

MOUNTAIN VIEWS

The Newsletter of the Consortium for Integrated
Climate Research in Western Mountains

CIRMOUNT



Informing the Mountain Research Community

Vol. 1, No. 2
August 2007

Mountain Views

The Newsletter of the Consortium for Integrated Climate Research in Western Mountains CIRMOUNT

<http://www.fs.fed.us/psw/cirmount/>
Contact: Henry.F.Diaz@noaa.gov

Table of Contents

The Mountain Views Newsletter	Henry Diaz and Connie Millar on Behalf of CIRMOUNT	1
Western Ground Water and Climate Change—Pivotal to Supply Sustainability or Vulnerable in its Own Right?	Michael Dettinger and Sam Earman	2
The SNOTEL Temperature Dataset	Randall P. Julander, Jan Curtis, and Austin Beard	4
Taking Stock of Patterns and Processes of Plant Invasions into Mountain Systems—Around the World	Catherine G. Parks and Hansjörg Dietz	8
Increasing Tree Death Rates in California's Sierra Nevada Parallel Temperature-Driven Increases In Drought	Phillip J. van Mantgem and Nathan L. Stephenson	9
Vulnerability and Adaptation—New Directions for WMI	David L. Peterson and Christina Lyons-Tinsley	11
Climate Change in Hawai'i's Mountains	Thomas W. Giambelluca and Mark Sung Alapaki Luke	13
The North America Monsoon Experiment (NAME): Warm Season Climate Research in the Mountainous Regions of Southwestern North America	David J. Gotchis	19
Recent CIRMOUNT Activities	Lisa J. Graumlich and Henry F. Diaz	26
The Mountain Research Initiative Introduces the Glowa Jordan River Project: Integrated Research for Sustainable Water Management	Claudia Drexler and Katja Tielbörger	27
Announcements		29

*Cover Photos: Top-San Juan Mountains near Silverton, CO, Bottom-Silverton, CO (Photographer: Connie Millar).
Graphic Designer: Barbara DeLuisi, NOAA/ESRL, Boulder, CO*

- *This page left blank intentionally* -

The Mountain Views Newsletter

Henry F. Diaz¹ and Connie I. Millar²

¹ NOAA Earth System Research Laboratory, Boulder, CO

² USDA Forest Service, PSW Research Station, Albany, CA

Out of the growing recognition that the climate of the West is changing, a group of scientists representing a wide range of disciplines organized themselves into a professional network, the Consortium for Integrated Climate Research in Western Mountains (CIRMOUNT), to promote public awareness of these looming problems and efforts to address them. One recent outgrowth of that effort was the mid-2006 publication of Mapping New Terrain (consult the website to download or order a free copy of the report: http://www.fs.fed.us/psw/cirmount/publications/pdf/new_terrain.pdf).

One tangible outreach effort of CIRMOUNT is the launching of the new Mountain Views Newsletter (MVN) whose goal is to inform our fellow citizens of the latest developments regarding the evolution of western climate, and the evolving natural and societal impacts associated with those changes. The newsletter is meant to be a clearinghouse for information about the state of regional and larger-scale climate patterns, and about climate- and related environmental and ecological-science activities bearing on western society.

The first issue of the Newsletter was “published” electronically in January of 2007. This second issue of MVN highlights a wide range of activities taking place in western mountains in the areas as diverse as potential impacts of climate change on ground water sources in the West, to increasing tree mortality in areas of

the Sierra Nevada, California, to large-scale warm season precipitation experiments in the mountains of the desert Southwest and Northwest Mexico. This issue also highlights some recent work evaluating the nature and impacts of climate change being done in Hawaiian mountains. Other activities covered in this issue of the Newsletter include work being done to improve climate monitoring at the higher elevations of the West (via improvements in the SNOTEL network), efforts to develop a global observing system to monitor and study invasive species in high elevation regions, and a summary of the Mountain Research Initiative effort to establish global change research networks in mountain regions.

This will be the last issue of *Mountain Views* published in 2007. We hope to publish at least two issues in 2008, and we welcome contributions from the readers on subject matters such as has been presented in this and in the previous inaugural issue of the Newsletter. In particular, *Mountain Views* Newsletter is meant to inform our fellow citizens of the latest developments regarding the evolution of western climate, and the evolving natural and societal impacts associated with those changes. The newsletter is meant to be a clearinghouse for information about the state of regional and larger-scale climate patterns, and about climate- and related environmental and ecological-science activities bearing on western society.



Western Ground Water and Climate Change—Pivotal to Supply Sustainability or Vulnerable in its Own Right?

Michael Dettinger¹ and Sam Earman²

¹US Geological Survey, Scripps Institution of Oceanography, La Jolla, CA

²Desert Research Institute, Reno, NV

The recent NGWA policy statement on ground water and global climate change (<http://www.ngwa.org/ngwainwashington/climatechange.cfm>) outlines several current and potential impacts of climate change on water supplies and concludes that ground water will be pivotal to sustainable water supplies because of its capacity to balance large swings in precipitation and demand. The impacts discussed include reductions in snow packs, changes in precipitation, sea level rise, warming surface waters, and changes in water demand. However, in the western United States (US), other important challenges also face ground water science and management communities because climate change may impact ground-water supplies directly and indirectly, in ways that have, to date, been largely unexplored.

Current climate-change projections are unanimous in predicting warming over the US with most ranging from about +3° to +6°C. Projected precipitation changes are more complicated with some consensus developing towards modestly wetter conditions in the northern tier of states and modestly drier conditions in the southwesternmost states, but with relatively small changes of uncertain sign in the regions between these projections (conclusions by the authors from analyses of projections used in IPCC, 2007). Based on these projections, the impacts of warming—the more confident of the projections—on water supplies, including ground water, are in urgently need assessment. Whether precipitation increases or decreases, warming will likely reduce runoff generation because of attendant increases in the potential for evapotranspiration, as discussed by Chris Milly in this issue. Because of the parallels between such runoff declines and historical droughts, it has been natural to envision ground water as a safeguard against climate change. However, the same tendency for ground water to respond more to slow climate fluctuations than to fast ones (e.g., Changnon 1987; Dickinson et al. 2004) that makes ground water an attractive option during droughts could also mean that ground water will respond more strongly to the comparatively slow trends associated with climate change than we would guess from isolated droughts. The linkages between climate and ground water are inherently complex. In anticipation of unprecedented times ahead, some of those intuitions need to be re-assessed.

There are likely many different ways that warming may influence ground-water supplies. One particular concern in the western US is through warming effects on snowpacks. In the West, because mountains are generally wetter and cooler than adjacent basins, most groundwater is derived from mountain precipitation. Some recharge occurs in place in mountain recharge areas, sustaining important surface-water baseflows and cooler water temperatures. Recharge also occurs by infiltration where runoff crosses from mountain blocks onto abutting fans and alluvium, or onto basin floors. A growing tide of studies is showing that snowmelt provides more mountain recharge than does rain in western settings (Earman et al., 2006). This is probably because large and intense infiltrations of water are required to break through the region's thick unsaturated zones. Additionally, snowpacks store and then release precipitation from several storms at once. Studies in the Great Basin indicate that 50 to 90% of the recharge there originates from snowmelt (Winograd et al., 1998). Recharge-temperature analyses based on dissolved gases show that recharge in the central part of the Chiricahua Mountains, AZ, is derived only from altitudes above seasonal snowlines and not from lower altitudes (Earman and Phillips, 2003). Geochemical hydrograph separations in the highest basins of the Rockies demonstrate that, even during the peak snowmelt, 60% or more of the streamflow is supplied by ground water (Liu et al., 2004). On the other hand, recharge from streamflow infiltration through fans and basin floors depends on large, rapid, but generally infrequent, outflows of runoff from the mountains onto surrounding fans and basins. The mix of mountain versus fan and basin recharge presumably varies from basin to basin, and from year to year, but these variations are poorly understood in most of the West.

As the West has warmed in recent decades (Cayan et al., 2001), precipitation has occurred more frequently as rain rather than snow (Knowles et al., 2006) and snowpacks have thinned (Mote, 2003). If warming continues, snowline elevations are expected to rise. If this happens, mountain recharge may also be expected to decline because recharge areas will shrink and the amount of snowmelt available to infiltrate at any one time will dwindle. Using the University of Washington's VIC model (Maurer et al 2002), recent simulations by the authors of near-surface

water budgets in the western mountains, with and without warming, suggest that the partitioning of net precipitation between surficial runoff and subsurface runoff may respond to warming with declines in subsurface runoff of as much as 50%. We conjecture that the significant simulated subsurface runoff declines would, most likely, be reflected also in ground-water recharge declines. On the other hand, another simulated result of warming in the western mountains is relatively more surficial runoff. Declines in mountain recharge triggered by loss of snowpack would have immediate impacts on mountain water resources, including low flows and stream temperatures, and may also have serious impacts on long-term ground-water supplies in surrounding basins through reductions in mountain recharge. Although recharge that supplies mountain ground water may decline, much of this uncharged water may run off onto the region's fans and basins and potentially increase recharge on fans and basin floors. However, if the uncharged water is instead mostly evapotranspired from the mountain soils, the overall recharge (mountain plus basin) may decline. At present, whether the overall recharge will increase, decrease, or stay the same is unknown at any scale in the West. Similarly, the impacts to ground-water supplies due to changed conditions of the location and timing of recharge are also insufficiently understood.

Given ground water's crucial role, especially in the West, the potential impacts of warming on recharge deserve more attention than they have received to date. It is possible that ground-water supplies will fare well, overall, in a warming world, but they may also fare poorly. At present, we rely largely on intuition. The projected climate changes are unprecedented in the modern era, and we lack the tools and data (e.g., long-term continuous monitoring of recharge processes) to confidently detect or predict ground-water responses to climate. In a world with a changing climate, our intuition and groundwater science's traditional focus on long-term average conditions may fail to recognize, predict, and alert us to significant changes in ground-water supplies. Monitoring commitments like the USGS's national-scale Ground-water Climate-Response Network are a start (<http://groundwaterwatch.usgs.gov/>), but that network's focus on ground-water level variations from days to years needs to be extended beyond ground-water level fluctuations to the full range of ground-water issues and processes on multi-decadal time scales. Otherwise, changes may come from unexpected directions to ground-water managers and users.

References

- Cayan, D.R., Kammerdiener, S., Dettinger, M.D., Caprio, J.M., and Peterson, D.H., 2001, Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, 82, 399-415.
- Changnon, S., 1987, Detecting drought conditions in Illinois: Illinois State Water Survey, Circular 169, 36 p.
- Dickinson, J.E., Hanson, R.T., Ferre, T.P.A., and Leake, S.A., 2004, Inferring time-varying recharge from inverse analysis of long-term water levels. *Water Resources Research*, 40, doi:10.1029/2003WR002650, 15 p.
- Earman, S., A. R. Campbell, F.M. Phillips, and B.D. Newman, 2006, Isotopic exchange between snow and atmospheric water vapor: estimation of the snowmelt component of groundwater recharge in the southwestern United States. *Journal of Geophysical Research*, 111 (D9), <http://dx.doi.org/10.1029/2005JD006470>.
- Earman, S., and Phillips, F.M., 2003, Groundwater recharge and movement in the central Chiricahua Mountains, Arizona: Geological Society of American Annual Meeting Abstracts with Program, 201-15.
- Intergovernmental Panel on Climate Change (IPCC), 2007, *Climate Change 2007, The Physical Science Basis-Summary for Policymakers*. IPCC Secretariat, <http://www.ipcc.ch>, 21 p.
- Knowles, N., Dettinger, M., and Cayan, D., 2006, Trends in snowfall versus rainfall for the western United States. *Journal of Climate*, 19(18), 4545-4559.
- Liu, F., Williams, M.W., and Caine, N., 2004, Source waters and flow paths in an alpine catchment, Colorado Front Range, United States. *Water Resour. Res.*, 40, 10.1029/2004WR003076.
- Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen, 2002, A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. *J. Climate*, 15(22), 3237-3251.
- Mote, P.W., 2003, Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters*, 30, DOI 10.1029/2003GL017258.
- Winograd, I.J., Riggs, A.C., and Coplen, T.B., 1998, The relative contributions of summer and cool-season precipitation to groundwater recharge, Spring Mountains, Nevada. *Hydrogeology Journal*, 6, 77-93.

The Snotel Temperature Dataset

Randall P. Julander¹, Jan Curtis², and Austin Beard³

¹NRCS, USDA, 245 North Jimmy Doolittle Rd Salt Lake City, UT 84116

²NRCS, National Water and Climate Center, Portland OR

³NRCS Bozeman, Mt.

Real-time weather data and its archived “climate” dataset must be used with an appreciation of its original purpose and inherent limitations. By knowing a stations history/metadata (e.g., location, equipment, maintenance schedule, sensor changes, etc.), operators and researchers can then expect the highest degree of data quality and use. The SNOTEL system was initially installed in the late 1970’s primarily as a water supply forecasting hydro-climatic data collection network. To that end, sites were located specifically to forecast water supply in the western United States and in most cases, replaced existing manual snow courses that historically had good correlations between snow water-equivalent (SWE) and streamflow.

There were limitations in the amount and type of data that the early system could process and transmit. Thus early on, only the SWE, precipitation and current air temperature data were initially collected. The observation times of these early data occurred without any uniformity. This situation was adequate for SWE and precipitation measurements but gave a much less than desired result for temperature. The data poll for individual sites typically started at midnight, 6:00 am, noon, and 6:00 pm and could last for up to five or more hours. Thus air temperature data would be reported at the time an individual station was contacted and might vary from as early as shortly after midnight to as late as 5:00 am. Polls were conducted four times daily but in that early period, a station might report between zero and four times per day and the time stamp on those data would be dependent on when the station reported. Temperature data were to be used in a relational context to calculate or predict snow melt rates, predict the onset of melt and generally be used in a water supply context. As the data collection, processing, and transmitting electronic components were improved, additional sensors were added to the system.

In the mid 1980’s, with the advent of better electronics, daily minimum, maximum and average temperature data were added as standard data collection to SNOTEL. Unfortunately, temperature sensors were not uniformly installed across the entire network and in fact, a rather poor job was done particularly in the mounting of these sensors. The first temperature sensors were generally Climatronics or Climet thermistors and were in small ~3x3 inch aluminum box shaped shields or in aspirated housings. Most of

these sensors were mounted on or very close to the brown SNOTEL shelters. Others were mounted to the antenna tower. Various mounting configurations were used, mostly dictated by the ease of installation and not to any technical standards. In some cases, they were mounted horizontally across the face of the shelter about six to 12 inches below the shelter roof and about 24 inches from the side and in all cardinal directions. In other cases, an “S” shaped aluminum tube was used to mount the sensor vertically to the side of the shelter which put the thermistor about six inches from the shelter side and up to 12 inches above the roof line. In yet another configuration, the sensor was mounted vertically above the shelter at a distance of between three and six feet. Clearly any mounting configuration that put the sensor near the brown radiating shelter would have a net warming bias on the early dataset. Some of these early sensors were mounted to remote antenna towers then moved to a shelter mount to be moved again to the antenna tower and finally moved to the meteorological tower.

Much of the early data from these sites are compromised by inappropriate mounting, sensor moves, and various changes in



Photo 1

sensors and aspirators. Another more isolated and easily identifiable problem with this mounting scheme is that occasionally, a shelter and its temperature sensor was completely buried in snow or the roof snow load encased the sensor in which case, the air temperature sensor became a snow temperature sensor. Later, some sensors were moved to the antenna towers, which in most

cases is a better location. However, some towers were directly adjacent or attached to the shelter and the temperature data at these sites could be compromised to some degree, other towers, remote from the shelter should have reasonably consistent data.

In Photo 1, the SNOTEL site at Beaver Divide, Utah is shown with a standard YSI thermistor, a three gill aluminum aspirator and the “S” mount attached to the side of the shelter and extending above the roof line. This configuration is perhaps the worst of all mounting scenarios.

Photo 2 shows the Rock Creek SNOTEL site and the impact on snow the brown shelter can have via long wave radiation. Notice the snowpack has melted to a distance of about 2 feet from the edge of the shelter and that the temperature sensor mounted horizontally across the top of the shelter in a northeastern direction is in a direct line above that obvious impact.

In photo 3, (Buck Flat, Utah) there is a standard YSI thermistor mounted on a remote tower. This sensor has subsequently been moved from this location to the meteorological tower some



Photo 2

20 feet distant, but the overall impact of this move would be small. Data from these sites would be the most consistent in relation to current standard location and mounting practices. Temperature sensors gradually migrated to YSI thermistors with a range of aspirators including the most commonly used, a silver three-vent aluminum model. There were tower mounted sensors and aspirators that were white, wind directed models and a variety of other configurations. In the mid 1990's, snow depth was added to many sites as a standard sensor and this began the installation of standardized meteorological data collection towers.

At that time, there was still a mix of temperature sensors mounted on shelters and on antenna towers with a wide variety of aspirators. Since snow accumulation is variable across the West, tower height is also variable with most meteorological towers



Photo 3



Photo 4

being in the 10, 20 and 30 foot ranges, depending on snow depth. Sensor mountings are therefore also variable in height being at about seven, 17 and 27 feet respectively. The majority of all sensors are at the 17-foot height. That stated, during a significant portion of the year, the ground surface level is constantly changing due to the accumulation and ablation of the snowpack and the respective height of any individual sensor may range from 17 feet to as low as five feet or less.

In photo 4, (Cascade Mountain, Utah) the current standard temperature mounting configuration is shown with the sensor at 17 feet, mounted three to six feet from the tower and in a white, six gill aspirator.

In the mid 1990's as the installation of meteorological towers progressed, another sensor change was made from the standard YSI sensor to the extended range YSI sensor in order to capture temperature readings to minus 40 degrees F. The coldest sites were the first to get the extended range sensor. Personnel in the Idaho region had the foresight to run both the standard YSI and the extended range YSI side by side for several years with identical mounting and aspirator configurations and noticed a plus one degree C difference in a very large portion of the observed temperature range of the extended sensor compared to the standard sensor.

Chart 1 displays a comparison of side by side mounted standard and extended range YSI temperature sensors, the results which show a one to two degree C difference between the two sensors, with the current extended range sensor warmer than the standard sensor. This difference is most noted at the lower end of the temperature scale whereas at the upper end, the difference becomes much less. This is consistent at all of the Idaho sites tested. Physical site changes will continue to pose some problems in overall data consistency. Vegetation grows, and at times, dies yielding an ever changing solar view and site characteristics. At some sites, this could be dramatic and at others, not likely to be much of a source of an inhomogeneous dataset. The removal of one or several trees at a site can impact the canopy, solar window and evapotranspiration characteristics which could change the temperature regime over some or all of a daytime pattern including nighttime pattern. The same could be true of growing vegetation altering the periods of full sun or shade at any given site. In photo 5, (Camp Jackson, Utah) one can clearly see the proximity of the vegetation to the tower and the temperature sensor as opposed to the vegetation in photo 4. Vegetation height and proximity is constantly changing at some sites, while at others it tends to be relatively stable.

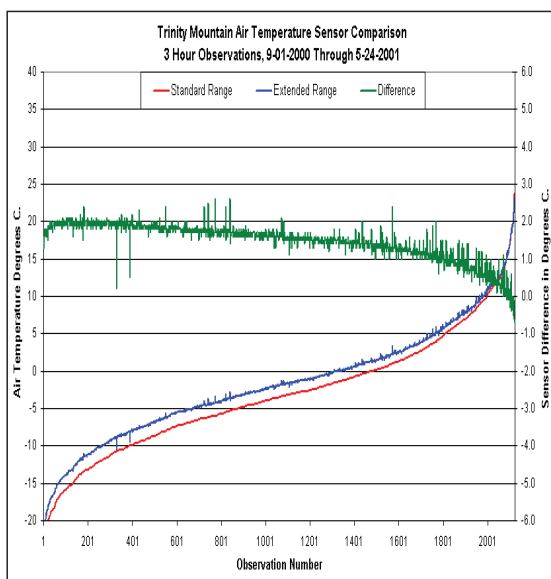


Chart 1

At this site, the dominant species is Aspen (*Populus Tremuloides*) that has the added feature of being deciduous, which changes the overall solar input as leaves are generated in the spring and subsequently lost in the fall. At other sites such as Big Flat, Utah, (photo 6) which is in a mature Spruce and Fir (*Picea* and *Abies*) forest, the vegetation is and has been very stable.

However, should the current beetle and bud worm infestation spread with subsequent high spruce mortality, currently experienced in southern Utah, the vegetation at this site could change dramatically and hence, the solar window.

Another source of potential inconsistency in the dataset is that of data editing and quality control. For the most part and with the exception of Idaho, the SNOTEL temperature dataset has undergone little in the way of systematic data quality control and



Photo 5



Photo 6

verification. The data editing that is done is primarily the removal of howlers and screamers and focused on the daily maximum, minimum and average. Some areas such as Idaho have done more and have concentrated on a serially complete dataset complete with estimated data points but the techniques of data estimation and editing have been far from standardized system wide at this point. The NRCS is attempting to use spatial climate station comparison methodology to resolve suspected data and fill-in missing data by assigning quality control flags that are quantified by confidence probabilities.

An un-quantified source of data error is in the electronics of the system and could be either random, systematic or a combination of both. There have been a series of joint transceiver/receiver/data processors in combination with the series of different temperature sensors. These include the Secode, MCC 550A, MCC 550B and the current version, the MCC 545 coupled to a Campbell CR10X data logger. Each of these systems measure voltages from each sensor which are then equationally converted to meaningful engineering units. Errors may occur due to: error in the thermistor, resistive errors such as line loss, ground potentials, excitation voltages, and errors associated with the data logger reading the voltages. These errors may occur from something as mundane as the type of cable used or in the connections from the cable to an interface. Drift in the voltage reading device could be the source of some un-quantified error.

In summary, the historic temperature data from the SNOTEL network have some significant systematic and random bias. This bias includes poor mounting techniques, sensor changes, location changes, aspirator changes, vegetation changes and electronic errors. Vegetation changes can be in the form of 20 to 30 years of

growth or instantaneous change due to fires, disease, or insects. Documentation of these changes has been inconsistent system wide and currently resides mostly on paper records difficult to access and digitize. Much of the very early record, from mid 1980's to the early 1990's will be difficult to salvage and much of those data are compromised by poor sensor mounting techniques and are suspected to record much warmer temperatures than actually occurred. General use of these early records as comparisons to current conditions is discouraged. Some records, particularly those sensors that were mounted to remote towers early on will have reasonable quality, subject only to observation time, aspirator and sensor changes and possibly some vegetation change. Useful metadata on dates of sensor, aspirator and location changes would facilitate the potential construction of a reasonable, corrected dataset for these specific sensors.

Currently, NRCS is moving to standardized temperature sensor mountings that are on a meteorological tower in a specified data collection area at a height of 7, 17 or 27 feet and a distance of four to six feet horizontally from the tower.

Taking Stock Of Patterns And Processes of Plant Invasions Into Mountain Systems—Around the World

Catherine G. Parks¹ and Hansjörg Dietz²

¹MIREN Co-chair, USFS Pacific Northwest Research Station, La Grande OR
cparks01@fs.fed.us

²MIREN Co-chair, Institute of Integrative Biology ETH, Swiss Federal Institute of Technology, Zurich hansjoerg.dietz@env.ethz.ch

Invasive alien plants increasingly threaten mountain ecosystems. The Mountain Invasion Research Network (MIREN) integrates surveys, monitoring and experimental research on plant invasions into mountains at a global scale. The objectives of MIREN are to understand plant invasions into mountain ecosystems, facilitate communication and exchange of expertise regarding mountain invasions, and to provide information needed by land managers to identify and implement specific management guidelines to address this urgent problem.

Launched in 2005, the MIREN organization of researchers, managers and practitioners has defined a multifaceted approach to meet this research and application challenge. Several important questions are addressed:

- How great is the threat to mountains from alien plants?
- Do plant invasions affect mountain ecosystem services?
- What are the main drivers of invasions into mountains?
- What can invasion biology learn from mountain systems?
- Are mountain invasions indicators of climate change?
- Are there efficient ways of preventing or managing mountain invasions?

MIREN operates at 3 levels, including a limited set of 6 core research regions, an extended set of mountain regions for general survey and case-specific management projects, and general information processing and dissemination that is relevant to all mountain regions. MIREN features 6 core high mountain regions (Pacific Northwest, (USA), Swiss Alps, Chilean Andes, Australean Alps, Hawaii (USA), and the Canary Islands (Spain); Figure 1), covering the major climatic zones and including island and continental systems. All core areas are participating in standardized field surveys and monitoring, and in standardized comparative experiments.

MIREN is associated with the mountain research community including CIRMOUNT, and plans to strengthen cooperation in research initiatives in the future. For more information on MIREN, including downloadable documents and a questionnaire for anyone interested in the problem of plant invasions into mountains, is available at www.miren.ethz.ch. For further questions contact the project coordinator Christoph Kueffer (miren@env.ethz.ch).

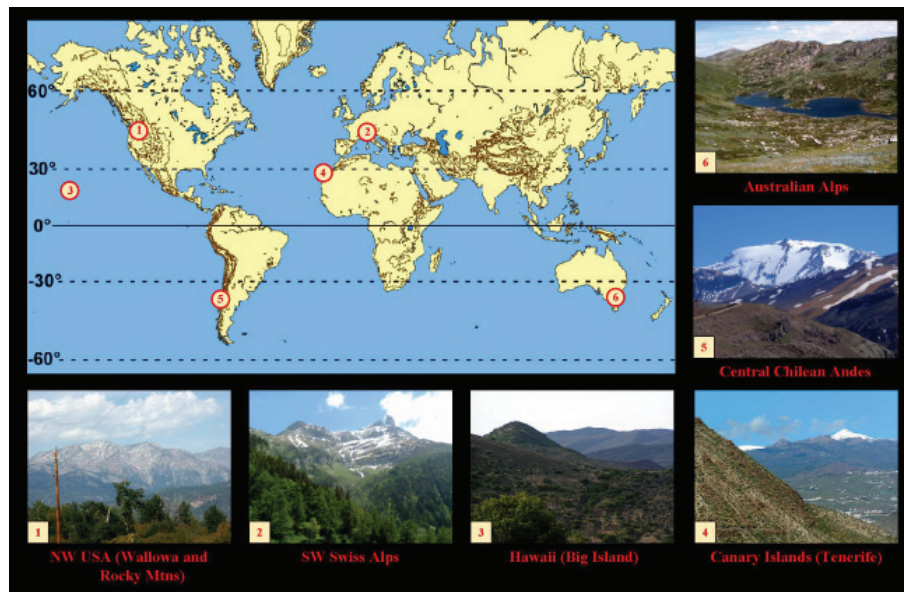


Figure 1. Location of the 6 core high mountain regions with ongoing MIREN activities.

Increasing Tree Death Rates in California's Sierra Nevada Parallel Temperature-Driven Increases in Drought

Phillip J. van Mantgem and Nathan L. Stephenson

USGS Western Ecological Research Center, Sequoia and Kings Canyon Field Station, 47050 Generals Highway #4, Three Rivers, CA 93271, USA

Sudden and widespread forest die-backs in montane forests of western North America have attracted significant attention (Breshears et al. 2005), as predictions of severe drought in this region become more certain (Seager et al. 2007). But the same environmental changes implicated in these die-backs may also be affecting forests that have not experienced catastrophic mortality, which represent the bulk of western forests. The well-established link between water stress and tree mortality (Waring 1987, Ferrell 1996) suggests that forests could respond to increasing drought, even if conditions have not reached thresholds causing catastrophic forest die-back. Non-catastrophic changes are slower and more difficult to detect, although chronically increasing mortality rates have the potential to profoundly change forest communities (Kobe et al. 1995). The pivotal role forests play in the global carbon cycle underscore a need to improve our understanding of environmentally-driven changes in forests.

Only a handful of studies of real forests have examined long-term changes in mortality rates. In old-growth forests of tropical Amazonia, mortality rates have increased over the last few decades, and the increases apparently have been paralleled by increases in forest productivity (Lewis et al. 2004). While the authors suggest that the increasing mortality rates may be driven by enhanced competition resulting from increased resource availability (e.g., atmospheric CO₂ or sunny, cloudless days), the mechanisms remain unknown. To our knowledge, no comparable studies of chronic long-term changes in mortality rates had been conducted in old-growth temperate forests.

We considered demographic trends using annual measurements from 1982 – 2004 in 21 permanent plots arrayed across a climatic gradient in old growth forests of the Sierra Nevada of California, encompassing 26.6 ha and 21 338 individual trees (van Mantgem and Stephenson 2007, Figure 1). We found that while recruitment rates changed little over the last two decades, mortality rates increased. The increase was not only evident for all trees combined, but also for each of two dominant genera of conifers (*Abies* and *Pinus*) and for most elevational zones (forest types).

The increase in mortality rates resulted from increases in deaths assigned to stress and biotic causes (such as insects and

pathogens) (Figure 2), which in turn paralleled a temperature-driven increase in annual climatic water deficit (drought), as determined from the PRISM model (Daly et al. 2002). Other factors, such as changes in air pollution concentrations or internal stand conditions (stand densities and biomass), were not correlated with mortality rates. We concluded that these forests may be experiencing increasing deaths related to temperature-driven evaporative stress, potentially making them more vulnerable to extensive die-back during otherwise normal periods of reduced precipitation (cf. Breshears et al. 2005). Our results highlight a need for better information regarding ongoing, climatically-driven changes in other temperate forests.



Figure 1. Annual measurements of permanent plots enable the correlation of short-term changes in forest demography (ingrowth and mortality rates) to short-term changes in climate. In the Sierra Nevada of California, widespread increases in forest mortality rates are paralleled by increasing summer drought due to warming temperatures. Photo by USGS.

It is possible the history of fire exclusion may indirectly affect climatic responses; fire exclusion has resulted in high stand densities in low to mid elevation forests, which could in turn intensify competition for water, creating stands more sensitive to drought. It is also probable that increased temperatures are affecting tree mortality indirectly by creating conditions favorable to patho-

gens, particularly bark beetles (Hicke et al. 2006). Regardless of the exact pathway to mortality for individual trees, changes in stand mortality rates appear to be precipitated by changes in climate.

These results pose a challenge to management. Forest restoration often attempts to mimic conditions prior to Euro-American settlement in the mid-1800s. However, this period occurred during the Little Ice Age when temperatures were considerably cooler (Millar and Brubaker 2006). If forests respond rapidly to warming temperatures, managing for conditions similar to this target era may not be feasible or desirable.

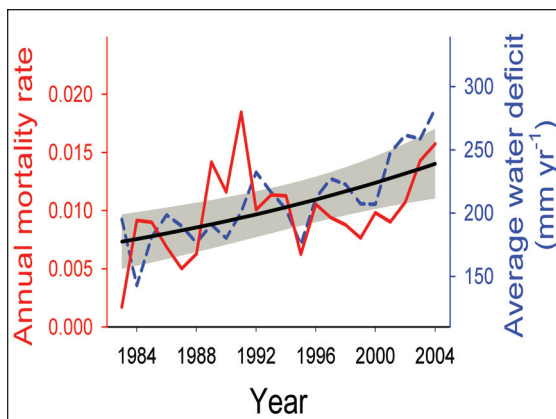


Figure 2. Annual tree mortality rates for stress and biotic causes (86% of all observed mortalities) for 21 permanent forest plots in the Sierra Nevada, California. The red line represents the annual mortality rate averaged among plots, with the black line showing the expected mortality rate (± 2 S.E., shaded area) from a model of the annual trend ($P < 0.001$). A three-year running average of annual climatic water deficits (dashed blue line) predicted changes in the annual mortality rate ($P = 0.0001$).

References

- Breshears, D. D., N. S. Cobb, P. M. Rich, K. P. Price, C. D. Allen, R. G. Balice, W. H. Romme, J. H. Kastens, M. L. Floyd, J. Belnap, J. J. Anderson, O. B. Myers, and C. W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Science of the United States of America* 102:15144-15148.
- Daly, C., W. P. Gibson, G. H. Taylor, G. L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. *Climate Research* 22:99-113.
- Ferrell, G. T. 1996. The influence of insect pests and pathogens on Sierra forests. Pages 1177-1192 in D. C. Erman, editor. *Sierra Nevada Ecosystem Project: Final Report to Congress*. University of California, Centers for Water and Wildland Resources, Davis.
- Hicke, J. A., J. A. Logan, J. Powell, and D. S. Ojima. 2006. Changing temperatures influence suitability of modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the western United States. *Journal of Geophysical Research* 111:G02019, doi:02010.01029/02005JG000101.
- Kobe, R. K., S. W. Pacala, J. A. Silander, and C. D. Canham. 1995. Juvenile tree survivorship as a component of shade tolerance. *Ecological Applications* 5:517-532.
- Lewis, S. L., O. L. Phillips, T. R. Baker, J. Lloyd, Y. Malhi, S. Almeida, N. Higuchi, W. F. Laurance, D. A. Neill, J. N. M. Silva, J. Terborgh, A. T. Lezama, R. Vásquez Martínez, S. Brown, J. Chave, C. Kuebler, P. Núñez Vargas, and B. Vinceti. 2004. Concerted changes in tropical forest structure and dynamics: evidence from 50 South American long-term plots. *Philosophical Transactions of the Royal Society of London B Biological Sciences* 359:421-436.
- Millar, C. I., and L. B. Brubaker. 2006. *Climate Change and Paleoecology: New Contexts for Restoration Ecology*. Pages 315-340 in M. Palmer, D. Falk, and J. Zedler, editors. *Restoration Science*. Island Press.
- Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, and N. Naik. 2007. Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. *Science* 316:1181-1184.
- van Mantgem, P. J., and N. L. Stephenson. 2007. Apparent climatically-induced increase of mortality rates in a temperate forest. *Ecology Letters* 10: doi: 10.1111/j.1461-0248.2007.01080.x.
- Waring, R. H. 1987. Characteristics of trees predisposed to die. *Bioscience* 37:569-574.

Vulnerability and Adaptation—New Directions for WMI

David L. Peterson¹ and Christina Lyons-Tinsley²

¹Pacific Northwest Research Station, U.S. Forest Service, Seattle, WA

²College of Forest Resources, University of Washington, Seattle, WA

With 15 years of empirical data and modeling results behind us, scientists in the Western Mountain Initiative (WMI) are now in a synthesis and integration phase in which resource vulnerabilities are being assessed within and among long-term research landscapes. WMI research encompasses the Olympic Mountains, North Cascade Mountains, Northern (U.S.) Rocky Mountains, Central Rocky Mountains, Southern Rocky Mountains, and Sierra Nevada, with focal sites in National Park Service units and surrounding landscapes. This geographic extent provides sufficient variation in latitude, longitude, and elevation to capture much of the biophysical and climatic variation in mountain ecosystems of the western United States.

Assessing Vulnerability

At this point in the research program, a clearer picture of which ecosystem components and which landscapes will be most vulnerable to a warmer climate is starting to emerge. In this case, we define vulnerability as the likelihood that particular processes, functions, and species distributions will exceed critical thresholds in an irreversible or undesirable (from the perspective of management objectives) manner. This could also be stated as the magnitude of disturbance or stress that can be absorbed (resilience) before the system structure is redefined. Time series of data on climate, snowpack, hydrology, and forest demography; paleo-ecological studies of vegetation and fire; and extensive studies of tree growth-climate relationships across environmental gradients provide the empirical basis for these inferences. Statistical and process modeling allow these inferences to be scaled up to large landscapes.

Whereas resource managers typically manage large administrative units with multiple resource values, individual processes and functions may be more pertinent to vulnerability assessments. Current management does focus on individual species with regulatory or charismatic interest, but again that management is typically done by administrative units rather than piecemeal across a particular landscape. A practical way to assess vulnerability for application to management and policy is to identify specific areas that contain one or more at-risk ecological thresholds.

Three different approaches are being considered for quantifying vulnerability. First, a series of “vulnerability layers” (sensu GIS

layers) can be developed for different environmental parameters in the current climate, then projected into a warmer climate. For example, one could concurrently examine individual layers for drought, fire, bark beetles, and invasive species. One can expect the highest overall vulnerability to climate change where multiple high-risk areas align. Second, specific landscapes considered to be representative of larger landscapes can be examined, with inferences scaled up to those larger landscapes. We have made considerable progress with this approach through intensive data collection in two large watersheds (one west side [wet], one east side [dry]) in each of three national parks—Olympic, North Cascades, and Glacier. We are optimistic that relationships for vegetation, productivity, hydrology, and ecological disturbance can be confidently extrapolated to adjacent watersheds, perhaps with some fine-tuning to account for known climatic differences. Third, modeling can be used to characterize very large landscapes after being calibrated with empirical data from representative portions of the area of interest. We are currently using the RHESSys modeling framework to examine expected patterns of productivity and hydrology in a warmer climate for mountain ecosystems in the WMI network. We anticipate that RHESSys output will provide a consistent means of generating absolute and relative magnitudes of change across mountain landscapes and will elucidate if and where similar responses can be expected across the West.

Using all three approaches will provide more credible scientific evidence of future changes in natural resources than any single approach individually, especially if the same vulnerabilities are identified by different approaches. Multiple lines of evidence will be a more compelling basis for actions by resource managers and policy makers than the latest output from the “model of the month.” NEPA documentation and other planning documents increasingly require a strong scientific basis (in the peer reviewed literature) to explore management alternatives and select among them. Advocacy groups are already challenging land management and policy on the premise that the effects of climate change have not been considered, and federal agencies require strong scientific documentation to facilitate proactive management and avoid litigation.

Adaptation—The Future is Now

Recent changes in the condition of some resources and the possibility of rapid changes in the future (e.g., more area burned by wildfire) make it imperative that agencies that manage mountain ecosystems begin planning for adaptation to climate change.

Once considered a peripheral issue, climate change is now a much higher priority for land managers than it was even a few years ago. There is, of course, no formula for adaptation, but the prospect of climate-induced changes in resources provides strong motivation for truly implementing adaptive management and management experiments at a broad scale.

Development of adaptation strategies will mostly need to rely on coarse-scale information and predictions for the foreseeable future, fine-tuned by the vulnerability assessments described above. This is the nexus where scientists must clearly communicate to managers about anticipated future conditions in resources over space and time. While scientists can suggest potential options for adaptation to achieve desired future conditions, experience suggests that managers have the expertise and intuition to suggest viable alternatives for adaptation, and in some cases are already implementing them.

All WMI principal investigators are involved in developing the scientific basis for adaptation on federal lands through Synthesis and Assessment Product 4.4 of the U.S. Climate Change Science Program. SAP 4.4 consists of a series of chapters for each of the major federal land management agencies and will provide the central concepts and recommendations for adaptation across federal lands. WMI authors are currently writing chapters for the National Park Service and U.S. Forest Service, with WMI research on mountain ecosystems featured prominently in the scientific documentation. We did not anticipate a document like SAP 4.4 when we started the first WMI projects 15 years ago, but are now realizing the potential of our collaborative research to influence the direction of management and policy in Western mountain ecosystems.

We need more than national overview documents to guide and implement adaptation to climate change on the ground. During the next few years, WMI scientists will engage managers of national parks and national forests in dialogs and planning meetings on adaptation to climate change. We have already developed case studies for adaptation in Olympic National Forest and Rocky Mountain National Park through information sharing and elicitation of adaptation strategies from natural resources staff. We have been impressed by the enthusiasm of participants and their willingness to explore options for adaptation within and outside

the current framework of regulations and policy.

We anticipate emulating this approach with other administrative units within the WMI region through the following steps:

- Compile and communicate to unit managers state-of-science information on expected trends in climate and resource conditions.
- Interpret this information in the context of the unit.
- Document desired future conditions for the unit.
- Elicit recommendations from unit staff about adaptation strategies that would achieve desired future conditions.
- Document opportunities and constraints provided by existing regulations and policy.
- Write a strategic plan for adaptation to climate change that can be included in planning documentation.
- As we gain experience with this approach, we anticipate that it will be possible to use the plan for one unit as a model or starting point for another unit. Alternatively, the six-step process above could be used for small clusters of units with similar kinds of landscapes and resources.

Based on our initial case studies, we found that resource managers are ready for the challenge of adapting to climate change and want scientific partners to assist with developing the information needed for planning and for dealing with uncertainty. There is mutual recognition that resource conditions will need to be monitored in order to test the effectiveness of adaptation practices and to provide feedback to the adaptive management process. As WMI continues to work with national parks and national forests where we have traditionally conducted research, we look forward to sharing experiences with other scientists working on vulnerabilities and adaptation to climate change in mountain landscapes.

The Western Mountain Initiative (WMI) is a consortium of research scientists from the U.S. Geological Survey, U.S. Forest Service, and cooperating institutions. Principal investigators are Craig Allen, Jill Baron, Dan Fagre, Don McKenzie, Dave Peterson, and Nate Stephenson. For information on WMI scientific activities and publications, see: <http://www.cfr.washington.edu/research/fme/wmi>.

Climate Change in Hawai'i's Mountains

Thomas W. Giambelluca and Mark Sung Alapaki Luke

Geography Department, University of Hawai'i at Mānoa
2424 Maile Way, Honolulu, HI 96822

Hawai'i's Mountains

As elsewhere, the mountains of Hawai'i are fundamentally important havens for biodiversity and for sources of fresh water. According to traditional Hawaiian belief, mountains are the realm of wao akua, a sacred place where the regeneration of the forests takes place.

The "wao akua is at that level of the forest in which plants are prolific and where the wind, rain and sun promises a continuous cycle of re-growth. The health of the forests also means that everything else which uses the forest for their lifecycle is also healthy, this being inclusive of the numerous micro-components within the ecosystems" (Kanahele and Kanahele 2007).

Mountains create a range of climates and support the varied environments that make up the ahupua'a system of ancient Hawai'i. Native Hawaiians revere and protect the 'āina (land) and recognize the interconnected nature of land and ocean by regarding the swath of land from the highest mauka (inland) areas to makai (shoreline areas) and the adjacent coastal waters as a unit, the ahupua'a. It is within this context that ancient Hawaiians organized their agricultural, aquacultural, and societal systems.

Today, the ahupua'a concept finds new relevance, as global climate change threatens to bring rapid shifts in temperature, rainfall, cloud cover, and fog frequency to the slopes of Hawai'i's mountains. Such shifts are likely to further stress the already vulnerable ecosystems and alter the hydrological cycle of the islands, especially in the higher elevations. But while local climate changes associated with global warming are likely to be most pronounced in the mountains, the impacts of those changes will also be felt downslope where most of the agriculture, industry, and residential development is located.

Hawai'i, "the most isolated island group of comparable size and topographic diversity on earth" (Loope and Mueller-Dombois 1989), has a remarkable biota, which has evolved in isolation resulting in high endemism, evolutionary adaptive radiation, and vulnerability to alien species invasions (Medeiros et al. 1995). Kaneshiro (1989) argued that Hawai'i's native biota provides the world's best laboratory for evolutionary studies and is the state's single most important natural resource. Lowland landscapes in



Figure 1. Endangered endemic Hawaiian honeycreeper 'akiapola'au (*Hemignathus munroi*). Photo: U.S. Geological Survey.

Hawai'i were altered by both Polynesian and Western migrants to the islands, through forest clearance, use of fire, and introduction of alien plant and animal species. While human impacts have become pervasive in the lowlands, the high-elevation ecosystems remain relatively intact (Medeiros et al. 1995). Native plant and animal species in Hawai'i's mountain forests are marked by extremely high rates of endemism (ca. 95% for flowering plants, ca. 50% for ferns, and ca. 65% for invertebrates).

The native birds of Hawai'i are especially vulnerable to human impacts. For example, more than half of the 57 species of Hawaiian honeycreeper (Drepanidinae) are now extinct (USGS 2006), and many of the surviving species are endangered (Figure 1). Habitat loss and introduced disease are the main threats to these birds. As a result, high-elevation forests are often their last refuge (Benning et al. 2002). As the climate in Hawai'i warms, the *Culex* mosquito and the *Plasmodium* parasites they carry will infect birds with avian malaria at increasingly higher elevations, raising the lower limit of their range. The birds' upper limit is defined by the treeline at roughly 2200 m (Figure 2).

A big question now is how climate change will affect the treeline on Hawai'i's high mountain slopes. It is not clear whether this important ecotone is controlled by temperature, as are treelines in many other parts of the world (Körner 1998), or by moisture. Melcher et al. (2000) provide some evidence that



Figure 2. The treeline on Kalapawili Ridge, Haleakala, Maui. Closed canopy 'ohia forest grades rapidly into shrub and grassland at about 2200 m elevation. Photo: Shelley Crausbay.

freezing may limit tree survival at high elevations in Hawai'i. However, the elevation of the treeline in Hawai'i is lower than expected based on temperature (e.g. Körner 1998, Fig. 1), but is approximately the same elevation as the mean trade-wind inversion (TWI) height (Cao et al. 2007), where rainfall decreases sharply with elevation (Loope and Giambelluca 1998). Although mean annual rainfall is still relatively high immediately above the TWI, tree seedlings in that area may be killed off periodically by drought events there (Menard 1999). If temperature limited, the treeline will almost certainly migrate upwards under a warming climate. If moisture is the limiting factor, the outcome will depend on how the TWI changes as the global climate shifts.

Temperature Trends

Climate changes due to increased levels of atmospheric greenhouse gases are already being detected in many areas of the world. How, then, has Hawai'i's climate changed in recent decades? Three locations with relatively long temperature records, Lihue, Honolulu, and Hilo (Figure 3), have all experienced significant warming over the past 100 years (Figure 4). However, all three sites, especially Honolulu, have seen expansion of their urban areas during that period. The increasing urban heat island effect explains at least some of the warming observed at these sites.

Mean global temperature has increased rapidly since the mid-1970s (IPCC 2007). For representative low elevation urban and high elevation undeveloped sites in Hawai'i for the period since 1976, recent temperature trends have varied by location (Figure 5). Of the near-sea-level stations, only Honolulu has a significant

upward trend in mean temperature. All the high elevation stations have significant warming trends in the mean. The graphs also show trends for maximum and minimum temperature. These time series show changes in daytime and nighttime conditions, respectively. In general, trends for maximum temperature are small or even negative during the period. However, minimum temperature is increasing more rapidly than maximum temperature at all stations. The increase in nighttime temperature is particularly steep for the high elevation stations, especially Haleakalā.

Globally, minimum temperature increased more rapidly than maximum temperature for the period 1950-2004 (IPCC 2007), indicating a downward trend in the diurnal temperature range (DTR). However, for the 1979-2004 period, trends in minimum and maximum temperature were about the same, i.e., with no DTR trend. Greater increases in nighttime temperature may be

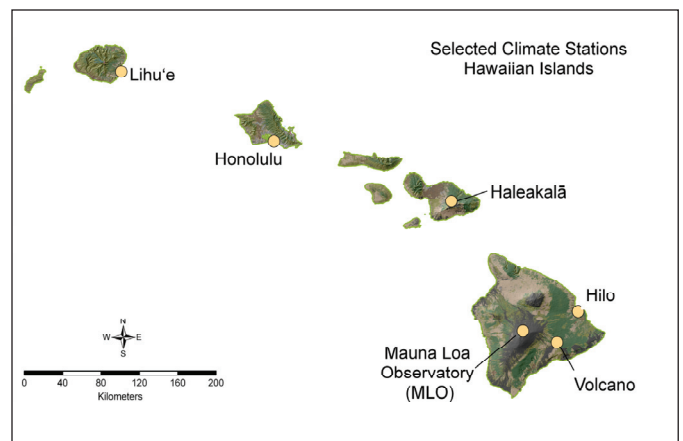


Figure 3. Map showing the location of selected climate stations in Hawai'i.

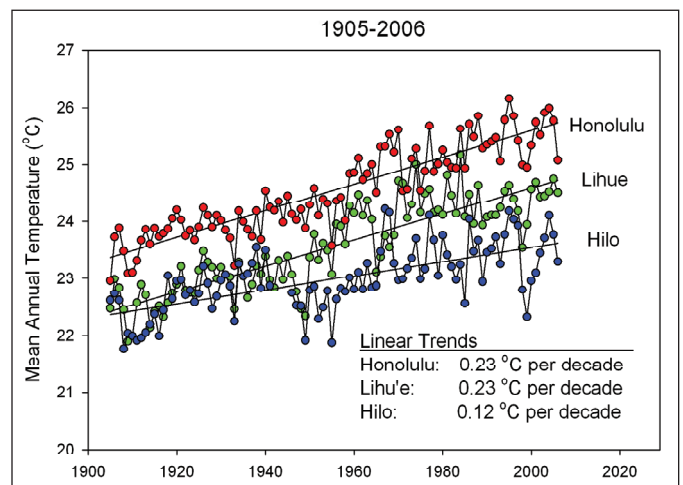


Figure 4. Mean annual temperature for the period 1905-2006 at three near-sea-level stations in Hawai'i.

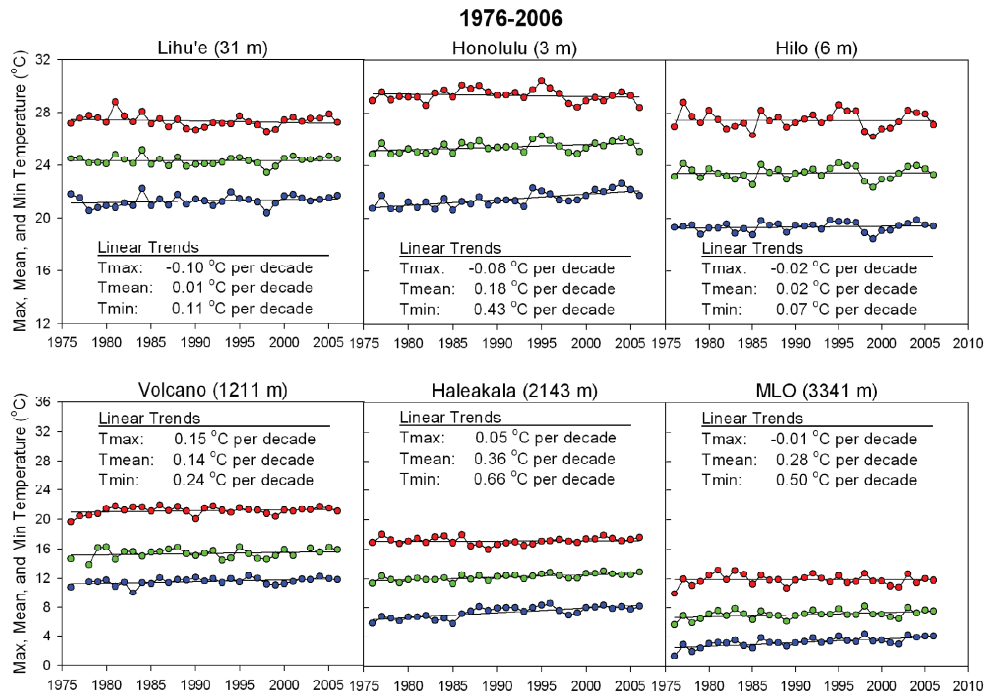


Figure 5. Annual means of daily maximum, minimum, and mean temperature for the period 1976-2006 at three near-sea-level stations (upper row) and three high-elevation stations in Hawai'i.

associated with changes in cloud cover (IPCC 2007). Increased cloudiness would tend to offset daytime warming and enhance nighttime warming. We haven't yet evaluated trends in cloudiness for Hawai'i, but cloud cover changes may help to explain the observed trends in maximum and minimum temperature.

Based on GCM simulations of global climate with 2xCO₂ levels, Bradley et al. (2004, 2006) show that predicted free air temperature changes along the axis of the American Cordillera increase with elevation. This portends enhanced warming in the high elevations of the tropical Andes with potential serious consequences for glacier-fed water resources in the region. The observed trends suggest that the higher elevations in Hawai'i are also experiencing more rapid warming, especially for nighttime temperature. Accelerated warming of the high elevations may be especially harmful to the fragile ecosystems there. The reduced temperature lapse rate implies a more stable atmosphere, and hence a drier climate.

Precipitation Trends

Possible changes in the amounts and patterns of precipitation may be more important than changes in temperature in Hawai'i. Hawai'i does not have the option of importing water from neighboring states to meet its domestic and agricultural water needs. The ground and surface water resources of the islands, already strained, are certain to come under greater pressure during the

coming decades as the population grows. Any changes to the water balance of the islands that reduce the amount of streamflow or the ground-water recharge, will have serious consequences.

The dominant precipitation-producing process in Hawai'i is orographic lifting—air mechanically forced upwards where trade winds meet the windward slopes of Hawai'i's mountains. Again, the TWI plays an important role, capping upward motion, thereby limiting cloud development and diverting the flow of air around the highest mountains (Figure 6). If the frequency of occurrence, or the height of the TWI are affected by climate warming, it will have profound effects on precipitation throughout Hawai'i, but especially on the upper mountain slopes.

Hawai'i has extraordinary diversity in precipitation. Mean annual rainfall ranges from about 250 mm to 11,000 mm (Giambelluca et al. 1986). With this extreme range of normal rainfall it may be difficult to detect generalized changes in rainfall for the islands. Meisner (1976) was the first to propose the Hawai'i Rainfall Index (HRI) to examine trends in state-wide rainfall. The index is based on the records of 27 stations on three islands and is the mean of the standardized rainfall amounts at each station during a given year. Chu and Chen (2005) used the HRI to study temporal changes in Hawaiian rainfall associated with the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Winter rainfall, in particular, is strongly related to ENSO and PDO. Chu and Chen (2005) also noted that HRI



Figure 6. Upward development of the orographic cloud on the north slope of Haleakala, Maui, is limited by the presence of the trade-wind inversion at an average elevation of about 2200 m. Photo: John DeLay.

calculated for the winter months (November–March) exhibited a downward trend over the past 100 years (Figure 7). It is not clear whether this apparent trend represents a long-term shift toward a drier climate or is part of a multi-decadal cycle related to the PDO.

Trade-Wind Inversion

The apparent downward trend in winter rainfall may be the result of increasing persistence of the TWI over Hawai'i. Cao et al. (2007) found that the frequency of occurrence of the TWI, as detected using atmospheric sounding data at Hilo and Lihue, has increased over the period since 1979 (Figure 8). Cao et al. (2007) speculate that the observed trend in TWI occurrence, may be associated with recent (Fyfe 2003, McCabe et al. 2001) and possible future (Yin 2005) poleward shifts in North Pacific storm tracks, resulting from global warming. Cao (2007) also found that the height of the TWI may be trending lower. He went on to show that changes in Pacific region atmospheric patterns simulated for future climate under global warming suggest the TWI will continue to become more persistent and lower in height (Cao 2007). While the connection between TWI changes and climate warming is uncertain, a continuation of a more persistent inversion would portend a shift toward a drier climate in Hawai'i, with serious ecological and hydrological consequences.

Cloud Water Interception

In Hawai'i, distinct ecological zones called tropical montane cloud forests (TMCF) are found along mountain slopes in the

zone where frequent fog adds to hydrological input through cloud water interception (CWI) and has profound effects on the biota. CWI may contribute a meter or more of water per year to soil, groundwater, and streamflow in some windward, high-rainfall areas (Giambelluca et al. in press). Fog also provides life-sustaining moisture on otherwise dry, leeward and high elevation slopes. Threats to TMCFs have been noted in other parts of the world. At Monteverde, Costa Rica, fog frequency declined dramatically in response to a step-like warming of tropical oceans in 1976 (Pounds et al. 1999) leading to speculation that global warming will negatively impact hydrological and ecological function in tropical maritime cloud forests (Foster 2001). This finding was supported by global climate model simulations showing upward shifts of 183 to 341 m in relative humidity surfaces at four TMCF sites for a 2x CO₂ climate (Still et al. 1999). The fog zone in Hawai'i is bounded by the lifting condensation level (LCL) at the

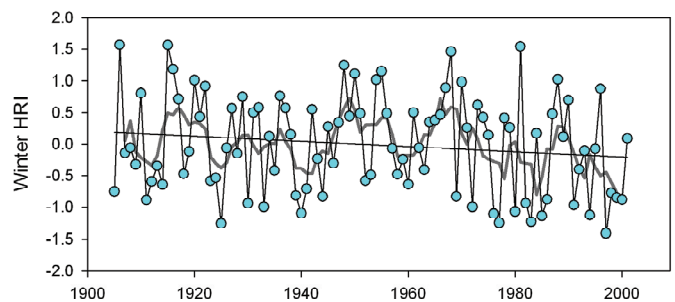


Figure 7. The winter Hawai'i Rainfall Index (HRI), calculated as the mean of standardized November–March rainfall totals at 27 representative stations each year (Chu and Chen 2005). The thick gray line is a five-year running mean. The thin line shows the trend based on least squares regression.

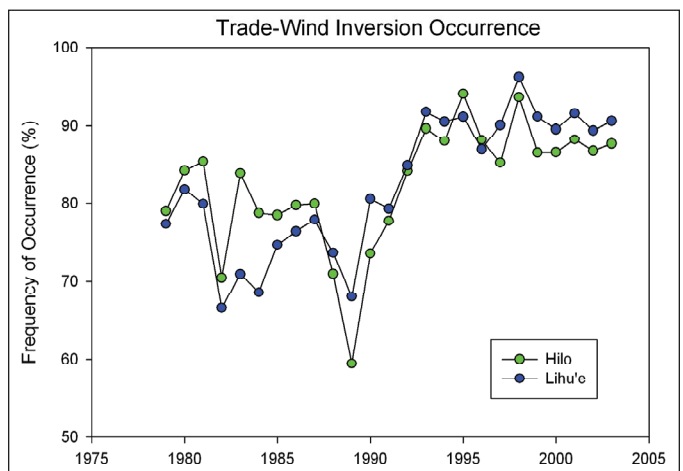


Figure 8. Frequency of occurrence of the trade-wind inversion over Lihue and Hilo based on twice-daily atmospheric sounding data (Cao et al. 2007).

bottom and the base of the TWI at the top. As discussed above, there is evidence that the TWI is becoming more persistent and perhaps lower. In the worst case scenario of global warming effects, the TWI could descend and the LCL rise, causing the fog zone in Hawai'i to contract dramatically.

A Warmer, Drier Future Climate for Hawai'i?

Numerical climate models simulations of future climate with increasing greenhouse gases have improved to the point where some relevant results can be derived for projecting changes in Hawai'i's climate. However, regional climate assessment remains a difficult task. Because of its small land area and extreme spatial diversity, Hawai'i's climate future is particularly hard to discern from model output. Temperature trends are generally consistent with model simulations of the past century, and so model projections may be useful for forecasting temperature change in the islands.

Model results are not as relevant, however, for predicting how global warming will influence precipitation in Hawai'i. Trends in rainfall and observed recent changes in the TWI suggest warming may result in drier conditions. Lower rainfall would be experienced everywhere, but especially for the areas above the mean inversion height (around 2200 m). This would result in severe impacts to the highly vulnerable ecosystems found there (Loope and Giambelluca 1998).

A warmer, drier climate would also have severe impacts on water resources in the islands. Baseflow in Hawai'i's streams has trended downward during the period since 1913 (Oki 2004), an apparent response to declining rainfall over the period. Groundwater resources are crucially important in Hawai'i. Baseflow in streams is derived from groundwater, and hence the observed decrease is a telling sign that Hawai'i's drying climate has already curtailed water availability.

Much work remains to be done in developing a reliable scenario of future climate for Hawai'i. Continued significant increases in temperature, especially at high elevations, seem almost certain. Changes affecting rainfall and fog are less certain, and recent trends toward drier conditions may prove to be part of natural multi-decadal variability (e.g. Chu and Chen 2005) rather than warming-related shifts. However, it is prudent to anticipate the consequences of a warmer, drier climate in Hawai'i and begin to take steps to prepare for this possible outcome. To do so will require that we consider the impacts across the whole range of environments with attention to the interconnections between mountain slopes, coastal plains, and near-shore waters. In this re-

gards, we would be well served to adopt the native Hawaiians' vision of land stewardship embodied in the ahupua'a concept when planning to protect the vulnerable ecosystems and safeguard the water supply of Hawai'i.

Acknowledgments

This paper is based, in part, upon work supported by the National Science Foundation (NSF) under grant no. EAR-0309731 and the U.S. Geological Survey's (USGS) Biological Resources Discipline, Global Change Research Program. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of NSF or USGS. We thank Carter Atkinson (USGS), Shelley Crausbay (University of Wisconsin), and John DeLay (University of Hawai'i) for providing photos used in this article.

References

- Benning, T.L., D. LaPointe, C.T. Atkinson, and P.M. Vitousek, 2002. Interactions of climate change with biological invasions and land use in the Hawaiian Islands: modeling the fate of endemic birds using a geographic information system. *PNAS* 99:14246-14249.
- Bradley, R.S., F.T. Keimig, and H.F. Diaz, 2004. Projected temperature changes along the American Cordillera and the planned GCOS Network. *Geophysical Research Letters* 31, doi:10.1029/2004GL020229.
- Bradley, R.S., M. Vuille, H.F. Diaz, and W. Vergara, 2006. Threats to water supplies in the tropical Andes. *Science* 312:1755-1756.
- Cao, G., 2007. Trade wind inversion variability, dynamics and future change in Hawai'i. PhD dissertation, Geography, University of Hawai'i at Mānoa.
- Cao, G., T.W. Giambelluca, D. Stevens, and T. Schroeder, 2007. Inversion variability in the Hawaiian trade wind regime. *Journal of Climate* 20:1145-1160.
- Chu, P.-S., and H. Chen, 2005. Interannual and interdecadal rainfall variations in the Hawaiian Islands. *Journal of Climate* 18:4796-4813.
- Fyfe, J.C., 2003. Extratropical Southern Hemisphere cyclones: harbingers of climate change? *Journal of Climate* 16:2802-2805.
- Giambelluca, T.W., J.K. DeLay, M.A. Nullet, M.A. Scholl, and S.B. Gingerich. (in press). Interpreting canopy water balance and fog screen observations: Separating cloud wa-

- ter from wind-blown rainfall at two contrasting forest sites in Hawai'i. In *Mountains in the Mist: Science for Conserving and Managing Tropical Montane Cloud Forests*, J.O. Juvik, L.A. Bruijnzeel, F.N. Scatena, and P. Bubba (eds.). Giambelluca, T.W., M.A. Nullet, and T.A. Schroeder, 1986. *Hawaii Rainfall Atlas*. Report R76, Hawai'i Division of Water and Land Development, Department of Land and Natural Resources, Honolulu.
- IPCC, 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
- Kanahele, P., and E. Kanahele, 2007. *Pana'ewa: Cultural description of indigenous Hawaiian life*. <http://www.hawaii.edu/hawaiiicc/hawaiian/KHaili/Panaewa.htm>.
- Kaneshiro, K.Y., 1989. Uniqueness of Hawai'i's biota. In C.P. Stone and D. Stone (eds.) *Conservation biology in Hawai'i*, Cooperative National Park Resources Studies Unit, University of Hawai'i at Manoa, Honolulu, pp. 7-10.
- Körner, C., 1998. A re-assessment of high-elevation treeline positions and their explanation. *Oecologia* 115:445-459.
- Loope, L.L. and T.W. Giambelluca, 1998. Vulnerability of island tropical montane cloud forests to climate change, with special reference to East Maui, Hawaii. *Climatic Change* 39:503-517.
- Loope, L.L. and D. Mueller-Dombois, 1989. Characteristics of invaded islands. In H.A. Mooney et al. (editors). *Biological invasions: a global synthesis*. John Wiley and Sons, Chichester, England, pp. 257-280.
- McCabe, G.J., M.P. Clark, and M.C. Serreze, 2001. Trends in Northern Hemisphere surface cyclone frequency and intensity. *Journal of Climate*, 14:2763-2768.
- Medeiros, A.C., L.L. Loope, and R.W. Hobdy, 1995. Conservation of cloud forests in Maui County (Maui, Moloka'i, and Lana'i), Hawaiian Islands. In L.S. Hamilton, J.O. Juvik, and F.N. Scatena (eds.) *Tropical Montane Cloud Forests*. Springer Ecological Studies 110:223-233.
- Melcher, P.J., S. Cordell, T. Jones, P.G. Scowcroft, W. Niemczura, T.W. Giambelluca, and G. Goldstein, 2000. Super-cooling capacity increases from sea level to tree line in the Hawaiian tree species *Metrosideros polymorpha*. *International Journal of Plant Science* 161:369-379.
- Menard, T., 1999. Ecology and hydrological effects of a rainless period on a montane cloud forest treeline on Haleakala, Maui. Master's thesis, Geography Department, University of Hawai'i at Mānoa.
- Meisner, B.N., 1976. A study of Hawaiian and Line Island rainfall. UHMET-76-04. Department of Meteorology, University of Hawai'i.
- Oki, D.S., 2004. Trend in Streamflow characteristics at long-term gaging stations, Hawaii. USGS Scientific Investigations Report 2004-5080, U.S. Geological Survey, Reston, VA.
- USGS, 2006. Feral pigs, introduced mosquitoes, and the decline of Hawai'i's native birds. USGS Fact Sheet 2006-3029, U.S. Geological Survey. http://biology.usgs.gov/pierc/Fact_Sheets/Pigs_and_mosquitoes.pdf
- Yin, J.H., 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophysical Research Letters* 32, doi:10.1029/2005GL023684.

The North American Monsoon Experiment (NAME): Warm Season Climate Research in the Mountainous Regions of Southwestern North America

David J. Gochis

National Center for Atmospheric Research, Boulder, CO

Introduction

The North American Monsoon (NAM) is a robust climatological feature that, in large part, controls the onset, intensity and demise of the summer rainy season throughout much of southwestern North America. The locus the NAM is centered over the Sierra Madre Occidental mountains of western Mexico which, on average, receive in excess of 60-70% of their annual rainfall in the summer months of June-September (Douglas et al., 1993). The rains of the NAM feed local ecosystems valuable moisture in an otherwise dry sub-tropical climate and provide a critical water resource for human activities in both the U.S. and Mexico.

The mountainous terrain of southwestern North America and its juxtaposition to seasonally warm water bodies of the eastern tropical Pacific, the Gulf of California, and the Gulf of Mexico serves as a driving component of the regional climate circulation, which helps to initiate and sustain extra-tropical moisture transport during the summer monsoon season. In essence, the elevated terrain of Mexico and the U.S. are both critically responsible for and responsive to the sustenance and variation of the NAM hydroclimate. Furthermore, it has been shown (Higgins et al., 1997; 1998, Hu and Feng, 2002) that there are remote teleconnection-like effects of the NAM monsoon across North America that are manifested by both in-phase and out-of-phase relationships in warm season precipitation.

In recognition of these features the North American Monsoon Experiment (NAME) was developed to improve our understanding and prediction capabilities of warm season precipitation across North America. In the following a short overview of the NAME research program is provided along with a brief description of its accomplishments to date, some of the ongoing observational efforts that have emerged out of NAME research and some of the principal challenges that remain. This overview is written with the aim of highlighting both the need and opportunity to integrate a sustained, mountain-focused climate research effort that has been focused on the NAM with a larger effort focused on the variability and change in mountain climates and ecosystems across the American Cordillera as discussed previously by Diamond and Helfert (2007) and Diaz et al. (2006). It is hoped from this writing, that future enhancements of both observation

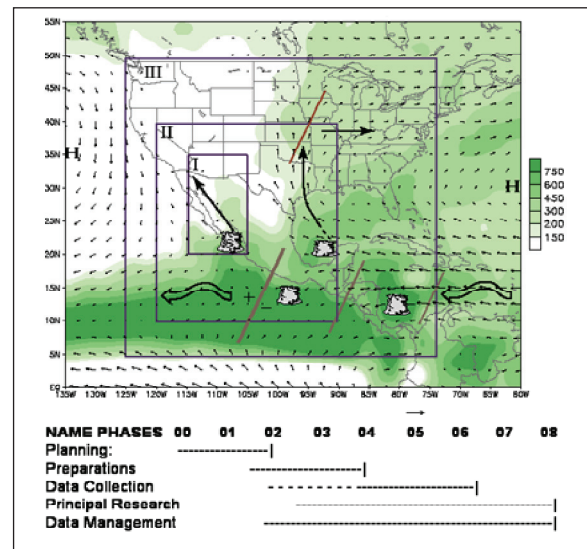


Figure 1. Three-tiered research framework and timeline of NAME. Vector field indicates JAS 925 hPa mean winds. Also shown are the N. American low-level jets (bold arrows) tropical and mid-latitude disturbances (block arrows and red lines) and merged satellite and gauge precipitation observations (green shading).

and prediction systems in southwestern North America will be able to significantly leverage upon the investments in observation and prediction infrastructure that has already been made through NAME.

Summary of NAME Research Program

The North American Monsoon Experiment (NAME) is a continental-scale process study now in its seventh year that was conceived to directly address the issue of improving predictions of warm season precipitation in North America. The NAME program is jointly sponsored by Climate Variability and Predictability (CLIVAR) and Global Energy and Water Cycle Experiment (GEWEX) research efforts. A fundamental first step towards improved prediction is the clear documentation of the major elements of the monsoon system and their variability within the context of the evolving O-A-L annual cycle (Higgins and Gochis, 2007). To achieve this NAME employs a multi-scale (tiered) approach with focused monitoring, diagnostic and modeling activities in the core monsoon region, on the regional-scale and

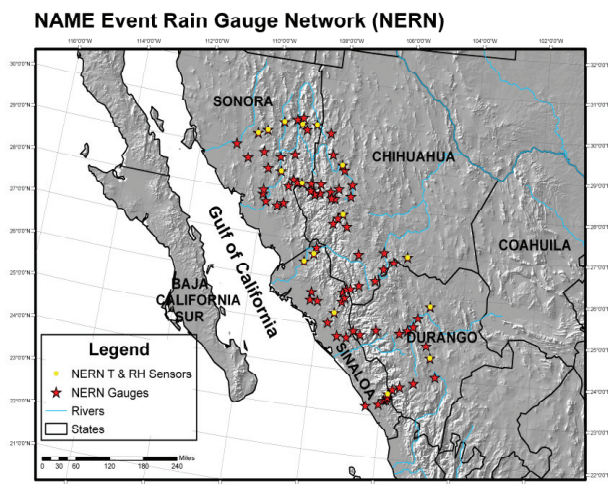


Figure 2. TMap of NAME Event Rain gauge Network (NERN) installed as part of the NAME research program and currently maintained through the present.

on the continental-scale (Fig. 1). (Additional detail on NAME background information and motivating science questions can be found in Higgins et al., 2006 and NAME-SWG, 2007).

The physical science objectives of NAME are to improve the understanding and simulation of 1) warm season convective processes over complex terrain (Tier I), 2) the modes and drivers of intra-seasonal variability (Tier II) and, 3) the response of the NAMS to oceanic and continental boundary conditions (Tier III). The timeline for NAME activities (Fig. 1) encompasses planning, data collection and principal research phases. As part of NAME a large, coordinated Enhanced Observing Period (EOP) or, field campaign, was conducted during the summer of 2004. The 2004 EOP was organized and conducted by an international coalition of university and agency scientists, and forecasters from México, the U.S. and Central America. Numerous instrument platforms, including surface meteorological stations, radars, aircraft, ocean research vessels, satellites, wind profilers, rawinsondes, pibals, rain gauge networks, soil moisture sensors and GPS integrated water vapor retrieval antennae were deployed within the Tier I and II regions in Figure 1. (Higgins and Gochis, 2007) All of the data collected during the 2004 EOP is now available online along with other NAME program documents, reports, journal publications and meeting presentations on the official NAME website (<http://www.eol.ucar.edu/projects/name/>).

While a majority of the instruments deployed as part of the 2004 NAME EOP were stationed close to the coast of the Gulf of California, numerous measurements were made in the complex terrain regions of the Sierra Madre Occidental mountains of western and northwestern Mexico and in and around the Ma-

dean Archipelago (a.k.a. desert ‘sky-islands’) of the southwest U.S and northwest Mexico. These instrument networks included automated surface meteorological stations, soil moisture sensors, eddy covariance flux towers, event logging rain gauges, GPS precipitable water vapor sensors and numerous manually operated accumulation rain gauges. A recent special issue (Volume 20, No. 9., 2007) of the *Journal of Climate* documents, in over 20 articles, many of the key findings that have emerged from the 2004 NAME EOP. A full description of these results is well beyond the scope of this short overview and interested readers are encouraged to review these recently published works.

Despite the progress achieved to date under NAME, many key research questions regarding atmospheric and eco-hydrological processes over the complex terrain of the Sierra Madre Occidental remain. These questions demand the development and maintenance of a robust regional climate observing network for their successful address. A handful of the instrument platforms deployed during the 2004 NAME EOP have been transitioned into an operational regional climate observing system and are still collecting data. A few of these ongoing measurements and research efforts are detailed in the following sections.

NAM Precipitation Measurements

As of this writing, 87 tipping bucket rain gauges are in operation recording liquid precipitation in the core region of the North American Monsoon in northwest Mexico as part of the NAME Event Rain gauge Network (NERN). (See Fig. 2 for a map of network) This work was initiated and sustained through an international partnership between Mexican and U.S. researchers and the Mexican Comisión Nacional del Agua (CONAGUA) and has been supported by the NOAA Climate Program Office. The underlying objective of the NERN was to sample the sub-daily, or event, characteristics of the precipitation-elevation relationship along several (six) east-west oriented transects that traverse the Sierra Madre Occidental mountains from the Gulf of California coast to the Mexican Plateau (Gochis et al., 2004). Portions of the network have now been operating for five years since their installation during the spring of 2002. In addition to tipping-bucket rain-gauge measurements over a dozen sites are also installed with automated temperature and humidity sensors thereby permitting characterization of the regional gradients in temperature and humidity as functions of topographic elevation across western Mexico.

Analysis of NERN data has now provided several detailed characterizations of the spatial and temporal patterns of rain-

fall across the Sierra Madre Occidental in a manner heretofore unprecedented in this remote, data-sparse region (c.f. Gochis et al., 2004 and Gochis et al., 2007b). As detailed in the continuing NERN technical documentation, regular servicing and calibration maintains the NERN as a research-grade regional precipitation observation network whose climate-observing value continues to grow with each additional season of data collected.

In addition to basic diagnostic analysis of rainfall patterns, the NERN data has found widespread use in the validation of regional and global model simulation experiments (c.f. Gao et al., 2007; Lee et al., 2007; Collier et al., 2007). This dataset has allowed, for the first time, a robust ground validation of precipitation rainfall occurrence and intensity at a range of topographic elevations and with sub-daily time resolution. Akin to validating numerical model simulations and forecasts, NERN data has also been used to validate remotely sensed quantitative precipitation estimates (QPE's) from both satellite (c.f. Huffman et al., 2007; Hong et al., 2007; Nesbitt and Gochis, 2007) and ground-based radar platforms (Nesbitt and Gochis, 2007). The principal asset of using NERN data for such analyses is the ability to resolve climatological relationships between seasonal and diurnal cycles of rainfall and elevation across a range of sub-tropical latitudes. This precipitation regime is defined by a strong diurnal cycle where precipitation is observed earliest in the day and most frequently over high terrain elevations, though with comparatively light intensity, and later in the day and less frequently, but with higher intensities, at lower elevations. This regime is analogous to many other terrain-forced convective environments found across the world. (c.f. Laing and Fritsch (1997) and Carbone et al., 2002).

In partnership with the U.S. Climate Prediction Center and the Mexican Servicio Nacional Meteorológico, the Instituto Mexicano de Tecnología del Agua (IMTA) has recently established a very dense network of manual observation, accumulation rain gauges in the northwest Mexico states of Sonora, Chihuahua and Sinaloa. This project represents a very ambitious grass-roots effort to engage local residents, civil protection agencies and additional stakeholders in the acquisition and use of climate data. In particular, the network is distributed amongst the major agricultural concerns in the state, including irrigation districts, farmers associations, research institutions and regional University partners. The network, operated by IMTA, collects data from over 1,000 stations on a routine basis and passes this data on to operational centers in Mexico and the U.S. A full description of the project and as well as data can be accessed in near real-time for regularly reporting stations through the project website (<http://galileo.imta.mx/DBNAME/>).

NAM Ecosystems and Hydrology

The ecosystems underlying the North American Monsoon are critically dependent on summer rainfall. Research conducted under NAME as well as other ongoing efforts (c.f. Watts et al., 2007 and Vivoni et al., 2007a and b) have significantly advanced understanding of the seasonal evolution of land surface processes and ecological communities in terms of their evolving vegetation characteristics and moisture and energy fluxes between the land and atmosphere. Figure 3, adapted from Watts et al., highlights the strong seasonal transition in vegetation greenness undertaken across the Sierra Madre Occidental in response to monsoon rains. This dramatic increase in vegetation greenness is largely attributed to the leaf-out of deciduous sub-tropical and tropical species which are dormant through the late-winter/spring dry season. Changes in vegetation characteristics such as spectral albedo and the partitioning of net radiation into sensible and latent heat components in response to seasonal ecosystem evolution have been implicated as significant modulating features of the NAM hydroclimate and the recycling of moisture back to the atmosphere. (e.g. Vivoni et al., 2007a; Dominguez et al., 2006).

Human activities that seek to exploit the copious natural resources of the region have also begun to impose significant changes in the regional ecosystems in the Sierra Madre Occidental. Livestock grazing, wildland/rangeland burning, and, at higher elevations (above 2000 m MSL), timber harvesting of Arizona pine (*Pinus arizonica*), ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga lindleyana*) as well as other

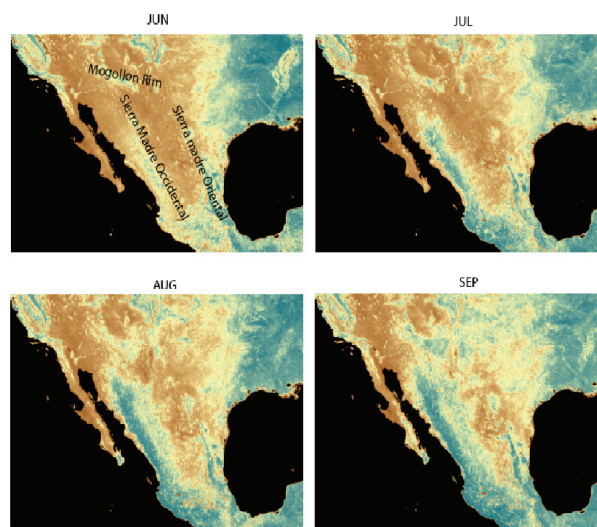


Figure 3. Monthly changes in 2006 vegetation greenness as represented by NDVI derived from SPOT-5 imagery. NDVI values are the mean from the first 10 days of each month. (Figure adapted for 2006 as in Watts et al., 2007, *J. Climate*, vol. 20)

species, are incrementally altering ecosystem state and function. One example of this influence was illustrated by Viramontes and Descroix (2003) who showed that decades of overgrazing along areas of the eastern slope of the Sierra Madre Occidental have altered seasonal runoff characteristics.

The regional hydrologic system of southwestern North America is also driven by monsoon rainfall. Proceeding southward from the Mogollon Rim region of the southern Rocky Mountains in northern Arizona, one observes a transition in the seasonal cycle of runoff from a regime that is winter dominated to one that is clearly summer dominated (Figure 4: see also Brito-Castillo et al., 2003; Gochis et al., 2006; Grantz et al., 2007). At the latitudes of the central Sierra Madre Occidental in southern Chihuahua and northern Durango, between 60-80% of the total annual flow is derived from summer rainfall, thereby providing critical replenishment of water resources to the string of reservoirs impounding the major river systems of the region. These reservoirs are the principal source of water for large municipalities and large irrigation projects along the coastal plains of the western Mexico mainland in Sinaloa and Sonora and, therefore, the need for a reliable and predictable water resource is paramount. However, along with the construction of large dams along the periphery of the Gulf of California has grown the concern that freshwater inputs into the Gulf have been diminished and will subsequently have an adverse effect on the highly productive fisheries of the region. (e.g., Aragón and García, 2002)

While seasonal streamflow from the monsoon has been found

to be correlated with large-scale teleconnective indices such as ENSO, North Pacific SSTs and SST's in the intra-America sea region, the magnitude of the correlations are modest and show appreciable inter-decadal transience. (Brito-Castillo et al., 2003; Gochis et al., 2007a) This complexity has hindered to a significant degree the development of robust empirical hydroclimate forecasts for this key water resource region.

Societal vulnerability in the North American Monsoon region Concomitant with the physical research agenda of NAME has been an increasing body of social science research that explores the vulnerability and capacity of monsoon affected communities in southwestern North America to cope with weather and climate related stresses that are often directly linked to monsoon variability. Ray et al. (2007) recently synthesized the results of this body of work and identified major societal sectors that were simultaneously vulnerable to variations in the NAM hydroclimate, but also possessed a capacity to use and apply climate information. The authors identified natural hazards (e.g., drought, floods and fire), agriculture, public health and water management as four principal sectors in which climate plays a significant role in overall vulnerability. While many of the larger settlements and municipalities in monsoon-affected regions exist at lower elevations these larger communities may be buffered from some weather and climate variations due to a comparatively greater access to economic and information resources compared with smaller high elevation communities. Monsoon variability can have a profound impact in higher elevation mountainous regions where the societal capacity is often limited. For instance, high elevation regions of Madrean Archipelago and Sierra Madre Occidental are particularly vulnerable to wildland fire in the dry, hot periods just prior to monsoon onset. Delays in monsoon onset, false onsets with dry thunderstorms and copious lightning can result in greatly enhanced risks of severe wildland fires, which in turn, can result in economic losses of productive timber, increased chances of soil erosion and increased risks of flooding and debris flows from fire-scarred landscapes. [An example of this fire-flood-debris flow cycle was recently observed during the 2006 summer monsoon in the Santa Catalina Mts. near Tucson, Arizona (Magirl et al., 2007)] Similarly, small-scale rain-fed agriculture operations and water resource systems (both surface and groundwater) in mountainous areas are particularly vulnerable to variations in monsoon precipitation as are the communities who depend on these resources.

Ray et al. (2007) recommend that improved monitoring and dissemination of climate relevant parameters along with improved forecasts of monsoon behavior on across a range of time-

Seasonal Transition in Peak Streamflow Month

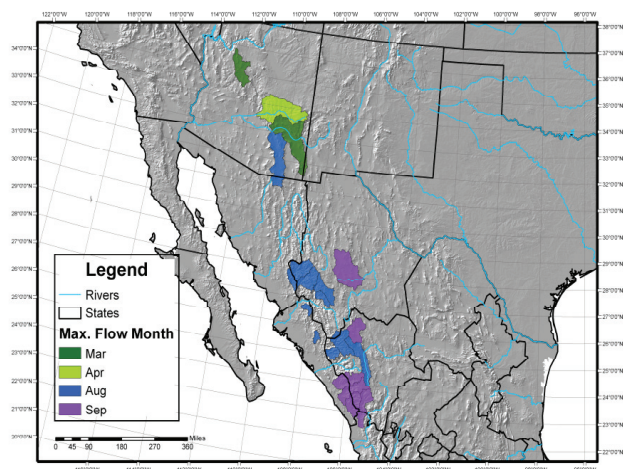


Figure 4. Month of maximum streamflow across selected basins in southwest North America.



Figure 5. Annual decision calendar for monsoon region applications. Shaded bars indicate the timing of information needs for planning and operational issues over the year. (From Ray et al., 2007).

scales from days to inter-annual could potentially be very useful in helping local and regional decision makers avoid losses to life, property and economic vitality. An analogous climate product focusing on a wider range of climate issues is currently produced by the CLIMAS project at the University of Arizona (CLIMAS, 2007). Ray et al. developed a table of 'Monsoon Information Needs' delineated by timescale and societal sector as well as an 'Annual Decision Calendar' (Figure 5) which identify and date major sector decision periods for monsoon-affected enterprises throughout the annual cycle.

Recommendations

Despite the progress that has been made in understanding many of the key components of the NAM, much work remains if NAME is to fulfill its programmatic goals of improving predictions of warm season precipitation. Furthermore, the improved understanding of the NAM regional climate system we have gained through NAME must now be applied to improving our understanding of ecological and hydrological processes in the region and how variability in these systems influence natural and societal vulnerability to climate variability and climate change.

Diagnostic and modeling studies from the 2004 NAME EOP and the years that have followed have taught us that the availability of a robust regional climate observing system is paramount

to monitoring monsoon behavior and to developing meaningful predictions across a range of time and space scales. However, critical gaps in our observing capability, particularly over the Sierra Madre Occidental, continue to limit insight, and modeling capacity, into land-atmosphere coupling, ecosystem function and terrestrial hydrologic response to monsoon rains. In short, the experiences of NAME summarized above and in other works, lead us to make the following three recommendations for advancing research in the NAM region:

1. A robust regional hydroclimate observing system must be maintained in the bi-national region of the NAM in which measurements from complex terrain locations are a critical component. These measurements should include: rainfall, streamflow, atmospheric sounding systems, automated weather stations, soil moisture sensors, timely remote sensing imagery and global positioning system-precipitable water vapor sensors. These networks must be maintained for a long-duration (i.e. many years) in order to be able to characterize and contextualize variations in key hydroclimatic variables.
2. Based on diagnostic insight, there is continued need to improve predictive capabilities of both empirical and dynamically-based systems. While NAME is addressing this issue through many of its ongoing programmatic activities there

is critical need to adapt new and existing climate forecasts to make them more relevant, in terms of spatial and temporal scales as well as predictor variables, for societal applications. In this regard, there is a significant need for value-added and regionally or locally downscaled forecast products over complex terrain regions.

3. There is now an acute imperative to improve our understanding of the NAM in the context of a changing climate. Since the release of the IPCC AR4, there have been numerous speculations on the fate of the hydroclimate of the western and southwestern regions of North America; most of these scenarios pointing to a drier and more arid climate. However, NAME research has highlighted the fact that there are significant shortcomings in the current generation of climate models to properly simulate the general climatology of the NAM rainfall much less its significant interannual variations. Therefore significant research is needed to provide a more physical basis for such speculations, which should be derived, in part, from a sound diagnostic understanding of the mechanisms that control the NAM.

Over the past seven years the NAME research program has begun to shed light on one of the most vexing problems in climate research; that of understanding and predicting warm season rainfall. This understanding has come through a committed and coordinated observation and modeling effort aimed at increasing our understanding of the physical nature of the monsoon system. Continued success in addressing longer timescale questions related to climate variability and change will undoubtedly also demand a sustained commitment to maintaining a robust climate observing system in the NAM region, particularly those mountainous regions which are critically vulnerable to subtle variations and changes in the climate system.

References

- Aragón, E.A. and A. García, 2002: Postlarvae recruitment of blue shrimp *Litopenaeus stylirostris* (Stimpson, 1871) in anti-estuarine conditions due to anthropogenic activities. *Hidrobiológica*, 12(1), 37-46.
- Brito-Castillo, L., A., Douglas, Layva-Contreras, A.V., Lluch-Belda, D., 2003: The effect of large-scale circulation on precipitation and streamflow in the gulf of California continental watershed. *Int. J. Climatology*, 23, 751-768.
- Carbone, R.E., J.D. Tuttle, D.A. Ahijevych, and S.B. Trier, 2002: Inferences of predictability associated with warm season precipitation episodes. *J. Atmos. Sci.*, 59, 2033-2056.
- CLIMAS, 2007: Southwest climate outlook—August 2006. Online climate Outlook published by the Climate Assessment for the Southwest (CLIMAS) project. Tucson, Arizona. Available online at: <http://www.ispe.arizona.edu/climas/forecasts/archive/aug2006/swoutlook.html>
- Collier, J.C., and G.J. Zhang, 2007: Effects of increased horizontal resolution on simulation of the North American Monsoon in the NCAR CAM3: An evaluation based on surface, satellite and reanalysis data. *J. Climate*, 20, 1843-1861.
- Diamond, H.J. and M.R. Helfert, 2007: The U.S. Global Climate Observing System (GCOS) Program: Plans for high elevation GCOS surface network sites based on the benchmark U.S. Climate Reference Network (CRN) System. Mountain Views, Newsletter of the Consortium for Integrated Climate Research in Western Mountains (CIRMOUNT), 1, 16-19.
- Diaz, H.F., R. Villalba, G. Greenwood and R.S. Bradley, 2006: The impact of climate change in the American Cordillera. *Eos, Transactions of the American Geophysical Union*, 87(32), August, 2006, p. 315.
- Dominguez, F., P. Kumar, X.Z. Liang and M.F. Ting, 2006: *J. Climate*, 19, 1513-1530.
- Douglas, M.W., R.A. Maddox, K. Howard and S. Reyes, 1993: The Mexican Monsoon. *J. Climate*, 6, 1665-1677.
- Gao, X., J. Li, and S. Sorooshian, 2007: Modeling intraseasonal features of 2004 North American Monsoon precipitation. *J. Climate*, 20, 1882-1896.
- Gochis, D.J., J.-C. Leal, A. Jimenez, C.J. Watts, J. Garatuza-Payan, W.J. Shuttleworth, 2004: Analyses of 2002 and 2003 North American Monsoon precipitation from the NAME Event Rain gauge Network (NERN). *Mon. Wea. Rev.*, 132, 2938-2953.
- Gochis, D.J., L. Brito-Castillo, W.J. Shuttleworth, 2006: Hydroclimatology of the North American Monsoon region of northwest México. *J. Hydrology*, 316, 53-70.
- Gochis, D.J., L. Brito-Castillo, W.J. Shuttleworth, 2007a: Correlations between sea-surface temperatures and warm season streamflow in northwest México. *Int. J. Climatology*, 27, 883-901.
- Gochis, D.J., C.J. Watts, J. Garatuza-Payan, and J.C. Rodriguez, 2007b: Spatial and temporal patterns of precipita-

- tion intensity as observed by the NAME event rain gauge network from 2002 to 2004. *J. Climate*, 20, 1734-1750.
- Grantz, K., B. Rajagopalan, M. Clark and E. Zagana, 2007: Seasonal shifts in the North American Monsoon. *J. Climate*, 20, 1923-1935.
- Higgins, R.W., Y. Yao and X. Wang, 1997: Influence of the North American Monsoon system on the U.S. summer precipitation regime. *J. Climate*, 10, 2600-2622.
- Higgins, R.W., K.C. Mo and Y. Yao, 1998: Interannual variability of the U.S. summer precipitation regime with emphasis on the southwestern monsoon. *J. Climate*, 11, 2582-2606.
- Higgins, R. W. and co-authors, 2006: The North American Monsoon Experiment (NAME) 2004 Field Campaign and Modeling Strategy. *Bull. Amer. Meteor. Soc.*, 87, 79-94.
- Higgins, R.W. and D.J. Gochis, 2007: Synthesis of results from the North American Monsoon Experiment (NAME) process study. *J. Climate*, 20, 1601-1607.
- Hong, Y., D.J. Gochis, J.-T. Cheng, K.-L. Hsu, and S. So-rooshian, 2007: Evaluation of PERSIANN-CCS rainfall measurement using the NAME Event Rain gauge Network. *J. Hydrometeorol.*, 8, 469-482.
- Hu, Q., and S. Feng, 2002: Interannual rainfall variations in the North American summer monsoon region: 1900-1998. *J. Climate*, 15, 1189-1202.
- Huffman, G.J., and co-authors, 2007: The TRMM multisatellite analysis (TMPA): Quasi-global multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeorol.*, 8, 38-55.
- Laing, A.G., and J.M. Fritsch, 1997: The global population of mesoscale convective complexes. *Quart. J. Roy. Meteor. Soc.*, 123, 389-405.
- Magirl, C.S., R.H. Webb, M. Schaffner, S.W. Lyon, P.G. Griffiths, C. Shoemaker, C.L. Unkrich, S. Yatheendradas, P.A. Troch, E. Pytlak, D.C. Goodrich, S.L.E. Desilets, A. Youberg and P.A. Pearthree. Impact of recent extreme Arizona storms. *Eos newsletter*, 88(17), 24 April, 2007.
- M.-I. Lee and co-authors, 2007: Sensitivity to horizontal resolution in the AGCM simulations of warm season diurnal cycle of precipitation over the United States and Northern Mexico. *J. Climate*, 20, 1862-1881.
- NAME Science Working Group, cited 2007: North American Monsoon Experiment Science and Implementation Plan. [Available online at <http://www.cpc.ncep.noaa.gov/products/monsoon/NAME.html>.]
- Nesbitt, S.W. and D.J. Gochis, 2007: Characteristics of convection along the Sierra Madre Occidental observed during NAME-2004: Implications for warm season precipitation estimation in complex terrain. Manuscript submitted to *J. Hydromet.*, June 2007.
- Ray, A.J., G.M. Garfin, M. Wilder, M. Vasquez-Leon, M. Lenart and A.C. Comrie, 2007: Applications of monsoon research: Opportunities to inform decision making and reduce regional vulnerability. *J. Climate*, 20, 1608-1627.
- Viramontes, D., L. Descroix, 2003: Changes in the surface water hydrological characteristics of an endoreic basin of northern Mexico from 1970-1998. *Hyd. Proc.*, 17, 1291-1306.
- Vivoni, E.R., H.A. Gutierrez-Jurado, C.A. Aragon, L.A. Mendez-Barrozo, A.J. Rinehart, R.L. Wycoff, J.C. Rodriguez, C.J. Watts, J.D. Bolten, V. Lakshmi and T.J. Jackson, 2007a: Variation of hydrometeorological conditions along a topographic transect in northwestern México during the North American monsoon. *J. Climate*, 20, 1792-1809.
- Vivoni et al., 2007b: International Research Experience for Students/New Mexico Tech. hydrology project website: <http://www.ees.nmt.edu/vivoni/sonora/www/index.html>.
- Watts, C.J., R.L. Scott, J. Garatuza-Payan, J.C. Rodriguez, J.H. Prueger, W.P. Kustas and M. Douglas, 2007: Changes in vegetation condition and surface fluxes during NAME 2004. *J. Climate*, 20, 1810-1820.

Recent CIRMOUNT Activities

Lisa J. Graumlich¹ and Henry F. Diaz²

¹School of Natural Resources, The University of Arizona, Tucson, AZ

²NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO

Over 100 scientists and managers gathered at Timberline Lodge on September 18-21, 2006 for the 2nd MTNCLIM Workshop. The conference provided an open forum for scientists working on climate science problems related to mountain environments in the United States to disseminate their research findings, to promote interdisciplinary research, and to communicate with stakeholders and decision makers. The conference program consisted of a series of keynote presentations, invited and contributed oral presentations, poster session, and working group sessions. Specifically, the conference provided:

- A forum for presentation and discussion of long-term multidisciplinary climate studies in the West, including topics related to the alpine cryosphere, hydrology, climate change detection, mountain ecology, the carbon cycle, and paleoclimate.
- Observational, modeling and process studies of climate and climate impacts in the West.
- A means to facilitate communication with local and regional resource managers.

The participants in MTNCLIM conference came from a wide range of state and federal governmental agencies, including the Forest Service, NOAA, USGS, NRCS, NPS, California Energy Commission, and from major institutions of higher education across the country. In addition, representatives from community-based non-governmental organizations (e.g., watershed management citizen groups) attended.

For those unable to attend CIRMOUNT, a record of the conference is available, including 1) the workshop program with abstracts, 2) posters and presentations in pdf format, and 3) a webcast of the invited and contributed talk is available on the CIRMOUNT website at <http://www.fs.fed.us/psw/mtnclim/>. A particularly compelling keynote presentation was made by Jon Jarvis (Regional Director, Pacific West Region, National Park Service). A transcript of Jarvis's remarks was subsequently published as "An Inarticulate Truth: Communicating the Science of Global Change" in the January 2007 issue of the George Wright Forum (<http://www.georgewright.org/forum.html>).

A half-day workshop was convened immediately following the conference, entitled: Resource Options for Forest Management In

the Context of Climate Change. The workshop was led by: Linda Joyce (USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO), Connie Millar (USDA Forest Service, Pacific Southwest Research Station, Albany, CA), Ron Neilson (USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR), Dave Peterson (USDA, Forest Service, Pacific Northwest Research Station, Seattle, WA) and John Townsley (USDA Forest Service, Okanogan and Wenatchee National Forests). The post-conference workshop's objectives were to communicate current projections of future climate variability in the Pacific Northwest and its consequences to natural vegetation and forest resources in the region and to discuss new contexts and strategies for forest management under conditions of climate variability and uncertainty. In addition, the workshop served to facilitate discussion on the needs and opportunities for developing case studies to incorporate climate change into forest management. The post-conference workshop was attended by 22 resource managers from Washington and Oregon.

Beyond the expected product of a well-structured series of relevant and informative scientific presentations, we report the following outcomes.

- We have undertaken to establish an NSF-funded CIRMOUNT program office at the Western Regional Climate Center in Reno, NV to improve the delivery of scientific results focused on western mountains generated by scientists worldwide and to enable collaborative activities by scientists working on climate issues across the West.
- We have begun publication of a periodic newsletter—Mountain Views—as an effective forum for communication and exchange of ideas and new cutting edge research activities.
- We are working to incorporate different individuals, groups and communities into CIRMOUNT by rotating the MTNCLIM workshops among different hosting institutions across the West. In this way, we highlight different geographical contexts of the impacts of climate change and engage local and regional stakeholders with regionally relevant information.

The Mountain Research Initiative Introduces the GLOWA Jordan River Project: Integrated Research for Sustainable Water Management

Claudia Drexler¹ and Katja Tielbörger²

¹The Mountain Research Initiative (MRI)
c/o Forest Ecology, ETH-Zentrum, 8092 Zurich, Switzerland.
mri@scnat.ch www.mri.scnatweb.ch

²University of Tübingen, Plant Ecology, 72067 Tübingen, Germany.
katja.tielboerger@uni-tuebingen.de

Global Change Research Networks

The Mountain Research Initiative (MRI) initiates and coordinates regional networks of scientists working on global change in mountain regions. The conceptual framework for MRI's activities is the GLOCHAMORE Research Strategy (see <http://mri.scnatweb.ch/content/category/3/10/31>), which becomes tangible through the regional networks. As coordinator the MRI convenes platforms for direct exchange, provides digital means of communication, and makes exemplary projects known to a larger audience.

The GLOWA Jordan River Project was presented at the February 2007 workshop of the MRI's network for global change research in European mountains (GCRN_EM). The members of the network met in Zürich, Switzerland, for a two-day workshop. This meeting was focussed on scientists interested in joining FP7 proposals, or in finding future partners. Integration and stakeholder participation arose as key issues of the European network. We therefore introduce Mountain Views readers to the GLOWA Jordan River Project as it provides exemplary responses to these issues.

The GLOWA Jordan River Project

Background

The GLOWA Jordan River Project is run by Dr. Katja Tielbörger, Professor of vegetation ecology at the University of Tübingen, Germany. It is part of GLOWA (Globaler Wasserkreislauf im Wandel: The Changing Global Hydrological Cycle) and is a large-scale experiment launched by the German Federal Ministry of Education and Research (BMBF) in 2001. GLOWA produces sciencebased management strategies for local authorities in 5 river basins: the Elbe, Danube, Jordan, Volta, and Impetus.

The Jordan River drains parts of Palestine, Israel, and Jordan, and empties into the Dead Sea. The region has one of the lowest water availabilities worldwide, dropping below the absolute scarcity threshold of 500 m³ to 1000 m³ per capita/yr (Falkenmark et al 1998). Water demand is increasing rapidly due to high popu-

lation growth rates and economic development. Furthermore, climate projections indicate future drying and more extreme events. Declining water availability could exacerbate conflict in the region.

The GLOWA Jordan River Project consists of 5 interlinked work packages, three 3-year phases, and 11 subprojects with over 50 partners (<http://www.glowa-jordanriver.de/Project/Structure>). The current (2nd) phase provides good examples of how to achieve integration: 1) the integration of non-scientific and scientific groups in joint scenario development through Story and Simulation (SAS) scenario development; and 2) the integration of the disciplinary results of the subprojects, and their translation for decision-makers and other local stakeholders by means of the Water Evaluation and Planning Tool (WEAP).

Scenario Development

The GLOWA Jordan River Project uses the Story and Simulation scenario approach (Alcamo 2001) to integrate stakeholder knowledge on an equal footing with scientific findings. In 2006 the project leaders invited administrators and scientists from Israel, Jordan, and Palestine to a first scenario workshop. The workshop participants brainstormed the factors that influence water scenarios for the Jordan River. These factors included global warming, demography, regional stability (peace/war), and trade. Then they focused on major uncertainties, collapsing these into 2 axes that define the scenario space of the Jordan River watershed. The first axis, labeled "Finance and Pricing," has recession at one end and growth at the other. The second axis, "Access to and Allocation of Water," contrasts unilateral appropriation of water with multi-lateral water sharing.

At the second scenario workshop in early 2007, the stakeholders developed initial storylines for each scenario. While "trade" had earlier been defined as a relevant factor, participants now had the task of "telling the story" of this factor's development under, for instance, the scenario "recession with multilateral water sharing." The projects' scientists quantified the scenarios on the basis

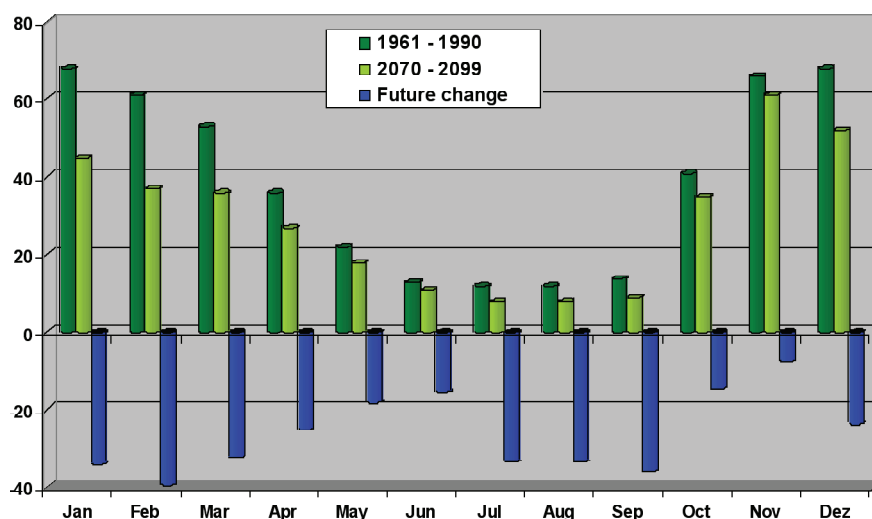


Figure 1. Monthly mean discharge in mm of the Upper Jordan catchment (control run vs future IPCC scenario B2), at gauge Yoseph Bridge. The dark bars show the massive percent reduction in discharge predicted for 2070–2099 by the hydrological model, WASIM, which will be problematic both during winter and summer months. (Source: Kunstmann et al 2006).

of the storylines and data from, for instance, the climate or hydrological models of the subprojects. Thus each scenario consists of specific values for factors influencing water management under conditions defined by the major uncertainties. An iterative process of refining qualitative scenarios with quantified factors will produce a set of rich, plausible and relevant quantitative scenarios by the end of 2008.

The Development of Understandable and Policy-Relevant Results

The GLOWA Jordan River Project uses the decision support system “Water Evaluation and Planning Tool” (WEAP) developed by SEI (Stockholm Environment Institute, <http://www.sei.se>) to merge the models developed within the scientific subprojects (see <http://www.glowa-jordan-river.de/Project/Models>), and to project the outcomes of the scenarios.

Figure 1 shows discharge outcomes associated with a climate change scenario. WEAP translates such hydrological outcomes into terms more relevant to policy and decision-makers. The underlying structure of WEAP is a spatial representation of the area indicating the major supply and demand nodes of the region, as well as any other water-relevant natural and built structures. WEAP then translates the quantified scenarios into changes in water supply and agricultural productivity. WEAP uses water as a currency and will provide the costs and benefits of management alternatives (eg of an orange plantation versus a housing development) under different scenarios (<http://www.weap21.org/>).

Application

The goal of producing applicable results has motivated the project from the beginning. Stakeholder involvement in scenario development promotes ownership of the process and its results. WEAP’s ease of use and transparency are great advantages when

it is used in water negotiations across sectors as well as between countries. Cultural tact and diplomacy will be critical in the third phase of the project. Prof. Tielbörger and her co-workers are preparing the ground for its introduction with the water authorities, a task easier in some countries than in others. The openness of authorities to WEAP depends on the availability of their own tools, on their partners in development aid, and also on concerns about data sharing. Of course, the results depend not only on the acceptance of the program, but also on the quality of the data fed into the system. Training workshops are planned in all 3 countries to transfer the scenarios and the WEAP tool to water managers and policy-makers. Once implemented via WEAP and SAS, the GLOWA Jordan River Project promises to be a successful example of the use of research for developing practical solutions.

References

- Alcamo J. 2001. Scenarios as Tools for International Environmental Assessments. Environmental Issue Report 24. Copenhagen, Denmark: European Environment Agency. Available at: http://reports.eea.europa.eu/environmental_issue_report_2001_24/en/issue_report_no_24.pdf.
- Falkenmark M, Klohn W, Lundqvist J, Postel S, Rockstrom J., Seckler D, Shuval H, Wallace J. 1998. Water scarcity as a key factor behind global food insecurity: Round table discussion. *Ambio* 27(2): 148–154.
- Kunstmann H, Suppan P, Heckl A, Rimmer A. 2006. Regional Climate Change in the Middle East and Impact on Hydrology in the Upper Jordan Catchment. Paper presented at the GLOWA Jordan River Status Conference, 19–21 September 2006, Esslingen, Germany. Available from the author at harald.kunstmann@imk.fzk.de.

Announcements

MtnClim 2008

We're proud to announce that the next Mountain Climate Workshop (MTNCLIM 2008) will be held on June 9–12, 2008 in Silverton, CO. The meeting will be held in collaboration with the Mountain Studies Institute (<http://www.mountainstudies.org>). A website has been established for the workshop at www.fs.fed.us/psw/mtnclim. The program will be developed over the next few months, and interested persons can obtain information about this meeting on the website.

PACLIM 2007

Oral/poster presentations on CIRMOUNT web: <http://www.fs.fed.us/psw/cirmount/meetings/pa-clim/paclim2007>.

Eastern Sierra/White Mountains - Mountain Climate Conference

Announcing a regional research symposium: White Mountains Research Station Symposium #5, entitled "Ecosystems and Resources in the Eastern Sierra, Owens Valley and the White Mountains. The meeting will include plenary sessions on Thursday and Saturday morning, invited talks, contributed talks, poster session, and concurrent sessions on Friday. Field trips sponsored by: University of California White Mountain Research Station, Consortium for Integrated Climate Research in Western Mountains (CIRMOUNT), USFS Pacific Southwest Research Station, and Sierra Nevada Aquatic Research Laboratories. A symposium website will be developed over the next few months and will be posted on the WMRS web site: <http://www.wmrs.edu>.

Special Session at AGU Fall Meeting 2007

Announcing a special CIRMOUNT-sponsored session at the American Geophysical Union (AGU) Fall 2007 meeting in San Francisco, the week of December 10, 2007. The session is titled, Climate Change in High Elevation Mountain Environments, and is listed as session GC-09 under the Global Environmental Change section of the AGU. A description of the themes and goals of the session can be found at <http://www.agu.org/meetings/fm07/?content=search&show=detail&sessid=168>. Interested persons may contact any of the convenors for more information:

Dr. Connie Woodhouse, Department of Geography and Regional Development, 409 Harvill Building, University of Arizona, Tucson, AZ 85721-0076. conniew1@email.arizona.edu

Dr. Connie Millar, USDA Forest Service, Sierra Nevada Research Center, 800 Buchanan St., Albany, CA 94710 cmillar@fs.fed.us

Dr. Henry Diaz, NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80303 Henry.F.Diaz@noaa.gov.



Photo: From the Mountains to the Sea (Oahu, Hawaii), by Tom Giambelluca.