NOAA-OGP
Regional Integrated Science and Assessment

Climate Variability and Water in the Interior West:

Pilot Phase Results

CIRES

Susan Avery, Andrew Barrett, Martyn Clark, Randall Dole, Martin Hoerling, Charles Howe, Douglas Kenney, William Lewis, Donald Mock, Diana Perfect, Roger Pielke Jr., John Pitlick, Andrea Ray, James Saunders, Paul Sperry, William Travis, Robert Webb, John Wiener and Klaus Wolter

24 September 2001

CONTENTS

INTRODUCTION

1 Development of a RISA Project

The objective of the Regional Integrated Sciences and Assessments (RISA) Program is to contribute to informing the development of place-based decision support and services in responding to climate-related risks and environmental stresses. Enabling such services at any point in time requires a critical mass of knowledge and of capacity to apply knowledge, e.g. tailoring information to meet local needs, within each region. The integrated scientific assessment component constitutes the sum of efforts to (1) characterize the state of knowledge of environmental variations and changes at appropriate scales of interest, (2) identify knowledge gaps and clarify linkages in selected climate-environment-society interactions, and (3) provide an informed basis for a) responding to climate-related risks, and for b) establishing priorities in basic research investments to meet these needs. RISA activities require innovative partnerships among a spectrum of interests (Federal, State, local and private etc.) to enable organizational capacity within a region for developing accurate balanced syntheses (i.e. identifying risks, uncertainties, critical knowledge gaps, etc.), and services on an ongoing basis. As such, the RISA Program relies heavily on consolidating the results and data from ongoing NOAA and other disciplinary process research already funded in a region, under an integrative and contextual framework.

- Pulwarty AMS Abstract (2001)

OGP's definition of a RISA Project focuses on enabling "organizational capacity" in order to provide "accurate balanced syntheses" and "services." Accomplishing these objectives involves two complementary lines of scientific inquiry. The regional synthesis component of a RISA requires assessing the consequences of the interactions of multiple stresses, and exploring alternative options that may alleviate those consequences. In a balanced regional synthesis the "multiple stresses" includes factors such as those associated with climate variability, but also other factors such as regional population growth, institutional changes, and environmental regulations. Examination of alternative options in response to the consequences of the interactions of such stresses may include improved climate information or the improved use of climate information, but may also include other options such as modification of water law and environmental regulations, land-use and housing controls, and water transfers and markets. The regional synthesis component of a RISA therefore demands a broad regional perspective, requiring integration of many relevant disciplines.

The services component of a RISA involves identifying areas where the introduction of new knowledge and information will improve decision-making, develop prototype or pilot products that could benefit decision-makers, and establish a process for the transfer of successful products from the research community to decision-makers. The successful development and transfer of services requires extensive research that includes the participation of users of climate information. Such research includes surveys, interviews, workshops, and briefings, as well as user input to applied hydro-climate research, leading to the development of experimental products that could ultimately be used in regular operations. In a RISA project the science priorities will thus be set according to considerations of scientific merit as well as the needs of decision-makers for whom products and services will eventually be developed.

The Western Water Assessment (WWA) in its pilot phase of development has built the capacity to focus a wide range of scientific expertise on questions of importance to decision-makers related to water supply, use and quality in the Intermountain West. The following sections review the experience of the WWA to date, present an intellectual plan for activities over the next five years, and discuss some of the institutional issues facing WWA (and other RISA programs) as it plans to transition from its pilot phase to a more mature component in the nation's climate services infrastructure.

2 The WWA RISA Project

2.1 Critical Regional Water Problems

Figure 1: Interior West Region

The focal area of WWA RISA research, the Interior West (Figure 1), is a semi-arid region where water supplies are relatively meager, and impacts of climate variability are pronounced. Intensifying these conditions, the region is undergoing rapid societal change. In the South Platte River basin, which includes greater Denver, population grew by 25% (600,000 people) in the 1990's. The South Platte basin is one of the fastest growing regions in the nation, and Douglas County, south of Denver, was the single fastest growing county in the nation for most of the decade. Regional growth projections indicate that population in the basin is expected to grow by another million people in the next 20 years. Regional population growth coupled with the semi-arid climate means that water management presents a formidable challenge. For instance, managers must retain as much water as possible in reservoirs to meet the traditional needs of irrigation, hydro-power generation, and municipal consumption, as well as emerging needs such as recreational uses, stringent water quality standards, maintenance of aquatic ecosystems, and the protection of threatened and endangered species. Reservoir space must also be maintained to protect downstream farms, homes, and businesses from flooding. This is a particular concern downstream on the Colorado River system where severe flooding of the lower Colorado River in the spring of 1983 resulted in $80 million of economic loss (Rhodes et al., 1984). Issues of water supply, use, and quality are central to the region's economic, social, and environmental health.

2.2 RISA Research Structure

In the Interior Western United States, vulnerability and sustainability hinge on the wise management of freshwater resources for multiple societal and ecosystem services. The Western Water Assessment thus seeks a) to assess the sensitivity of the region to climate variability, and the feasibility of various adaptations, and to identify the residual vulnerability, and b) to assess and develop hydro-climate products on a regional scale.

The first pathway of WWA research examines the vulnerability of the region to climate variability in the context of other (e.g., socio-economic, legal/political, and environmental) stresses. Because the context of this study is itself rapidly changing, we are devising a long-term program of research designed to understand the issues, opportunities, and constraints that will dominate the world of water management in the future. Our initial vulnerability assessment has focused on the impacts of climate extremes on water supply, socio-economic trends, environmental factors and water quality, legal and policy issues, and changes in water ownership and transfers. Our long-term goal is to assess linkages among climate variations and social and economic activities and capacities as they evolve by looking at a multiplicity of stresses and their cumulative impacts.

The second pathway of WWA research is to assess and develop hydro-climate products on a regional scale. Here, we conduct applied hydro-climate research to aid the decisions of climate-sensitive stakeholders in the Interior West. These activities are aimed at both regional and local levels. This involves a) assessing decision processes of climate-sensitive stakeholders and identifying the entry-points for hydro-climate information, b) applied hydro-climate research to address critical gaps in knowledge, and development of experimental products that can be incorporated in the operations of official state and federal agencies to fill stakeholder needs, and c) assessment of the use/value of new knowledge and experimental products. This can be viewed as a longitudinal study where we will identify climate information needs, fill the critical knowledge gaps, develop experimental products that can address those information needs, and engage in an ongoing dialogue over a period of five years or more to assess both the value of the information and barriers to its use. In the pilot phase, we have made significant progress in understanding climate information needs of specific reservoir managers, and are currently engaged in related applied hydro-climate research projects.

Understanding water in the Interior West requires collaborative research between physical and social scientists in both components of WWA research. In our assessment of the vulnerability of the region to climate variability, we have established a research methodology—an integrative water model—that allows diagnosis of the interplay of climate and hydrology with the sensitivity of human and environmental systems. The integrative water model permits an evaluation of scenarios of historical and anticipated variations in climate, as well as scenarios describing the changing demographics of the region; the evolving relationship between water and energy; demand management policies and conservation technologies; drought monitoring, management, and planning; changes in agricultural policies (and more general industry-wide changes) and intrastate agricultural-to-urban water marketing; changes in water law and institutions (including prior appropriation reform, interstate water management, and further interpretations of federal reserved rights issues, including tribal rights); and increases in the value placed on (and water used for) environmental protection. Perturbations in each scenario can be viewed as a single sensitivity experiment. We ultimately hope to use Monte Carlo techniques to assess the sensitivity of individual variables in the context of changes in other variables to describe coupled vulnerabilities and battendant implications for regional policy and planning. Similarly, in our assessment and development of hydro-climate products on a regional scale, the physical science research activities are intimately linked to regional societal stresses, and address specific needs for improved climate information by climate-sensitive stakeholders.

2.3 Management

The management structure of this assessment has evolved over the last four years to its current structure as shown in Figure 2. The two project goals are reflected in this diagram as themes of the project: (1) Vulnerability, Policy and Planning and (2) Experimental Monitoring and Prediction Products. The scientific steering committee provides the intellectual leadership for the project, identifies appropriate researchers and engages them in the assessment, has authority over project budget, and provides integration of the two themes. In addition, these scientists and faculty coordinate and write proposals and reports, develop project budgets, provide oversight to ensure work is being accomplished, coordinate reviews as needed, and work closely with project management. The goals of the Project Integration activities are to facilitate interactions amongst the themes, help synthesize the science, coordinate resource requirements, conduct meetings as required, provide finished documents, ensure project deliverables are completed as agreed, organize and conduct a seminar series, maintain a Web site, provide a contact point for NOAA-OGP (Office of Global Programs), and resolve problems. The CIRES and Climate Diagnostics Center (CDC) Directors provide the project's vision and leadership, integrate the assessment with other NOAA initiatives, and have broad oversight of the program. As WWA enters the next phase of its development, new structures of organization will emerge. Evolution in the activities will necessitate evolution of how we organize to get the work done. The strengths and weaknesses of the present organizational structure are discussed in greater detail in several sections to follow.

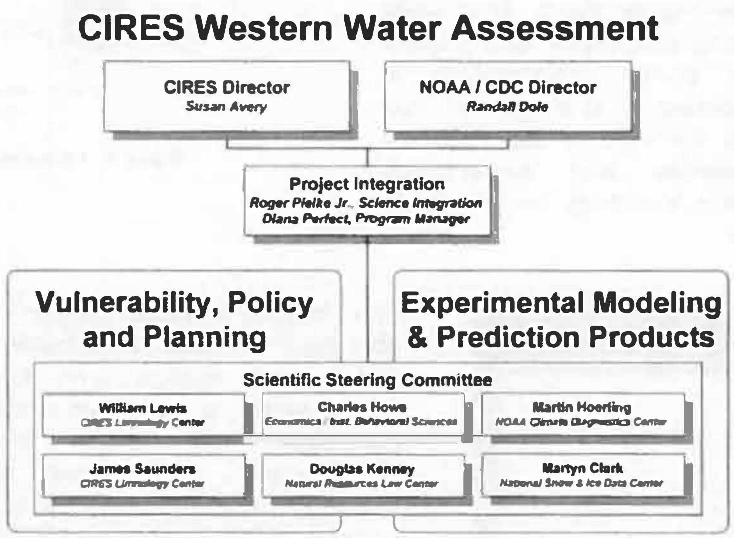


Figure 2: Organizational structure

CLIMATE VARIABILITY AND WATER IN THE INTERIOR WEST: PILOT PHASE RESULTS

1 Evolution of This Assessment Program

The Cooperative Institute for Research in Environmental Sciences (CIRES) at its 1995 scientific retreat began a proactive experiment that engaged the climate expertise of NOAA's Environmental Research Laboratories with that of the University of Colorado in climate, hydrology, water quality, and social sciences. As a result of that retreat, a white paper was developed that called for an interdisciplinary study of water, its relation to climate and weather variability, and its impacts on water resources in the Interior West. That white paper's integrating philosophy was "Follow the Water" as shown schematically in Figure 3. It defined a strategy that has evolved to form the core of our Regional Integrated Sciences and Assessment (RISA) on Climate Variability and Water in the Interior West.

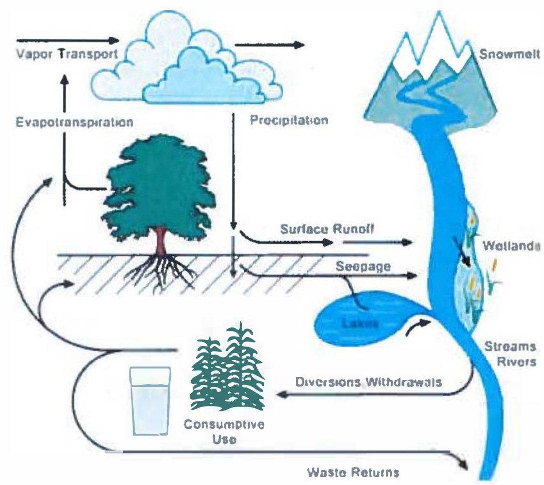


Figure 3: Follow the Water

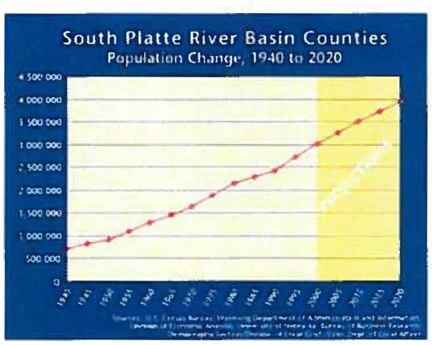


Figure 4: Population growth in South Platte Basin

The Interior Western region is characterized by abundant montane precipitation in the form of snow that sustains surface flows across semi-arid plains where water is intensively managed for irrigated agriculture and other forms of economic development. As previously displayed (Figure 1), this region encompasses the upper or upper-middle portions of the South Platte, Arkansas, Colorado, and Rio Grande drainages. The region is experiencing rapid population growth (Figure 4) and economic development with resulting stress on water quantity and quality. Understanding the potential impacts of climate variability on the regional hydrologic cycle, water quality, ecosystem vitality, and water management in the context of social and demographic change serves as the basis for the assessment. The goals of our project are two-fold: (1) to determine the regional sensitivities and responses to climate variations, and (2) to assess and develop hydro-climate products on a regional scale.

Our initial pilot study areas are the three river basins shown in Figure 5. All of these basins are interconnected through diversions of water from one basin to another. The South Platte basin in particular demonstrates the many issues that decision-makers face in the management of water across the region. In the following sections of this paper, we highlight some of our accomplishments during our pilot phase of operation and discuss some of our current and future challenges.

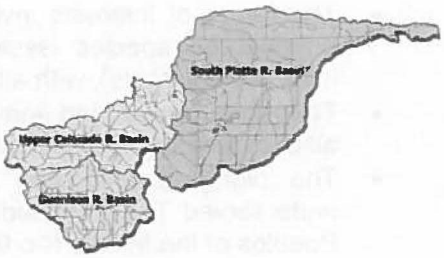


Figure 5: Initial river basins for study

2 Highlights of Pilot Phase

Traditionally, water managers and other planners have used information on climate variability in only a rudimentary manner (if at all). In recent years, WWA has made progress in identifying the causes of regional climate variation and this has laid the groundwork for successful medium and long-range climate forecasting. The incorporation of climate information in water management has the potential to greatly increase system efficiencies and significantly benefit decision-making related to both society and the environment.

This promising work in climate research comes at a time when the need for improved resource management is great. Rapid population growth and economic development, along with changing social demands on freshwater resources, have imposed new challenges on water management. Systems must continue to meet traditional needs such as irrigation, hydropower generation, and domestic consumption, while also providing for new, emerging needs such as recreational uses, water quality standards, and aquatic ecosystems. For climate information to be most useful, it must be developed for and applied at the local and regional level where most water management decisions take place.

2.1 Understanding Decision Processes

To achieve the main goals of WWA, it is essential to work with decision-makers to learn about current and potential uses of climate information in water resource management (and related sectors), and to investigate potential improvements in management. Through these partnerships, climate scientists improve the relevance of existing information and apply user input to their climate research agenda. Three accomplishments in the pilot phase were: 1) interviews and development of an ongoing dialogue with leaders of the water management community, 2) a study of the decision-processes used by reservoir managers, and 3) a study of several types of users and water managers, from farmers to wastewater engineers, as an extension of the "Three States" project.

The Three States and Tribes Project

A separately funded NOAA project, the "Three States" effort, preceded the decision-making studies in the regional assessment, and its goals, methods and findings helped to inform the methodology for interacting with decision-makers. The project interviewed four major categories of water users and managers:

- The whole hierarchy of water management in a basin (Arkansas Valley in Colorado), focusing on state, federal agencies, and water users in irrigation.

- The range of interests involved in a major controversy and revision of management (an endangered species issue on the Middle Rio Grande involving municipal, tribal, and interstate interests), with attention to how drought affects the problem.
- The more gradual and somewhat less public adjustments underway in the Salt Lake Valley, also undergoing dramatic urbanization and growth.
- The highly diverse and increasingly asserted needs and preferences of the long-underserved Tribes, including the Navajo, Zuni, Southern Ute, Ute Mountain Ute, and the Pueblos of the Middle Rio Grande.

The project applied a general set of questions in personal interviews and was able to gain access and information from parties on all sides of the controversies. Recruiting researchers whose previous work has made them welcomed by the interviewees enabled good interaction with the Tribes. Sustained interactions were established in several cases, and consideration of the potential use of climate information has begun. In some cases, this effort included frequent contacts, follow-ups, and the use of multiple interviews. This interview approach has been grafted into the regional assessment with surveys of water users and other stakeholders (e.g., ski area managers) in the Arkansas, South Platte, and Upper Colorado River basins. Results from the water quality work also argued for attention to the information needed for wastewater managers.

Over two-dozen interviews were conducted under the Three States Project. Findings include:

- There is great variation in the use of climate information.
- There is strong interest in continued interaction with researchers, and for NOAA participation in collaborative research projects. Several proposals for investigation have been generated.
- The intelligibility of NOAA products is low.
- A track record of accuracy is often requested.
- There is a strong desire for better short-term weather and threats forecasting, especially concerning flash floods and threats to livestock.
- Interest in the weather in other agricultural areas and its impact upon economic markets is strong.
- Critical climate variables such as soil moisture, evapotranspiration, fire behavior, and sublimation are poorly measured or forecasted.
- Inter-agency coordination and increased use of water banking may benefit substantially from improved annual and seasonal forecasting.
- A few critical dates and forecast targets show up repeatedly (e.g., the April 1 snow-water content measurement), but a surprisingly wide range of other forecasts is requested.

Reservoir Managers

A second study that provides insight on the potential use of climate information to improve annual reservoir operating plans uses a problem-oriented approach to identify issues that are sensitive to climate variability, and to examine the decision processes that are associated with these issues. Our approach relies on direct interaction with regional reservoir managers. We are building on several years of NOAA/CDC interaction with the U.S. Bureau of Reclamation (USBR). Partnership activities have included workshops with reservoir managers and their stakeholders and regular contributions to the Colorado Drought Task Force Meetings, the operations meetings for several reservoirs, and the USBR river systems management workshop (Ray and Redmond, 1999). We wrote and distributed an early winter "Forecast Discussion" for the upper Colorado basin which presented and explained both official and experimental forecasts and relevant research results. We also discussed the Climate Prediction Center (CPC) monthly seasonal outlooks with reservoir managers, and evaluated problems with the CPC products and the obstacles that prevent their routine use. One major problem identified was their coarse spatial resolution, and WWA researchers are currently engaged in experimental research to address this concern. We interviewed reservoir managers and some of their key stakeholders to determine their climate information needs and current uses. Finally, we are observing how the climate information is used in actual decision-processes.

Figure 6 illustrates a typical decision calendar for reservoir managers. The color code indicates when planning processes occur, when operational issues must be implemented, and where potential use of climate information and forecasts can be infused into the decision process.

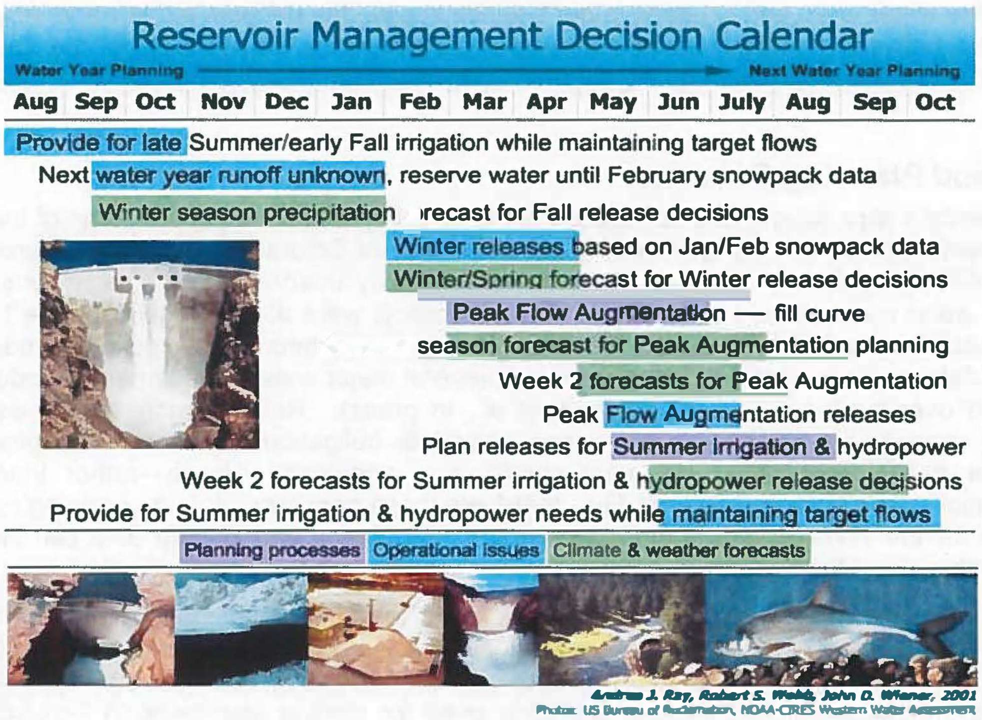


Figure 6: Decision-process calendar for water reservoir managers

In the semi-arid Interior West, water is intensively managed through an extensive network of reservoirs and inter-basin tunnels which transport water from the Western Slope across the Great Divide to densely populated areas on the eastern plains. Reservoir managers strive to optimize the use of water during fall and winter so as to ensure an adequate supply for the growing season while still leaving enough space in the reservoir to absorb flood events. Early in the year, management decisions are made using spring and summer water supply outlooks, based primarily on existing mountain snowpack. In addition, reservoir managers are faced with the decision of whether or not to augment peak flow to levels necessary for habitat building. Hydrologic changes associated with reservoir operations have reduced the habitat of endangered native fish. Lower peak flows in the spring have resulted in infilling of side channel and backwater habitats. Through a coordinated effort, reservoir operators seek to augment the natural springtime peak flow as necessary to flush sediment and build and maintain fish habitats.

Better use of climate information represents one tool that may enable reservoir managers to meet such new uses while minimizing conflicts. Critical questions for deciding the operation of a reservoir include:

- What will warm weather demands be for water?
- How much water is stored in the snowpack?
- How quickly will the snowpack melt and how much runoff will be produced?
- When will the peak flow occur?

The decision calendar illustrates three factors in the use of climate information: (1) climate information is needed on a water year, not a calendar year basis; (2) different types of information and forecasts with different temporal scales are needed at the crucial decision points in the water year; and (3) gaps in our science knowledge become explicit and include the relationship between species habitat and hydrologic flows; the predictability of the southwest monsoon; and the need for high quality river-basin hydrometeorology products.

Policy and Planning Concerns

WWA scientists also sought to understand the major policy and planning concerns of the water management community. Researchers at the University of Colorado's Natural Resources Law Center (NRLC) conducted a series of approximately sixty interviews with the leaders of the Colorado water management community. These subjects were asked to describe the types of water-related issues and solutions they expect to comprise the future public policy agenda. This interview data was supplemented by a review of several major water assessments conducted in the region over the past 5 years (Nichols et al., in press). Results suggest that issues of particular concern are trans-basin diversions, interstate obligations, environmental protection, and water quality regulation. In most cases, it is population growth—rather than other considerations such as climate variability—that fuels these concerns. It is an ongoing research challenge for the WWA to determine how climatic phenomena and climate data can influence these problems and their solutions.

The possibility of long-term drought is of key concern to many water managers in the Interior West. WWA researchers have regularly attended Colorado Drought Task Force (CDTF) meetings for more than a year presenting both official and experimental climate forecasts. We addressed problems with the Climate Divisions used for climate monitoring in Colorado, and presented to CDTF stakeholders an alternate set of climate divisions that provide a more physical basis for monitoring environmental conditions. Furthermore, we discussed with drought-sensitive stakeholders aspects of the complicated seasonal cycle of climate in the Interior West, and possible implications for the vulnerability of water systems. This dialogue with the CDTF is continuing, and will help shape and prioritize our physical science research agenda.

2.2 Development of Hydrologic Prediction Capabilities

Several applied research projects were initiated to address the information needs of reservoir managers in the Upper Colorado River basin. Building on a large body of CDC research on understanding and predicting El Niño/Southern Oscillation (ENSO) variability and its impacts, we conducted a detailed analysis of the influence of El Niño and La Niña events on the seasonal evolution of snowpack, and the potential utility of ENSO-snow relationships for seasonal predictions of runoff. This directly addresses stakeholder needs for climate information, particularly in mid-winter when reservoir releases are based on anticipated runoff in spring and summer (see Figure 6). Currently, forecasts of runoff are based solely on knowledge of the amount of water stored in the seasonal snowpack. We examined snow water equivalent (SWE) and streamflow data from several hundred sites in the major sub-basins of the Columbia and Colorado River systems to assess if ENSO information could improve seasonal runoff forecasts (Clark et al., 2001). Predictions of spring-summer runoff based solely on ENSO information had modest skill in the major sub-basins of the Columbia River and the Lower Colorado River. ENSO-based predictions of runoff were less skillful for basins in the Upper Colorado River. Interestingly, predictions of spring-summer runoff based on the water stored in the mid-winter snowpack were significantly more skillful than predictions based on ENSO information alone. This was true for almost all basins, including those with strong ENSO signals. Combining ENSO information with knowledge of mid-winter snowpack conditions only improves seasonal predictions of runoff for basins in which ENSO signals exhibit strong seasonality.

The small value of ENSO information for mid-winter forecasts of spring-summer runoff is sobering. The modest skill of ENSO-based predictions of runoff in the major sub-basins of the Columbia and the Lower Colorado River systems have some utility for planning reservoir releases during autumn. But, as stated earlier, ENSO signals in the upper Colorado River system are much weaker than those in the Pacific Northwest and desert Southwest. Meticulous analysis of ENSO impacts in the four states of Colorado, Utah, Arizona and New Mexico reveals that some signals do exist in specific months and specific locations (e.g., Wolter et al., in prep), and the possible use of these signals for seasonal runoff forecasts is promising. More details of this work are provided in the next section. Nevertheless, compared with other areas of the country, the generally weaker ENSO signals in the Inter-mountain West region pose significant challenges for us to provide reliable seasonal forecasts of runoff. In the next five years we will thus examine possibilities for non-ENSO based predictions of runoff and exploit such information in an empirically-based seasonal predictive scheme.

Returning to the decision calendar (Figure 6), another important entry-point for climate information is during spring and summer when reservoir operators are scheduling by-pass flows to increase the size of the natural peak in the annual hydrograph. The purpose of these operations is to flush sediment through lower reaches of the river and restore and maintain the habitat of endangered fish species. Reservoir operators need to release water to coincide with the natural peak in spring runoff, so short-term forecasts of the magnitude and timing of spring-summer runoff are extremely useful. The short-term streamflow forecasting problem is actually easier in the Interior West than in other areas of the country. Daily variations in runoff in snowmelt-dominated river basins are more closely tied to maximum temperature than precipitation. Because medium-range forecasts of temperature are much more reliable than precipitation forecasts, possibilities for reliable forecasts of runoff are much greater in the snowmelt-dominated basins in the Interior West than in rainfall-dominated basins in other areas of the country.

Traditionally, hydrologic forecasts have been made using the extended streamflow prediction (ESP) procedure (e.g., Day, 1985). In this approach, a hydrologic model is driven with observed precipitation and temperature data up to the beginning of the forecast (e.g., 1 January), and then run using precipitation and temperature data for the same date from every other year in the historical record. This provides an ensemble of possible outcomes given the antecedent hydrologic conditions (e.g., soil moisture, water equivalent of the accumulated snowpack) at the start of the forecast. Forecast accuracy is therefore entirely dependent on accurate specification of conditions over the basin at the start of the forecast, and the influence of those conditions on the basin hydrologic response. The approach works well in river systems where significant lag times occur due to storage of water in snowpack or subsurface and groundwater reservoirs. However, because the ESP methodology equally weights the history for each year in the historical record, the approach often yields a wide range of possible outcomes and low probabilistic skill. An obvious entry-point for climate information is to include weather forecasts and climate outlooks in the ESP approach, and thus potentially improve streamflow forecasts

Our experimental streamflow forecasting system uses information from medium-range atmospheric forecast models as input to hydrologic models to provide short-term (1-2 week) forecasts of runoff. This involves a) downscaling the global-scale atmospheric forecast model output to provide estimates of precipitation and temperature at local scales in individual river basins; b) assimilate station observations of precipitation and temperature (and, in mountainous basins, satellite estimates of snow extent) to estimate basin initial conditions; c) run hydrologic models in ensemble mode to estimate forecast uncertainty; and d) post-process hydrologic model output to remove systematic biases (Clark et al., 2000; Clark and Hay 2000, Hay et al., 2000; Clark et al., in prep; Hay et al., in prep). We used the eight-day forecasts archived as part of the 40 plus year National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis project to compare the performance of this system against the traditional ESP approaches.

The skill of the eight-day forecasts is summarized in Figure 7. Here we demonstrate the performance of the two (ESP-and NCEP-based) forecasting techniques for the Animas River Basin, a small mountain snowmelt-dominated watershed in southwestern Colorado. The contour plots show the month along the x-axis, the forecast day along the y-axis, and the Root Mean Square Error (RMSE) or the forecast improvement as the contoured variable. The top panel shows the climatology forecast error, computed using the difference between the observed flow and climatology forecasts. Climatology forecasts are analogous to the mean value in the ESP ensemble, used operationally at the National Weather Service (NWS) River

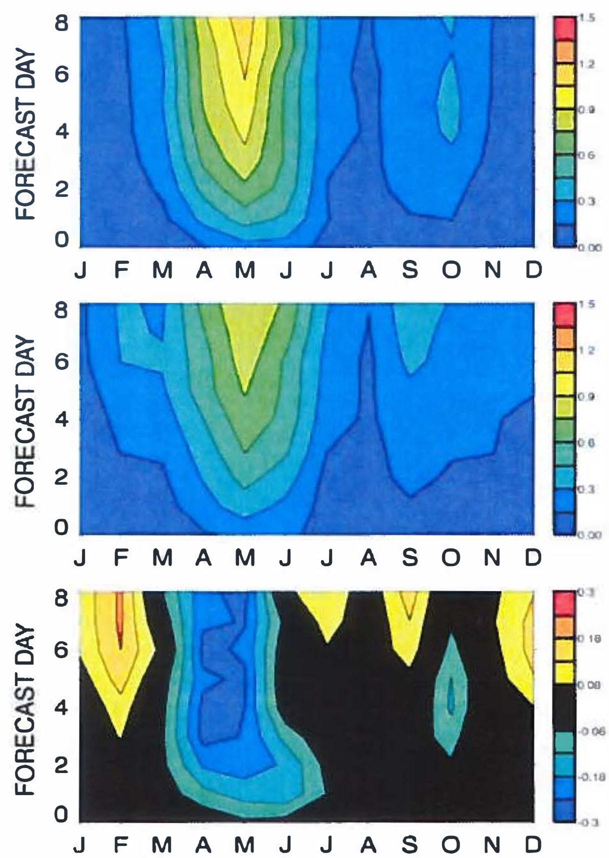


Figure 7: River forecast error when using climatology (top), NCEP forecasts (middle), and the difference between the two (bottom)

Forecast Centers. The middle panel shows the forecast error using the NCEP forecasts in place of the climatology. The bottom panel is the difference between the top and middle panels. The most notable feature is the significant improvement of the NCEP-based runoff forecasts over runoff forecasts based on climatology, most apparent during spring when runoff in the Animas basin is highest and most variable. Improvements in forecast accuracy are derived from reliable springtime forecasts of maximum temperature that translates into credible estimates of snowmelt and runoff. The accuracy of the NCEP precipitation forecasts over the Animas basin was poor. Useful forecasts using NCEP output most likely occur because the Animas River basin is dominated by snowmelt (which is influenced by variations in temperature), and may not hold in other river basins where the surface hydrology is predominately influenced by rainfall.

Our techniques still need to be refined, but we have already developed a collaborative relationship with the U.S. National Weather Services' Hydrology Laboratory to perform a side-by-side comparison of our approaches with operational NWS techniques, and infuse these techniques in the NWS Advanced Hydrologic Prediction System (AHPS).

2.3 Historical Climate Information for Management and Planning

The demand for climate information and outlooks on local scales leads to particular challenges in the Interior West. Here, terrain organizes weather and climate, and our initial focus has been to define terrain-specific climate variability. Two examples are used to illustrate the use of long-term climate and streamflow records in management and planning: (1) Regulation of water quality, and (2) Long-term water supply planning in a growing urban area. Both of these projects highlight the issues facing water use planners in the South Platte Basin.

Climate Variability and Water Quality

Climatic variability contributes directly to hydrologic variability in streams, and hydrologic variability affects the quality of aquatic environments. Even so, the susceptibility of aquatic environments to climatic variation has received little attention, especially in the Interior West. Our studies of the connection between hydrologic variability and maintenance of water quality in the South Platte Basin indicate that one of the most prominent influences on water is the discharge of treated wastewater. The regulatory framework created by the Clean Water Act (CWA) protects uses, such as municipal and agricultural water supply, recreation, and aquatic life through the issuance of permits that regulate the concentrations of pollutants in waters receiving treated wastewater. Protection of aquatic life has been the most important motivation for the extensive improvements in wastewater quality that have occurred since passage of the CWA. River flows have a direct connection to the permitting process because historical flow records are used to define the amount of dilution that will be available at the point of discharge. The success of the permit in protecting aquatic life depends on the accuracy with which dilution flow is estimated. Accuracy is influenced by the timing and duration of the historical record used in estimating dilution flow because the estimate will reflect hydrologic (and thus climatic) variability represented in the data set. Longer flow records are more likely to encompass a broad range of climate variability, including ENSO signals and major droughts. Shorter records are much more likely to result in errors that may undermine protection of aquatic life or require unnecessary, costly additions to treatment.

Our analysis of daily discharge records from several gauging stations in Colorado shows that the use of a short (e.g., ten-year) record typically yields dilution flow estimates that may differ by a factor of two from the estimate based on a long-term (70-year) record. Figure 8 shows an analysis where uncertainty in the acute minimum flow needed for water quality decreases with increasing climate record. The biases are large when climate records of less than 10 years are used. The vertical bars encompass 80% of the values and the horizontal bar represents the median. The long-term record for the South Platte includes four major droughts, the most recent of which ended about 20 years ago. Short records, especially in recent years, may not reflect low flows characteristic of droughts.

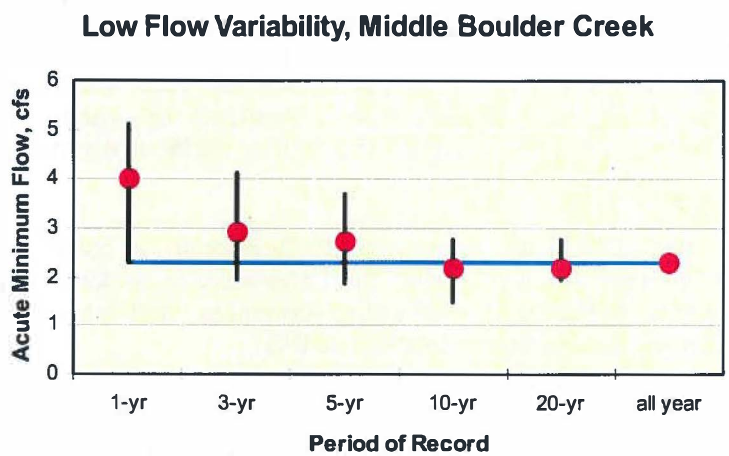


Figure 8: Climate impacts on low flow

Natural variability in the stream flows may be overshadowed by significant trends caused by water development activities such as the construction of impoundments or the importation of water from another basin. For most locations within the South Platte Basin, the effect of water development projects has been to increase the lowest annual flows in a manner that is generally favorable to wastewater dischargers. However, the effect of climate variation on these altered flows is difficult to assess for two reasons. First, many of these developments are recent; there is only a short record representing the altered flow regime during which there have been no droughts. Second, and perhaps the more important issue, concerns hidden assumptions about water-use practices. There is a risk in having permit limits set on the basis of altered flow regimes in situations where there is no record of severe drought since the completion of a water development project. During a severe drought, municipal demand may take precedence over other beneficial uses in a way that could drastically alter low flow, leading to unanticipated degradation of water quality.

At present, the regulatory practice for establishing low flow conditions that govern discharge permits is very rigid; it lacks a mechanism for incorporating climate variability not already reflected in a data set. Thus it seems likely that some discharge permits are too restrictive, and others not restrictive enough, due in large part to failure of the flow record to incorporate consequences of climatic variability. The situation can be improved through a better understanding of the relationship between flow variability and climatic variability.

The Occurrence of Drought

Examination of the long-term climate and hydrology signals in the South Platte clearly demonstrate previous periods of extreme drought both in terms of duration and severity (Woodhouse, 2001). A 300-year reconstruction using stream flow and tree ring data for a tributary of the South Platte (Clear Creek) which supplies the City of Westminster shows four droughts during the last century and an extremely dry period during the mid-1800s. At present, most long-term water resource planning is based primarily on 20th century instrumented records that do not capture all of the natural climate variability in the basin. Interestingly, the rapid municipal growth of the past two decades has occurred under a climate regime that has been completely absent of drought conditions. Analysis of the paleoclimate record, therefore, draws attention to the potential for significant drought-related stresses in the Interior West, and the need to plan for extended drought conditions.

The variability of streamflow is further complicated by the extensive trans-basin diversions from the upper Colorado Basin to the South Platte Basin (see Figure 9). In fact, the South Platte River receives 30% of its flow from this diversion. While growth is occurring everywhere in Colorado, most is on the Front Range and is serviced by this water supply. Long-term water plans along the Front Range assume increased trans-basin diversions. In order to determine the impact of drought on streamflow, it is therefore necessary to study the climate variability on the two sides of the Continental Divide. Of particular interest is whether these two regions are covariable.

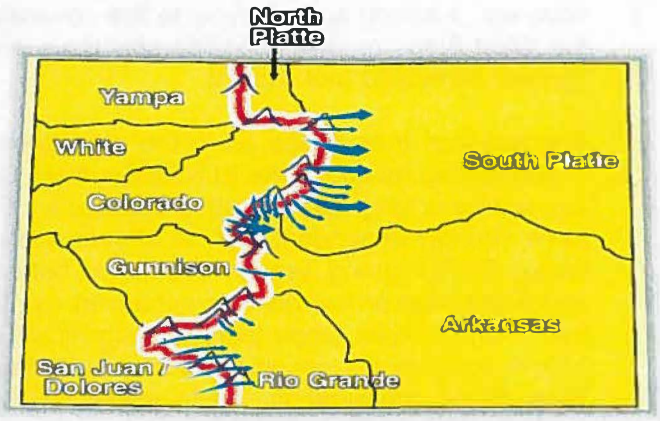


Figure 9: Colorado climate divisions

For purposes of historical climate monitoring, Colorado is segmented into five climate divisions that represent the State's main river basins. For the South Platte basin, the western boundary of this hydro-climate division is the Continental Divide, while the eastern edge is in the agricultural expanses of the Great Plains. The elevation change across this climate division is 10,000 feet. The Platte Climate Division is heavily weighted by reporting stations in the Front Range, whereas comparatively sparse sampling exists in the Eastern Plains. We have examined the coherence of seasonal variability among the stations of the South Platte Basin. During the March-June period when this region receives most of its annual precipitation, an index of Front Range stations correlates at 0.72 with an index of Eastern Plains stations. Climate spatial trends indicate that snow accumulates in the mountains between October and May with April being the wettest month. Along the Front Range, May and June are the wettest months whereas southwest of Denver, July and September receive the greatest precipitation, primarily associated with the southwest monsoon. Temporal trends indicate that in mid-winter the mountains are wet and the plains are generally dry whereas during spring there is significant coherence in precipitation across most of the state.

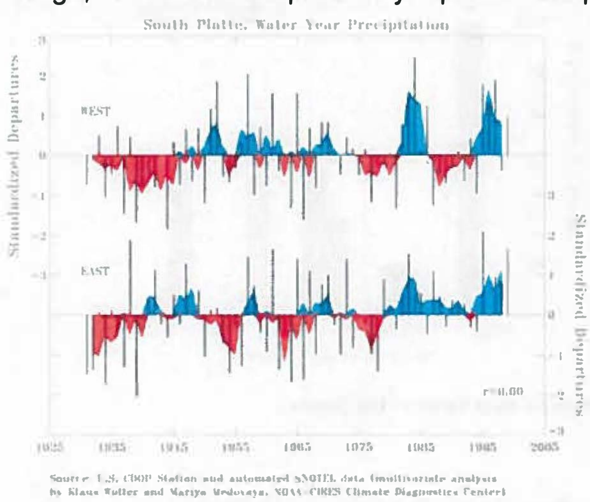


Figure 10: Time series of precipitation on both sides of the Divide

We are also interested in climate covariability across the divide in view of the Front Range's dependence on both West and East Slope water sources. The time series of precipitation shown in Figure 10 for an average of stations located on the West Slope and in the Front Range correlate at 0.66 during spring for the last half century. Consistent with this high covariability, consecutive seasons of below average rainfall, conducive for drought, occurred on both sides of the Continental Divide during the mid-1950s and early 1960s, and likewise both regions share the same years for the extreme wettest Springs. It is also noted that during the last several decades, when growth has been largest, precipitation has been above normal. There is, however, a strong annual cycle to the covariability across this region, and during winter when the West Slope receives considerably more precipitation than the East Slope, the two regions are anti-correlated (not shown).

The question then arises as to the predictability of any of these climate variations. Tropical ocean forcing related to the El Niño/Southern Oscillation (ENSO) phenomenon is known to be a key source of long-lead climate predictability. For Colorado, we find ENSO-related predictability to be strongly dependent on time of year and on location. Figure 11 shows the increased risk during ENSO spring season events on both the west and east slopes. An asterisk shows significant high or low odds of enhanced risk, where even odds across the quintiles would be 20%. On the East Slope there is a significant enhanced probability of wet conditions during El Niño's and very dry conditions during La Niña's. In general these signals also appear true for West Slope precipitation, again indicating the covariability now associated with a climate variability signal. The insights gained from this analysis are:

- Correlations of precipitation anomalies across the Divide indicate a higher than expected risk for regional drought
- Advance knowledge of the state of ENSO may be the key to water management in the South Platte Basin because the odds of either wet or dry conditions during spring are clearly shifted by El Niño or La Niña

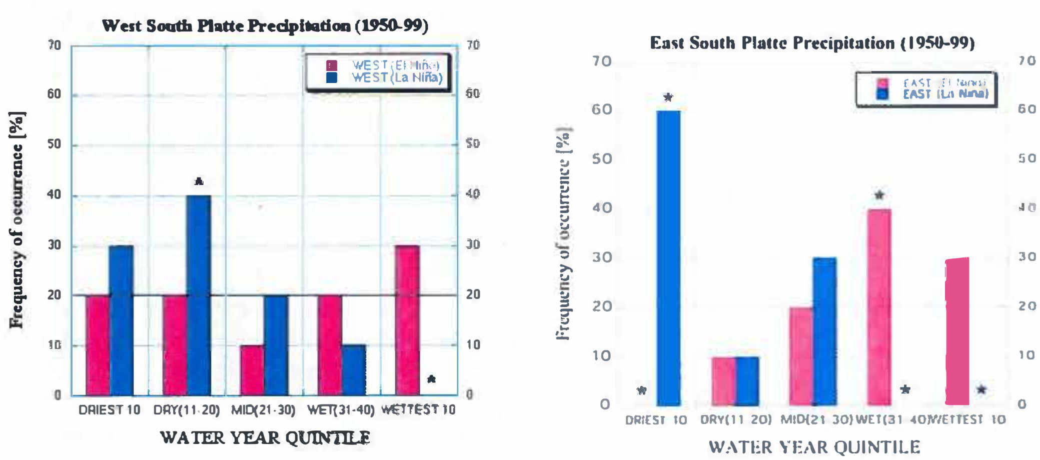


Figure 11: Enhanced risk of ENSO signals on both sides of the Divide

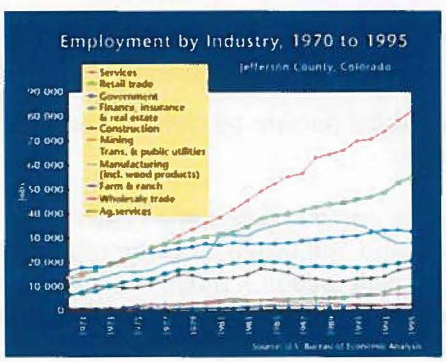
2.4 *Social Dimensions of Climate, Society & Vulnerabilities*

Our work on the social aspects of regional development and water use takes on the RISA goals of assessing regional sensitivities in selected climate-environment-society interactions, and identifying trends and factors influencing climate-sensitive human activities. It is also founded in the evolving field of climate impact assessment (a field codified in Kates et al., 1985, and more recently by Parry and Carter, 1998). A regional approach, as opposed to global or local, emerged as the most appropriate scale to capture climate-resource interactions and human response. We have initially limited our focus to water-related vulnerabilities and water decision-makers within the South Platte Basin. Steps in this effort include:

- Assessing regional trends in land and resources development and resource use
- Developing concepts and hypotheses about climate and society relationships
- Identifying climate-sensitive decision-makers
- Examining potential climate impacts
- Assessing potential uses of improved climate information

Regional Trends

Briefly, we found the South Platte basin exhibiting strong population growth and undergoing an economic transition. Basin population grew by about 600,000 people in the 1990s, or 25% (Figure 4). The South Platte Basin is one of the fastest growing regions of the U.S., and Douglas County, south of Denver, was the single fastest growing county in the United States for most of the decade. This basin is expected to grow by another million people in the next 20 years. Virtually all-regional economic growth is in services, high-tech business, and construction. Natural resource industries like agriculture, logging, and mining are flat or decreasing in terms of jobs and their share of the regional economy (Figure 12).



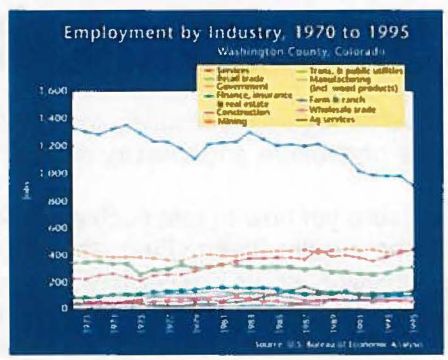


Figure 12: Employment trends in South Platte Basin for two counties

Economic and demographic growth means that the South Platte is marked by burgeoning urban, suburban and exurban development patterns in which residential, commercial, and infrastructure land uses replace agriculture, natural areas and other open spaces. The "footprint" of development is expanding rapidly along with population growth in the basin, a pattern we projected using residential density. Besides changes in water use and increased wastewater discharges associated with this urban sprawl, previous research and common experience indicate that urban growth leads to increased and more polluted storm runoff.

Water use in the basin is of course increasing with population growth, but a large proportion of increased urban supply comes from previously developed agricultural supplies, so urban growth does not necessarily mean a concomitant growth in *new* supply. In 1985, agricultural users accounted for 91.6% of total water use in Colorado, while municipalities used 4.4%. Such proportions are typical for arid, sparsely populated areas of the American West. In the South Platte River Basin, however, agriculture comprised only 80.2% of water use while municipalities used 12.9% by the late-1980s, a proportion that has certainly increased (Litke and Appel, 1989). Still, irrigated agriculture consumes the lion's share of water, and the South Platte retains a large irrigated area; indeed most of Colorado's irrigated cropland lies within a triangle formed by Boulder, Fort Collins and Greeley and along the South Platte main stem (Smith et al., 1996).

Over 2.5 million municipal water consumers in the South Platte Basin used approximately 638,000 acre-feet of water in 1996. At "build-out" it is estimated that the South Platte Basin will have 4.3 million residents and require 1,124,000 acre-feet of water (Hydrosphere Inc., 1999). But we don't really know what "build-out" means for a region, as there seems no logical limits to urbanization (consider Los Angeles, another semi-arid western city that has yet to reach "build-out"). More pertinent to the assessment, though, is that when Hydrosphere Consultants examined county and municipal growth and water supply plans, they found that planned supplies were generally adequate for this near-doubling of basin population.

On average, more than half of residential water goes toward landscaping, so both urban and agricultural uses are climate-sensitive. A 1995 study of water use in a Boulder subdivision found that outdoor use accounts for about 54% of total water use, mostly for landscaping, and that residents applied an average of 16 inches of water to their yards in a summer (Mayer, 1995). The study also found that residents water more during drought years, indicating both their sensitivity and their adjustment to climate variability.

The Basin in Transition: More or Less Sensitive?

These regional development and water use trends suggest a simple hypothesis about climate and water resource relationships in the basin:

> *Overall regional sensitivity to climate impacts should decline as climate-sensitive sectors like agriculture and forestry decline in importance.*

We're not sure yet how to test such a proposition, but we can suggest some reasons it might not hold for the South Platte. First, the growing urban and suburban society requires several climate-sensitive inputs, especially water. Because cities acquire most of their water from agricultural users, we expect climate vulnerabilities to transfer along with the water. And because urban uses are growing, whereas regional supplies are relatively fixed, it would follow that:

> *Vulnerability to climate variation (i.e., chance of system failure) increases as use grows to meet supply.*

This hypothesis has been presented in several water studies (Colorado River, Sacramento Basin, Denver water system, etc.), and could almost be considered a truism—less buffer means more vulnerability—except that its truth depends so much on the status of the given water system and how use and supply are defined and measured. If we define supply as storage (which makes sense in the Interior West), then Denver's system would appear to be getting much more vulnerable (they were not able to build their next planned reservoir). Yet, there's evidence that Denver and surrounding communities have solid plans for acquiring supply as needed from agriculture; they have already exhibited skill at doing this.

We have also found that the relationships between land use and water use are not as clear as often argued due to complications in the transition from agricultural to urban development. According to some studies, and conventional wisdom, the South Platte Basin is losing agriculture as subdivisions replace farms and cities acquire water supplies. Smith et al. (1996) found that between 1978 and 1992, the Front Range lost 8% of irrigated agricultural land, and the Colorado Agriculture Commissioner reports that between 1992-1997, agricultural land was converted to other uses at a rate of 270,000 acres/year, nearly double what it had been previously (Ament, 2000). But our first assessment efforts show a more complicated picture. Although the transition from resource to service economies is reflected in urban water transfers and declining farmland, urban development does not necessarily obliterate as much cropland as one might expect. Irrigated land did decrease in the 1990s, a decline from a 1980s maximum that seems quite modest given the spreading urban area (Figure 13).

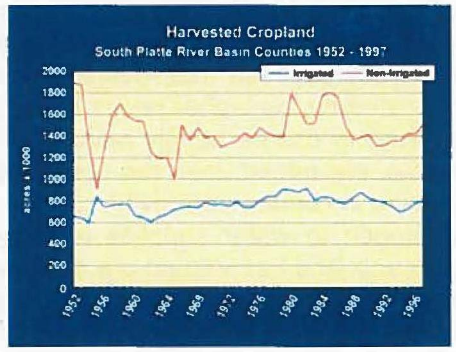


Figure 13: Trends in cropland

The complexity of this relationship between urban and agricultural water use is further illustrated by the Colorado-Big Thompson (C-BT) Project. As the largest water project in the basin (and third largest irrigation project in the Western U.S.), it is evolving from an agricultural system into an urban water system (Figure 14, left). Yet, actual deliveries (Figure 14, right) in the CB-T service area suggest that either alternative water is available or that greater efficiencies are allowing irrigators to continue cropping similar acreages while still selling water to cities.

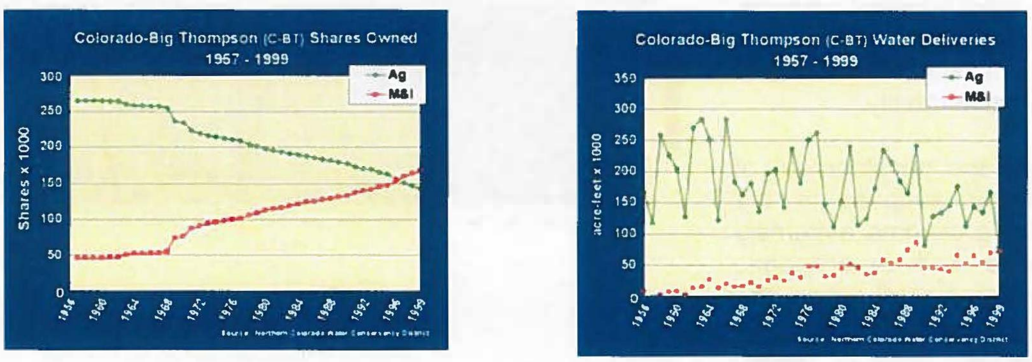


Figure 14: Water shares and deliveries from the Colorado-Big Thompson project

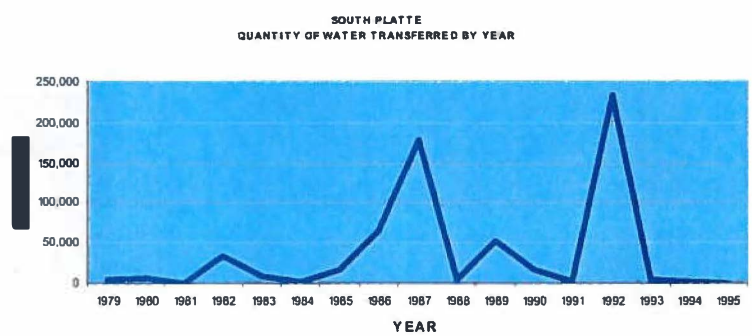
Returning to our broad hypothetical question: Is the South Platte becoming more or less sensitive to climate in terms of water resources as its economy transitions from resource-based to post-industrial? By vulnerability we mean the likelihood of failing to meet water demand for some period of time due to climate impacts on multiple time and space scales, and failing to produce the suite of desired goods and services with that water. If our initial assessment holds, it may mean that agriculture is becoming more sensitive as it increases efficiency and uses as much land, but with less water (in a way, inefficiency provides a climate buffer). An obvious mechanism for this increased sensitivity comes in the form of “interruptible supply contracts” where cities buy water they do not currently need and lease it back to farmers during normal years. In dry years, they use it themselves and give farmers cash instead of water. It is generally believed that, overall, urban uses are less flexible than agricultural uses, a quality indicated by the higher prices fetched for urban water and the great efforts that urban suppliers expend to assure supply reliability (Howe and Smith, 1993, 1994). If urban supplies, on the whole, are robust, then the net transfer of water to urban uses in the basin might lead to a net decline in climate sensitivity. Just how long the fast-growing cities can maintain this expansive approach to water supplies is uncertain. Right now, the fastest-growing cities in the U.S. (Phoenix and Las Vegas) are also the climatologically driest big cities. Eventually, demand may squeeze supply and reliability will decrease while climate vulnerability will increase. But the current agricultural-to-urban transition, however, may still mean lower vulnerabilities in the near-term.

Obviously, we need to hone these ideas and test them carefully. A RISA goal is to assess linkages among climate variations and social and economic activities, actions, and capacities over time by looking at a multiplicity of stresses and their cumulative impacts. Such multiple-factor, cumulative analysis is difficult. We are studying relationships among climate, water use, poverty, and land use. For example, water transfers affect water resource vulnerability in different ways, and next we briefly describe some efforts underway to assess transfers and their effects.

Water Ownership and Transfers in the South Platte.

We are investigating water transfers as a form of adjustment to changing economic, demographic, and climatic conditions in the South Platte Basin. Our sense is that this is the most obvious ongoing water use change and one that interacts with climate and climate vulnerability.

Because the development of new water supplies in the West have become extremely expensive, both in economic and environmental terms, the transfer of water from older, lower-valued uses to newer, higher-valued ones adds efficiency to the overall system. This is especially true since roughly 85% of consumptive water use still takes place in irrigated agriculture, much in the production of low-valued crops. Water changes ownership through largely



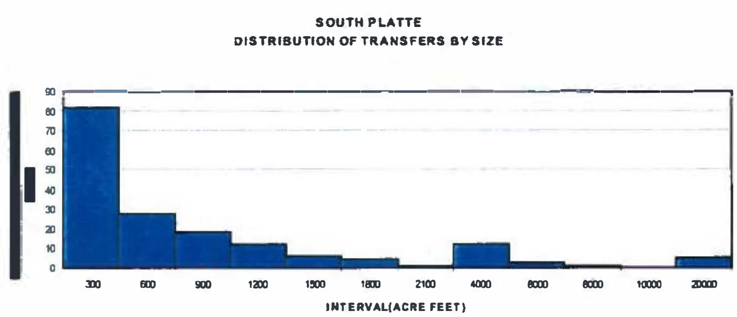


Figure 15: Native water rights transfers (quantity and size)

informal water markets within which buyers and sellers search for one another in ways varying from phone calls and local bulletin boards to water brokers and regional computer networks. In addition to permanent transfers of water ownership, it is possible for water owners to "rent" or "lease" water to other users for periods of up to one year, greatly facilitating adjustments to short-term weather events, especially droughts. Figure 15 shows the acre-feet of native water rights transferred by year as well as the distribution of transfers by size with a small median size of about 400 acre-feet. The vast majority of these transfers are from agriculture to non-agricultural use.

A slightly different transfer scenario holds for the Northern Colorado Water Conservation District (NCWCD) which was established in 1937 to contract with the Bureau of Reclamation for waters from the federal C-BT project that brings 270,000 acre-feet of water into the South Platte Basin from the Colorado River headwaters on the Western Slope of the Rockies. This extra-basin supply constitutes about 30% of the total supply in the South Platte. The establishment of a market for this water (in the form of shares in the Northern District) is greatly facilitated by the fact that imported water is totally owned (initial use and all return flows) by the importer and transfers are not subject to the court review process. Figure 14 (shown earlier) illustrates both the changing pattern of ownership and actual use of NCWCD water. Cities and industry are increasing their share of ownership, but the share in actual use is not increasing as rapidly because towns typically "rent" some of their water back to agriculture on an annual basis, subject to recall in drought years. Figure 16 shows the volume of water transferred by year and an average price for each year. The patterns of prices and volume of transfers show cycles that relate in part to varying business and demographic conditions and in part to varying climatic conditions. Statistical analyses of these relationships are continuing.

An ongoing activity that is drawing the social science components of our project closer to the climatologic components is the analysis of ways in which climate variations affect the water market, i.e. the volume of water transfers and their prices. While there are cycles in these measures, some of the variation is due to economic fluctuations, demographic changes and, occasionally, to new sources of water (like the completion of the Windy Gap supplemental project to the C-BT Project in 1980). It appears, however, that climatic effects play an important role in determining these variables. The quantification of these effects will be useful in understanding the possible impacts of long-term climate changes on the uses and prices of water and is a next step in this analysis.

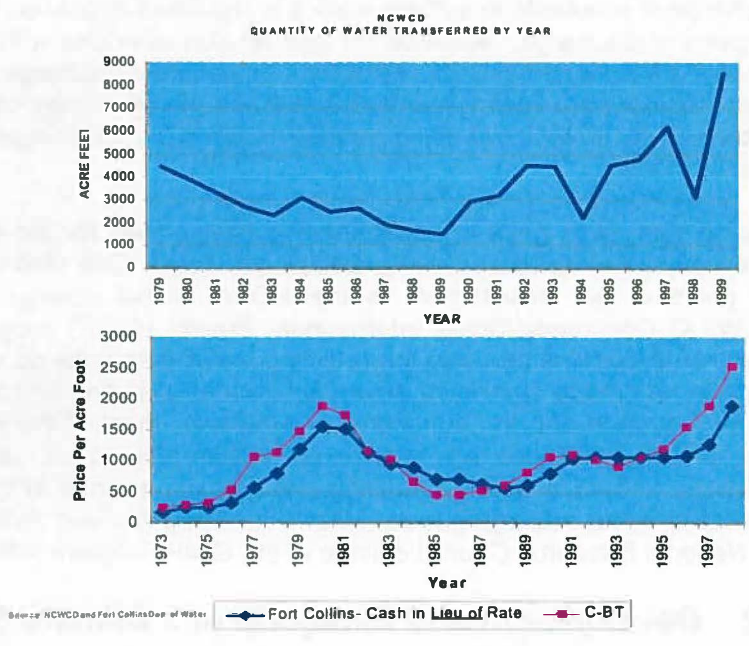


Figure 16: Trends in volume of water transfers and price

3 Vision and Challenges

3.1 Identifying Gaps in Research and Research Funding

The premise of the Interior West assessment, and indeed of OGP's RISA program, is that society has evolved to a point where day-to-day decisions and the development of policy require integration of the knowledge and expertise of a number of different fields of study. By analyzing the decision-making framework of water managers in the Interior West, WWA scientists have found that this premise is firmly grounded in reality. Fields relevant to water issues include climatology, hydrology, biology, economics, demography, and environmental law. Moreover, WWA scientists have concluded that the scientific basis needed to support many water management decisions does not exist. For example, we have only recently developed techniques for predicting short-term variations in runoff [Clark and Hay, 2000; Hay et al., 2000], and have yet to develop procedures to predict features of the annual cycle of runoff (e.g., the timing and magnitude of peak flow) that may be important for specific management applications. In terms of environmental quality concerns, we do not understand the myriad of linkages between climate, hydrology, ecology, and the changing structure and values of society. Identifying and understanding such linkages is necessary for optimal management of the region's water resources.

As an example, consider the environmental concerns associated with the dilution of pollutant discharge into the South Platte River Basin under conditions of extreme low flow. We do not understand relationships between climate variability and low flow and how these relationships are modulated by the construction of reservoirs or diversions and changes in land use. The discharge of pollutants to surface waters is regulated largely on the basis of expected dilution at the point of discharge. Because minimal dilution coincides with the lowest flows, predictions of low flow are a major basis for restrictions on pollutant discharge. Present methods of prediction do not take climate variability into account and therefore may be biased because of their failure to account for ENSO events, extended droughts, or other types of climate variability that will affect low flows.

In large part, such gaps in understanding have arisen for the simple reason that science has historically been structured along disciplinary lines. One step in the right direction relevant to the goals of our assessment is the NOAA Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP) program, which has as its primary objective to demonstrate skill in predicting water resources on various time scales. The GCIP program has made significant advances in understanding and modeling relationships between the land surface and the atmosphere. However, most of the effort has focused on effects of land-surface conditions on climate on continental scales rather than climate impacts on hydrology and advances in modeling and predicting runoff at the basin scale which is of most interest to water managers (see reviews by Coughlan and Avissar, 1996, Lawford, 1999, and the National Research Council critique of the GCIP Program [NRC, 1998]).

3.2 Development and Evolution of a Climate Service

Fundamental questions are being addressed by the regional assessments that bear directly on the matter of developing a national climate service. These include: what would be the contents of climate services and who would be served? Regarding the first question, our experiences and those of other regional assessments are confirming that climate information is important. This information may include monitoring, for example, of snowpack and soil moisture. It may also include the construction of scenarios designed to assess the exposure of infrastructure and society to plausible climate events, such as prolonged drought, or climate change and its long-term affect on water availability. Thus, while researchers have focused considerable attention on the utility of skillful climate outlooks issued one season or more in advance, accurate descriptions of the state of the climate system (i.e., a "nowcast") are also valuable to decision-makers.

Many agencies have expressed a need for improved climate services to support increasingly complex decision-making processes. Examples include the management of public lands by the Forest Service and Bureau of Land Management, management of reservoirs through the Bureau of Reclamation, and the management of streams, reservoirs and ecological systems within riparian corridors by the Fish and Wildlife Service. State and municipal governments increasingly are also voicing needs for climate information. In the Interior West especially, annual operating plans for water management involve important decisions at the local level and require information on the expected supply and demand for water, each of which has an underlying climate component.

The infrastructure necessary to deliver such services is a matter of active debate, but it will likely require a strong regional component that can accommodate the need for local climate services on scales where decision-making takes place, such as at a river headwater. It is in recognition of this fact that NOAA has funded several regional integrated science assessments across the U.S. Some structures have been in place for over a decade. The Western Region Climate Center in particular provides an extensive suite of climate products, services a wide range of user needs in the region, and in many ways is an excellent model for a climate service organization. At the national level, the Climate Prediction Center generates suites of operational forecast and monitoring products, and the challenge is emerging on how to tailor these to a growing spectrum of diverse and local user needs.

3.3 Transition to an Operational Information Dissemination System

Part of the task to which the regional assessments have been charged is determining the value of existing climate products for decision-making processes. In the course of such efforts, the need for new products has been expressed. Some of these are being met experimentally on a case-by-case basis through an assessment's interaction with specific users, and the question of which ones should become operational is now emerging. A related issue is the method of dissemination, either at the national scale at which operational climate predictions are now provided, or at a regional or local scale.

It is reasonable to examine the model of the National Weather Service, which in addition to a centralized location producing national-scale forecasts, consists of regional weather forecast offices that tailor products to local conditions. Its structure has evolved through nearly 100 years of interactions between the weather services and users. Climate services by comparison are just now emerging, and the suite of current and future users are only now being identified. The current constellation of regional weather service offices is without substantial climate expertise, whereas the regional climate centers are arguably too few and far between to meet the emerging demand for offering climate information at a regional or local scale.

The challenge to develop a new suite of climate information and products is considerable, and in this initial stage it will require increased coordination of activities among the assessments, regional climate centers, and the national climate centers. One question being addressed in the assessments is scalability, as this could accelerate the transition toward new operational products. Diverse sectors clearly have differing climate information requirements, but there is a strong likelihood that many lessons learned in one region will find application in others. It is for this reason that the WWA is attempting to document decision calendars and the role of climate information in various sectors with the interest of comparing these with similar analyses performed in NOAA's other regional assessment projects.

3.4 User Attributes, Risk Tolerance, and Liability

Some issues to be considered in the implementation of a climate service are development of scientific understanding, proper use of probabilistic information, and users' tolerance for risk. To be effective, climate information must be technically sound and appropriate, accurately disseminated, and properly used. Climate professionals are responsible for creation of the information and for its initial dissemination. However, if the information is poorly disseminated or improperly used, climate scientists may still be held responsible for any negative impacts that result. Past studies have shown that even modest predictive skill can be beneficially applied to many climate-sensitive decisions if done so correctly. However, the use of such information requires a sophisticated user. A goal for climate services then, must be to identify sophisticated users and to help increase the sophistication of others.

The routine application of climate outlooks remains hindered by a large set of constraints which include an understanding of probabilistic information and users' risk tolerance. Allan Murphy conducted a series of studies on the formulation, dissemination, and use of probabilistic forecasts in the 1970s and 1980s (e.g., Murphy, 1985) and found that while most users were able to use probabilistic forecasts in a statistically-correct manner, difficulties in the communication of the probability and the event being predicted often limited the value of the information products. This suggests that a challenge in climate forecasting is to convey both a conceptual understanding of forecasts and a technical method for their interpretation. Some users may also be highly risk-adverse, for example, a water manager who could face serious consequences with multi-year implications because of a "wrong" decision.

3.5 Education

The "compartmentalization" of science is largely at odds with society's need for an interdisciplinary scientific approach, and the process of funding research should be updated to promote a research framework that addresses societal needs. If we are serious about the notion of the interdisciplinary approach being the next scientific revolution, our efforts must begin with education. We need a course of study to examine interactions between different facets of the physical environment as well as interactions between humans and nature. In the sphere of physical science, courses are needed to examine interactions between climate, hydrology, geomorphology, coastal processes, and biological systems. Superimposed on these physical linkages, it is necessary to provide students with knowledge and expertise on human-environment interactions.

The Cooperative Institute in Environmental Sciences (CIRES) is seeking to address these issues in a number of ways. As an institute having formal connections with eight University departments and nine NOAA laboratories, CIRES is perfectly positioned to facilitate multiple research and academic links between disciplines. We recently created an *Interdisciplinary Lecture Series* that jointly invites speakers who can bridge different disciplines and establish enduring links between departments and laboratories. CIRES also just created a *Research and Education Fellowship* to enable a science faculty member to simultaneously advance their research and develop an educational curriculum that embodies interdisciplinary concepts. It is intent on enhancing science education, expanding research opportunities among a broad range of students and disciplines, and in building new partnerships with other educational institutions. CIRES' first candidate is a hydrologist who has been working with the White Mountain Apache Tribe for four years and is seeking to increase the number of qualified Native environmental science professionals while contributing to informed decision-making by tribal members in the context of limited water supplies for a region experiencing rapid population growth.

Realizing that crossing boundaries constitutes a risk for scientists and academicians who reside in traditionally disciplinary structures, CIRES is also seeking to create a research environment that welcomes and rewards innovation. To that end, it conducts an *Innovative Research Program* designed to encourage creative, unconventional and/or fundamental research that might otherwise be difficult to fund. The intent is to provide an uncomplicated mechanism for supporting small research efforts that can quickly provide concept viability or rule out further consideration. It is to promote novel research and encourage synergy between disciplines where an expected outcome need not be guaranteed.

3.6 Lessons Learned

The *Water in the Interior West* assessment has evolved during its formative stages in ways that were not entirely foreseen, and the difficulty of conducting integrative research should not be underestimated. Challenges included not only the structure of the management, but also how the team was assembled and is developed and sustained. Finding scientists interested in working directly with users as well as with other disciplines was the first challenge. Establishing a solid science theme helps in attracting such scientists. A long-term commitment is needed to begin understanding and respecting each other's methodologies realizing that natural sciences are more than satellite images and that social sciences are more than anecdotal stories.

Interdisciplinary Approach

As a result of three years of work together, we have witnessed an evolution in our approach from multidisciplinary goals toward more fully integrated objectives. A multidisciplinary effort indeed combines multiple inputs, but the elements retain a separate identity where linkages are far from dominant. An interdisciplinary approach results in a new and intellectually coherent entity that is more than the simple combination of its parts. This approach requires a shift from the focused study of objects (often in isolation) to their interrelationships within the system. For us, this transformation has come in part from team development and in part from interaction and experience gained with users. As a result we have learned that the framing of interdisciplinary research questions is very different than disciplinary or multidisciplinary research. The development of innovative approaches for identifying research "drivers" and for framing research questions is an ongoing discussion within our group. For example, some have suggested that a focus on user *decision processes* may be a better driver of research than *user needs* alone, since the latter can be difficult to assess. It is likely that discussions with users that involve both concepts will lead to a more complete picture of what users think they need while they learn more about the potential products that we might be able to provide. By understanding decision processes, the synthesis of research needs required by the user can be identified. Such lively debate and exchange of ideas is central to our integration process and teambuilding.

Research Structure

Often the greatest obstacle to conducting true interdisciplinary research lies not with the people who seek to conduct it, but in the structures that would support it. Organizational structures and labels can result in self-limiting perceptions of individual roles and responsibilities within a group. Typical hierarchies have traditionally worked very well in addressing disciplinary issues, but they hinder the collaboration across structures and between projects that is required in more interdisciplinary endeavors. Any departure from the norm requires a trust in the leadership and team that must be earned and therefore takes time to develop. We have created a distributed structure that is defined by the scientific questions being addressed where responsibilities are backed by the delegated authorities to accomplish them. We have learned to value disciplines and participants by their connections, not their boxes, and have begun moving from a collaboration of convenience to one of interdependence.

Project Management

When attempting truly interdisciplinary research, innovative management can become as important to a successful outcome as the science itself. We are seeking to create relationships that dissolve boundaries, not erect them. We have established simultaneous top-down and bottom-up planning through a program management structure (Figure 4) that can equally support all groups without a particular bias toward any one of them. This management structure is facilitative, not directive in nature, and seeks to place the majority of day-to-day responsibility in the hands of the projects themselves. The joint CIRES and CDC Directors set directions and overall objectives, yet seek input and ownership prior to major decisions affecting all participants. Our project management team conducts regular meetings, sets up lectures, provides research tools, tracks budgets, disseminates information, ensures deliverables on deadlines, and generally coordinates research endeavors. Project leaders frame their scientific objectives, determine their own activities and manage their resources. When the management team was formed, definition and delegation of responsibilities and authorities was immediately established to clarify and preclude many of the problems that can plague embryonic group efforts.

Resource Allocation

If planning interdisciplinary research is challenging, its budgeting and cost control is daunting. Designing successful interdisciplinary infrastructures is compounded by their shared leadership, constraints to the distribution of funding, and the complication of tracking resources across multiple affiliations. We have separated initial research planning into the distinct steps of science needed and funding expected so that we don't slip into the mode of "designing to budget." To ensure a science-driven program and enhance direct collaboration between projects, we have broken new ground by allocating budget authority to leaders regardless of affiliation (e.g., University departments including Geography, Economics and the Natural Resources Law Center). While CIRES will receive and track the funding, accountability and signature authorities will be distributed to the degree possible. When funding fell substantially short on a recent proposal, we departed from the conventional "meat cleaver" approach to one of redefining our scope and sequentially rebuilding budgets based upon what was required between groups to meet revised objectives.

Creating an Integrative Environment

We are learning that truly interdisciplinary thinking does not automatically emerge from the assembly of the disciplinary components, but requires a mutual grasp of the differences in language, techniques, and perspectives of all collaborators. Effectively integrating the physical sciences of climate and hydrology with the social sciences including economics and user assessment requires a willingness to build and maintain unfamiliar bridges. We are attempting to create a research environment that encourages risk taking and facilitates cross-boundary dialog. Questioning is welcomed, and openly identifying areas of incomplete understanding is a step toward convergence.

Synthesis Methodologies

As an outgrowth of our integrative process, new techniques are being applied or developed to enable a meaningful synthesis of our work. Examples of these integrating tools include 1) data assimilation techniques to merge observations with model output and assist the integration of different forms of data; 2) the application of Geographical Information Systems (GIS) that are useful in analyzing spatially-referenced data; 3) the development of climate scenarios for use in impact research; and 4) the use of decision calendars to help researchers anticipate and respond to users and the tools they need.

Communication

Effective communication is always identified as an essential element in collaboration, but it is particularly crucial when conducting interdisciplinary research. We have established interactive *team meetings* to report results, discuss strategies, plan work, become aware of other project strengths and foster team building. We conduct regular *management meetings* to coordinate activities, devise strategies, handle logistics and provide for the timely completion of deliverables. We have established a regular *seminar series* of invited speakers to keep us abreast of developments in related disciplines and to stimulate a cross-fertilization of ideas. We organize and conduct *workshops* to exchange ideas and develop relationships between researchers and users. Our project manager records and posts detailed notes on an internal Web site to exchange preliminary results among collaborators, and a searchable external Web interface enables us to communicate final results to our users.

User Interactions

We have used and intend to apply four different modes of interactions with users. The *first* consists of briefings to users on the upcoming climate outlooks and projections. These briefings have been at regular time intervals and are now also being used to survey user interests. There is ample time scheduled at briefings to hear from users, and several have participated in planning and hosting the briefings. The *second* approach is development of capacity to assist in rapid response to extreme climate events, such as the recent southwestern drought aggravated by low snowpack in the Interior West. We want to be able to quickly develop useful partnerships with users, expanding on efforts by the Regional Climate Centers, and supporting the State Climatologists. A *third* type of interaction includes longer-term relationships between scientists and ongoing user communities, such as the current involvement with Upper Colorado River water managers working on strategies for aquatic ecosystem maintenance. We are also moving into user studies incorporating interactive inquiry with selected groups and sectors to investigate sensitivity to climate variability and capacity to incorporate climate information into decision-making.

Reporting Results

Reporting physical scientific information in a social science context assists the public in grasping the issues and decision-makers in devising effective policies. We are developing complementary techniques that promote interpretation between disciplines, such as reporting physical results within an economic context or reporting social assessments in quantitative terms. Conventional ways of reporting absolutes must increasingly be augmented with probabilities. Scenarios need to be developed to help leaders understand the range of possibilities and potential options for response to them. Publishing results in a risk assessment format allows the estimation of probable costs (both of taking action and of doing nothing).

Closing

At a time when a world view is called for in addressing problems of increasingly global perspective, new paradigms are emerging to facilitate the kind of research needed. Complex systems cannot be understood by analyses of their intrinsic qualities alone, but additionally call for the observance of relationships between disciplines at their interfaces. The synergy provided between the NOAA federal laboratories and University community provides an ideal model for integrative research. One of the next steps is to establish a protocol for the exchange of data and results between assessments and coordinate them into complementary activities.

4 References

Ament, D. (2000) Impacts of Water Transfers on the Agricultural Sector. Conference on Water and Growth in the West, Natural Resources Law Center, University of Colorado, Boulder.

Changnon, S.A. (Editor), 2000. El Niño 1997-1998: the climate event of the century. Oxford University Press, London and New York, 215 pp.

Clark, M.P., L.E. Hay, G.J. McCabe, G.H. Leavesley, M.C. Serreze, and R.L. Wilby (2000) The use of weather and climate information in management of water resources in the western United States. Plenary Paper for the Special Conference on Climate Variability and Water Resources,June 1999, accepted, publisher unknown.

Clark, M.P., and L.E. Hay (2000) Use of atmospheric forecasts in hydrologic models. Part One: Errors in output from the NCEP atmospheric forecast model. Proceedings, American Water Resources Association s Spring Specialty Conference Water resources in Extreme Environments , May 1-3 2000, Anchorage, Alaska, pp 215-220.

Clark, M.P., L.E. Hay, G.J. McCabe, M.C. Serreze, and R.L. Wilby, 2001: Use of medium-range weather forecasts for predictions of runoff. Part One: Correcting problems in medium-range forecast model output. To be submitted to the Journal of Hydrometeorology.

Clark, Martyn P., Lauren E. Hay, John Pitlick, Andrea J. Ray, Daniel R. Cayan, Michael Dettinger, Mary Meyer-Tyree and George H. Leavesley (2000b) Poster submitted for the 2001 AMS meeting. Development of short-term streamflow forecasts for specific management applications: Case study of flow augmentation requirements for the maintenance of endangered fish habitat.

Clark, M.P., M.C. Serreze, and G.J. McCabe, 2001: Historic effects of El Niño and La Niña events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River basins. Water Resources Research, 37, 741-757.

Day, G.N., 1985: Extended streamflow forecasting using NWSRFS. J. Water Res. Plann. And Management, 111, 157-170.

Hay, L.E., M.P. Clark, and G.H. Leavesley (2000) Use of atmospheric forecasts in hydrologic models. Part Two: Case study. Proceedings, American Water Resources Association s Spring Specialty Conference Water resources in Extreme Environments , May 1-3 2000, Anchorage, Alaska, pp. 221-226.

Hay, L.E. and M.P. Clark, 2001: Use of medium-range weather forecasts for predictions of runoff. Part Two: Case studies. To be submitted to the Journal of Hydrometeorology.

Howe, Charles W. and Mark G. Smith (1993) Incorporating public preferences in planning urban water supply reliability. Water Resources Research 29: 3363-3369.

Howe, Charles W. and Mark G. Smith (1994) The value of water supply reliability in urban water systems. Journal of Environmental Economics and Management 26: 19-30.

Hydrosphere Resource Consultants (1999) Metropolitan Water Supply Investigation Final Report. Boulder: Hydrosphere Resource Consultants.

Mayer, P.W. (1995) Residential Water Use and Conservation Effectiveness: A Process Approach. M.A. thesis, University of Colorado at Boulder.

Parry, M. and T. Carter (1998) Climate Impact and Adaptation Assessment. (London: Earthscan).

Pulwarty, R. and Melis, T. (2000) Climate extremes and adaptive management on the Colorado River: Lessons from the 1997/98 ENSO event. In press, Journal of Environmental Management.

Pulwarty, R.S. and Redmond, K.T. (1997) Climate and Salmon Restoration in the Columbia River Basin: the role and usability of seasonal forecasts. Bull. Am. Met. Soc, 78(3): 381-397.

Ray, A.J. (2000) Seasonal forecasts and water management in the Upper Colorado Basin: using climate information to assist ecosystem management. An oral presentation for the AMS annual meeting, January 2000, Long Beach, CA.

Ray, A.J. and K.T. Redmond (1999): 1999-2000 winter season outlook and interpretation. Poster presentation at the U.S. Bureau of Reclamation River Systems Management Workshop, October 19-21, 1999, Reno, NV

Smith, D.H. et al. (1996) Irrigation Water Conservation: Opportunities and Limitations in Colorado. CO: Colorado Water Resources Research Institute, Fort Collins, CO.

Stern, P.C. and Easterling, W.E. (Editors) (1999) Making Climate Forecasts Matter. National Academy Press, Washington, DC, 175 pp.

Wolter, K., J. Eischeid, and M. Medovaya, 2001: Seasonal cycle of southwestern U.S. precipitation associations with ENSO. To be submitted to International Journal of Climatology.

Woodhouse, C. A., 2001: A Tree-Ring Reconstruction of Streamflow for the Colorado Front Range. Journal of the American Water Resources Association, 37, 3, 561-570.

RESEARCH PLAN FOR THE NEXT FIVE YEARS

1 Overview

The overall vision for the Water in the Interior West RISA is a *regionally integrated science and assessment approach that seeks to increase scientific understanding within an evolving social context in order to develop decision-making strategies*. This approach is fundamentally based in the decision-process recognizing that decisions are made in a multi-stress context involving not only climate information but also information about social trends (demographics, energy use, land use, and ecosystem health); institutional structures such as policies and laws; public values; and politics. This intersection of natural systems and human systems requires the integration of knowledge building on traditional disciplinary approaches. Understanding the decision process helps inform the regional assessment, which one might view as an ongoing dialog between the researchers and decision-makers, on what climate information is needed and how it is used. The assessment determines the types of research questions to be addressed. Integrated research teams are developed that frame the research questions. The interdisciplinary research is aided by the use of synthesis tools such as geographic information systems (GIS), data assimilation, and scenario development. Critical to the success of the integrated research is a fundamental understanding of different disciplinary methodologies as well as different methodologies for the integration of knowledge. This entire process is focused on the goal of contributing to an enhanced decision-process.

Two overarching considerations motivate our planned activities. The first will be to bridge the gap between physical/social science research and the information needs of climate-sensitive stakeholders in the Interior West. We thus seek to understand the decision processes of climate-sensitive stakeholders and identify the entry-points of weather and climate information in their decisions. Where information gaps are apparent, we plan to develop experimental products and assess their value and that of existing products in addressing societally-relevant problems. A key goal in our applied research is to understand where and why such information is either not employed or has been deemed irrelevant.

The second overarching goal of our project is to understand the sensitivity of regional water resources to climate variability, the feasibility of various forms of adaptation, and the residual regional vulnerability. We are interested in the stresses imposed on water management systems by humans, the stresses due to climate extremes, and the resultant impacts on environmental quality. In terms of adaptation, we are interested in response options related to law and policy (for example, land use and housing controls), and also responses in which improved use of climate information allows regional water management systems to adapt to human and climatic stresses. Products from these integrated assessments will elucidate water management system vulnerabilities to climate variability in the Interior West and identify potential new uses of climate information for long-range policy and planning.

Our research approach requires collaboration between physical and social scientists to achieve shared objectives. Examples of this joint interaction are evident in both components of WWA research. In our assessment of the vulnerability of the region to climate variability we use a research methodology, our integrative water model (described later), that allows diagnosis of the interplay of climate and hydrology with the sensitivity of human and environmental systems. Similarly, in our assessment and development of hydro-climate products on a regional scale, the physical science research activities are intimately linked to regional societal stresses, and address specific needs for improved climate information. Note, for example, the strong linkage between our applied research projects and the decision process calendar for reservoir managers. Such an integrated approach is difficult and time-consuming, but is necessary to address societal problems.

2 Planned WWA Activities

Our vision for research during the next five year period is organized around a suite of activities that work towards the two overarching goals of our project; experimental monitoring and prediction products, and assessments of regional vulnerability in the South Platte River basin. Each activity denotes a process that identifies pathways and, where feasible, lays the foundation for increasing the overlap between decision making, climate products, and social/physical science research. The integrator is the decision process itself, and we recognize that our success in developing accurate and informed services must carefully account for the dynamic and evolving nature of decision making.

2.1 Experimental monitoring and prediction products

2.1.1 Decision processes on synoptic to seasonal scales

Evaluating the usefulness of climate information and products will continue to focus on decision processes associated with critical natural resource or society-relevant problems affected by climate. We will use the decision calendar framework to assess the role of climate information in decision-making associated with water-related problems such as forest fires, rangeland management, and human health issues. Research to determine what climate information is wanted and when and how such information relates to specific decisions will be carried out primarily through our WWA regional assessment activities. Related research to understand the decision processes associated with problems concerning forest fires is expected to be pursued in collaboration with the Desert Research Institute (DRI) and the Climate Assessment Project for the Southwest (CLIMAS). Rangeland management is expected to be pursued in collaboration with Colorado State University (CSU), Montana State and the University of Arizona. Human health issues will be addressed in conjunction with Scripps, CLIMAS and the U.S. Geological Survey (USGS). Analyses of the resulting decision calendars will allow us to identify common climate information needed to address a variety of society relevant problems and can suggest directions for physical climate system research within the university and CDC, and other parts of NOAA.

Based on this analysis of decision processes of climate-sensitive stakeholders, and identification of the entry-points for climate information, future physical science research will be engaged in developing targeted hydro-climate products that directly address societal needs. In terms of climate monitoring, we will seek to develop and sustain near real-time monitoring of snowpack, streamflow, weather and its statistics in the Interior West. A preliminary example of such an effort for the Yampa River can be found at http://www.cdc.noaa.gov/~sjain/waterpulse/. We expect to expand and refine such efforts based on the emerging synthesis (from user interactions) on decision processes and calendars for consumptive and non-consumptive water usage in our study region.

We will continue to assess the potential of ENSO impacts as a means to inform water management decisions having seasonal to interannual time horizons. Part of the challenge will be to differentiate ENSO's role at high elevations, which is key for snow accumulation and the annual hydrograph, from that at lower elevations where most of the conventional research has focused. New data sets are becoming available (e.g., SNOTEL) whose quality and suitability will be assessed and used in diagnostic studies if feasible. We will also explore other (non-ENSO) leading indicators for the Interior West's seasonal climate variability, some of which have been found useful in the Southwest (Gutzler et al. 2000, Wolter, personal communication).

Given the state of the large-scale climate forcings on seasonal time scales, we seek to develop a modeling framework for generating seasonal streamflow outlooks. Two new methods will be implemented that combine climate variability information with physical and statistical techniques for generating seasonal streamflow forecasts. These empirically-based seasonal streamflow forecasting strategies will be generated in conjunction with forecasts from more physically-based streamflow prediction systems, where output from atmospheric forecast models are used in hydrologic models to simulate runoff (Clark et al., 2000; Clark and Hay, 2000; Hay et al., 2000, Clark et al., 2001, Hay and Clark, 2001). We will employ a multi-model approach where output from multiple seasonal forecast models will be optimally combined to provide the best possible probabilistic and deterministic forecasts of runoff.

From analysis of the decision processes of reservoir managers, we learned when intra-seasonal hydrologic forecasts are critical for management decisions, and we thus plan to generate improved experimental intra-seasonal streamflow forecasts for important headwater basins in the Interior West. On time scales of one to two weeks, the higher predictive skill in numerical weather prediction models allows for direct streamflow forecasting techniques. Our proposed experimental hydrologic prediction system involves five main elements: a) generate an archive of atmospheric forecasts using the same numerical weather prediction model that is used operationally; b) develop statistical relationships between this archived forecast output and precipitation and temperature at local scales in individual river basins and apply these relationships to the operational forecast model output to provide unbiased, improved forecasts of precipitation and temperature; c) assimilate real-time station observations of precipitation and temperature into hydrologic models to estimate basin initial conditions; d) using the forecasted precipitation and temperature as input to hydrologic models, run hydrologic models in ensemble mode to forecast runoff and estimate forecast uncertainty; and e) post-process hydrologic model output to remove systematic biases. We will collaborate with the U.S. National Weather Services Hydrology Laboratory to perform side-by-side comparisons of these techniques with the operational NWS procedures, and, where appropriate, infuse our procedures in the NWS Advanced Hydrologic Prediction System (AHPS).

These experimental intra-seasonal and seasonal streamflow forecasts will also be compared against operational forecasts issued by the National Weather Service River Forecast Centers. Each forecast will be input to management/operational models (such as RiverWare developed by USBR) to evaluate various decision options (e.g. reservoir yield, profit/loss, etc.). Products of this research will determine the value added (over existing forecast procedures) at various times throughout the water year and identify the basic research necessary for forecast improvements.

2.1.2 Decision processes on multi-annual time scales

Our interactions with the Northern Colorado Water Conservancy District (NCWCD) have revealed unique planning and decision processes for which climate information having longer than interannual time scales is relevant. The storage within the Big Thompson system is roughly 3-4 years of annual precipitation, a capacity that minimizes the impact of short-term climate variations. The efficacy of this system to meet the region's water demands since its time of inception in the late 1950s has been virtually flawless.

Yet, time series of regional precipitation indicate large multi-decadal swings and trends in the semi-arid West, and the recent 40-year period has been unique in the instrumental records in that it contains no severe and sustained drought epoch. Given that a significant fraction of the Colorado Front Range water demand, and the flow within the South Platte system itself, is met by West Slope water, we are analyzing long-term climate variations. Related to this is a need to define the covariability between West Slope supply and East Slope demand zones. Physical science research will involve a long-time scale perspective and regional water resources diagnostic studies to assess the multi-decadal and longer time scale hydrologic variations. We are interested in understanding their relevance for system design and their implications for vulnerability assessment and planning. This effort cuts across several of our proposed climate service activities and will seek to inform decision-makers on sustained development and vulnerability to climate in the South Platte basin and toward identifying State-wide water systems at risk due to drought.

Our case-studies of the drought-sensitivity of the NCWCD lead nicely into higher-level interactions with the Colorado Drought Task Force (CDTF). The CDTF is commissioned by the State of Colorado to inform the Governor's office on drought, and is also vested with the responsibility to recommend the activation of the State's emergency drought plan. In addition to monitoring, the emergency plan includes an assessment of the potential impact of drought, and a response component to seek mitigation of drought impacts. A further charge of the CDTF is to advise the Colorado Office of Emergency Management on "at risk waters systems" in the State. The Task Force is currently planning to carry out a detailed survey of drought preparedness at the municipal level, and has proposed developing a drought sensitivity map for Colorado.

In support of the CDTF decision process, we will develop drought monitoring tools of regional relevance. At a glance, this task seems elementary, but the fact is that one of the most difficult problems regarding drought is recognizing it. In this task, we will also determine the infrastructure needs for drought monitoring and seek to quantify the uncertainties in such monitoring. This will take account of the complicated seasonal cycle of precipitation in the area, and the changes that occur in the spatially-coherent regions of climate covariability throughout the year. To assist the CDTF in their assessments of drought sensitivity, research will focus on assessing the range of climate variability in the region, and the statistics of drought in particular. These matters elicit climate information having decadal to centennial time scales that could be relevant to long-term planning and vulnerability assessment. Our studies will employ multi-proxy data sets (Jain et al., 2001) and climate model simulations (e.g., Bates et al., 2001; Hoerling et al. 2001) to understand the range of historical and modeled drought variability in the region.

2.1.3 Assessing the value of experimental products and technology transfer

By better understanding the decision processes of climate-sensitive stakeholders, we can expose a broader set of decision-makers to the expertise and services available from the climate research community. A related function of WWA is to ensure that those decision-makers in the public and private sector that solicit and use climate predictions do so in an appropriate way. Many users have little understanding of the accuracy of climate predictions, and are not prepared to systematically evaluate the performance or utility of the information provided. Decision-makers, therefore, find it difficult to assess the value of predictions that they receive. Moreover, there are few, if any, institutional mechanisms for rewarding and highlighting good, policy-relevant predictions, or for comparing the outcomes of decisions made with competing predictions.

In the advanced stages of our WWA activities, experimental physical science research products will be developed that will have immediate practical value in the decision process. We propose, therefore, to examine carefully the process of "technology transfer" and the identification of appropriate "service providers." Examples include the Western Regional Climate Center and the National Weather Service's River Forecast Centers. The overriding question is whether such mechanisms of technology transfer can be purposively designed and implemented to further decision objectives. We will take on this aspect of technology policy as a participant/observer with the transfer of knowledge and its use within the WWA as the focus of research. This effort will draw on examples throughout NOAA-OAR to create a plan for the transfer of research to operations. Collectively this technology-transfer assessment will provide CDC and NOAA with a better understanding of the pathway to success for climate services to evolve from experimental to operational status.

2.2 Sustained Growth in the South Platte and Climatic Vulnerability

This integrated project is based on WWA's belief that the South Platte basin, owing to its concentration of population and industry, together with projections of growth, may become increasingly vulnerable to climate variations and extremes. Vulnerability is expected to be expressed both in terms of the difficulties in meeting competing demands for water (i.e., water shortages in various sectors) and the adverse environmental impacts caused by the combined impacts of regional growth and climate extremes. The effort will require a thorough assessment of historical and anticipated climate extremes in the South Platte basin, human-related stresses on South Platte water systems, and the flexibility of water management systems to meet multiple objectives in the face of significant human and climatic stresses. A key product from this study will be an assessment of the environmental impacts of human and climatic stresses, and an identification of mechanisms for protecting environmental quality.

2.2.1 Vulnerability assessment for the South Platte

We will undertake an integrated modeling study to assess the sensitivity of the region to climate variability, the feasibility of various forms of adaptation, and the residual vulnerability. We will assess the climate-related stress on regional water resources in the context of other socio-economic and environmental stresses. For example, the regional vulnerability to a multi-year drought will be examined in conjunction with the impacts of burgeoning economic activity and the demand for environmental protection. For responses to regional stresses, we will examine the benefits realized from improved use of climate information in the context of socio-economic, legal, political, and environmental responses such as water law and policy reform, land-use and housing controls, changes in water transfers and markets, regional cooperation, and changing standards and mechanisms for environmental protection.

Our diagnosis of the interplay of climate and hydrology with the sensitivity and vulnerability of human and environmental systems will be facilitated through the continued development of an integrated water model of the South Platte. This model is the result of collaboration with Hydrosphere Inc. of Boulder—a leading consultant to water agencies in the Front Range. This model unites climate-related river flow scenarios, quantified water demands, institutional arrangements for water allocation, and the effects of the resultant flows on water shortages and water quality within a quantitative framework designed for evaluation policy options. It is thus a major integrative mechanism for the WWA. We will develop scenarios of historical and anticipated variations in climate, as well as scenarios describing the changing demographics of the region; demand management policies and conservation technologies; and drought monitoring, management, and planning. Other scenarios to be examined include changes in agricultural policies and intrastate agricultural-to-urban water marketing; changes in water law and institutions; and increases in the value placed on environmental protection. Each scenario can be viewed as a sensitivity experiment. We ultimately hope to use Monte Carlo techniques to assess the impact of changes in one variable in the context of changes in other variables and thus provide a probabilistic description of regional vulnerabilities and the attendant impacts on policy and planning.

In developing a methodology for vulnerability assessments of the South Platte, we must ensure that it can be applied to other basins. The South Platte on the plains of Colorado, with its rapid population growth, increasingly complex water management practices, and environmental quality concerns, is a microcosm of conflicts and interactions that will be more widely represented throughout the western U.S. as population growth and economic development continue. There is a strong likelihood that many lessons learned in the South Platte can be applied elsewhere. To test this idea, and more precisely outline regional similarities and differences throughout the Interior West, we will apply the South Platte assessment methodology to other basins. The specific basins to be selected will depend on our stakeholder interactions and assessment of societally-relevant problems throughout the region, but a natural regional expansion of our assessment work is to focus on the Upper Colorado River basin, where population is much lower but there is a much stronger regional emphasis on recreation and natural beauty. Ultimately, we hope that our assessment methodology will provide a synthesis of regional vulnerabilities throughout the Interior West region.

2.2.2 Environmental quality in the South Platte

Environmental quality research will encompass three components: a) assessment of the relationship between climate variability, low flows, and water quality in the western U.S., b) interactions between climate variability, water management, and stream metabolism, and c) assessment of the basin-wide mass balance for salts and regulated substances in the South Platte basin and its connection to climate variability and water management. We will keep state and federal regulatory agencies apprised of findings that identify potential environmental vulnerabilities, and will involve them in discussions of possible solutions.

Water quality protection regulations are based on anticipation of low flows, which is based on analysis of the historical record (USEPA, 1986). The historical records typically are short, and our analysis shows that phenomena such as ENSO have multi-year recurrence intervals which significantly bias assumptions about low flow that underlie the permitting of wastewater discharges. The most extreme examples of error would occur in the case of multi-year drought, which we have not seen since permitting became a serious matter in Colorado. We have finished an analysis of the South Platte River with the objective of showing the effects of unanticipated climate variation on protection of water quality (Saunders and Lewis in review). We propose briefings for representatives of state and federal regulatory agencies (Colorado Department of Health Water Quality Control Division and USEPA Region VIII) to explain implications of climate variability for low flow analysis. With their cooperation, we expect to develop a scheme for incorporating climate variability in a manner that will enhance the protection of designated uses.

The second component of our environmental quality research will address interactions between climate variability, water management, and stream metabolism. Examples of important biotic processes that define the health of streams include photosynthesis, respiration, mineralization of organic matter, assimilation of nutrients (nitrogen and phosphorus), redox transformations of iron and manganese, nitrification (conversion of ammonium into nitrate), denitrification (conversion of nitrate to nitrogen gas), and many others. We have discovered important connections between climate variability, water management, and the metabolic status of streams including the South Platte River (Cronin et al. in preparation). We propose to link discharge, substrate mobilization, and metabolism to specific types of climate and hydologic events. Once the linkage is accomplished over a spectrum of event types, both the physical and biological responses to changes in discharge can be modeled, and thus the effects of various flow regimes can be predicted. We are generating a data base for this type of modeling for a reach of the South Platte River and plan its completion during the coming five years.

Finally, we will assess problems of salination associated with the intensive water management in the South Platte basin. The outcome of water management is to retain water for use and for reuse prior to release of residual water from the basin. The use and reuse of water results in a concentration of dissolved and suspended loads. The result is the accumulation of an inventory of dissolved and suspended substances, some of which have adverse effects on water use and aquatic life which we believe to be especially evident during climatically-extreme events, such as multi-year droughts. We propose to investigate the escalation of salination during a multi-year drought, and the related accumulation of substances that may be harmful to the use of water or the support of aquatic life.

3 Linkages with other research activities

In the Interior West (and beyond) there are a multitude of activities in both science and management related to use and quality of water resources. Such activities span a wide spectrum and include, for example, intramural and extramural research on climate and hydrology supported by federal agencies such as NOAA, NSF and NASA, existing climate services activities such as the National Weather Service's Climate Prediction Center, the NOAA-supported International Research Institute for Climate Prediction and Western Regional Climate Center, state climatologist offices, university-based research centers such as Colorado State University's Colorado Water Resource's Research Institute, state and local water and land management agencies, non-governmental organizations, and considerable efforts in the private sector. Taken together these activities comprise a complex tapestry of research and action related to the foci of the WWA. If the WWA is to take the next step in its evolution from its pilot phase to a more fully developed assessment activity, it will need to comprehensively map these activities and their inter-relations, in order to identify where information needs are and are not being met, and to establish mechanisms of transfer of existing and newly developed knowledge into the hands of those who would use it in their decision processes. WWA is explicitly aware of the need to establish both a broad perspective and healthy partnerships in the Interior West if it is to fulfill the long-term mission of the RISA program and OGP to support the development of "climate services."

4 References

el-Ashry, M., and D. Gibbons, Water and Arid Lands of the Western United States. Cambridge University Press, New York, 1988.

Bates, G. T., M. P. Hoerling, and A. Kumar, 2001: Central US Springtime precipitation extremes: Teleconnections and relationships with sea surface temperatures. *J. Climate*, in press.

Clark, M.P., L.E. Hay, G.J. McCabe, G.H. Leavesley, M.C. Serreze, and R.L. Wilby (2000) The use of weather and climate information in management of water resources in the western United States. Plenary Paper for the Special Conference on Climate Variability and Water Resources, June 1999, accepted, publisher unknown.

Clark, M.P., and L.E. Hay (2000) Use of atmospheric forecasts in hydrologic models. Part One: Errors in output from the NCEP atmospheric forecast model. Proceedings, American Water Resources Association s Spring Specialty Conference Water resources in Extreme Environments , May 1-3 2000, Anchorage, Alaska, pp 215-220.

Clark, M.P., L.E. Hay, G.J. McCabe, M.C. Serreze, and R.L. Wilby, 2001: Use of medium-range weather forecasts for predictions of runoff. Part One: Correcting problems in medium-range forecast model output. To be submitted to the Journal of Hydrometeorology.

Clark, M.P., M.C. Serreze, and G.J. McCabe, 2001: Historic effects of El Niño and La Niña events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River basins. Water Resources Research, 37, 741-757.

Changnon, S.A. (Editor), 2000. El Niño 1997-1998: the climate event of the century. Oxford University Press, London and New York, 215 pp.

Day, G.N., 1985: Extended streamflow forecasting using NWSRFS. J. Water Res. Plann. And Management, 111, 157-170.

Hay, L.E., M.P. Clark, and G.H. Leavesley (2000) Use of atmospheric forecasts in hydrologic models. Part Two: Case study. Proceedings, American Water Resources Association s Spring Specialty Conference Water resources in Extreme Environments , May 1-3 2000, Anchorage, Alaska, pp. 221-226.

Hay, L.E. and M.P. Clark, 2001: Use of medium-range weather forecasts for predictions of runoff. Part Two: Case studies. To be submitted to the Journal of Hydrometeorology.

Hoerling, M. P., J. Hurrell, and T. Xu, 2001: Tropical origins for North Atlantic climate change. *Science*, **292**, 90-92.

Howe, Charles W. and Mark G. Smith (1993) Incorporating public preferences in planning urban water supply reliability. Water Resources Research 29: 3363-3369.

Howe, Charles W. and Mark G. Smith (1994) The value of water supply reliability in urban water systems. Journal of Environmental Economics and Management 26: 19-30.

Hydrosphere Resource Consultants (1999) Metropolitan Water Supply Investigation Final Report. Boulder: Hydrosphere Resource Consultants.

Jain, S., C. A. Woodhouse, and M. P. Hoerling, 2001: Multidecadal streamflow regimes in the interior western United States: Implications for water resources vulnerability. Geophysical Research Letters (in preparation).

Nichols, P..D., M. K. Murphy, and D. S. Kenney. Forthcoming. Water and Growth in Colorado: A Review of Legal and Policy Issues Facing the Water Management Community. Boulder: Natural Resources Law Center, University of Colorado School of Law.

Rhodes, S.L., D. Ely, and J.A. Dracup, Climate and the Colorado River: The limits of management. Bull. Amer. Meteor. Soc., 65, 682-691, 1984.

Pulwarty, R. and Melis, T. (2000) Climate extremes and adaptive management on the Colorado River: Lessons from the 1997/98 ENSO event. In press, Journal of Environmental Management.

Pulwarty, R.S. and Redmond, K.T. (1997) Climate and Salmon Restoration in the Columbia River Basin: the role and usability of seasonal forecasts. Bull. Am. Met. Soc, 78(3): 381-397.

Ray, A.J. and K.T. Redmond (1999) 1999-2000 winter season outlook and interpretation. Poster presentation at the U.S. Bureau of Reclamation River Systems Management Workshop, October 19-21, 1999, Reno, NV.

Ray, A.J., R.S. Webb, and J.L. Wiener (2000) Demand-side perspectives on climate information: Decision calendars as tool for organizing user studies (to be submitted to Bulletin of the American Meteorological Society).

Saunders, James F. III and W. M. Lewis, Jr. 2001. Implications of Climate Variability for Regulatory Low Flows in the South Platte Basin, Colorado. Journal of the American Water Resources Association (Submitted).

Serreze, M.C., M.P. Clark, R.L. Armstrong, D.A. McGinnis, and R.S. Pulwarty, Characteristics of the western U.S. snowpack from SNOTEL data. Water Resour. Res., 35, 2145-2160, 1999.

Smith, D.H. et al. (1996) Irrigation Water Conservation: Opportunities and Limitations in Colorado. CO: Colorado Water Resources Research Institute, Fort Collins, CO.

Stern, P.C. and Easterling, W.E. (Editors) (1999) Making Climate Forecasts Matter. National Academy Press, Washington, DC, 175 pp.

USEPA. 1986. Technical guidance manual for performing wasteload allocation, Book VI Design Conditions, Chapter 1 Stream design flow for steady-state modeling. USEPA Office of Water.

Woodhouse, C. A., 2001: A Tree-Ring Reconstruction of Streamflow for the Colorado Front Range. Journal of the American Water Resources Association, 37, 3, 561-570.

ORGANIZATIONAL ALTERNATIVES

In 2001, the Western Water Assessment finds itself at a critical point in its evolution, finalizing its pilot activities and preparing to expand to a full assessment. NOAA-OGP has described this evolutionary point in RISA-supported projects as:

> Those in pilot or preliminary stages focus on clarification of initially defined critical regional issues, team building, developing cooperative stakeholder linkages, and data assimilation. Pilot efforts will undergo comprehensive reviews and evaluation for consideration of expansion to full assessments.[1]

The transition from pilot to full assessment involves choices that will influence the structure and functions of the Western Water Assessment going forward. These choices are significant because, over the next five years, they will dictate the strategy, tactics, and substantive approach of the Western Water Assessment and its role in the broader national and regional evolution of "climate services." The purpose of this section of the Five-Year Plan is to make explicit these choices and the implications of each.

1 Two Perspectives on RISA Projects

In its description of the RISA Program NOAA-OGP, provides two distinct, but inter-related perspectives on its component Assessments. The "end goals" of the RISA Program go beyond those of traditional scientific research programs, and have an explicit focus on taking the results of research and ensuring that they are well-integrated with the practical concerns of decision-makers in particular regions.

> The end goals are to expand the range of choices available to different communities in a region, and, to increase practical learning and benefits to these communities as systems evolve and new knowledge and information arises.[2]

The two perspectives present by NOAA-OGP for its RISA Program are thus research and applications.

In order to achieve these "end goals" NOAA-OGP describes the RISA program as synthesizing research and applications through a focus on Regional Integrated Assessments that:

> involve the intersection of three major coordinates: (1) climate and environmental monitoring and research, (2) economic and human dimensions research, especially on trends and factors influencing climate-sensitive human activities, and (3) applications i.e. the transformation and communication of relevant research results to meet specific needs.3

---

[1] Pulwarty, R. 2000. NOAA-Office of Global Programs – The Regional Assessments Program, *The ENSO Signal*, Issue 12, January.
[2] Ibid.
[3] Ibid.

Items 1 and 2 suggest an interdisciplinary science agenda focused on research. Item 3 suggests the development and transfer of applications, i.e., specific products and services that result from research activities, to those in, for example, operational agencies. NOAA-OGP describes the research agenda as having three components:

> Research components involve (A) interdisciplinarity, including syntheses of related scientific knowledge, (B) bridging the gap between climate and societal interactions on different temporal and spatial scales, and (C) development of decision support and services.

This research agenda explicitly acknowledges that integrated research is needed that spans the physical climate and social sciences, and as well, research is also needed to design mechanisms of transfer of knowledge and technology from the Assessment projects to users of information. Thus, the perspectives of research and assessment are viewed not as separate components linked linearly, with research occurring first then application as a follow-on activity, but as activities that occur in parallel with close interaction.

In the early years of an Assessment NOAA-OGP expects a focus on items (1) and (2) quoted above.

> Years 1-2 Team building, regional definition, identification of critical interdisciplinary issues and affected groups, assessment of climate-related knowledge to date, expectations;
>
> Years 2-3 Start-up projects: refining and developing preliminary studies: definitions of region, criticality, vulnerability, sensitivity, capacity. Developing criteria for interaction with stakeholders and for self-evaluation, etc. Program Evaluation;

Beginning in the fourth year, Assessments are expected to evolve into a greater focus on establishing linkages with decision-makers in the regions, i.e., increasing a focus on (3) quoted above.

> Years 4- Fully integrate lines of communication and research developed in preliminary studies and expansion to other sectors, including enlargement of region and/or scope if necessary. Inclusion of other public and private agencies and institutions as partners etc.

This implies a change not only in the maturity of the research but a capability to serve as an institutional interface between (a) closely linked research and application activities, and (b) those decision-makers and organizations in the region for whom the Assessment's activities are particularly relevant.

The transition from years three to four for a NOAA-OGP Assessment project involves a critical change in perspective. In the first three years the primary focus is on integrated research, which itself can be a difficult challenge. In the Fall of 2000, participants in the Western Water Assessment described how they met this challenge:

> As a result of three years of work together, we have witnessed an evolution in our approach from multidisciplinary goals toward more fully integrated objectives. A multidisciplinary effort indeed combines multiple inputs, but the elements retain a separate identity where linkages are far from dominant. An interdisciplinary approach results in a new and intellectually coherent entity that is more than the simple combination of its parts. This approach requires a shift from the focused study of objects (often in isolation) to their interrelationships within the system. For us, this transformation has come in part from team development and in part from interaction and experience gained with users. As a result we have learned that the framing of interdisciplinary

research questions is very different than disciplinary or multidisciplinary research. The development of innovative approaches for identifying research "drivers" and for framing research questions is an ongoing discussion within our group…

We are learning that truly interdisciplinary thinking does not automatically emerge from the assembly of the disciplinary components, but requires a mutual grasp of the differences in language, techniques, and perspectives of all collaborators. Effectively integrating the physical sciences of climate and hydrology with the social sciences including economics and user assessment requires a willingness to build and maintain unfamiliar bridges. We are attempting to create a research environment that encourages risk taking and facilitates cross-boundary dialog. Questioning is welcomed, and openly identifying areas of incomplete understanding is a step toward convergence.4

In successfully meeting the challenge of interdisciplinary research, the Western Water Assessment has met one of the criteria set forth by NOAA-OGP for activities to take place in the first three years of an Assessment project.

The Assessment has also successfully addressed the objective of "developing criteria for interaction with stakeholders":

We have used and intend to apply four different modes of interactions with users. The first consists of briefings to users on the upcoming climate outlooks and projections. These briefings have been at regular time intervals and are now also being used to survey user interests. There is ample time scheduled at briefings to hear from users, and several have participated in planning and hosting the briefings. The second approach is development of capacity to assist in rapid response to extreme climate events, such as the recent southwestern drought aggravated by low snowpack in the Interior West. We want to be able to quickly develop useful partnerships with users, expanding on efforts by the Regional Climate Centers, and supporting the State Climatologists. A third type of interaction includes longer-term relationships between scientists and ongoing user communities, such as the current involvement with Upper Colorado River water managers working on strategies for aquatic ecosystem maintenance. We are also moving into user studies incorporating interactive inquiry with selected groups and sectors to investigate sensitivity to climate variability and capacity to incorporate climate information into decision-making.5

Thus, the Western Water Assessment finds itself well positioned to take the evolutionary step from a primary focus on integrated research to a dual focus on integrated research and the means to successfully transfer that research to those individuals and organizations in the region that would benefit.

It is this transition that raises fundamental questions about the organization of the Western Water Assessment as it moves into the future. The following sections describe several issues and then a range of alternatives that should be considered carefully as the Western Water Assessment moves to its next phase.

[4] Susan Avery, Andrew Barrett, Martyn Clark, Randall Dole, Martin Hoerling, Charles Howe, William Lewis, Donald Mock, Diana Perfect, Andrea Ray, William Riebsame, James Saunders, Paul Sperry and John Wiener, 2000. PROSPECTS AND CHALLENGES FOR THE WATER IN THE INTERIOR WEST ASSESSMENT, November, http://cires.colorado.edu/wwa/docs/prospects0900/#IIIF1
[5] Ibid.

2 Issues

- *An organization focused on integrated science will not necessarily serve the needs of transferring knowledge to decision-makers.*

The process of research in the United States typically follows an approach in which an agency funds "projects" lead by a "principal investigator." The selection of projects is typically determined via the peer-review process, i.e., the NSF model. It has been enormously successful in advancing disciplinary understandings. This model has a weakness in that it does not lend itself to the integration of knowledge across disciplines. NOAA-OGP created the RISA program in part to help stimulate such interdisciplinary research. The Western Water Assessment has fostered its successful approach to interdisciplinary research by encouraging a decentralized approach.

> Often the greatest obstacle to conducting true interdisciplinary research lies not with the people who seek to conduct it, but by the structures that would support it. Organizational structures and labels can result in self-limiting perceptions of individual roles and responsibilities within a group. Typical hierarchies have traditionally worked very well in addressing disciplinary issues, but they hinder the collaboration across structures and between projects that is required in more interdisciplinary endeavors. Any departure from the norm requires a trust in the leadership and team that must be earned and therefore takes time to develop. We have created a distributed structure that is defined by the scientific questions being addressed where responsibilities are backed by the delegated authorities to accomplish them. We have learned to value disciplines and participants by their connections, not their boxes, and have begun moving from a collaboration of convenience to one of interdependence.6

This approach has allowed and encouraged collaboration where previously there was very little. This speaks to the success of both the NOAA-OGP approach to integrated science as well as the Western Water Assessment's implementation of that approach.

However, a problem exists in that a decentralized approach that works so well for research is unlikely to be as effective in serving interactions with stakeholders. Communication with stakeholders will be more effective if there exists a central point of contact, "one stop shopping" for products and services, a straightforward and transparent process of technology transfer, and if the results of research are presented in a manner directly relevant to their concerns. While it is certainly true that some stakeholders will have interactions with the Western Water Assessment as collaborators and even as subjects of research, they can represent only a tiny fraction of relevant stakeholders in the region. Other mechanisms are needed to successfully link the Assessment with the broad needs of stakeholders in the region.

Participants and reviewers of the CLIMAS Assessment at the University of Arizona came to a similar conclusion. The report of a NOAA-OGP panel review of that project February 2000 concluded that

> We agree with the CLIMAS team that the core office plays a central role in facilitating researcher interactions and links to stakeholders. The workings of the core office are crucial to successful integration. CLIMAS has achieved considerable progress in achieving integration using the core office. We recommend, in agreement with the CLIMAS team, that the core office should be

---

[6] Ibid.

strengthened, both in terms of resources and staff charged with overseeing and implementing integrative functions.7

The notion of a "core office" suggests an organizational structure for applications that in principle need not be inconsistent with a decentralized approach to integrated research. However, the CLIMAS experience does suggest that a completely decentralized approach to applications (i.e., those activities taking place in years four and beyond) places inherent limitations on its potential success.

- *Institutional Obstacles Limit the Scale and Scope of Integrated Science*

The NOAA-OGP Assessments Program is a one of a number of "program elements" within OGP. It shares a home in "Climate and Societal Interactions" with four other elements: Applications Research, Climate Information Project, and Human Dimensions. NOAA-OGP has a second set of program elements under the moniker of "Climate Dynamics Research" which include elements that focus on the water cycle, climate observations, climate variability, global carbon cycle, climate dynamics and experimental prediction, climate change data and detection, and atmospheric chemistry. With such a diverse range of primarily disciplinary programs,

> the NOAA-OGP Regional Assessments Program relies heavily on consolidating the results and data from ongoing NOAA disciplinary process research (in Physical sciences, Economic and Human Dimensions, and Applications), already funded in a region, under an integrative framework.8

In principle, the Regional Assessments Program is ideally situated to foster the integration of the diverse suite of OGP programs elements conducting research of potential relevance to a particular region.

However, with the exception of the Human Dimensions program, NOAA-OGP provides no mechanism for supporting the integration of its disciplinary research through the RISA Program. For instance, a proposed project directly related to a particular RISA Assessment may also be directly related to the science objectives of the OGP water cycle program (i.e., GAPP). Ideally, that project would be integrated with the RISA program and jointly reviewed by the RISA and GAPP program elements. However, the current structure is such that each proposal must be submitted, reviewed and funded independently. This leads to a balkanization of effort and is contrary to the stated goals of integration of the RISA program.

Because of such institutional obstacles, securing funding from, for instance, the NOAA-OGP climate variability program (i.e., CLIVAR) is in practice no different than securing funding from an NSF or NASA program. The goal of integration of knowledge would be better served if instead of submitting multiple proposals across OGP, one synthesis proposal could be submitted. This single proposal, related to a potentially integrated science program, would include a clear delineation of the scientific and practical benefits of integration as well as the specific contributions to the scientific objectives of specific disciplinary program elements. Lacking such a synthetic mechanism, it will be difficult for the RISA projects to do much more than post hoc synthesis of the results of research conducted by the OGP program elements.

---

[7] emphasis in original, Panel Report, NOAA-OGP RISA Program, Climate Assessment of the Southwest, February 2001.

[8] Pulwarty, op. cit.

Another possibility would be for the RISA program to serve as the "synthesizing umbrella" for integrating research support by the various NOAA-OGP Program Elements. The RISA would support only that research not supported by the disciplinary programs (e.g., integrated science or research on the process of developing useful knowledge) and would also support the basic infrastructure needed to coordinate both the development of applications and the challenge of securing and integrating research support from a wide range of disparate sources. From this perspective, the RISA program could cap the size of each Assessment at a certain sustaining level, and create the expectation that additional support for the requisite research would necessarily come from the disciplinary programs under the Assessment's "synthetic umbrella."

Yet another option would be to consider supporting some aspects of current RISA activities under the mantle of "climate services" within NOAA. Given that the RISA goals are ostensibly consistent with the broader objectives of developing regional climate services capabilities, it would seem logical that NOAA's climate services activities could provide a mechanism to enhance the transfer of research to decision-makers, especially those decision-makers within NOAA who might benefit from RISA activities. In practice, the RISA might support the integrated research while climate services could support the infrastructure necessary to systematically connect the results of research with the needs of decision-makers in regional settings.

Each of these options has strengths and weaknesses, but should be considered as realistic alternatives for the RISAs to develop into more mature institutions at the interface of science and society.

3 Resources

Based upon our analyses of where we believe this RISA should be in its evolutionary path, we recently justified and submitted a budget request for nearly $900,000. The OGP funding that became available for WWA's current year was $475,000. The successful conduct of highly integrated research is more sensitive than traditional research to key personnel and cannot automatically shrink to available funding and hope to retain its hard-won integration. To preserve the critical mass deemed necessary for this project, CIRES and CDC augmented the resultant budget by approximately $35,000 in cash as well as in-kind staff support, but this patchwork support cannot be sustained. A project office, at minimum, would require an additional $250,000 per year. Furthermore, as we expand toward other river basins in the region, bring in new partners, interface with CLIMAS (the Southwest RISA), and develop stronger ties with operational climate services, budget needs will scale accordingly. We estimate that it will take somewhere between $1.5M and $2.0M for the next few years to achieve what we are proposing.

4 Alternatives

Based on the issues raised above, we see a number of alternatives for the future organization and support of the Western Water Assessment. Several obvious alternatives are listed below; there are of course others. The alternatives presented below are such that the choices are whether the Western Water Assessment should pursue (a) Option 1 or (b) Options 1 and 2. Within 1 and 2 are various approaches that could be combined in a number of combinations.

1. Focus primarily on integrated research
    1a. Scale WWA to RISA funding availability

1b. Work with OGP to design innovative funding capabilities that synthesize OGP Program Elements, Scale WWA to resulting funding

1c. Expand the scope of WWA activities to multi-agencies

2. Focus dually on integrated research and applications
   2a. Secure OGP-RISA funding for a "core office" and related activities
   2b. Secure NOAA support under climate services for selected activities related to RISA activities

WWA thus stands at a crossroads and is poised to take the next step. We believe we have the talent and the will, so look to our partnerships within the OGP RISA program to transform our shared vision into reality.

PRODUCTS ENTIRELY FUNDED BY RISA

1 Oral Presentations

Avery, S.K., R.M. Dole, 2001, Climate variability and water in the interior west, 12th Symposium on Global Change Studies and Climate Variations. 81stAMS Annual Meeting, Albuquerque, New Mexico.

Avery, S.K., 2001, Follow The Water: A new integrated research approach to climate and its impacts on water in the Interior West. President's Teaching Scholars Lecture Series, Grand Junction, CO.

Clark, M.P., 2000, Hydro-climatic research in the CIRES-NOAA Western Water Assessment. Invited Talk, Geography Department, University of Iowa, Iowa City, Iowa, August 2000.

Clark, M.P., 2000, Is it possible to forecast streamflow? Invited Talk, Hydrological Sciences Seminar Series, Civil Engineering, October 2000.

Clark, M.P., 2000, Recent advances in streamflow forecasting. Invited Talk, Department of Atmospheric Sciences, Iowa State University, Ames, Iowa, August 2000.

Clark, M.P., 2000, Recent successes in and potential for improving streamflow forecasts. 55th Annual Meeting, Rocky Mountain Hydrologic Research Center, Wild Basin Lodge, Allans park, October 2000.

Clark, M.P., 2000, Recent successes in and potential for improving streamflow forecasts. Invited Talk, Workshop with Water Managers at Denver Water, October 2000.

Clark, M.P., 2001, Hydrologic modeling. Guest Lecture, Engineering Hydrology, Engineering Department, April 2001.

Clark, M.P. and L.E. Hay, 2000, Use of atmospheric forecasts in hydrologic models. Part One: Errors in output from the NCEP atmospheric forecast model. Proceedings, American Water Resources Association Spring Specialty Conference, Water resources in Extreme Environments, May 1-3, 2000, Anchorage, Alaska.

Clark, M.P., L.E. Hay, and G.H. Leavesley, 2000, Short-term streamflow forecasts using global-scale atmospheric forecast models. International Conference on Alpine Meteorology, Innsbruck, Austria, September 2000.

Hoerling, M.P., 1999, Use of models for climate diagnostics and forecasting: Understanding variations in 1997 and 1998. Weather and Climate Reservoir Operations Meeting, 25 September 1999, Frisco, CO.

Hoerling, M.P., 1999, What is predictable in climate? Monitoring the 1999 US Southwest drought: A dialogue With Water Resources Managers. NOAA/CDC, CO, April 1999.

Hoerling, M.P., 2001, Principals and methods of seasonal climate forecasting. Oral presentations at National Weather Service Briefing. NOAA/CDC, CO, February 2001.

Lewis, W. M. Jr., 2001, Barker Reservoir: A River Runs Through It. Boulder Watershed Forum. July, 2001.

Wolter, K., 2000, Precipitation variability across the South Platte climate division. WWA monthly meeting, Boulder, March 2000.

2 Posters

Clark, M.P., L.E. Hay, J. Pitlick, A.J. Ray, D.R. Cayan, M.D. Dettinger, M. Meyer-Tyree, and G.H. Leavesley, 2001, Development of short-term streamflow forecasts for specific management applications. Case study of flow augmentation requirements for the maintenance of endangered fish habitat. Annual Meeting of the American Meteorological Society, Albuquerque, New Mexico, January 2001.

Cronin, G., W. M. Lewis, Jr., and S. Klemm. June 2001. Effects of a flood event on whole stream metabolism of a plains reach of the South Platte River. Poster presentation, North American Benthological Society annual meeting, Duluth, MN.

Hoerling, M., K. Wolter, M. Clark, and G. Bates, 1999, Hydro-climatic assessment of the Interior West. NOAA Science Advisory Board meeting, Boulder, CO, October 1999.

Lewis, W.M., Jr., J.F, Saunders, III, and S. Kaushal, 1999, Water quality in the Interior West. NOAA Science Advisory Board meeting, Boulder, CO, October 1999.

Riebsame, W.E., Huff, J., Platt, R., Theobald, D., Dickinson, T., 2001, Assessing regional change and vulnerability. Annual Meeting of the American Meteorological Society, Albuquerque, New Mexico, January 2001.

Riebsame, W., Dickinson, T., Theobald, D., Land use and economic change in the South Platte basin: Some human dimensions of the Western Water Assessment. NOAA Science Advisory Board meeting, Boulder, CO, October 1999.

Saunders, J. F. III, W.M. Lewis, Jr., and S. Kaushal, 2001, Water quality and climate variability in the Interior West. American Meteorological Society Meeting, Albuquerque, NM. January 2001.

Wolter, K, M. Medovay, M. P. Hoerling, C. Woodhouse, G. Bates, J. Eischied, C. Anderson, and M. P. Clarke, 2001, Climate impacts on water supply and demand zones of the South Platte. 81st Annual AMS Meeting, Albuquerque, NM, January 2001.

3 Publications

Clark, M.P., and L.E. Hay, 2000, Use of atmospheric forecasts in hydrologic models. Part One: Errors in output from the NCEP atmospheric forecast model. Proceedings, American Water Resources Association's Spring Specialty Conference, Water Resources in Extreme Environments, May 2000, Anchorage, Alaska, pp 215-220.

Clark, M.P., L.E. Hay, G.J. McCabe, M.C. Serreze, and R.L. Wilby, 2001, Use of medium-range numerical weather prediction output for hydrologic forecasting. Part One: Correcting problems in medium-range forecast model output. Journal of Hydrometeorology, in preparation.

Hay, L.E., M.P. Clark, and G.H. Leavesley, 2000, Short-term streamflow forecasts using global-scale atmospheric forecast models. International Conference on Alpine Meteorology, Innsbruck, Austria, 12pp (Compact Disk)

Hay, L.E., M.P. Clark, and G.H. Leavesley, 2000, Use of atmospheric forecasts in hydrologic models. Part Two: Case study. Proceedings, American Water Resources Association's Spring Specialty Conference, Water resources in Extreme Environments, May 1-3 2000, Anchorage, Alaska, pp. 221-226.

Hay, L.E., M.P. Clark, W.J. Gutowski, R.W. Arritt, E.S. Takle, and Z. Pan, 2001, Use of regional climate model output for hydrologic applications. Journal of Hydrometeorology, submitted.

Saunders, J. F. III and W. M. Lewis, Jr., 2001, Implications of climate variability for regulatory low flows in the South Platte Basin, Colorado, Journal of the American Water Resources Association.

Wolter, K., and M. Medovaya, 2001, Climate impacts on water supply and demand zones in the South Platte basin (in prep.).

4 WWA Conference Proceedings

Lewis, W.M. Jr., 2002, Editor, Managing Western Water Resources in an Uncertain Climate, University Press of Colorado, Boulder. (in press)

The following papers by WWA researchers and others will be included in the publication:

Dendrochronological Evidence for Long-Term Hydroclimatic Variability.
Connie Woodhouse (Institute of Arctic and Alpine Research, University of Colorado at Boulder)

Predicting Climate Variations in the Interior West: What are our Prospects?"
Randall M. Dole (NOAA-CIRES Climate Diagnostics Center)

Climate Variability in the Intermontane West: Complex Spatial Structure Associated with Topography, and Observational Issues.
Kelly Redmond (Western Regional Climate Center, Desert Research Institute, Reno, Nevada)

How can Useful Climate Data be Acquired, Managed, and Disseminated?
Rene Reitsma (University of St. Francis Xavier, Antigonish, Nova Scotia) and Phil Pasteris (National Water and Climate Center, Natural Resouces Conservation Service, United States Department of Agriculture, Portland, Oregon)

Atmospheric Controls on the Montane Snowpack and Water Resources in the Western United States
Martyn Clark[1], Lauren Hay[2], Gregory McCabe[2], George Leavesley[2], Mark Serreze[1], and Robert Wilby[3] (1. Cryospheric and Polar Processes Division, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, 2. U.S. Geological Survey, Lakewood, Colorado, 3. Department of Geography, University of Derby, United Kingdom)

Opportunities for Improving Water Resource System Performance through Long-Range Climate Forecasts: The Pacific Northwest Experience
Dennis Lettenmaier and Alan Hamlet (Department of Civil and Environmental Engineering and Joint Institute for the Study of Atmosphere and Ocean, Climate Impacts Group, University of Washington, Seattle)

Has Modeling of Water Resources Reached its Full Potential?
John Labadie and Luis Garcia (Colorado State University, Fort Collins)

The Impact of Climate Change and Variability on Water Resources Management in the Interior West: Hydrology, Engineering, Institutions
Kenneth Strzepek (Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder) and David Yates (Civil, Environmental, and Architectural Engineering, University of Colorado, and National Center for Atmospheric Research, Boulder, Colorado)

Managing Colorado River Resources in a Changing Climate.
Terrance Fulp (U.S. Bureau of Reclamation, Lower Colorado Region)

Water Management Policies and Priorities for Climate Possibilities.
Eugene Stakhiv (Institute for Water Resources, U.S. Army Corps of Engineers, Alexandria, VA)

Water Development and Management Along the South Platte River of Colorado.
Tom Cech (Executive Director, Central Colorado Water Conservancy District, Greeley, Colorado)

Can Climate Predictions be of Practical Use in Western Water Management?
David Matthews (River Systems and Meteorology Group, Technical Service Center, U.S. Bureau of Reclamation, Denver, Colorado) and C. Booth Wallentine (Utah Farm Bureau Federation, Sandy, Utah)

The Changing American West: Geographic Trends that Affect Water Resources Management.
William Riebsame Travis (Department of Geography, University of Colorado, Boulder)

The Metamorphosis of Western Water Policy: Have Federal Laws and Local Decisions Eclipsed the States' Role?
David Getches (Natural Resources Law Center, University of Colorado, Boulder)

Economic and Institutional Strategies for Adapting to Water Resource Effects of Climate Change.
John Loomis and Jessica Koteen (Department of Agricultural and Resource Economics, Colorado State University, Fort Collins) and Brian Hurd (Stratus Consulting, Boulder, Colorado)

Social, Policy, and Institutional Issues: More of the Same, Radical Change, or Gradual Evolution?
Kathleen Miller (Environmental and Societal Impacts Group, National Center for Atmospheric Research, Boulder, Colorado) and Steven Gloss (Department of Zoology and Physiology, University of Wyoming, Laramie)

PRODUCTS JOINTLY FUNDED BY RISA AND OTHER SOURCES

(shown in parentheses)

1 Oral Presentations

Clark, M.P., 2000, The climate of the West. Guest Lecture, Center for the American West class, The American West, September 2000. ***(NSF)***

Clark, M.P., 2001, Climate variability in the western USA. Guest Lecture, Mountain Climatology, Geography Department, April 2001. ***(NSF)***

Hoerling, M.P., 2001, Multi-time scale hydrologic variations and predictable climate patterns. Seminar to CU Civil Engineering Dept, April 2001. ***(NOAA-OGP CLIVAR-Pacific)***

Howe, C. and C. Goemans, 2001, The influence of economic and social conditions on the functioning of water markets. Annual Conference of the European Association of Environmental and Resource Economists, Southampton, U.K., June 2001. ***(General Service Foundation)***

Jain, S., M. P. Hoerling, G. T. Bates, and R. M. Dole, 2001, Diagnosis of variations in the climate-related flood risk - Some results from the Interior Western United States. Presented at the 8th International Meeting on Statistical Climatology, Luneburg, Germany, March 2001. ***(CIRES Fellowship)***

Jain, S., M. P. Hoerling, A. Ray, and R. M. Dole, 2001, Large-scale climate controls on Streamflow variations: Relevant diagnostics for reservoir management and stream habitat maintenance. Presented at the EGS XXVI General Assembly, Nice, France, March 2001.
(CIRES Fellowship and CDC)

Jain, S., U. Lall, and M. P. Hoerling, 2001, Non-stationary aspects of flood risk and climate variations in the Western United States. Presented at the EGS XXVI General Assembly, Nice, France, March 2001. ***(CIRES Fellowship)***

Kenney, D.S., 2000, Law and Policy Across the Great Divide: The Upper Colorado and South Platte River Systems, in the CIRES lecture series, University of Colorado. Boulder; December, 2000. ***(William and Flora Hewlett Foundation)***

Kenney, D.S., 2001, Climate Variability and Human Adaptation: Some Thoughts on the Water Law and Policy Environment, at the Climate and Water Policy Workshop, sponsored by the University of Washington. Skamania Lodge, Washington; July, 2001. ***(Climate Impacts Group, University of Washington, and the William and Flora Hewlett Foundation).***

Kenney, D.S., 2001, Water and Growth in Colorado, in the Environmental and Behavior lecture series sponsored by the Institute for Behavioral Studies, University of Colorado. Boulder; February, 2001. ***(William and Flora Hewlett Foundation)***

Ray, A.J., 2000, Seasonal forecasts and water management in the Upper Colorado Basin: using climate information to assist ecosystem management an oral presentation for the AMS annual meeting, Long Beach, CA, January 2000. ***(CDC)***

Ray, A.J., 2001, Geographical concepts in a regional case study: Climate variability and Geography in the "New" Place-based science, Annual Meeting of the Association of American Geographers, New York, NY, 27 Feb-3 March, 2001. ***(CDC and Sussman Grant)***

Ray, A.J., and R.S. Webb, 2000, CDC Experimental Climate Services: some perspectives from current activities. NOAA Applied Research Centers meeting, Palisades, NY,
March 2000. ***(CDC)***

Wolter, K., 1999, Expected La Niña impacts in Colorado during the upcoming winter, at the Workshop on Weather and Climate, Reservoir Operations, and Endangered Fish in the Upper Colorado Basin. Breckenridge, September 1999. ***(NOAA-OGP PACS)***

Wolter, K., 1999, Regional seasonal climate impacts during this La Niña winter. 1999-2000 Southwest Climate Outlook, Albuquerque, October 1999. ***(NOAA-OGP PACS)***

Wolter, K., 1999, Niwot Ridge climate: Canary in the coalmine, or just whistling in the wind?
INSTAAR Seminar Series, Boulder, October 1999. ***(NSF/LTER)***

Wolter, K., 2000, ENSO, Seasonal climate forecasting and uncertainty. CLIMAS Workshop on The Implications of La Niña and El Niño for fire management in Tucson, February 2000. ***(NOAA-OGP PACS)***

Wolter, K., 2000, *Three talks given during sabbatical included perspective on the WWA. Germany*, June-July 2000. ***((WWA, NOAA-OGP PACS and CLIVAR-Pacific)***

Wolter, K., August 2000, ENSO relationships with climate in the southwestern U.S. ESA Annual Meeting, Snowbird, UT, August 2000. ***(NOAA-OGP PACS and NSF/LTER)***

Wolter, K., 2000, Outlook for WY 2001 in the Gunnison Basin. Water Manager Briefing, Montrose, CO, September 2000. ***(NOAA-OGP PACS)***

Wolter, K., 2000, Outlook for WY 2001 in the Upper Colorado and South Platte Basins. Water Manager Briefing, Boulder, October 2000. ***(NOAA-OGP PACS)***

Wolter, K., 2001, Seasonal climate and variability in the Southwestern U.S./WFO BOU Forecast Region. Training Workshop for National Weather Service, Boulder, February 2001. ***(NOAA-OGP PACS, and NSF/LTER)***

Wolter, K., 2001, ENSO, seasonal climate forecasting and uncertainty. CLIMAS Fire and Weather, Tucson, February 2001. ***(NOAA-OGP PACS)***

Wolter, K., 1999 to present, *periodic presentations at Colorado Drought Task Force meetings.*
(NOAA-OGP PACS)

2 Posters

Clark, M.P., M.P. Hoerling, K. Wolter, A. J. Ray, M. C. Serreze, and G. J. McCabe, 2001, Use of ENSO information in improving seasonal water supply outlooks. Annual Meeting of the American Meteorological Society, Albuquerque, New Mexico, January 2001. ***(NSF)***

Howe, C. and C. Goemans, 2001, The influence of economic and social conditions on the functioning of water markets. Annual Conference of the European Association of Environmental and Resource Economists, Southampton, U.K., June 2001. Also given at the University of Colorado Environmental and Resource Economics Workshop, Breckenridge, CO., July, 2001. ***(General Service Foundation)***

Ray, A.J. and K.T. Redmond. 1999, 1999-2000 winter season outlook and interpretation. Poster presentation at the U.S. Bureau of Reclamation River Systems Management Workshop, October, 1999, Reno, NV. ***(CDC and the Western Regional Climate Center)***

Ray, A.J., R.S. Webb, and J.D. Wiener, 2001, User studies in the Interior West: Investigating current uses of climate information and user needs. Annual Meeting of the American Meteorological Society, Albuquerque, New Mexico, January 2001. ***(CDC)***

3 Publications

Barrett, A.P., R. Viger, G.H. Leavesley, A.W. Nolin, and M.P. Clark, 2001, A comparison of satellite and model derived snow covered area for a mountain watershed. Remote Sensing and Hydrology 2000, IAHS Publ. (in press). ***(NASA)***

Clark, M.P., L.E. Hay, G.J. McCabe, G.H. Leavesley, M.C. Serreze, and R.L.

Wilby, 2001, The use of weather and climate information in management of water resources in the western United States. Plenary Paper for the Special Conference on Climate Variability and Water Resources, June 1999, accepted, publisher unknown. ***(NSF)***

Clark, M.P., M.C. Serreze, and G. J. McCabe, 2001, The historical effect of El Niño and La Niña events on the seasonal evolution of the Montane snowpack in the Columbia and Colorado River basins. Water Resources Research, 37, 741-756. ***(NSF)***

Nichols, P.D., M.K. Murphy, and D.S. Kenney, 2001, (forthcoming). Water and Growth in Colorado: A Review of Legal and Policy Issues Facing the Water Management Community. Boulder: Natural Resources Law Center, University of Colorado School of Law. ***(William and Flora Hewlett Foundation)***

Ray, A.J. and R. S. Webb 2001. Demand-side perspective on climate services for reservoir management. Proceedings of the 25th Climate Diagnostics & Prediction Workshop, October 2000, 219-222. ***(CDC)***

Ray, A.J, R.S. Webb, and J.L. Wiener, 2000, Demand-side perspectives on climate information: Decision calendars as tool for organizing user studies. (To be submitted). ***(CDC and the NOAA-OGP Human Dimensions Program)***

Serreze, M.C., M.P. Clark, and A. Frei, 2001, Characteristics of large snowfall events in the Montane western U.S. as examined using snowpack telemetry (SNOTEL) data. Water Resources Research, 37, 675-690. ***(NSF)***

Sjodin, A., W. M. Lewis, Jr., and J. F. Saunders, III, 2001, Analysis of groundwater exchange for a large plains river in Colorado (USA). Hydrological Processes 15: 609-620. ***(USGS)***

Wilby, R.L., L.E. Hay, W.J. Gutowski, Jr., R.W. Arritt, E.S. Takle, Z. Pan, G.H. Leavesley, and M.P. Clark, 2000, Hydrologic responses to dynamically and statistically downscaled General Circulation Model output. Geophysical Research Letters (in press). ***(NSF)***

Wolter, K., 2001, ENSO relationships with climate in the southwestern U.S. *ESA Annual Meeting,* Snowbird, UT – this will be a peer-reviewed book chapter in "Climate Variability and Ecosystem Response", Oxford University Press. ***(NOAA-OGP PACS)***

Wolter, K., and M. Medovaya, 2001, Summer-time rainfall patterns and regionalization over the southwestern U.S. (in prep.). ***(NOAA-OGP PACS)***

4 Briefings and Workshops

<u>The following briefing and workshops were organized by A.J. Ray:</u>

Workshop on Weather and Climate, Reservoir Operations, and Endangered Fish in the Upper Colorado Basin, 20-21 September 1999, Frisco, Colorado. Co-sponsored by Denver Water and the Colorado River Water Conservation District. ***(CDC)***

2nd Workshop on Weather and Climate, Reservoir Operations, and Endangered Fish in the Upper Colorado Basin, 20 September 2000, Frisco, Colorado, sponsored by the Colorado Water Division 5 Coordination Group, and hosted by the Colorado River Water Conservation District. ***(CDC)***

Workshop on Weather and Climate, Reservoir Operations, and Endangered Fish in the Gunnison basin, 12 October, 2000. Sponsored by the Colorado Water Division 5 Coordination Group and hosted by the Uncompahgre Water Users Association. ***(CDC)***

5 Educational Benefits

Ray, A.J., Decision Analysis of Reservoir Management in the Upper Colorado Basin: implications for using climate information to provide water for endangered species recovery, Dissertation in preparation, Department of Geography, University of Colorado. anticipated completion, Spring 2002.

RISA-RELATED PRODUCTS FUNDED BY OTHER SOURCES

1 Oral Presentations

Avery, S.K., 2000, It's a new world out there: A new environmental science. Ted Scripps Fellows Seminar, University of Colorado, Boulder, CO.

Jain, S., U. Lall, and B. Rajagopalan, 2001, Low-frequency variability in the West coast U. S. floods: A diagnostic study of the large-scale climate influences. Presented at the EGS XXVI General Assembly, Nice, France, March 2001.

Ray, A.J., 1999, Climate and water management in the Interior West: a critical water problems approach. 16th Annual Pacific Climate Workshop on Climate Variability of the Eastern North Pacific and Western North America (PACLIM) Ray, A.J., 1999, Colorado Basin water management: Relating responses to critical water problems and climate. 1999 Annual Meeting of the Association of American Geographers, Honolulu, HI, March 1999

Wiener, J.D., C.W. Howe, D.S. Brookshire, C.N. Garcia, D. McCool, and G. Smoak, Preliminary Results for Colorado from An Exploratory Assessment of the Potential for Improved Water Resources Management by Increased use of Climate Information in Three Western States and Selected Tribes, 25th Annual Workshop on Climate Diagnostics, held at International Research Institute, Lamont Doherty Earth Observatory,
Columbia University, New York, October, 2000.

Wolter, K., 1997, ENSO-related climate risks in the western U.S. CIRES GCEQ Symposium, Boulder, April 1997.

Wolter, K., 1997, Colorado River Basin climate risks associated with ENSO. Colorado Basin River Forecast Center (CBRFC) Briefing, Salt Lake City, October 1997.

Wolter, K., 1998, Spring-time climate risk in the wake of the recent El Niño. Workshop on El Niño Impacts on the Climate, Weather, and Water in the Western U.S., Boulder, April 1998.

Wolter, K., 1998, Hydrological associations with ENSO in the interior Western U.S. AGU Fall Meeting, San Francisco, CA, December 1998.

Wolter, K., 1999, Recent climate conditions in the Southwest and links to ENSO. Workshop on Monitoring the 1999 U.S. Southwest Drought -- A Briefing for Water Resources Managers, Boulder, April 1999.

Wolter, K., J. Eischeid, and M.P. Hoerling, 1999, Southwestern U.S. precipitation and associations with ENSO. 24th Climate Diagnostics and Prediction Workshop, Tucson, November 1999.

Wolter, K., 2000, Seasonal cycle of ENSO influences in the American Southwest. NCAR-CGD Seminar Series, Boulder, February 2000.

Wolter, K., 2000, Rainfall patterns over the Southwestern U.S. in relation to ENSO during the summer monsoon season. U.S. CLIVAR Pan American PI Meeting, Potomac, MD, September 2000.

Wolter, K., 2000, ENSO-Drought Connections in the (Western) U.S., Drought: Monitoring, mitigation, effects. International Conference at Cagliari-Villasimius, Italy, September 2000.

Wolter, K., 2000: "Let it snow, let it snow, let it snow!" NOAA Science Festival, Boulder, September 2000.

Wolter, K., 2000, ENSO and snowstorms in Colorado. DOT Meeting, Longmont, December 2000.

Woodhouse, C.A. The Paleoclimatic Record of Drought: Putting 20th Century Droughts in Perspective. Unitarian Universalist Fellowship, Boulder, CO.

Woodhouse, C.A. 2000. Tree-ring reconstructions of drought: putting 20th century droughts in perspective. Mountain Research Station summer lecture series, University of Colorado, Boulder, CO.

Woodhouse, C.A. 2000. Clues on Climate Change: Reconstructing Middle Boulder Creek Streamflows from Tree Ring Data. Boulder Creek Watershed Forum, Boulder, CO.

Woodhouse, C.A. 2000. Streamflow and Drought Reconstructed from Tree Rings. Denver Water Board lecture series, Denver, CO.

Woodhouse, C.A., 2001, A Tree-ring reconstruction of streamflow for the Colorado Front Range: are instrumented streamflow records representative of past conditions? Society of American Foresters National Convention, Denver, CO.

Woodhouse, C.A., 2001, Tree-ring reconstructions of Colorado drought with applications to water resource management. Geography Department Colloquium series, University of Colorado, Boulder CO.

Woodhouse, C.A. and Lukas, J.J., 2000. Clear Creek Streamflow Reconstructions from Tree Rings and Applications to Water Resource Management. Rocky Mountain Hydrologic Research Center, 55th Annual Meeting, Allenspark, CO.

2 Posters

Jain, S., U. Lall, and B. Rajagopalan, 2001, Low-frequency variability in the West coast U. S. floods: A diagnostic study of the large-scale climate influences. Presented at the EGS XXVI General Assembly, Nice, France, March 2001.

Woodhouse, C., and D. Meko, 2001, Dendrohydrologic reconstructions: Applications to water resource management. Annual Meeting of the American Meteorological Society, Albuquerque, New Mexico, January 2001.

3 Publications

Barrett, A., A. W. Nolin, and M. P. Clark, A comparison of satellite- and model-derived snow covered area of a mountain watershed, IAHS Publ. no. 267, in press.

Diaz, H.F., 2001, Drought and the demise of the Anasazi. *The Albuquerque Tribune*, February 16, 2001.

Diner, D. J., G. P. Asner, R. Davies, J-P. Muller, A. W. Nolin, B. Pinty, C. B. Schaaf, and J. Stroeve, 1999, New directions in Earth observing: Scientific applications of multi-angle remote sensing, Bull. Am. Meteorol. Soc., 80, 2209-2228, 1999.

Frei, A., R. L. Armstrong, M. P. Clark, and M. C. Serreze, 2001, Catskill Mountain water resources: Vulnerability, hydro-climatology, and climate change sensitivity. Annals of the Association of American Geographers (in press).

Gutowski, W.J., Jr., R.L. Wilby, R.L., Hay, L.E., Anderson, C.J., Arritt, R.W., Clark, M.P., Leavesley, G.H., Pan, Z., Silva, R., Takle, E.S., Statistical and dynamical downscaling of global model output for U.S. National Assessment hydrological analyses. Eleventh Symposium on Global Change Studies, American Meteorological Society, Long Beach, CA, 9-14 January 2000.

Hall, D. K., S. Li, A. W. Nolin, J. C. Shi, Pre-launch validation activities for the MODIS snow and sea ice algorithms, The Earth Observer, 11, 31-35, 1999.

Hall-McKim, E. A., A. W. Nolin, M. P. Clark, F. Lo, and M. C Serreze, Effects of synoptic events on modulation seasonal variations in the North American Monsoon System, Proceedings of the American Meteorological Association, 12th Symposium on Global Change and Climate Variations, 159-160, 2001.

Howe, C.W., 2000, Protecting Public Values in a Water Market Setting: Improving Water Markets to Increase Economic Efficiency, University of Denver Water Law Review, Vol. 3, Issue 2, Spring.

Howe, C.W., L.L. Bennett, and J. Shope, 2000, "The Interstate River Compact as a Water Allocation Mechanism: Efficiency Aspects, American Journal of Agricultural Economics, 84(4), November.

Jain, S., and U. Lall, 2000, The magnitude and timing of annual maximum floods: Trends and large-scale climatic associations for the Blacksmith Fork River, Utah, Water Resources Research, 36, 12, 3641-3651.

Jain, S. and U. Lall, 2001, Floods in a changing climate: Does the past represent the future? Water Resources Research, accepted for publication.

Marshall, S., R. J Oglesby and A. W. Nolin, Effect of western U.S. snow cover on climate, Ann. Glaciol., in press.

Nolin, A. W. and J. Dozier, 2000, A hyperspectral method for remotely sensing the grain size of snow, Remote Sens. Environ., 74, 207-216, 2000.

Nolin, A. W. and A. Frei, 2001, Remote Sensing of Snow and Snow Albedo Characterization for Climate Simulations, In: Beniston, M. and M. M. Verstraete (Eds.), Remote Sensing and Climate Simulations: Synergies and Limitations, Advances in Global Change Research, Kluwer Academic Publishers, Dordrecht and Boston, pp. 159-180.

Nolin, A., A. Frei, and S. Pitter, 2001, Assessment of modeled snow cover from general circulation models, Proceedings of the American Meteorological Association, 12th Symposium on Global Change and Climate Variations, 128-129.

Nolin, A. W. and S. Liang, 2000, Progress in bidirectional reflectance modeling and applications for surface particulate media: Snow and soils, Remote Sensing Reviews, S. Liang and A.H. Strahler (Eds.) Land Surface Bidirectional Reflectance Distribution Function (BRDF): Recent Advances and Future Prospects, 18, 307-342.

Nolin, A., T. Scambos, J. Stroeve, and F. Fetterer, 2001, Cryospheric applications of MISR data, IGARSS '01 Proceedings, Sydney, Australia, issued on CD-ROM.

Nolin, A. W. and Stroeve, J. C., 1999, Snow albedo determination and validation for MODIS and MISR. Proc. of the 2nd International Workshop on Multiangular Measurements and Models. Ispra, Italy, p. 41.

Nolin, A. W. and Stroeve, J. C., 1999, Validation of the MODIS snow albedo product: An update. Proc. of the Annual Meeting of the Association of American Geographers, Honolulu, Hawaii, issued on CD-ROM.

Pitlick, J., 2001, Chapter 7. Surface Water Hydrology, in Physical Geography of North America, edited by A. Orme, Oxford University Press, (in press).

Pitlick, J. and R. Cress, 2000, Longitudinal Trends in Channel Characteristics of the Colorado River and Implications for Food-Web Dynamics, Final Report, U.S. Fish and Wildlife Service Recovery Implementation Program, Grand Junction, 57 pp.

Pitlick, J. and M.M. Van Steeter, 1998, Geomorphology and Endangered Fish Habitats of the Upper Colorado River 2: Linking Sediment Transport to Habitat Maintenance, Water Resources Research, v. 34, p. 303-316

Pitlick, J., M. Van Steeter, R. Cress, B. Barkett, and M. Franseen, 1999, Geomorphology and hydrology of the Colorado and Gunnison Rivers and implications for habitats used by endangered fishes, Final Report, US Fish and Wildlife Service Recovery Implementation Program, Grand Junction, 64 pp.

Pitlick, J. and P.R. Wilcock, 2001, Flow, sediment transport, and aquatic habitat in large rivers, in Geomorphic Processes and Riverine Habitat, edited by J. Dorava, F. Fitzpatrick, D. Montgomery and B. Palcsak, AGU Monograph (in press

Van Steeter, M.M. and J. Pitlick, 1998, Geomorphology and Endangered Fish Habitats of the Upper Colorado River 1. Historic Changes in Streamflow, Sediment Load and Channel Morphology, Water Resources Research, v. 34, p. 287-302

Wolter, K., 1998, Hydrological associations with ENSO in the interior Western U.S. *AGU Fall Meeting*, San Francisco, CA, 6-10 December 1998. Supplement to *Eos*, Transactions, AGU Volume 79, Number 45, November 10, 1998, p. F309.

Wolter, K., J. Eischeid, and M. Medovaya, 2001, Seasonal cycle of southwestern U.S.precipitation associations with ENSO (in prep.).

Wolter, K., 1998-2000, Twenty newspaper articles written for the Boulder Daily Camera:

3/16/98	"El Niño and Front Range climate"
4/13/98	"Front Range snowstorms, Part I"
5/11/98	"Spring flooding dangers"
6/22/98	"Forest fires: could this be the big one?"
7/20/98	"Summer monsoon and flash-floods"
8/30/98	"Higher foothill climates, Part I"
10/4/98	"La Niña is coming, La Niña is coming..."
11/8/98	"Seasonal climate forecasting"
12/20/98	"Boulder windstorms"
1/24/99	"Cold weather in Boulder"
2/28/99	"Forecasting winter weather in the Front Range"
4/11/99	"Ruminations on drought, Part I"
5/23/99	"Ruminations on drought, Part II"

7/04/99	"Lightning – the price to pay for living in a great outdoors state?"
8/15/99	"Higher foothill climates, Part II"
9/26/99	"Dejavu all over again? Another La Niña winter on its way!"
12/05/99	"Colorado Snowstorms, Part I"
1/09/00	"Are you under the weather? Human health and climate"
2/13/00	"Colorado Snowstorms, Part II (Four corners lows) "
3/19/00	"Tying up loose ends – my last column"

Woodhouse, C.A. 2001, A tree-ring reconstruction of streamflow for the Colorado Front Range. Journal of the American Water Resources Association 37, 561-570.

Woodhouse, C.A. and P.M. Brown. 2001, Tree-ring evidence for Great Plains drought. Tree-Ring Research, 57, 89-103.

Woodhouse, C.A. 2000, Extending hydrologic records with tree rings. Water Resources Impact 2:25-27.

Woodhouse, C.A. 1999, Artificial neural networks and dendroclimatic reconstructions: an example from the Front Range, Colorado, USA. The Holocene 9: 521-529.

4 Briefings and Workshops

<u>The following briefing was organized by A.J. Ray:</u>

National Weather Service Briefing, Boulder, CO, February 2001.