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## **Climate forecast and prediction product dissemination for agriculture in the United States**

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### **ABSTRACT**

A wealth of climate forecast information and related prediction products are available, but impediments to adoption of these products by ranchers and farmers in the United States remain to be addressed. Impediments for agricultural applications include modest forecast skill; limited climate predictability; inappropriate forecast scale for site-specific applications; difficulties in interpretation of probabilistic forecasts by farmers and integration into agricultural decision systems; uncertainty about the value and impact of forecast information in multi-variable decision system; and generally low frequency of relevant forecasts. Various research institutions have conducted case-studies of climate impacts on agricultural production systems, particularly impacts of historical ENSO signals in the southeastern United States. A number of studies addressed risk and economic values of seasonal climate forecasts, and others bridged the gap between current forecasting software and products and agricultural applications. These studies attest to the availability and suitability of forecast and impact-prediction software, as well as derived products for agricultural applications. Yet, little attention has been given to operational and application-specific prediction products for general agricultural use, and to effective and affordable delivery system that reaches and resonates with the agricultural end-user (a prerequisite for adoption). The two later impediments are the focus of this paper. Two existing approaches, the top-down and the participatory end-to-end approach for development and delivery of prediction products are reviewed. A third approach, the hybrid approach, is emphasized and utilizes the top-down approach for climate forecast delivery and a participatory approach for development and delivery of farm-specific prediction information for the agricultural end-user. Suitability of such prediction products for agricultural applications and constraints to successful adoption are also discussed.

**KEY WORDS:** Climate-Forecast, Climate-Prediction, Climate, Agriculture, Application, Decision.

## INTRODUCTION

In recent decades the science of seasonal-to-interannual climate prediction has evolved to the point where seasonal climate forecasts are being issued operationally for many parts of the world. While research on climate forecasts continues, existing operational forecasts represent a window into the future that allows us to anticipate likely departures from the most recent 30-year climatology (“normal” conditions). Knowledge of likely future climate departures and their potential impact can lead to real societal benefits (Changnon, 2004). Water resources and agriculture are often singled out as the likely beneficiaries of the new technology (Varis et al., 2004; Archer, E. R. M., 2003; Changnon, S. A. and Kunkel, K. E., 1999; Brown, B. G., Katz, R. W., and Murphy, A. H., 1986). However, the full potential of these regional climate forecasts for water resources and agricultural applications can only be achieved if the forecasts are translated into useful information that directly contributes to the decision making process. This forecast translation includes: (1) downscaling forecasts to temporal and spatial scales relevant to the application under consideration; (2) assessing the impact of forecasts on decision variables such as water quantity, crop productivity, farm profitability, economic loss, risk and sustainability, water security, water quality, and environmental impacts; and (3) communicating and integrating climate-derived decision information into the overall decision process.

These issues were studied by an Expert Team (ET) of the World Meteorological Organization (WMO). The focus of the ET was on impacts of climate change/variability on medium- to long-range predictions for agriculture, and, in particular, on the availability and suitability of software packages for the calculation of appropriate seasonal climate variability indices for agricultural applications. There is little doubt that prediction software for climate indices and impacts on water resources and agriculture are an essential and necessary component for practical applications of climate forecasts. But the availability of climate indices does not guarantee that they will be adopted and used. In fact, there is accumulating evidence that significant segments of United States agriculture, particularly low end-users, are not using much if any of the currently available climate forecasts (Hartmann, H. C., Pagano, T. C., Sorooshian, S., and Bales, R., 2002; Jochev, K. G., Mjelde, J. W., Lee, A. C., and Conner, J. R., 2001). Thus, while prediction software and products are available, the broader adoption issue with regard to agricultural applications also hinges on the development and dissemination of agriculture-specific decision information and its integration into the decision making process.

With this framework, relevant questions can be restated as follows. Are forecast products and prediction software for agricultural applications generally available? What is inhibiting adoption of forecasts and prediction products for decision making in agriculture? And, how might forecast and prediction products be effectively transferred to the agricultural end-user to ensure broad adoption potential? These questions will be reviewed from a user perspective, for prediction products in the United States, and with emphasis on product dissemination. While the authors recognize that producer and commodity organizations that act over broad regions may benefit more from regional climate forecasts than single ranchers or farmers, the intended user in the context of this paper is the small to medium agricultural producer. Furthermore, only medium-range seasonal forecasts for up to a year in advance are considered because these forecasts are issued operationally, made available to the public at large, and seem to hold the best immediate potential for a wide array of annual management decisions in agriculture. Decade- and century-long climate forecasts are not considered. Long-range climate forecasts reflecting

climate change at decade-to-century scales are of limited value for agricultural applications that deal with short-term annual crop management and production decisions. Simply put, farmers and ranchers work and plan at scales of a decade or less for good reasons. Decade-long climate variations, while relevant for some decisions in agriculture, are difficult to predict at this time; forecasts are few, highly experimental and not available on an operational basis. In addition, decisions for crop rotations, switch in crop type, and conversion of land use that could benefit from decade-scale forecasts, depend very much on future energy and labor costs, commodity prices, subsidy payments, and global market conditions that are poorly known or difficult to forecast. It is likely that any possible benefits gained from considering decade-scale climate forecasts will be overridden by the speculative extrapolation of key economic variables.

In the following, a selection of forecast related software currently available in the United States is reviewed and their suitability for agricultural applications is examined. Current impediments to adoption are summarized. Existing approaches for developing and transferring forecast information and impact predictions are described, and a hybrid approach targeted primarily to small to medium sized agricultural end-users is emphasized. This hybrid approach represents a possible mechanism and institutional structure to facilitate development and communication of prediction products and decision information for agricultural applications. Finally, other factors that need to be considered for successful adoption of forecasts, prediction products, and related decision information are summarized. The scope of the review of forecast and prediction products presented herein is to provide an adequate background to frame the subsequent discussion of delivery systems, and there is not pretend or intent to be comprehensive.

## **AVAILABILITY AND SUITABILITY OF CLIMATE FORECASTS, PREDICTION SOFTWARE AND PRODUCTS.**

Forecast and prediction products depend heavily on computer-intensive dynamical and statistical models to simulate or extrapolate climatic conditions and their impacts into the future. These models and computer programs are classified for the purposes of this discussion into forecast software, downscaling software, impact prediction software, and decision support systems. Forecasting software refers to computer programs that forecast global climate; downscaling software refers to computer programs that convert global forecasts to smaller temporal and spatial scales relevant to local water resources and agricultural applications; impact prediction software refers to computer programs that simulate hydrologic and agricultural impacts of the downscaled climate forecasts; and decision support systems refer to software systems that integrate downscaled climate forecasts and impact predictions with economic, management, risk and marketing tools.

### **Forecasting software**

Seasonal climate forecasting software consists primarily of dynamically based General Circulation Models (GCM) and statistical correlation models. GCMs simulate the major physical processes controlling the state of the earth's oceans, atmosphere, and land surfaces. They are complex and resource intensive models that are used to study and predict the global climate, typically at a grid scale of about 2.8 degrees (individual grid elements cover roughly  $10^5$  km<sup>2</sup>). Government agencies and research institutions usually develop, maintain and operate these sophisticated models. A few examples of GCMs are given in Table 1.

Statistical correlation models establish spatio-temporal links between selected ocean/atmospheric indices or states, and climatic conditions at a location of interest. While these models are conceptually simple, they require location-specific searches for meaningful predictors and development of suitable and (frequently) sophisticated correlation functions. However, once developed, they operate like a black box and can be applied by a trained user, assuming the input data to drive these models are readily available. Thoughtful combinations of output from statistical models have traditionally outperformed even the most sophisticated GCMs, although there are reports that the skill of ensembles of GCM predictions is now approaching that of the statistical models (Goddard et al., 2003). A few examples of statistical correlation models are given in Table 2.

Table 1. Examples of General Circulation Models (GCM)

GCM Name	Agency/Institution	Reference
Coupled Forecast System (CFS)	NOAA/NCEP <sup>a</sup>	Kanamitsu et al., 2002
Global Spectral Model (GSM)	NOAA/NCEP <sup>a</sup>	Watson and Colucci, 2002
Multi-Model Ensemble (MME)	IRI <sup>b</sup>	Barnston et al., 2003
Community Climate Model (CCM3)	NCAR <sup>c</sup>	Tribbia and Baumhefner, 2004
Seasonal Forecasting System (SFS)	ECMWF <sup>d</sup>	Vitart and Stockdale, 2001
Anomaly Coupled Model (ACM)	NOAA/COLA <sup>e</sup>	Kirtman et al., 2002
Coupled General Circulation Model (CGCM)	NOAA/GFDL <sup>f</sup>	Gudgel et al., 2001

a: NOAA National Center for Environmental Prediction

b: International Research Institute for Climate Prediction

c: National Center for Atmospheric Research

d: European Center for Medium-Range Weather Forecasts

e: NOAA Center for Ocean-Land-Atmosphere Studies

f: NOAA Geophysical Fluid Dynamics Laboratory

Table 2. Examples of statistical correlation models.

Statistical Model	Agency/Institution	Reference
Optimal Climate Normals (OCN)	NOAA/CPC <sup>a</sup> , IRI <sup>b</sup>	Huang et al., 1996
Canonical Correlation Analysis (CCA)	NOAA/CPC <sup>a</sup> , IRI <sup>b</sup>	Barnston and Ropelewski, 1992
Canonical Correlation Analysis (CCA)	NOAA/GFDL <sup>c</sup>	Anderson et al., 1999
Singular Value Decomposition Analysis (SVD)	Montana State University	Cherry, 1996
Discriminant Analysis	NERC <sup>d</sup>	DeGaetano et al., 2002
Cluster Analysis	CIMMS <sup>e</sup>	Gong and Richman, 1995

a: NOAA National Center for Environmental Prediction

b: International Research Institute for Climate Prediction

c: NOAA Geophysical Fluid Dynamics Laboratory

d: Northeast Regional Climate Center

e: Cooperative Institute for Mesoscale Meteorological Studies

### Downscaling software

Seasonal climate forecasts generally have spatial and temporal scales that are too large for many impact studies. The mismatch is resolved by downscaling forecasts to smaller scales. Statistical-empirical downscaling, dynamical downscaling, and combinations thereof are the prevailing

downscaling methods in use today. Weather generators, transfer functions and weather typing schemes are the three main categories for statistical-empirical downscaling, whereas high or variable resolution GCMs with nested limited area models (LAM) or embedded regional climate models (RCMs) is the main approach for dynamical downscaling. The statistical-dynamical downscaling (SDD) methods link global and regional model simulations through statistics derived for large scale weather types. A few examples of downscaling software are given in Table 3. Most of the downscaling software are complex and require experience in setting up a viable downscaling application, and in interpreting the climate information in light of inherent limitations associated with downscaling climate forecasts.

Table 3. Examples of dynamical and statistical downscaling.

Downscaling model	Agency/Institution	Reference
WGEN (weather generator)	USDA, ARS <sup>a</sup>	Richardson and Wright, 1984
WEATHERMAN (weather generator)	ICASA <sup>b</sup>	Pickering et al., 1994
SIMMETEO (weather generator)	ICASA <sup>b</sup>	Soltani and Hoogenboom, 2003
RSM (dynamical)	NCEP <sup>c</sup>	Gershunov et al., 2000 Sun et al., 2005
RCSM (dynamical)	UC-LLNL <sup>d</sup>	Kim et al., 2000
CCM5 (dynamical)	ISWS <sup>e</sup>	Liang et al., 2004

a: Agricultural Research Service

b: International Consortium for Agricultural Systems Applications

c: National Centers for Environmental Prediction

d: University of California Lawrence Livermore National Laboratory

e: Illinois State Water Survey

### Impact prediction software

Impact prediction software is any computer program that links downscaled climate forecasts with prediction variables of applications under consideration. Prediction software includes complex process-based rainfall-runoff models, empirical crop growth and productivity models, distributed environmental impact models, conceptual hydrologic models, lumped water balance models, and simple statistical regression models. Some statistical regression models directly link large-scale ocean/atmosphere indices to decision variables for the location and application of interest, bypassing the downscaling issue all together. Most of these prediction models are developed and supported by government agencies, research institutions, and private consulting companies. A few examples of impact prediction models are given in Table 4. Operation of these models with the incorporation of climate forecast information is generally beyond the reach of the typical end-user. Climate scenarios must be developed, input data assembled and verified, and models calibrated and validated for each new application and location. Also, operation of the model for ensembles of probabilistic weather outcomes, and reduction and interpretation of results requires technical expertise. Thus, it is unlikely that the typical end-user of the prediction information will actually be the person operating the software and summarizing the output into decision information.

### Decision support systems

Decision support integrates forecasts and forecast impacts with economic, management, risk and marketing considerations, and places these factors into a systems context. Decision-support software may include optimization routines, cost-return calculations, enterprise budgets, and evaluation of economic risk factors.

Table 4. Examples of impact assessment tools.

Tool name	Description	Author
SWAT	Water, soil erosion and water quality assessment tool	Arnold et al., 1998
RZWQM	Management effects on water quality and crop growth	Ahuja et al., 1999
WEPP	Hillslope soil erosion assessment	Flanagan and Nearing, 1995
ANNAGNPS	Evaluation of management decision on agricultural non-point source pollution	Binger and Theurer, 2001
ALMANAC	Process based crop growth	Kiniry, 1992
CERES-WHEAT	Effects of cultivar, weather, soil water and nutrients on wheat growth and yield	Ritchie, 1991

Educational software, such as visualization, gaming and scenario analysis also fall into this category. Decision support software should provide the end-user with alternative options that increase profitability under favorable forecasts, reduces losses for adverse forecasts, or results in other economic, environmental, and societal benefits. A few examples of decision support systems are shown in Table 5. Note that none of these decision support systems explicitly incorporates operational climate forecast information at this time.

The above cursory overview illustrates the availability of software for climate forecasting, climate downscaling and impact prediction. Many existing prediction software continually undergo improvements as research findings are incorporated, and new software are developed that take advantage of modeling advances and expanded data acquisition capabilities provided by earth observation systems. Prediction products derived from these DSS can be picked up by a user, or are fed into subsequent software that derive related decision information for the end user. Suffice to say that a wide range of software and prediction products are available.

Table 5: Examples of Decision Support Systems (DSS) in agriculture.

DSS name	Description	Authors
GOSSYM	Cotton production decisions, includes weather, crop growth and management	Hodges et al., 1998
AspireNZ	Management in root carbohydrate in asparagus crops	Wilson et al., 2002
Maize Calculator	Optimization of fertilizer application	Reid et al., 1999
PCYield	Soybean management, risk assessment	Welch et al., 2002
GRAZPLAN	Optimization of animal nutrition management	Donnelly et al., 2002
WHEATMAN	Selection of wheat cultivar, risk assessment of terminal water stress.	Woodruff, 1992
DSSAT	Integration of soil, crop, weather and management	Jones et al., 2003
GPFARM	Whole farm management, incl. socio-economic and environmental analysis	Shaffer et al., 2004

Software suitability involves matching a software or prediction product with one or more particular application objectives. Thus, software and prediction products can be suitable for one application while at the same time being unsuitable for another. For the case of agricultural applications, global and regional climate forecast products do not generally represent the scale or decision values desired by the end user. Prediction software must first translate the forecast products into decision relevant impacts. In other words, they must answer the key questions from small to medium agricultural producers: “What do these forecasts mean for my operation, and how do they fit within the wider decision making context where economic factors can override weather factors?”. The vast majority of current products fail to deliver the answer. However, this does not imply that existing forecasting and downscaling software are not important or suitable for agricultural applications. To the contrary, they are absolutely necessary in the functional chain of software and prediction products that lead to decision information desired by agricultural end users.

In summary, a range of forecast and prediction software is available for predicting seasonal climate variability and impacts in support of agricultural applications, but final products are usually not immediately suitable for end users. The impediments are not due to any shortcoming in hydrologic or agricultural models and their linkage with the climate (Varis et al., 2004). Established hydrologic and agricultural prediction software are mature and have a track record of successful use in agricultural and water resource planning, operation, management, and impact assessment. Much of the uncertainty resides with the modest but improving skill of global climate forecasts and the difficulties of downscaling forecasts to high-resolution application scales (Varis et al., 2004). Also, software operation, data acquisition/preparation and result interpretation are complex and resource intensive activities that are generally beyond the reach of the typical agricultural end user in the United States. Other impediments to software, forecast, and prediction product adoption are discussed below.

## **ADOPTION IMPEDIMENTS**

Case applications of climate forecasts, demonstration projects of impact predictions, and user surveys on adoption impediments have been conducted, and a range of impediments have been reported in the published literature (e.g. Changnon, 2004; Stewart et al., 2004; Nichols, 1999; Pulwarty and Redmon, 1997; Changnon et al., 1995). For the purpose of this discussion, the

impediments can be grouped into three kinds: 1) shortcomings of the forecast products themselves; 2) shortcomings inherently associated with the decision process and decision maker; and 3) lack of relevancy and accessible prediction products and decision information for agriculture.

In the first group, impediments to wider use of climate forecasts relate to limitations of forecast capabilities themselves. Climate forecasts have limited skill, or accuracy, which affects user confidence and hampers effective application. For example, precipitation forecasts show extremely modest or no skill in many regions in the United States (Schneider and Garbrecht, 2003 and 2004). Skill at lead times longer than 3 to 6 months has not been demonstrated for most of the contiguous United States. The limited skill is partly the result of limited climate predictability over the United States. Other problems include the low frequency of useful forecasts. This low frequency of relevant forecasts is likely related to the fact that nearly all skill in seasonal terrestrial precipitation over the United States is found during El Niño Southern Oscillation (ENSO) extremes (Schneider and Garbrecht, 2003). Most forecasts issued across the contiguous United States have been either "EC" (Equal Chances, meaning the odds are identical to climatology), or for very small departures from climatology. Such forecasts have little apparent utility in agricultural management, since current best management practices are built around and implicitly reflect climatology. Accordingly, forecasts for "normal odds" or "close to normal" do not generate much interest among agricultural users. Last, but not least, the possible further reduction in skill and quality of forecast information due to downscaling is not well quantified. In other words, modest skill at larger time and space scales may not survive the downscaling process and degenerate into climatological probabilities. Developing significant improvements in forecast skill is a considerable challenge, and such improvements are unlikely to be forthcoming soon. Solutions to these impediments lie primarily in the scientific forecasting domain and are not discussed further in the context of this paper.

In the second group, impediments are related primarily to the ability of the end-user to deal effectively with probabilistic forecasts, and to limitations associated with the overall decision support system. In particular, users have difficulty correctly interpreting graphical displays of forecast products, including recognizing that CPC seasonal forecasts are statements of shifts in odds compared to a 30-year record. There are also many cognitive illusions and ingrained perceptions that often lead to pre-conceived expectations, distorted interpretations and questionable decisions, which even affect experts (Nichols, 1999). These limitations can be addressed through training and education of the end-user or by providing consulting services. More importantly, many agricultural end-users have difficulty relating climate forecasts with other economic factors involving uncertainty and risk in the decision making process. In other words, when do the changes in risk associated with a climate forecast become as relevant as or more important than other economic risks? It remains to be defined, for each application and location, when and how the forecast information will have comparable value to the other factors currently incorporated in decision support systems. These factors include market demands, commodity prices, labor and energy costs, environmental impact regulations, and subsidies. So it should be no surprise that most agricultural end-users in the U.S. are not integrating forecast information. A related economic factor that may limit the use of prediction products involves established lending practice in agriculture versus potential failures to meet contractual production targets due to decisions based on imperfect forecasts and uncertain information. Bankers require a solid case before they are willing to finance innovative agricultural practice, and that case needs to be made on a much wider basis across the contiguous U.S.

The third group of impediments relates specifically to the lack of relevant and application-specific prediction products, and lack of an effective and affordable delivery system that resonates with the end-user. While demonstration projects have illustrated the relevance and usefulness of climate forecasts for a few selected agricultural applications, application-specific prediction information for a wide range of agricultural applications, along with effective delivery mechanisms, are not available at this time. These problems relate primarily to bridging the gap between science-based forecast products and problem-specific and user-defined decision needs. While bridges have successfully been established for a few large government and private projects (high-end users), the link is largely non-existent for most agricultural applications (especially low end-users). This leads to the question of how, by whom and for whom climate forecasts, impact predictions and decision information should be prepared for effective technology transfer and adoption by the full range of agricultural decision makers. The remainder of this paper reviews two institutional structures for transfer of forecast products and proposes a hybrid structure that is more suitable for wide-spread adoption of climate forecast products by low-end agricultural users.

## **TECHNOLOGY TRANSFER APPROACHES**

Climate forecasts and derived impact predictions and decision information are currently passed along to end-users by way of two prevalent technology-transfer approaches: the "loading-dock" and the "end-to-end" approach. The advantages and limitations of each are discussed and a hybrid approach more suitable for low-end agricultural applications is examined.

### **Loading-dock approach.**

In the "loading-dock" approach for technology transfer, a forecast product is developed by a specialized group and made available to the public with little input from the end-user. It is basically a top-down approach where a generalized forecast product is offered to all potential users (Figure 1).

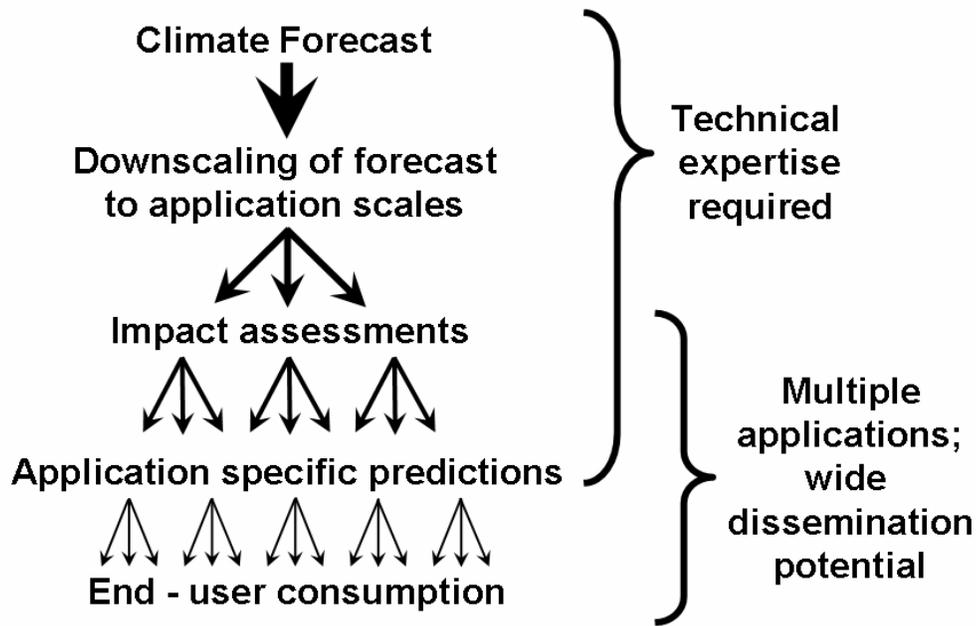


Figure 1. Schematic of a loading-dock approach.

Users pick up the product from a public source and figure out for themselves how to make the best use of it. In general, other specialized groups with technical resources use loading-dock products and process these into derived prediction products that are again made available to the public, and so forth. The chain of product development and transfer by this approach is often the result of partnerships between various government agencies and also research institutions. The products are often provided as a free service and enjoy wide dissemination potential. However, it may require several layers of derived products before prediction information relevant to the end-user is obtained. Also, the final prediction information may lack specificity and may not exploit the full potential of a forecast for the specific application under consideration.

Water-level forecasts for the Great Lakes are an example of a prediction produced by a loading-dock approach. The Climate Prediction Center (CPC) of the National Weather Service (NWS) first develops and issues a seasonal climate forecast. The United States Corps of Engineers (USCE) and Environment Canada (EC) take the forecast, evaluate the impact on the hydrology of the Great Lakes Basin using the Advance Hydrologic Prediction System (AHPS; Croley, 2000 and 2003), and issue predictions for water level in the Great Lakes. The water-level predictions from the AHPS are made public as general advisories, and are then used by harbor masters to issue expected maximum draft depth for ships to access harbors. This information is in turn picked up by shipping companies to determine maximum cargo-load so ships can safely access destination harbors. Other users may include the Coast Guard, shoreline businesses, marina operators, dredging companies, power industries, and lake front property owners. Each user will interpret the predictions in light of their application and develop decision information that fits their decision process.

Similarly, NOAA's River Forecast Centers plan to use CPC climate forecasts to develop stream flow forecasts in major river basins (Ensemble Streamflow Predictions) (Franz et al., 2003). The stream flow forecasts will subsequently be used by the USCE, the Bureau of Reclamation, or other river-system management authorities to anticipate water-storage levels in

reservoirs; by power companies to estimate departures from normal hydropower production goals; and by navigation companies to anticipate likely low or high flow conditions.

In a similar effort, National Weather Service Forecast Offices (NWSFO) in the southern region of the United States are developing and implementing downscaling techniques for CPC climate forecasts, in order to offer climate forecast products for individual major cities within their areas of responsibility (e.g., <http://www.srh.noaa.gov/tsa/climate/downscale/climfcst.php>). As these are developed, they are expected to be picked up and used by local governments (e.g., states, counties, municipalities), and by local TV and news outlets.

In the "loading-dock" approach it is assumed that the receiving user can either use the forecast information directly, or has the technical expertise and resources to further process the forecast into an impact prediction or decision support information. As the information-processing cascades down the tiers of the "loading dock" approach, it becomes more and more specific, requires fewer resources to process and reaches a wider range of potential users (Figure 1). The "loading-dock" approach is generally supported by government organizations that routinely deliver products to the public or to other agencies which in turn provide a public service. Government organizations in the United States are often organized by discipline and function, and the "loading-dock" products reflect institutional constraints related to the often narrow mission of the government organization producing the product.

### **End-to-end approach**

In the "end-to-end" approach, all components in the chain of processing steps from initial forecast development to end-user decisions are considered in an integrated fashion (Figure 2).

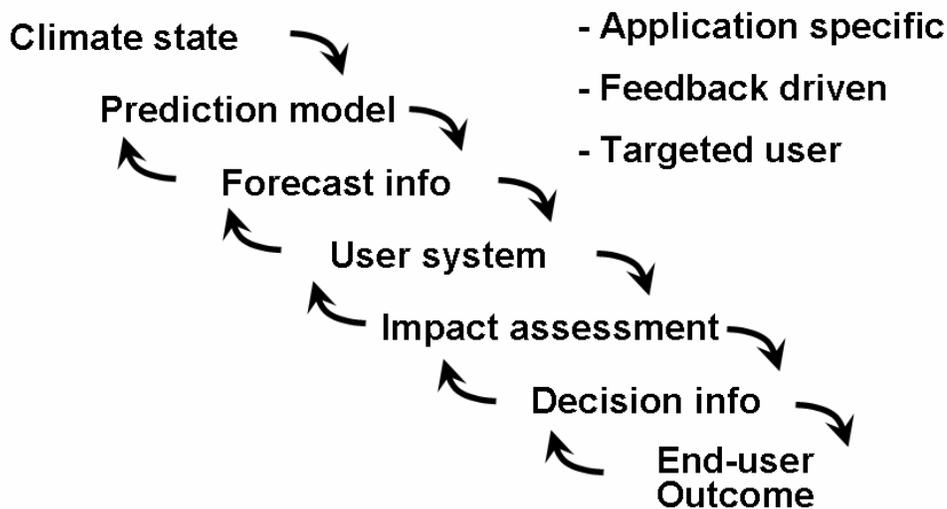


Figure 2. Schematic of an end-to-end approach.

Factors to be considered may include selection of climate forecast and downscaling models, choice of impact assessment models, adaptation and modification of models, institutional constraints, design and communication of products, and decision making support. An end-to-end forecast application generally involves a set of complex interactions, transformations and feedbacks at the research and operational stage. The end-to-end approach requires trans-disciplinary collaboration and close interaction between users, producers, their intermediaries, and the applications scientists (Goddard et al., 2001). End-to-end applications are generally demand-driven and provide a specific service to a specific client.

The International Research Institute for Climate Prediction (IRI) is an example of a research institution that has embraced the end-to-end approach in its effort to produce forecasts and develop applications for a range of water resource, agricultural, environmental, food security, social, and health problems, primarily in Africa, Asia, Pacific, Latin America, and Caribbean (<http://iri.columbia.edu/aboutiri/mission.html>; accessed Oct 2006). In addition to producing and disseminating climate forecasts globally, the IRI develops and provides a suite of prediction products and facilitates their application to practical decision making through targeted research, demonstrations and training. All essential elements required for an end-to-end forecast application are included in the organizational structure of IRI: a modeling division, a forecast division, an applications research division, a climate monitoring and dissemination division, and a training program (Upmanu, is there a reference for this??). While the research and development approach relies heavily on the end-to-end approach involving user participation, the final delivered product in operational mode has a greater resemblance to the hybrid approach discussed in the next section (L. Goddard, communication, October 2006). [Upmanu, is there anything else you suggest I should add; please include sentence.]

The end-to-end approach is very effective at targeting forecast and prediction products to address the decision criteria of a specific end-user application. This effectiveness, however, comes at a cost. The effort and resources that are brought to bear on an individual application must also be justified by the expected benefits. Cost-benefit considerations of the end-to-end approach favor large projects such as irrigation projects, corporate plantations, regional agricultural systems, water resources management of large river basins, regional power industries, fishery industries, control of vector born diseases (e.g., West Nile virus), and regional flood risk and control. These applications have identifiable clients, impact regional economies, and indirectly touch many people. Clients and users that take advantage of end-to-end products are typically governments, corporations, private and public organizations, and industries that can afford the service. The end-to-end prediction service is more difficult to justify economically for individual ranchers and farmers with small- and medium-size family enterprises.

### **Hybrid approach**

The hybrid approach develops and transfers climate prediction products in a way that is expected to provide affordable prediction and decision information to agricultural end-users at the local level. The approach consists of four consecutive components (Figure 3).

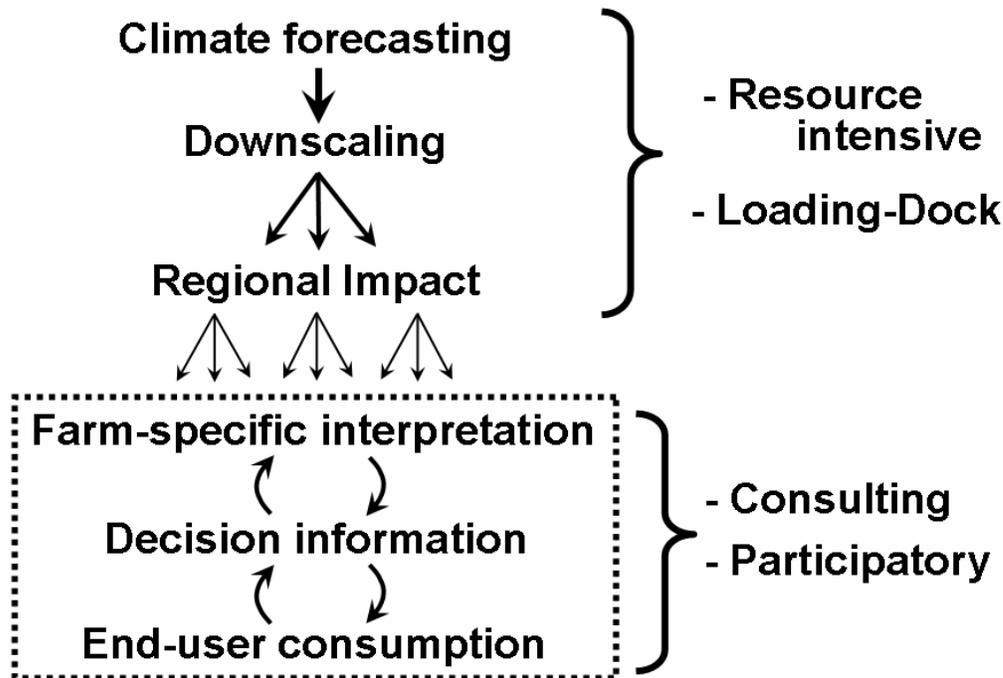


Figure 3. Schematic of a hybrid approach.

A top-down or "loading-dock" approach for the two resource intensive components of forecast development and downscaling, followed by a top-down component for regional impact assessment, and a bottom-up component for site- and problem-specific interpretation of the forecast products and development of decision information.

The first component includes development and dissemination of regional climate forecasts using the top-down "loading-dock" approach. This component is the most complex, technical and resource intensive portion of a forecast application effort. It is generally performed by climate specialists working for the government or a research institution. In the United States, the CPC produces and publishes the seasonal climate forecasts following the loading-dock approach.

The second component addresses the spatial and temporal downscaling of monthly forecasts in preparation for subsequent impact assessment. This downscaling would be performed in two steps. First, the three-month overlapping regional forecasts produced by CPC need to be downscaled to monthly time and local space scales. Agricultural applications would require that the spatial downscaling be done to the county scale. The CPC, in conjunction with local National Weather Service Forecast Offices, could potentially provide this service using techniques similar to those employed to produce individual city 3-month average temperature forecasts (see [http://www.cpc.ncep.noaa.gov/pacdir/NFORdir/citydir/explanation\\_ctydf.html](http://www.cpc.ncep.noaa.gov/pacdir/NFORdir/citydir/explanation_ctydf.html)). Temporal downscaling from 3-months to individual months could be based on the technique in Schneider et al. (2005). Second, monthly climate forecasts at the county level need to be further downscaled to daily weather to drive existing crop production, rangeland, water resources and environmental models. This step involves stochastic generation of daily weather representing monthly forecasted conditions. It is noted here that the more complex dynamical downscaling, while technically feasible, is not necessarily a practical approach for repeated evaluations and generation of daily weather ensembles for every county. Stochastic downscaling is straight-

forward and can rapidly produce ensembles of daily weather by county and on a monthly basis. For example, ensembles could consist of 100 or more daily weather sequences that start at the time of forecast issuance and extend through the forecast period (up to one year ahead). The downscaling to daily weather could be performed by state climatology offices, or alternatively, by a state agricultural extension service as part of the impact assessment component. In either case, the downscaled climate and weather products are disseminated by the "loading-dock" approach.

The third component deals with the prediction of forecast impacts. This component prepares the groundwork for the end-user application. It generally involves evaluation of a crop, plant or environmental computer simulation model for typical physiographic and agronomic conditions in a county, driven with the downscaled forecast ensembles of daily weather. This county level impact assessment could be provided by an agricultural extension service using the "loading-dock" approach. Agricultural specialists of the extension service are well suited for this task because of their familiarity with local and regional cropping practices, and likely management and cropping alternatives for various climate forecast scenarios. The prediction products may include prediction of soil moisture, crop yield for predominant crops, forage production, or environmental response under forecasted versus climatological (no-forecast) climate conditions, and for predominant soils, topography, and agronomic conditions of the county under consideration. The results of the application may also include qualitative recommendations regarding possible adaptation, or agronomic management strategies to take advantage of the current climate forecast.

The fourth component is a bottom-up consulting service for site- and problem-specific applications and involves the agricultural end-user. This service would provide a location-specific adaptation and detailed interpretation of the county scale impact assessment previously developed by the agricultural extension service, as well as estimation of related decision variables, integration of these variables into an overall decision matrix, economic evaluation of decision options, and final recommendations for suitable action. The depth and extent of the service is tailored by agreement between the service provider and the client. The service provider could be a private and for-profit business, or a state supported government service.

In the above described hybrid approach the climate forecasting, downscaling, and impact assessment are complex, technical and resource intensive. The products are largely generic (i.e. non-specific to any particular farm-level application) and the 'loading-dock' approach to development and delivery seems appropriate. Personalized consulting for site- and problem-specific application of the prediction products at the farm level only applies to the last tier of the approach, thereby limiting the scope and cost of consulting work. Thus, the heavy reliance on generic products and product transfer by the "loading-dock" approach would lead to forecast products that require a comparatively limited consulting support. This should minimize the cost of the service and increase the accessibility for low-end agricultural users, a prerequisite for their adoption.

## **DISCUSSION**

The successful implementation of the hybrid approach depends on a number of factors and impediments, several of which were mentioned earlier. First, regions of potential applications should have skillful and actionable forecasts, i.e. forecasts should depart sufficiently from average conditions to lend themselves to alternative agronomic actions. Such actionable

forecasts should occur at least every second or third year to generate user interest in operational prediction products and justify the cost and effort of implementation of a forecast application.

Second, regions considered for application should be agriculturally active and support crops that are sensitive to climate variations, and timing of related agronomic decisions and activities should coincide with seasons that display predictable climate patterns. The only regions in the United States where these criteria are currently met for precipitation forecasts are peninsular Florida and eastern and southern Texas. It is no coincidence that the successful demonstration projects to date of application of climate forecasts to agricultural operations have been in the southern United States. In other regions where precipitation forecasts have marginal utility (such as the southern Great Plains), demonstration projects are needed to explore the actual value of transformed climate forecasts for specific agricultural enterprises.

Third, agricultural end-users of forecast products, affected commodity groups, and related agribusiness should promote the use of prediction products and generate political and financial support that encourages agricultural service agencies to include forecast-based decision support in their services. In regions where the first two conditions are met, demonstrated forecast-application methodologies and existing software packages can be used to conduct impact assessments, develop agricultural prediction products, and provide related decision support on an operational basis. It is critically important that development, implementation and communication of farm-specific prediction products and decision support should be the result of a participatory approach that includes all interested parties. The realization of such a prediction system could increase productivity, enhance profitability, and reduce economic risk for agricultural enterprises.

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