"Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected Sectors and Regions"

(Climate Change Science Program, Synthesis and Assessment Product [SAP] 5.1)

Executive Summary

Earth information—the diagnostics of Earth's climate, water, air, land, and other dynamic processes—is essential for our understanding of humankind's relationship to our natural resources and our environment. Earth information can inform our scientific knowledge, our approach to resource and environmental management and regulation, and our stewardship of the planet for future generations. New data sources, new ancillary and complementary technologies in hardware and software, and ever-increasing modeling and analysis capabilities characterize the current and prospective states of Earth science and are a harbinger of its promise. A host of Earth science data products is enabling a revolution in our ability to understand climate and its anthropogenic and natural variations. Crucial to this relationship, however, is understanding and improving the integration of Earth science information in the activities that support decisions underlying national priorities: ranging from homeland security and public health to air quality and natural resource management.

Also crucial is the role of Earth information in improving our understanding of the processes and effects of climate as it influences or is influenced by actions taken in response to national priorities. Global change observations, data, forecasts, and projections are integral to informing climate science.

The Synthesis and Assessment Product (SAP), "Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected Sectors and Regions" (SAP 5.1), examines the current and prospective contributions of Earth science information in decision support activities and their relationship to climate change science. The SAP contains a characterization and catalog of observational capabilities in an illustrative set of decision support activities. It also contains a description of the challenges and promise of these capabilities and discusses the interaction between users and producers of information (including the role, measurement, and communication of uncertainty and confidence levels associated with decision support outcomes and their related climate implications).

Decision Support Tools and Systems

In 2002, the National Aeronautics and Space Administration (NASA) formulated a conceptual framework in the form of a flow chart (Figure 1) to characterize the link between Earth science data and their potential contribution to resource management and public policy. The framework begins with Earth observations, including measurements made *in situ* and from airborne and space-based instruments. These data are input into Earth system models that simulate the dynamic processes of land, the atmosphere, and the oceans. These models lead in turn to predictions and forecasts to inform decision support tools (DST).

In this framework, DSTs are typically computer-based models assessing such phenomena as resource supply, the status of real-time events (e.g., forest fires and flooding), or relationships among environmental conditions and other scientific metrics (i.e., water-borne disease vectors and epidemiological data). These tools use data, concepts of relations among data, and analysis functions to allow analysts to build relationships—including spatial, temporal, and process-based—among different types of data, merge layers of data, generate model outcomes, and make predictions or forecasts. Decision support tools are an element of the broader decision making context or Decision Support System (DSS). DSSs include not just computer tools but the institutional, managerial, financial, and other constraints involved in the decision-making process.

The outcomes in these decision frameworks are intended to enhance our ability to manage resources (management of public lands and measurements for air quality and other environmental regulatory compliance) and evaluate policy alternatives (as promulgated in legislation or regulatory directives) affecting local, state, regional, national, or even international actions. To be exact, for a variety of reasons, many decisions are not based on data or models. In some cases, formal modeling is not appropriate, timely, or feasible for all decisions. But among decisions that are influenced by this information, the flow chart (Figure 1) characterizes a systematic approach for science to be connected to decision processes.

For purposes of providing an organizational framework, the CCSP provides additional description of decision support:

> In the context of activities within the CCSP framework, decision-support resources, systems, and activities are climate-related products or processes that directly inform or advise stakeholders in order to help them make decisions. These products or processes include analyses and assessments, interdisciplinary research, analytical methods (including scenarios and alternative analysis methodologies), model and data product development, communication, and operational services that provide timely and useful information to decision makers, including policymakers, resource managers, planners, government officials, and other stakeholders. *("Our Changing Planet," CCSP FY2007, Chapter 7, p. 155).*

Our Approach

Our approach to this SAP has involved two overall tasks. The first task defines and describes an illustrative set of DSTs in areas selected from a number of areas deemed nationally important by NASA and also included in societal benefit areas identified by the intergovernmental Group on Earth Observations (GEO) in leading an international effort to build a Global Earth Observation System of Systems (GOESS) (see Tables 1 and 2).

The areas we have chosen as our case studies are air quality, agricultural efficiency, energy management, water management, and public health. As required by the *SAP 5.1 Prospectus*, in the case studies we:

- explain the observational capabilities that are currently or potentially used in these tools;

- identify the agencies and organizations responsible for their development, operation, and maintenance;
- characterize the nature of interaction between users and producers of information in delivering accessing and assimilating information;
- discuss sources of uncertainty associated with observational capabilities and the decision tools and how they are conveyed in decision support context and to decision makers; and
- describe relationships between the decision systems and global change information, such as whether the tools at present contribute or in the future could contribute to climate-related predictions or forecasts.

Because our purpose in this first task is to offer case studies by way of illustration rather than a comprehensive treatment of all DSTs in all national applications, in our second task we have taken steps to catalog other DSTs which use or may use, or which could contribute to, forecasts and projections of climate and global change. The catalog is an exciting first step toward an ever-expanding inventory of existing and emerging DSTs. The catalog can be maintained on-line for community input, expansion, and updating to provide a focal point for information about the status of DSTs and how to access them.

The information in this report is largely from published literature and interviews with the sponsors and stakeholders of the decision processes, as well as publications by and interviews with the producers of the scientific information used in the tools.

Our Case Studies

We illustrate the following DSTs:

1. The Production Estimate and Crop Assessment Division and its Crop Condition Data Retrieval and Evaluation (PECAD/CADRE) system of the US Department of Agriculture, Foreign Agricultural Service (FAS). PECAD/CADRE is the world’s most extensive and longest running

(over two decades) operational user of remote sensing for evaluation of worldwide agricultural productivity.

2. The Community Multiscale Air Quality (CMAQ) modeling system of the US Environmental Protection Agency (EPA). CMAQ is a widely used, US continental/regional/urban-scale air quality decision support tool.
3. The Hybrid Optimization Model for Electric Renewables (HOMER), a micropower optimization model of the US Department of Energy's National Renewable Energy Laboratory (NREL). HOMER is used around the world to optimize deployment of renewable energy technologies.
4. Decision Support System to Prevent Lyme Disease (DDSPL) of the US Centers for Disease Control and Prevention (CDC) and Yale University. DDSPL seeks to prevent the spread of the most common vector-borne disease, Lyme disease, of which there are tens of thousands of cases annually in the US
5. RiverWare, developed by the University of Colorado-Boulder's Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) in collaboration with the Bureau of Reclamation, Tennessee Valley Authority, and the Army Corps of Engineers. RiverWare is a hydrologic or river basin modeling system that integrates features of reservoir systems, such as recreation, navigation, flood control, water quality, and water supply, in a basin management tool with power system economics to provide basin managers and electric utilities a method of planning, forecasting, and scheduling reservoir operations.

Taken together, these DSTs demonstrate a rich variety of applications of observations, data, forecasts, and other predictions. In four of our studies, agricultural efficiency, air quality, water management, and energy management, the DSTs have become well established as a basis for public policy decision making. In the case of public health, our lead author points out reasons why direct applications of Earth observations to public health have tended to lag behind these other applications and thus is a relatively new application area. He also reminds us that management of air quality, agriculture, water, and energy—in and of themselves—have implications for the quality of public health. The DST he selects is a new, emerging tool intended to assist in prevention of the spread of infectious disease.

Our selection also varies in the geographic breadth of application, illustrating how users of these tools tailor them to relevant regions of analysis and how, in some cases, the geographic coverage of the tools carries over to their requirements for observations. For instance, PECAD/CADRE is used for worldwide study of agricultural productivity and has data requirements of wide geographic scope, HOMER can be used for renewable energy optimization throughout the world, and DDSPL focuses on the eastern, upper Midwest, and West Coast portions of the US. CMAQ is used to predict air quality for the contiguous US as well as regions and urban locales. RiverWare provides basin managers and electric utilities a method of planning, forecasting, and scheduling reservoir operations.

With the exception of DDSPL, none of the DSTs we considered for potential selection, nor those we discuss in this report, have to date made extensive use of climate change information or been used to study the effect of a changing climate. However, in all cases, the developers and users of these DSTs fully recognize their applicability to climate change science. In the discussion of the five DSTs presented in this SAP, the authors describe how climate data and/or predictions might be used in these DSTs so that long-range decisions and planning might be accomplished.

Overview of the Chapters

We next summarize the case studies. For each case study, we describe the DST and its data sources, highlight potential uses as well as limits of the DSTs, note sources of uncertainty in using the tools, and finally, discuss the link between the DST and climate change and variability. After our summary, we offer general observations about similarities and differences among the studies.

Agricultural Efficiency: The Production Estimate and Crop Assessment Division (PECAD) of the US Department of Agriculture, FAS is the world’s most extensive and longest running operational user of remote sensing data for evaluation of worldwide agricultural productivity. PECAD supports the FAS mission to collect and analyze global crop intelligence information and provide periodic estimates used to inform official USDA forecasts for the agricultural market, including farmers; agribusiness; commodity traders and researchers; and federal, state, and local agencies. PECAD is often referred to as PECAD/CADRE with one of its major automated components known as the Crop Condition Data Retrieval and Evaluation (CADRE) geospatial database management system. Of all the DSTs we consider in this report, CADRE has the oldest pedigree as the operational outcome of two early, experimental earth observation projects during the 1970s and 1980s: the Large Area Crop Inventory Experiment (LACIE) and the Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing (AgRISTARS).

Sources of data for CADRE include a large number of weather and other earth observations from US, European, Japanese, and commercial systems. PECAD combines these data with crop models, a variety of GIS tools, and a large amount of contextual information, including official government reports, trade and news sources, and on-the-ground reports from a global network of embassy attaches and regional analysts.

Potential future developments in PECAD/CADRE could include space-based observations of atmospheric carbon dioxide (CO_2) measurements and measurement of global sea surface salinity to improve understanding of the links between the water cycle, climate, and oceans. Other opportunities for enhancing PECAD/CADRE include improvements in predictive modeling capabilities in weather and climate.

One of the largest technology gaps in meeting PECAD requirements is the practice of designing earth observation systems for research rather than operational use, limiting the ability of PECAD/CADRE to rely on data sources from non-operational systems. PECAD analysts require dependable inputs, implying use of operational systems that ensure continuous data streams and that minimize vulnerability to component failure through redundancy.

Sources of uncertainty can arise at each stage of analysis, from the accuracy of data inputs to the assumptions in modeling. PECAD operators have been able to benchmark, validate, verify, and then selectively incorporate additional data sources and automated decision tools by way of detailed engineering reviews. Another aspect of resolving uncertainty in PECAD is the extensive use of a convergence methodology to assimilate information from regional field analysts and other experts. This convergence of evidence analysis seeks to reconcile various independent data sources to achieve a level of agreement to minimize estimate error.

The relationship between climate and agriculture is complex, as agriculture is influenced not only by a changing climate, but agricultural practices themselves are a contributory factor (e.g., in affecting land use and influencing carbon fluxes. At present, PECAD is not directly used to address these dimensions of the climate-agriculture interaction. However, many of the data inputs for PECAD are climate-related, thereby enabling PECAD to inform understanding of agriculture as a “recipient” of climate-induced changes. For instance, observing spatial and geographic trends in the output measures from PECAD can contribute to understanding how the agricultural sector is responding to a changing climate. Likewise, trends in PECAD’s measures of the composition and production of crops could shed light on the agricultural sector as a “contributor” to climate change (for instance, in terms of greenhouse gas emissions or changes in soil that may affect the potential for agricultural soil carbon sequestration). PECAD may also be influenced by, as well as a barometer of climate-induced changes in land use, such as conversion from food production to biomass fuel production.

Air Quality: The EPA CMAQ modeling system has been designed to approach air quality by including state-of-the-science capabilities for modeling tropospheric ozone, fine particles, toxics, acid deposition, and visibility degradation. CMAQ is used to guide the development of air quality regulations and standards and to create state implementation plans for managing air emissions. CMAQ also can be used to evaluate longer-term as well as short-term transport from localized sources and to perform simulations using downscaled regional climate from global climate change scenarios.

The CMAQ modeling system contains three types of modeling components: a meteorological modeling system for the description of atmospheric states and motions, emission models for man-made and natural emissions that are injected into the atmosphere, and a chemistry-transport modeling system for simulation of the chemical transformation and fate. Inputs for CMAQ, and their associated regional meteorological model, mesoscale model version 5 (MM5), can include, but are not limited to, the comprehensive output from a general circulation model, anthropogenic and biogenic emissions, description of wildland fires, land use and demographic changes, and meteorological and atmospheric chemical species measurements by *in-situ* and remote sensing platforms, including satellites and aircraft.

CMAQ can be used to study questions such as: How will present and future emission changes affect attainment of air quality standards? Will present and future emissions and/or climate/meteorological changes affect the frequency and magnitudes of high pollution events? How will land use changes due to urbanization and global warming affect air quality? How does long-range air pollution from other regions affect US air quality? How will changes in the long-range transport due to the climate change affect air quality? How does wildland fire affect air quality and will climate change affect wildland fire and subsequently air quality? How sensitive are the air quality predictions to changes in both anthropogenic and biogenic emissions?

Energy Management: HOMER is a micropower optimization model of the US Department of Energy’s NREL. HOMER is able to calculate emission reductions enabled by replacing diesel-generating systems with renewable energy systems in a micro-grid or grid-connected configuration. HOMER helps the user design grid-connected and off-grid renewable energy systems by performing a wide range of design scenarios. HOMER can be used to address questions such as: Which technologies are most cost-effective? What happens to the economics if the project's costs or loads change? Is the renewable energy resource adequate for the different technologies being considered to meet the load? HOMER does this by finding the least-cost combination of components that meet electrical and thermal loads.

The earth observation information serving as input to HOMER is centered on wind and solar resource assessments derived from a variety of sources. Wind data include surface and upper air station data, satellite-derived ocean and ship wind data, and digital terrain and land cover data. Solar resource data include surface cloud, radiation, aerosol optical depth, and digital terrain and land cover data from both *in-situ* and remote sensing sources.

All of the input data for HOMER can have a level of uncertainty attached to them. HOMER allows the user to perform sensitivity tests on one or more variables and has graphical capabilities to display these results to inform decision makers. As a general rule, the error in estimating the performance of a renewable energy system over a year is roughly linear to the error in the input resource data.

One of the largest challenges in HOMER is the absence of direct or *in-situ* solar and wind resource measurements at specific locations to which HOMER is applied. In addition, in many cases, values are not based on direct measurement at all but are approximations based on the use of algorithms to convert a signal into the parameter of interest as is the case with most satellite-derived data products. For example, satellite-derived ocean wind data are not based on direct observation of the wind speed above the ocean surface but from an algorithm that infers wind speed based on wave height observations. Observations of aerosol optical depths (for which considerable research is underway) can be complicated by irregular land-surface features that complicate the application of algorithms for satellite-derived measures.

For renewable energy resource mapping, improved observations of key weather parameters (for instance, wind speed and direction at various heights above the ground, particularly at the hub height of wind energy turbine systems, and over the open oceans at higher and higher spatial resolutions, and improved ways of differentiating snow cover and bright reflecting surfaces from clouds) will be of value to the renewable energy community. New, more accurate methods of related parameters, such as aerosol optical depth, would also improve the resource data.

The relationship between HOMER and global change information is largely by way of the dependence of renewable energy resource input measurements on weather and local climate conditions. Although HOMER was not designed to be a climate-related management decision-making tool, by optimizing the mix of hybrid renewable energy technologies for meeting load conditions, HOMER also enables users to respond to climate change and variability in their energy management decisions. HOMER could be used to evaluate how renewable energy systems can be used cost-effectively to displace fossil-fuel-based systems.

Public Health: The DDSPL is operated by the US CDC and Yale University to address questions related to the likely distribution of Lyme disease east of the 100th meridian, where most cases occur. Lyme disease is the most common vector-borne disease in the US, with tens of thousands of cases annually. Most human cases occur in the Eastern and upper Midwest portions of the US, although there is a secondary focus along the West Coast. Vector-borne diseases are those in which parasites are transmitted among people or from wildlife to people by insects or arthropods (as vectors, they do not themselves cause disease). The black-legged tick is typically the carrier of the bacteria causing Lyme disease.

Early demonstrations during the 1980s showed the utility of earth observations for identifying locations and times that vector-borne diseases were likely to occur, but growth of applications has been comparatively slow. Earth observing instruments have not been designed to monitor disease risk; rather, data gathered from these platforms are “scavenged” for public health risk assessment. DDSPL uses satellite data and derived products, such as land cover together with meteorological data and census data, to characterize statistical predictors of the presence of black-legged ticks. The model is validated by field surveys. The DDSPL is thus a means of setting priorities for the likely geographic extent of the vector; the tool does not at present characterize the risk of disease in the human population.

Future use of DDSPL partly depends on whether the goal of disease prevention or the goal of treatment drives public health policy decisions. In addition, studies have shown that communication to the public about the risk in regions with Lyme disease often fails to reduce the likelihood of infection. Use of the DDSPL is also limited by restrictions on the dissemination of detailed information on the distribution of human disease. The role of improved Earth science data is unclear in terms of improving the performance of DDSPL because at present the system has a level of accuracy deemed “highly satisfactory.” Future use may instead require a model of sociological/behavioral influences among the population.

Standard statistical models and in-field validation are used to assess the uncertainty in decision making with DDSPL. The accuracy of clinical diagnoses also influences the ultimate usefulness of DDSPL as an indicator tool to characterize the geographic extent of the vectors.

The DDSPL is one of the few public health DSTs that has explicitly evaluated the effects of climate variability. Using outputs of a Canadian climate change model, study has shown that with warming global mean temperatures by the year 2050 to 2080 the geographic range of the tick vector will decrease at first, with reduced presence in the southern boundary, and then expand into Canada and the central region of North America where it now absent. The range also moves away from population concentrations.

Water Management: RiverWare was developed and is maintained by CADSWES in collaboration with the Bureau of Reclamation, Tennessee Valley Authority, and the Army Corps of Engineers. It is a river basin modeling system that integrates features of reservoir systems, such as recreation, navigation, flood control, water quality, and water supply in a basin management tool, with power system economics to provide basin managers and electric utilities a method of planning, forecasting, and scheduling reservoir operations. RiverWare uses an object-oriented software engineering approach in model development. The object oriented software-modeling strategy allows computational methods for new processes, additional controllers for providing new solution algorithms, and additional objects for modeling new features to be added easily to the modeling system. RiverWare is data intensive in that a specific river/reservoir system and its operating policies must be characterized by the data supplied to the model. This allows the models to be modified as new features are added to the river/reservoir system and/or new operating policies are introduced. The data-intensive feature allows the model to be used for water management in most river basins.

Riverware is menu driven through a graphical user interface (GUI). The basin topology is developed through the selection of a reservoir, reach, confluence, and other necessary objects and by entering the data associated with each object manually or through importing files. Utilities within RiverWare provide a means to automatically execute many simulations, to access data from external sources, and to export model results. Users also define operating policies through the GUI as system constraints or rules for achieving system management goals (e.g., related to flood control, water supplies, water quality, navigation, recreation, and power generation). The direct use of earth observations in RiverWare is limited. Unlike traditional hydrologic models that track the transformation of precipitation (e.g., rain and snow) into soil moisture and streamflow, RiverWare uses supplies of water to the system as input data. These data are derived from a hydrologic model where direct use of earth observations can be and have been made. Application of RiverWare is limited by the specific implementation defined by the user and by the quality of the input data. It has tremendous flexibility in the kinds of data it can use, but long records of data are required to overcome the issue of data non-stationarity.

The specific application of RiverWare in the context of mid- or long-range planning for a specific river basin will reflect whether decisions may rely on global change information. For mid-range planning of reservoir operations, characterization and projections of interannual and decadal-scale climate variability (e.g., monitoring, understanding, and predicting interannual climate phenomena such as the El Nino-Southern Oscillation) are important. For long-term planning, global warming has moved from the realm of speculation to general acceptance. The impacts of global warming on water resources, and their implications for management, have been a major focus in the assessments of climate change. The estimates of potential impacts of climate change on precipitation have been mixed, leading to increasing uncertainty about the reliability of future water supplies.

General Observations

Application of all of the DSTs involves a variety of input data types, all of which have some degree of uncertainty in terms of their accuracy. The amount of uncertainty associated with resource data can depend heavily on how the data are obtained. Quality *in-situ* measurements of wind and solar data suitable for application in HOMER are can have uncertainties of less than ± 3% of true value; however, when estimation methods are required, such as the use of earth observations, modeling, and empirical techniques, uncertainties can be as much as ± 10% or more. The DSTs address uncertainty by allowing users to perform sensitivity tests on variables. With the exception of HOMER, a significant amount of additional traditional on-the-ground reports are a critical component. In the case of PECAD/CADRE, uncertainty is resolved in part by extensive use of a convergence methodology to assimilate information from regional field analysts and other experts. This brings a large amount of additional information to PECAD/CADRE forecasts, well beyond the automated outputs of DSTs. In RiverWare, streamflow and other hydrologic variables respond to atmospheric factors such as precipitation, and obtaining quality precipitation estimates is a formidable challenge, especially in the western US where orographic effects produce large spatial variability and where there is a scarcity of real-time precipitation observations and poor radar coverage.

In terms of their current or prospective use of climate change predictions or forecasts as DST *inputs,* or the contributions of DST *outputs* to understanding, monitoring, and responding to a changing climate, the status is mixed. DDSPL is one of the few public health decision support tools that has explicitly evaluated the potential impact of climate change scenarios on an infectious disease system. None of the other DSTs at present is directly integrated with climate change measurements, but all of them can and may in the future take this step. PECAD/CADRE’s assessment of global agricultural production will certainly be influenced by observations and forecasts of climate change and variability as model inputs, just as the response of the agricultural sector to a changing climate will feedback into PECAD/CADRE production estimates. HOMER’s renewable energy optimization calculations will be directly affected by climate-related changes in renewable energy resource supplies and will enhance our ability to adapt to climate-induced changes in energy management and forecasting. Air quality will definitely be affected by global climate change. The ability of CMAQ to predict those affects is conditional on acquiring accurate predictions of the meteorology under the climate change conditions that will take place in the US and accurate emission scenarios for the future. Given these inputs to CMAQ, reliable predictions of the air quality and their subsequent health affects can be ascertained. It was noted that there is great difficulty in integrating climate change information into RiverWare and other such water management models. The multiplicity of scenarios and vague attribution of their probability for occurrence, which depends on feedback among social, economic, political, technological, and physical processes, complicates conceptual integration of climate change impacts assessment results in a practical water management context. Furthermore, the century timescales of climate change exceed typical planning and infrastructure design horizons in water management.

Audience and Intended Use

The *CCSP SAP 5.1 Prospectus* describes the audience and intended use of this report:

> This synthesis and assessment report is designed to serve decision makers and stakeholder communities interested in using global change information resources in policy, planning, and other practical uses. The goal is to provide useful information on climate change research products that have the capacity to inform decision processes. The report will also be valuable to the climate change science community because it will indicate types of information generated through the processes of observation and research that are particularly valuable for decision support. In addition, the report will be useful for shaping the future development and evaluation of decision-support activities, particularly with regard to improving the interactions with users and potential users.
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> There are a number of national and international programs focusing on the use of Earth observations and related prediction capacity to inform decision support tools (see Table 3, "Related National and International Activities"). These programs both inform and are informed by the CCSP and are recognized in the development of this product.
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> (*CCSP Synthesis and Assessment Product 5.1, Prospectus for "Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected Sectors and Regions," 28 February 2006)*