Applications of monsoon research: Opportunities to inform decisionmaking and reduce regional vulnerability

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ABSTRACT

This article presents ongoing efforts to understand interactions between the North American Monsoon and society, in order to develop applications for monsoon research in a highly complex, multicultural and binational region. The North American Monsoon is an annual precipitation regime that begins in early June in Mexico and progresses northward to the southwestern United States. The region includes stakeholders in large urban complexes, productive agricultural areas, and sparsely populated arid and semi-arid ecosystems. The political, cultural, and socioeconomic divisions between the U.S. and Mexico create a broad range of sensitivities to climate variability as well as capacities to use forecasts and other information to cope with climate.

We highlight methodologies to link climate science with society and analyze opportunities for monsoon science to benefit society in four sectors: natural hazards management, agriculture, public health, and water management. We synthesize a list of stakeholder needs and a calendar of decisions to help scientists link user needs to potential forecasts and products. To ensure usability of forecasts and other research products, we recommend iterative scientist-stakeholder interactions, through integrated assessments. These knowledge-exchange interactions can improve the capacity for stakeholders to use forecasts thoughtfully and inform the development of research, and for the research community to obtain feedback on climate-related products and receive insights to guide research direction. We expect that integrated assessments can capitalize on the opportunities for monsoon science to inform decisionmaking, in the best instances, reduce regional climate vulnerabilities and enhance regional sustainability

1. Introduction

The goal of the multinational, multi-year North American Monsoon Experiment (NAME) program is to improve understanding of monsoon dynamics to improve prediction skill (NAME, 2004). A larger goal for monsoon research is to enhance society's ability to cope with climate variability and therefore reduce its vulnerability by providing monsoon information and predictions. Lemos and Morehouse (2005) recently described models to facilitate the "co-production of knowledge," i.e., the development of usable information and the identification of meaningful responses to climate variability and change. They find that addressing vulnerability to climate requires a balance between research to understand complex science problems and research on what stakeholders perceive as necessary for making decisions. Furthermore, interactions between scientists and stakeholders are necessary to achieve "fit" between stakeholders' needs and science products, and these interactions are most successful in the context of integrated assessments (Lemos and Morehouse, 2005). This article reviews recent work in the monsoon region to synthesize knowledge on vulnerability for specific sectors in the region, and identify opportunities for scientist-stakeholder interactions that might inform decisionmaking and reduce vulnerability in the region.

The North American Monsoon (hereafter, "the monsoon") is the major source of warm-season precipitation across the U.S. Southwest and Northern Mexico, contributing more than 50% of the annual precipitation in some areas (Sheppard et al. 2002). The monsoon typically begins in southern Mexico in early June and progresses northward to the southwestern U.S. by early July (Adams and Comrie 1997; Higgins et al. 1999). The region's climate is highly variable: in northern Sonora over the past decade, climate variability has included seven to eight years of drought, intense rains in 1994-1995, and freezing temperatures in 1996 (Browning-Aiken et al. 2005).

Over the past decade, significant advances in the observation and understanding of the monsoon system have contributed to the potential to predict monsoon parameters, including: the timing of onset and retreat; total precipitation during the season; intra-seasonal and intra-annual features, such as moisture surges, bursts and breaks; and the consequent hydroclimatology of the region (Barlow et al. 1998; Magaña et al. 1999; Gutzler 2000; Higgins and Shi, 2000; Castro et al. 2001; Hawkins et al. 2002; Douglas and Leal, 2003; Li et al. 2004;).

In recent years, federal science programs have focused on improving the connection between science and society by making science more relevant and usable to decisionmakers (NRC 2001; Jacobs et al. 2005a). However, decades of research have shown that the effective delivery of climate information to stakeholders is less straightforward than simply making information available (Changnon et al. 1988; Stern and Easterling 1999; Hartmann et al. 2002a,b; Greenfield and Fisher 2003; Gamble et al. 2003; Rayner et al. 2005). Stakeholders – including organizations and individuals who own or manage land, manage or use water, contribute to the economy, or live in the region (Bales et al. 2004) -- require climate information tailored to their specific decisionmaking contexts, for example, suit the timing and spatial scale of management decisions, and in language understood by information users (Chagnon et al. 1988; Ray 2004; Lemos and Morehouse 2005; Jacobs et al. 2005a). These contexts encompass institutional, socioeconomic, and political settings with a range of sensitivities, vulnerabilities, and capacities to respond to climate and forecasts. Growing population and rising water use increase vulnerability in both the U.S. (Liverman and Merideth 2002) and northern Mexico (Magaña and Conde 2000).

Fortunately, efforts to apply monsoon research for decisionmaking are beginning just as integrated assessment projects and methodologies are bearing fruit. Integrated assessments are interdisciplinary efforts to produce usable science through participatory stakeholder processes and research-applications partnerships that bring together researchers, managers, policy makers and others. These efforts, such as the Climate Assessment for the Southwest (CLIMAS) at the University of Arizona (Liverman and Merideth 2002) have shown that stakeholders require information at appropriate scales (Gamble et al. 2003), that forecast products often do not match stakeholders' interests (Bales et al. 2004), and that scientists' questions may not be aligned with those of stakeholders (Lemos and Morehouse 2005).

This article discusses current efforts to understand the interaction of climate and society in order to develop applications for monsoon research. Because many stakeholders are sensitive to an interlocking set of climate phenomena including winter precipitation, ENSO impacts, and climate change, we draw on insights about climate vulnerability across time scales. After summarizing the state of monsoon forecasting, we present methodologies to study vulnerability and to develop usable climate science. We next introduce the monsoon region and its socioeconomic and institutional characteristics, because these contexts for vulnerability are critical to an understanding of climate and society interactions. The fourth section highlights four principal stakeholder communities: natural hazards management, public health, agriculture, and water management. Based on these studies, we synthesize a list of information needs associated with the North American Monsoon. To ensure that products are usable by stakeholders, we recommend that monsoon researchers interested in developing usable research and products should participate in integrated assessment activities in the region, including capacity-building efforts such as a Monsoon Outlook.

2. State of monsoon forecasting

Currently, monsoon-related forecasts include the official NOAA/NWS monthly and seasonal U.S. precipitation forecasts issued by the Climate Prediction Center (CPC). These forecasts are issued mid-month, and an updated monthly forecast is issued on the last day of the month.[1] The Mexican *Servicio Meteorológico Nacional* (National Meteorological Service, SMN) issues analogous seasonal precipitation forecasts.[2] Although some experimental forecasts and monsoon-related information are available, primarily on research or experimental webpages, no operational[3] forecasts of key seasonal features of the monsoon currently exist (e.g. onset, overall strength, duration). Forecasts of a number of monsoon-related parameters exist primarily at short-term (weather) time scales and with only a few days lead time. Leading up to and during the monsoon, NWS Weather Forecast Offices (WFOs) and some commercial meteorological services make short-term weather forecasts of monsoon-related parameters and may provide related information. The Predictive Services Group of the National Interagency Coordination

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[1] http://www.cpc.ncep.noaa.gov/products/forecasts/month_to_season_outlooks.shtml

[2] http://smn.cna.gob.mx/SMN.html

[3] Operational is a specific NWS term referring to, "products and data that have been fully tested and evaluated that are produced on a regular and ongoing basis," http://www.cpc.ncep.noaa.gov/products/outreach/glossary.shtml.

Center (NIFC) makes monsoon-related weather forecasts as part of assessing fire potential before and during the fire season. A webpage maintained by the NWS/WFO Tucson tracks precipitation totals and other variables for several sites in southern Arizona, with data comparing the current year to previous years, start dates, and educational material on the monsoon.[4]

A major goal of the NAME program is to improve the simulation of monsoon variability in coupled (ocean-land-atmosphere) climate models in order to predict features of the monsoon months to seasons in advance (Higgins et al. 2006). The NAME Model Assessment Project (NAMAP) analysis found current models can simulate the basic evolution of a summer precipitation maximum near the core monsoon region, but there are important differences in the monthly evolution and diurnal cycle of precipitation generated by the models compared to observations (Gutzler et al. 2005). Several metrics have been identified to quantify model simulation quality and improvement focused on monsoon onset and the diurnal cycle of precipitation, surface air temperature and fluxes, low-level winds, and moisture transport.

3. Methodologies

The assessment of social vulnerability has become a widely accepted theoretical and methodological framework for analyzing climate-society interactions. Vulnerability is a dynamic social indicator linking human society, natural ecosystems, and socioeconomic and political structures. Kelly and Adger (2000) define vulnerability as "the ability or inability of individuals and social groups to respond to, in the sense of cope with, recover from or adapt to, any external stress placed on their livelihoods and well-being." Vulnerability assessment is not simply a measure of exposure to hazards, but a broader assessment encompassing human-environment systems and factors both within and outside those systems that affect their vulnerability (Turner et al. 2003), including exposure to events, capacity to respond, and resilience (Bohle et al. 1994). An assessment also identifies which stakeholder groups are especially susceptible or sensitive to climatic conditions, degrees of sensitivity among different socioeconomic groups, and the causes of that sensitivity (Vásquez-León et al. 2002; Ribot 1996). A less vulnerable community or

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[4] http://www.wrh.noaa.gov/twc/monsoon/monsoon_info.php

social group has a better response capacity, i.e., a broader range of short-term responses, as well as greater resilience, i.e., chance of quick recovery and long-term adaptation (Blaikie et al. 1994). Assessing social vulnerability is a significant starting point in identifying the adaptive capacities of a community, which, in turn, may lead to improved resilience over time to climate change and climate events (Kelly and Adger 2000). After changes in public policy, social institutions, and private decisionmaking, a community may view itself as less vulnerable to climate variability or specific events (Finan et al. 2002; Vásquez-León et al. 2003).

In addition to the social vulnerability methodology, theoretical frameworks of institutional analysis and policy sciences (e.g. analysis of decision processes) may be used. Research tools may include in-depth or focus-group interviews, questionnaires, participant observation, and review of secondary data. Research can involve participatory methods such as vulnerability mapping, where stakeholders sketch out their interpretations of vulnerable areas for eventual integration by researchers (Finan and West 2000). Often, a multi-method approach is used to evaluate a context in several ways in order to gather a more complete assessment. Although quantitative measures of vulnerability have been used in this region (see Luers et al. 2003), studies considered in this article use primarily qualitative methods: researchers are attempting to gain holistic or integrated understandings of the context under study (Finan and West 2000), rather than produce a quantitative measurement or improve predictive skill of human behavior.

Understanding how society interacts with climate is the foundation for developing applications. It establishes what climate information is needed, the appropriate temporal and spatial scales, and how that information should be formatted and communicated (Jacobs et al. 2005b). But a mechanism is needed to bring together social science studies with advances in physical science. An integrated assessment process, illustrated in Figure 1, has been successful in bringing multidisciplinary groups of scientists together with stakeholders to develop usable science. Examples of integrated assessments include studies of regional climate impacts for the Pacific Northwest (Miles et al. 2000), the region-by-region approach of the National Assessment of Climate Change (USGCRP 2000), and the CLIMAS regional integrated assessment, which is the source of several of the studies described below. CLIMAS' integrated assessment strategy involves evaluating and synthesizing current knowledge about climate and its impacts in a given area, as well as integrating the formulation of research questions, methods, and data from both the physical and social sciences (Bales et al. 2004). Integrated assessments may facilitate interactions between scientists and stakeholders, including activities designed to improve the two-way flow of knowledge between researchers and climate information users. Scientist-stakeholder interactions are probably best implemented through integrated assessment teams or climate service operations (Lemos and Morehouse 2005). These interactions include assessments of decisionmaking contexts and information needs, workshops and other activities to build capacity for the thoughtful use of climate information, the co-development of research products, and the enhancement of product usability through stakeholder feedback and rigorous product evaluation (e.g., Hackos and Redish, 1998). The CLIMAS approach facilitates interactions among researchers, policymakers, and other stakeholders (Liverman and Merideth 2002), and conducts user-oriented experiments (NRC 2001), which are a specific form of these interactions.

4. Overview of the applications context

The NAME Science Plan defines the monsoon region in process-based tiers including the core monsoon area dominated by frequent, diurnal convective processes (Tier I), an area associated with intraseasonal, transient variability of the monsoon (Tier II), and the area in which continental-scale, warm-season circulation and precipitation patterns respond to slowly varying oceanic and continental surface boundary conditions (Tier III) (NAME 2004, Figure 2). The region can also be defined human terms, including large urban complexes, irrigated agricultural valleys, ranches, forests, deserts, protected areas, and national parks in monsoon-influenced areas of several states in Mexico and the U.S. (Figure 2). Variability of climate and the monsoon itself is embedded in the culture of the region (Meyer 1996), for example, festivals timed around the monsoon onset in Native American cultures and Hispanic communities (Nabhan 1992).

The U.S.-Mexico border divides the monsoon region, a political boundary separating regions in two countries that have a common cultural heritage. Many of the demographic, socioeconomic, and cultural characteristics identified with the border extend further north and south of that arbitrary designation. The border region is an area of unusually high vulnerability to climate variability, due to factors including high population growth, increasing demands on a limited water supply, uneven access to adaptive resources, and marked structural inequalities related to social class and ethnicity. During the 1990s, Arizona's population growth rate was 40% compared to a 13% growth rate nationwide (Liverman and Merideth 2002). In Sonora, the Hermosillo and Nogales urban areas grew at 3.13% per year and 4.0% per year respectively, compared to the Mexican national growth rate of about 2.0% per year (INEGI, 2000). The North American Free Trade Agreement (NAFTA) has contributed to population growth by accelerating border industrialization. Associated with the high growth rate of the border region are increasing water demand, greater urban-rural competition over water and land, and needs for extended infrastructure and additional housing.

The border population is diverse in ethnicity, language, and socioeconomic status, and contains a high concentration of socially vulnerable populations (Austin et al. 2000; Vásquez-León et al. 2003). While border *municipios* (similar to U.S. counties) within Mexico are wealthier than average, the opposite is true for U.S. border counties. Border cities are located in four of the seven poorest counties in the U.S. (U.S. Census 2000). The large and increasing Hispanic/Latino population of Arizona and New Mexico represent 25% of the states' total population (U.S. Census 2000; Liverman and Merideth 2002). Arizona is home to 18 Native American tribes, several of which were split historically by the border, including the Tohono O'odham, Apache, and Cocopah tribes. In northwest Mexico, sizeable indigenous populations include the Seri, the Yaqui, Mayo, and Tarahumara indigenous populations as well as small-scale *mestizo* farmers, mostly found in the highlands of the Sierra Madre in eastern Sonora. These populations have been largely excluded from decades of development efforts by the state focused on urban areas and the flat coastal valleys (Vásquez-León and Liverman 2004).

Ranching and agricultural livelihoods have been key to the economic development and cultural identity of Sonora and Arizona (Vásquez-León et al. 2003), but also are highly vulnerable to monsoon variability and extreme events, especially long-term drought. Farmers on both sides of the border are vulnerable to changes in the availability of irrigation water because large sectors of the economy are based on commercial crop production (Wilder and Whiteford 2006). Sonora is one of Mexico's top five agricultural producers, especially for wheat, meat, grapes, citrus, asparagus and raisins (Wilder and Whiteford 2006), and the most highly irrigated Mexican state, with 60% of its land under irrigation (Wilder 2005). Intensified agriculture is competing with water demand from rapidly growing cities – especially along the border – and there is a decline of water quality and quantity, particularly in the state's overdrafted coastal aquifers (Magaña and Conde 2000; Wilder 2002).

Evolving relations between the U.S. and Mexico also influence regional vulnerability and efforts to address it. On one hand, interactions and linkages across the border proliferate with respect to water and resource management (Varady and Morehouse, 2003). On the other hand, the U.S. increasingly conflates border issues with national security in the post- September 11 era. In May 2005, the U.S. Congress voted to give precedence to national security concerns at the border over environmental protections. The July 2006 elections in Mexico, will bring a new presidential administration, also may bring changes in environmental governance.

5. Vulnerability assessments and user-oriented experiments

Natural hazards, public health, agriculture, and water management are four of the sectors identified by regional assessments in which climate plays a role in overall vulnerability (Benequista and James 1999; Liverman and Merideth 2002; Ray et al. 2003; Vasquez-Leon et al. 2003). In some cases, researchers interact in user-oriented experiments with administrators and planners who, in turn, manage the effects of climate for many other stakeholders (fire, water supply, drought). For others (public health), the research focus has been to understand climatic impacts on that community and assess information needs. In the cases of agriculturalists and individual water managers, the stakeholders themselves have been the focus of detailed social science assessments. In each sector, however, applications researchers have found contexts in which improved monsoon information may be useful to reduce vulnerability and to enhance society's ability to cope with climate variability.

a. Natural hazards: Drought, floods, and fire

Natural hazards risk management is one of the most climate-affected sectors. The monsoon influences floods, power outages, wind damage, fire, drought, and human health emergencies. Although these events often occur in a short-response time frame, emergency managers place a high priority on reducing disaster impacts through mitigation, preparedness, planning and training (ADEM 2004). Improved monsoon-related forecasts and monitoring can increase the potential for local, state, and federal emergency management agencies (EMAs) to reduce impacts of natural hazards. This information can help EMAs balance climate-related risks with other influences on decisionmaking, such as risks of domestic terrorism.

1) DROUGHT

Drought is not an isolated issue but interacts with other sectors, especially fire, water management, health, land management, dryland agriculture and ranching. Adaptation to drought in the region has been a human activity from ancient social traditions (Liverman et al. 1999) to modern drought mitigation planning (Jacobs et al. 2005a; WGA 2004). Monsoon precipitation significantly affects drought in the timing and quantity of summer precipitation, and impacts the balance of summer supply and demand for many sectors. Delays in monsoon onset also hinder the development of summer grasses, which are crucial to the ranching industry. The needs for drought information are related to the specific information and forecast needs, and decision calendars of the particular sectors described in below.

2) FLOODS AND WINDS

Severe monsoon windstorms and rains are a hazard, especially in rural areas. In August 1996, severe monsoon storms caused extensive damage to private and public property in Yuma and Maricopa counties, resulting in estimated emergency fund expenditures of $2.6 million (ADEM 1997). In 2002, severe summer thunderstorms caused damages of $1 million to the Gila River Indian Community (FEMA 2002). Power outages caused by lightning and high winds may result in interruptions to hospital functioning, enhanced risk to special-needs populations, loss of infrastructure, problems in traffic management and law enforcement, increased food spoilage, and disruption of public schools. Power outages can also interrupt water delivery, a concern among water managers (Carter and Morehouse 2003). Summer floods are another monsoon-related emergency management concern (Pagano et al. 2001; ADEM 1997, 2004). Summer floods particularly concern managers regarding burned areas, such as the 2002 Rodeo-Chedeski fire that left 468,000 acres of central Arizona prone to flooding.

Improved pre-season forecasts of monsoon-season precipitation can allow EMAs to better preposition flood-response resources and mount public information campaigns. False monsoon onsets are particularly vexing to EMAs, as they are preoccupied by a variety of early summer demands, including fire, drought-related emergencies, and human health threats. For flood mitigation, EMAs need predictions of precipitation intensity, not just totals (McCord 2005). EMAs could use predictions and monitoring of the spatial variability of precipitation to improve resource coordination within each agency and across agencies.

3) FIRE MANAGEMENT

The connections between fire and climate have been studied extensively through interactions between climate and ecosystem researchers, knowledge transfer experts, and the fire community, which includes federal, state, and local agencies, with coordination though mechanisms like the NIFC Geographic Area Coordination Centers (Morehouse 2000; Garfin and Morehouse, 2001; Austin et al. 2000). Atmospheric conditions related to the monsoon have both fire-producing and fire-mitigating effects, and the monsoon's role in fire occurrence displays high intraseasonal and interannual variability (Crimmins and Comrie 2004; Mohrle 2003; Brandt, 2005), For example, breaks of 8-10 days may lead to a post-onset increase in fire numbers (Brandt, 2005), and monsoon conditions also impact future fire seasons, as fire severity and extent depend on fuel accumulation resulting from climatic conditions during the previous 10-18 months (Westerling et al. 2003).

The peak fire season in the US-Mexico borderlands is the pre-monsoon period because it is arid and accompanied by dry lightning and seasonally low fuel moisture, increasing the risk of large fires. Generally, monsoon onset signals the beginning of the end of the fire season (Swetnam and Betancourt 1998). In southeastern Arizona, for example, the number of wildfires generally peaks about a week before monsoon onset, then declines from about 14 fires a week to three fires a week by mid-August (Brandt et al., 2005). Meanwhile, fire starts peak in August for much of the western United States (Westerling et al. 2003). This shift northward of fire starts is relevant for West-wide fire management: improved prediction of monsoon onset at longer lead times may allow national fire coordinators to shift people and resources to areas with higher risk. Researchers and fire managers have worked together to evaluate the existing definition of onset (defined in Arizona as three consecutive days with a dewpoint meeting or exceeding a local threshold of 55°F) and have concluded that this definition is not a useful metric for fire management: in Southeastern Arizona, 77% of fires with natural starts (i.e., lightning strikes) occurred at or above dewpoints of 55° F (Mohrle et al. 2003). Wildfire numbers declined only after dewpoint temperatures reached about 60°F. Until minimum relative humidity values remain above 20% for five of seven days per week, southwestern fire fuels can still burn aggressively regardless of dewpoint temperature (Maxwell, 2005). Because of the importance of humidity, another topic of interest an assessment of accuracy of relative humidity forecasts.

Monsoon information was among the climate information most frequently used by the fire management community during the 2000 season (Garfin et al. 2001). Based on a needs assessment of the fire community, researchers are now collaborating with the fire community to enhance use of climate information in fire management. The National Seasonal Assessment Workshops (NSAW) bring climate scientists together with fire managers to create pre-season fire potential outlooks, based on official NOAA-CPC outlooks, experimental fire forecasts (e.g., Roads et al. 2005; Brown et al. 2004), and analyses of vegetation and fuel moisture conditions (Garfin et al. 2003, 2004; Lenart et al. 2005). These workshops help bridge gaps in the use of climate information by consolidating information scattered across multiple agencies and sources, and enhancing fire managers' understanding of fire-climate interactions via knowledge about climate diagnostics and seasonal climate forecasts. The fire community further disseminates workshop outlooks through briefings, websites, trade journals, and reports to regional fire managers (Lenart et al. 2005).

The workshop process is a mechanism for climate professionals to disseminate knowledge about climate, for applications researchers to collect feedback on stakeholder needs and improve information dissemination, and for climate scientists to identify new fire-relevant climate research questions. Fire managers express the following needs for climate information: seasonal and medium-range forecasts of onset and strength improved ability to recognize monsoon false-starts; forecasts on the likelihood of breaks within the monsoon season; intraseasonal predictions of monsoon strength and consistency and wet versus dry thunderstorms. In particular, they desire a monsoon definition and indices relevant to fire management, such as a monsoon threshold for humidity that more directly relates to fire potential. Fire managers could use improved monsoon forecasts to assess the timing and extent of future firefighting resources (Garfin and Morehouse 2003) and for evaluating fire use opportunities (i.e., allowing fires to burn to promote forest restoration). Although not all of the information desired by fire managers is available, the potential benefits of improved information to mitigate fires includes protection of lives and property as well as firefighting dollars saved: federal agencies spent more than $40 million to suppress Arizona's Rodeo-Chediski fire alone (U.S. Forest Service, 2003).

b. Agriculture

From a socioeconomic perspective, agriculture in the monsoon region is highly vulnerable to climate variability. The region's low and erratic precipitation does not support rain-fed farming in most of the region, except for areas at higher elevations like the eastern mountainous region of Sonora. The sierra is dotted with small-scale farms scattered in the rugged terrain where patches of flat lands in combination with higher and more reliable precipitation allow rain-fed subsistence and commercial farming. Ranching is dependent on natural vegetation (particularly in Arizona) or cultivated fodder that is susceptible to the same limitations. For example, in 2005 despite average to above-average winter precipitation across much of the monsoon region, summer grass development in rangelands was hindered by the second-latest monsoon onset on record, and ranchers required supplemental feed (Crimmins, 2005).

1) AGRICULTURE IN SONORA

Near the Sonora-Arizona international border, agricultural producers in rural Mexican municipios of the Santa Cruz and Magdalena river basins typically integrate farming and cattle ranching (Vásquez-León and Bracamonte 2005), and depend both on surface water and groundwater. This region produces sorghum, corn, beans, a variety of fruits and vegetables, and forage crops for cattle. Ranching typically involves cow-calf operations in which a breeding herd is maintained and calves are sold to feedlots in the US or other parts of the state.

This region experienced a severe meteorological drought from 1996 to 2005, as monitored by the long-term Standardized Precipitation Index (SPI) for the Santa Cruz River Basin (see Vásquez-León and Bracamonte 2005). Sonoran farmers also have observed anomalously high summer temperatures, erratic monsoon rains, and localized, heavy, short duration rains that contribute greatly to erosion. They perceive a greater incidence of late monsoon rains that have been particularly damaging. As a result of the drought the number of groundwater wells in use has declined (SAGARPA 2003) as they either dry up or the water table lowers to the point that water becomes too expensive to pump. Cultivated area declined 46.5% from 1998 to 2004. This region also suffers periodically from devastating floods; in 1993, a major flood devastated crops and entire fruit orchards. These climatic factors all impact farmers' ability to cultivate and harvest crops (Vásquez-León et al. 2002).

Vulnerability to climate factors is determined not only by the physical events, but by factors related to differential welfare levels and access to adaptive resources, including social class, access to water, technology, financial resources, government programs, marketing, and institutional networks. In particular, the adaptive resources available to commercial private sector landowners are significantly greater than those of smallholders, including *ejidatarios* (communal landowners). Government programs and policies tend to benefit large producers more than smaller ones, and ownership type and size of operation impacts access to credit and banking. National and international agricultural policies such as land privatization, which began in 1992, and NAFTA, have had major impacts on producers' ability to respond to the drought and other climatic events (Vásquez-León and Liverman 2004). Short-term strategies to cope at the farm-level include storing forage crops during years of good rains, buying supplemental feed during dry years, and selling stock. During a multi-year drought farmers reduce the area under cultivation, change to lower water demand crops, or decrease the production of food crops and increase the production of forage to keep some cattle. On both sides of the border, coping strategies depend on the access to and ability to control water required during critical times, the managerial skill of individual farmers, the successful application of technologies, and the use of improved climate forecasts (Vásquez-León et al. 2003).

Although most farmers have access to weather forecasts from local news, few farmers in the region have access to on-line forecasts. Only a few farmers have computers and are computer literate, typically those who are better off. Furthermore, government programs designed to help producers deal with the consequences of natural hazards also tend to be more accessible to those who are wealthier, better connected, and better educated. Climate forecasting information may contribute to reducing the level of uncertainty under which farmers and ranchers must make critical decisions, and by providing a basis for planning. For example, based on a 90-day outlook of a drier than normal summer, a farmer may plant less corn and more forage. User associations might incorporate forecasts into irrigation plans made every six months for each agricultural cycle. Agriculturalists are interested in forecasts of both wet and dry conditions, because in either case yields may be reduced and crop quality affected, and information on monsoon variability, particularly the onset and retreat of monsoon precipitation; and in better forecasts of unusual events and forecasting information that ties climate to specific weather events. Farmers say they would like a five-year outlook for precipitation to inform decisions on longer-term adaptive strategies to deepen wells, invest in irrigation technology, or to change cropping strategies.

2) RANCHING IN ARIZONA

Ranching in Arizona is also highly sensitive to climatic variability, where this sector is almost entirely dependent on natural vegetation in low- and high-desert ecosystems, with few ranchers relying on irrigated pastures. Eakin and Conley (2002) conducted a ranch-level analysis based on in-depth interviews during and following medium to severe droughts in the region, including the dry summers of 1996 and 1997 and the dry fall-winter of 1998-1999. As in Sonora, most ranches are cow-calf operations. Drought periods are associated with poor forage quality, delayed breeding, significant declines in the number of calves produced. Anticipatory actions and in-season responses available to ranchers include pasture and forage acquisition, supplemental feed, securing alternate water supplies, and cutting back the herd size. Failure to respond can compromise both economic returns and long-term sustainability of the ranch.

Climate information has the potential to reduce vulnerability by facilitating ranching decisions during times of stress. About half of the ranchers surveyed thought that climate forecasts would be valuable to their operations, and most of those already paid attention to them. These users almost all received the NOAA long-range forecasts in livestock or agricultural journals, not directly from NOAA. As in Sonora, climate variability is not the only factor in the vulnerability of ranchers; market factors, changing land use policies, political pressures and individual management decisions also contribute. Use of climate information is likely to improve if the information is integrated with market, policy, and other information, and is provided via accustomed information distribution channels, including agricultural journals and reports, and extension programs.

c. Public Health

Diseases and air-quality problems are two public health issues for which improved monsoon information might allow mitigative responses. The arid pre-monsoon period and the onset of the monsoon are strongly related to seasonal outbreaks of valley fever (*coccidioidomycosis*), a disease endemic to the region caused by a soil fungus that responds to soil moisture and temperature. There are thousands of human cases per year in the U.S. alone, and over a hundred deaths (Comrie, 2005). Anomalous moisture and wind conditions in the pre-monsoon period lead to outbreaks of the disease over the subsequent 18-24 month period (Comrie (2005). The monsoon itself leads to greater soil moisture and apparent suppression of fungal spore dispersal. State public health agencies are using experimental models of climate-related valley fever incidence to assess health risks.

Another disease influence of the monsoon is to provide surface moisture for mosquito species that are recognized vectors for dengue fever and West Nile virus in the region. These mosquitoes increase dramatically during the monsoon, and the use of seasonal climate information might be used to aid in understanding and managing the mosquito populations

(Hoeck et al. 2003; Zinser et al. 2004). Public health officials might use observations of conditions and forecasts to mitigate these diseases, for example, observations of a relatively wet pre-monsoon period might alert health officials to watch for later cases of valley fever. A forecast or observation of a dry monsoon (and lack of suppression of spore dispersal) might be used to advise the public to avoid exposure to dust.

Two important aspects of air quality in the southwestern U.S, ozone and particulate matter, both are significantly influenced by the monsoon, which alters conditions for ozone photochemistry and dust dispersion (Wise and Comrie 2005a,b). Particulate matter (PM) is strongly negatively correlated with relative humidity and other moisture variables altered by the onset of the monsoon. The arid pre-monsoon is the time of year with the highest windblown dust; thunderstorms in the early part of the season are frequently windy with relatively little precipitation, and they can raise particulate matter pollution levels to hazardous levels (Wise and Comrie 2005a). PM is also a factor in valley fever outbreaks. Early or late monsoon onsets alter the moisture and wind regimes controlling PM, for example, higher soil moisture levels during the monsoon keep particulate levels lower, and they rise again in the dryer post-monsoon period. Local and state air quality agencies require dust mitigation (e.g., spraying water at construction sites) when dry and windy conditions are forecast or present.

In contrast to some other parts of the U.S. where temperature is the major meteorological factor controlling ozone, in the southwest mixing height and relative humidity are major factors associated with high ozone events (Wise and Comrie 2005a). Ozone pollution peaks in the summer months due to high ultraviolet radiation and temperatures driving photochemical activity. The monsoon leads to a seasonal greening of vegetation and release of biogenic hydrocarbons that alter the local and regional photochemistry, and can either increase or decrease ozone levels (Diem and Comrie 2001). Given the influence of the monsoon on air-quality related variables, these managers are interested in the role of the monsoon in daily air quality parameters, and in forecasts of air-quality relevant parameters on time scales from days to seasonal and longer-term, and the potential of the timing of monsoon onset to influence ozone precursors from vegetation (Wise and Comrie 2005a,b). Monitoring of air-quality relevant parameters is also of interest, including humidity and other moisture variables, wind regimes, and mixing heights. Improved monsoon information could assist air quality managers in efforts to improve management strategies to avoid detrimental affects of ozone and PM to humans and ecosystems. Meteorological variability also influences how managers evaluate results of efforts to protect and improve air quality on short term, seasonal, and longer time scales (Wise and Comrie 2005b).

d. Water management

Water management in both the U.S. (Liverman and Merideth 2002) and Mexico (Magaña and Conde 2000) is sensitive to climate variability because rivers and aquifers already face shortages from increased use due to agricultural expansion, urbanization, and groundwater mining. Additional concerns that may affect surface water supply include Native American water rights, retaining in-stream flows for ecosystems, and endangered species recovery programs. Climate variability may exacerbate all these factors, raising the interest in climate information among water managers.

The monsoon region is a transition zone with respect to water resources. In northern parts of the region, winter precipitation the most important factor determining supply (Pagano et al. 2003; Sheppard et al. 2002), but in central and southern Sonora and Chihuahua, summer precipitation and summer streamflow dominates the annual hydrograph (Gochis et al. 2006). In much of the region, summer precipitation is important for determining the balance between supply and demands which peak in the summer for agricultural and urban use, and for determining water supply where summer precipitation dominates. For example, monsoon precipitation is a large proportion of the water supply for the Pecos River in New Mexico, and the *Sistema Hidráulico Interconectado del Noroeste* (Interconnected Northwestern Hydraulic System), a system of reservoirs and supply canals for a large and important agricultural region of northwest Mexico (Ray et al. 2003). Another intriguing application of summer precipitation forecasts is implementation of the Glen Canyon Dam Adaptive Management Program (GCDAMP), intended to provide releases from Glen Canyon Dam to benefit the downstream ecosystems on the Colorado River (Jain et al. 2006). Research by the GCDAMP indicates that the releases are likely to have the most benefit soon after summer storms flush sediment into the Colorado River from the Paria River. Monsoon-related outlooks of storms could allow improved implementation of the program. Finally, several transboundary river systems are influenced by monsoon precipitation, including the Rio Grande (called the *Rio Bravo* in Mexico), the Colorado and San Pedro Rivers. Binational treaties determine water allocation to each country, and existing conflicts between the nations due to the scarcity of surface water are further exacerbated by drought (Morehouse et al. 2000). Shared water resources can also serve as a point of cooperation as in the Santa Cruz River that flows through Nogales, Sonora, then through Nogales, Arizona, supplying both towns. These towns cooperated to mitigate flood risk posed by the 1997-1998 El Niño (Sprouse and Vaughn 2003).

1) URBAN WATER MANAGEMENT IN NORTHWEST MEXICO

The adoption of a new national water law in 1992 dramatically changed the context for water management in Mexico, and the new decentralized system has impacts and opportunities for the use of climate science. Previously a highly centralized system managed out of Mexico City, water is now managed by a decentralized market-based system, with water fees to cover operation and maintenance and potential privatization of urban and rural water systems. The new law also created *consejos de cuenca* (watershed councils) charged with participatory planning representing interests of all water users in a watershed (Wilder 2005). There are three of these councils in Sonora, that bring together the major water user sectors on a regular basis to discuss current problems and means to resolve them, as well as long-term plans for the watershed. At this early stage, the watershed councils seem preoccupied with resolving pressing current issues relating to water shortages due to drought, agricultural use, and growing urban demand and are not yet utilizing climate data and forecasts in any systematic way for better long-term planning. However, the focus of river basin councils on longer-term planning for environmental sustainability could result in an increased desire for climate knowledge and climate products (Wilder and Pineda, 2006).

Many participants in a 2002-2004 study conducted in seven major urban centers in Sonora, Mexico appreciate and value climate data and climate science, and would like to have the resources to engage in planning to reduce climate-related vulnerability (Wilder, 2006). Municipalities in Sonora are in a double-bind of rapid and unplanned population growth coupled with the new financial burden of urban water service provision under the decentralized system, during a period marked by severe and prolonged drought. Long-term planning to enhance environmental sustainability is a lower priority given the daily operational demands that local water managers face.

The study also found uneven distribution of climate information. Larger urban areas such as Hermosillo had very good access to models, forecasts and data, as well as personnel with advanced training and degrees who are able to interpret the science and develop appropriate applications for it, but small municipalities such as Alamos, in southern Sonora, had almost no access to or knowledge of climate data, models or forecasts (Wilder, 2006). Most of the water and climate modeling is conducted at the Mexico City headquarters of the *Comisión Nacional del Agua* (National Water Commission, CNA) and the SMN, and local water managers, outside Hermosillo, have limited access their products and models. Rainfall data was cited as the most often used climate data. These managers expressed interest in improved access to forecasts and models, yet they stress that forecasts must be sufficiently localized and very timely, in order to be utilized effectively for urban water management. The water managers widely agreed that even if more climate products--such as drought monitoring or forecasting tools--were readily accessible, financial resources are not available to implement mitigation strategies, for example, to develop and implement drought mitigation strategies and plans (Wilder 2006).

2) URBAN WATER MANAGEMENT IN ARIZONA

A study based on surveys and interviews of water providers in four groundwater management areas in southern Arizona found that urban water supply is in some ways buffered from climate variability because of groundwater use and interconnected water systems (Carter and Morehouse 2003), but it is still impacted by several monsoon-related factors. Managers say that delayed onset of the monsoon or scanty summer precipitation may affect the supply and demand equation more than dry winters. Peak annual urban demand is usually in May and June, just before monsoon onset, and water systems can be stressed if rains begin late (Marra 2002). Lightning or electrical storms may occur almost daily during the early July-late August monsoon period (and in conjunction with storms other times of the year), and can lead to power outages affecting water delivery by disabling wells.

The study found both an interest in and lack of localized information on the likely climate impacts of drought, e.g. forecasts of length or severity. Advance knowledge of monsoon onset would help water managers better plan summer water supplies, and to plan for water conservation measures necessary during drought. Information on whether lightning and precipitation associated with the storms will be widespread or scattered could be used to better plan response to power outages. However, none of water providers interviewed had a staff person specifically responsible for climate for forecast analysis, and they expressed that they had little time to learn about them on their own. Similar to the urban water managers in Sonora, they also expressed interest in assessment of forecast accuracy, and in being able to test the accuracy and utility of forecasts themselves, before they would become a regular factor in planning and decisionmaking (Carter and Morehouse 2003).

e. A user-oriented experiment in knowledge exchange

In 2002, as drought severity increased in the Southwest and NOAA/CPC issued a forecast for developing El Niño conditions in the equatorial Pacific, CLIMAS began a user-oriented experiment in communicating climate information. The project began as the El Niño-Drought Initiative in 2002 (Garfin et al. 2003), and continues as a quasi-operational monthly climate information newsletter called the Southwest Climate Outlook (SWCO). The SWCO is a monthly summary of value-added climate information, layperson-friendly research articles, and forecasts for the Southwest, delivered to approximately 2000 stakeholders. The initial project was designed to 1) provide comprehensive, up-to-date, multi-agency information on the concurrently developing drought and El Niño, 2) increase the capacity for stakeholders to use climate forecasts and information related to El Niño, 3) garner stakeholder feedback about "off-the-shelf" web-based climate products and forecasts, 4) bring scientists and the news media together, in order to improve the accuracy of reporting on climate variations and events (vis. Glantz, 1995), and 5) stimulate research on ENSO, drought, and knowledge transfer. In order to garner feedback and build capacity CLIMAS researchers used mixed methods, including written surveys, telephone interviews, media briefings, and a scientist-stakeholder workshop. CLIMAS researchers found that regular, iterative interaction with stakeholders built trust for the region-specific value-added climate products, as well as improved stakeholder ability to interpret climate information and use the information in decisions (Lemos and Morehouse, 2005). Stakeholder feedback was incorporated into the SWCO, with the result that readers are better able to comprehend complex situations – such as an El Niño episode in the midst of persistent drought (Bales et al. 2004). Moreover, CLIMAS researchers found that communication was enhanced when information was endorsed by well-respected early adopters within a sector (Jacobs et al. 2005b), or trusted knowledge brokers, such as cooperative extension programs (e.g., Jagtap et al. 2002).

6. Discussion

Across a range of stakeholders, there is potential for monsoon and climate information to contribute to the reduction of vulnerability by providing specific information that decisionmakers can act on, or by raising awareness of risks in order to improve preparedness. Based on the analysis of vulnerability studies and user-oriented experiments, we find that the diversity of stakeholders and the realities of the border region that should inform how we conduct applications; that there are a number of unmet needs common to many stakeholders; and that scientist-stakeholder interactions are necessary to realize the potential of monsoon information to reduce vulnerability. These interactions can raise the capacity to use information, and also provide the link for stakeholders to feedback to science planning and product development.

a. Stakeholder diversity

There is a large variation in stakeholders' adaptive resources, access to and understanding of climate information, and capacities to use it. For example, larger municipalities and water management agencies, compared to smaller agencies, are more likely to have resources to consider climate information, but in general, natural resource agency personnel rarely have training in climate or even the time to learn on their own about weather or climate products. Provision of and access to climate information is highly variable especially within Mexico (Wilder and Pineda, 2006). Urban water managers both in Arizona and Sonora expressed interest in climate information but need the resources to be able to engage in planning to reduce climate-related vulnerability; most agencies have limited or no resources to employ the climate science effectively, for example, to develop and implement drought mitigation plans. Capacity-building efforts, including training and extension activities will increase the ability of stakeholders to understand and use climate information effectively.

The level of interactions between scientists and stakeholders varies considerably. Some communities -- notably fire managers in the U.S. and some water managers -- are now participating in scientist-stakeholder interactions to enhance use of information in their decisionmaking and planning. However, these activities are limited or do not yet exist for other communities such as ranching, agriculture, and public health, for which needs have been identified. Finally, studies have not been done to identify specific needs and entry points for climate information in some cases for which climate sensitivity and vulnerability has been identified, including border water management, and natural hazards and urban water management in Mexico. Ongoing assessments are necessary to determine stakeholder interests and translate them into specific scientific questions to be investigated, answered, and translated back into climate information that stakeholders can (Gamble et al. 2003).

The binational border also presents special challenges for developing applications. Despite common cultural, demographic, and socio-economic characteristics, this area provides profound examples of differential vulnerabilities associated with class, ethnicity, and access to adaptive resources (Vásquez-León et al. 2002). In cross-border watersheds, drought and water availability influence the economic and social implications of, for example, agricultural prices that influence decisions and choices about livelihoods across the border area. These choices have ramifications for other parts of the monsoon region. For these reasons, climate services efforts that recognize and integrate an understanding of border complexities are important to reducing the overall vulnerability of the region. Efforts to create transboundary products and information dissemination pathways are important contributions to capacity building, such as the North American Drought Monitor (Lawrimore et al. 2002) and Spanish translations from CLIMAS (e.g. Shipek et al. 2005a,b).

b. A synthesis of user needs

We have identified some unmet needs for forecasts that are common among the diverse sectors described above. Many users also are interested in near–real-time monitoring, easy access to historical observations, and outlooks of individual monsoon parameters, even though there are no climate-scale operational monsoon forecasts. These information and forecast needs can be organized in two ways: a list of specific needs (Table 1) and an annual decision calendar (Figure 3). Stakeholders are interested in seasonal outlooks of monsoon onset and strength, within-season precipitation totals, spatial distribution of precipitation, intraseasonal breaks, and monsoon duration and demise (Table 1). In addition to information on total precipitation, stakeholders are interested in how onset affects relative humidity, dry lightning, and mixing height. Within-season parameters of interest include forecasts of bursts, breaks, and precipitation intensity. Medium-range (e.g., 6-14 day) forecasts of these parameters are particularly valuable, because managers can implement mitigation strategies with several days notice of an event.

Decision calendars can help researchers identify user needs by relating stakeholder planning processes and operational issues to climate factors (Ray 2004, Pulwarty and Melis, 2002). Monsoon information needs follow a seasonal cycle, as illustrated in an annual decision calendar (Figure 2). As early as January, monsoon season outlooks are needed by fire managers to make resource allocation decisions for the upcoming fire season, and by reservoir managers to plan water releases. At about the same time, farmers require forecasts of summer season precipitation for planting decisions. Somewhat later, ranchers are beginning to make decisions on herd management for the year. Several fire and air-quality management planning issues and decisions relate to the timing of monsoon onset. Later, the timing of the monsoon retreat affects a different aspect of fire management: planning post-fire season prescribed burns, or allowing naturally occurring fires to run their course, in order to meet management objectives. Potential uses extend the annual time scale, for example, antecedent moisture anomalies influence disease outbreaks, and climate conditions 10-18 months before the fire season influences the fuel accumulation, and multi-year planning needs by farmers and others.

c. Benefits of scientist-stakeholder interactions

Recent evaluations of the potential for science to benefit society have found that the development of usable science is most likely where there is a high level of interaction between scientists and stakeholders, conducted in the context of integrated assessment activities (Lemos and Morehouse 2005). Product development models (Hackos and Redish, 1998) suggest the following elements to incorporate stakeholder needs: (1) sector or place-based vulnerability studies to elucidate decisionmaking contexts, identify potential early adopters (e.g., Rogers, 1995), and identify the potential to reduce vulnerability; (2) efforts to increase the capacity of stakeholders to use information in decisionmaking and planning; and (3) activities using scientist-stakeholder interactions to inform research planning and product development, i.e., to provide feedback (Figure 1).

Scientist-stakeholder interactions can play a significant role in capacity building, which in this case involves developing a basic level of knowledge about climate, the monsoon, drought, and various forecasts. As a result of the National Seasonal Assessment Workshops and the CLIMAS Southwest Climate Outlook, the targeted stakeholders now have enhanced capacity to use climate information in decisionmaking and understanding of the role of climate in decisions. At the same time, they have influenced research programs by refining research questions by scientists working on fire-climate interactions, and scientists working on climate questions (e.g., Reinbold et al. 2005; Brown et al. 2004; Hall and Brown 2003).

Stakeholders across the region are fascinated with phenomena such as the monsoon and drought. This interest can be channeled into use of climate information in decisionmaking, provided that stakeholders can understand the links between historical climate information and impacts on their operations (Gamble et al. 2003; Changnon et al. 1988). By understanding of products, stakeholders can begin using them thoughtfully in ways that acknowledge the products' inherent limitations and opportunities (Pulwarty and Redmond 1997; Hartmann et al. 2002; Ray 2004; Lemos and Morehouse 2005). In this context, stakeholders also can develop the capacity to use probabilistic information and historical climate associations characterized by uncertainty (e.g., the association between late monsoon onset and lower-than-average total precipitation in most, but not all, years). Continuity of communication even when there is no significant ongoing climate event, such as an extreme ENSO or drought episode (Jagtap et al. 2002), maintains stakeholder interest and reinforces understanding of the links between climate and impacts.

Given the demonstrated contributions of these scientist-stakeholder interactions in the co-development of usable knowledge, we recommend that the monsoon research community, SMN, and NWS undertake collaborations with integrated assessment activities to ensure that products and forecasts are usable. The users' needs for monsoon information (Table 1) and decision calendar (Figure 3) can help refine research plans by NAME and the related Climate Test Bed that seeks to improve NOAA seasonal models and forecasting (Higgins et al. 2006). NAME goals for improving models include simulating the initiation of regular deep convection (i.e. monsoon onset) within a week of its observed initiation; reproducing the full diurnal cycle of observed precipitation, including the magnitude of the afternoon peak in latent and sensible heat fluxes; and reproducing the correct position of the Gulf of California low-level jet (Gutzler et al. 2005, and NAMAP atlas[5]). These metrics for improving forecasting overlap with the interests we find in forecasts and the monsoon; however, assessments provide a richer sense of stakeholders' needs. CPC should consider the ways in which different stakeholders define parameters such as monsoon onset, and plan for research and products to address these. For example, some stakeholders are interested in metrics of onset that convey changes in humidity, lightning strikes and mixing layer depth. CPC and monsoon scientists can substantially increase the likelihood of

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[5] http://www.cpc.ncep.noaa.gov/research_papers/ncep_cpc_atlas/11/index.html

creating usable products by engaging early on with the stakeholders identified by integrated assessments in the region, and by using findings of scientist-stakeholder interactions to inform research planning and product development (feedbacks in Figure 1). Farmers' interests in 5-year outlooks of precipitation may be unrealistic, but interactions can also help stakeholders understand what improvements scientists can realistically deliver in the near future or within several years. Stakeholders can then thoughtfully inform research planning and product development.

At this time, there is no product that brings together information on the monsoon. Existing monsoon information is scattered across a variety of government, university, and research institution web sites across the U.S. and Mexico. Information is not consistent or coordinated across sources and temporal scales. While a centralized access point on the web would improve accessibility of information, many stakeholders do not have internet access, and a webpage alone is not enough to build capacity to use information.

We recommend the creation of a regularly issued product focused on the monsoon, a bi-national *Monsoon Outlook*. Such a product would draw successful models such as the CLIMAS Outlook, the U.S. Drought Monitor (Svoboda et al. 2002), the North American Drought Monitor (Lawrimore 2002), and the web-based "Monsoon On-Line" product that tracks the Asian monsoon by indices and regions, compares values with averages, and provides station data and forecasts.[6] Even in before a monsoon forecast is available, a monsoon product could provide monitoring of current climate conditions, background material on monsoon variability and dynamics, and summary articles on recent research, written for non-experts. Articles on how the monsoon influences drought and fire risk, for example, will help improve stakeholders' understanding of climate influences on their activities. The product should take advantage of improved understanding of how to improve communication of climate information, e.g., the need to avoid technical jargon, include simple or easily accessible ancillary information such as a legend, definitions of terms, or units (e.g., mm. or in.), and to explain of probabilistic information (e.g., Hartmann et al. 2002b).

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[6] http://www.tropmet.res.in/~kolli/MOL/

This product should be a joint effort of U.S. and Mexican climate-services organizations. Ideally, several issues should be published through the season, in English and Spanish. The first issue should be in early spring, when stakeholders' interest begins and some have planning and operational issues that require information on the potential strength and duration of the monsoon. Several updates should be released as onset approaches and throughout the season. A web-based product can also be available as a printable document, with provisions for dissemination to those without web access. A Monsoon Outlook could be disseminated as a stand-alone product, and also through user-oriented experiments other experimental climate services efforts. Many stakeholder organizations have their own newsletters or professional publications including the fire community, ranchers and farming publications, and state extension products that could ingest and disseminate this value-added monsoon information to a larger audience.

7. Conclusions

The monsoon region as a binational, multilingual, and multicultural region poses challenges for the development of monsoon science applications and for climate products and services. This article has described integrated sector-based assessments and user-oriented experiments in the contexts of natural hazards, agriculture and ranching, public health, and water management. Underlying our analysis is an integrated definition of "region" that recognizes the interdependencies of climate, ecosystems, and human communities on both sides of the binational border, while acknowledging the socioeconomic, linguistic, cultural and institutional distinctions that also are a reality. Across a range of stakeholders, there is potential for monsoon and climate information to contribute to the reduction of vulnerability in the region by providing specific information that decisionmakers can act on, or by raising awareness of risks in order to improve preparedness. We have identified a list of products (Table 1) and a calendar of timing of monsoon information needs (Figure 3), that provide starting points for developing usable monsoon science. Although there are no climate-scale operational monsoon forecasts, many users are interested in near–real-time monitoring, easy access to historical observations, and outlooks of individual monsoon parameters. We recommend creating a binational Monsoon

Outlook to enhance the capacity to use forecasts when they are available, and to maintain ongoing communication between scientists and stakeholders.

To realize the potential for monsoon research to benefit society, usable, stakeholder-focused products must be developed. The monsoon research and forecasting community can substantially increase the likelihood that products will be usable by collaborating with integrated assessment activities to co-produce knowledge about the monsoon. Through a process of interactions, stakeholders can thoughtfully inform the scientific questions to be investigated by NAME and the operational products to be issued by the NWS, SMN, and other climate service providers. These efforts should capitalize on the opportunities for monsoon science to inform decisionmaking, and, in the best instances, reduce regional climate vulnerabilities and enhance regional sustainability.

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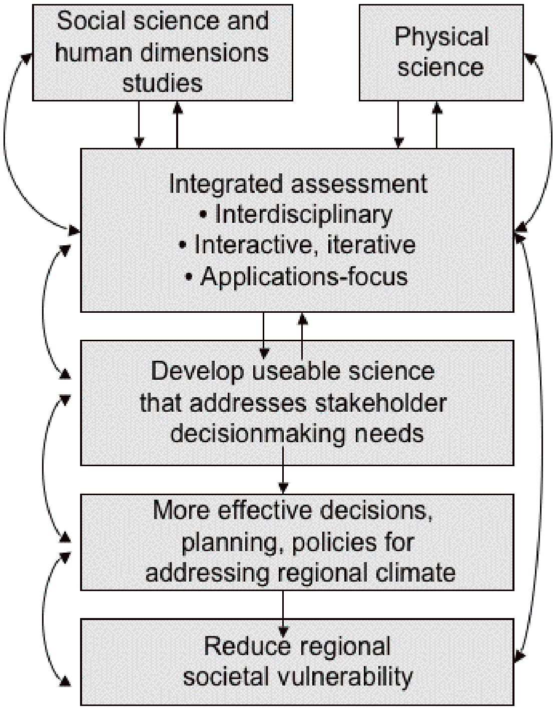
Figure Captions

Figure 1. Integrated assessment process for monsoon applications. Straight arrows indicate feedback among science communities. Curved arrows indicate the process of useable science informing decisions, and the process of feedbacks from stakeholders to inform research questions and assessment activities.

Figure 2. The North American Monsoon region. Areas influenced by monsoon precipitation include the Mexican states of Sonora, Sinaloa, Durango, and Chihuahua, and the U.S. states of Arizona, New Mexico, Utah, and Colorado, as well as some surrounding areas. Major geographic features include the Sonoran Desert and portions of the Sierra Madre and the southern Rocky Mountains. Dark lines indicate the boundaries of NAME Tier I and Tier II regions; All of Tier III is not shown, it extends from 5° N to 50 N° and 125° W to 75° W

Figure 3. Annual decision calendar for monsoon applications. This calendar is a framework for assessment scientists to link user needs to potential uses of forecasts and information products. Shaded bars indicate the timing of information needs for planning and operational issues over the year.



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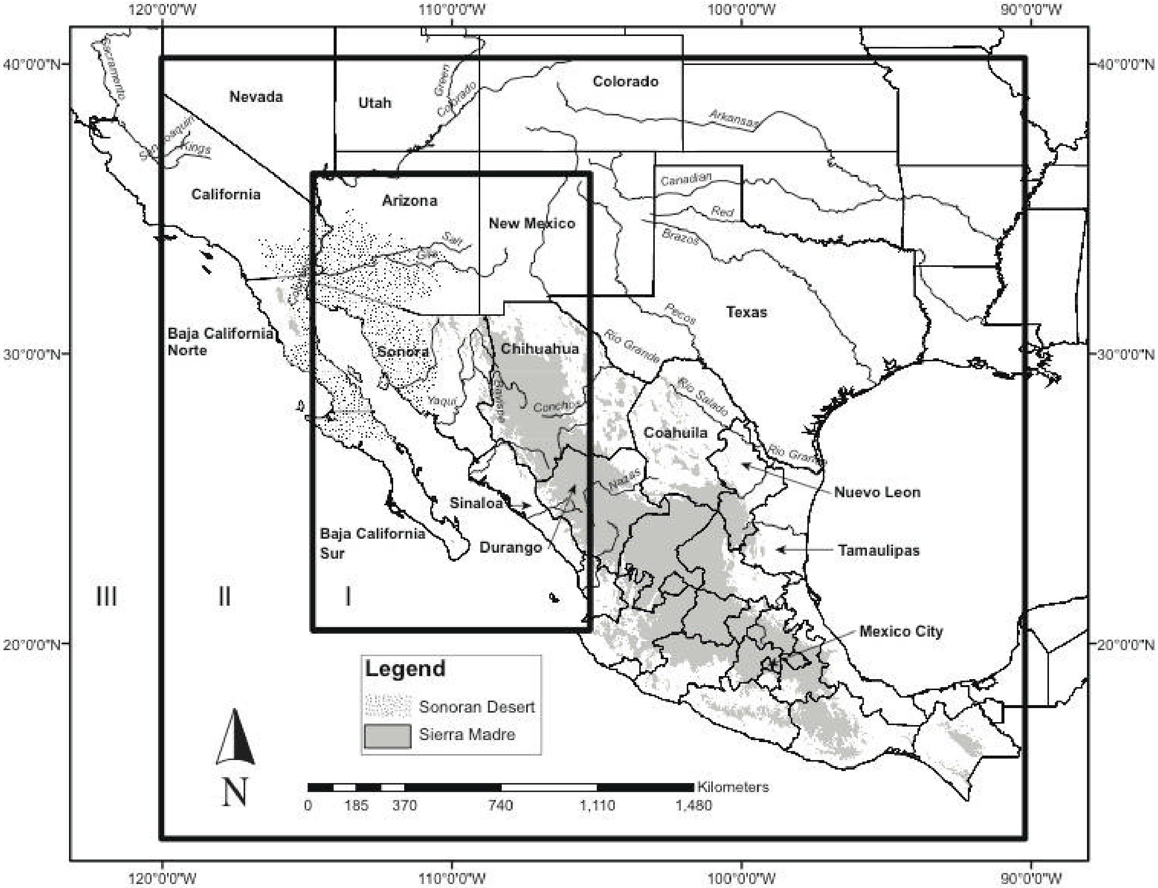

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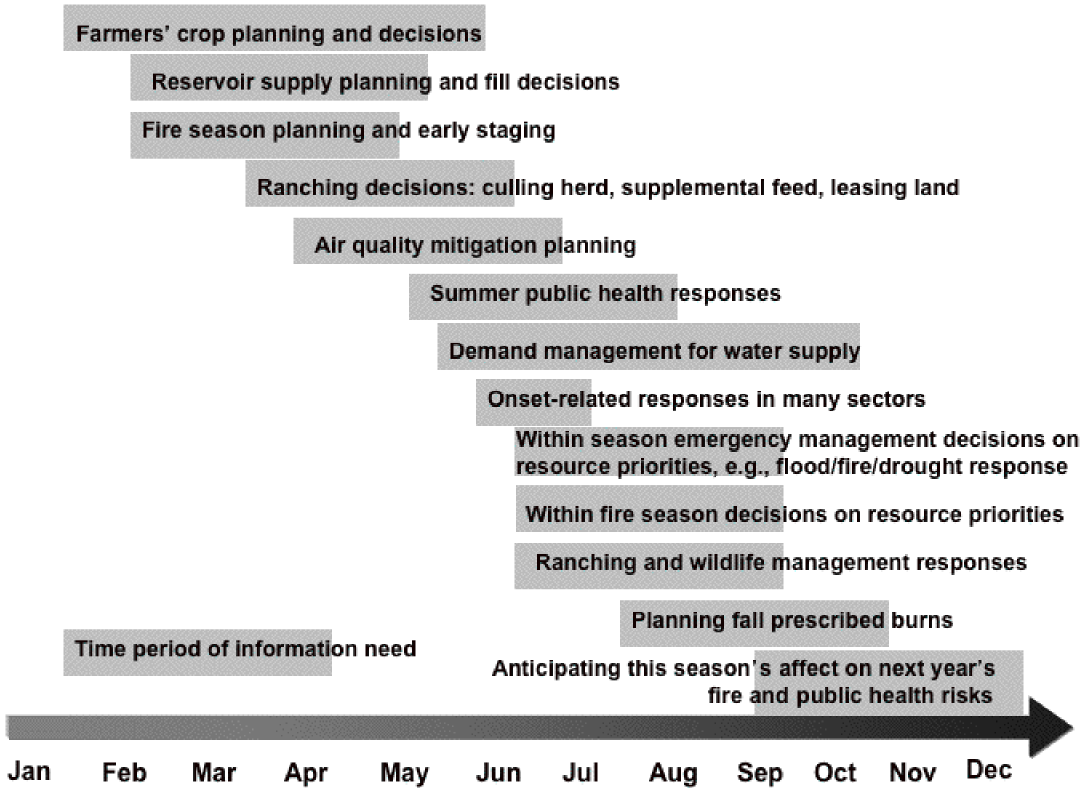

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Table 1. Monsoon information needs of several stakeholder sectors, with variables and potential uses in five categories: a seasonal outlook; monsoon onset; within-season parameters; monsoon breaks, and demise or retreat.

***Monsoon Feature*/** Stakeholder group	**Variables of interest**	**Potential use**
Seasonal outlook		
Farmers	Seasonal precipitation	January-February for crop planning; or if a dry conditions are anticipated, to find other work; for allocation plans for user associations
Fire Managers	Seasonal precipitation; weak/ strong monsoon, outlook for early/late onset	In March-April and updated later for west-wide planning and deployment of firefighting resources to the highest risk areas
Reservoir managers	Seasonal precipitation	In February and updated to estimate reservoir contents and agricultural water supply; to estimate risk of flooding and assist in reservoir decisions involving trade-offs between flood control and water storage
Air quality managers	Length and strength of season; outlook for early/late onset	Weeks to months in advance to plan for management and mitigation of ozone and PM management, over the season
Monsoon onset		
Fire Managers	Relative humidity (RH); probabilistic forecasts of dry lightening strikes prior to onset; improved ability to recognize false-starts	Days to weeks in advance to anticipate peak wildfire numbers, and potential decline in the fire season; potential to redeploy those resources to higher risk areas

Emergency fire response	Precipitation; assessment of whether there is a "false-start"	Dry lightening at the beginning of the monsoon season starts many fires; false-starts are not followed by rains which mitigate fire strength
Ranchers	Precipitation anomalies associated with early/late onset	Information necessary to plan for supplemental feed if onset is expected to be late
Wildlife managers	Precipitation anomalies associated with late onset	Outlook for long lapses in precipitation, so they can plan for emergency water hauling for various habitats
Air Quality managers	Mixing height and RH	Days to weeks, for ozone and PM mitigation
Public Health officials	Early onset prediction or observation of wet pre-season	Days-weeks in advance to mitigate exposure to dust associated with valley fever outbreak
Urban water managers	Precipitation associated with monsoon onset	Days to weeks in advance to plan for peak seasonal water demand, which occurs just prior to onset, and to plan conservation during drought
Within-season parameters		
Ranchers	JAS precipitation; spatial extent of precipitation	About a month in advance to anticipate forage for cattle and plan for supplemental feed if dry
Fire managers and responders	Parameters related to fire ignition efficiency: cloudiness, temperature, RH, wind	Days in advance: these parameters are related to energy release and rate of fire spread, and risk for a fire start to develop into a large fire

Emergency managers	Precipitation intensity	Day to a week in advance, for flash flood response, especially if there is wide-spread heavy precipitation requiring coordination of resources across wide areas
Emergency Managers	Forecasts of widespread and intense storms; moisture surges (wind, lightening, intense precipitation)	Day to a week in advance, to allow pre-positioning of flood response; planning and recovery for wind damage, including power outages (associated with wind and lightening)
Public health and emergency response	Cloudiness (may be inversely correlated with daytime maximum temperatures)	Days to weeks in advance to anticipate heat stress, which is correlated with substantial numbers of heat related deaths each summer
Farmers	Within season precipitation, forecasts of early/late demise or tropical storm precipitation	Days to weeks in advance for within season crop planning. Late precipitation due to a late end or tropical storms may impede crop harvest
Urban water managers	Weather forecasts, especially for high temperatures	A week in advance for planning water use and groundwater pumping, because demand is higher in high temperatures and repairs.
Irrigated farming	Medium range precipitation and monsoon-surge predictions; forecasts of late monsoon end or tropical storm precipitation	Days to two weeks in advance to schedule irrigation deliveries. Water delivered but not needed in wet periods may be wasted. Anomalous late rain may impede crop harvest
Wildlife managers	Timing of summer precipitation or periods without precipitation	Week(s) in advance for planning and implementation of habitat management for endangered wildlife species

Monsoon breaks		
Fire managers	Breaks, storminess; probability of dry lightening strikes; consistency of precipitation	Within-season management of resources; breaks of 8-10 days may lead to an increase in wildfires
Air Quality managers	Mixing height and humidity variables	Days in advance for ozone and PM mitigation
Monsoon demise/retreat		
Fire Managers	Decrease in relative humidity and lightening strikes; within-season forecast of demise	Days to weeks in advance for planning for proscribed burns after the monsoon season ends
Wildlife managers	Precipitation deficit; early end to the monsoon	Planning and implementation of habitat management for endangered wildlife species
Farming	Forecasts of late monsoon demise or tropical storm precipitation	Harvest planning: later than usual precipitation due to a late demise or tropical storms may impede the ability of farmers to harvest crops