Colorado Water

Colorado State University

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Highlights

In Every Issue

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Front Cover: Overlooking the Animas River from the Colorado/Molas Trail by Silverton, Colorado. Photo by Kyle Thompson

This Page: Clouds over Henderson Lake in the San Juan National Forest (Durango, Colorado). Photo by Kyle Thompson

Editorial

by Reagan Waskom, Director, Colorado Water Institute

Climate, weather and water are completely intertwined. It is a fact that the most damaging extreme weather events usually involve water in some form. Already this year, the U.S. has experienced record-setting floods along the Mississippi River, deadly tornadoes in the South, and severe drought in Texas and Oklahoma. We have already seen eight $1 billion-plus disasters in the U.S. during 2011, with total damages at more than $32 billion, according to the National Oceanic and Atmospheric Administration (NOAA). The second half of April 2011 brought tornadoes that devastated communities in the Midwest, including a single twister that killed 151 people in Joplin, Missouri.

The southern plains have experienced extraordinarily hot weather in 2011. Oklahoma's average temperature in July (88.9 degrees) was the hottest for any state for any month on record. Nationally, 2011 brought the fourth hottest July on record, with high temperature records set in all 50 states. Meanwhile, the climate is great here in Colorado, but the weather is not always so good. This year we experienced extreme drought conditions in the southeast corner of the state and the San Luis Valley at the same time that West Slope rivers were flooding.

As these statistics indicate, the study of climate and weather is vitally important to society. Weather and climate affect virtually every aspect of our economy and everyday life—how we live, what we grow, our ecosystems, our energy needs, how our buildings and roads are built, the services we require, and how we recreate. We must monitor and understand climate in order to safely design and manage the infrastructure society depends upon.

The impacts of climate and weather on our water resources, both water supply and demand, are obvious. Our climate provides the water supply that we plan for; our weather is what we must manage for and mitigate. The difference is a matter of time scale. Weather includes conditions of the atmosphere over a short period of time, and climate is how the atmosphere behaves over longer periods of time. Our dependence on the weather for annual water supplies brings the atmospheric sciences and water management disciplines together in interesting ways.

Atmospheric sciences have long been a critical component of our water resources expertise at CSU. As you will read in this issue of Colorado Water, CSU researchers are currently working to develop improved information in the form of climate forecasts, runoff predictions, drought monitoring, and regional vulnerability assessments needed to assist water resource decision makers.

Colorado has one of the highest concentrations of atmospheric science research labs in the nation. Major research centers in Boulder and Fort Collins include NOAA, University Corporation for Atmospheric Research (UCAR), National Center of Atmospheric Research (NCAR), Cooperative Institute for Research in the Atmosphere (CIRA), Western Water Assessment (WWA), and Cooperative Institute for Research in Environmental Sciences (CIRES). The Colorado Climate Center, led by State Climatologist Nolan Doesken, was established at CSU in 1974 to provide information and expertise on Colorado's climate. Collectively, these research labs and centers constitute a huge reservoir of climate monitoring and modeling expertise.

The scale and complexity of climate and weather forecasting requires highly sophisticated monitoring systems, computer models, remote sensing, and visualization techniques. Communicating this complexity and the science behind it is a daunting task, but differs from other scientific disciplines in that the public is continually exposed to atmospheric sciences during the daily weathercast. The models used for the weather forecast seem to be widely accepted by the public, in contrast to the models used for assessing climate change. In both contexts the purpose of modeling is to assess likelihood, not to predict the future. Best case, climate models create a context for decision making that can be understood and acted upon. Colorado is fortunate to have an array of climate science professionals who use their expertise to help us better understand and manage our water resources.

CSU's Contribution to Improved Weather Forecasting

Richard H. Johnson, Department of Atmospheric Science, Colorado State University

It's often said, "Everybody talks about the weather, but nobody does anything about it." Well, the Atmospheric Science Department at Colorado State University (CSU) is doing something about it. In fact, they have been doing something about the weather for the past fifty years. Ever since 1962, when the department formed, problems related directly to weather phenomena and weather forecasting have been at the forefront of the department's research. Many discoveries that have led to overall improvements in weather prediction in the U.S. and around the world have taken place at CSU.

In the 1960s, computer models were in their infancy, so most forecasts of day-to-day weather were based on manual analysis of weather charts and skill that individual forecasters developed over the years. A lot has changed since then. Over the past half-century, steady improvement has been made in numerical weather prediction, both in terms of basic understanding and in the power of computers to run forecast models. Operational forecast centers around the world have realized a marked improvement in forecast skill. With each passing decade, forecasts have been getting better, with the three-day forecast being more skillful than the two-day forecast just a decade earlier.

However, one forecast problem that continues to baffle the forecast community is severe weather. While there continues to be an overall improvement in forecasting large-scale weather patterns such as the polar jet stream, the prediction of severe events—tornadoes, hailstorms, flash floods, hurricanes, etc.—remains a major challenge. For example, while hurricane track forecasting has steadily improved over the past several decades, corresponding improvements in hurricane intensity forecasts have remained elusive. Particularly difficult has been the prediction of rapid intensification of tropical cyclones, which is of critical importance for the preparation and evacuation of coastal communities around the world.

Hurricane Katrina of 2005 is a famous example of the challenges posed by rapid intensity change. After Katrina passed over the Florida Peninsula on August 25, it rapidly intensified from a Category 3 to a Category 5 hurricane with 175 mph winds in just 12 hours. Then, just before landfall near New Orleans on the 29th, Katrina weakened to a Category 3 storm. However, high winds continued to cover a very large area, and the weakening did not prevent Katrina from being the most destructive hurricane ever to strike the U.S. These rapid intensity changes are very difficult to forecast, but extremely important for accurate

Figure 1. *Hurricane Katrina in the Gulf of Mexico on August 28, 2005 packed winds of 175 mph.*

Courtesy of Richard H. Johnson

warning of impending damage due to high winds, storm surge, and flooding.

The Atmospheric Science Department has had a long tradition of hurricane research. For nearly 30 years, William Gray has been disseminating seasonal hurricane forecasts, which have shown skill at predicting the annual number of tropical storms in the Atlantic. Wayne Schubert and Mark DeMaria (Cooperative Institute for Research in the Atmosphere, CIRA) have been studying how both the inner core dynamics and the environment of hurricanes affect their intensity change. Their research findings have led to notable improvements in operational forecasts by the National Hurricane Center in Miami.

Much of the damage and loss of life from hurricanes comes from flooding, but flooding also occurs in association with severe convective storms. Such storms have been the subject of investigation by the department for decades. One very notable event to our local community was the Fort Collins, Colorado flash flood of July 28, 1997, which led to five fatalities. An astounding 10 inches of rain fell in the southwest part of town in just four hours, almost two-thirds of the city's annual precipitation. The storm was poorly forecast and flash flood warnings were late in arriving, in part because the storm's behavior was so anomalous. While all the other storms in northeast Colorado were moving quickly off to the northeast, the single Fort Collins storm remained stationary, reforming again and again in the same location, which led to the extreme rainfall.

This anomalous behavior is not well understood, but it and other aspects of severe storms have been the subject of study of William Cotton, Richard Johnson, Steve Rutledge, and Susan van den Heever for years. The storm that produced the Fort Collins flash flood was also unique in the sense that it was tropical in nature, having what is called a "low-echo centroid" in the radar pattern and very little lightning. It is noteworthy that the flash flood occurred during a strong El Niño event, when very humid air was prevalent over the entire southwestern U.S., which contributed to its tropical-storm-like characteristics.

When heavy rainfall occurs, verifying just how much has fallen is a difficult task, considering the large variation of precipitation in both space and time. The department, through its Colorado Climate Center, has taken an important step toward filling the gap in precipitation measurements with the establishment of the Community Collaborative Rain, Hail & Snow Network (CoCoRaHS) project. CoCoRaHS was launched just after the Fort Collins Flood to improve the understanding of local precipitation variability not just in Colorado but throughout the nation. CoCoRaHS is a project led by Colorado State Climatologist Nolan Doesken aimed at installing rain gauges and hail pads in the backyards of citizens throughout the country. There are now over 15,000 observers in all 50 states who report daily measurements to a central website. This network of observations has now become a vital part of the overall observation system for the National Weather Service.

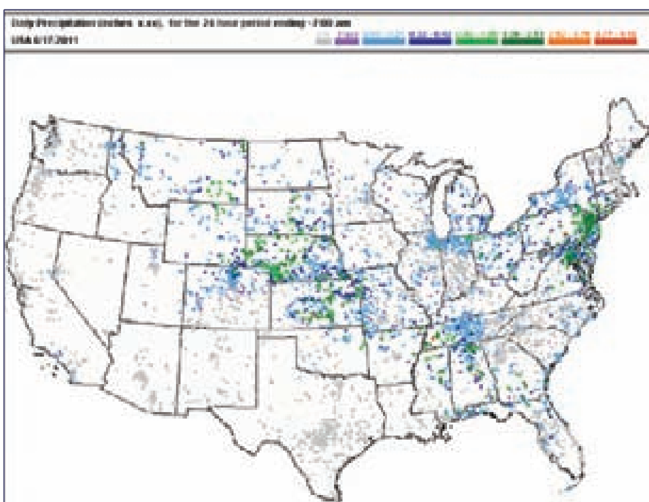


Figure 2. *Precipitation amounts at CoCoRaHS stations over the United States for a 24-hour period ending at 7 a.m. on June 17, 2011.*

One of the most difficult forecast problems is the severe thunderstorm. These storms often produce large hail and tornadoes. The most common occurrence of hail in the country happens to be where Colorado, Nebraska, and Wyoming meet, an area known as "Hail Alley." The relatively high elevation combined with the frequent occurrence of thunderstorms accounts for the high frequency of hail in this region. Storms with large hail are particularly difficult to forecast. Fort Collins' worst hailstorm occurred on July 30, 1979, when hailstones up to 4 ½ inches in diameter fell on the city, killing one 3-month-old baby and injuring 25 people. The largest hailstone ever to be recorded in the United States, measuring 8 inches in diameter, fell just last year on 23 July 2010 at Vivian, South Dakota. The stone was transported to the National Center for Atmospheric Research for analysis of its internal structure by several scientists, one of whom was Henry Reges of CoCoRaHS.

Figure 3. *United States record hailstone from Vivian, South Dakota, hailstorm on July 23, 2010 carried by Henry Reges on a journey to National Center for Atmospheric Research.*
Courtesy of Richard H. Johnson

The department has also conducted research on tornadic thunderstorms, often referred to as "supercells." Cotton and van den Heever have carried out numerical simulations of such storms using high-resolution models with sophisticated representations of the detailed cloud processes, or microphysics. The May 2008 Windsor, Colorado, tornado was investigated by Russ Schumacher, the department's newest faculty member, as well as Daniel Lindsey, Andrea Schumacher, Jeff Braun, and Steve Miller of CIRA. They found that due to the rare occurrence of strong tornadoes in Colorado and the unusual northwesterly track of the Windsor storm, warning systems along the Front Range were inadequate and are in need of significant improvement if future warnings are to be effective.

So far this year, tornadoes have killed at least 530 people in the U.S., the highest total since 1950. Just why there have been so many devastating tornadoes this year is unclear, but the La Niña conditions in the Pacific Ocean and associated strong jet stream over the southern U.S. may have played a key role. The department is pursuing these types of questions in an effort to unravel the complex behavior of the often unpredictable atmosphere.

Figure 4. *Windsor, Colo. Tornado on May 22, 2008.*
Courtesy of Resident Realty

Understanding Precipitation using Satellite and Ground-based Observations

Matt Rogers, Research Scientist II, Cooperative Institute for Research in the Atmosphere, Colorado State University

The water cycle is one of the fundamental components of the Earth's environment; precipitation forms one leg of the cycle, and is one of the more difficult aspects of the water cycle to observe directly. Prior to the 20th century, observations of precipitation were limited to a relatively scarce network of surface stations equipped with buckets of various manufacture. The buckets were very accurate for what they did, which was give an accurate record of rainfall at one particular point, but the weather patterns that generate precipitation are often spread out on a scale of hundreds of miles; a few stations, located largely near population centers, couldn't hope to accurately characterize the full spatial and temporal properties of precipitation, nor could they be used for prediction or analytical purposes. To understand these properties of precipitation, we would need new observational techniques capable of seeing vastly larger areas of the atmosphere.

The science of remote sensing came out of the scientific advances of the early 20th century and is revolutionizing the way we measure precipitation. The principle behind remote sensing is to measure the properties of one system by taking observations of another system that directly interacts with the system of interest. For most applications of remote sensing for the earth sciences, this means observing how electromagnetic radiation interacts with the properties of the environment. Natural radiation sources, such as sunlight emitted by the Sun and reflected off the Earth, or infrared and microwave radiation emitted by the Earth, are one set of sources used to study the environment; scientists also can design instruments to emit different kinds of radiation, then study the interaction of that human-created radiation with the environment.

Precipitation (which includes rainfall, snow, hail, and any other form of liquid or solid water that falls from the sky and reaches the ground) has many unique properties that interact with electromagnetic radiation. Rain droplets, for example, are very good at scattering many forms of radiation, including radio waves. Harnessing this property, radar (an acronym which stands for 'RAdio Detection And Ranging') was developed in the 1940s, first as a tool for remotely detecting aircraft, and then to measure precipitation. Radars work by sending out timed pulses of radio energy at a specific frequency from a station equipped to transmit and receive radio signals. When the radio waves encounter a target (such as a raindrop), some of the radio energy is reflected off the target and is recorded back at the radar station. By measuring how much energy returns to the station, we can gain information about how many reflecting targets must have been in the atmosphere; by measuring the time it takes for the radio signal to go out and return, we can estimate how far away those targets are. Combining these properties gives us a nearly-instantaneous map of where raindrops are in the atmosphere over a large area.

Currently, the National Weather Service operates a network of 159 high-resolution weather radars, giving nearly complete operational coverage of the United States. Additionally, research radars such as the Colorado State University (CSU)-CHILL radar (see the following article on the CSU-CHILL system) are used to develop new techniques for observing precipitation. With the dawn of the space age, the ability to launch radars into space came about, and spaceborne radars such as the Tropical Rainfall Measuring Mission (TRMM) and the CloudSat mission are giving us global information on clouds and precipitation. A future mission, the Global Precipitation Measurement mission (GPM), is in development as well and promises to extend even further our understanding of global precipitation.

Because radars see the instantaneous picture of where raindrops are located in the atmosphere at a given time, a little work must be done to translate that picture into an accurate measurement of precipitation rate. One way to accomplish this task is to develop relationships between the radar return signal and the amount of precipitation measured by a surface network of bucket stations. These relationships depend very much on the kind of precipitation being measured (rainfall, snow, hail, etc.) and other factors; one of these factors is the shape of the precipitation particle in relation to the radio energy being used to detect it. Large raindrops and hailstones are rarely symmetrical, for example, and more information about their shape is needed to gain a good observation of precipitation rate for these particles. Most operational radars only emit radiation in the horizontal plane, and therefore only see the horizontal component of these precipitation particles. Research radars (such as the CSU-CHILL radar) can employ a technique called 'dual polarization,' which means they emit radiation in both the horizontal and vertical plane, providing a better understanding of the shape of the precipitation particles. This improved measuring leads to a better understanding of precipitation rates.

An example of the difference between single- and dual-polarized observations of precipitation is shown in Figure 1. For these two figures, the different colors represent the different amounts of rainfall in a thunderstorm for a particular day as seen from the CHILL radar. The top figure is a measurement of rain rate using the standard rain rate analysis, which uses only the horizontal information from the radio signal. The bottom figure uses the differential signal from the polarimetric radar, and a few differences can be seen in the rain rates measured, especially in the core of the storm and the eastern portion of the storm, where enhanced rainfall seen only by the polarimetric radar is noted. By using a network of surface bucket observations, scientists can confirm the enhanced accuracy of the dual-polarized observations.

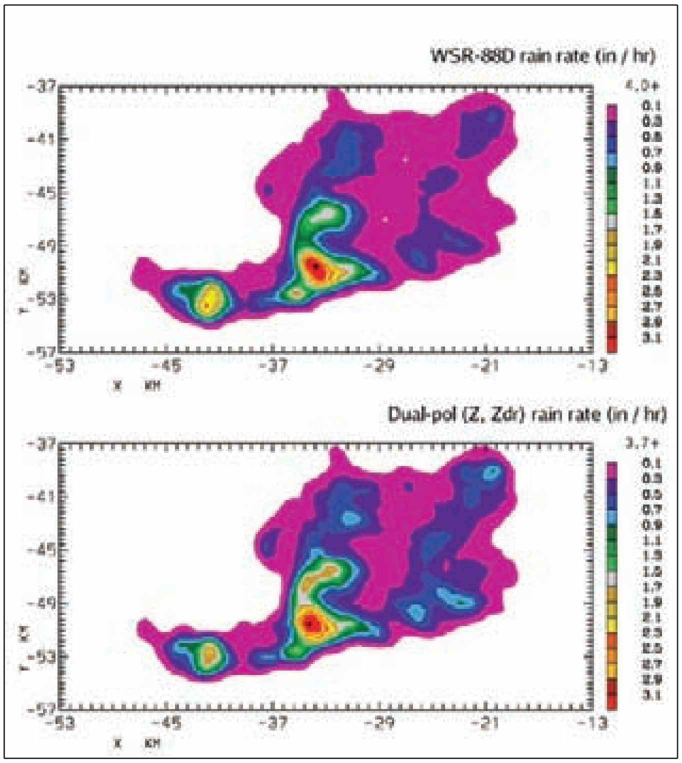


Figure 1. *Comparison of radar rain rates derived from single-polarization vs. dual-polarization data. Data from the 16th of July 2004 from the CSU-CHILL radar site in eastern Colorado.*

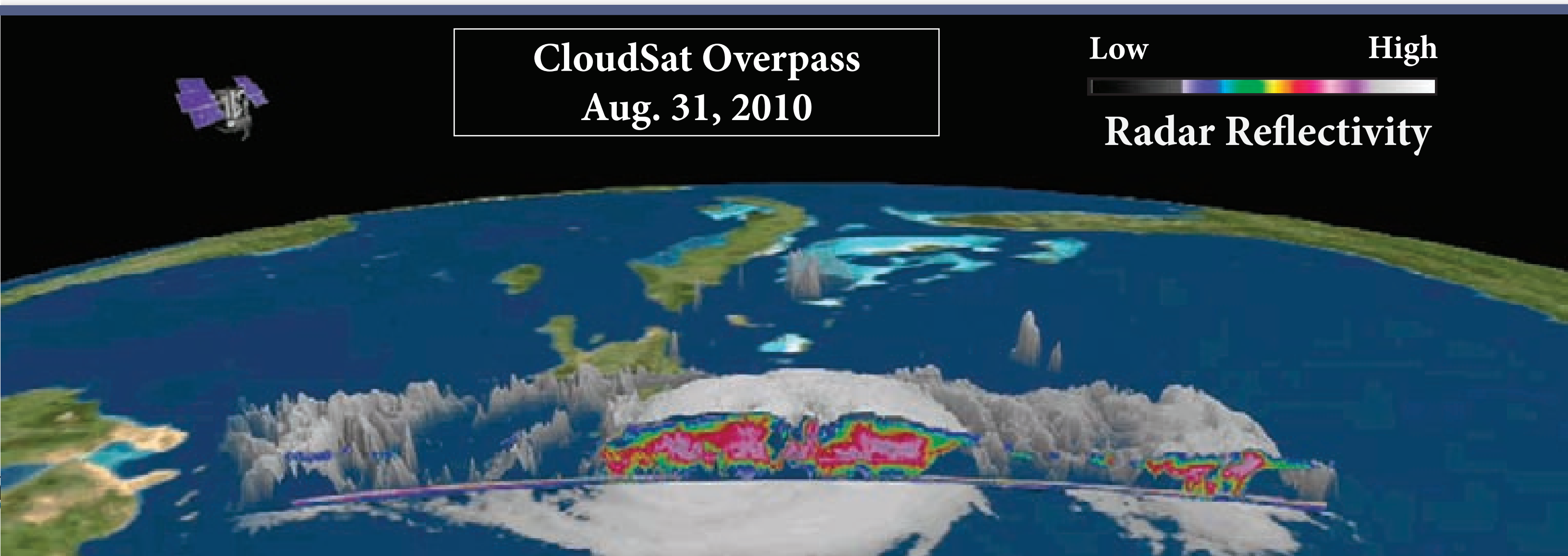
Courtesy of CHILL

Surface-based radars can give us extremely accurate measurements of precipitation in the areas that can be 'seen' with their beams, but what about precipitation in places where there are no radars, such as over the ocean or sparsely populated areas? Flying a precipitation radar in space goes a long way toward addressing that issue. From orbit, a precipitation radar can scan massive swaths of the Earth's atmosphere, and given enough orbits, it can even measure the global amount of precipitation. The CloudSat mission, launched in 2006, is a partnership between CSU (through the Department of Atmospheric Science and the Cooperative Institute for Research in the Atmosphere, CIRA) and the NASA Jet Propulsion Lab, and has provided nearly five full years of global observations. Figure 2 presents CloudSat observations of the structure of rainfall and cloud water inside Hurricane Earl taken in August 2010. The colors represent the reflected radar signal, which varies depending on the amount of cloud and rain droplets inside the convective rainbands (bands of heavy, convective showers that spiral toward the center of the hurricane) making up the hurricane. Not only can these kinds of observations be used to pinpoint the strongest rainbands inside the hurricane, but the scientific analysis of general hurricane structure using these observations can also be used to improve our understanding of how hurricanes work. The result is better forecasting for hurricanes and other forms of severe weather.

Validating the measurements of precipitation from space is one of the challenges of spaceborne radars. The satellite

Figure 2. *Satellite observations of cloud water and rainfall inside Hurricane Earl, August 2010.*

Courtesy CloudSat/NASA/JPL



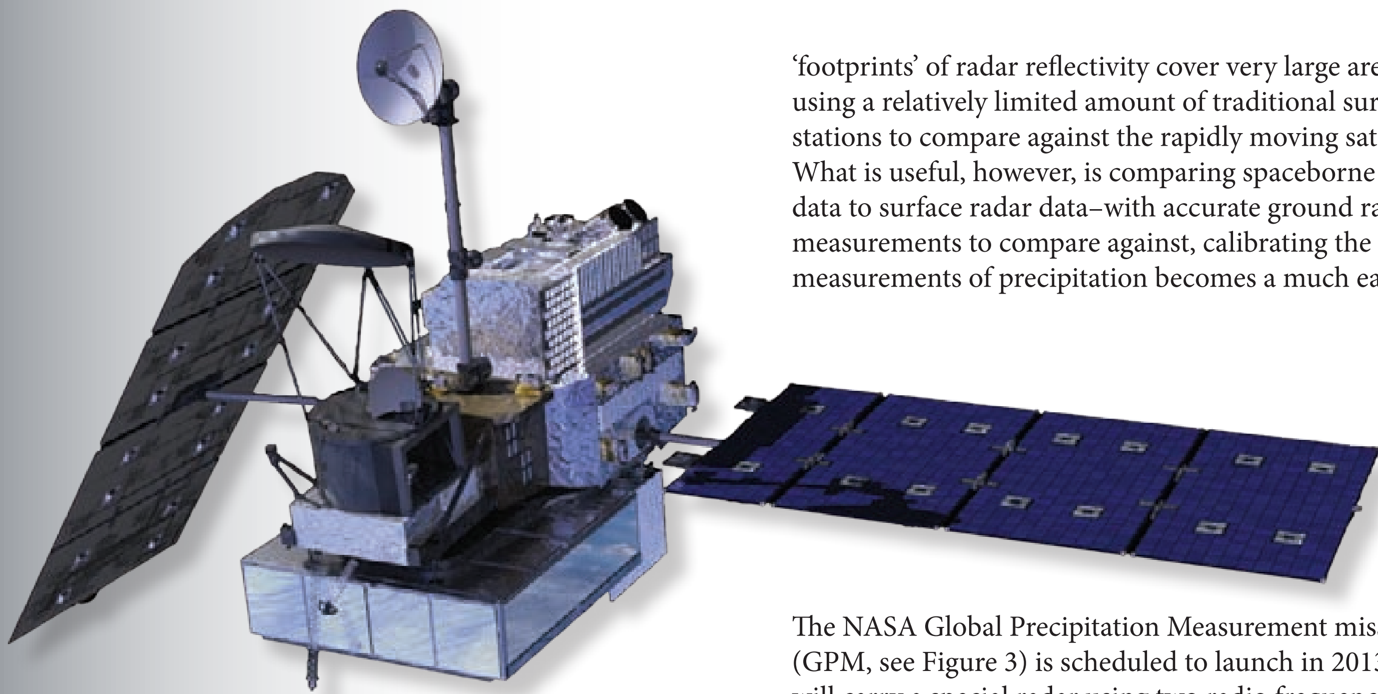


Figure 3. *Artists' representation of GPM core spacecraft.*

Courtesy of NASA

'footprints' of radar reflectivity cover very large areas, using a relatively limited amount of traditional surface stations to compare against the rapidly moving satellite. What is useful, however, is comparing spaceborne radar data to surface radar data–with accurate ground radar measurements to compare against, calibrating the satellite's measurements of precipitation becomes a much easier task.

The NASA Global Precipitation Measurement mission (GPM, see Figure 3) is scheduled to launch in 2013 and will carry a special radar using two radio frequencies that will have similar capabilities to the dual-polarization radar used by the CSU-CHILL radar. There have been several opportunities for CSU scientists and the CHILL radar system to provide validation data for the GPM program; one such opportunity came about in 2004 (Figure 4.)

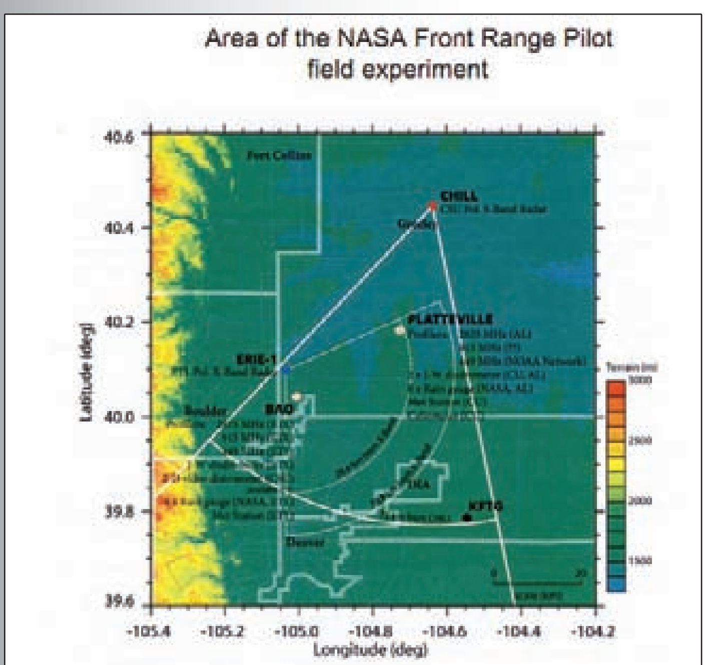


Figure 4. *GPM-CHILL validation area and instruments for 2004 validation campaign.*

Courtesy of CHILL

The NASA Front Range Pilot field experiment utilized several radars, including the CSU CHILL radar, the Denver WSR-88D operational weather radar, an additional NOAA research radar located in Erie, and several other research instruments. This field campaign utilized different radars with different capabilities to characterize the most accurate radar frequencies for different rainrates; this kind of information is very useful to plan the GPM mission. As the launch date for the GPM mission approaches, additional opportunities to perform ground validation for this unique satellite using the unique capabilities of instruments at CSU, including the CHILL radar system, will take place.

Our understanding of the water cycle and precipitation has been greatly improved over the last 30 years. By using new technologies such as satellite-based observations and polarimetric radar observations, scientists are helping to unravel some of the mysteries of precipitation and are providing accurate observations of water for many end users. With the ability to use sophisticated systems for ground validation for satellite missions, the capability to extend the knowledge gained about local precipitation systems to a global scale becomes possible, and the gains made in our understanding of the earth and its water environment prove promising indeed.

Rainfall Mapping Procedures using Dual-polarization Observations from the CSU-CHILL Radar

Patrick C. Kennedy, Radar Facility Manager, CSU-CHILL
Steven A. Rutledge, Atmospheric Science Department, CSU and Scientific Director, CSU-CHILL

CSU-CHILL is a research weather radar system funded by the National Science Foundation (NSF) and Colorado State University (CSU). The facility is jointly operated by the Departments of Atmospheric Science and Electrical and Computer Engineering at CSU. The radar was originally designed and assembled in the 1970s under an NSF grant that was shared by the University of Chicago and the University of Illinois. To take advantage of CSU's nationally-recognized expertise in atmospheric science and electrical engineering, NSF transferred the operational responsibilities of the CHILL radar to CSU in 1990 following a national competition. During the intervening years, continuing technical improvements have been made to the radar's antenna and digital signal processing hardware; very little of the original 1970s era equipment remains in use.

The radar is installed adjacent to the Greeley-Weld County Airport on property that was formerly used for CSU agricultural research. An air-supported dome protects the antenna from loading applied by wind, snow accumulations, etc. The dome's large size (top height of 19.8 m / 65 ft and base diameter of 30.5 m / 100 ft) make it the most prominent visual feature of the radar site (Figure 1a). The large 9.1 m (~30 ft) antenna reflector diameter is necessary to focus the 11 cm wavelength transmitted signals into a narrow (1º wide) beam (Figure 1b). The radar electronics equipment and system control areas are housed in several semi-trailers (Figure 2). The radar equipment is designed to be transportable, allowing the CSU-CHILL system to be temporarily relocated to support NSF-funded research projects at other sites.

The basic operating principle behind weather radars involves the scattering phenomena that occur when microwave radiation interacts with the water molecules that compose raindrops, snowflakes, hail, etc. When electric field vibrations in the microwave pulse emitted by the radar interact with these atmospheric water particles, oscillations are induced in the water molecules that cause a small fraction of the radar power intercepted by the particle to be scattered back to the radar, where it is received and processed. This return power is referred to as an "echo." The strength of the received echo (called the radar reflectivity; Z) is strongly affected by the scattering particle's diameter and composition (water vs. ice).

The CSU-CHILL radar is designed to selectively radiate pulses in which the electric field vibrations occur in either the horizontal or vertical plane. This capability is particularly useful for making observations of thunderstorm precipitation. The aerodynamic forces acting on raindrops larger than ~1 mm in diameter cause them to assume oblate (flattened) cross-sectional shapes as they fall

Figure 1a. *External view of the air-supported dome that protects the CSU-CHILL radar antenna and the semi-trailer (lower right) that contains the real time operational control area.*

Photo by Patrick C. Kennedy

(Figure 3, central section). Due to this asymmetrical shape, the diameter presented by a flattened drop is larger for a horizontally-polarized radar pulse than for a vertically-polarized pulse. Consequently, the average radar signal strength received at horizontal polarization will exceed that received at vertical polarization when large, oblate raindrops are present. The ratio of the horizontally-polarized received signal strength compared to that of the vertically-polarized signal defines differential reflectivity (Z_h/Z_v; Z_{dr}). Z_{dr} provides information on the average degree of oblateness among a population of raindrops. Rain composed primarily of small diameter, relatively spherical drops will produce a low Z_{dr} value since Z_h is similar to Z_v. In contrast, when many large, oblate drops are present, Z_h can exceed Z_v by a factor of two or more.

The Z_{dr} characteristics of hailstones differ distinctly from those of oblate raindrops. The aerodynamic forces acting on solidly-frozen hailstones are not capable of altering their quasi-spherical shapes. Furthermore, hailstones typically gyrate through random, large-amplitude orientation changes as they fall. The combination of these effects tends to equalize the Z_h and Z_v values received from hail, thereby reducing Z_{dr}. (Due to the large backscattering diameters of hailstones, the reflectivity levels at each polarization are both generally quite high when hail is present.)

The capability to measure Z_{dr} allows dual-polarization weather radars to remotely sense the mean shape characteristics of precipitation particles. This shape information can be used to identify hail areas and to refine the basic rain rate estimations that historically have been calculated using only the strength of the signal received at a single polarization (normally Z_h).

The oblate shape of raindrops also imposes differences in the propagation characteristics of the H and V radar pulses as they pass through areas of rain. Due to the collective effects of the flattened drops, the progress of the H pulses becomes slightly delayed relative to that of the V pulses as they travel along the same beam path. Dual-polarization radars can measure the magnitude of this delay by calculating the phase difference between the received H and V waveforms (Figure 3, left and right sections). This H – V received phase difference maximizes in areas where the high concentrations of large diameter, oblate raindrops exist (i.e., where heavy rain is present). The rate at which this phase difference changes per kilometer of range traveled by the H and V pulses defines specific propagation phase (K_{dp}). Power law expressions have been developed that allow rainfall rates to be estimated from the radar-measured K_{dp} magnitudes with considerable accuracy. Since the random tumbling motions of hailstones cause essentially no differential impacts upon the propagation of the H and V pulses, K_{dp}-based rain rate values remain usable when hailstones coexist with raindrops and significantly increase reflectivity (Z_h) relative to the level generated by the raindrops alone.

Figure 1b. *The dual offset feed antenna inside the radome.*
Photo by J. Eisele

Figure 2. *The CHILL radar site near Greeley, Colo., as seen from the air.*
Photo by Tom Trout, provided by Matt Rogers

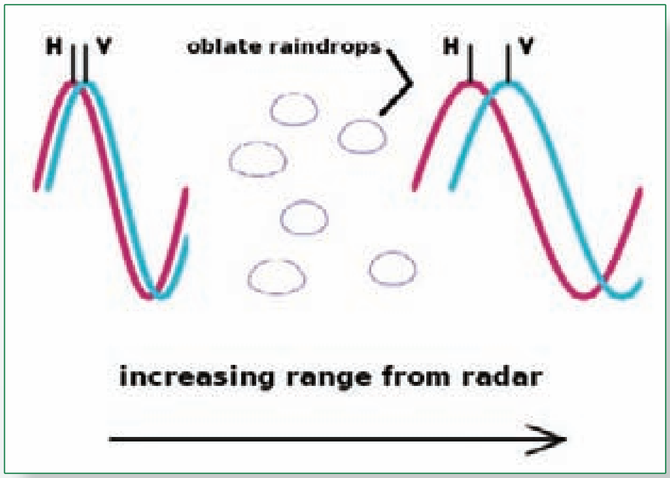


Figure 3. *The oblate shapes typical of raindrops with diameters of 2 – 4 mm are shown in the central portion of the figure. Color-coded sine waves at the left and right portions of the figure are a schematic representation of the phase lag that develops between the horizontally- and vertically-polarized radar pulses as they propagate through a region containing large, oblate raindrops.*

The Atmospheric Science and Electrical and Computer Engineering departments at CSU have conducted research into methods for optimally combining Z_h, Z_{dr}, and K_{dp} data to improve the accuracy of radar-based estimations of thunderstorm rainfall rates. These dual-polarization rainfall estimation procedures were applied to thunderstorms that were observed with the CSU-CHILL radar during the evening hours of July 6, 2010. This thunderstorm activity affected the area around Byers, Colorado (located ~50 km east of Denver along I-70) between 6:15 p.m. and 8:30 p.m. MDT (mountain daylight time). National Weather Service (NWS) severe weather spotters reported 19 mm in diameter (0.75 in) hail and heavy rain at 1852. Figure 4 shows the rainfall totals in inches for the greater Byers area calculated using conventional, Z_h only procedures (Figure 4a) and using the CSU optimized combination of Z_h, Z_{dr} and K_{dp} data (Figure 4b). The conventional Z_h only method produced a north-south oriented area of greater than three inches of rain located just west of Byers. In contrast, the dual-polarization rainfall estimation method resulted in a more localized maximum rainfall area containing accumulations between two and 2.5 inches. One point of validation data was provided by an observer in the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) who reported a 2.25 inch total rain accumulation in central Byers. The generally greater rainfall totals produced by the conventional Z_h only based method are probably caused by reflectivity enhancements due to hail.

Research radars like CSU-CHILL have provided investigators with a wealth of data for examining the dual-polarization characteristics of precipitation. The results of these efforts have confirmed that polarimetric radar technology can be used to improve the accuracy of hail detection and rainfall estimation in thunderstorm precipitation. In recognition of these findings, the NWS is currently upgrading their network radars to a dual polarization configuration that will bring the benefits of this technology to their operational forecasting and severe weather warning responsibilities. The polarization technology featured on the CHILL radar is also useful for evaluating snow storms. CHILL is currently adding a second frequency to its basic system, 9.3 GHz, or X-band. This higher frequency, in combination with the present S-band frequency, will further expand the capabilities of the radar to study precipitation.

Figure 4. *Rainfall accumulations in inches (outer contour is 0.5; interval is 0.5; 2.0 inch contour is darkened) calculated from CSU-CHILL data collected during the 6:15 – 8:30 p.m. MDT period on July 6, 2010. Accumulations in panel a were computed using current NWS methods that only consider reflectivity (Zh). Panel b results are based on CSU procedures that combine Zh data with the additional polarimetric information contained in the Zdr and Kdp data.*

From Airplanes to Climate Change

David Randall, Department of Atmospheric Science, Colorado State University

The development of a new type of airliner is way too expensive for guesswork. Before the first real plane is built, the engineers *know* how much thrust the engines will produce, how much the plane will weigh, how fast it will be able fly at various altitudes, how much fuel will be needed to travel from Denver to Dallas, how the plane will respond to a pilot's commands, and how much it will cost to manufacture. They have to know these things, because they are betting the company on the success of the design, and because you and I (and the engineers' mothers) will be riding on the plane.

So how do they know?

The answer is arithmetic. Lots of arithmetic. The engineers can simulate the airliner before it is built, using what is called a "mathematical model." The "mathematical" models are based on physical ideas developed by Isaac Newton and other scientists. The math is just a language that can be used to express those ideas, in the same way that English can be used to express ideas about history or art. The models work very well.

The modern world is full of mathematical models. They are used to design skyscrapers, bridges, cars, and space ships. They are used to search for oil, to forecast the weather, and to predict where and when rivers will flood when snow melts in the spring. And they are used to predict how the climate will change between now and the end of this century.

A climate model has a lot in common with the models used to simulate airplanes. Fluid dynamics and thermodynamics are front and center in both. Even the mathematical methods used are very similar. When a climate model simulates the winds, or when an airplane model simulates how the air moves past a wing, the underlying principles are Newton's laws of motion, which say that a particle of air moves in a straight line at constant speed unless acted upon by a force. When a climate model simulates the change from winter to summer, or when an airplane model simulates the temperature inside a jet engine, the underlying principle is that the temperature of the air increases when heat is added.

To measure the climate of the real world, we average together measurements accumulated over a long period of time, usually thirty years or more. The measurements come from weather stations, balloons, radars, satellites, airplanes, and buoys floating in the oceans. They represent a record of the weather, hour by hour, all over the world. A picture of the climate is built up by calculating long-term averages and other statistics from the hour-by-hour weather data.

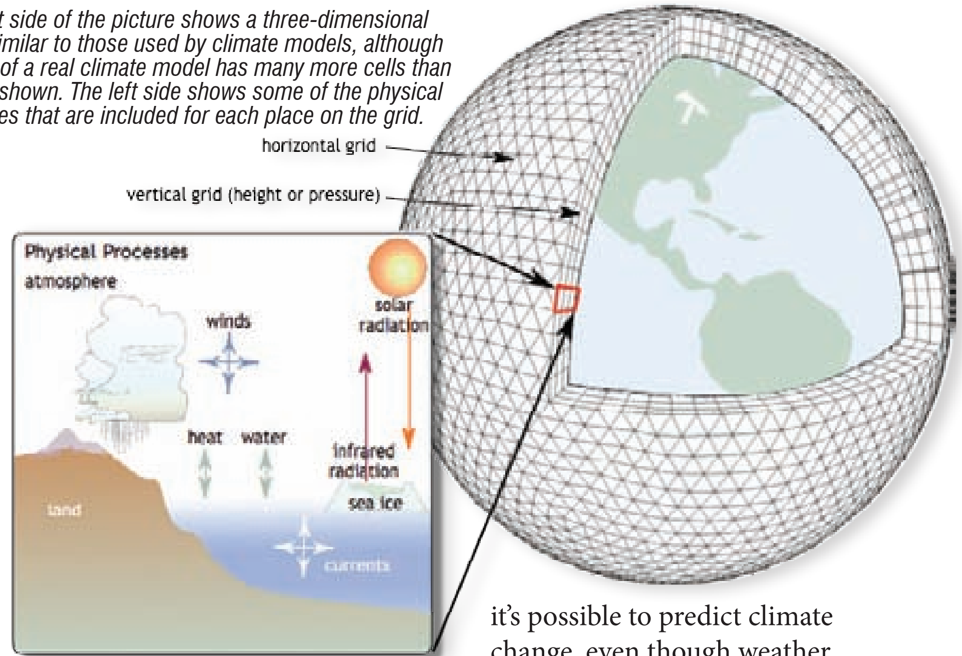
Climate models work in much the same way. They simulate the hour-by-hour weather, all over the world. When a climate model is used to predict how the climate will change by the year 2100, it "marches" forward in time, taking time step after time step, starting from today's weather. Each time step is just a few minutes long. It takes a lot of time steps to simulate a century. As the model marches along, the sun rises and sets, storms grow and decay, and the seasons change, all in the simulated world.

Many things affect the climate. In addition to the forces that affect the winds, an atmosphere model includes the effects of visible and infrared radiation, cloud formation, and small-scale turbulence. The simulated climate is determined by averaging the simulated weather. In fact, the models used to simulate climate are very similar to the models used to forecast the weather.

Both weather and climate models include sub-models of the land surface, as well as the atmosphere. Land surface models predict the temperature and moisture content of the soil. They are needed for weather forecasting because the ground warms and cools quickly during the day-night cycle, and this has a strong effect on the air temperature and weather systems such as thunderstorms.

Climate models have to include more components than weather models. They predict the ocean's temperature, salinity, and currents, from the sea surface right down to the bottom. The ocean can hold tremendous amounts of heat, which the ocean currents carry from the warm tropics towards the poles. The formation and melting of sea ice are also included. The newest models also predict the chemical composition of the air, the greenness of the trees and grass, and changes in the polar ice sheets. The figure at right gives an idea of how this all fits together.

Climate models include less spatial detail than forecast models, because this allows them to simulate a year as quickly as forecast models can simulate ten days. Today, a state-of-the-art climate model represents the area of the Earth with about 50,000 points. That works out to about 10,000 square kilometers per point, a little bigger than the area of Larimer County in Colorado. The vertical structure of the atmosphere is represented with about 50 layers or "shells," extending from the surface into the stratosphere, for each of the 50,000 points. The ocean is represented with about 50 layers. As computers get faster, the spatial detail of the models can be increased. Both weather and climate models need the fastest computers in the world.



The right side of the picture shows a three-dimensional "grid" similar to those used by climate models, although the grid of a real climate model has many more cells than the one shown. The left side shows some of the physical processes that are included for each place on the grid.

Tomorrow's weather is usually predicted with good accuracy, but we all know from experience that the forecasts go bad beyond a few days. How then can a climate model predict what is going to happen in a hundred years? The answer is that weather and climate forecasting are very different kinds of prediction. Here's an example: I'm writing these words on June 8th, in Fort Collins, Colorado. Starting from today, no one (and no model) can make a skillful weather forecast for December 8th of this year. Nevertheless, I can predict, with high confidence, that next December 8th in Fort Collins will be colder than today, because I know that the average weather here in December is colder than the average weather in June. A climate model can predict that too. It's kind of a no-brainer.

Ask yourself, *why is it possible* to predict the seasonal change from June to December, even though we can't predict the weather that far out? Why is the average weather in Fort Collins different between June and December? You probably know that seasonal changes in the average weather are due to the seasonally changing position of the Sun in the sky, which is caused by the movement of the Earth in its orbit around the Sun. The movement of the Earth in its orbit is a time-dependent "forcing." Barring some fantastic catastrophe, the Earth will keep moving around the Sun, just like it did last year. Naturally, climate models have been designed to take that into account, and as a result, they can easily simulate the observed seasonal changes of the average weather.

In contrast, day-to-day changes in the weather are *not* due to changes in forcing, because the forcing hardly changes from one day to the next. The day-to-day changes in the weather arise from the chaotic movements of individual weather systems, which can't be skillfully predicted beyond a few days.

Predicting climate change is something like predicting seasonal change, because both occur in response to changes in forcing. For example, what would happen if the Sun went dark, or if a giant asteroid hit the Earth? Answer: The climate would change in a hurry. Is such a climatic response predictable? You bet it is. Less dramatically, the climate can also change in response to large volcanic eruptions, changes in the shape of the Earth's orbit, or changes in the composition of the atmosphere. These are all examples of time-dependent "forcings." If changes in the forcing can be predicted in advance, then the response of the climate system can also be predicted. That's why it's possible to predict climate change, even though weather forecasts go bad after a few days.

The models that are used to design airplanes have been developed over a period of decades, and are tested by comparing their predictions with measurements. They are not perfect, but their limitations are well known, and they are getting better year by year.

Climate models were first developed in the 1960s and are currently being improved at a couple dozen centers around the world, including several in the U.S. They are tested, in part, at the component level. For example, the components that represent cloud processes are tested by comparison with specially collected, highly detailed measurements of clouds. The models are also tested as complete systems, through weather forecasting, simulations of the present climate, and simulations of past climates such as ice ages. The models are not perfect, but their limitations are well documented. Improvements are made every year through the work of the world-wide climate research community, and also by taking advantage of the increasing power of computers. Within the next ten years, faster computers may make it possible to run climate models with 50 million points, instead of the 50 thousand that we use today. Each of the 50 million points will represent an area about the size of the combined Fort Collins campuses of Colorado State University.

If you are interested in learning more about climate models, especially their history, you might want to take a look at this recently released book, which is aimed at a fairly general audience:

Donner, L., W. H. Schubert, and R. C. J. Somerville, Eds., 2011: *The Development of Atmospheric General Circulation Models: Complexity, Synthesis, and Computation*. Cambridge University Press, 272 pp.

Monitoring Drought: Using Indices to Simplify Complex Climate Data

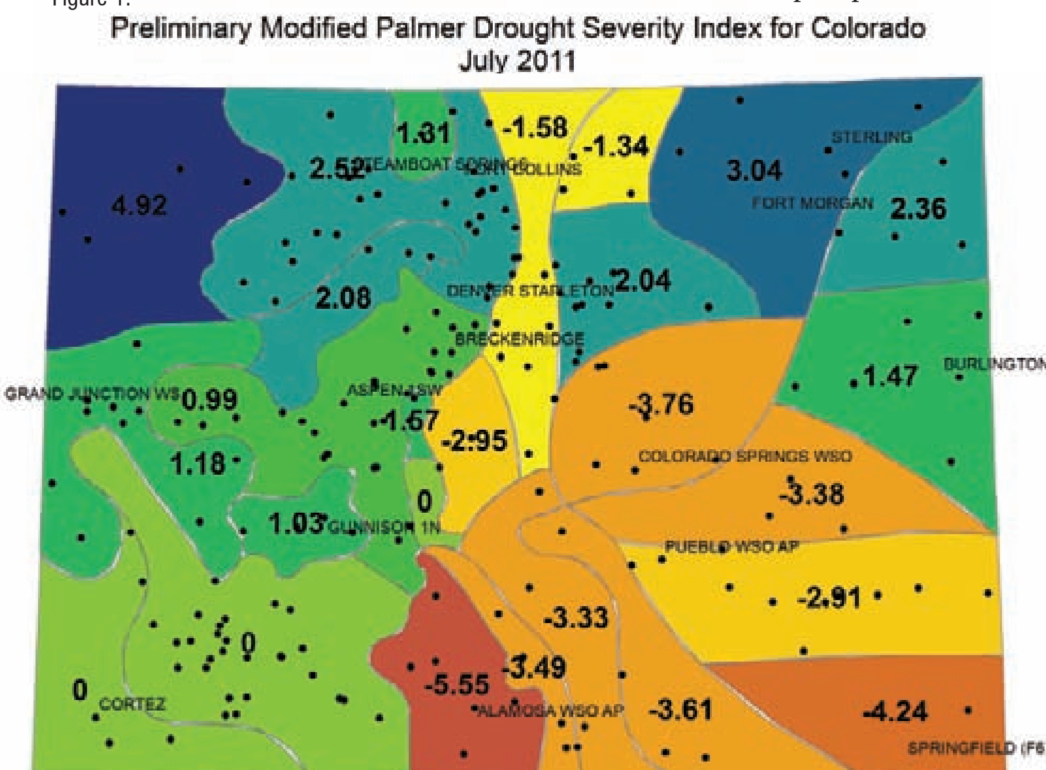
Nolan Doesken and Wendy Ryan, Colorado Climate Center

The Stock Market isn't the only system that uses indices to summarize data into a simplified form well-suited for graphing. Climatologists, especially climatologists that provide climate data and information to decision makers, often develop and use indices. You know this for a fact if you have ever attended one of Colorado's regular Water Availability Task Force (WATF) meetings facilitated by the Colorado Water Conservation Board. These meetings typically last about two hours and are filled with charts, graphs, maps, and reports containing data galore and more than a handful of indices.

Palmer Drought Severity Index Modified for Use in Colorado

Colorado (WATF) meetings have been held periodically for 30 years, since Colorado's first Drought Response Plan was implemented in 1981. Federal, state, local, university, and private sector representatives familiar with various aspects of Colorado weather, climate, water, and water management gather to share information on precipitation, snowpack, streamflow, soil moisture, reservoir levels, and climate predictions. They work together to try to ensure that drought and related water shortages don't sneak up on us. Back then (1981), there were only two drought indices in common use—the Palmer Drought Severity Index and the Crop Moisture Index, both developed in the 1960s by Wayne Palmer, meteorologist for the U.S. Weather Bureau. Palmer's Index was certainly not perfect and has received much criticism over the years. Nevertheless, more than 45 years after it was first published, that index is still in use—see Figure 1. Why? Because it has served the purpose of taking myriad temperature and precipitation data over many years for many areas and combining them into a single number for each region of the country showing relative wetness and dryness—a number that someone who is not a climate expert can quickly look at an interpret. That had and continues to have value.

Figure 1.



Surface Water Supply Index

It didn't take long for the WATF participants to come up with ideas for new indices suitable for and, in some cases, specific to Colorado. For example, in 1981, the Natural Resources Conservation Service (then know as the Soil Conservation Service) Colorado Snow Survey Supervisor teamed up with a water engineer from the Colorado Division of Water Resources, also called the Office of the State Engineer, to devise a relatively simple Surface Water Supply Index (SWSI) that would take Colorado's precipitation, mountain snowpack, stream flow, and stored water in reservoirs into account in a way that was specific to each major Colorado watershed. The index was scaled to produce numbers similar to the Palmer Drought Severity Index, with numbers near zero representing normal or near average conditions, positive numbers representing wet conditions, and negative numbers representing dry conditions. For both the Palmer Index and SWSI, numbers of -3 or lower indicated very dry conditions. This index has been produced every month for 30 years by either the NRCS Snow Survey (during winter and spring) or the Colorado State Engineer's Office (in summer and fall). Once again, while imperfect and often criticized, the index prevailed because it incorporated complex data into a simple number so that anyone could quickly judge conditions.

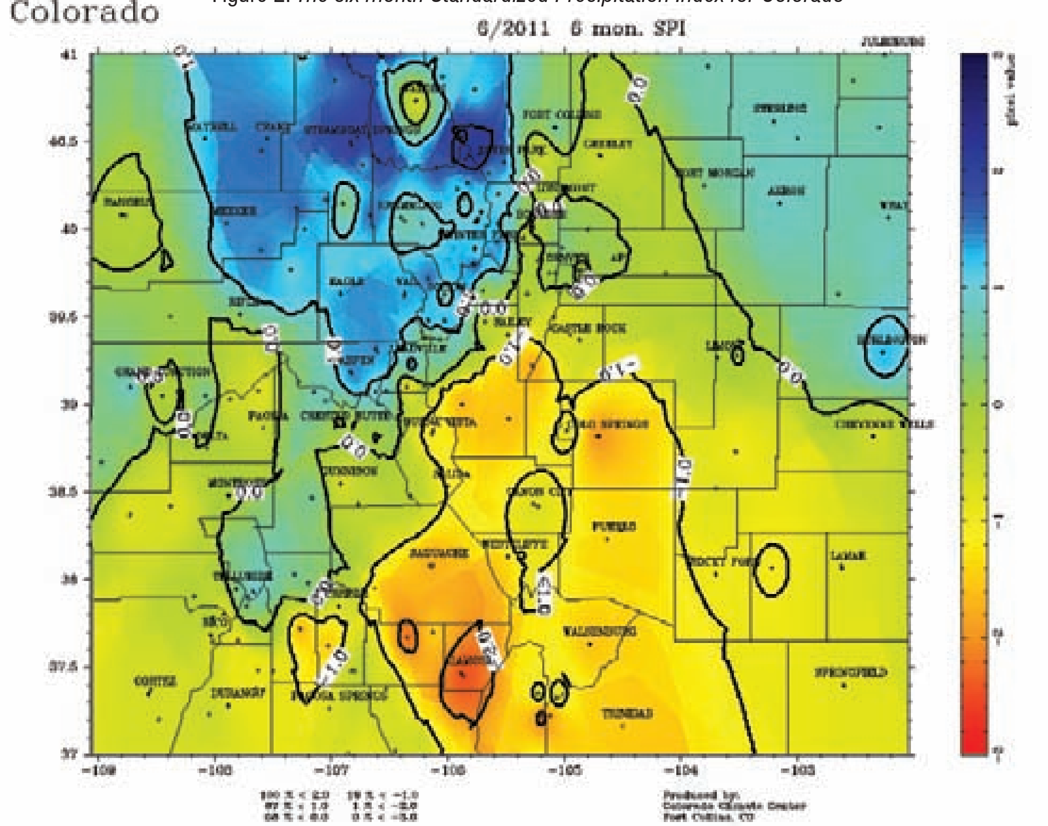
In the past two years, this SWSI has been undergoing modernization to take advantage of considerable advances in streamflow forecasting that have occurred during the past several decades. A new SWSI is now being generated for each river forecast point in the Colorado River Basin in western Colorado, and this will soon be expanded to the other river basins in Colorado as well.

Our office, the Colorado Climate Center at Colorado State University, was next to get into the drought index act. In the early 1980s, we acquired the FORTRAN computer code for the Palmer Drought Severity Index. Then, through a long process of historical data analysis, we divided the state into 25 climatically similar "divisions" and developed a procedure to produce monthly temperature and precipitation statistics for each of these divisions. The result became known as the "Colorado Modified Palmer Drought Severity Index." This index was used regularly in the 1980s, lost favor in the 1990s, and nearly disappeared from use in the past decade until a recent analysis funded by the Colorado Water Conservation Board showed that this index was surprisingly skillful in tracking the relationship of drought severity with certain impacts such as stream flow volumes in the Upper Colorado River and wheat yields in the drier portions of eastern Colorado.

Standardized Precipitation Index

Colorado's former State Climatologist, Thomas McKee, spearheaded an effort in the 1990s to develop, test, and utilize a simpler index that was based solely on precipitation data. Dr. McKee, in his over 25 years as State Climatologist, had always been troubled by the fact that drought meant different things to different people depending on the location and the application, but existing drought indices were not flexible enough to describe and address these differences. For example, a dryland farmer in eastern Colorado might be greatly concerned by precipitation shortages over 30-90 days at critical times of year, while dam and reservoir operators were more concerned about long-term multiyear water shortages. The myriad different concerns resulted in many and varied drought definitions. But a simple index, based solely on the variability of observed precipitation over any of several different time scales (from a few weeks to a few years), could be calculated in the same way but serve many different users. The result was the Standardized Precipitation Index, or SPI, as it is now commonly called. While never published in a scientific journal, this Colorado-devised index has spread in popularity and use so that it is now one of the most widely used drought indices in the U.S. and is recommended for use internationally by the World Meteorological Organization (see Figure 2).

Figure 2. *The six month Standardized Precipitation Index for Colorado*



The U. S. Drought Monitor

The most popular index of all, and a relatively new one (dating to the late 1990s), is the U.S. Drought Monitor. Responding to the nationwide need to systematically track drought conditions across the diverse climatic zones of the entire U.S., a team of climatologists from multiple federal agencies, universities, and other organizations collaborated to begin to producing weekly updates showing drought severity on national, regional, and state maps. Categories range from no drought (white) to abnormally dry (D0), on up to Extreme Drought (D3), and Exceptional Drought (D4). Each level is defined to a large extent by the probability of occurrence with D4 equating to drought severity

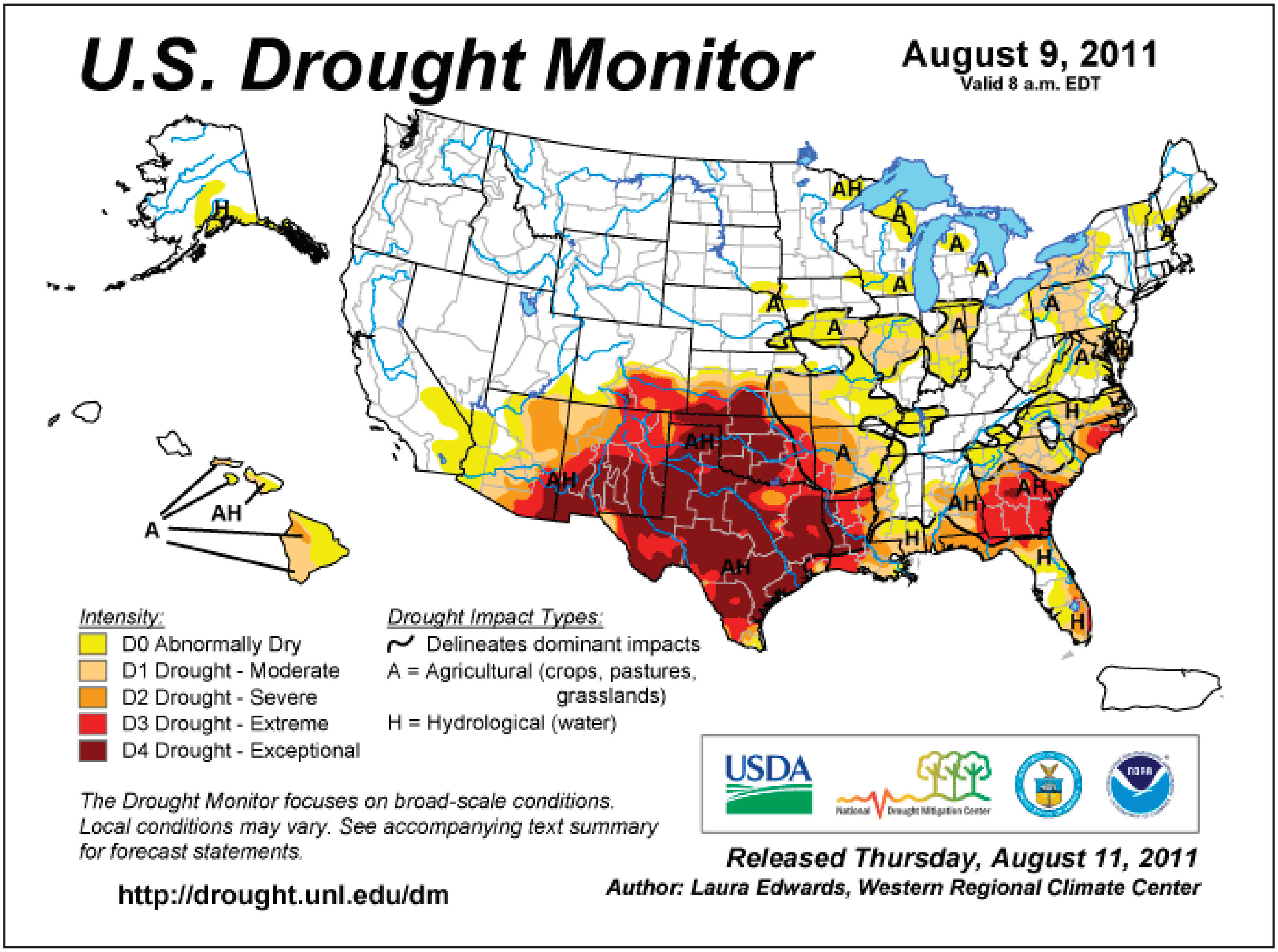


Figure 3. *The current U.S. Drought Monitor shows drought conditions in southern Colorado and throughout the southern U.S.*

that only has about a two percent probability of occurrence for that time and place. Assembling data from a variety of sources, and accepting input from local experts, the U.S. Drought Monitor maps (http://www.drought.unl.edu/dm/monitor.html) are visited millions of times each month and used to aid decisions such as drought declarations and agricultural assistance programs.

Perfect Index?

If there is one, we haven't found it yet. Because drought means different things to different people, it is impossible to find a single index that pleases everyone. The U.S. Drought Monitor is extremely popular but still has significant "issues." For example, this year, the Mississippi River was producing near record floods as it passed through drought-stricken Louisiana in May and June. And how do you handle the fact that water supplies in the Arkansas River in Colorado are in good shape, and irrigation water supplies are adequate, even though much of the Arkansas Basin is experiencing one of its driest years on record? Each drought index serves a need and may be better and more useful in some situations than others, but users need to be aware of the limitations. But when drought gets pronounced and widespread, like it is in Texas this year and like it was in Colorado in 2002, you can bet that it wouldn't much matter what index you were looking at. They would have all indicated a bad drought.

For More Information

To learn more about the various drought indices used frequently here in Colorado, go to the CWCB "drought toolbox": http://cwcb.state.co.us/technical-resources/drought-planning-toolbox/Pages/main.aspx

If you would like to be on an e-mail list to receive weekly drought and water supply updates, please contact Henry Reges at the Colorado Climate Center (hreges@atmos.colostate.edu). These reports are also available on the Colorado Climate Center website at http://ccc.atmos.colostate.edu/drought_webinar.php

Advancing Snow Science in Changing Climate and Complex Terrain

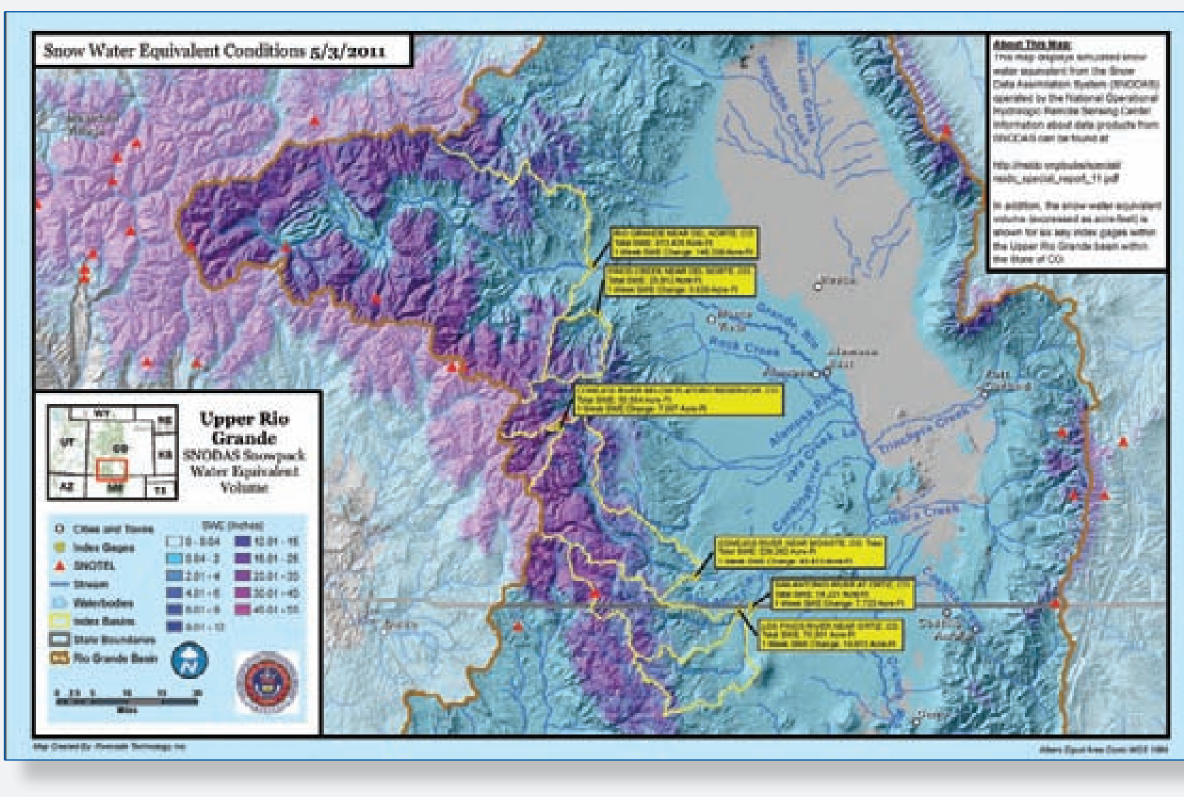
Joe Busto, *Scientist/Researcher, Colorado Water Conservation Board*

Colorado holds the headwaters of eight major rivers, with snowfall providing 80 percent of the water for stream flow in the state. Inter- and intra-state water arrangements are complex, creating intricate management scenarios that are further complicated by water supply forecast uncertainties. Utilizing the maximum amount of water in the state is a component of the Colorado Water Conservation Board (CWCB) mission. Climate change may complicate the situation with general drying and more frequent or severe floods and droughts. We need increased accuracy for precipitation observations and hydrologic forecasts, since they have significant socio-economic implications. Water supply forecasts are often based on historical regression models using limited discrete point data primarily from Natural Resources Conservation Service (NRCS) SNOTEL sites. Improvements in water supply forecasts are expected from better models, methods, and observations. The CWCB has developed partnerships with private, local, and federal entities to create better tools and provide critical coordination in fostering an environment for operational applications of ongoing research. Several of these efforts are described below.

Since 2004, the CWCB has partnered with the NRCS and water users to establish 20 new SNOTEL sites for an 18 percent increase and a total of 110 SNOTEL sites in Colorado. However, SNOTEL sites represent a fraction of a basin's area and are limited in developing spatial assessments of snow water equivalent (SWE). Many sub-basins do not have SNOTEL sites. This lack of representation directly translates to water supply forecast difficulties. In search of spatially-continuous data, the CWCB contracted with Riverside Technologies, Inc. (RTi) to utilize data from the NWS/NOHRSC—Snow Data Assimilation System. SNODAS is a full energy mass balance model aimed at spatial assessment of conditions in near-real time. The Division Engineer uses SNODAS SWE maps to track melt-out in three key basins in the Rio Grande delineated in yellow, Figure 1. SNOTEL sites are shown as red triangles. This represents use of spatial modeled snowpack data to compliment the point measurement snowpack data. Some estimation of SWE left is needed, as there can be large river volumes when SNOTEL sites read zero and lead to uncertainty. SNODAS maps with labels at key points could be a statewide product in the CWCB Flood Decision Support System (Flood DSS). For more information about the CWCB SNODAS Project, visit: http://www.riverside.com/projects/uscanada/tabid/121/ItemId/45/Default.aspx.

More recently, RTi developed the Flood DSS, a near real-time data display tool. The DSS incorporates various layers, including current SWE and SWE change, derived from SNODAS and SNOTEL data. Streamflow and radar-derived Quantitative Precipitation Estimates (QPE) can assist with identifying areas of concern for decision makers (e.g., rain or snow events). Visit http://flooddss.state.co.us/Default.aspx for more information.

Figure 1. *This map shows SNOTEL sites combined with modeled snowpack data to produce a more detailed map and assessment of snow water equivalent left in the mountains.*



Through statute, the CWCB issues weather modification permits and curtails operations based on high snowpack and avalanche danger. The CWCB also administers a wintertime cloud seeding grant program to support water user efforts to augment mountain snowpack. In 2007, the CWCB entered into agreements with water users in Nevada, California, Arizona, and New Mexico to provide grants to locally sponsored winter cloud seeding. To date, $882,000 in out-of-state grants has been spent providing both West Slope and Front Range benefits. The consensus and research findings are that seeding can increase snowpack SWE in well designed and executed programs. What we lack are the observations to guide seed/no seed decisions and ground validation tools to detect the efficacy of those efforts.

Solutions for observational gaps require a multi-radar, multi-sensor (MRMS) approach. An MRMS system integrates radar, satellite, surface, and numerical weather prediction model data and more. Recognizing the limitations in NEXRAD radar coverage in western Colorado, the CWCB sponsored gap-filling radar demonstration projects in Gunnison County in the summer of 2009 and in Durango in 2010. The Durango project was also supported by the Division of Emergency Management and the Southwest Water Conservation District. The NOAA/National Severe Storms Laboratory (NSSL) in Norman, Oklahoma deployed mobile Doppler weather radars, and the National Center for Atmospheric Research (NCAR) in Boulder installed research rain gauges. These projects collected data in radar voids to draw comparisons with the NWS NEXRAD radar on the Grand Mesa at 9,900 feet above sea level. The NWS has good radar coverage on top of the 602-square-mile Grand Mesa but leaves many Colorado headwaters areas deficient of coverage. While deployed, the mobile radar near Durango provided significant coverage into Utah, Arizona, and New Mexico in a well known black hole with live data to weather forecast offices, airport officials, and emergency managers.

While these summer radar projects demonstrated the benefit of additional data for flash flood warnings and storm observations (e.g. heavy rainfall, hail, storm motions, and interactions with terrain), snowfall has the largest water supply impact for the state. In February 2011, NSSL deployed a radar at the La Plata County Airport and sampled three snow storms. The 24 hour SWE total QPE for the southern San Juan Mountains is shown in the basin average QPE graphic, Figure 2. This depicts a 1.2 inch SWE snow storm February 19-20, 2011. The radar estimated 34,696 acre-feet of SWE in the Animas River Basin from this storm. Significant SWE was also depicted in basins without SNOTEL sites. The results were part of a 2011 Western Snow Conference presentation, "Use of radar for spatial snow mapping: Implications for run-off forecasts."

The winter radar project showed that radar can help snowpack in real time and can be helpful when integrated with SNODAS and new distributive hydrologic models. Beyond water supply, better observations will help a broad number of sectors. Together the CWCB and weather and climate data management agencies are developing the vision for "complete" observational coverage for Colorado. This includes coalition building, stakeholder identification and support, a business case for additional radars, and support for ground-based observations and other remote sensors. Radar in the Four Corners could accomplish

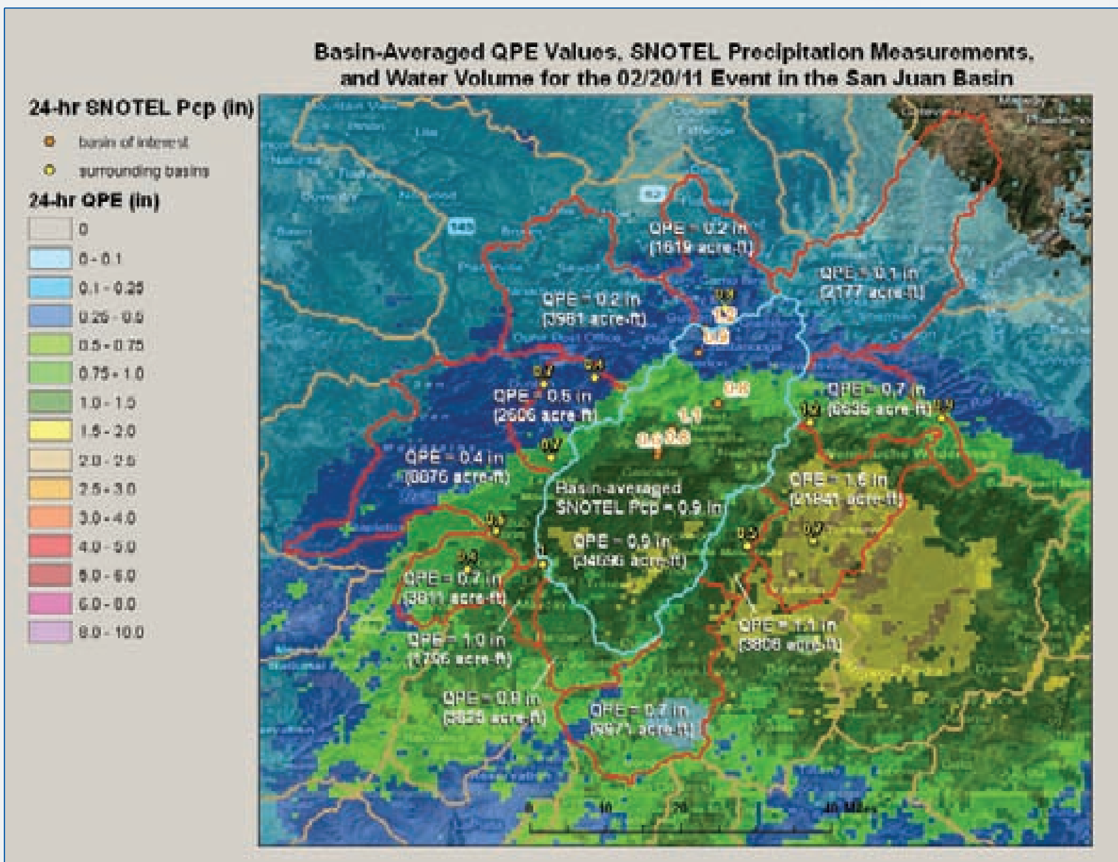


Figure 2. *This map shows radar estimated water from a snow storm in the Animas River Basin and adjacent basins. The radar data collected was calibrated to SNOTEL sites and snow gauges to spatially depict the impact of water generated from a single snow event and its potential benefit to water supply forecasts.*

several goals. However, resources for additional radars can be substantial, requiring an economy scale where low-cost solutions and distributed support from local, state, and federal entities will be necessary. An example of radar collaboration is the North Dakota Atmospheric Resources Board (ARB). The ARB purchased two surplus NWS radars and upgraded and deployed them for $450,000 in the western part of the state. The operations during growing/seeding season are part of the budgets for a large regional rain enhancement and hail suppression cloud seeding program. The $24,000 annual operations and maintenance is shared among eight counties, outside of growing/seeding season, to provide year round data at one site. Real-time data are available to NWS free through the Internet.

In addition to new radar sites in Colorado, new surface meteorological observation assets are recommended to be deployed in important mountain ranges to address current representative shortcomings. A typical surface sensor suite could include a 20-foot tower, satellite communications, a weighing-type precipitation gauge, wind sensors, a temperature gauge, humidity sensors, incoming solar radiation and pressure sensors, soil moisture and temperature sensors, frost/dew sensors, a freezing-liquid sensor, a snow depth sensor, and an optical disdrometer (hydrometeor particle size)/visibility sensor. Combined, this sensor suite would greatly improve characterization of the local meteorological regimes preceding and during precipitation events and allow for improved characterization of the physics controlling snowpack accumulation and ablation (melt). This is also important data for warm season heavy rainfall. Ideally, 10 stations could be deployed in key headwater regions where the dominant fraction of water resources are generated but are presently under-sampled.

Natural resource management is not immune to the phenomena of aging infrastructure in the U.S. The NWS is in dire need of new data collection platforms for weather stations used for forecasts in Colorado, and the Colorado Agricultural Meteorological Network (CoAgMet) has similar modernization needs. To ensure that adequate real-time data are available for decisions and studies, local, state, and federal priorities should include: 1) collaborating on maintaining our current observational network, 2) continuing to enhance our observation network, 3) modeling and data assimilation support for flash flood and water supply forecasts, and 4) implementation of gap filling radars and radar derived products as inputs for models, forecasts, and decisions.

In 2005, the June 1 forecasts were 112,000 acre-feet less than actual. In 2007, the June 1 forecasts were 143,000 acre-feet higher than actual. Irrigation water can be leased in the Rio Grande for up to $135/acre-feet. Thus the potential impact or benefit of forecast errors could be argued to be in the -$15.1M to +$19.3M range to all of the individual water users in a given year. Minimizing forecast errors is important, and investing in our observations and methodologies is merited. Through administration, the DWR seeks to minimize these impacts on a basin wide level. However, these numbers are realistic to individual agricultural water users.

"The benefits of better observations and forecasts are tremendous. In the Rio Grande Basin, our compact operations are based exclusively on streamflow forecasts. Inaccurate streamflow forecasts can cause unnecessary curtailment of ditches, over- or under-delivery of Colorado's compact obligations, and a disruption of the priority system." Craig Cotten, Division Engineer, CDWR, Division 3.

The CWCB thanks partners at NOAA–NSSL and NCAR for sculpting vision statements in this document. The CWCB also thanks all the consultants, local, state, and federal partners that provide the best research, studies, services, and products possible given funding constraints and the limitations of our network.

Photo by Joe Busto

Lightning in Colorado

Robert Glancy, Warning Coordination Meteorologist, National Weather Service, Boulder, Colorado

Why talk about lightning? Thunderstorms produce tornadoes, hail, and flash floods with millions of dollars in damage every year. We have seen graphic pictures of tornado damage in Joplin and Tuscaloosa this spring. There are on average 50 tornadoes a year in Colorado, but there are 500,000 cloud-to-ground lightning strikes. In an average year in Colorado, there are more fatalities (3 per year) and injuries (around 15 per year) from lightning than from each of the other hazards.

Every thunderstorm produces lightning. Lightning is a giant spark that moves within the cloud, between clouds, or between the cloud and the ground. As lightning passes through the air, it heats the air rapidly to a temperature of about 50,000 degrees Fahrenheit. This causes a rapid expansion of the air near the lightning channel. This rapid expansion causes a shock wave that we hear as thunder.

Thunderstorms grow tens of thousands of feet into the atmosphere. In the cloud, precipitation forms as ice crystals, hail, and rain. Collisions between ice particles cause a charge separation, and positively charged ice crystals are carried by the updraft high into the thunderstorm. The heavier hail gathers a negative charge and falls toward the lower part of the storm. The top of the cloud becomes positively charged, and the lower part of the storm becomes negatively charged.

Normally, the earth's surface has a slight negative charge. As the negative charges build up in the lower part of the storm, the ground near the thunderstorm becomes positively charged. As the cloud moves, these induced positive charges on the ground follow the cloud like a shadow. Farther away from the cloud base, but under the positively charged anvil, a stronger negative charge may be induced.

Air normally acts as an insulator. However, when the electrical potential between the positive and negative charges becomes too great, there is a discharge of electricity that we know as lightning.

Cloud-to-ground lightning can either be a negatively charged flash or a positively charged flash. The negative flash usually occurs between the negative charges in the lower part of the storm and the positive charges on the ground under and near the cloud base. Positive flashes usually occur between the positively-charged upper levels of the storm and the negatively-charged area on the ground surrounding the storm.

In the negative cloud-to-ground flash, an invisible negatively-charged step leader forms near the cloud base and surges downward toward the ground. As this step leader approaches the ground, streamers of positive charge move upward from trees, buildings, and other objects on the ground. When these streamers meet the step leader, the connection is completed, and the result is lightning. The entire process takes place in fractions of a second. If you are under a thunderstorm and your hair rises, or you see

A storm in Arapahoe County, Colorado in June 2008, 30 second exposure.
Courtesy of Roger Hill

sparks coming from the metal frame of your backpack, you are in an area where the positive charges are raising up objects toward the storm. These are warning signs from Mother Nature that lighting may be about to strike.

The process for a positive flash is similar except that a positive channel usually originates in the anvil of the storm and surges downward. In this case, streamers of negative charge shoot up to meet the positively-charged channel as it approaches the ground. When a connection is made, a positive flash of lightning occurs.

While both negative and positive flashes of lightning can be deadly, the positive flashes generally are more destructive and are more apt to catch people by surprise. Positive flashes are infrequent and may strike the ground miles from the main part of the storm. The positive flashes may involve the exchange of a much greater charge and are usually more destructive. Positive flashes also strike well beyond the area where rain is falling and away from the bulk of the lightning. Consequently, many victims of positive lightning strikes are caught completely off guard.

The best advice in order to minimize your risk of becoming a lightning victim is to be proactive rather than reactive. Proactively address the threat and quickly get to a safe shelter sooner and to stay there longer. In general lightning experts say, "When thunder roars – go indoors." Stay in shelter for 30 minutes after the end of the storm.

If you are a parent, participant, coach, or league administrator of a youth sports team, your league should have a lightning safety plan. Keeping your schedule is not worth putting your players at risk. Every coach and team should have a consistent approach to lightning safety. Put an adult in charge of monitoring conditions with the authority to postpone or cancel the game due to lightning.

Most lightning injuries occur outside. The best lightning shelters are inside a building, or inside a metal roofed vehicle. There is no protection in golf carts, on motorcycles, or on bicycles. Stay in the shelter for 30 minutes after the end of the storm. While in shelter, minimize phone conversations on corded phones, and stay away from computers and other electrical equipment.

Thunderstorms in Colorado are more frequent over the higher terrain, with fewer storms in the valleys. We see the same pattern in the lightning frequency maps. (See Figure 2.)

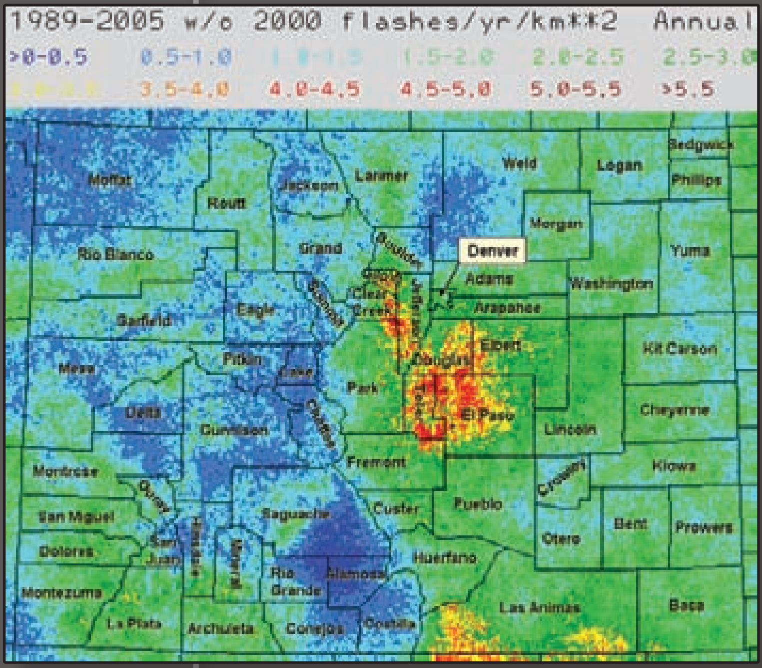


Figure 2. *Lightning frequency map for Colorado. Red and yellow indicate highest frequency, blue lowest frequency.*

From Hodanish and Wolyn, Lightning Climatology for the State of Colorado, AMS

For more information on lightning in Colorado, visit the Colorado Lightning Resource page on the National Weather Service, Pueblo website: http://www.crh.noaa.gov/pub/?n=ltg.php

For additional information about lightning or lightning safety, visit NOAA's Lightning Safety Awareness web site at: http://www.lightningsafety.noaa.gov

The Importance of Decision Support Systems and Climate Change Impacts

Brian M. Ashe, Business Development Manager, Donna M. Murphy, Proposal Manager, and Michael D. Kane, Director of Operations, Riverside Technology, inc.

Climate change is one of the greatest environmental challenges we face in the 21st century global community. Governments and private industry have an increasing need for solutions that will minimize or take advantage of the impacts associated with a changing climate. A growing global population combined with the impending effects of a changing climate places increased demands on water resources, particularly in arid and semi-arid regions. Companies and state, local, and federal agencies are developing solutions to help organizations adapt day-to-day operations to address changing temperatures and precipitation patterns. One of these solutions is the decision support system (DSS), a software tool used to improve the process of decision making in complex situations involving incomplete or uncertain information.

A Brief History of Decision Support Systems

DSS became highly popular in the 1970s and 1980s, but their development and implementation date back to the mid-1960s, a time when researchers extensively studied how using computerized, analytical models could help managers make key business planning decisions.

In the 1970s, the popularity of DSS grew because of the increased availability of interactive, computer-based methods employing databases, models, and user interfaces to provide and manage vast amounts of information to assist the decision-making process.

The appeal of the DSS concept gained intensity during the early 1980s as desktop computing power increased. This progress led to DSS applications beyond those for business management. DSS were developed to assist all forms of management models, including the observation and management of environmental resources.

In the early 1990s, major technological advances contributed to shifting DSS from desktop installations to more client/server-based technology such as On-Line Analytical Processing (OLAP). DSS applications and capabilities are ever evolving as technology continues to shift. The Internet and Web-based applications are speeding up

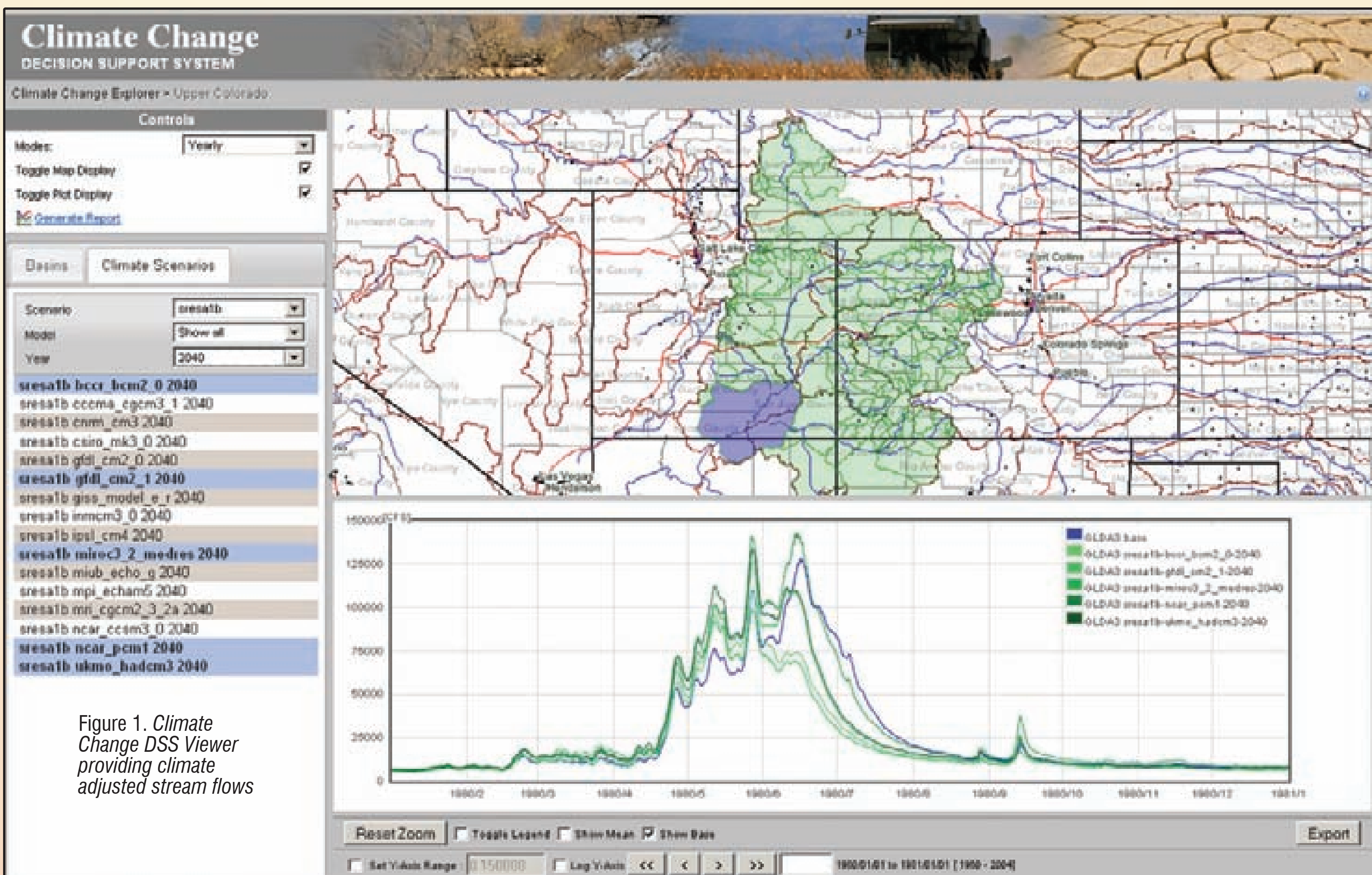


Figure 1. *Climate Change DSS Viewer providing climate adjusted stream flows*

the development of decision support and are providing new media for capturing and recording development activities in this relatively young industry. The inclusion of geographic information systems (GIS) as primary DSS components has led to improvements in use, analysis, and display of the overabundance of spatial data sets that are prevalent in most environmental disciplines.

Decision Support Systems in Management of Environmental Resources

Successful management of environmental resources requires increasingly advanced strategies to make decisions. These decisions depend upon reliable data, extracted and processed from our dynamic environment. The use of information to make considered and correct decisions forms a critical competency for the 21st century global economy, especially with the ongoing development of next-generation communication technology. Consequently, DSS experts and companies with strong DSS expertise are assuming progressively more important roles in managing environmental resources.

Traditionally, DSS software was designed for and used by managers who needed to make high-level business decisions. Today, DSS applications can be developed, tailored for, and implemented across a broader spectrum of business and industry. For example, Riverside Technology, inc. (Riverside), an expert designer of DSS applications, has developed a climate change DSS to help water managers understand and exploit anticipated climate changes.

Riverside has been developing, managing, and implementing decision support systems since 1993; it is an area of the company's expertise and one of its core competencies. From the state of Colorado to China's Ministry of Water Resources to the Eastern Nile Technical Regional Office to the Panama Canal, Riverside has been developing and implementing DSS applications for national and international private industry and government agencies. The focus of these systems has ranged from looking at the feasibility of a national flood control system to improving the operations and management of local reservoirs to designing a water-resources planning model for the Nile River Basin.

Riverside's DSS are typically data focused, meaning that components responsible for the collection, storage, manipulation, and display of data are of primary importance. The flow of data through a DSS—from field observations of raw data to dissemination of information in user-appropriate formats—forms the core of the DSS and is shared in common among Riverside's wide variety of DSS projects.

The Role of Decision Support Systems in Climate Change Analysis

Decision makers and stakeholders in the water-resources community are faced with the challenge of understanding climate change variability and assessing how to minimize the risks from its effects. To manage global resources and reduce societal vulnerability, water managers and planners can benefit from strategically developed DSS that can provide insight into the impacts of climate change on water resources.

The need for environmental decision support systems is increasing because of the growing requirement to effectively manage large amounts of environmental information and natural resources interactions. As environmental data become more readily available, businesses and government agencies are looking for reliable, computer-based modeling systems that can manage, analyze, and model this data in a way that helps water managers and planners with intelligent analysis and strategic decision making.

A Decision Support System Solution Addressing Climate Change Impacts

Water managers are faced with planning to meet future demands on water supplies under a very uncertain climate future. The uncertainty is caused by our inability to predict future greenhouse gas emissions as well as the inability of current global circulation models (GCMs) to adequately simulate climate at the temporal and spatial scales needed for water-management decisions. Climate change impact studies can be expensive and difficult to justify, especially in today's strained economic environment. Water managers need cost-effective tools to help them explore the range of current GCM climate projections, assess the uncertainties of the climate projections, and determine the impacts of these projections on future water supplies.

Riverside Technology, inc. has developed a Web-based decision support application that provides water managers and planners the opportunity to assess the impact of climate change on water resources. This application uses current Web-based technology and available global circulation and hydrologic models to create a simple, yet complete assessment tool for water managers. The **Climate Change Decision Support System** (http://www.climatechangedss.com) employs downscaled GCM data as input to small-scale watershed models to produce time series of climate-projected water supplies for various emission scenarios and GCM simulations.

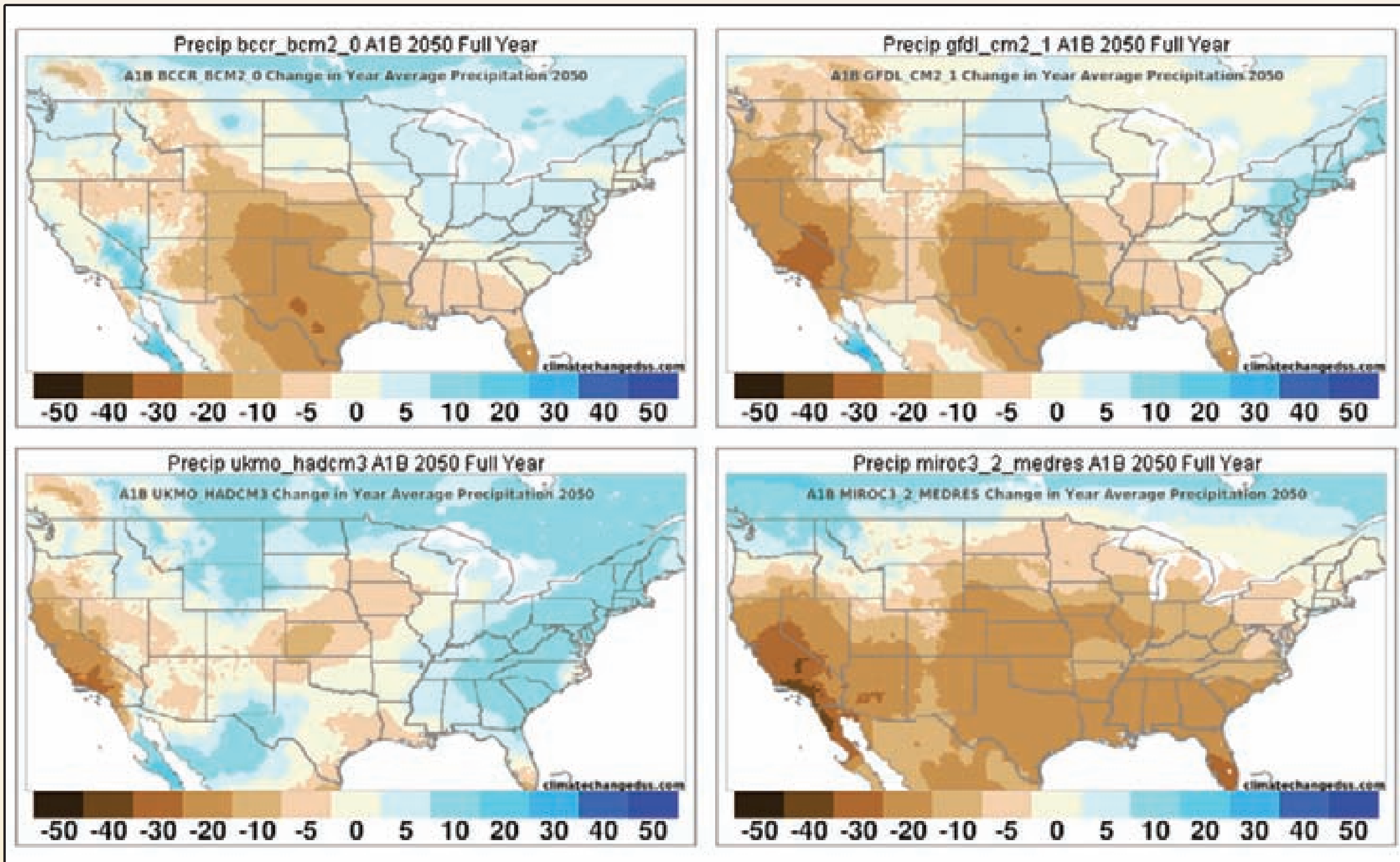


Figure 2. *Climate Change DSS display illustrating four GCM results of changing precipitation patterns over the US*

The system provides summary products that enable users to compare the climate-adjusted streamflow to the historical baseline undepleted flow (e.g., 1950–1999).

Initial system implementation focused on the needs of the state of Colorado's Front Range water-supply agencies, helping them assess vulnerability of the local water supply to climate change. The Climate Change DSS has now been implemented for the Colorado, South Platte, Apalachicola and Sacramento River basins. Other river basins are planned, including expansion to the mid-Atlantic region.

To manage global resources and reduce societal vulnerability, water managers and planners can benefit from using effectively developed climate change decision support tools. The future of water management will be driven by climate change, forcing water resource managers to adopt new strategies in the coming decades. Riverside developed the Climate Change DSS with the goal of helping users understand and assess anticipated climate variability.

Conclusions

As decision support becomes more integrated in business processes, it is clear that DSS design, development, and implementation will become more commonplace.

The research, practice, and science of DSS will continue to evolve alongside the next-generation technological advancements.

Web-based technology will have a significant impact on the application of DSS and will provide even greater capabilities to enhance decision making tools for climate change and other environmental issues.

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Colorado Water 2012

Caitlin Coleman, OSM/VISTA Communications Coordinator, Colorado Foundation for Water Education

Fishing, skiing, rafting, irrigating, drinking, and simply living—the ways in which we use water are countless. Coloradans and visitors alike regularly enjoy recreational opportunities, tree-lined streets, rolling lawns, and local produce, seldom remembering that we've worked hard to adapt to Colorado's arid climate and create this illusion of bounty over the past 150 years.

Now, partners across the state are engaging Coloradans in a year-long celebration of water through an initiative called Colorado Water 2012.

"We want 2012 to be fun—a series of activities, events, and contests in every part of the state that makes people think about the value of water," said Wendy Newman, Colorado Water 2012 project consultant.

In addition to raising awareness about water as a valuable and limited resource, Water 2012 aims to increase support for managing and protecting Colorado's water and waterways. Ideally, Water 2012 partners will see this increased support as more people attend their events, as they receive more donations and inquiries, and as they attract more volunteers.

Colorado Water 2012 also hopes to showcase models of cooperation and collaboration among Colorado water users. This will strengthen the bond between water organizations and their constituents, connect Coloradans to existing and new opportunities to learn about water, and motivate Coloradans to become proactive participants in Colorado's water future. The hope is that new people will seek information about water throughout 2012 and will take steps to continue learning and using that knowledge, Newman said.

"Water is a vital aspect of our local and state economies, ecosystems, and our quality of life," Newman said. "Let's celebrate that and get people involved in learning and planning for the future of water in Colorado."

Colorado Water 2012 volunteers accept a $10,000 grant from the Xcel Energy Foundation to assist with the production of library and museum exhibits. June 1, 2011.

Erika Arment, a student volunteer from the Art Institute, works on designing a suite of marketing materials for Colorado Water 2012

Months before the January kick-off of Water 2012, partners are busy planning activities and working together to coordinate their efforts. Newman leads a group of more than 200 partners in a meeting on the first Wednesday of each month to review their progress in planning the celebration. From Denver in June to the Rio Grande Basin in July, with other basins soon to come, monthly meeting locations rotate throughout the state, ensuring that all reaches of Colorado hear about 2012 and have the opportunity to get involved in the celebration.

These partners represent state and local governments, basin roundtables, water providers, non-profit leaders, artists, students, educators, and other citizens. The basin roundtables and the Interbasin Compact Committee are using Colorado Water 2012 as a platform within their local river basins to communicate what they're doing to plan for Colorado's water future.

Partners are grouped into committees and are designing displays, building a website, creating a calendar of events, seeking and applying for funding, and planning the local festivals, contests, and activities that will become the core of Colorado Water 2012. Events will educate Colorado's residents about our water history, create awareness about current and emerging water issues, highlight careers in water, connect people to volunteer opportunities, and grow Colorado's culture of stewardship.

"There's a lot going on now to prepare for 2012—it's incredible to see so many people involved in and doing a great job developing this initiative," said Nicole Seltzer, executive director of the Colorado Foundation for Water Education and chair of Colorado Water 2012.

To date, a group of student volunteers from the Art Institute in Denver has created an entire suite of branded marketing materials, including a website template, letterhead, museum exhibit design, and more. It will be possible to produce their exhibits thanks to Colorado Water 2012 partners Liz Gardener and Christel Webb, who wrote and received a $10,000 grant from the Xcel Energy Foundation. In addition to this grant, Colorado Water 2012 has been funded by a $30,515 contribution from the Colorado Water Conservation Board (CWCB) from the Water Supply Reserve Account, while local partners have contributed a tremendous $27,000.

"It's truly a grassroots effort but partners are working together and really making this happen," Seltzer said.

Initially, 2012 was a simple milestone for Colorado water—the 100 year anniversary of the Rio Grande Reservoir and the 75th anniversary of the General Assembly's 1937 legislation that created the Colorado River Water Conservation District, the Northern Colorado Water Conservancy District and the CWCB. It's also the 50th anniversary of the Southeastern Water Conservancy District and the 10 year anniversary of the Colorado Foundation for Water Education.

The Colorado Foundation for Water Education saw these anniversaries as an opportunity to reach people throughout the state and began thinking of fun ways to celebrate the organizations that have shaped the management of Colorado's water resources—this idea led the foundation to spearhead Colorado Water 2012.

"We started out small but have been gaining a lot of momentum. As each new person joins Colorado Water 2012, they bring new ideas and additional capacity to reach more Coloradans," Seltzer said. "Although we have more than 200 partners now, there's still a lot that people can do to help—we want to reach as many people as possible in every part of the state."

All are invited to partner with Colorado Water 2012. For more information, to be added to the email list, to make a financial contribution, or to schedule a meeting in your area, contact Wendy Newman, Colorado Water 2012 project consultant at wnewman@cfwe.org or 720-289-6015 and visit www.water2012.org.

Photo by Kyle Thompson

Irrigation Water Management Update

Denis Reich, Water Resource Specialist, Colorado Water Institute

So far, 2011 has been an eventful year for water, including record snowpack, West Slope flooding, eastern plains drought, and a new agreement between east and West Slope water managers. When water grabs the headlines, it feels like vindication for the many hours of less glamorous but by no means less important water work put in by hydrologists, engineers, and educators throughout the state. Newspapers don't usually get a lot of copy from aquatic weed studies, groundwater well monitoring, or irrigation scheduling, yet the many unrecognized hours of hard graft on these oft overlooked topics provide the foundation for milestone improvements in statewide water resource management.

In terms of scale, work across the state with irrigation, particularly within agriculture, still has the potential to provide the largest bang for the buck. Today, agriculture still owns the rights to use the bulk of Colorado's water on the lion's share of private land. Whether or not we fully appreciate agriculture, it still remains a large piece of the state's water personality in 2011.

Integral to agriculture's continued relevance is optimal irrigation water management, or IWM. IWM is defined by the Natural Resources Conservation Service (NRCS) as "the process of determining and controlling the volume, frequency, and application rate of irrigation water in a planned, efficient manner." Such a broad definition leaves plenty of room for how the "process" of "planned" efficiency should occur. Thanks to many years of IWM application and experimentation, it is clear that the process has two key determinants: the system being employed to irrigate, and how water is scheduled and applied.

Improving the system or the efficiency of a system being used for irrigation increases the precision with which water can be applied to a crop. This has a number of advantages, including the ability to maintain optimum soil moisture more consistently, which enhances yields, and significant reductions in runoff and groundwater percolation, which have historically contributed to water quality problems such as salinity and selenium. Improvements can also be expensive, which is why pivot, side-roll, drip, and micro-spray systems tend to be more prevalent in areas of the state where water is also expensive and/or crops are of higher value, such as the South Platte and Rio Grande basins. The NRCS also offers financial assistance through programs like the Environmental Quality Incentive Program (EQIP) to help agricultural producers cover the costs of installing new, more efficient programs. Cost share can be as high as 75 percent for beginning farmers and ranchers or producers in salt affected watersheds.

Denis Reich (right) of CWI talks irrigation scheduling with Uncompahgre Valley producers.
Courtesy of Denis Reich

Where producers have justified the expense and invested in an upgrade to a high efficiency system—and there are many that have—they invariably come to appreciate the reduced labor and improved control of water delivery. But when moving to a system that manages irrigations more precisely, the need for equally precise scheduling information becomes essential to avoid overwatering early in a season and under-watering as temperatures climb. The NRCS is also beginning to require producers to track water use and record their irrigation scheduling as a component of contracted system improvements.

The Benefits of Scheduling

Irrigation scheduling is the more affordable piece of the IWM puzzle. Scheduling can also have more influence on crop performance than the system itself, but it is usually the first to be overlooked since it is largely invisible. It's only over time that the symptoms of a mismanaged system become clearly apparent producers scramble to cover the costs of a poor harvest. Applying the correct amount of water at the appropriate rate with a suitable frequency is critical to fulfilling the potential of any irrigation system. Each of these factors is determined by the depth and thirstiness of a crop's root system in combination with the soil type, irrigation system, and daily weather. Optimum soil moisture is the key to a well irrigated operation, and estimating soil moisture and the optimum point at which to irrigate is what all good irrigators are concerned with.

Producers employ various techniques for tracking soil moisture and triggering irrigations, with soil moisture sensor equipment, ball probes, moisture by feel, and weather stations being some of the more common techniques. A balanced approach using both weather stations and some form of soil moisture assessment is a proven formula to account for microclimates and soil variability. An astute irrigator treats his soil like a checking account for moisture, carefully filling it to capacity where possible without drowning the root system, and refilling before soil gets "overdrawn," which can lead to crop stress and hurt yields.

CoAgMet Expansion

The Colorado Climate Center at Colorado State University (CSU) led by State Climatologist Dr. Nolan Doesken is the current custodian of the CoAgMet (Colorado Agricultural Meteorological) network. CoAgMet is the statewide network of 64 active weather stations specifically designed for monitoring localized weather conditions in agricultural regions of the state. CoAgMet had its humble beginnings in the early 1990s as a partnership between CSU Extension's Plant Pathologists and the USDA's Agricultural Research Services Water Management Unit. The first group of eight stations monitored crop water use and disease pressure via landlines and modems. As water efficiency became a larger player in producer's bottom lines the demand for reliable weather station data grew. Individual producers, ditch companies, and conservancy districts began sponsoring stations to bring more local weather information to their area.

Wendy Ryan and Noah Newman of the Colorado Climate Center install a CoAgMet Weather Station.

Courtesy of Denis Reich

In recent years, CoAgMet has gone online with a website at www.CoAgMet.com that is updated daily to provide crop, turf, and reference evapo-transpiration amounts. New algorithms allow for green-up after hay cuttings, and the 1996 Kimberley-Penman Equation (which includes a more accurate wind coefficient) is available along with the standardized ASCE standard Penman-Monteith reference equation. By the end of the 2011 growing season, the hourly ASCE Penman-Monteith equation will also become available, which accounts for hourly fluctuations on top of the standard diurnal maximum and minimum.

Despite the shoestring budget that CoAgMet operates on, it not only provides a valuable service to all irrigators, but allows the Climate Center to track trends in various regions of the state that may be helpful to producers looking to fine-tune their seasonal planting, spraying, or harvest schedule. As Doesken and CSU wrestle with the obvious budget problems, support from irrigators has become more critical to sustain this important meteorological tool. Doesken recently received some greatly appreciated support from the Upper Arkansas Water Conservancy District to install and maintain three new stations in Chaffee, Fremont, and Custer counties. Funding also became available to install a station at the Carpenter Ranch in Hayden as part of the high altitude crop coefficient work. The Climate Center continues to partner on with The Nature Conservancy and the Yampa/White/Green Roundtable.

In addition to these efforts, the Colorado Water Institute's Water Resource Extension Specialists Perry Cabot of the Southern Region and Denis Reich of the Western Region are both in the process of procuring funds for important upgrades to the CoAgMet network. Proposals have been submitted by Cabot and Reich to the Water Supply Reserve Account (WSRA) program administered by the House Bill 1177 Roundtables and the Colorado Water Conservation Board (CWCB).

In May, Cabot received formal CWCB approval on an Arkansas Basin Roundtable sponsored WSRA grant for $46,971. The grant will fund data delivery improvements rolled out over three years. These improvements will allow producers to receive daily or weekly evapotranspiration updates on their cell phones or smart phones without the need for Web access.

In September, Reich is hopeful of receiving final CWCB approval on a Gunnison Basin Roundtable sponsored WSRA grant for $112,347. The two year project plans to expand the number of stations in the Uncompahgre Valley and provide additional funds to improve the website, all in coordination with a local soil moisture monitoring program. Producers will be able to manage a CoAgMet "account" for their operation that would employ the smart phone improvements provided by the Arkansas grant.

Producers in the Arkansas, Gunnison, and all basins throughout the state are looking not only at system improvements, but also crop mixes that best capitalize on system improvements. Whether the shift is to melons, sweet corn, onions, or vegetables, as the next generation of irrigator seizes the agricultural reigns in Colorado, their demand for easy access to reliable weather data and scheduling information will only increase. Efforts by Doesken, Cabot, Reich, and many others at CSU are part of a combined effort with Colorado Agriculture to ensure that CoAgMet remains functional and helpful as this happens.

Weather Information Where You Would Not Expect It

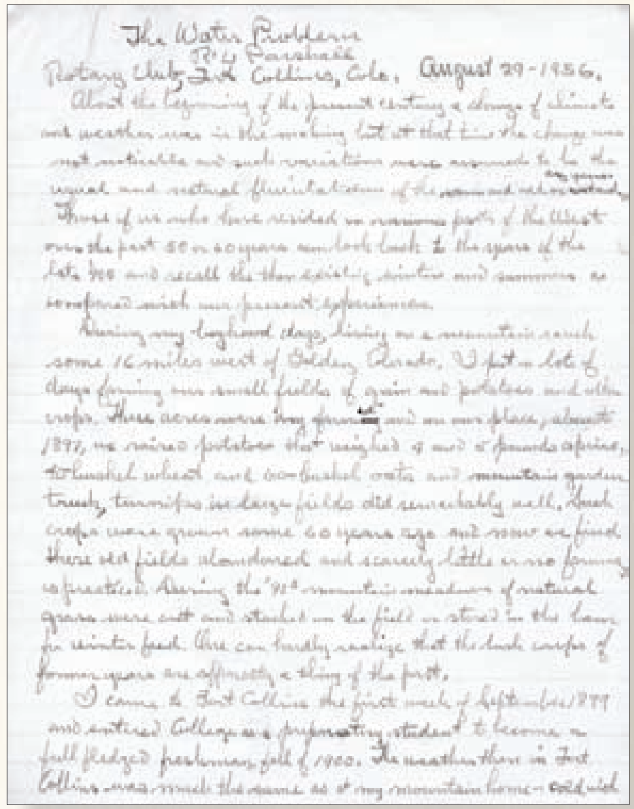
Patricia J. Rettig, Head Archivist, Water Resources Archive, Colorado State University Libraries

> "Our weather is changing and unfortunately in the wrong direction. Only during the past few years have we become conscious that something is going wrong and each year, especially just at present, we are becoming more alarmed about the water supply. In view of what is known at present we can conclude that mean temperatures are increasing and precipitation is decreasing. ... There is evidence at this time that this change has been going on for a considerable time where the world weather is causing a rise in ocean temperatures..."

This sounds like it could have been written yesterday. The modern phrases "climate change" and "global warming" are not used, but the ideas are along the same lines. However, three sentences omitted in the middle of the paragraph refer more specifically to the speaker's present year and look ahead to the next one: 1957.

This paragraph comes from a handwritten speech entitled "The Water Problem," delivered to the Rotary Club in Fort Collins on August 29, 1956. At the time, Colorado was in the midst of a drought that was in its sixth year, so the audience was understandably concerned about the state's water supply. In addition to changing weather, the speaker also addressed the effects of over-pumping of groundwater and population growth on the state's water resources. He concluded, "At the moment there does not appear to be a solution to this problem." Unbeknownst to him, 1957 would be one of Colorado's wettest years ever, but the multitude of problems affecting the state's water supply would continue for decades.

The speaker was someone who had spent more than fifty years studying a variety of water issues in Colorado. Indeed, he was the man who solved one of the most significant irrigation engineering problems by improving the Venturi flume to measure water flow rates. In the early 1920s, Ralph Parshall perfected the flume now named for him. If Parshall is known at all now, it is for this work and nothing else. But Parshall spent following decades studying


The Water Problem
R. L. Parshall
Rotary Club, Fort Collins, Colo. August 29-1956.
About the beginning of the present century a change of climate and weather was in the making but at that time the change was not noticeable and such variations were assumed to be the usual and natural fluctuations of the [illegible].
Those of us who have resided in various parts of the West over the past 50 or 60 years can look back to the years of the late '90s and recall the then existing winters and summers as compared with our present experience.
During my boyhood days, living on a mountain ranch some 16 miles west of Golden, Colorado, I put in a lot of days farming our small fields of grain and potatoes and other crops. These acres were dry farmed and on our place, about 1897, we raised potatoes that weighed 4 and 5 pounds apiece, 40 bushel wheat and 60 bushel oats and mountain garden truck, turnips in large fields did remarkably well. Such crops were grown some 60 years ago and now we find these old fields abandoned and scarcely little or no farming is practiced. During the '90s mountain meadows of natural grass were cut and stacked in the field or stored in the barn for winter feed. One can hardly realize that the lush crops of former years are apparently a thing of the past.
I came to Fort Collins the first week of September 1899 and entered College as a preparatory student to become a full fledged freshman fall of 1900. The weather then in Fort Collins was much the same as at my mountain home — cold and

Page 1 of Ralph Parshall's speech, "The Water Problem." From the Parshall Collection.

Courtesy of the Water Resources Archive

other irrigation, snowpack, and groundwater issues. During his life, he was prominent in Colorado's water community and locally in Fort Collins, where he directed the USDA's Division of Irrigation for thirty years following over a decade of employment at his alma mater, Colorado Agricultural College (now Colorado State University).

Eighty years and four weeks before Parshall made his speech in Fort Collins, Colorado became a state. That day, August 1, 1876, the weather near Greeley "was cool most of the day. It rained a little this P.M. Not enough to stop work." This was noted by a farmer, someone who spent many of his days working in the fields, clearly concerned about the daily weather. Lucky for us, he summarized most of each those days in a diary entry of a few sentences, never failing to note the weather. Though gaps exist in the volumes left behind, the diaries span over fifty years of the life of this man who worked the land and observed the weather on his Greeley farm. The diaries are a treasure of historical documentation, as they pre-date the state's weather observation system. Though not detailed with temperatures and precipitation amounts, the diaries capture the presence of sun, rain, snow, and cloudiness.

A sampling of more than 50 years of Leroy Carpenter's diaries. From the Carpenter Papers.
Courtesy of the Water Resources Archive

These personal diaries are not a source one would think of for discovering historical weather information. In fact, they likely survived at all only because of their connection to the farmer's son, Delph Carpenter. Delph grew up on that Greeley farm and went on to become the "father of interstate river compacts." His father, Leroy Carpenter, moved to the Union Colony of Greeley in 1871, participating in establishing the colony and the ditches that would make it flourish. His influence on Delph cannot be measured, but Delph clearly treasured his father's diaries, saving them throughout his lifetime and passing them, along with other family and professional papers, on to his own son.

No one has yet mined the Parshall or Carpenter collections, or other, less likely Water Resources Archive collections, for weather or climate data. Yet these and others provide unique information and perspectives that can inform modern research questions.

Certainly, the most obvious source and cornerstone collection for climate-related information in the Water Resources Archive is the Climate Data Collection. This is a 62-box accumulation of Colorado climate data recorded by observers from 1893 to 2005, primarily from the National Weather Service's (NWS) Cooperative Observer Program (COOP) and the Mountain States Weather Service. Straight numerical data is crucial to tracking historical trends and deviations, but data does not give much perspective or context from those who are directly affected by day-to-day weather. Mining the Climate Data Collection along with other historical collections can give a fuller picture of the past climate.

More information about these collections and others is available on the Water Resources Archive website (http://lib.colostate.edu/archives/water/). To find the full text of Parshall's "The Water Problem" speech, recently digitized and posted online, enter the title in the search box on the home page or go to http://hdl.handle.net/10217/40928.

Leroy Carpenter in 1863, early in his long life of farming and observing weather. From the Carpenter Papers.
Courtesy of the Water Resources Archive

2011—What a year! Can we blame it on El Niño?

Nolan Doesken and Wendy Ryan, Colorado Climate Center

When it comes to climate in Colorado, every year is different. Yes, we have the same annual cycle—winter, summer, and back to winter—but every year plays out a little differently. This is true for all elements of our climate, but especially for precipitation and water supply. 2011 is an outstanding example and has provided no end of head scratching and fascination for the weather and water watchers of our state.

After a very dry autumn (2010) in Colorado, the winter storm track finally established. Every few days almost all winter, storms moved inland from the Pacific and dropped snow across the mountains of Utah, Colorado, and Wyoming. Very few storms tracked south, and few storms spilled any moisture into eastern Colorado. Frequent and heavy snows steadily piled up all winter in the northern and central mountains, while almost no snow fell from the lower foothills eastward to Kansas and Nebraska. In December, the storms were accompanied by unseasonably warm air –we had one of the warmest Decembers in western Colorado history. The storms continued in February, but this time they were accompanied by some very cold weather. An impressive cold wave in February dropped temperatures in the mountains down to minus 35 and as cold as minus 50 F and stayed that way for 2-3 days. For many areas, it hadn't been that cold for at least 20 years.

When the time came for the mountain snows to begin melting, as they usually do in late April and May, the contrary happened. Cool, cloudy weather persisted over northern Colorado. The already deep mountain snows got even deeper, not reaching their maximum until mid- to late May (Figure 1). Ski areas stayed open, and a few even reopened for the 4th of July. Then came concern over widespread river flooding. What would happen with so much snow on the ground so close to summer? Fortunately, there were no prolonged heat waves in early to mid-June. Rivers ran very high for several consecutive weeks, going out of their banks in some areas. But with almost no additional precipitation in June in the high country, the snowmelt progressed steadily and with surprisingly little flood fanfare, unlike in our neighboring states to the north and east.

While the mountains were buried with snow, drought and wildfire became commonplace east of the mountains and in southern Colorado. By late March and early April, there were already catastrophic early wild fires along the Front Range. The potential for a terrible fire season seemed certain. Just in time, a series of spring storms soaked the forests and grasslands from the Front Range urban corridor to the northeastern plains of Colorado. The fire threat ended, at least for a time, and wheat and forage made a remarkable recovery.

Unfortunately, these same storms bypassed southern and southeastern Colorado. While not as large or catastrophic as the fires in New Mexico or Arizona, Colorado wildfires still burned furiously into June. Prospects for any sort of agricultural crops without the help of irrigation dwindled, and cattle ranchers wrestled with hard decisions about selling cattle to save feeding costs and help protect

Figure 1. *Digging out flumes, which measure flow rate, in southern Wyoming (Glacier Lakes Ecosystem Experiments Site) at the end of April.*

rangeland. Moving through summer, severe to exceptional drought (as categorized by the U.S. Drought Monitor, see page 14) still gripped southern Colorado, while many northern Colorado rivers remained high for weeks. On more than one occasion this spring and early summer, we've been called to participate in both flood planning and drought preparedness meetings—on the same day. Nationally, the picture is similar, only more extreme. Severe drought has been widespread across the South from Arizona to Florida with intense early summer heat. Meanwhile, the northern states and Pacific Northwest have been chilly and wet—really, really wet in some areas.

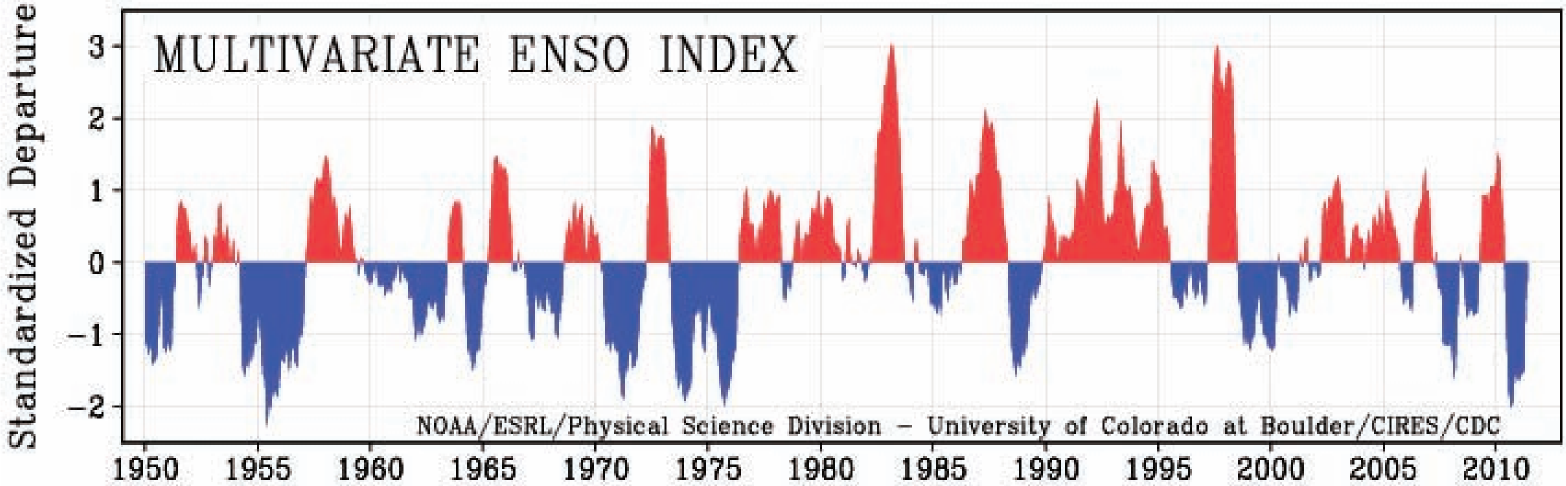
What is responsible for this? Is there a direct cause? Is there something we can blame this weather on? In nature, cause and effect relationships are never clear cut. Multiple influences interact. But that being said, it turns out that just over a year ago, there was a strong El Niño—warmer than average sea surface temperatures in the Pacific Ocean from the coast of South America into the central Pacific, with associated anomalies in wind patterns as well. There is a tendency to associate El Niño with wet weather in Colorado, but it's not always that simple. In fact, history has shown that El Niño winters may be snowy along the Front Range and over the southern Rockies, but north of I-70, all bets are off and many winters are dry. That was the case in the Upper Colorado River Basin upstream from Grand Junction for the winter of 2009-10. Big snows fell east of the mountains. Fort Collins had its second snowiest winter season that year in 123 years of observation.

Then, as is common and normal with weather patterns, things changed. In the spring of 2010, there was a dramatic change in the tropical Pacific, and in a matter of just a few months, the El Niño pattern came to an abrupt end and was replaced by very cool sea surface temperatures and associated wind patterns—what we call "La Niña." La Niña strengthened and became one of the strongest on record in recent decades (Figure 2).

La Niña in our region is often associated with drought conditions, especially when cool tropical sea surface temperatures persist for more than a year. Also associated with La Niña is a northerly jet stream that tends to track storms across the northern Rockies and keep the southern Rockies and Gulf Coast states dry. Hmmm—this sounds a lot like what's happened in 2011. Yes, there were some exceptions. Some of the storms did dip into southern California, Nevada, and southern Utah before lifting northward, and some winter blasts of Arctic cold dipped all the way into southern Florida—more than once. But minus these few exceptions, La Niña weather patterns followed the script, and even exaggerated it a bit. For Colorado, that pattern ended up delivering month after month of heavy snows to the northern mountains, adequate snows in the central mountains, and skimpy snows farther south and east—places like Pikes Peak and the Sangre de Cristo mountains were nearly snow free for most of the winter and spring. For those who pay attention to the Colorado River and the water levels in Lake Powell, this has been a year of rejoicing. The decade-long decline of Colorado River water has been, at least for the time being, arrested, and reservoir levels have been recovering as both the Upper Colorado and the Green River deliver abundantly this year.

What comes next? La Niña (cool sea surface temperatures in the eastern and central tropical Pacific) have weakened already, and we are now what is called "ENSO (El Niño Southern Oscillation) neutral." Moving into midsummer 2011, tropical moisture has found its way north to Colorado. Summer thunderstorms have been rumbling across much of the state, providing at least some temporary relief from nearly a year of drought conditions in southeast Colorado. But this may be temporary. Strong La Niñas are often followed by persisting dryness across southern and eastern Colorado that might even spread farther north this coming winter. We don't know for sure, but one thing we do know—we're very grateful for one more year of reservoir-filling generous water supplies from the Gunnison River and the Upper Arkansas northward to the Yampa and the Poudre. It won't always be like that.

Figure 2. *An MEI (multivariate ENSO index) represents El Niño (red) and La Niña (blue) events over time.*



Nutrient Workshop Results in Recommendations for EPA and State Water Quality Agencies

Colorado Water Institute

James Bauder, Land Resources and Environmental Science, Montana State University
MaryLou Smith, Policy and Collaboration Specialist, Colorado Water Institute

Nutrients. The word sounds so healthy, but those who work with water quality know that "nutrients" can mean trouble. Nutrients can degrade important water resources and create health and environmental risks.

As part of its responsibility under the Clean Water Act, the U.S. Environmental Protection Agency (EPA) has directed states to develop numeric standards for how much phosphorus and nitrogen can be present in water after it has been treated, as well as in streams and lakes.

Jennifer Meintz moderates the largest breakout group session, AFO/CAFO (animal/confined animal feeding operations), as they identify barriers to nutrient controls and make recommendations for the EPA.

Water quality numeric standards from EPA are not new. Standards are already in place for water contaminants such as NH_4 (ammonium), pathogens, ammonia, and selenium. But the coming imposition of nutrient standards has stirred considerable controversy. For one thing, much of the nutrients problem stems from introduction of nutrients into water from diffuse, or nonpoint sources (NPS), such as stormwater and agriculture, which are exempted by the Clean Water Act. But point sources, easily identifiable and traceable, are impacted by NPS, over which they have little, if any, control. Also, nutrients can naturally occur at higher levels than the proposed standards for streams and lakes.

The April/May issue of *Colorado Water* reported that 200 stakeholders and agency representatives gathered in Salt Lake City in February 2011 to delve into the issue in EPA Region 8: Colorado, Utah, Montana, Wyoming, and North and South Dakota. The report from the workshop was recently released and can be downloaded at http://www.cwi.colostate.edu/nutrients

Workshop organizers, including Colorado Water Institute, worked with EPA Region 8 to convene the regulators and regulated and see if together, the two groups might create solutions.

Because the science is complex, we need policy and management that can adapt and evolve as we know more. With emphasis on what's practical, workshop participants were challenged to consider a full range of societal values and weigh benefits against costs while seeking to apply limited resources where they could gain the most improvement. The workshop was divided into three sections to address three distinct questions.

Question 1: What is the Problem?

University professors and researchers from the USDA and EPA shared perspectives. They discussed that data are not always consistent, and impairment we see today may reflect activities long past. The interplay of nitrogen and phosphorus together in lakes may create more harm than phosphorus alone. Findings of a major USGS study of nutrients in streams and groundwater between 1992 and 2004 showed that though there are natural sources of nitrogen and phosphorus in water, the highest concentrations are found in areas of highest input. Nutrients create complexities that span many different fields.

Responders shared experiences and observations from stakeholder and agency points of view. Hearing how Wisconsin gained support to develop numeric standards by engaging stakeholders garnered significant interest. A watershed group activist from Montana relayed her group's problems convincing water quality degradation contributors such as golf courses and

Alan Johnstone participates in a dialogue/response session during the What is the Problem? Portion of the workshop.

horse operations to take action because they fell back on arguments that interfering or masking biological factors in the stream confounded the data.

Questions 2: What is Being Done About the Problem?

Participants heard from each of the six Region 8 state departments of water quality.

Colorado

According to Steve Gunderson from Colorado Department of Public Health and Environment (CDPHE), Colorado has had nutrient controls on several major reservoirs since the 1980s and has been developing state-wide numeric nutrient criteria for lakes, reservoirs, and flowing waters for more than ten years. Recently, the state's water quality control division proposed to EPA an alternative nutrients standard approach they believe will achieve water quality improvements better and faster while reducing transaction costs. A group of dischargers who formed a coalition to promote its interests supports the proposal, according to a coalition representative at the workshop.

Montana

Mike Suplee from Montana said his state already has nutrient standards in the Clark Fork, an EPA-designated superfund site, but they apply only to the Clark Fork during summer flow conditions. Now the state DEQ believes it can implement nutrient standards for many of Montana's wadeable streams and the Lower Yellowstone River. Montana wants to develop nutrient criteria and standards that are science based while giving full consideration to the need for flexibility, ecological diversity, and an evolving approach.

Utah

Walt Baker from the Utah Division of Water Quality says his state's attention has been centered around the total maximum daily loads (TMDL) process, with the most useful metric for urban control appearing to be measures of total phosphorus. The state is proud of its model effort in working with animal/concentrated animal feeding operations (AFO/CAFO) to manage nutrients sourced from livestock. The state commits $1 million annually to bolster 319 funding directed toward dealing with nonpoint source (NPS) issues. Cost effectiveness compared to ecological benefits appears to be a prime topic of discussion in Utah.

North Dakota, South Dakota, and Wyoming

In contrast to Colorado, Montana, and Utah, the other three Region 8 states appear to be taking a slower, wait and see approach to nutrients. These states are predominantly agricultural with low populations, so they are dealing primarily with agricultural NPS issues and some impacts related to the rapidly growing oil, gas, coal, and mineral extraction industries in North Dakota and Wyoming. The Wyoming DEQ, according to John Wagner, participates in an extensive on-going water quality monitoring and data collection effort, however, providing a solid base for future standards development. Patrick Snyder from the South Dakota Department of Environment and Natural Resources said they rely primarily on narrative standards for nutrients, though they have developed a water quality assessment tool called Trophic State Index to rate lakes, ponds, and reservoirs based on the amount of biological productivity in the water. North Dakota's Mike Ell reported that his state seeks active engagement of stakeholders before standards are seriously investigated, though they are incorporating nutrient criteria into their ongoing monitoring and database development as they address other water resource issues.

Innovative Tools and Case Studies

Both the regulators and the regulated introduced a smorgasbord of innovative tools being used to deal with nutrients in water, as well as some uplifting success stories. The use of precision agriculture to match fertilizer applied to fertilized needed and urban "Don't P on Your Lawn" campaigns to eliminate phosphorus as a lawn fertilizer were strategies suggested to minimize the amount of nutrients imported into watersheds. A consulting engineer recommended striking a balance between nutrient removal and other sustainability goals—he described a study about the relative benefit vs. cost of aggressive nutrient treatment, which in some cases may require high energy input and introduce fuel based chemicals and polymers that can cause other undesired consequences. A public works director discussed hydrologic mirroring of predevelopment conditions in post development site construction as a strategy for keeping sediment out of stormwater in the first place. Nutrient credit trading was introduced as a strategy for meeting aggressive nutrient reduction goals when certain conditions apply, like an availability of nutrient reduction alternatives.

A North Dakota State speaker plainly stated that finding solutions for nonpoint source pollution is a lot more about people than it is about the hard sciences. "By involving producers, we can identify which water quality improvement practices give us the most bang for the buck," he said. But working with farmers means meeting with them out on their farms in the mud and the rain listening to what they have to say.

Success Stories

In Colorado's Bear Creek Watershed, between trading, a coordinated erosion stormwater control program, and treatment plant upgrades, phosphorus discharge load was reduced from 5,255 pounds per year to 1,334. They advised that producing convincing data is not always easy, but without data, progress and conviction come slowly.

In eastern South Dakota, establishing regional groundwater protection areas with groundwater protection ordinances led to significantly reduced nitrate concentrations—from 10 milligrams per liter in 1994 to one to two milligrams per liter by 2010.

Troy Bauder participates in the NPS breakout group session, which ultimately narrowed down a list of recommendations to give to the EPA about regulating nutrients in that sector.

In Park City, Utah, an $18 million advanced tertiary treatment facility solved the problem of nutrient-rich wastewater being discharged into a small trout stream often dewatered downstream by pre-existing irrigation water rights. The frustrating downside of that success story, which could have been avoided by a watershed-scale planning approach, is that now the community has an acute ammonia toxicity issue downstream because of reduced in-stream flows.

A favorite success story was about a partnership of agencies and stakeholders in Utah who worked together to reduce livestock degradation of water quality through voluntary, locally-driven actions. Agencies gained the trust of stakeholders to cooperate in inventorying AFO operations, developing and implementing nutrient management and mitigation plans, providing cost assistance for corrective actions, and tracking progress. As of July 2010, 98% of the operations needing to correct unacceptable conditions have developed and implemented nutrient management plans.

Question 3: How can Stakeholders and Agencies Work Together Better to Resolve the Problem?

Representatives from key stakeholder groups relayed their experiences trying to collaborate with agencies. A Colorado Nutrient Coalition representative suggested that stakeholders and agencies cooperate to articulate a reasonable vision for dealing with nutrients, and that vision may need a legal structure. Two agricultural producers stressed that we need to factor in the value of our food supply when we make decisions about nutrient standards, because nutrients are necessary for growing food.

Summary of Workshop Recommendations

While there was a consensus among workshop participants that there is a nutrient problem in the region, there were expressions of concern and strong suggestions about how nutrient controls and standards should be developed and implemented to increase likelihood that they will truly lead to cost-effective water quality improvements.

Flexibility in Approach to Improve Water Quality

"One size will not fit all" was commonly voiced. Workshop participants believe real solutions will come from site-specific, sector-specific approaches, championed by those directly aware of local circumstances, allowing flexibility as more is learned. Specifically:

- We need to think and work smarter, to focus resources on issues and circumstances which will achieve the most benefit per unit of resources and effort expended, to learn lessons from others wherever possible.
- Adaptive management should be considered integral to any TMDL, nutrient controls and standards. We need to be allowed variances in dealing with nutrient sources and loads where appropriate.
- Regulatory agencies need to recognize and accept that 100% achievement many not either be possible or necessary with respect to controls and standards. For example, controls applied to a smaller percentage of sources may result in higher overall water quality results.

Building Relationships to Improve Water Quality

Much of the dialogue among workshop participants revolved around the need for building trust between stakeholders and regulators. Specifically:

- Communication, relationships and trust should be established as foundational, involving all stakeholders. This would bring a new, improved image to the EPA and state agencies, and the cooperation it fosters at the local level would lead to water quality improvements.
- Regulators and regulated should work together to do away with the current us-versus-them attitude. Regulated groups should be connected to the process.
- Individuals from agencies interacting with stakeholders relative to nutrients should become more knowledgeable about day-to-day operations of stakeholders. Regulatory agencies and policymakers need to gain a better understanding and appreciation for stakeholders' situations, perspectives, and financial means.
- Continuity in agency staff is needed to foster productive relationships to solve water quality problems.
- Education, information exchanges and continued dialog on nutrients are needed to provide continuity in the engagement of the public, stakeholders, and regulated entities.

Financing Improvements in Water Quality

Since current fiscal realities are not expected to turn around overnight, creative approaches will be needed. Specifically:

- We should investigate nutrient trading across sectors in order to achieve water quality goals.
- Means of financing the costs of nutrient controls and minimizing the economic burden to stakeholders need to be built into any nutrient control program. Our society creates and externalizes our nutrient problems and will benefit from nutrient controls, thus society needs to bear the costs of control.
- The relationship between benefits and costs needs to be understood and communicated to stakeholders, ratepayers, and dischargers, along with discussion of who is going to bear the cost of controls.

Nutrient Controls and Standards to Improve Water Quality

Workshop participants from across all sectors were consistent in their assertion that nutrient controls and standards will benefit from enhanced local engagement.

- Nutrient controls and standards should be based on local level input and management constraints, with participation and involvement of local stakeholders through the entire process.
- On the other hand, uniform sampling and data collection protocols should be established for each sector involved in the nutrient control/nutrient management issue. Data sharing should be improved among all entities.
- Nutrient controls and standards should be based on sound science that elucidates relationships between nutrient loading, water quality impairments, and effectiveness of best management practices.
- Water quality improvement or protection through nutrient controls and standards should be marketed where appropriate, rather than mandated or regulated. To this end, education needs to be used as a complementary tool for achieving nutrient controls and standards. Education is needed for the general public, policymakers, stakeholders, and managers.

Finally, workshop participants unanimously recommended the need for the Region, States, and stakeholders to continue and sustain dialog leading to creative and collaborative solutions to nutrient problems.

Workshop Sponsors

2011 Annual Universities Council on Water Resources Conference Held in Boulder, Colorado, July 12-14

Lindsey A. Knebel, Editor, Colorado Water Institute

Members from the Universities Council on Water Resources (UCOWR) and the National Institutes for Water Resources (NIWR) met in July for the annual UCOWR conference in Boulder, Colorado.

The 2011 conference committee included members from the Colorado Water Institute (CWI), New Mexico State University, Utah State University, Texas AgriLife Research, University of Arizona, and UCOWR. The conference focused on "Planning for Tomorrow's Water: Snowpack, Aquifers, and Reservoirs."

Keynote sessions at the conference were Water in the West, Water and Society, and International Water. Some of the other technical sessions included Snowpack and Snowmelt, Crop Water Use and Management, Climate and Water, Water Governance, and Remote Sensing, among others.

Several keynote speakers gave presentations on timely water issues. During the Water in the West Session, Tom Iseman of Western Governors' Association, and Roger S. Pulwarty, director of the National Integrated Drought Information System at the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, presented on what's being done in the West.

Keynote speakers for the Water and Society session were Colorado Supreme Court Justice Greg Hobbs and Steve Solomon, book author and writer for the New York Times and other publications.

For the final keynote session, International Water, speakers were Robert Pietrowsky, Director of the U.S. Army Institute for Water Resources (IWR), and Mike O'Neill, National Program Leader for Water Resources with the USDA National Institute of Food and Agriculture. Pietrowsky discussed the necessity of developing international water infrastructure, education, and institutional capacity, and O'Neill talked about international water issues and solutions to global problems.

Warren Hall medalists Chuck Howe, Neil Grigg, 2011 medalist Jery Stedinger, and medalist Robert Ward at the UCOWR banquet.

Photo by Jessica L. May

Highlights of the conference included a tour of the Boulder Creek Watershed (pre-conference), a poster session, and an awards banquet.

The 2011 Warren A. Hall Medal went to Jery Stedinger of Cornell University for his outstanding career contributions in hydrologic science. "He really brings energy, enthusiasm, engagement, dedication, and commitment to whatever task he undertakes," said the award presenter. Other awards included Friends of UCOWR recognitions, Education and Public Service awards, and notable dissertation awards.

UCOWR is an organization of over 90 member universities and organizations from both the U.S. and abroad that focuses on water resources education, research, and public service. The annual conference explores timely water topics. UCOWR also publishes the *Journal of Contemporary Water Research & Education*, which can be accessed on their website at www.ucowr.org.

During the conference, Boulder Creek was experiencing unusually high flow rates.

Photo by Jessica L. May

Kimberly Catton

Lindsey A. Knebel, Editor, Colorado Water Institute

Kimberly Catton, Department of Civil and Environmental Engineering, conducts research in the fields of freshwater and marine ecology, fluid mechanics, and environmental engineering.

Catton began her studies in Northern California, at the University of California at Davis, with a Bachelor of Science in Biological and Agricultural Engineering and a Master of Science in Environmental Engineering. After working with Carollo Engineers as an engineering consultant and earning a Civil Engineering P.E. (professional engineer) license, Catton pursued her doctorate work at the Georgia Institute of Technology, where she studied environmental fluid mechanics and marine ecology in an NSF IGERT (Integrative Graduate Education and Research Traineeship) program. She researched zooplankton behavior and formation of aggregations in response to fluid cues in Tasmania and Hawaii. Catton continues to research the interactions between ecological systems and hydraulic systems at CSU.

Like other professors at the university, Catton balances her work at CSU between teaching classes, mentoring students, and conducting research. Her goals include growing a research program at CSU that focuses on problems in water quality specific to Colorado reservoirs and rivers. "Colorado's rivers and reservoirs are affected by a variety of natural and anthropogenic stressors which can degrade the water quality," says Catton.

Currently, Catton is involved in a project to predict the ecological processes in Colorado reservoirs based on the complex interactions between their physical (e.g., stratification regimes, turbulence), chemical (e.g., nutrient levels), and biological variables. She explains that her earlier research on zooplankton and phytoplankton found that different aquatic organisms are successful under different environmental factors, such as temperature, water chemistry of their surroundings – that type of research could be applied to many Colorado water bodies to predict the effects of climate change, changing nutrient levels, water quality, and other related factors. She is currently looking at improving water quality with ecological engineering methods, specifically, improving water clarity, algal toxin levels, and taste and odor production.

In addition to her research projects, Catton teaches Hydraulic Engineering and the graduate-level Hydrometry course. In the future, Catton says she'd like to teach lower division engineering courses to teach students applied engineering at an early stage in their education. When working with upper division and graduate students, she provides opportunities for independent projects within her courses that are motivated by the students' interests. "I encourage students to pursue graduate degrees to gain more specific education in their area of interest," she says.

"A lot of big questions still haven't been answered," Catton says about her chosen field of ecological interactions in water systems. "The problems are complex and region-specific." Catton says finding those solutions will involve interdisciplinary research. "That's my background, and what I have been trained to do," she says. "I'm comfortable with multidisciplinary, complex problems." Catton hopes to collaborate on future research projects to understand and explain the complexities of Colorado's water systems.

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Recent Publications

The National Map; 2011; FS; 2011-3042; Sugarbaker, Larry J.; Carswell, William J., Jr. http://pubs.usgs.gov/of/2011/1092/

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Water Research Awards

Colorado State University (May 16 to July 15, 2011)

Abt, Steven R, Civil & Environmental Engineering - USDA-USFS-Rocky Mtn. Rsrch Station - CO, Bedload Transport in Gravel-Bed Rivers and Channel Change, $85,667

Arabi, Mazdak, Civil & Environmental Engineering - DOI-USGS-Geological Survey, Environmental Impacts of Ag-to Urban Water Rights In the South Basin, $5,000

Bauder, Troy A, Soil & Crop Sciences - Colorado Department of Agriculture, Training and Education for Agricultural Chemicals and Groundwater Protection, $169,968

Bauder, Troy A, Soil & Crop Sciences - Colorado Department of Agriculture, Training and Education for Agricultural Chemicals and Groundwater Protection, $15,032

Bauerle, William L, Horticulture & Landscape Arch - Regenesis Management Group, Measurement and modeling physiological processes to determine optimal seasonal cycle metrics for deficit irrigation, $19,734

Bestgen, Kevin R, Fish, Wildlife & Conservation Biology - DOI-Bureau of Reclamation, Evaluating Effects of Non-Native Predator Fish Removal on Native Fishes in the Yampa River, $85,976

Bestgen, Kevin R, Fish, Wildlife & Conservation Biology - DOI-Bureau of Reclamation, Population Estimate of Humpback Chub in Black Rock, $5,000

Bestgen, Kevin R, Fish, Wildlife & Conservation Biology - DOI-Bureau of Reclamation, Floodplain Inundation & Entrainment Studies, $9,920

Bestgen, Kevin R, Fish, Wildlife & Conservation Biology - DOI-Bureau of Reclamation, Yampa & Middle Green CPM & RBS Larval Survey, $94,219

Binkley, Daniel E, Natural Resource Ecology Lab - USDA-USFS-Rocky Mtn. Rsrch Station - CO, Impacts of Mountain Pine Beetle & Spruce Beetle on Forest Carbon & Water Balance, $34,770

Bledsoe, Brian, Civil & Environmental Engineering - City of Fort Collins, Stream Geomorphic Assessments and Prioritization of Stream Restoration Projects, $64,409

Bledsoe, Brian, Civil & Environmental Engineering - Colorado Water Conservation Board, Investigation of the Effects of Whitewater Parks on Aquatic Resources in Colorado, $25,000

Fausch, Kurt D, Fish, Wildlife & Conservation Biology - Wyoming Game & Fish Department, Climate Change Tool for Cutthroat, $33,237

Hansen, Neil, Soil & Crop Sciences - Parker Water & Sanitation District, Lower South Platte Irrigation Research and Demonstration Project, $280,166

Hansen, Neil, Soil & Crop Sciences - DOI-Bureau of Reclamation, Demonstrating Limited Irrigation Technology as an Approach to Sustain Irrigated Agriculture While Meeting Increasing Urban Water Demand in Colorado, $78,385

Jacobi, William R, Bioagric Sciences & Pest Mgmt - DOI-USGS-Geological Survey, Impacts of Mountain Pine Beetle Infestations on Forested Ecosystems Along the Colorado Front Range, $5,000

Jha, Ajay K, Agric & Resource Economics - USDA-Foreign Agricultural Service, Trilateral Initiative: Afghanistan-Pakistan-US Facilitating Relationship-Building Activities in Watershed Rehabilitation and Irrigation Technologies, $438,680

Johnson, Brett Michael, Fish, Wildlife & Conservation Biology - DOI-Bureau of Reclamation, Chemically Fingerprinting Nonnative Fishes in Reservoirs, $65,082

MacDonald, Lee H, Natural Resource Ecology Lab - USDA-USFS-Rocky Mtn. Rsrch Station - CO, Evaluating & Predicting Postfire Logging Effects on Erosion, $23,199

Myrick, Christopher A, Fish, Wildlife & Conservation Biology - University of Washington, Cost-Effective, Alternative Protein Diets for Rainbow Trout that Support Optimal Growth, Health, and Product Quality: Growth Trials at CSU, $37,227

Myrick, Christopher A, Cooperative Fish & Wildlife Research - Colorado Division of Wildlife, Evaluation & Development of Fish Passage Designs, $25,000

Prenni, Anthony J, Atmospheric Science - NSF - National Science Foundation, ETBC: Collaborative Research: Exploring Forest Ecosystem Response to Water Availability and the Impact on Biogeochemical and Water Cycles, $96,967

Pritchett, James G, Agric & Resource Economics - USDA-ARS-Agricultural Research Service, Drought and Risk Assessment of Forage Crops, $63,625

Ramirez, Jorge A, Civil & Environmental Engineering - NSF - National Science Foundation, WATER-IGERT: Integrated Water Atmosphere and Ecosystem Education and Research, $598,055

Roesner, Larry A, Civil & Environmental Engineering - Water Environment Research Foundation, Task Order 2C: Linking Stormwater BMP Systems Performance to Receiving Water Protection to Improve BMP Selection and Design, $131,929

Sale, Thomas C, Civil & Environmental Engineering - DOI-USGS-Geological Survey, Aquifer Storage ad recovery Optimization, $5,000

Schneekloth, Joel, CSU Extension, Monsanto, Response of Drought Genetics to Water Stress, $68,372

Stednick, John D, Forest Rangeland Watershed Stwrd - Colorado Division of Wildlife, Monitoring Impacts of Irrigation Recharge Projects on Main Stem South Platte Native Fish Populations, $85,651

Thornton, Christopher I, Civil & Environmental Engineering - DOD-ARMY-Corps of Engineers, Full Scale Wave Overtopping Testing, $113,479

Wohl, Ellen E, Geosciences - DOI-USGS-Geological Survey, Variables Controlling Reservoir Sedimentation in the Colorado Front Range, $5,000

Zupanski, Milija, CIRA - DOC-NOAA-Natl Oceanic & Atmospheric Admn, Utility of GOES-R Instruments for Hurricane Data Assimilation and Forecasting, $149,555

Calendar

August

23-25 **Colorado Water Congress Summer Conference and Membership Meeting; Steamboat Springs, CO**
Water professionals go to stay well-informed on the most important issues, current legislation, and latest developments that impact water users in Colorado and other western states.
www.cowatercongress.org

25 **Water 2012: Vail, CO**
CFWE has amassed over 125 volunteers across Colorado who are ready to celebrate water in 2012. Committees are working on K-12 activities, university collaboration, library displays, web-based tools, watershed groups and a speakers bureau. There are many opportunities to get involved, including leading events in your community. Recently, a new Water 2012 Coordinator was hired to help move the effort forward.
www.cfwe.org/2012

September

15 **Colorado River District's Annual Water Seminar; Grand Junction, CO**
"Seeking Balance Under Imbalanced Conditions:
www.crwcd.org/page_305

October

4-6 **2011 Sustaining Colorado Watersheds Conference; Avon, CO**
This annual conference, hosted by Colorado Watershed Assembly, the Colorado Foundation for Water Education and the Colorado Riparian Association, expands cooperation enhancement by informing participants about new issues and innovative projects and through invaluable networking.
www.coloradowater.org/Conferences

14 **Third Annual Colorado WaterWise Conservation Workshop; Denver, CO**
See featured speakers Hunder Lovins of National Capitalism Soulutions and Jonathan Waterman of National Geographic.
www.coloradowaterwise.org

19-20 **22nd Annual South Platte Forum; Longmont, CO**
"Making River Music"
www.southplatteforum.org

31 **Upper Colorado River Basin Watershed Forum; Grand Junction, CO**
The forum will provide an opportunity for water experts focused on Upper Colorado River Basin water issues to share information about current water-related projects, research, and educational efforts and to share ideas for future projects.
Email hholm@mesastate.edu for more information.

December

1 **Colorado Ag Water Alliance: "Ag Water Summit"; Loveland, CO**
One day meeting to explore agricultural water issues and solutions for keeping water in agriculture
coagwater.colostate.edu/

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A thunderstorm passes over Memorial Park in Colorado Springs, Colorado.
Photo by Jared Hagan