Journal of Agricultural and Applied Economics, 34,3(December 2002):603–632

Challenges and Opportunities Provided by Seasonal Climate Forecasts: A Literature Review

Harvey S.J. Hill and James W. Mjelde

Use of seasonal climate forecasts is a rapidly evolving area. Effective research and application of climate forecasts require close cooperation between scientists in diverse disciplines and decision makers. Successful collaboration requires all players to at least partially understand each other's perspectives. Issues associated with seasonal forecasts, through a selected review of both physical and social sciences literature, is presented. Our hope is that the review will improve research in this area by stimulating further collaborations.

Key Words: climate forecasts, review, value of information

JEL Classifications: D80, D81, O30, Q00

One has to look no further than the past few years to realize that climate variability affects the economy. Access to skillful seasonal climate forecasts could potentially allow society to take advantage of beneficial and mitigate adverse effects of climate variability (Stern and Easterling). Numerous questions are raised by this seemingly simple statement. What are climate forecasts? What methods are available to make such forecasts? What physical processes are the basis for current and potentially improved climate forecasts? What makes climate forecasts valuable to society? Why are not all decision makers using available climate forecasts? What, if anything, is being done to disseminate and use climate forecasts? As simple as the statement seems, in reality, the physical and socioeconomic aspects of forecasting climate and associated use are complex. Through a survey of the physical and socioeconomic literature, this review addresses the complexity of the aforementioned statement.

For society to realize the benefits of climate forecasts, physical scientists, social scientists, and decision makers must work in close cooperation with each other (Pielke et al.). Successful collaboration requires all players to at least partially understand each other's perspective. By reviewing physical and socioeconomic studies, the perspectives of different researchers are raised. Many studies have ignored the current state of knowledge from both the physical and social science perspective. Our hope is that our review will enhance research in this area by stimulating further col-

---

Harvey S.J. Hill is program specialist, National Oceanic and Atmospheric Administration, Office of Global Programs, Regional Assessments Program, Silver Springs, MD. James W. Mjelde is professor, Department of Agricultural Economics, Texas A&M University, College Station, TX.

This research was partially supported by Department of Commerce, National Oceanographic and Atmospheric Administration Grant NA66GPO189 and United States Department of Agriculture CSREES Grant 00-35400-9124. The authors thank John Penson for his useful comments and willingness to publish literature review articles.

laborations. In addition, we hope it will help researchers avoid reinventing the wheel.

This review begins with a nontechnical review of climate forecasting from the physical side. Current climate forecasts have more skill than simply using historical probabilities of occurrence. Furthermore, potential improvements in forecasting skill appear to be on the horizon. Socioeconomic literature is then reviewed, concentrating on the economic valuation of climate forecasts. These studies clearly show that economic valuations of climate forecasts are providing new directions in the more general realm of the economics of information.

Unfortunately, as with all reviews, including all articles is impossible. Some excellent studies are omitted in this rapidly expanding field. We apologize to those authors.

Definition of and Methods for Forecasting Climate

Weather forecasts are made for events up to 2 weeks into the future (Lorenz), and climate forecasts are for periods greater than 2 weeks (National Research Council [NRC] 1996). Point forecasts (specific predictions) for variables such as precipitation and temperature levels constitute weather forecasts. Point forecasts more than 2 weeks into the future have no greater statistical confidence than historic variability (also known as climatology), because of the chaotic nature of atmospheric dynamics (Lorenz; NRC 1996). The inability to make long-range point forecasts with any degree of increased confidence has led some scientists to conclude that seasonal-to-annual forecasts of climatic variability are not possible (Charney et al.; Lorenz). Although point forecasts are not possible, the probability of variations from climatology can be forecasted, because predictable patterns can be discerned in the chaotic system (Charney and Shukla; NRC 1996; Shukla).

Research has identified sea surface temperatures (SST) as a significant forcing agent for climatic variability (Bjerknes 1966, 1969; Chang et al.; Enfield). Climatologists have hypothesized that seasonal point forecasts of SST may be possible, which would improve climate forecasts. Unfortunately, attempts to make long-range point forecasts of SST have been plagued with similar constraints to those encountered in climate forecasting (Cane and Zebiak 1987).

Climate forecasting has a long history, dating back at least to the interpretation of the Egyptian Pharaoh's dreams by Joseph of seven good and seven bad cropping seasons. The first recorded use of combining climatic information with experience is attributed to a Peruvian Indian tribe in the sixteenth century. They observed environmental clues related to the El Niño/Southern Oscillation (ENSO) phenomenon: (ENSO refers to an interaction between the tropical Pacific sea temperatures with the atmosphere and is associated with climatic variability in many regions of the world (Cane and Zebiak 1985; Ropelewski and Halpert 1986, 1987, 1989)). These clues, related to characteristics of the western Southern Hemispheric winter horizon, allowed them to make crude predictions of seasonal climate for the season (Cane).

Today, the most common form of forecasting is the probabilistic or synoptic (statistical) method. Known as an analog approach, this method uses historic records of meteorology variables to construct the probability distributions of climate variables for a region associated with different oceanic or climatic events (Podbury et al.). Early in this century, Walker, using analog methods, identified oscillations in sea surface air pressure patterns across the tropical Pacific. Walker did not provide any theory to explain the relationship he identified in his statistical analysis. The oscillations have become known as the Southern Oscillation (SO) and have been associated with climate patterns in regions outside the Pacific basin. A major disadvantage of the analog method is that the probability distribution functions associated with different events are often so disperse that the functions for climate events highly overlap. As a result, the analog method's skill for many regions is very low (Podbury et al.). To improve on the analog method requires the application of theory to the interaction of oceans with the atmosphere.

Approximately four decades later, Bjerknes (1966, 1969) succeeded in providing a theoretical basis linking the SO to SST anomalies in the equatorial Pacific known as EL Niño. Bjerknes (1966, 1969) explained the basis for the air circulation patterns in the tropical Pacific and the higher latitudes as an interaction of the SO with the Walker and Hadley Circulations. Bjerknes' discoveries remain key elements in current advances in climatology.

In 1904, V. Bjerknes theorized that precise climate forecasts should be possible using the laws of physics (Katz and Murphy). Richardson, a mathematician, attempted to predict the weather 6 hours in advance in Germany just after World War I using Bjerknes' concepts. His methodology and resources for calculating the atmospheric dynamics were not adequate. He concluded that 64,000 people working continuously would be required to calculate an accurate weather forecast (Tribbia). Current computing power makes the exercise attempted by Richardson a routine event. McGuffie and Henderson-Sellers provided a technical review of numerical climate modeling.

Today, global coupled models (GCM) use supercomputers, massive amounts of data, and theoretical advances to make forecasts that in many ways are extensions of the original work of V. Bjerknes and Richardson. GCM are now powerful enough to model climatic patterns for periods extending months into the future, with varying levels of skill. Limitations in current computing power and gaps in the knowledge of oceanic, atmospheric, and topographic interactions reduce the effectiveness of this approach for climate forecasting as a stand-alone method. The quality of GCM forecasts are enhanced by the interpretation and knowledge of experienced climatologists. Podbury et al. noted that GCM have several disadvantages, including that they require copious amounts of data, which means there is a major time lag between the occurrence of a climatic event; the recording, collation, and entry into a GCM; they require up to several weeks to complete a single run; and they provide low-resolution forecasts.

Bates, Charles, and Hughes stated that GCM simulate annual or seasonal climate means at a subcontinental scale reasonably well, but perform poorly for smaller space and timescales relevant to local and regional impact analysis. At least two approaches are being used to address the resolution problem. The first approach embeds more finely defined models of subregions (known as limited area models) within the more coarsely defined grid of a larger GCM. This approach tends to underestimate the intensity and overestimate the frequency of daily precipitation (Bates, Charles, and Hughes).

A second approach is downscaling. With downscaling, historic or synoptic information is used to stochastically predict the range of expected climatic variability in a region based on the background conditions simulated by the GCM. One of the more promising techniques currently being pursued in this area is the stochastic downscaling method, of which the nonhomogeneous hidden Markov model is an example. These Markov models determine the most specific patterns of precipitation occurrence records at multiple sites instead of patterns in atmospheric circulation (Bates, Charles, and Hughes). Stone, Smith, and McIntosh have developed a method of downscaling GCM information via the use of SO index analog years. An advantage of limited area models and downscaling is that they can produce daily weather data that can be used in other models such as crop-growth simulation models or water management models.

Forecasts based on experience use a combination of modeling, data, and professionals' subjective knowledge. Neural network–based forecasting (Derr and Slutz) could arguably be an example of an experience-based forecasting method that uses relatively little human input. Derr and Slutz concluded that, when rules are uncertain and experts are not available, a neural network can produce accurate forecasts if high-quality data are available. The Canadian Institute for Climate Studies includes neural network models in their forecasting.

Today, the most important basis for seasonal forecasts are ENSO events. It must be stressed, however, that the ENSO phenomenon is not the only mechanism providing promise for making climate forecasts. Other mechanisms, some of which are discussed later, provide promise. Given its central importance in seasonal forecast research (Glantz [1996] called ENSO "scientists' gift to the twenty-first century"), the ENSO phenomenon is discussed in depth. Trenberth notes that the meaning of El Niño and La Niña has changed over time, and it is important for each study to identify their definition of ENSO events.

ENSO—An Historical Perspective

As noted earlier, Walker, a mathematician, observed in 1924 that the sea surface air pressure (SSAP) "oscillates" across the Pacific Ocean. When SSAP rises in the eastern Pacific, it tends to fall in the western Pacific and vice versa (University Corporation for Atmospheric Research). This oscillation was named the SO by Walker (Glantz 1996). He identified associations of the SO with precipitation patterns in Australia, Africa, the Indian subcontinent, and South America. Lower SSAP in the eastern Pacific and higher SSAP than normal in the western Pacific (a low index) is associated with drought conditions in eastern Australia, Indonesia, India, and parts of Africa (University Corporation for Atmospheric Research). Conversely, a high index tends to lead to opposite climatic conditions. Although Walker suspected that some oceanic mechanism was responsible for the oscillation, data constraints did not allow him to establish any link with anomalous warming of the eastern equatorial Pacific sea surface now known as El Niño (NRC 1994). His work did result in the SO being the first identifiable meteorological process that has a global spatial pattern of interannual climate variations with identifiable centers of action (NRC 1996). Initial reaction to Walker's work was highly skeptical, because his work was purely of an empirical nature with no theoretical justification (Katz and Murphy). Doubt concerning his work was reflected in his obituary notice:

> "Walker's hope was presumably not only to unearth relations useful for forecasting, but to discover sufficient and sufficiently important relations to provide a productive starting point for a theory of world weather. It hardly seems to be working out like that" (Royal Meteorological Society p. 186).

Walker's work was never completely dismissed, however, because of the rigor of his analysis (Glantz 1996). As a consequence, a few scientists continued to explore the possibility of a relationship between the SSAP in the equatorial Pacific and climatic events. Berlage's work confirmed Walker's findings. Bjerknes (1966, 1969) provided a key breakthrough by associating El Niño SST anomalies to the trade-wind circulation patterns in both the Northern and Southern Hemispheres of the Pacific. Under normal conditions, air flows west from the colder waters of the eastern Pacific to the warmer waters of the western Pacific, where convection and precipitation occur. The now-dry air returns to the eastern Pacific at a higher altitude and descends to repeat the process. Acknowledging Walker's earlier work, Bjerknes (1966) named this air flow the Walker circulation. During El Niño SST anomalies, the probability increases that easterly wind patterns will diminish and convection patterns will shift from the Indonesian, east Australian region to the mid-Pacific. Bjerknes' (1966, 1969) theoretical developments led to the conclusion that the ocean's influence cannot be ignored in describing the SO.

Our understanding of the linkages between (or coupling of) oceanic and atmospheric processes is increasing. Data, however, has been and remains, a major constraint to gaining a more thorough understanding of the interactions between the oceans and the atmosphere. The Tropical Ocean and Global Atmosphere program (NRC 1996), a 10-year (1985–1995) international cooperative scientific effort, improved data collection via a network of sea surface and subsurface measuring devices and atmospheric and space monitoring systems in the equatorial Pacific region. This program helped in improving the understanding of how ocean and atmosphere interact. What has not been accomplished is an explanation of how the ENSO mechanism begins.

The Genesis and Development of an ENSO Event

Before an ENSO event begins, the "warm pool" in the tropical western Pacific typically extends to a depth of 100 m (325 ft.). The warm waters extend north of the equator from the latitudes 5–15°N. In the eastern Pacific, warmer waters are displaced by easterly winds that cause cooler subsurface water to rise to fill the resulting void. The winds and subsequent upwelling result in a cold "tongue" of water extending along the equator from Peru to the mid-Pacific, most noticeably from October to February. The sea surface level is approximately 60 cm (2 ft.) higher in the west Pacific than in the east Pacific because of the displacement caused by the easterly winds from the eastern Pacific (Glantz 1996) and expansion because of the relatively warmer water.

When a warm anomaly (El Niño event) occurs, the easterly winds subside, reducing the upwelling of colder subsurface waters in the eastern Pacific. As a consequence, the thermocline deepens in the eastern Pacific. This creates a warm pool of water similar to that in the western Pacific. The decline in winds reduces the amount of warm water being forced to the western Pacific, causing the thermocline there to become more shallow (Wyrtki et al.).

An important factor affecting the thermocline is subsurface Kelvin waves possibly triggered by eastward-moving wind "bursts" or Maddelin Julian waves in the western Pacific. Kelvin waves travel from the western to eastern Pacific redistributing the thermocline and, as a result, the heat concentrations across the Pacific basin. A second subsurface wave, the Rossby wave, travels from the eastern to the western Pacific after a Kelvin wave. Rossby waves appear to play a role in returning the thermocline to its more typical profile. Kelvin waves have been linked to the onset of El Niño events; however, the presence of Kelvin waves does not guarantee that an El Niño event will occur (Busalacchi and O'Brien). Kelvin-wave movements also influence the movement of the heat in the ocean along the west coast of North and South America. These movements have implications for seasonal climate variability and fish movements and densities (Glantz 1996; Mantua et al.).

During a cool (La Niña) event, the water in the eastern Pacific becomes relatively colder than normal. The easterly wind pattern increases in intensity causing the thermocline to deepen in the western Pacific and narrow in the eastern Pacific. Regional climatic patterns associated with La Niña events tend to be opposite of those observed in the El Niño events, although it is not a linear response (Hoerling, Kumar, and Zhang; Montroy, Richman, and Lamb).

In a La Niña event, the colder-than-normal SST in the eastern Pacific translates into a decrease in convection that is proportionately less than the increase experienced in an El Niño event. As a result, climate variability associated with the La Niña event is not a linear (an exact mirror) image of the El Niño event in terms of magnitude or regional association (Hoerling, Kumar, and Zhang). Although the associations among SST, air pressures, and climatic variability are different, there is a lagged association between the La Niña event with regions far removed from the Pacific Ocean. Some correlations have been established between Pacific temperatures and climate variability in other regions on a simultaneous (within a month) basis (Montroy; Montroy, Richman, and Lamb).

Teleconnections

Bjerknes' (1969) coupling of the ocean and atmosphere with the Walker circulation also laid the foundation for explaining teleconnections between SSTs in the Pacific and climate events in areas removed from the Pacific basin. A teleconnection is a linkage between a physical process in one region and climate anomalies in other regions (Glantz 1996). Fleer describes teleconnections as statistically (or empirically) determined couplings of large-scale abnormalities of the atmospheric circulation, both in space and time. The teleconnections established by Bjerknes (1966, 1969) between El Niño anomalies and distant climate anomalies are now well documented (Kiladis and Diaz; Rasmusson and Wallace; Ropelewski and Halpert 1986, 1987, 1989). Teleconnections partially depend on the Walker and Hadley circulations. Shifts in the Walker circulation change air flows east and west over the tropical Pacific, whereas the Hadley circulation moves air north and south of the equator. These shifts affect the jet stream, which, in turn, modifies storm patterns. Teleconnections between ENSO and climate conditions have been made for parts of Australia, North and South America, southern Africa, India, northern Africa, and southeast Asia (Kiladis and Diaz; Ropelewski and Halpert 1986, 1987, 1989; Stone, Hammer, and Marcussen). The equatorial Pacific teleconnection with regions outside the Pacific is real but is only observed when the ENSO event is particularly strong (Glantz 1996). What is interesting about teleconnections is that the effect of changes in sea temperatures may show a stronger correlation with crop yields than weather parameters such as precipitation or temperature (Berte and Ward; Nicholls 1986). ENSO events have been correlated with crop yields in southern Africa, North and South America, Australia, and India (Cane, Eshel, and Buckland; Mjelde and Keplinger; Nicholls 1986; Rimmington and Nicholls; Rosenzweig). Furthermore, Keppenne has shown a relationship between commodity prices and ENSO.

For the United States, teleconnections between ENSO events and regional climate variability are not uniform. Teleconnections have been identified with the Gulf Coast, northeast, southwest, and northwest regions of the United States (Ropelewski and Halpert 1986, 1987, 1989). The teleconnections between ENSO events and the midwestern United States are weak (Ropelewski and Halpert 1986, 1987, 1989). There is conflicting evidence whether a strong correlation exists between yields and ENSO events (Handler; Handler and Handler; Stefanski; Thompson).

Stone and Auliciems have attempted to improve seasonal forecasts by using trends or phases based on a moving average of the SO index (SOI). The SOI is the ratio of sea surface air pressures across the equatorial Pacific. This phase analysis may improve the quality of climate forecasts in regions of Australia and other parts of the world (Chen, McCarl, and Hill; Hammer and Nicholls; Hill et al. 2000; Stone, Hammer, and Marcussen). Other measures of ENSO, such as sea surface temperature index and the multivariate ENSO index, which uses a combination of variables such as air pressure and sea surface temperatures, hold promise for improving seasonal climate forecasts.

A great deal of uncertainty, however, remains. An example of this stochasticity is the higher than expected rainfall in eastern Australia during the 1997–1998 El Niño event (Kuhnel). This stochasticity is partially caused by a lack of understanding of all the processes affecting climatic variability at the microclimate, regional, and global level. Examples of microclimate factors are prevailing local wind conditions, soil moisture, soil types, mountain ranges, and vegetation types. The atmosphere is, however, an inherently chaotic system, which means a complete understanding of the factors influencing the atmosphere may not necessarily result in perfect climate forecasts. The importance of the stochasticity cannot be overemphasized, especially given the media coverage of ENSO events.

As noted by Mason and Goddard (p. 619), "There is a danger of overstating the global impact of ENSO events. . . ." Reasons for this cautionary statement are (1) only about 20%–30% of land areas are significantly affected by ENSO events, (2) areas are affected differently during different times of the year, (3) combining reasons one and two reduces the land area affected by ENSO in any given season to approximately 15%–25%, and (4) asymmetric (nonlinearities discussed earlier) weather responses to ENSO events. The importance of the ENSO phenomenon is clear, but what is also clear is that ENSO is not a stand-alone savior.

Forecasts based solely on the ENSO process will, therefore, not reach the potential skill level of forecasts that incorporate other factors. It is beyond the scope of this review to describe all the physical processes and the microclimate factors that are being studied to improve climate forecasts. However, several regional and global physical processes that can potentially improve climate forecasts are discussed in the following section.

Other Physical Processes Affecting Seasonal Climate Forecasts

North Atlantic Oscillation/Atlantic Sea Surface Temperatures

An understanding of other mechanisms besides ENSO may improve the quality of seasonal forecasts. Promising mechanisms for climate forecasting are the North Atlantic Oscillation (NAO) and SST variability in both the northern and southern Atlantic (Lamb and Peppler 1987; Marshall et al.). Similarities have been established between the NAO and the SO; however, the relationship theorized and found by Bjerknes in the Pacific with SST and the atmosphere has yet to be established in the Atlantic (Marshall et al.). Although the relationship between the SST and sea surface air pressures for interannual periods is not understood, associations between the NAO and regional climatic variability have been established.

The NAO association with climate variability is significant for parts of Europe and northern Africa (Lamb and Peppler 1985, 1987). Associations have also been established between North Atlantic SST and precipitation for the southeastern United States and tropical Atlantic SST and northeastern Brazil's precipitation (Chang et al.; Enfield). Chang et al. (p. 1) noted:

> "Although SST anomalies (SSTA) in the tropical Atlantic are generally weaker than those associated with El Niño-Southern Oscillation (ENSO) in the Pacific, they can cause disastrous climate hazards over the Americas and Africa. The fact that rainfall variability in these regions is highly correlated with the SSTA implies that a skillful prediction of the low-frequency SST variability in the tropical Atlantic Ocean may be crucially important for improving long-term rainfall forecasts around the Atlantic basin, which has tremendous social and economic values."

Correlations between Atlantic SSTs and crop yields appear to exist. A relationship between Atlantic SST variability and Côte D'Ivoirean precipitation patterns suggests that Atlantic SST information could be used to predict crop yields (Berte and Ward). This type of association has its counterpart with the associations established between ENSO events and crop yields.

Indian Monsoon

Factors triggering the Indian monsoon cycle and how the cycle is teleconnected to other regions have yet to be established for most regions (NRC 1994). Lowther identified a teleconnection between monsoon patterns, the Inter Tropical Convection Zone and East African climate variability. Associations between the Indian Ocean SST and climate variability in regions of Australia are also suspected (Webster and Yang; Webster et al.). An association between Canadian climate variability and the Indian monsoon process has also been suggested (Garnett et al.; Khandekar). Gaining a fuller understanding of this process is important because such a large proportion of the earth's population is dependent on the Indian monsoon cycle for food production.

Pacific North American Index

The Pacific North American (PNA) Index, a series of high- and low-pressure zones stretching from the equator to the North American continent, may be a useful tool for seasonal climate prediction. The PNA sequence of pressure zones in conjunction with SST has been used to analyze climate and crop variation on the Canadian prairies (Bonsal, Chakravarti, and Lawford; Garnett et al.; Shabbar and Barnston; Wittrock).

Cyclical Patterns

As the physical processes become better understood, scientists are also considering how these processes relate to longer term cyclical patterns in climate variability. Work by paleoclimatologists has suggested that the cycles in climatic variability range from the seasonal such as ENSO events up to the decadal and centennial (Biondi et al.). The potential causes of these cycles include variability in solar radiation and oceanic conditions such as the speed of ocean currents, upwelling, and salinity levels. Burroughs described cycles with periodicities ranging between 2 and 100 years in length.

Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO), a decadal pattern, has been described as a long-lived El Niño–like pattern of Pacific climate variability (Zhang, Wallace, and Battisti). Like the described extremes in the ENSO process, the PDO is classified as either warm or cool as determined by anomalies in sea temperatures in the northeast and tropical Pacific Ocean. The PDO is distinct from the ENSO in that they are persistent with periods in a specific pattern lasting between 20 and 30 years (Mantua et al.; Minobe). The causes of the PDO are unknown. Like the ENSO process, certain sea temperature and sea air pressure characteristics are observed across the North Pacific basin. Warm-phase PDO are associated with above-average precipitation and below-average temperatures in the October/March period for the southeastern United States and below-average northwestern United States and Great Lakes precipitation. Decreased precipitation results in reduced snowpack and springtime stream flow in the northwestern United States. During a cold PDO phase, the opposite precipitation patterns are expected (Mantua).

It appears the teleconnections between ENSO events and weather in North America are strongly dependent on the PDO phase (Gershunov and Barnett). Gershunov and Barnett suggested that weather patterns associated with El Niño (La Niña) over North America are strong only during the cool (warm) phase of the PDO. Climate anomalies associated with warm PDO–El Niño and cool PDO–La Niña are weak and inconsistent. The PDO has also been associated with droughts in North America (Barlow, Nigam, and Berbery). Barlow, Nigam, and Berbery suggested that a relationship exists between United States weather and the three primary modes of Pacific sea surface temperature variability—ENSO, PDO, and the North Pacific mode. They concluded that further analysis is necessary to understand the impact of Pacific sea surface temperatures and climate.

Quasi Biennial Oscillation

A biennial cycle of radiation intensity may be related to the Quasi Biennial Oscillation (QBO). The QBO refers to wind patterns in the stratosphere that alternate between westerly and easterly wind direction phases (Kane). A correlation exists between the QBO when it is in its west phase and the sun is simultaneously in its active high radiation-output phase with higher mean temperatures for North American winters. Conversely, during quiescent solar periods, North American winter mean temperatures tend to be colder during the west phase of the QBO (Van Loon and Labitzke 1988). Ropelewski, Halpert, and Wang found evidence that biennial variability is an integral part of the SO and that it may relate to the QBO. ENSO events' magnitude may be enhanced or muted by the wind direction of the QBO. Naranjo-Diaz noted that the QBO appears to modulate the effect of ENSO events on Cuba's climate.

Solar Cycles

The biennial cycles are not the only cycles thought to influence climate variability. Cycles at the decadal level are also thought to affect longer-term climate variability. A correlation has been established between the 11-year solar cycle and variability in sea-level air pressure. A decadal oscillation of temperatures in the stratosphere and upper troposphere has been associated with the 11-year solar cycle (Van Loon and Labitzke 1995a). The mean temperatures increase in the stratosphere and upper troposphere during a solar maximum and, conversely, are lower during the solar minima. Such changes in tropospheric temperature may be caused by changes in the Hadley circulation. Current research is pointing toward an interactive process between the 11-year solar radiation intensity cycle and absorption of ultraviolet rays in the upper atmosphere by ozone (Van Loon 1998). Complicating the effect of decadal variability is the modification of the Hadley circulation by the QBO, particularly during the North American fall and winter months (Van Loon and Labitzke 1992, 1995b).

A lower frequency event approximately 80 years in length, the Gleissberg cycle, appears to influence climate by causing the atmosphere to cool for 40 years and then warm for 40 years (Friis-Christensen and Lassen). The ability to use solar cycles to make predictions of climatic variability other than stratospheric temperatures is not yet possible. It may be that the observed decadal cycles in climate variability may be caused by other factors.

Other Cycles/Thoughts

There may be some form of a decadal cycle in ENSO- and NAO-associated climate variability caused by changes in ocean currents (Enfield; Marshall et al.). Rajagopalan, Kushnir, and Tourre have identified an association between the NAO and Atlantic midlatitude and tropical SST with climate variation of up to a decade in length. The ability to make forecasts that include cyclical patterns is hampered by insufficient data and a limited theoretical understanding of the processes. A 65–80 year cycle known as the Atlantic Multidecadal Oscillation (Kerr) has been shown to influence the association between interannual rainfall and ENSO events (Enfield, Mestas-Nuñez, and Trimble).

It is clear that the ENSO phenomenon is the most highly recognizable physical phenomena affecting global seasonal climate. Other physical phenomena and interactions between the phenomena are, however, important. Decadal and longer cyclical patterns also have a significant effect on global climate. Although most seasonal forecast application research is currently focused on seasonal variability, ultimately research related to decadal variability may be more important than interannual variability. Crowley et al. (p. 5) stated:

> "Understanding these changes is very important from an economic viewpoint. Although inter-annual changes may result in severe, but relatively short-term economic setbacks, decadal scale oscillations by their very nature may cause long term disruptions in the economic system."

Goddard et al. provided a more technical review on climate forecasting.

What Makes a Climate Forecast Valuable?

Climate forecasts, a form of information, have economic value if they enable individuals or institutions to increase their utility from the level they would expect without the forecasts. Hilton specified four factors influencing the value of information: (1) the decision set's structure, (2) the decision environment's structure, which includes the decision maker's technology environment and relative preference for outcomes, (3) the decision maker's initial beliefs about the stochastic variables' distribution, and (4) the information system's characteristics. Embedded in Hilton's factors are three conditions that must be met for information to have value. First, the decision variables must be able to take on differing levels at the decision maker's discretion (Merkhofer). Second, an interaction between the decision variables and the uncertain variables must exist (Byerlee and Anderson 1969). Finally, the decision maker must have flexible management strategies to use the information (Sonka et al.).

Flexible strategies allow for the reevaluation of management strategies as the decision environment including available information changes. Characteristics of the forecasting system affect the value of the forecast. Two characteristics receiving the most attention are quality (accuracy) and lead time. Within the economics of information literature, several quality measures have been used (Brown, Katz, and Murphy; Chavas and Pope; Gould; Khinchin; Moore and Armstrong). A one-to-one relationship between these single-valued measures and the economic value of climate forecasts does not exist (Mjelde et al. 1993; Murphy; Wilks 2001). Continued research concerning quality measures is necessary. Easterling found that the lack of lead time (the time from the issuance of a forecast to the period being forecasted) is an important determinate in discriminating between users and nonusers of climate forecasts. Mjelde and Dixon showed that a less accurate forecast received earlier may be more valuable than a more accurate forecast received later.

Decision makers may benefit from improvements in other forecast characteristics that have received little attention. These characteristics are specificity, categorical versus probabilistic, knowledge of climate forecasts for adjacent periods, spatial resolution of the forecasts, time span of the forecast, and changes in the weather parameters reported (Easterling; Easterling and Mjelde; Mjelde, Sonka, and Peel; Mjelde et al. 1988; Stuart; Vining, Pope, and Dugas; Weiss 1982). It has been shown that increasing the specificity (the number of events the system forecasts) of the forecasts does not necessarily increase the value of the forecasts (Hill et al. 2000; Mjelde). Other studies found similar results, although the settings are not climate forecast valuation (Gould; Marschak; White). More important, such results suggest that generalizations when dealing with the economics of information are a risky proposition. As early as 1949, researchers were touting the importance of probabilistic forecasts (Price). Buizza suggested probabilistic forecasts have a higher potential value than categorical forecasts. Furthermore, Buizza (p. 2,345) concludes the ". . . design of a forecasting system should follow the definition of its purposes. . . ." Richardson suggests that the current probabilistic European Centre Medium-range forecasts are more valuable than deterministic forecasts from the same model. In dynamic systems, interactions between knowledge of climates in adjacent periods exist (Mjelde et al. 1988). To our knowledge, the other characteristics have received no formal valuation.

Economic Valuation of Forecasts

Decision theory combined with Bayesian analysis provides the basis for valuing climate forecasts. This approach requires explicit recognition of the decision maker's prior expectations of the climate conditions. These prior expectations are then updated using the seasonal forecast. In most studies, the decision maker's prior knowledge is assumed to be the historical or climatologic distribution of the climate variables. Studies have shown the prior knowledge assumed affects the value of the climate forecasts (Mjelde et al. 1988; Sherrick et al.). The decision maker's expected utility, using only his or her prior knowledge of climatologic information is

$$(1)\qquad u(H) = \max_{D} E_c[u(D, c)h(c)],$$

where $u(H)$ is the maximum expected utility using climatologic information, E_c represents the expectation operator for the range of climate conditions of interest, c, $h(c)$ represents the historical probability density function (pdf) climate conditions, u represents the utility function, and D represents the decision set.

When seasonal forecast information (F_i) becomes available, the pdf of climate conditions is modified to $g(c|F_i)$. The decision maker's problem becomes

$$(2)\qquad u_i(F_i) = \max_{D} E_{(c|F_i)}[u(D, c)g(c|F_i)].$$

Forecast F_i is only one of many possible forecasts; the expected utility associated with the entire forecasting system, F, is

$$(3)\qquad u(F) = E[u_i(F_i)Z(F_i)],$$

where $Z(F_i)$ is the pdf associated with the probability of receiving each forecast. The value of the forecast system is

$$(4)\qquad V = u(F) - u(H),$$

where V represents the difference between the optimal expected utility with use of seasonal forecast versus optimal expected utility without seasonal forecast. If V is in utility terms, the difference in utility can be placed in monetary units by using certainty equivalence dollars (Mjelde, Thompson, and Nixon). When risk neutrality is assumed, V is in monetary units.

Marshall, Parton, and Hammer listed four ways to account for risk attitudes (1) assume risk neutrality and, consequently, a goal of maximizing (minimizing) expected monetary gains (losses) (Byerlee and Anderson 1969; Mazzocco et al.), (2) specify a utility function (Byerlee and Anderson 1982; Messina, Hansen, and Hall), (3) use stochastic efficiency criteria (Mjelde and Cochran), or (4) directly elicit farmers' risk attitudes (Baquet, Halter, and Conklin). They advocate the use of the second method for individual decision makers that are not risk-neutral for two reasons. First, the method avoids the high costs associated with elicitation of risk attitudes. Second, manipulation of the risk preference parameter may provide an upper and lower bound on the value of the information. The literature dealing with risk attitudes and decision making is enormous and beyond the scope here. A synergism between the risk literature and climate forecast literature is almost nonexistent. Combining these areas is a natural extension; it appears that this combination would be a fruitful avenue of research. Considering all these studies, one can summarize the relationship between the value of information and the determinates of information as follows, "there is not a monotonic relationship between any of the determinates of information value and the value of the information."

As awareness of the skill of seasonal forecasts increases, the number of studies valuing and describing the use of seasonal forecasts is also increasing. This is in addition to the rich body of literature concerning the impact of climate variability on society, which is a related but separate issue. Mjelde, Hill, and Griffiths pointed out that distinguishing between the value of seasonal forecasts and the economic impact of a particular climate event is important. Even with a perfect forecast, all of the adverse effects (e.g., decreased yields caused by drought conditions) cannot be avoided using seasonal forecasts. Hansen, Hodges, and Jones reported, for example, that ENSO phases explain approximately 25% of the value of corn in southeastern United States. The value of ENSO forecasts are not the entire 25%, but rather how much of the 25% can be altered using ENSO forecasts, implying that the entire 25% is the value of ENSO knowledge is common, especially in the popular media.

Valuation Studies Through 1990

Lave's 1963 study was one of the first to estimate the economic value of climate forecasts. Using a game tree approach, Lave concluded that, because of inelastic downward sloping demand, the aggregate result of individual producers using forecast information would be to increase raisin supply and reduce the equilibrium price. Lower prices would result in lower net revenues for the producers. He stated that the relative supply and demand elasticities in a sector determine which participants benefit from the use of weather and climate forecasts. Babcock suggested that, as forecast accuracy increases, individual decision makers increase production. In aggregate, this leads to an increase in supply. If product demand is inelastic, increased supply results in a net decline in producer surplus. However, Babcock and Lave's studies had very simplistic climate scenarios and economic conditions. Their findings may not hold under more realistic climate and economic scenarios.

Most studies through 1990 focused on the value of weather predictions. These studies focused on the effect of improved weather information for individual decision. Studies estimated, for example, the value of frost forecasting (Baquet, Halter and Conklin; Katz, Murphy, and Winkler; Stewart, Katz, and Murphy). Baquet, Halter, and Conklin, using a Bayesian simulation model, found that the value of weather forecasts was higher for risk-adverse utility maximizers than for profit maximizers. Baquet, Halter, and Conklin estimated that the National Weather Service weather forecasts were capturing 66% of the value of perfect forecasts. Katz, Murphy, and Winkler also concluded the National Weather Service weather forecasts capture much of the value of a perfect forecast.

Greenberg estimated the annual benefits of improved weather forecasts from satellite-based forecasts for several sectors of the U.S. economy. His estimates ranged from $1 to $70 million (1975 dollars) for disaster control, $1 to $10 million for recreation, $5 million to $1 billion for heavy industry (depending on the industry), and $5 to $400 million for industries within the agricultural and timber sector. Greenberg's study, like many studies during that period, provided estimates of potential value of hypothetical weather forecasts. They illustrated, however, that the use of weather forecasts may have a substantial effect on society.

Some studies during this period did, however, focus on valuing seasonal climate forecasts. Mjelde et al. (1988) concluded that (1) Midwestern corn producers have the flexibility to respond to seasonal forecast information and could adopt more flexible strategies that use seasonal forecasts, (2) the lead time and period predicted affect the value of seasonal forecasts, (3) output and input prices affect the value of seasonal forecasts, and (4) the use of crop simulation models is a viable methodological approach to estimate management responses to seasonal forecasts. Glantz (1976) concluded that the full value of seasonal forecasts can only be extracted if the political, social, and economic structure of the country are taken into account. Sonka et al. concluded that Midwestern grain producers had enough flexibility to use climate forecasts.

The preceding studies were done during a period when the ability to make quality seasonal forecasts was very limited. Despite this limitation, the theoretical and applied work of the period laid the groundwork for the current research regarding the value of seasonal forecasts. Mjelde, Sonka, and Peel and Global Climate Observation System provided more detailed reviews of the earlier literature on the socioeconomic value of climate and weather forecasts.

Valuation Studies After 1990

Since 1990, it has been increasingly accepted that forecasts of seasonal climate variability could potentially benefit decision makers in many regions. This acceptance has resulted in an increasing amount of research on climate forecasting-related issues. Economic effects of weather forecasts has become a lost subject (one exception would be Wilks and Wolfe). Social-science literature on climate forecasts follows four interrelated avenues: (1) value of the use of information by decision makers at the field or firm level (Ferreyra et al.; Jones et al.), (2) aggregate (sector and/or trade) level impacts of the use of forecasts (Chen and McCarl; Sumner, Hallstrom, and Lee), (3) effect of climate variability caused by specific physical phenomenon, such as ENSO, on economic activities such as agriculture (Hansen et al.; Naylor et al.; Phillips and McIntyre; Phillips, Cane, and Rosenzweig), health (Hales et al.; Kovats; Maelzer et al.; Pascual et al.), hurricane damage (Pielke and Landsea 1999), and floods and stream flow (Chiew et al.; Guetter and Georgakakos; Kahya and Dracup; Wang and Eltahir), and (4) applications or specific use of climate forecasts by decision makers (Broad and Agrawala; Glantz 2001; Klopper). The nature of the present review is to examine the value of climate forecasts; therefore, studies in avenues three and four are mentioned only as they relate to concepts and results on value being discussed. This is not meant to imply that any avenue is more important than the others. Avenues three and four relate to concepts discussed by Lamb (1979, 1981) and Sonka et al. on the potential use of climate forecasts by decision makers.

There is no doubt that weather and climate variability impact economic and human health. Kunkel, Pielke, and Changnon reviewed recent studies concerned with the impact of extreme weather and climate events. They estimated annual economic losses at greater than $15.8 billion/year, in addition to the more than 1,500 lives lost. In nominal value, weather-related losses have shown an increasing upward trend since the 1940s. However, in dollars per person, no discernable trend is noted (Kunkel, Pielke, and Changnon). Pielke and Landsea (1998) showed that damage caused by hurricanes, normalized for population, wealth, and inflation, was much greater earlier this century than in the past several decades. They argued that recent climate disasters are perceived to be greater today than in the past because of increased population densities in regions affected by hurricanes. A goal of weather and climate forecasting is to mitigate some adverse impacts and take advantage of the adventitious impacts.

Nicholls (1996) concluded that the benefits of forecasts are dominated by cases relating to agriculture, construction, manufacturing, and the energy sector. He noted that current forecasts have captured up to 18% of the value of perfect forecasts in Peru. Nicholls (1996) also observed that seasonal forecasts can help maintain economic stability and sustain development in Africa and South America. One way this stability can be maintained is by helping reduce disease and improve health care and nutrition.

Field/Firm-Level Valuation Studies

Field- and/or firm-level studies (no price changes) have generally concluded that the use of climate forecasts is valuable to decision makers (e.g., Hammer, Nicholls, and Mitchell; Hammer et al.). In agriculture, the vast majority of these studies have used crop-growth simulation models as the basis for crop yields under different climate conditions. The use of crop-growth models forces the studies to be interdisciplinary in nature, a unique aspect of the valuation of climate forecast studies. The main reason for crop-growth models is that few to no real-world data exist on how producers would change production practices in response to climate forecasts (Hill et al. 2002). Crop-growth models generate simulated data that can be used to determine "optimal" production practices and associated yields under the producer's assumed different prior knowledge and climate forecast scenarios with a fixed technology. One exception to the use of crop-growth simulation models is Mjelde et al. (1997b), which used experimental field plot data.

Mjelde, Thompson, and Nixon examine the impact of government institutions on the value of seasonal forecasts. Farm programs may reduce producers' management flexibility by limiting the number of planted acres. Crop insurance may substitute for forecasts. In a related study, Mjelde et al. (1997a) showed that the greatest changes in net returns in response to seasonal forecasts were caused by changes in crop mix. Nitrogen application rates are the second most important management practice. Besides crop mix and nitrogen rates, the only other production input receiving much attention is cultivar type. Mjelde and Hill compared results from several models that varied in location, crop, and aggregation level. They concluded that the use of climate forecasts will have a complicated impact on the agriculture sector. Different regions and crops will be affected differently. Furthermore, physical and economic variables such as production, costs, and input usage may increase or decrease with the use of climate forecasts.

Within the climate science and political arena, there has been a push for the development of end-to-end, value-added forecasting technology. This technology implies that climate research and modeling must be integrated with the ultimate users of useful forecasts (Agrawala, Broad, and Guston). What defines useful or value-added remains undefined. McNew et al. suggested that a role may exist for public and private entities to transform forecasts into recommendations to crop and livestock producers. Jochec et al. reported that a focus group of ranchers recognized the importance of user-friendly form of forage production instead of separate precipitation and temperature forecasts. The ranchers, however, expressed concern that poor forage production forecasts would be misinterpreted as poor management and not weather-related by the public. The ranchers concluded that they would rather have precipitation and temperature forecasts than forage-based forecasts. End-to-end, value-added forecasts will most likely remain problem specific.

As one would expect, the value of using

ENSO-based climate forecasts has received attention in the literature. Results have suggested that current skill in climate forecasting is sufficient to warrant use in some areas (Hammer, Holzworth, and Stone; Hansen et al.). Such conclusions are, however, site and crop specific. Mjelde et al. (1997b) indicated that the use of ENSO-based forecasts have a value of $1–2/acre for corn, but for sorghum provide little additional information for adjusting nitrogen application rates. Bowman, McKeon, and White (p. 687) indicated that the value ENSO-based forecasts for wool production in southern Australia ". . . is probably substantially less than generally anticipated. . . ." Hill et al. (2000) compared two ENSO-based climate forecast methods. The two systems differed in the number of phases (three or five) of the SOI. Results suggested that not all producers will prefer the same method. Furthermore, results suggested that ENSO-based climate forecasts ranged 0%–23% of the value of perfect forecasts depending on site and price. Hammer, Holzworth, and Stone found that the five-phase forecasts provide the most value. Forecasts need to be tailored to specific regions.

Besides agriculture, several studies have suggested that the use of climate forecasts may improve decision making in the power industry, although the economic modeling is limited. Russo et al. showed that utility-based decision makers may experience benefits in some years by using ENSO information. Changnon et al. (1999, 2000), using limited case studies, suggested that the use of ENSO information in purchasing natural gas may return cost-effective decisions.

Aggregate-Level Studies

A natural extension of the field-level studies is determining the aggregate effect of the use of climate forecasts on society. A word of caution concerning aggregate studies is necessary. Readers must carefully review the methodology used and assumptions made in the studies, more so than in field-level studies. Some studies, for example, aggregate field-level results without consideration of price and acreage responses. In other studies, limited input changes are assumed or a small number of years are considered. Furthermore, assumptions on the impact of climate and development of climate forecast scenarios are sometimes questionable. The fallacy of composition is an important issue in aggregate studies, because they usually aggregate up from field- and farm-level data. With these caveats, we present findings from aggregate studies.

Sumner, Hallstrom, and Lee noted that fundamental to modeling the impact of the use of climate forecasts is modeling the effect of climate variability on commodity production and the endogenous responses of growers, traders, and others to climate forecasts. Their theoretical model shows a potential interaction between trade policy and the use of climate forecasts. For example, Sumner, Hallstrom, and Lee (p. 1107) stated, ". . . the value of a forecast might be more or less under an import quota relative to free trade, depending on the nature of local market demand." Such theoretical results are consistent with results at the decision-maker level and the value of information studies noted earlier. Specific empirical studies are necessary. Petersen and Fraser concluded that a forecasting technology that decreased seasonal uncertainty by 30% would increase annual profits of Western Australian farmers by approximately 5%.

Not surprisingly, several studies have examined the value of ENSO-based forecasts at the aggregate level. Glantz, Betsill, and Crandall concurred with earlier information that the Zimbabwean government could have prepared for the 1991–1992 El Niño event by terminating exports of corn, using more efficient transportation routes, and encouraging farmers to switch to drought-resistant crops. If Zimbabwe had had access earlier to ENSO information and acted on it, they could have saved up to $60 million (1996 U.S. dollars). Naranjo-Diaz concluded that seasonal forecasts could potentially help reduce the incidence of crop diseases in Cuba during certain climate events, which could potentially reduce Cuba's food import requirements and foreign exchange expenditures. Hansen et al. suggested that if their field-level results hold, ENSO-based forecasts for the southeastern United States are worth $9 million/year for corn and $3.6 million/year for wheat producers at a fixed price.

Hill et al. (1998) found that, depending on the price, the expected Texas aggregate sorghum supply curve using ENSO information shifted both to the left and right of the supply curve generated without use of ENSO information. Hill et al. (2001a) found similar results for wheat in the United States, Canada, and Australia. Shifts in supply caused by climate events are relatively greater than the shifts in supply within a specific climate event caused by using ENSO-based forecasts. Potential environmental impacts are also noted in Hill et al. (1998). They suggested that the expected aggregate amount of applied nitrogen will decrease with the use of ENSO-based climate forecasts. Potential environmental issues have been relatively ignored in the literature.

A series of related studies examined the effect of ENSO-based climate forecasts on the agriculture sector (Adams et al. 1995; Chen and McCarl; Chen, McCarl, and Adams; Chen, McCarl, and Hill; Solow et al.). These studies assumed the agriculture sector responds to seasonal forecasts by altering crop mix (because of changes in yields caused by ENSO-related climate and price changes) to maximize producer plus consumer surplus in a price endogenous mathematical programming model. In contrast to the previously discussed farm-level study, Adams et al. (1995) suggested that the overall economic value of either perfect or ENSO-based forecasts is greater under the 1990 U.S. Farm Program provisions than with a free market. Solow et al. estimated the value of ENSO-based seasonal forecasts to be approximately $2 billion (1996 dollars) for the U.S. agriculture sector over a 10-year period discounted at 6%. This represents 1%–2% of the value of farm receipts. Chen and McCarl showed that if phase strength (probabilistic information) is considered instead of using just average ENSO information, the value of ENSO-based forecasts increases by a factor of almost two. Inclusion of rest-of-the-world ENSO effects had little impact on the overall value of ENSO-based forecasts but did redistribute some gains. In their model, foreign surplus gains are minor compared with U.S. surplus gains. They concluded that if ENSO-based forecasts are widely adopted, conditional marketing strategies will need to be considered because of the effect of the use of the forecasts on prices, production, acreage, and storage. Even with producers reacting to ENSO-based forecasts, Chen, McCarl, and Adams showed an increase in ENSO strength or frequency will have overall negative economic consequences. Chen and McCarl and Chen, McCarl, and Adams reported that producer surplus decreases by using ENSO-based forecasts but consumer surplus increases such that overall economic welfare increases. Using a limited number of years (22), Chen, McCarl, and Hill examined the implications on agricultural welfare of adoption of the five-phase ENSO definition of Stone and Auliciems as opposed to the more standard three-phase definition. Their results indicated that the use of the five-phase definition almost doubles the welfare impact observed under the three-phase definition.

Using a conceptual model similar to the previous studies, Adams et al. (2001) estimated the value of an ENSO-based warning system on Mexican agriculture for various ENSO frequency scenarios and accuracy levels. Using their base of 70% accuracy, producer surplus increases by 6% by use of the system but consumer surplus decreases by 3%. They state that the reason is that producers adjust their crops to those that perform best under the ENSO phase. This adjustment causes increased prices in staple crops for the consumer.

In a dynamic model of the impact of perfect forecasts on the U.S. corn sector, Mjelde, Penson, and Nixon showed the importance of the sequence of climatic events. Expected net present value of the change in net surplus (consumer plus producer surplus) varied between $1.27 and $2.92 billion over a 10-year planning horizon, depending on the sequence of events. Consumers are the winners and producers are the losers. In any given year, however, producers and consumers may gain or lose welfare over the prior knowledge scenario. They showed that the use of seasonal forecasts in the production agriculture sector will affect machinery manufacturers, food processors and retailers, and financial services. Hill et al. (2002) used a stochastic, dynamic world wheat trade model to estimate the potential effects of producers using ENSO-based seasonal climate forecasts. They noted that the potential distribution (beyond presenting simple means) of the effect on economic measures will have policy and adoption implications. Their distributions showed a probability of any measure to increase or decrease depending on the sequence of years experienced.

Agriculture has by far received the most attention in the value of climate forecast literature. Other sectors such as fisheries and reservoir management have received some attention, although very limited in terms of economic modeling. Fisheries, such as the salmon fishery, are another area affected by climatic variability because of their dependence on stream flows for spawning. Costello, Adams, and Polasky estimated that perfect El Niño forecasts could lead to a welfare gain of $1 million (1998 dollars), using a conservative management strategy of lower catches, higher wild fish escapement, and lower hatchery releases. Net welfare gains of imperfect forecasts would be lower. Pulwarty and Redmond found, however, no significant use of current climate forecasts in salmon management. They also concluded that the use of climate information in large complex management systems such as the northwest Columbia River system bears significant promise. Pfaff, Broad, and Glantz, in discussing the Peruvian response to the 1997–98 El Niño, noted that artisanal and industrial fishing groups responded differently. They also noted that some groups will benefit, whereas others may suffer by using forecasts. For example, closing a fishery may benefit society through the increased sustainability of the fishery, but fishermen will suffer. Yao and Georgakakos showed that integrated management decision systems along with reliable stream flow forecasts can improve reservoir performance. They also stated that such procedures may help coping with climate change. Georgakakos et al. demonstrated that using forecasts in appropriate decision systems can mitigate some adverse effects of climate variability on regional water resources. Hamlet, Huppert, and Lettenmaier concluded that increases in the currently available forecast lead time increase the Columbia River hydropower generation system's operating performance, especially in years of expected above-average stream flows.

Remarks

Previous studies, when taken together, raise some interesting questions. One issue is the typical technological progress issues faced by production agriculture. For producers or consumers, are forecasts that approach the skill of perfect forecasts desirable? For society overall, it appears that skillful forecasts are desirable. Results also support Lamb's (1979, 1981) premise that we cannot assume that forecasts are automatically beneficial nor that current forecasts necessarily provide relevant information for decision makers. Issues concerning the benefits, distribution, and characteristics of seasonal forecasts are still mostly academic. Most decision markers are aware of weather forecasts, and those who can act on the information do so. Fewer decision makers are aware of or act on climate forecasts.

Throughout this review, seasonal forecasts have been referred to as information. One theoretical question previous research has raised relates to the role of seasonal forecasts. Within the decision process, are seasonal forecasts a form of technological advance, or are they substitutes or complements for other inputs? The assumed increase in supply in the Lave and Babcock articles suggests that forecasts are viewed as a technology advance in decision making. A technical innovation or change increases efficiency that translates into increased output for the same input level (Chambers). Use of climate forecasts does not necessarily change the physical or biological relationships between weather parameters (precipitation, temperature, solar radiation, etc.) and crop growth. Hill et al.'s (1998) research concluded that seasonal forecasts may not be a technical innovation but instead an input substitute. This supports the work of Sonka et al. Agrawala and Broad also raised the question, can climate forecasts be viewed as technology? They answered this question by noting that although seasonal forecasts are not pieces of hardware, they are a knowledge product, which falls in the realm of technology. Agrawala and Broad also noted that two key features differentiate seasonal forecasts from other cases of technology transfer. First, each forecast is unique, so there is a different product to base decisions on in each period. Second, seasonal forecasts are probabilistic, and, unlike other technology, deterministic expectations are not appropriate. Whether seasonal forecasts are a technical advance or input substitutes, the end result is that use of seasonal forecasts results in more efficient input use.

Constraints to the Adoption of Seasonal Forecasts

As noted earlier, forecasts have no value unless decision makers are able and willing to use the forecasts. Glantz (1976) identified fallacies in the assumptions regarding institutions' and individuals' ability to use seasonal forecasts. His observations were made primarily regarding the long-term Sahelian drought that occurred in the late 1960s and early 1970s. Many of his findings can, however, be generalized: (1) people are not always willing to change practices in response to seasonal forecasts, (2) education of decision makers does not automatically increase the use of seasonal forecasts, (3) solutions cannot be undertaken on a piecemeal basis, (4) political leaders do not always say what they mean, and (5) technology is not always going to provide a solution. Glantz's first and second points address the problem of adoption by risk-adverse individuals. Risk is involved in adopting new strategies when uncertainty about the outcome of the event exists. Points three and four address institutional constraints to responding to the information. Attempts by some groups such as international relief agencies, domestic extension services, or credit institutions only succeed if they can work in a coordinated manner with conducive government policies. In discussing climate forecasts' role in alleviating food crisis, Broad and Agrawala (p. 1693) stated, "[T]his review of the Ethiopian food crisis and some of the challenges facing seasonal forecasting is sobering and underscores the need to foster more realistic expectations among both policy makers and scientists about the uses and limits of seasonal climate forecasts in alleviating complex social problems." Glantz's fifth point may be the most important. Technology does not always solve problems. If constraints such as education limitations, government policy obstacles, or economic barriers exist, a physically viable technology (information) may not be practical. One of Glantz's major contributions is to have illustrated that the necessary conditions for seasonal forecast information to have value are not always met.

Changnon identified factors that U.S. decision makers view as impediments to using seasonal forecasts. These impediments fall into two categories: problems with the forecasts themselves and problems within the institutions the decision makers operate. Forecast problems he identified are that (1) decision makers are unaware the seasonal forecast exists, (2) the forecasts for specific future periods do not satisfy the decision makers' needs, (3) for many decision makers the forecasts lack adequate lead times, (4) analogs of past years similar to the forecasts are needed for reference purposes, and (5) knowledge about future weather conditions of other variables besides precipitation and mean temperatures is necessary. Institutional impediments are that (1) many decision makers and institutions express a skepticism about the scientific credibility of forecasting because of unclear indications of the accuracy levels, (2) decision makers lack decision models that can integrate forecast information into multifaceted decision processes, and (3) government policies limit how seasonal forecasts can be used.

The listed impediments reflect, for the most part, the difficulty that end users have with using or understanding stochastic information. Another source of impediments to the use of seasonal forecasts is cognitive illusions (Nicholls 1999). Nicholls called cognitive illusions the psychological equivalent of optical illusions. They are errors in assessing forecasts because of inappropriate reference points, erroneous prior expectations, fallacious interpretation of probabilistic statements, bias to current practices, and group conformity. Attempts to mitigate this source of error currently focus on providing the information in different formats and attempts to sensitize decision makers to the nature of the information. This means that one of the most important features of a forecasting effort has to be an outreach program combined with an educational effort to help users.

Although not the primary subject of this review, some studies have attempted to ascertain the use and nonuse of climate forecasts by decision makers using surveys or application case studies. Several studies (by no means comprehensive) are presented herein to provide the flavor and potential of such studies. Although they provide no empirical evidence, Changnon and Kunkel (p. 821) stated, "[T]he use of climate data and information in agriculture, water resources, and other weather-sensitive sectors has grown dramatically in the last 20 years. . . ." Reasons for the growth include (1) increased awareness of the impact of climate variability caused by widely publicized climate extremes, (2) improvement of computer systems that can rapidly update models and the use of personal computers, (3) arrival of the Internet for ease of transporting data, (4) development of sophisticated physical and statistical models, (5) assessment of users' needs, (6) overall growth of the use of all types of information to manage complex systems, (7) development of entities to service users, and (8) increasing accuracy of forecasts.

Pulwarty and Redmond's survey of potential users indicated that climate forecasts have to be right 75% of the time to be useful. This accuracy level is strikingly similar to the necessary accuracy level of 70%–80% given by the focus group conducted by Jochec et al. Sonka, Changnon, and Hofing indicated that, on average, a 66% accuracy level is necessary for forecasts to be valuable. These similarities exist though the studies differ in location and commodities. Phillips, Makaudze, and Unganai indicated that 90% of Zimbabwe farmers use some type of traditional climate forecasting method such as earliness of leaves/abundance of fruit. In addition, Phillips, Makaudze, and Unganai (p. 96) stated, "[i]n spite of indications that the majority believed the forecast, action was obviously not taken to use this information in management, implying that there may be degrees of belief limiting action." In fact, most, if not all, surveys of the use of climate forecasts have indicated that decision makers believe the use of improved climate forecasts would have value, but there are impediments to implementation. Impediments usually cited include some or all of the following: accuracy level too low, lack of lead time, institutional constraints, such as credit availability, lack of appropriate models to apply to the decision process using climate forecasts, lack of knowledge concerning the forecasts, lack of geographical spatial resolution of climate forecasts, and lack of knowledge concerning climate variability impacts and associated decision responses (Callahan, Miles, and Fluharty; Changnon, Changnon, and Changnon; Phillips, Makaudze, and Unganai; Pulwarty and Redmond; Sonka, Changnon, and Hofing). These studies have usually concluded that education for users and interactions among climate forecasters, modelers, and decision makers are necessary. Survey studies also have addressed the specific type of information needed by decision markers and how decision makers are using forecasts (e.g., Letson et al.). Letson et al. noted that the application of forecasts is more complex than many researchers assume. In line with earlier studies, they also noted the importance of the user perceptions in the use of information and their interpretations of forecasts. Pulwarty and Melis concluded that the use of probabilistic climate information requires flexible information-gathering decision and evaluation environments.

Mjelde, Sonka, and Peel stated that earlier adopters of climate forecasts may receive Schumpeterian profits. Early adopters will be more efficient, but their output changes will only have a slight impact on price. How the rate of adoption of the use of climate forecasts will affect a sector has not been examined. Adoption rates within regions of a country and between countries will be important in determining societies' overall welfare (Mjelde et al. 2002).

Liability issues for erroneous forecasts are addressed by Weiss (1982). She concluded that liability issues should not "... constrain the development, dissemination and use of such forecasts" (Weiss 1982, p. 516).

Efforts to Apply Seasonal Forecasts

Climate forecasts are no longer strictly an academic issue. The development of improved forecasts has led to the issue of what should be done to assist decision makers in using climate forecast effectively. As previously noted, many studies have concluded that the effective use of seasonal forecast requires close collaboration between scientists and decision makers. Along this line, many entities and application efforts are arising with a goal of assisting decision makers in using seasonal climate forecasts. Some entities are briefly mentioned to illustrate the diverse range of effort being spent worldwide on application of seasonal climate forecasts. This discussion is by no means comprehensive.

The International Research Institute (IRI) for Climate Prediction is an example of a recently created (1996) worldwide entity. Based at Lamont-Dougherty in New York and at Scripps Institute in California, IRI's mission is to create a multinational institution dedicated to integrating high quality research results into predictive models and disseminating these state-of-the-art experimental climate forecasts to decision makers (Agrawala, Broad, and Guston). A broader based established entity is the World Meteorological Organization (WMO) associated with the United Nations. Within the WMO, the Applications of Meteorology Programme helps member countries in the use of climate and weather forecasts (WMO).

Currently, seasonal climate outlooks with lead times of up to 13 months are being disseminated (Mason et al.; O'Lenic 1994). Wilks (2000) provided indications that the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center's revised (revision occurred in December 1994) probabilistic temperature and precipitation outlooks are improvements over their previous outlooks. Providing further evidence, the ability to provide useful seasonal climate outlooks is improving. Besides providing forecasts, NOAA, particularly the Office of Global Programs, has been involved in activities and research focused toward making seasonal climate forecasts useable by decision makers (NOAA 1999). Buizer, Foster, and Lund summarized activities related to the 1997–1998 El Niño event. They stated that, prior to this El Niño event, few decision makers (individual or organizational) used seasonal climate forecasts. In anticipation of the 1997–1998 event, NOAA and its partners organized Outlook Fora worldwide, which brought together researchers and representatives from climate sensitive sectors in hopes of improving the application of climate forecasts. Buizer, Foster, and Lund and NOAA (1999) also provided listings of other longer-term activities being conducted, which includes Regional Assessments of Climate Variability and Applied Research Centers (NOAA 2002a, 2002b).

An example of a state- or regional-level activity is the successful pioneering efforts of the Queensland Department of Primary Industries' Agricultural Production System Research Unit (Queensland Centre for Climate Applications). Scientists with this unit have had a close collaborative relationship with decision makers, particularly with agriculture-sector decision makers in Queensland. They have emphasized the probabilistic nature of the information both in the forecasts they make regarding ENSO events and in the decision making software they are developing (Hammer). In the United States, the Pacific ENSO Applications Center is a multi-institutional partnership that conducts research and produces applications-oriented information products on climate variability in the United States and affiliated Pacific Islands (Pacific ENSO Applications Center).

The National Center for Atmospheric Research, Environment and Societal Impact Group have helped develop a better understanding of the influence climatic variability has on society. This group has played a significant role as an information source about the current state of seasonal forecast applications in the fields of risk and disaster management, water management, agriculture, and the media (National Center for Atmospheric Research). In Canada, the Canadian Institute for Climate Studies produces seasonal forecasts and provides consulting information to its clients. It does not yet have an extensive application section. The International Fertilizer Development Center is leading application efforts in southeastern South America (Baethgen).

A few countries have made a commitment to using ENSO-based seasonal forecasts. Peruvian meteorologists work with the agricultural community to determine which crops are most appropriate for the upcoming year. Cotton is advised for drier periods, whereas rice is recommended for rainy seasons (Lagos). Lagos and Buizer claimed that the use of seasonal forecasts in the agricultural sector has helped avoid declines in the Peruvian GNP during droughts. Pfaff, Broad, and Glantz, Pulwarty and Melis, and Glantz (1996) have provided examples of the success and setbacks of the use of climate forecasts. Setbacks are not necessarily failures but are the result of the imperfect and probabilistic nature of climate forecasts.

Another source of potential application is in the risk-management area (Stern; Zeng). Insurance companies are beginning to offer policies designed to protect revenues and cap expenses in case of severe and unexpected weather caused by climate influencing processes such as the El Niño. Companies with sufficient financial resources may be able to manage climate risk by hedging in weather derivatives' markets (Zeng).

Conclusions

The ability to improve decision making using seasonal forecast information is gradually becoming a reality. Climate forecasting, however, is in its infancy. A great deal of research remains to be done if the potential of seasonal forecasts is to be achieved. How quickly long-range climate forecasts and their applications take to be refined depends on data collection improvements, theoretical developments, computing, and application advances. Despite the early developmental nature of this technology, much is already known.

Seasonal forecasts of 15 days to 18 months into the future with more skill than the climatologic forecast are a reality for some regions. ENSO-based forecasts are currently the primary basis for seasonal forecasts. Teleconnections between ENSO events and climatic variability in many regions are well established. Other processes show potential for improving seasonal forecasting. The ability to forecast for periods of more than a year and a half into the future remains more a goal than a reality. Current research on global coupled models may lead to more accurate forecasts with longer lead times than are now available.

Although this review is lengthy, it only provides an abbreviated description of what is going on in this fascinating field of study. This review started with the premise that seasonal forecasts have the potential to provide benefits for society. It also began by stating that these benefits cannot be achieved without multidisciplinary research efforts. That is simple to say, but to retain the integrity of one's professional discipline while effectively working with professionals from other disciplines and end users is a genuine challenge. The challenge of improving climate forecasts and facilitating their widespread use will likely occupy researchers and decision makers' energies for some time into the future. It is worth the effort, particularly if climate change is real, regardless of its cause. The lessons learned about climate variability may be even more important in the future if that variability is increasing because of climate change.

We conclude with some comments on the role of economics and seasonal climate forecasts. One key point we wish to emphasize is that research into valuing seasonal climate forecasts is much broader than simply valuing a forecast. Research on valuing forecasts has expanded our knowledge in the broader field of the economics of information. Continuing research into the theoretical aspects of the value of information with valuing climate forecasts is a fruitful avenue of research. Valuing climate forecasts is inherently multidisciplinary. Unfortunately, the value of climate forecasts has received more attention by other disciplines than economics. This has led to a misunderstanding of economic linkages and price reactions. Economists have been conspicuously absent in application efforts. Because of the global nature of climate variability, climate forecasts will affect the global economy. (This review has attempted to give an international flavor to climate forecast literature.) Climatologists are well adapted by training and academic paradigm to address this issue. Economists, for various reasons, have tended not to think globally in research projects and collaboration beyond development projects. Valuing climate forecasts allows for a more global perspective.

References

Adams, R.M., L.L. Houston, B.A. McCarl, M. Tiscareño, J. Matus, and R. Weiher. "The Benefits and Costs of an El Niño Southern Oscillation (ENSO) Early Warning System in Mexican Agriculture." Draft Report to U.S. Department of Commerce, National Oceanic and Atmospheric Administration and the InterAmerican Development Bank, August 2001.

Adams, R.M., K.J. Bryant, B.A. McCarl, D.M. Legler, J. O'Brien, A. Solow, and R. Weiher. "Value of Improved Long-Range Weather Information." *Contemporary Economic Policy* 13(July 1995):10–19.

Agrawala, S., and K. Broad. "Technology Transfer Perspectives on Climate Forecast Applications." *Knowledge and Society* 13(2001):45–69.

Agrawala, S., K. Broad, and D.H. Guston. "Integrating Climate Forecasts and Societal Decision Making: Challenges to an Emergent Boundary Organization." *Science, Technology, and Human Values* 26(Autumn 2001):454–77.

Babcock, B. "The Value of Weather Information in Market Equilibrium." *American Journal of Agricultural Economics* 72(November 1990):63–72.

Baethgen, W. "Applying Climate Forecasts in the Agricultural Sector: The Experience of South East South America." Paper presented at the International Research Institute for Improved Climate Forecasts International Forum on Climate Prediction, Agriculture, and Development, Palisades, NY, April 26–29, 2000.

Baquet, A.E., A.N. Halter, and F.S. Conklin. "The Value of Frost Forecasting: A Bayesian Appraisal." *American Journal of Agricultural Economics* 58(August 1976):511–20.

Barlow, M., S. Nigam, and E.H. Berbery. "ENSO, Decadal Variability, and U.S. Summertime Precipitation, Drought, and Steam Flow." *Journal of Climate* 14(May 2001):2105–28.

Bates, C.B., S.P. Charles, and J.P. Hughes. "Developing Seasonal Climate Forecasts by Stochastic Downscaling of GCM Simulations." *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems The Australian Experience.* G.L. Hammer, N. Nicholls, and C. Mitchell, eds. Dordrecht, The Netherlands: Kluwer Academic, 2000.

Berlage, H.P. "Fluctuations of the General Atmospheric Circulation of More Than One Year, Their Nature and Prognostic Value." *Royal Netherlands Meteorological Institute Yearbook* 69(1957):151–59.

Berte, Y., and M.N. Ward. "Experimental Forecast of Seasonal Rainfall and Crop Index for July–September 1997 in Cote D'Ivoire." *NOAA Experimental Long-Lead Forecast Bulletin* 6(September 1997):27–29.

Biondi, F., C.B. Lange, M.K. Hughes, and W.H. Berger. "Inter-Decadal Signals During the Last Millennium (AD 1117–1992) in the Varve Record of Santa Barbara Basin, California." *Geophysical Research Letters* 24(January 15 1997):193–96.

Bjerknes, J. "A Possible Response of Hadley Circulation to Equatorial Anomalies of Ocean Temperature." *Tellus* 18,4(1966):820–29.

———. "Atmospheric Teleconnections from the Equatorial Pacific." *Monthly Weather Review* 97(March 1969):163 72.

Bjerknes, V. "The Problem of Weather Forecasting Considered from the Point of View of Mathematics and Mechanics." *Meteorologische Zeitschrift* 21(1904):1–7.

Bonsal, B.R., A.K. Chakravarti, and R.G. Lawford. "Teleconnections Between North Pacific SST Anomalies and Growing Season Extended Dry Spells on the Canadian Prairies." *International Journal of Climatology* 13(December 1993):865–78.

Bowman, P.J., G.M. McKeon, and D.H. White.

"An Evaluation of the Impact of Long-Range Climate Forecasting on the Physical and Financial Performance of Wool-Producing Enterprises in Victoria." *Australian Journal of Agricultural Research* 46,4(1995):687–702.

Broad, K., and S. Agrawala. "The Ethiopia Food Crisis-Uses and Limits of Climate Forecasts." *Science* 289(September 2000):1693–94.

Brown, B.G., R.W. Katz, and R.M. Murphy. "On the Economic Value of Seasonal Precipitation Forecasts: The Fallowing/Planting Problem." *Bulletin of the American Meteorological Society* 67(July 1986):833–41.

Buizer, J.L, J. Foster, and D. Lund. "Global Impacts and Regional Actions: Preparing for the 1997–98 El Niño." *Bulletin of the American Meteorological Society* 81(September 2000): 2121–39.

Buizza, R. "Accuracy and Potential Economic Value of Categorical and Probabilistic Forecasts of Discrete Events." *Monthly Weather Review* 129(September 2001):2329–45.

Burroughs, W.J. "Weather Cycles." *Weather* 49(June 1994):202–9.

Busalacchi, A.J., and J.J. O'Brien. "The Seasonal Variability in a Model of the Tropical Pacific." *Journal of Physical Oceanography* 10(December 1980):1929–51.

Byerlee, D.R., and J.R. Anderson. "The Value of Predictors of Uncontrolled Factors in Response Functions." *Australian Journal of Agricultural Economics* 13(December 1969):118–27.

___. "Risk Utility and the Value of Information in Farmers Decision Making." *Review Marketing and Agricultural Economics* 50(December 1982):231–46.

Callahan, B., E. Miles, and D. Fluharty. "Policy Implications of Climate Forecasts for Water Resources Management in the Pacific Northwest." *Policy Science* 32(September 1999):269–93.

Canadian Institute for Climate Studies. University of Victoria, Victoria, Canada. Internet site: http://www.cics.uvic.ca/index.cgi (Accessed January 2002).

Cane, M.A. "Putting the Pieces Back Together: What are the Problems We Need to 'Tackle' in the Next Five Years?" Paper presented at the Systems Approach to ENSO, ENSO Colloquium, National Center for Atmospheric Research, Boulder, CO, July 20–August 1, 1997.

Cane, M.A., and S.E. Zebiak. "A Theory for El Niño and the Southern Oscillation." *Science* 228(May 1985):1085–87.

___. "Prediction of El Nino Events Using a Physical Model." *Atmospheric and Oceanic Variability*. H. Cattle, ed. London, U.K.: Royal Meteorological Society Press, 1987.

Cane, M.A., G. Eshel, and R.W. Buckland. "Forecasting Zimbabwean Maize Using Eastern Equatorial Pacific Sea Surface Temperature." *Nature* 370(July 1994):204–5.

Chambers, R.G. *Applied Production Analysis*. Cambridge, U.K.: Cambridge University Press, 1988.

Chang, P., C. Penland, L. Ji, H. Li, and L. Matrosova. "Prediction of Tropical Atlantic Sea Surface Temperature." *Geophysical Research Letters* 25(April 15, 1998):1193–96.

Changnon, D., T. Creech, N. Marsili, W. Murrell, and M. Saxinger. "Interactions with a Weather-Sensitive Decision Maker: A Case Study Incorporating ENSO Information into a Strategy for Purchasing Natural Gas." *Bulletin of the American Meteorological Society* 80(June 1999): 1117–26.

Changnon, D., M. Ritsche, K. Elyea, S. Shelton, and K. Schramm. "Integrating Climate Forecasts and Natural Gas Supply Information into a Natural Gas Purchasing Decision." *Meteorological Applications* 7(September 2000):211–16.

Changnon, S.A. "Assessment of Uses and Values of the New Climate Forecasts." Paper presented to the University Corporation of Atmospheric Research, Boulder, CO, March 1997.

Changnon, S.A., and K.E. Kunkel. "Rapidly Expanding Uses of Climate Data and Information in Agriculture and Water Resources: Causes and Characteristics of New Applications." *Bulletin of the American Meteorological Society* 80(May 1999):821–30.

Changnon, S.A., J.M. Changnon, and D. Changnon. "Uses and Applications of Climate Forecasts for Power Utilities." *Bulletin of the American Meteorological Society* 76(May 1995):711–20.

Charney, J.G., and J. Shukla. "Predictability of Monsoons." *Proceedings of the Joint IUTAM/IUGG International Symposium on Monsoon Dynamics, New Delhi, India, December 1977.* J. Ligththill and R.P. Pierce, eds. Cambridge, U.K.: Cambridge University Press, 1981.

Charney, J.G., R.G. Fleagle, H. Riehl, V.E. Lally, and D.Q. Wark. "The Feasibility of a Global Observation and Analysis Experiment." *Bulletin of the American Phyical Society* (March 1966):200–20.

Chavas, J.P., and R.D. Pope. "Information: Its Measurement and Valuation." *American Journal of Agricultural Economics* 66(December 1984): 705–10.

Chen, C.C., and B.A. McCarl. "The Value of ENSO Information to Agriculture: Consideration of Event Strength and Trade." *Journal of Agricultural Resource Economics* 25(December 2000):368–85.

Chen, C.C., B.A. McCarl, and R.M. Adams. "Economic Implications of Potential ENSO Frequency and Strength Shifts." *Climatic Change* 49(April 2001):147–59.

Chen, C.C., B.A. McCarl, and H.S.J. Hill. "The Value of ENSO Information Under Alternative ENSO Phase Definitions." Forthcoming in *Climatic Change*, 2002.

Chiew, F.H.S., T.C. Piechota, J.A. Dracup, and T.A. McMahon. "El Niño/Southern Oscillation and Australia Rainfall, Streamflow and Drought: Links and Potential for Forecasting." *Journal of Hydrology* 204(January 1998):139–49.

Costello, C.J., R.M. Adams, and S. Polasky. "The Value of El Niño Forecasts in the Management of Salmon: A Stochastic Dynamic Assessment." *American Journal of Agricultural Economics* 80(November 1998):765–77.

Crowley, T.J., W.D. Nowlin, Jr., B.A. McCarl, and J.W. Mjelde. "Benefits of Improved Climate Prediction." Technical Report No. 2, Center for Climate Studies, Texas A&M University, College Station, TX, November 1995.

Derr, V.E., and R. J. Slutz. "Prediction of El Niño Events in the Pacific by Means of Neural Networks." *AI Applications: Natural Resources, Agriculture, and Environmental Science* 8(July 1994):51–63.

Easterling, W.E. "Subscribers to the NOAA Monthly and Seasonal Weather Outlook." *Bulletin of the American Meteorological Society* 67(April 1986):402–8.

Easterling, W.E., and J.W. Mjelde. "The Importance of Seasonal Climate Prediction Lead Time in Agricultural Decision Making." *Agricultural and Forest Meteorology* 40(June 1987):37–50.

Enfield, D.B. "Relationships of Inter-American Rainfall to Tropical Atlantic and Pacific SST Variability." *Geophysical Research Letters* 23(November 1996):3505–8.

Enfield, D.B., A.M. Mestas-Nuñez, and P.J. Trimble. "The Atlantic Multidecadal Oscillation and Its Relationship to Rainfall and River Flows in the Continental U.S." *Geophysical Research Letters* 28(May 2001):2077–80.

Ferreyra, R.A., G.P. Podestá, C.D. Messina, D. Letson, J. Dardanelli, E. Guevara, and S. Meira. "A Linked-Modeling Framework to Estimate Maize Production Risk Associated with ENSO-Related Climate Variability in Argentina." *Agricultural and Forest Meteorology* 107(April 2001):177–92.

Fleer, H.E. "Teleconnections of Rainfall Anomalies in the Tropics." *Monsoon Dynamics*. J. Lightfoot and R. P. Pearce, eds. Cambridge, U.K.: Cambridge University Press, 1981.

Friis-Christensen, E., and K. Lassen. "Length of the Solar Cycle: An Indicator of Solar Activity Closely Associated with Climate." *Science* 254(November 1991):652–53.

Garnett, R., E. Khandekar, L. Madhav, and J.C. Babb. "On the Utility of ENSO and PNA Indices for Long-Lead Forecasting of Summer Weather Over the Crop Growing Regions of the Canadian Prairies." *Theoretical and Applied Climatology* 60(January 1997):37–45.

Georgakakos, A.P., H.M. Yao, M.G. Mullusky, and K.P. Georgakakos. "Impacts of Climate Variability on the Operational Forecast and Management of the Upper Des Moines River Basin." *Water Resources Research* 34(April 1998):799–821.

Gershunov, A., and T.P. Barnett. "Interdecadal Modulation of ENSO Teleconnections." *Bulletin of the American Meteorological Society* 79(December 1998):2715–26.

Glantz, M.H., ed. *The Politics of Natural Disaster: The Case of the Sahel Drought*. New York: Praeger Publishers, 1976.

___. *Currents of Change: El Nino's Impact on Climate and Society*. Cambridge, U.K.: Cambridge University Press, 1996.

___. *Once Burned, Twice Shy? Lessons Learned from the 1997–98 El Niño*. New York: The United Nations University, 2001.

Glantz, M.H., M. Betsill, and K. Crandall. "Food Security in Southern Africa: Assessing the Use and Value of ENSO Information." Environmental and Societal Impacts Group, National Center for Atmospheric Research, Boulder, CO, 1997.

Global Climate Observation System, Working Group on Socio-Economic Benefits. "The Socio-Economic Benefits of Climate Forecasts: Literature Review and Recommendations." Geneva, Switzerland: World Meteorological Organization GCOS-12 WMO/TD No. 674, 1995.

Goddard, L., S.J. Mason, S.E. Zebiak, C.F. Ropelewski, R. Basher, and M.A. Cane. "Current Approaches to Seasonal to Interannual Climate Predictions." *International Journal of Climatology* 21(July 2001):1111–52.

Gould, J.P. "Risk, Stochastic Preference, and the Value of Information." *Journal of Economic Theory* 8(May 1974):64–84.

Greenberg, J. "Economic Benefits of Improved

Meteorological Forecasts." *Weather Forecasting and Weather Forecasts: Models, Systems, and User.* Boulder, CO.: National Center For Atmospheric Research, Volume 2, pp. 608–29, 1976.

Guetter, A.K., and K.P. Georgakakos. "Are El Niño and La Niña Predictors of the Iowa River Seasonal Flow?" *Journal of Applied Meteorology* 35(May 1996):690–705.

Hales, S., P. Weinstein, P. Souares, and A. Woodward. "El Niño and the Dynamics of Vectorborne Disease Transmission." *Environmental Health Perspectives* (February 1999):99–102.

Hamlet, A.F., D. Huppert, and D.P. Lettenmaier. "Economic Value of Long-Lead Streamflow Forecasts for Columbia River Hydropower." *Journal of Water Resources Planning and Management* 129(March/April 2002):91–101.

Hammer, G. L. Personal Communication. Principal Scientist, Agricultural Production Systems Research Unit (APSRU). Toowoomba, Queensland, Australia, October 22, 1998.

Hammer, G.L., and N. Nicholls. "Managing for Climate Variability—The Role of Seasonal Climate Forecasting in Improving Agricultural Systems." Invited Paper, 2nd Australian Conference on Agricultural Meteorology, Brisbane, Australia, October 1–4, 1996.

Hammer, G.L., D.P. Holzworth, and R. Stone. "The Value of Skill in Seasonal Climate Forecasting to Wheat Crop Management in a Region with High Climatic Variability." *Australian Journal of Agricultural Research* 47,5(1996):717–37.

Hammer, G.L., N. Nicholls, and C. Mitchell, eds. *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems The Australian Experience.* Dordrecht, The Netherlands: Kluwer Academic, 2000.

Hammer, G.L, J.W. Hansen, J.G. Phillips, J.W. Mjelde, H. Hill, A. Love, and A. Potgieter. "Advances in Application of Climate Prediction in Agriculture." *Agricultural Systems* 70(November–December 2001):515–53.

Handler, P. "USA Corn Yields, the El Niño and Agricultural Drought: 1867–1988." *International Journal of Climatology* 10(June 1990): 819–28.

Handler, P., and E. Handler. "Climatic Anomalies in the Tropical Pacific Ocean and Corn Yields in the United States." *Science* 220(June 1983): 1155–56.

Hansen, J.W., A.W. Hodges, and J.W. Jones. "ENSO Influences on Agriculture in the Southeastern United States." *Journal of Climate* 11(March 1998):404–11.

Hansen, J.W., J.W. Jones, A. Irmark, and F. Royce. "El Niño-Southern Oscillation Impacts on Crop Production in the Southeastern United States." American Society of Agronomy, Special Publication Number 63, *Impacts of El Niño and Climatic Variability on Agriculture,* Madison, WI, pp. 55–76, 2001.

Hill, H.S.J., J.W. Mjelde, W. Rosenthal, and P.J. Lamb. "The Potential Impacts of the Use of Southern Oscillation Information on the Texas Aggregate Sorghum Production." *Journal of Climate* 12(February 1998):519–30.

Hill, H.S.J., J. Park, J.W. Mjelde, W. Rosenthal, H.A. Love, and S.W. Fuller. "Comparing the Value of Southern Oscillation Index-Based Climate Forecast Methods for Canadian and U.S. Wheat Producers." *Agricultural and Forest Meteorology* 100(February 2000):261–72.

Hill, H.S.J, J.W. Mjelde, H.A. Love, S.W. Fuller, D.J. Rubas, W. Rosenthal, and G.L. Hammer. "Potential Implications of the Use of Seasonal Climate Forecasts on World Wheat Trade." Working Paper, Department of Agricultural Economics, Texas A&M University, College Station, TX, 2002.

Hill, H.S.J., D.B. Butler, S.W. Fuller, G.L. Hammer, D. Holzworth, H.A. Love, H. Meinke, J.W. Mjelde, J. Park, and W. Rosenthal. "Effects of Seasonal Climate Variability and the Use of Climate Forecasts on Wheat Supply in the U.S., Australia, and Canada." American Society of Agronomy, Special Publication Number 63, *Impacts of El Niño and Climatic Variability on Agriculture,* Madison, WI, pp. 101–23, 2001a.

Hilton, R.W. "The Determinants of Information Value: Synthesizing Some General Results." *Management Science* 27(January 1981):57–64.

Hoerling, M.P., A. Kumar, and M. Zhang. "El Niño, La Niña, and the Nonlinearity of Their Teleconnections." *Journal of Climate* 10(August 1997):1769–86.

Jochec, K.G., J.W. Mjelde, A.C. Lee, and J.R. Conner. "Use of Seasonal Climate Forecasts in Rangeland-Based Livestock Operations in West Texas." *Journal of Applied Meteorology* 40(September 2001):1629–39.

Jones, J.W., J.W. Hansen, F.S. Royce, and C.D. Messina. "Potential Benefits of Climate Forecasting to Agriculture." *Agricultural, Ecosystems, and Environment* 82(December 2000): 169–84.

Kahya, E., and J.A. Dracup. "U.S. Streamflow Patterns in Relation to the El Niño/Southern Oscillation." *Water Resources Research* 29(August 1993):2491–503.

Kane, R.P. "Relationship Between QB's of Stratospheric Winds, ENSO Variability and Other Parameters." *International Journal of Climatology* 12(May 1992):435–47.

Katz, R.W., and A.H. Murphy. *Economic Value of Weather and Climate Forecasts.* Cambridge, U.K.: Cambridge University Press, 1997.

Katz, R.W., A.H. Murphy, and R.L. Winkler. "Assessing the Value of Frost Forecasts to Orchardists: A Dynamic Decision-Making Approach." *Journal of Applied Meteorology* 21(April 1982): 518–31.

Keppenne, C.L. "An ENSO Signal in Soybean Futures Prices." *Journal of Climate* 8(July 1995): 1685-89.

Kerr, R.A. "A North Atlantic Climate Pacemaker for the Centuries." *Science* 288(June 2000): 1984–86.

Khandekar, M.L. "El Niño/Southern Oscillation, Indian Monsoon and World Grain Yields—A Synthesis." *Advances in Natural and Technological Hazards Research,* Volume 7. M.I. El-Sabh, S. Venkatesh, H. Denis, and T.S. Murty, eds. Dordrecht, The Netherlands: Kluwer Publishers, 1996.

Khinchin, A.I. *Mathematical Foundations of Information.* R.A. Silverman and M.D. Friedman translators. New York: Dover Publications, 1957.

Kiladis, G.N., and H.F. Diaz. "Global Climatic Anomalies Associated with Extremes of the Southern Oscillation." *Journal of Climate* 2(September 1989):1069–90.

Klopper, E. "The Use of Seasonal Forecasts in South Africa During the 1997/98 Rainfall Season." *Water SA* 25(July 1999):311–16.

Kovats, R.S. "El Niño and Human Health." *Bulletin of the World Health Organization* 78(September 2000):1135–2000.

Kuhnel, I. "Nature's Tax: The East Gippsland Floods." *Natural Hazards Quarterly* 4(July 1998):1–2.

Kunkel, K., R.A. Pielke, Jr., and S.A. Changnon. "Temporal Fluctuations in Weather and Climate Extremes that Cause Economic and Human Health Impacts: A Review." *Bulletin of the American Meteorological Society* 80(June 1999):1077–98.

Lagos, P. "Application of El Niño Prediction to the Agriculture Sector in Peru." Paper presented at the ENSO Colloquium, National Climate and Atmospheric Research Center, Boulder, CO, July 20–August 1, 1997.

Lagos, P., and J. Buizer. "El Niño and Peru: A Nation's Response to Interannual Climate Variability." *Natural and Technological Disasters: Causes, Effects, and Preventative Measures.* S.K. Majumdar, G.S. Forbes, E.W. Miller, and R.F. Schmaltz, eds. Harrisburg, PA: Pennsylvania Academy of Sciences, 1992.

Lamb, P.J. "Some Perspectives on Climate and Climate Dynamics." *Progress in Physcial Geography* 3(June 1979):215.

___. "Do We Know What We Should Be Trying to Forecast-Climatically?" *Bulletin of the American Meteorological Society* 62(July 1981):1000.

Lamb, P.J., and R.A. Peppler. "Large-Scale Atmospheric Features Associated With Drought in Morrocco." *Proceedings of Drought, Water Management and Food Production Conf., Kingdom of Morrocco, Rabat.* Agadir, Morocco, November 21–24, 1985.

___. "North Atlantic Oscillation: Concept and Application." *Bulletin of the American Meteorological Society* 68(October 1987):1218–25.

Lave, L.B. "The Value of Better Weather Information to the Raisin Industry." *Econometrica* 31(January–April 1963):151–64.

Letson, D., I. Llovet, G. Podesta, F. Royce, V. Brescia, D. Lema, and G. Parellada. "User Perspectives of Climate Forecasts: Crop Producers in Pergamina, Argentina." *Climate Research* 19(November 2001):57–67.

Lorenz, E.N. "A Study of the Predictability of a 28 Variable Atmospheric Model." *Tellus* 17(August 1965):321–33.

Lowther, P.L. "The Development of a Seasonal Climate Forecasts Methodology for ITCZ Associated Rainfall Applied to Eastern Africa." Ph.D. dissertation. Texas A&M University, College Station, Texas, 1998.

Maelzer, D., S. Hales, P. Weinstein, M. Zalucki, and A. Woodward. "El Niño and Arboviral Disease Prediction." *Environmental Health Perspectives* 107(October 1999):817–18.

Mantua, N.J. "The Pacific Decadal Oscillation." *The Encyclopedia of Global Environmental Change. Volume 1: The Earth System's Physical and Chemical Dimensions of Global Environmental Change.* New York: John Wiley & Sons, Inc., 2001.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. "A Pacific Inter-Decadal Climate Oscillation with Impacts on Salmon Production." *Bulletin of the American Meteorological Society* 78(June 1997):1069–79.

Marschak, J. "Remarks on the Economics of Information." *Contributions to Scientific Research in Management.* The proceedings of the scientific program following the dedication of the Western Data Processing Center, Graduate School of Business Administration, University of California, Los Angeles, University of California Printing Department, January 29–30, 1959.

Marshall, G.R., K.A. Parton, and G.L. Hammer. "Risk Attitude, Planting Conditions and the Value of Seasonal Forecasts to a Dryland Wheat Grower." *Australian Journal of Agricultural Economics* 40(December 1996):211–33.

Marshall, J., Y. Kushnir, D. Battisti, P. Chang, J.Hurrell, and M. McCartney. "Atlantic Climate Variability." White Paper, CLIVAR, Massachusetts Institute of Technology, Cambridge, MA, 1997.

Mason, S.J., and L. Goddard. "Probabilistic Precipitation Anomalies Associated with ENSO." *Bulletin of the American Meteorological Society* 82(April 2001):619–38.

Mason, S.J., L. Goddard, N.E. Graham, E. Yulaeva, L. Sun, and P.A. Arkin. "The IRI Seasonal Climate Prediction System and the 1997/98 El Niño Event." *Bulletin of the American Meteorological Society* 80(September 1999):1853–73.

Mazzocco, M.A., J.W. Mjelde, S.T. Sonka, P.J. Lamb, and S.E. Hollinger. "Using Hierarchical Systems Aggregation to Model the Value of Information in Agricultural Systems: An Application for Climate Forecast Information." *Agricultural Systems* 2,4(1992):393–412.

McGuffie, K., and A. Henderson-Sellers. "Forty Years of Numerical Climate Modeling." *International Journal of Climatology* 21(July 2001): 1067–1109.

McNew, K.P., H.P. Mapp, C.E. Duchon, and E.S. Merritt. "Sources and Uses of Weather Information for Agricultural Decision Makers." *Bulletin of the American Meteorological Society* 72(April 1991):491–98.

Merkhofer, M.W. "The Value of Information Given Decision Flexibility." *Management Science* 23(March 1977):716–27.

Messina, C.D., J.W. Hansen, and A.J. Hall. "Land Allocation Conditioned on El Niño-Southern Oscillation Phases in the Pampas of Argentina." *Agricultural Systems* 60(June 1999):197–212.

Minobe, S. "A 50–70 Year Climatic Oscillation Over the North Pacific and North America." *Geophysical Research Letters* 24(March 1997): 683–86.

Mjelde, J.W. "Dynamic Programming Model of the Corn Production Decision Process with Stochastic Climate Forecasts." Unpublished Ph.D. dissertation. University of Illinois Urbana-Champaign, 1985.

Mjelde, J.W., and M.J. Cochran. "Obtaining Lower and Upper Bounds on the Value of Seasonal Climate Forecasts as a Function of Risk Preferences." *Western Journal of Agricultural Economics* 13(December 1988):184–92.

Mjelde, J.W., and B.L. Dixon. "Valuing the Lead Time of Periodic Forecasts in Dynamic Production Systems." *Agricultural Systems* 42(October 1993):41–55.

Mjelde, J.W., and H.S.J. Hill. "An Analysis of the Impact of Improved Climate Forecasts on Economic and Production Factors." *Agricultural Systems* 60(June 1999):213–25.

Mjelde, J.W., and K. Keplinger. "Using the Southern Oscillations to Forecast Texas Winter Wheat and Sorghum Crop Yields." *Journal of Climate* 11(January 1998):54–60.

Mjelde, J.W., H.S.J. Hill, and J.F. Griffiths. "A Review of Current Evidence on Climate Forecasts and Their Economic Effects in Agriculture." *American Journal of Agricultural Economics* 80(December 1998):1080–95.

Mjelde, J.W., J.B. Penson, and C.J. Nixon. "Dynamic Aspects of the Impact of the Use of Perfect Climate Forecasts in the Corn Belt Region." *Journal of Applied Meteorology* 39(January 2000):67–79.

Mjelde, J.W., S.T. Sonka, and D.S. Peel. *The Socioeconomic Value of Climate and Weather Forecasting: A Review.* Midwestern Climate Center, Climate and Meteorology Section, Illinois State Water Survey, Champagne, IL, Research Report 89-01, 1989.

Mjelde, J.W., T.N. Thompson, and C.J. Nixon. "Government Institutional Effects on the Value of Seasonal Climate Forecasts." *American Journal of Agricultural Economics* 78(February 1996): 175–88.

Mjelde, J.W., D.S. Peel, S.T. Sonka, and P.J. Lamb. "Characteristics of Climate Forecast Quality: Implications for Economic Value to Midwestern Corn Producers." *Journal of Climate* 6(November 1993):2175–87.

Mjelde, J.W., S.T. Sonka, B.L. Dixon, and P.J. Lamb. "Valuing Forecast Characteristics in a Dynamic Agricultural Production System." *American Journal of Agricultural Economics* 70(August 1988):674–84.

Mjelde, J.W., T.N. Thompson, C.J. Nixon, and P.J. Lamb. "Utilizing a Farm-Level Decision Model for Prioritizing Future Climatic Research Needs." *Meteorological Applications* 4(June 1997a):161–70.

Mjelde, J.W., H.A. Love, D.J. Rubas, W. Rosenthal, and H.S.J. Hill. "Potential Effect of Seasonal

Climate Forecasts on Competitiveness in the World Wheat Market." Draft of a Report to the United States Department of Agriculture, No. 00-35400-9124, August 2002.

Mjelde, J.W., T.N. Thompson, F.M. Hons, J.T. Cothren, and C.G. Coffman. "Using Southern Oscillation Forecasts for Determining Corn and Sorghum Profit-Maximizing Levels in Central Texas." *Journal of Production Agricultural* 10(January–March 1997b):168–75.

Montroy, D.L. "Linear Relation of Central and Eastern North American Precipitation to Tropical Pacific Sea Surface Temperature Anomalies." *Journal of Climate* 10(April 1997):541–58.

Montroy, D.L., M.B. Richman, and P.J. Lamb. "Observed Nonlinearities of Monthly Teleconnections Between Tropical Pacific Sea Surface Temperature Anomalies and Central and Eastern North American Precipitation." *Journal of Climate* 11(July 1998):1812–35.

Moore, J.L., and J.M. Armstrong. "The Use of Linear Programming Techniques for Estimating the Benefits from Increased Accuracy of Water Supply Forecasts." *Water Resource Research* 12(August 1976):629–39.

Murphy, A.H. "What is a Good Forecast—An Essay on the Nature of Goodness in Weather Forecasting." *Weather and Forecasting* 8(June 1993):281–93.

Naranjo-Diaz, L.R. "ENSO Impact on Cuba." Paper presented at the ENSO Colloquium, National Center for Atmospheric Research, Boulder CO, July 16–August 2, 1997.

National Center for Atmospheric Research, Environment and Societal Impact Group. Internet site: http://www.esig.ucar.edu/ (Accessed January 2002).

National Oceanic and Atmospheric Administration (NOAA). *An Experiment in the Application of Climate Forecasts: NOOA-OGP Activities Related to the 1997–98 El Niño Event.* Office of Global Programs National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Springs, MD. Internet site: http://www.ogp.noaa.gov/enso/retro/ensodoc.htm (Accessed January 1999).

____. Regional Integrated Sciences and Assessments Program. Internet site: http://www.ogp.noaa.gov/mpe/csi/risa/index.htm (Accessed January 2002a).

____. Regional Integrated Sciences and Assessments Program. Climate Dynamics and Experimental Prediction. Internet site: http://www.ogp.noaa.gov/mpe/cdep/index.htm (Accessed January 2002b).

National Research Council. Climate Research Council, Board on Atmospheric Sciences and Climate. *Goals For Predicting Seasonal-to-Interannual Climate.* Washington, DC: National Academy Press, 1994.

____. Advisory Panel for the Tropical Oceans and Global Atmosphere Program (TOGA Panel). *Learning to Predict Climate Variations Associated With El Niño and the Southern Oscillation.* Washington, DC: National Academy Press, 1996.

Naylor, R.L., W.P. Falcon, D. Rochberg, and N. Wada. "Using El Niño/Southern Oscillation Climate Data to Predict Rice Production in Indonesia." *Climatic Change* 50(August 2001): 255–65.

Nicholls, J.M. "Economic and Social Benefits of Climatological Information and Services: A Review of Existing Assessments." World Meteorological Organization WMO/TD No. 780, Switzerland, 1996.

Nicholls, N. "Use of the Southern Oscillation to Predict Australian Sorghum Yield." *Agricultural and Forest Meteorology* 38(October 1986): 9–15.

____. "Cognitive Illusions, Heuristics, and Climate Predictions." *Bulletin of the American Meteorological Society* 80(July 1999):1385–97.

Nigam, S., M. Barlow, and E.H. Berbery. "Analysis Links Pacific Decadal Variability to Drought and Streamflow in United States." *Eos* 80(December 1999). Internet site: http://www.agu.org/eos_elec/99088e.html (Accessed November 2000).

O'Lenic, E.A. "Operational Long-Lead Outlooks of Seasonal Mean Temperature and Precipitation." Technical Procedures Bulletin 418, National Oceanic and Atmospheric Administration, Climate Prediction Center, Washington D.C., 1994.

Pacific ENSO Applications Center. PEAC Background Information. Internet site: http://lumahai.soest.hawaii.edu/Enso/back/background.html (Accessed January 2002).

Pascual, M., X. Rodo, S.P. Ellner, R. Colwell, and M.J. Bouma. "Cholera Dynamics and El Niño-Southern Oscillation." *Science* 289(September 2000):1766–69.

Petersen, E.H., and R.W. Fraser. "An Assessment of the Value of Seasonal Forecasting Technology for Western Australian Farmers." *Agricultural Systems* 70(October 2001):259–74.

Pfaff, A., K. Broad, and M. Glantz. "Who Benefits from Climate Forecasts?" *Nature* 397(February 1999):645–46.

Phillips, J.G., and B. McIntyre. "ENSO and Interannual Rainfall Variability in Uganda: Implications for Agricultural Management." *International Journal of Climatology* 20(February 2000):171–82.

Phillips, J.G., M.A. Cane, and C. Rosenzweig. "ENSO, Seasonal Rainfall Patterns and Simulated Maize Yield Variability in Zimbabwe." *Agricultural and Forest Meteorology* 90(March 1998):39–50.

Phillips, J.G., E. Makaudze, and L. Unganai. "Current and Potential Use of Climate Forecasts for Resource-Poor Farmers in Zimbabwe." American Society of Agronomy, Special Publication Number 63, *Impacts of El Niño and Climatic Variability on Agriculture*. Madison, WI, pp. 87–100, 2001.

Pielke, R.A., Jr., and C.W. Landsea. "Normalized Hurricane Damages in the United States: 1925–1995." *Weather and Forecasting* 13(September 1998):351–61.

———. "La Niña, El Niño, and Atlantic Hurricane Damages in the United States." *Bulletin of the American Meteorological Society* 80(October 1999):2027–33.

Pielke, R.A., Jr., J. Kimple, C. Adams, J. Baker, S. Changnon, K.F. Heideman, P. Leavitt, R.N. Keener, J. McCarthy, K. Miller, A.H. Murphy, R.S. Pulwarty, R. Roth, E.M. Stanley, T. Stewart, and T. Zacharias. "Societal Aspects of Weather: Report of the Sixth Prospectus Development Team of U.S. Weather Research Program to NOAA and NSF." *Bulletin of the American Meteorological Society* 78(May 1997): 867–76.

Podbury, T., T.C. Sheales, I. Hussain, and B.S. Fisher. "Use of El Niño Climate Forecasts in Australia." *American Journal of Agricultural Economics* 80(December 1998):1096–1101.

Price, S. "Thunderstorm Today?" *Weatherwise* 2(1949):61–67.

Pulwarty, R.S., and T.S. Melis. "Climate Extremes and Adaptive Management on the Colorado River: Lessons from the 1997–1998 ENSO Event." *Journal of Environmental Management* 63(November 2001):307–24.

Pulwarty, R.S., and K.T. Redmond. "Climate and Salmon Restoration in the Columbia River Basin: The Role and Usability of Seasonal Forecasts." *Bulletin of the American Meteorological Society* 78(March 1997):381–97.

Queensland Centre for Climate Applications. Queensland Department of Primary Industries, Toowoomba, Australia. Internet site: http://www.dpi.qld.gov.au/qcca/Welcome.html (Accessed April 1998).

Rajagopalan, B., Y. Kushnir, and Y.M. Tourre. "Observed Decadal Midlatitude and Tropical Atlantic Climate Variability." *Geophyscial Research Letters* 25(November 1998):3967–70.

Rasmusson, E.M., and J.M. Wallace. "Meteorological Aspects of the El Niño/Southern Oscillation." *Science* 222(December 1983):1195–1202.

Richardson, D.S. "Skill and Relative Economic Value of the ECMWF Ensemble Prediction System." *Quarterly Journal of the Royal Meteorological Society* 126(January 2000):649–67.

Rimmington, G.M., and N. Nicholls. "Forecasting Wheat Yields in Australia with the Southern Oscillation Index." *Australian Journal of Agricultural Research* 44,4(1993):625–32.

Ropelewski, C.F., and M.S. Halpert. "North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation (ENSO)." *Monthly Weather Review* 114(December 1986):2352–62.

___. "Global and Regional Scale Precipitation and Temperature Patterns Associated with the El Nino/Southern Oscillation." *Monthly Weather Review* 115(August 1987):1606–26.

___. "Precipitation Patterns Associated with the High Index Phase of the Southern Oscillation." *Journal of Climate* 2(March 1989):268–84.

Ropelewski, C.F., M.S. Halpert, and X. Wang. "Observed Tropospheric Biennial Variability and Its Relationship to the Southern Oscillation." *Journal of Climate* 5(June 1992):594–614.

Rosenzweig, C. "Maize Suffers a Sea-Change." *Nature* 370(July 1994):27.

Royal Meteorological Society. "Sir Gilbert Walker." *Quarterly Journal of the Royal Meteorological Society* 85(April 1959):186.

Russo, M., D. Changnon, M. Podolak, H. Freestrom, and J.B. Davis. "Using Equatorial Pacific Sea Surface Temperature Anomalies to Forecasts Seasonal Energy Demand in Four U.S. Regions: An Applied Climate Research Experience for Undergraduate Meteorology Students." *Bulletin of the American Meteorological Society* 80(June 1999):1130–47.

Shabbar, A., and A.G. Barnston. "Skill of Seasonal Climate Forecasts in Canada Using Canonical Correlation Analysis." *Monthly Weather Review* 124(October 1996):2370–85.

Sherrick, B.J., S.T. Sonka, P.J. Lamb, and M.A. Mazzocco. "Decision-Maker Expectations and the Value of Climate Prediction Information:

Conceptual Considerations and Preliminary Evidence." *Meteorological Applications* 7(December 2000):377–87.

Shukla, J. "Predictability in the Midst of Chaos: A Scientific Basis for Climate Forecasting." *Science* 282(October 1998):728–31.

Solow, A.R., R.F. Adams, K.J. Bryant, D.M. Legler, J.J. O'Brien, B.A. McCarl, W. Nayda, and R. Weiher. "The Value of Improved ENSO Prediction to U.S. Agriculture." *Climatic Change* 39(May 1998):47–60.

Sonka, S.T., S.A. Changnon, Jr., and S.L. Hofing. "How Agribusiness Uses Climate Predictions: Implications for Climate Research and Provision of Predictions." *Bulletin of the American Meteorological Society* 73(December 1992): 1999–2008.

Sonka, S.T., P.J. Lamb, S.A. Changnon, and A. Wiboonpongse. "Can Climate Forecasts for the Growing Season be Valuable to Crop Producers: Some General Considerations and an Illinois Pilot Study." *Journal of Applied Meteorology* 21(April 1982):471–76.

Stefanski, R.J. "Potential El Niño Impacts on U.S. Feed Grain Production." *Feed, Situation, and Outlook Report.* Washington, DC: U.S. Department of Agriculture, Economic Research Service FDS-322, May 1992.

Stern, H. "The Application of Weather Derivatives to Mitigate the Financial Risk of Climate Variability and Extreme Events." *Australian Meteorological Magazine* 50(September 2001):171–82.

Stern, P.C., and W.E. Easterling, eds. *Making Climate Forecasts Matter.* Washington, DC: National Academy Press, 1999.

Stewart, R.T., R.W. Katz, and A.H. Murphy. "Value of Weather Information: A Descriptive Study of the Fruit-Frost Problem." *Bulletin of the American Meteorological Society* 65(February 1984): 126–37.

Stone, R.C., and A. Auliciems. "SOI Phase Relationships with Rainfall in Eastern Australia." *International Journal of Climatology* 12(April 1992):625–36.

Stone, R.C., G.L. Hammer, and T. Marcussen. "Prediction of Global Rainfall Probabilities Using Phases of the Southern Oscillation Index." *Nature* 384(November 1996):252–55.

Stone, R.C., I. Smith, and P. McIntosh. *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems The Australian Experience.* G.L. Hammer, N. Nicholls, and C. Mitchell, eds. Dordrecht, The Netherlands: Kluwer Academic, 2000.

Stuart, A. "On the Economic Value of Probability of Precipitation Forecasts in Canada." *Journal of Applied Meteorology* 21(April 1982):495–98.

Sumner, D.A., D.G. Hallstrom, and H. Lee. "Trade Policy and the Effects of Climate Forecasts on Agricultural Markets." *American Journal of Agricultural Economics* 79(December 1999): 309–22.

Thompson, L.M. "Relationship of the El Niño Cycle to Droughts in the U.S. Corn Belt." *Cycles* 41(February 1990):14.

Trenberth, K.E. "The Definition of El Niño." *Bulletin of the American Meteorological Society* 78(December 1997):2771–77.

Tribbia, J.J. "Weather Prediction." *Economic Value of Weather and Climate Forecasts.* R. Katz and A.H. Murphy, eds. Cambridge, U.K.: Cambridge University Press, 1997.

University Corporation for Atmospheric Research. "El Niño and Climate Prediction." *Reports to the Nation on Our Changing Planet.* NOAA Award No. NA27GP0232-01, Boulder, CO, Spring 1994.

Van Loon, H. Personal Communication. National Center for Atmospheric Research, Boulder, CO, February 1998.

Van Loon, H., and K. Labitzke. "Association Between the 11-Year Solar Cycle, the QBO, and the Atmosphere. Part II: Surface and the 700 mb in the Northern Hemisphere in Winter." *Journal of Climate* 1(September 1988):905–20.

———. "Association Between the 11-Year Solar Cycle and the Atmosphere, Part V: Summer." *Journal of Climate* 5(March 1992):240–51.

———. "Connection Between the Troposphere and Stratosphere on a Decadal Scale." *Tellus* 47A(March 1995a):275–86.

———. "Connection Between the Troposphere and Stratosphere on the Time Scale of the Sunspot Cycle." *Journal of Geomagnetism and Geoelectricity* 47,11(1995b):1249–56.

Vining, K.C., C.A. Pope, III, and W.A. Dugas, Jr. "Usefulness of Weather Information to Texas Agricultural Producers." *Bulletin of the American Meteorological Society* 65(December 1984):1316–19.

Walker, G.T. "Correlation in Seasonal Variations of Weather, IX: A Further Study of World Weather." *Indian Meteorological Department* 24(1924):275–332.

Wang, G., and E.A.B. Eltahir. "Use of ENSO Information in Medium- and Long-Range Forecasting of Nile Floods." *Journal of Climate* 12(June 1999):1726–37.

Webster, P.J., and S. Yang. "Monsoon and ENSO:

Selectively Interactive Systems." *Quarterly Journal of the Royal Meteorological Society* 118(July 1992):877–926.

Webster, P.J., V.O. Magaña, T.N. Palmer, J. Shulka, R.A. Tomas, M. Yanai, and A. Yasunari. "Monsoons: Processes, Predictability and the Prospects for Prediction." *Journal of Geophysical Research* 103,C7(June 1998):14451–510.

Weiss, E.B. "International Implications of Seasonal Climate Forecasting." *Stanford Journal of International Law* 17(1981):315–45.

____. "The Value of Seasonal Climate Forecasts in Managing Energy Resources." *Journal of Applied Meteorology* 21(1982):510–17.

White, D.J. "Forecasts and Decisionmaking." *Journal of Mathematical Analysis and Applications* 14(1966):163–73.

Wilks, D.S. "Diagnostic Verification of the Climate Prediction Center Long-Lead Outlooks, 1995–98. *Journal of Climate* 13(July 2000):2389–403.

____. "A Skill Score Based on Economic Value for Probability Forecasts." *Meteorological Applications* 8(June 2001):209–19.

Wilks, D.S., and D.W. Wolfe. "Optimal Use and Economic Value of Weather Forecasts for Lettuce Irrigation in a Humid Climate." *Agricultural and Forest Meteorology* 89(February 1998):115–29.

Wittrock, V.S. "The Influence of Synoptic-Scale Forcing on Soil Moisture Over the Eastern Canadian Prairies." M.S. thesis. University of Saskatchewan, 1996.

World Meteorological Organization (WMO). "About Us." Internet site: http://www.wmo.ch/indexflash.html (Accessed December 2001).

Wyrtki, K.E., W. Patzert, R. Williams, and W. Quinn. "Predicting and Observing El Niño." *Science* 191(January 1976):343–46.

Yao, H., and A. Georgakakos. "Assessment of Folsom Lake Response to Historical and Potential Future Climate Scenarios 2." *Journal of Hydrology* 249(August 2001):176–96.

Zeng, L.X. "Weather Derivatives and Weather Insurance: Concept, Application, and Analysis." *Bulletin of the American Meteorological Society* 81(September 2000):2075–82.

Zhang, Y., J.M. Wallace, and D.S. Battisti. "ENSO-Like Interdecadal Variability: 1900–93." *Journal of Climate* 10(May 1997):1004–20.