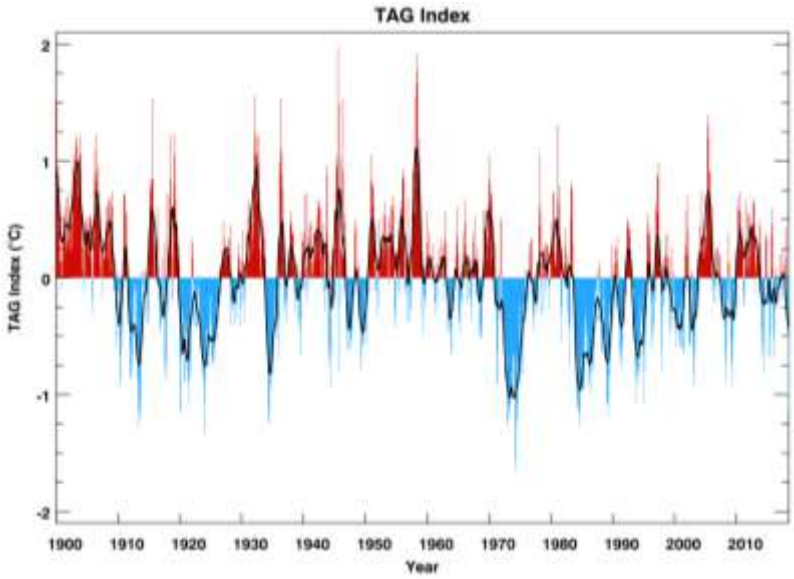

Figure 3b: The tropical Atlantic sea-surface temperature gradient (TAG) index (bars) from January 1900 to December 2015 and its 12-month running-average smoothed version (black line).

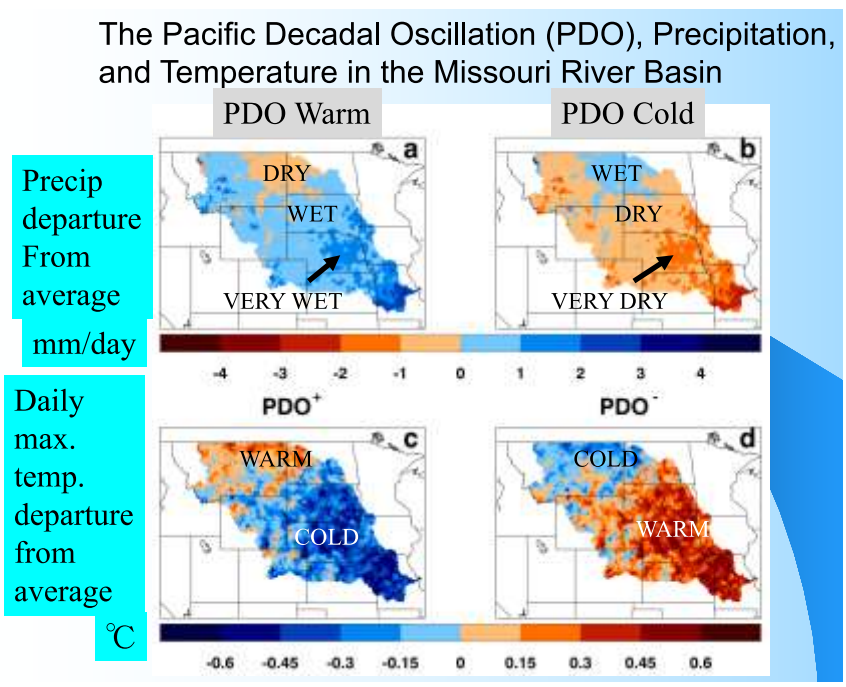

Figure 4: Annual-average precipitation (mm/day) and daily maximum temperature (°C) anomalies associated with (a) PDO$^+$, precipitation, (b) PDO$^-$, precipitation, (c) PDO$^+$, temperature, and (d) PDO$^-$, temperature. Color scales for each variable are shown below each row.

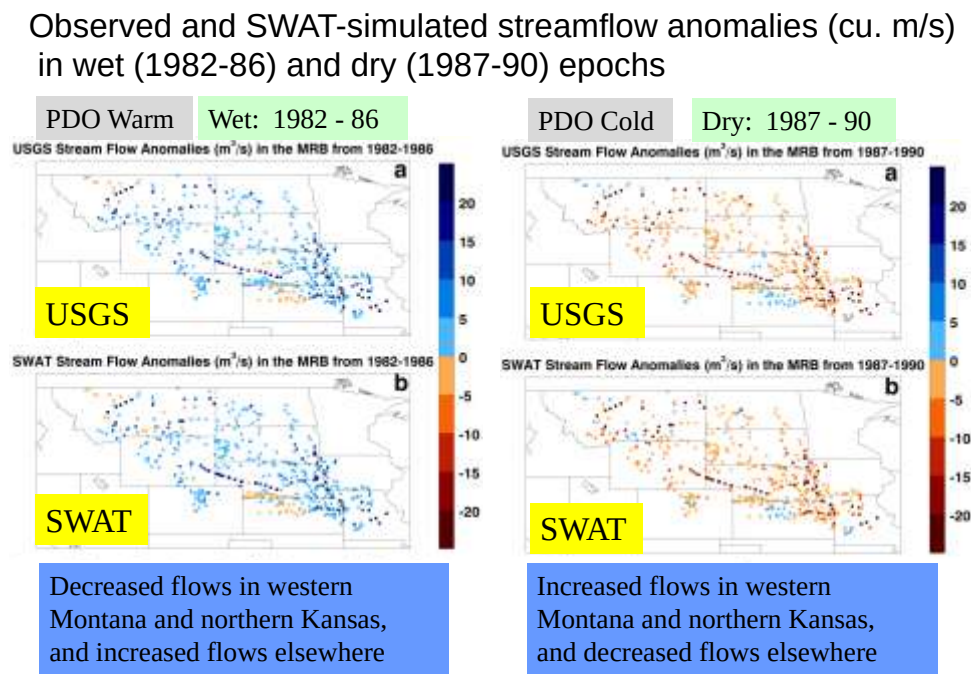

Figure 5: Left column: Annual-average streamflow (m^3/s) in the Missouri River Basin from 1982 to 1986. (a) Observed USGS estimate, (b) simulated SWAT estimate. Right column: Annual-average streamflow (m^3/s) in the Missouri River Basin from 1987 to 1990. (a) Observed USGS estimate, (b) simulated SWAT estimate.

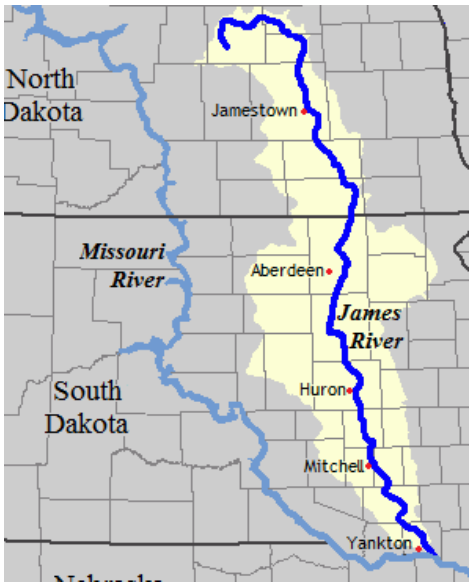

Figure 6: A map of the James River sub-basin with its catchment area outlined in light yellow.

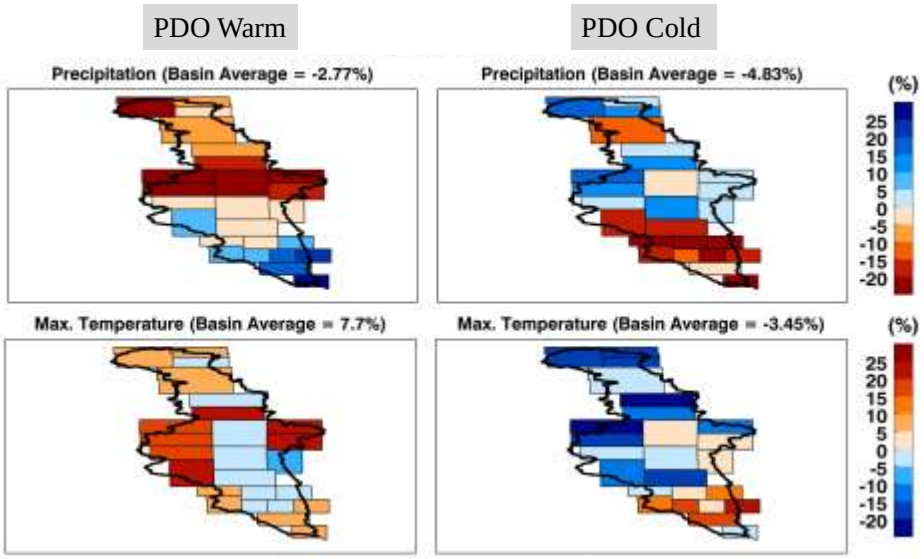

Figure 7: Differences in probabilities of above- and below-average precipitation and daily maximum temperatures in positive (warm) and negative (cold) phases of the Pacific Decadal Oscillation (PDO). Upper row: Precipitation; Lower row: Daily maximum temperature.

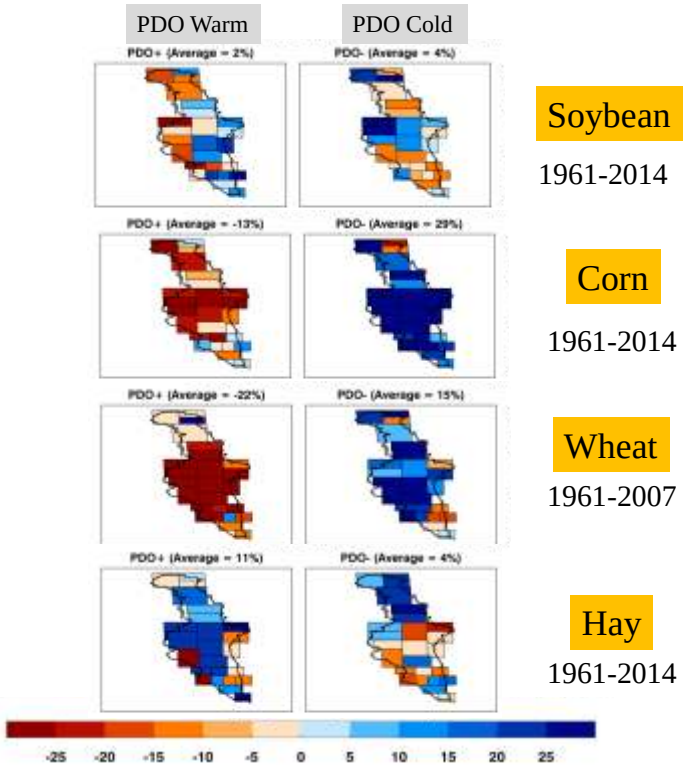

Figure 8: Differences in probabilities of above- and below-average crop yields in positive (warm) and negative (cold) phases of the Pacific Decadal Oscillation (PDO).

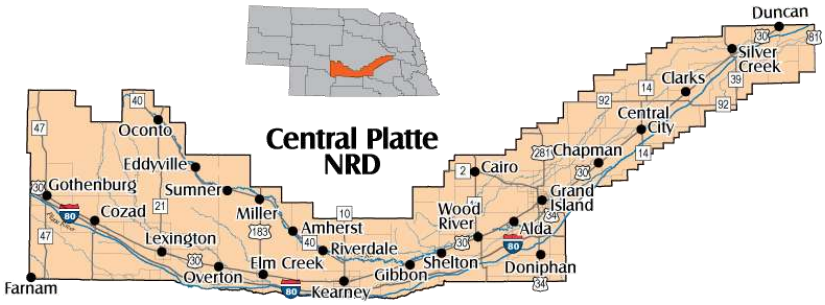

Figure 9: A map of the Platte River sub-basin with its catchment area outlined in light green and major tributaries in blue.

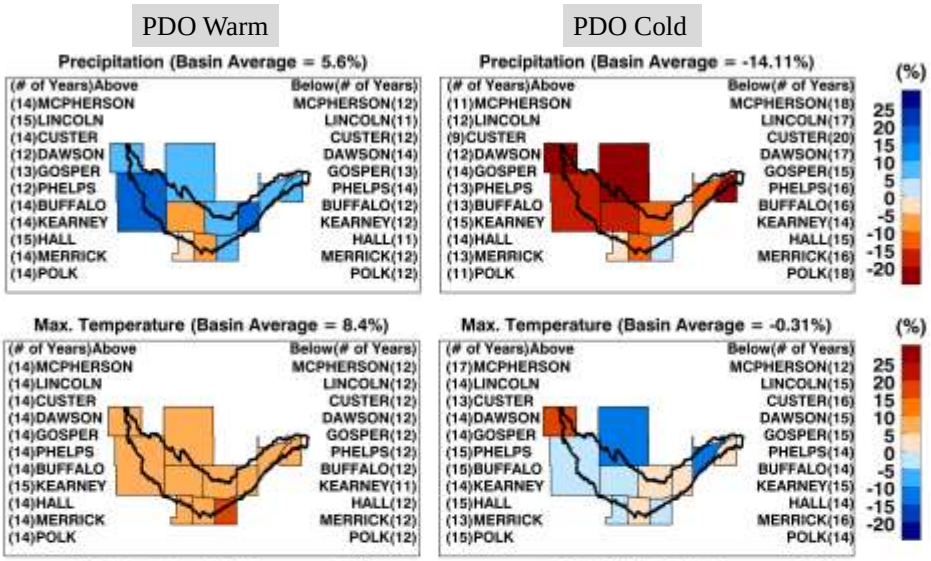

Figure 10: Differences in probabilities of above- and below-average precipitation and daily maximum temperatures in positive (warm) and negative (cold) phases of the Pacific Decadal Oscillation (PDO). Upper row: Precipitation; Lower row: Daily maximum temperature.

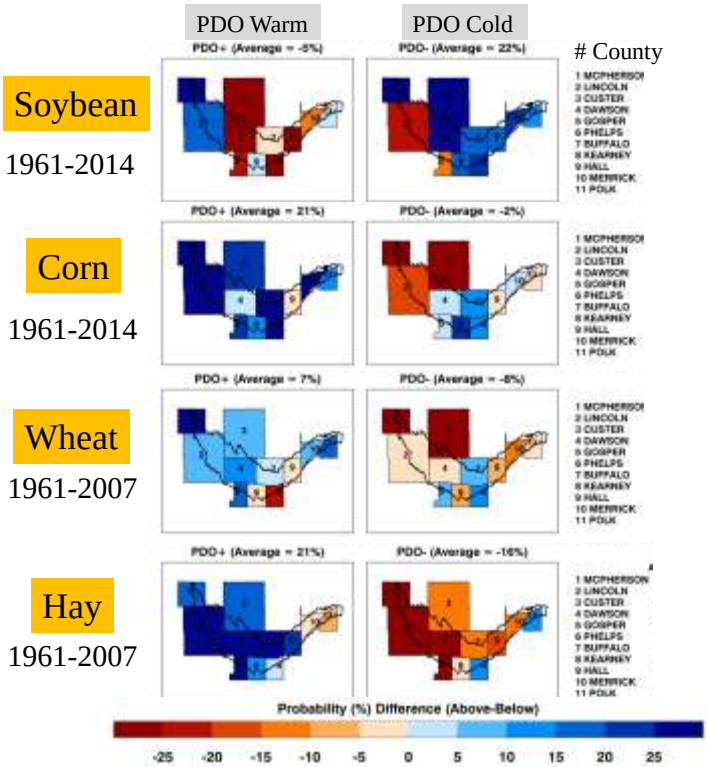

Figure 11: Differences in probabilities of above- and below-average crop yields in positive (warm) and negative (cold) phases of the Pacific Decadal Oscillation (PDO).

Figure 12: A map of Missouri and Iowa, with the Lower Grand River sub-basin outlined in yellow/orange. (From: content.govdelivery.com/accounts/MODNR/bulletins/764b75)

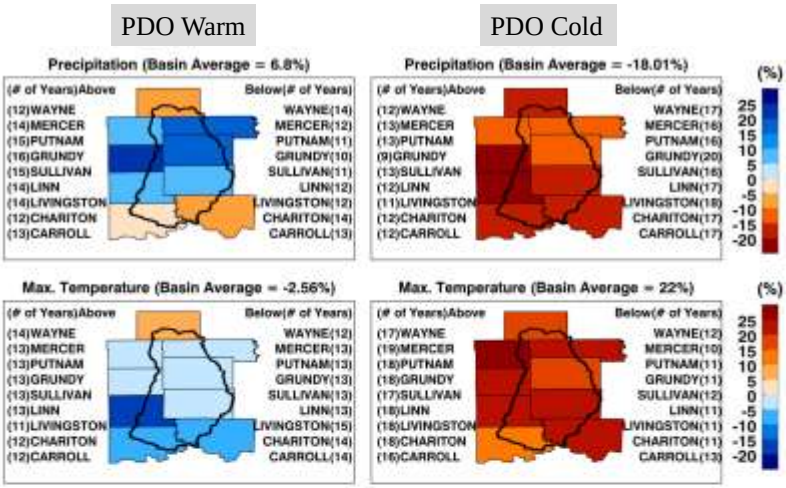

Figure 13: Differences in probabilities of above- and below-average precipitation and daily maximum temperatures in positive (warm) and negative (cold) phases of the Pacific Decadal Oscillation (PDO). Upper row: Precipitation; Lower row: Daily maximum temperature.

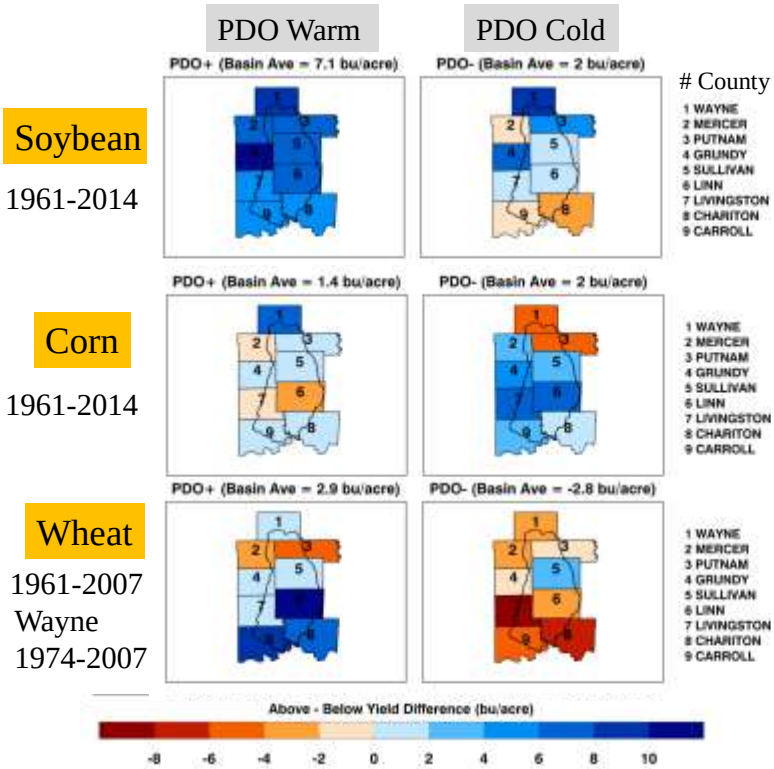

Figure 14: Differences in probabilities of above- and below-average crop yields in positive (warm) and negative (cold) phases of the Pacific Decadal Oscillation (PDO).

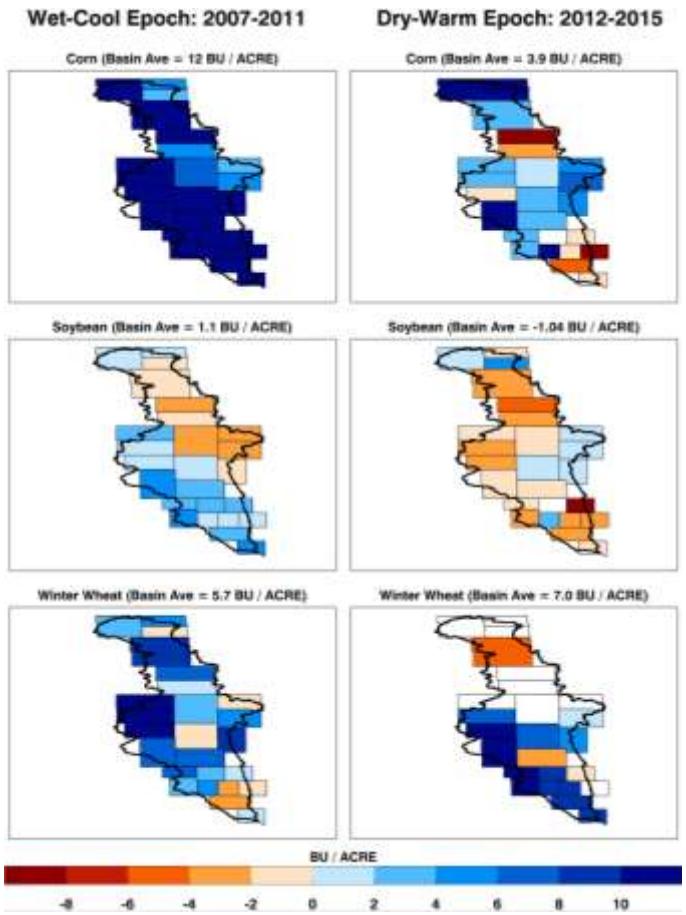

Figure 15: Observations-based scenarios of crop yield anomalies in the James sub-basin in wet and dry epochs.

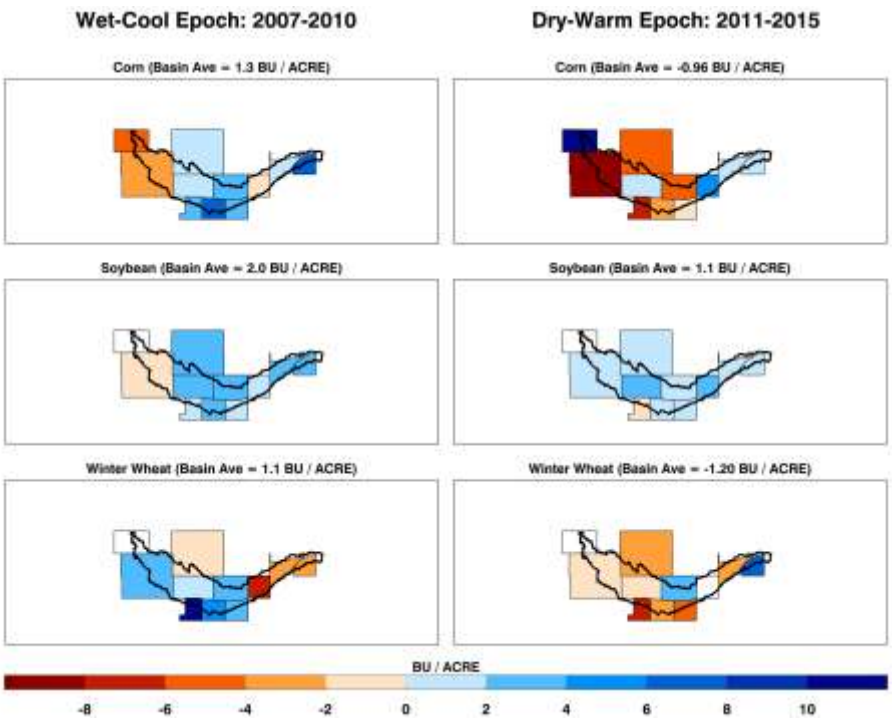

Figure 16: Observations-based scenarios of crop yield anomalies in the Central Platte sub-basin in wet and dry epochs.

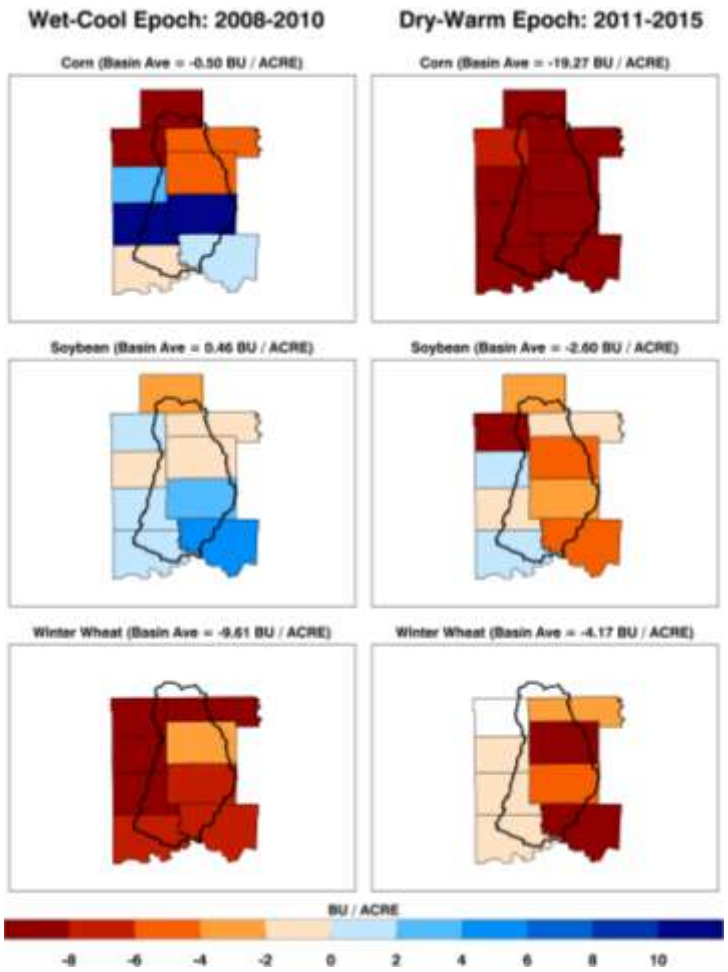

Figure 17: Observations-based scenarios of crop yield anomalies in the Lower Grand sub-basin in wet and dry epochs.