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3

18   **"Uses and Limitations of Observations, Data, Forecasts, and Other Projections**

19   **in Decision Support for Selected Sectors and Regions"**

20

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

22

23   **Executive Summary**

24

25   Earth information—the diagnostics of Earth's climate, water, air, land, and other dynamic processes—is essential for

26   our understanding of humankind's relationship to our natural resources and our environment. Earth information can

27   inform our scientific knowledge, our approach to resource and environmental management and regulation, and our

28   stewardship of the planet for future generations. New data sources, new ancillary and complementary technologies in

29   hardware and software, and ever-increasing modeling and analysis capabilities characterize the current and prospective

30   states of Earth science and are a harbinger of its promise. A host of Earth science data products is enabling a revolution

31   in our ability to understand climate and its anthropogenic and natural variations. Crucial to this relationship, however, is

32   understanding and improving the integration of Earth science information in the activities that support decisions

33   underlying national priorities: ranging from homeland security and public health to air quality and natural resource

34   management.

35

36   Also crucial is the role of Earth information in improving our understanding of the processes and effects of climate as it

37   influences or is influenced by actions taken in response to national priorities. Global change observations, data,

38   forecasts, and projections are integral to informing climate science.

39

40   The Synthesis and Assessment Product (SAP), "Uses and Limitations of Observations, Data, Forecasts, and Other

41   Projections in Decision Support for Selected Sectors and Regions" (SAP 5.1), examines the current and prospective

42   contributions of Earth science information in decision support activities and their relationship to climate change science.

43   The SAP contains a characterization and catalog of observational capabilities in an illustrative set of decision support

44   activities. It also contains a description of the challenges and promise of these capabilities and discusses the interaction

45   between users and producers of information (including the role, measurement, and communication of uncertainty and

46   confidence levels associated with decision support outcomes and their related climate implications).

47

48   **Decision Support Tools and Systems**

49   In 2002, the National Aeronautics and Space Administration (NASA) formulated a conceptual framework in the form of

50   a flow chart (Figure 1) to characterize the link between Earth science data and their potential contribution to resource

51   management and public policy. The framework begins with Earth observations, including measurements made *in situ*

52   and from airborne and space-based instruments. These data are input into Earth system models that simulate the

53   dynamic processes of land, the atmosphere, and the oceans. These models lead in turn to predictions and forecasts to

54   inform decision support tools (DST).

55

56   In this framework, DSTs are typically computer-based models assessing such phenomena as resource supply, the status

57   of real-time events (e.g., forest fires and flooding), or relationships among environmental conditions and other scientific

58   metrics (i.e., water-borne disease vectors and epidemiological data). These tools use data, concepts of relations among

59   data, and analysis functions to allow analysts to build relationships—including spatial, temporal, and process-based—

60   among different types of data, merge layers of data, generate model outcomes, and make predictions or forecasts.

61   Decision support tools are an element of the broader decision making context or Decision Support System (DSS). DSSs

62   include not just computer tools but the institutional, managerial, financial, and other constraints involved in the

63   decision-making process.

64

65   The outcomes in these decision frameworks are intended to enhance our ability to manage resources (management of

66   public lands and measurements for air quality and other environmental regulatory compliance) and evaluate policy

67   alternatives (as promulgated in legislation or regulatory directives) affecting local, state, regional, national, or even

68   international actions. To be exact, for a variety of reasons, many decisions are not based on data or models. In some

69   cases, formal modeling is not appropriate, timely, or feasible for all decisions. But among decisions that are influenced

70   by this information, the flow chart (Figure 1) characterizes a systematic approach for science to be connected to

71   decision processes.

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

73

74   In the context of activities within the CCSP framework, decision-support resources, systems, and

75   activities are climate-related products or processes that directly inform or advise stakeholders in order

76   to help them make decisions. These products or processes include analyses and assessments,

77   interdisciplinary research, analytical methods (including scenarios and alternative analysis

78   methodologies), model and data product development, communication, and operational services that

79   provide timely and useful information to decision makers, including policymakers, resource

80   managers, planners, government officials, and other stakeholders. *("Our Changing Planet," CCSP*

81   *FY2007, Chapter 7, p. 155).*

82

83   **Our Approach**

84   Our approach to this SAP has involved two overall tasks. The first task defines and describes an illustrative set of DSTs

85   in areas selected from a number of areas deemed nationally important by NASA and also included in societal benefit

86   areas identified by the intergovernmental Group on Earth Observations (GEO) in leading an international effort to build

87   a Global Earth Observation System of Systems (GOESS) (see Tables 1 and 2).

88

89

90   The areas we have chosen as our case studies are air quality, agricultural efficiency, energy management, water

91   management, and public health. As required by the *SAP 5.1 Prospectus*, in the case studies we:

92

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

94   •   identify the agencies and organizations responsible for their development, operation, and maintenance;

95   •   characterize the nature of interaction between users and producers of information in delivering accessing and

96   assimilating information;

97   • discuss sources of uncertainty associated with observational capabilities and the decision tools and how they

98   are conveyed in decision support context and to decision makers; and

99   • describe relationships between the decision systems and global change information, such as whether the tools

100   at present contribute or in the future could contribute to climate-related predictions or forecasts.

101

102   Because our purpose in this first task is to offer case studies by way of illustration rather than a comprehensive

103   treatment of all DSTs in all national applications, in our second task we have taken steps to catalog other DSTs which

104   use or may use, or which could contribute to, forecasts and projections of climate and global change. The catalog is an

105   exciting first step toward an ever-expanding inventory of existing and emerging DSTs. The catalog can be maintained

106   on-line for community input, expansion, and updating to provide a focal point for information about the status of DSTs

107   and how to access them.

108

109   The information in this report is largely from published literature and interviews with the sponsors and stakeholders of

110   the decision processes, as well as publications by and interviews with the producers of the scientific information used in

111   the tools.

112

113   **Our Case Studies**

114   We illustrate the following DSTs:

115   1. The Production Estimate and Crop Assessment Division and its Crop Condition Data Retrieval and Evaluation

116   (PECAD/CADRE) system of the US Department of Agriculture, Foreign Agricultural Service (FAS).

117   PECAD/CADRE is the world's most extensive and longest running (over two decades) operational user of

118   remote sensing for evaluation of worldwide agricultural productivity.

119   2. The Community Multiscale Air Quality (CMAQ) modeling system of the US Environmental Protection

120   Agency (EPA). CMAQ is a widely used, US continental/regional/urban-scale air quality decision support tool.

121   3. The Hybrid Optimization Model for Electric Renewables (HOMER), a micropower optimization model of the

122   US Department of Energy's National Renewable Energy Laboratory (NREL). HOMER is used around the

123   world to optimize deployment of renewable energy technologies.

124   4.   Decision Support System to Prevent Lyme Disease (DDSPL) of the US Centers for Disease Control and

125   Prevention (CDC) and Yale University. DDSPL seeks to prevent the spread of the most common vector-borne

126   disease, Lyme disease, of which there are tens of thousands of cases annually in the US

127   5.   RiverWare, developed by the University of Colorado-Boulder's Center for Advanced Decision Support for

128   Water and Environmental Systems (CADSWES) in collaboration with the Bureau of Reclamation, Tennessee

129   Valley Authority, and the Army Corps of Engineers. RiverWare is a hydrologic or river basin modeling

130   system that integrates features of reservoir systems, such as recreation, navigation, flood control, water

131   quality, and water supply, in a basin management tool with power system economics to provide basin

132   managers and electric utilities a method of planning, forecasting, and scheduling reservoir operations.

133

134   Taken together, these DSTs demonstrate a rich variety of applications of observations, data, forecasts, and other

135   predictions. In four of our studies, agricultural efficiency, air quality, water management, and energy management, the

136   DSTs have become well established as a basis for public policy decision making. In the case of public health, our lead

137   author points out reasons why direct applications of Earth observations to public health have tended to lag behind these

138   other applications and thus is a relatively new application area. He also reminds us that management of air quality,

139   agriculture, water, and energy—in and of themselves—have implications for the quality of public health. The DST he

140   selects is a new, emerging tool intended to assist in prevention of the spread of infectious disease.

141

142   Our selection also varies in the geographic breadth of application, illustrating how users of these tools tailor them to

143   relevant regions of analysis and how, in some cases, the geographic coverage of the tools carries over to their

144   requirements for observations. For instance, PECAD/CADRE is used for worldwide study of agricultural productivity

145   and has data requirements of wide geographic scope, HOMER can be used for renewable energy optimization

146   throughout the world, and DDSPL focuses on the eastern, upper Midwest, and West Coast portions of the US. CMAQ is

147   used to predict air quality for the contiguous US as well as regions and urban locales. RiverWare provides basin

148   managers and electric utilities a method of planning, forecasting, and scheduling reservoir operations.

149

150   With the exception of DDSPL, none of the DSTs we considered for potential selection, nor those we discuss in this

151   report, have to date made extensive use of climate change information or been used to study the effect of a changing

152   climate. However, in all cases, the developers and users of these DSTs fully recognize their applicability to climate

153   change science. In the discussion of the five DSTs presented in this SAP, the authors describe how climate data and/or

154   predictions might be used in these DSTs so that long-range decisions and planning might be accomplished.

155

156   **Overview of the Chapters**

157   We next summarize the case studies. For each case study, we describe the DST and its data sources, highlight potential

158   uses as well as limits of the DSTs, note sources of uncertainty in using the tools, and finally, discuss the link between

159   the DST and climate change and variability. After our summary, we offer general observations about similarities and

160   differences among the studies.

161

162   *Agricultural Efficiency*: The Production Estimate and Crop Assessment Division (PECAD) of the US Department of

163   Agriculture, FAS is the world's most extensive and longest running operational user of remote sensing data for

164   evaluation of worldwide agricultural productivity. PECAD supports the FAS mission to collect and analyze global crop

165   intelligence information and provide periodic estimates used to inform official USDA forecasts for the agricultural

166   market, including farmers; agribusiness; commodity traders and researchers; and federal, state, and local agencies.

167   PECAD is often referred to as PECAD/CADRE with one of its major automated components known as the Crop

168   Condition Data Retrieval and Evaluation (CADRE) geospatial database management system. Of all the DSTs we

169   consider in this report, CADRE has the oldest pedigree as the operational outcome of two early, experimental earth

170   observation projects during the 1970s and 1980s: the Large Area Crop Inventory Experiment (LACIE) and the

171   Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing (AgRISTARS).

172

173   Sources of data for CADRE include a large number of weather and other earth observations from US, European,

174   Japanese, and commercial systems. PECAD combines these data with crop models, a variety of GIS tools, and a large

175   amount of contextual information, including official government reports, trade and news sources, and on-the-ground

176   reports from a global network of embassy attaches and regional analysts.

177

178   Potential future developments in PECAD/CADRE could include space-based observations of atmospheric carbon

179   dioxide (CO_2) measurements and measurement of global sea surface salinity to improve understanding of the links

180   between the water cycle, climate, and oceans. Other opportunities for enhancing PECAD/CADRE include

181   improvements in predictive modeling capabilities in weather and climate.

182

183   One of the largest technology gaps in meeting PECAD requirements is the practice of designing earth observation

184   systems for research rather than operational use, limiting the ability of PECAD/CADRE to rely on data sources from

185   non-operational systems. PECAD analysts require dependable inputs, implying use of operational systems that ensure

186   continuous data streams and that minimize vulnerability to component failure through redundancy.

187

188   Sources of uncertainty can arise at each stage of analysis, from the accuracy of data inputs to the assumptions in

189   modeling. PECAD operators have been able to benchmark, validate, verify, and then selectively incorporate additional

190   data sources and automated decision tools by way of detailed engineering reviews. Another aspect of resolving

191   uncertainty in PECAD is the extensive use of a convergence methodology to assimilate information from regional field

192   analysts and other experts. This convergence of evidence analysis seeks to reconcile various independent data sources to

193   achieve a level of agreement to minimize estimate error.

194

195   The relationship between climate and agriculture is complex, as agriculture is influenced not only by a changing

196   climate, but agricultural practices themselves are a contributory factor (e.g., in affecting land use and influencing

197   carbon fluxes. At present, PECAD is not directly used to address these dimensions of the climate-agriculture

198   interaction. However, many of the data inputs for PECAD are climate-related, thereby enabling PECAD to inform

199   understanding of agriculture as a "recipient" of climate-induced changes. For instance, observing spatial and geographic

200   trends in the output measures from PECAD can contribute to understanding how the agricultural sector is responding to

201   a changing climate. Likewise, trends in PECAD's measures of the composition and production of crops could shed light

202   on the agricultural sector as a "contributor" to climate change (for instance, in terms of greenhouse gas emissions or

203   changes in soil that may affect the potential for agricultural soil carbon sequestration). PECAD may also be influenced

204   by, as well as a barometer of climate-induced changes in land use, such as conversion from food production to biomass

205   fuel production.

206

207   *Air Quality:* The EPA CMAQ modeling system has been designed to approach air quality by including state-of-the-

208   science capabilities for modeling tropospheric ozone, fine particles, toxics, acid deposition, and visibility degradation.

209   CMAQ is used to guide the development of air quality regulations and standards and to create state implementation

210   plans for managing air emissions. CMAQ also can be used to evaluate longer-term as well as short-term transport from

211   localized sources and to perform simulations using downscaled regional climate from global climate change scenarios.

212

213   The CMAQ modeling system contains three types of modeling components: a meteorological modeling system for the

214   description of atmospheric states and motions, emission models for man-made and natural emissions that are injected

215   into the atmosphere, and a chemistry-transport modeling system for simulation of the chemical transformation and fate.

216   Inputs for CMAQ, and their associated regional meteorological model, mesoscale model version 5 (MM5), can include,

217   but are not limited to, the comprehensive output from a general circulation model, anthropogenic and biogenic

218   emissions, description of wildland fires, land use and demographic changes, and meteorological and atmospheric

219   chemical species measurements by *in-situ* and remote sensing platforms, including satellites and aircraft.

220

221   CMAQ can be used to study questions such as: How will present and future emission changes affect attainment of air

222   quality standards? Will present and future emissions and/or climate/meteorological changes affect the frequency and

223   magnitudes of high pollution events? How will land use changes due to urbanization and global warming affect air

224   quality? How does long-range air pollution from other regions affect US air quality? How will changes in the long-

225   range transport due to the climate change affect air quality? How does wildland fire affect air quality and will climate

226   change affect wildland fire and subsequently air quality? How sensitive are the air quality predictions to changes in both

227   anthropogenic and biogenic emissions?

228

229   *Energy Management:* HOMER is a micropower optimization model of the US Department of Energy's NREL.

230   HOMER is able to calculate emission reductions enabled by replacing diesel-generating systems with renewable energy

231   systems in a micro-grid or grid-connected configuration. HOMER helps the user design grid-connected and off-grid

232   renewable energy systems by performing a wide range of design scenarios. HOMER can be used to address questions

233   such as: Which technologies are most cost-effective? What happens to the economics if the project's costs or loads

234   change? Is the renewable energy resource adequate for the different technologies being considered to meet the load?

235   HOMER does this by finding the least-cost combination of components that meet electrical and thermal loads.

236

237   The earth observation information serving as input to HOMER is centered on wind and solar resource assessments

238   derived from a variety of sources. Wind data include surface and upper air station data, satellite-derived ocean and ship

239   wind data, and digital terrain and land cover data. Solar resource data include surface cloud, radiation, aerosol optical

240   depth, and digital terrain and land cover data from both *in-situ* and remote sensing sources.

241

242   All of the input data for HOMER can have a level of uncertainty attached to them. HOMER allows the user to perform

243   sensitivity tests on one or more variables and has graphical capabilities to display these results to inform decision

244   makers. As a general rule, the error in estimating the performance of a renewable energy system over a year is roughly

245   linear to the error in the input resource data.

246

247   One of the largest challenges in HOMER is the absence of direct or *in-situ* solar and wind resource measurements at

248   specific locations to which HOMER is applied. In addition, in many cases, values are not based on direct measurement

249   at all but are approximations based on the use of algorithms to convert a signal into the parameter of interest as is the

250   case with most satellite-derived data products. For example, satellite-derived ocean wind data are not based on direct

251   observation of the wind speed above the ocean surface but from an algorithm that infers wind speed based on wave

252   height observations. Observations of aerosol optical depths (for which considerable research is underway) can be

253   complicated by irregular land-surface features that complicate the application of algorithms for satellite-derived

254   measures.

255

256   For renewable energy resource mapping, improved observations of key weather parameters (for instance, wind speed

257   and direction at various heights above the ground, particularly at the hub height of wind energy turbine systems, and

258   over the open oceans at higher and higher spatial resolutions, and improved ways of differentiating snow cover and

259   bright reflecting surfaces from clouds) will be of value to the renewable energy community. New, more accurate

260   methods of related parameters, such as aerosol optical depth, would also improve the resource data.

261

262   The relationship between HOMER and global change information is largely by way of the dependence of renewable

263   energy resource input measurements on weather and local climate conditions. Although HOMER was not designed to

264   be a climate-related management decision-making tool, by optimizing the mix of hybrid renewable energy technologies

265   for meeting load conditions, HOMER also enables users to respond to climate change and variability in their energy

266   management decisions. HOMER could be used to evaluate how renewable energy systems can be used cost-effectively

267   to displace fossil-fuel-based systems.

268

269   *Public Health:* The DDSPL is operated by the US CDC and Yale University to address questions related to the likely

270   distribution of Lyme disease east of the 100th meridian, where most cases occur. Lyme disease is the most common

271   vector-borne disease in the US, with tens of thousands of cases annually. Most human cases occur in the Eastern and

272   upper Midwest portions of the US, although there is a secondary focus along the West Coast. Vector-borne diseases are

273   those in which parasites are transmitted among people or from wildlife to people by insects or arthropods (as vectors,

274   they do not themselves cause disease). The black-legged tick is typically the carrier of the bacteria causing Lyme

275   disease.

276

277   Early demonstrations during the 1980s showed the utility of earth observations for identifying locations and times that

278   vector-borne diseases were likely to occur, but growth of applications has been comparatively slow. Earth observing

279   instruments have not been designed to monitor disease risk; rather, data gathered from these platforms are "scavenged"

280   for public health risk assessment. DDSPL uses satellite data and derived products, such as land cover together with

281   meteorological data and census data, to characterize statistical predictors of the presence of black-legged ticks. The

282   model is validated by field surveys. The DDSPL is thus a means of setting priorities for the likely geographic extent of

283   the vector; the tool does not at present characterize the risk of disease in the human population.

284

285   Future use of DDSPL partly depends on whether the goal of disease prevention or the goal of treatment drives public

286   health policy decisions. In addition, studies have shown that communication to the public about the risk in regions with

287   Lyme disease often fails to reduce the likelihood of infection. Use of the DDSPL is also limited by restrictions on the

288   dissemination of detailed information on the distribution of human disease. The role of improved Earth science data is

289   unclear in terms of improving the performance of DDSPL because at present the system has a level of accuracy deemed

290   "highly satisfactory." Future use may instead require a model of sociological/behavioral influences among the

291   population.

292

293   Standard statistical models and in-field validation are used to assess the uncertainty in decision making with DDSPL.

294   The accuracy of clinical diagnoses also influences the ultimate usefulness of DDSPL as an indicator tool to characterize

295   the geographic extent of the vectors.

296

297   The DDSPL is one of the few public health DSTs that has explicitly evaluated the effects of climate variability. Using

298   outputs of a Canadian climate change model, study has shown that with warming global mean temperatures by the year

299   2050 to 2080 the geographic range of the tick vector will decrease at first, with reduced presence in the southern

300   boundary, and then expand into Canada and the central region of North America where it now absent. The range also

301   moves away from population concentrations.

302

303   *Water Management:* RiverWare was developed and is maintained by CADSWES in collaboration with the Bureau of

304   Reclamation, Tennessee Valley Authority, and the Army Corps of Engineers. It is a river basin modeling system that

305   integrates features of reservoir systems, such as recreation, navigation, flood control, water quality, and water supply in

306   a basin management tool, with power system economics to provide basin managers and electric utilities a method of

307   planning, forecasting, and scheduling reservoir operations. RiverWare uses an object-oriented software engineering

308   approach in model development. The object oriented software-modeling strategy allows computational methods for new

309   processes, additional controllers for providing new solution algorithms, and additional objects for modeling new

310   features to be added easily to the modeling system. RiverWare is data intensive in that a specific river/reservoir system

311   and its operating policies must be characterized by the data supplied to the model. This allows the models to be

312   modified as new features are added to the river/reservoir system and/or new operating policies are introduced. The

313   data-intensive feature allows the model to be used for water management in most river basins.

314

315   Riverware is menu driven through a graphical user interface (GUI). The basin topology is developed through the

316   selection of a reservoir, reach, confluence, and other necessary objects and by entering the data associated with each

317   object manually or through importing files. Utilities within RiverWare provide a means to automatically execute many

318   simulations, to access data from external sources, and to export model results. Users also define operating policies

319   through the GUI as system constraints or rules for achieving system management goals (e.g., related to flood control,

320   water supplies, water quality, navigation, recreation, and power generation). The direct use of earth observations in

321   RiverWare is limited. Unlike traditional hydrologic models that track the transformation of precipitation (e.g., rain and

322   snow) into soil moisture and streamflow, RiverWare uses supplies of water to the system as input data. These data are

323   derived from a hydrologic model where direct use of earth observations can be and have been made. Application of

324   RiverWare is limited by the specific implementation defined by the user and by the quality of the input data. It has

325   tremendous flexibility in the kinds of data it can use, but long records of data are required to overcome the issue of data

326   non-stationarity.

327

328   The specific application of RiverWare in the context of mid- or long-range planning for a specific river basin will reflect

329   whether decisions may rely on global change information. For mid-range planning of reservoir operations,

330   characterization and projections of interannual and decadal-scale climate variability (e.g., monitoring, understanding,

331   and predicting interannual climate phenomena such as the El Nino-Southern Oscillation) are important. For long-term

332   planning, global warming has moved from the realm of speculation to general acceptance. The impacts of global

333   warming on water resources, and their implications for management, have been a major focus in the assessments of

334   climate change. The estimates of potential impacts of climate change on precipitation have been mixed, leading to

335   increasing uncertainty about the reliability of future water supplies.

336

337   **General Observations**

338   Application of all of the DSTs involves a variety of input data types, all of which have some degree of uncertainty in

339   terms of their accuracy. The amount of uncertainty associated with resource data can depend heavily on how the data

340   are obtained. Quality *in-situ* measurements of wind and solar data suitable for application in HOMER are can have

341   uncertainties of less than ± 3% of true value; however, when estimation methods are required, such as the use of earth

342   observations, modeling, and empirical techniques, uncertainties can be as much as ± 10% or more. The DSTs address

343   uncertainty by allowing users to perform sensitivity tests on variables. With the exception of HOMER, a significant

344   amount of additional traditional on-the-ground reports are a critical component. In the case of PECAD/CADRE,

345   uncertainty is resolved in part by extensive use of a convergence methodology to assimilate information from regional

346   field analysts and other experts. This brings a large amount of additional information to PECAD/CADRE forecasts, well

347   beyond the automated outputs of DSTs. In RiverWare, streamflow and other hydrologic variables respond to

348   atmospheric factors such as precipitation, and obtaining quality precipitation estimates is a formidable challenge,

349   especially in the western US where orographic effects produce large spatial variability and where there is a scarcity of

350   real-time precipitation observations and poor radar coverage.

351

352   In terms of their current or prospective use of climate change predictions or forecasts as DST *inputs,* or the

353   contributions of DST *outputs* to understanding, monitoring, and responding to a changing climate, the status is mixed.

354   DDSPL is one of the few public health decision support tools that has explicitly evaluated the potential impact of

355   climate change scenarios on an infectious disease system. None of the other DSTs at present is directly integrated with

356   climate change measurements, but all of them can and may in the future take this step. PECAD/CADRE's assessment of

357   global agricultural production will certainly be influenced by observations and forecasts of climate change and

358   variability as model inputs, just as the response of the agricultural sector to a changing climate will feedback into

359   PECAD/CADRE production estimates. HOMER's renewable energy optimization calculations will be directly affected

360   by climate-related changes in renewable energy resource supplies and will enhance our ability to adapt to climate-

361   induced changes in energy management and forecasting. Air quality will definitely be affected by global climate

362   change. The ability of CMAQ to predict those affects is conditional on acquiring accurate predictions of the

363   meteorology under the climate change conditions that will take place in the US and accurate emission scenarios for the

364   future. Given these inputs to CMAQ, reliable predictions of the air quality and their subsequent health affects can be

365   ascertained. It was noted that there is great difficulty in integrating climate change information into RiverWare and

366   other such water management models. The multiplicity of scenarios and vague attribution of their probability for

367   occurrence, which depends on feedback among social, economic, political, technological, and physical processes,

368   complicates conceptual integration of climate change impacts assessment results in a practical water management

369   context. Furthermore, the century timescales of climate change exceed typical planning and infrastructure design

370   horizons in water management.

371

372   **Audience and Intended Use**

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

374

375   This synthesis and assessment report is designed to serve decision makers and stakeholder

376   communities interested in using global change information resources in policy, planning, and other

377   practical uses. The goal is to provide useful information on climate change research products that

378   have the capacity to inform decision processes. The report will also be valuable to the climate change

379   science community because it will indicate types of information generated through the processes of

380   observation and research that are particularly valuable for decision support. In addition, the report will

381   be useful for shaping the future development and evaluation of decision-support activities, particularly

382   with regard to improving the interactions with users and potential users.

383

384   There are a number of national and international programs focusing on the use of Earth observations

385   and related prediction capacity to inform decision support tools (see Table 3, "Related National and

386   International Activities"). These programs both inform and are informed by the CCSP and are

387   recognized in the development of this product. (*CCSP Synthesis and Assessment Product 5.1,*

388   *Prospectus for "Uses and Limitations of Observations, Data, Forecasts, and Other Projections in*

389   *Decision Support for Selected Sectors and Regions," 28 February 2006*)

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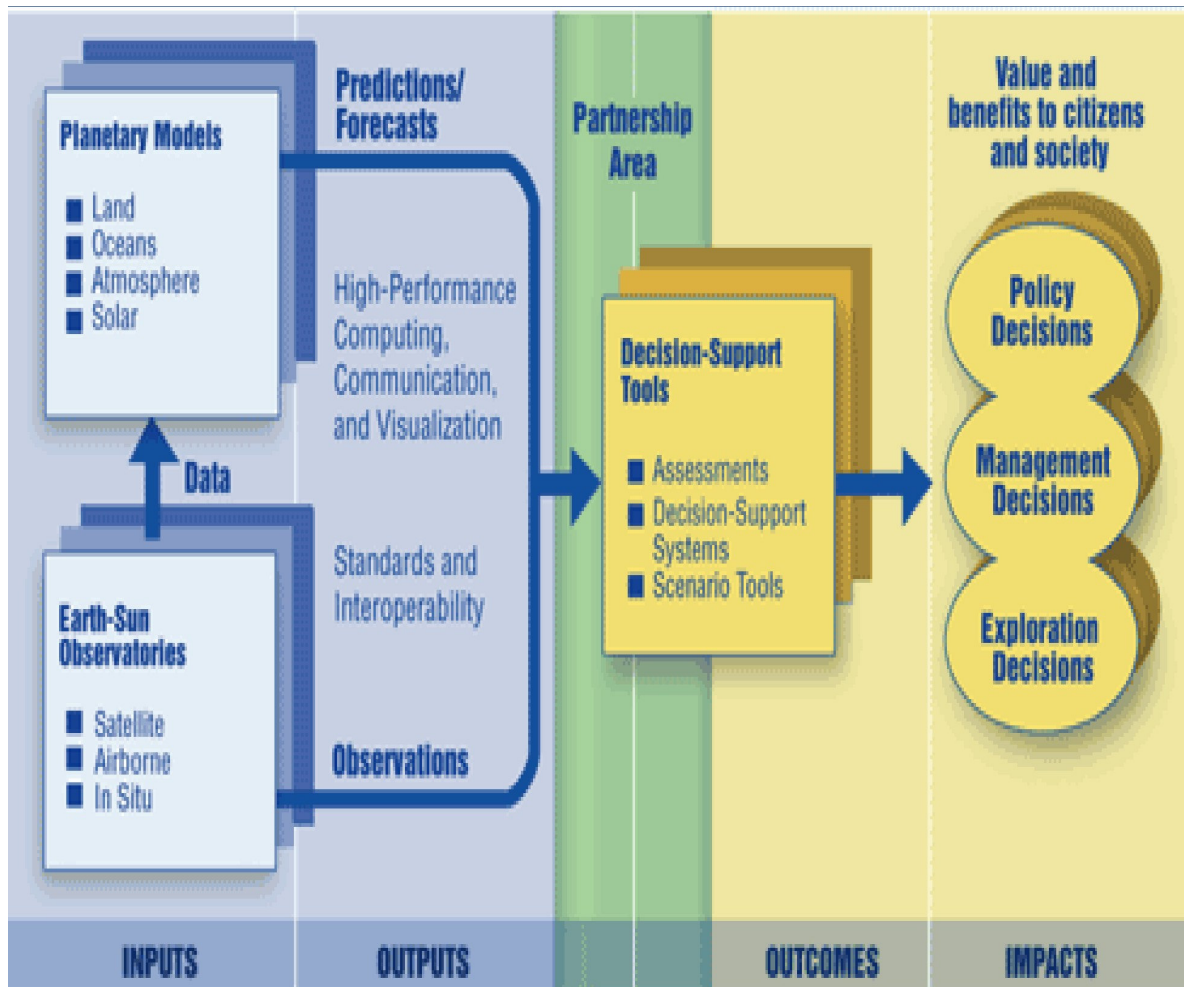
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394

395 Figure 1: The flow of information associated with decision support in the context of variability and change in climate

396 and related systems (Source: CCSP Product 5.1 Prospectus, Appendix D).

397

398   Table 1: List of NASA National Applications Areas (*Appendix B, CCSP SAP 5.1 Prospectus*).

399

400

Nationally Important Applications	Nationally Important Applications
Agricultural Efficiency	Ecological Forecasting
Air Quality	Energy Management
Aviation	Homeland Security
Carbon Management	Invasive Species
Coastal Management	Public Health
Disaster Management	Water Management

401

402

403   Table 2. Societal benefit areas identified by the Group on Earth Observations (GEO) for the Global Earth Observations

404   System of Systems (GEOSS) (http://www.earthobservations.org/about/about_GEO.html) (accessed May 2007)

405

406

GEOSS Socio-Benefit Area Keywords	GEOSS Socio-Benefit Area Descriptions
Health	Understanding environmental factors affecting human health and well-being
Disasters	Reducing loss of life and property from natural and human-induced disasters
Forecasts	Improving weather information, forecasting, and warning
Energy	Improving management of energy resources
Water	Improving water resource management through better understanding of the water cycle
Climate	Understanding, assessing, predicting, mitigating, and adapting to climate variability and change

Agriculture	Supporting sustainable agriculture and combating desertification
Ecology	Improving the management and protection of terrestrial, coastal, and marine ecosystems

407

408

409   Table 3. References to Related National and International Activities (*Source: Appendix C, CCSP SAP 5.1 Prospectus*

410

Priority	National	International
Climate Change	Climate Change Science Program and Climate Change Technology Program	Intergovernmental Panel on Climate Change and World Climate Research Programme
Global Earth Observations	NSTC CENR U.S. Interagency Working Group on Earth Observations	Group on Earth Observations (GEO)
Weather	U.S. Weather Research Program (USWRP)	World Meteorological Organization
Natural Hazards	NSTC CENR Subcommittee on Disaster Reduction	International Strategy for Disaster Reduction
Sustainability	NSTC CENR Subcommittee on Ecosystems	World Summit on Sustainable Development
E-Government	Geospatial One-Stop and the Federal Geographic Data	World Summit on the Information Society

411

412

413   **"Uses and Limitations of Observations, Data, Forecasts, and Other Projections**

414   **in Decision Support for Selected Sectors and Regions"**

415

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

417

418

419   **Introduction**

420

421   This Synthesis and Assessment Product (SAP), "Uses and Limitations of Observations, Data, Forecasts, and Other

422   Projections in Decision Support for Selected Sectors and Regions" (SAP 5.1), examines the current and prospective

423   contribution of Earth science information/data in decision support activities and their relationship to climate change

424   science. The SAP contains a characterization and catalog of observational capabilities in an illustrative set of decision

425   support activities. It also contains a description of the challenges and promises of these capabilities and discusses the

426   interaction between users and producers of information, including the role, measurement, and communication of

427   uncertainty and confidence levels associated with decision support outcomes and their related climate implications.

428

429   The organizing basis for the chapters in this SAP is the decision support tools (DST), which are typically computer-

430   based models assessing such phenomena as resource supply, the status of real-time events (e.g., , forest fires and

431   flooding), or relationships among environmental conditions and other scientific metrics (for instance, water-borne

432   disease vectors, and epidemiological data). These tools use data, concepts of relations among data, and analysis

433   functions to allow analysts to build relationships—including spatial, temporal, and process-based—among different

434   types of data, merge layers of data, generate model outcomes, and make predictions or forecasts. DSTs are an element

435   of the broader decision-making context, the decision support system (DSS). DSSs include not just computer tools but

436   also the institutional, managerial, financial, and other constraints involved in decision making.

437

438   Our approach to this SAP is to define and describe an illustrative set of DSTs in areas selected from topics deemed

439   nationally important and included in societal benefit areas identified by the intergovernmental Group on Earth

440 Observations in leading an international effort to build a Global Earth Observation System of Systems. The areas we

441 have chosen as our focus are air quality, agricultural efficiency, energy management, water management, and public

442 health. The DSTs we illustrate are:

443   1. The Production Estimate and Crop Assessment Division and its Crop Condition Data Retrieval and Evaluation

444   system (PECAD/CADRE) of the US Department of Agriculture, Foreign Agricultural Service (FAS).

445   PECAD/CADRE is the world's most extensive and longest running (over two decades) operational user of

446   remote sensing for evaluation of worldwide agricultural productivity.

447   2. The Community Multiscale Air Quality (CMAQ) modeling system of the US Environmental Protection

448   Agency (EPA). CMAQ is a widely used, US continental/regional/urban-scale air quality decision support tool.

449   3. The Hybrid Optimization Model for Electric Renewables (HOMER), a micropower optimization model of the

450   US Department of Energy's National Renewable Energy Laboratory (NREL). HOMER is used around the

451   world to optimize deployment of renewable energy technologies.

452   4. The Decision Support System to Prevent Lyme Disease (DDSPL) of the US Centers for Disease Control and

453   Prevention (CDC) and Yale University. DDSPL seeks to prevent the spread of the most common vector-borne

454   disease, Lyme disease, of which there are tens of thousands of reported cases annually in the United States.

455   5. RiverWare, developed by the University of Colorado-Boulder's Center for Advanced Decision Support for

456   Water and Environmental Systems (CADSWES) in collaboration with the Bureau of Reclamation, Tennessee

457   Valley Authority, and the Army Corps of Engineers, is a hydrologic or river basin modeling system that

458   integrates features of reservoir systems, such as recreation, navigation, flood control, water quality, and water

459   supply, in a basin management tool with power system economics to provide basin managers and electric

460   utilities a method of planning, forecasting, and scheduling reservoir operations.

461

462 Taken together, these DSTs demonstrate a rich variety of applications of observations, data, forecasts, and other

463 predictions. In four of our studies—agricultural efficiency, air quality, water management, and energy management—

464 the DSTs have become well established as a basis for public policy decision making. In the case of public health, our

465 lead author points out reasons why direct applications of Earth observations to public health have tended to lag behind

466 these other applications and thus is a relatively new applications area. He also reminds us that management of air

467   quality, agriculture, water, and energy—in and of themselves—have implications for the quality of public health. The

468   DST selected for public health is a new and emerging tool intended to assist in prevention of the spread of infectious

469   disease.

470

471   With the exception of DDSPL, none of the DSTs we considered for potential selection, nor those we discuss in this

472   report, have to date made extensive use of climate change information or been used to study the effect of a changing

473   climate. However, in all cases, the developers and users of these DSTs fully recognize their applicability to climate

474   change science. In the discussion of the five DSTs presented in this SAP, the authors describe how climate data and/or

475   predictions might be used in these DSTs so that long-range decisions and planning might be accomplished.

476

477   Chapter 1

478

479   **Decision Support for Agricultural Efficiency**

480

481   **Lead Author: Molly K. Macauley**

482

483

484   **1. Introduction**

485   The efficiency of agriculture has been one of the most daunting challenges confronting mankind in its need to

486   manage natural resources within the constraints of weather, climate, and other environmental conditions. Defined as

487   maximizing output per unit of input, agricultural efficiency reflects a complex relationship among factors of production

488   (including seed, soil, human, and physical capital) and the exogenous influence of nature (such as temperature, sunlight,

489   weather, and climate). The interaction of agricultural activity with the environment creates another source of

490   interdependence, (e.g., the effect on soil and water from applications of pesticides, fungicides, and fertilizer).

491   Agricultural production has long been a large component of international trade and of strategic interest as an indicator

492   of the health and security of nations.

493   The relationship between climate change and agriculture is complex. A changing climate can influence

494   agricultural practices (e.g., climate-induced changes in patterns of rainfall could lead to changes in these practices).

495   Agriculture is not only influenced by a changing climate, but agricultural practices themselves are a contributory factor

496   through emissions of greenhouse gases and influences on fluxes of carbon through photosynthesis and respiration. In

497   short, agriculture is both a contributor to and a recipient of the effects of a changing climate (Rosen Zweig, 2003;

498   National Assessment Synthesis Team, 2004).

499   The use of Earth observations by the agricultural sector has a long history. The Large Area Crop Inventory

500   Experiment (LACIE), jointly sponsored by the US National Aeronautics and Space Administration (NASA), the US

501   Department of Agriculture (USDA), and the National Oceanic and Atmospheric Administration (NOAA) conducted

502   from 1974 to 1978 demonstrated the potential for satellite observations to make accurate, extensive, and repeated

503   surveys for global crop forecasts. LACIE used observations from the Landsat series of multi-spectral scanners on sun-

504   synchronous satellites. The Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing

505   (AgRISTARS) followed LACIE and extended the use of satellite observations to include early warning of production

506   changes, inventory and assessment of renewable resources, and other activities (Congressional Research Service, 1983;

507   National Research Council, 2007; Kaupp *et al.,* 2005). Today these data are used by agencies of the federal government,

508   commodity trading companies, farmers, relief agencies, other governments, and essentially anyone with an interest in

509   crop production at a global scale.

510

511   An approach, among others, to increasing agricultural efficiency is to expand and enhance uses of Earth

512   observation data for (1) policy and resource management decision support, (2) monitoring and measuring climate

513   change affects, and (3) providing policy and resource climate change decision support. The foremost example of the

514   application of Earth observations in agriculture is found in the USDA's crop-monitoring decision-support system, the

515   Production Estimates and Crop Assessment Division (PECAD) of the USDA's Foreign Agricultural Service (FAS).

516   (Reorganization at USDA finds the PECAD functionality, but not the name, residing within the USDA's FAS as part of

517   the Office of Global Analysis, Impact Analysis Division, International Production Assessment

518   [USDA/FAS/OGA/IAD/IPA]). PECAD is now the world's most extensive and longest running (over two decades)

519   operational user of remote sensing data for evaluation of worldwide agricultural productivity (NASA, 2001). A

520   Description of the PECAD decision-support system, its functionality, its analysis style, how it deals with making

521   decisions under uncertainty, and its future uses form the basis of this chapter.

522

523   **2. Description of PECAD**

524   The USDA/FAS uses PECAD to analyze global agricultural production and crop conditions affecting planting,

525   harvesting, marketing, commodity export and pricing, drought monitoring, and food assistance. Access to and uses of

526   PECAD are largely by the federal government, rather than state and local governments, as a means of assessing regions

527   of interest in global agricultural production.

528   PECAD uses satellite data, worldwide weather data, and agricultural models in conjunction with FAS overseas

529   post reports, foreign government official reports, and agency travel observations to support decision making. FAS also

530   works closely with the USDA Farm Service Agency and the Risk Management Agency to provide early warning and

531   critical analysis of major crop events in the US. (FAS OnLine Crop Assessment at

532   http://www.fas.usda.gov/pecad2/crop_assmnt.html, accessed April 2007). FAS seeks to promote the security and

533   stability of the US food supply, improve foreign market access for U.S. agricultural products, provide reports on world

534   food security, and advise the US government on international food aid requirements. FAS bears the primary

535   responsibility for USDA's overseas activities: market development, international trade agreements and negotiations, and

536   the collection and analysis of statistics and market information. FAS also administers USDA's export credit guarantee

537   and food aid programs.

538   PECAD's Crop Condition Data Retrieval and Evaluation (CADRE) database management system, the

539   operational outcome of the LACIE and AgRISTARs projects, was one of the first geographic information systems (GIS)

540   designed specifically for global agricultural monitoring (Reynolds, 2001). CADRE is used to maintain a large satellite

541   imagery archive to permit comparative interpretation of incoming imagery with that of past weeks or years. The

542   database contains multi-source weather data and other environmental data that are incorporated as inputs for models to

543   estimate parameters such as soil moisture, crop stage, and yield. These models also indicate the presence and severity of

544   plant stress or injury.   The information from these technologies is used by PECAD to produce, in conjunction with the

545   World Agricultural Outlook Board, official USDA foreign crop production estimates. (FAS OnLine Crop Assessment at

546   http://www.fas.usda.gov/pecad2/crop_assmnt.html, accessed April 2007)

547   Figure 1 (Kaupp *et al.,* 2005, p. 5) illustrates the global data sources and decision support tools for PECAD.

548   The left-hand portion of the figure shows sources of data for the CADRE geospatial DBMS. These inputs include

549   station data from the World Meteorological Organization and coarse resolution data from Meteosat, Scanning

550   Multichannel Microwave Radiometer (SSMR), and Geostationary Satellite (GOES). Meteosat, operated by the

551   European Organization for the Exploitation of Meteorological Satellites (EUTMETSAT), provides visible and infrared,

552   weather-oriented imaging. The SSMR and its successor, the Special Sensor Microwave/Imager (SSM/I), are microwave

553   radiometric instruments in the US Air Force Defense Meteorological Satellite Program. Additional weather data come

554   from the US GOES program.

555   Medium resolution satellite data include Advanced Very High Resolution Radiometer (AVHRR)/NOAA,

556   Spot-Vegetation, and Terra/Aqua MODIS. AVHRR/NOAA, operated by NOAA, provides cloud cover and land, water,

557   and sea surface temperatures at approximately 1-km spatial resolution. The Systeme Pour L'Observation de la Terre

558   (SPOT) supplies commercial optical Earth imagery at resolutions from 2.5 to 20 meters (m); SPOT-Vegetation is a

559   sensor providing daily coverage at 1 km resolution. The NASA Moderate Resolution Imaging Spectroradiometers

560   (MODIS) on the Terra and Aqua satellites, part of the US Earth Observation System, show rapid biological and

561   meteorological changes at 250 to 1,000 m spatial resolution every two days. NASA's Global Inventory Modeling and

562   Mapping Studies (NASA/GIMMS) group processes data acquired from SPOT and Terra/Aqua MODIS.

563   NASA/GIMMS provides PECAD with cross-calibrated global time series of Normalized Difference Vegetation Index

564   maps from AVHRR and SPOT-Vegetation. Moderate-resolution Earth observation data are also used from the US

565   Landsat program.

566   Sources of high resolution and radar altimeter satellite data include SPOT, IKONOS, Poseidon, and Jason.

567   IKONOS is a commercial Earth imaging satellite providing spatial resolution of 1 and 4 m. Data from Poseidon and its

568   successor, Jason, provide lake and reservoir surface elevation estimates. Poseidon, part of the TOPEX/Poseidon

569   mission, and Jason-1, a follow-on mission, are joint ventures between NASA and the Centre National d'Etudes

570   Spatiales (CNES) using radar altimeters to map ocean surface topography (including sea surface height, wave height,

571   and wind speed above the ocean). These data enable analysts to assess drought or high water-level conditions within

572   some of the world's largest lakes and reservoirs to predict effects on downstream irrigation potential and inform

573   production capacity estimates (Birkett and Doorn, 2004; Kanarek, 2005). The assimilation of these data into PECAD is

574   described in detail in a recent systems engineering report (NASA, 2004b).

575   PECAD combines the satellite and climate data, crop models (along the bottom portion of the figure), a variety

576   of GIS tools, and a large amount of contextual information, including official government reports, trade and new

577   sources, and on-the-ground reports from a global network of embassy attaches and regional analysts. The integration

578   and analysis is attained by "convergence of evidence analysis" (Kaupp *et al.,* 2005). This convergence methodology

579   seeks to reconcile various independent data sources to achieve a level of agreement to minimize estimate error (NASA,

580   2004a).

581   The crop assessment products indicated along the right-hand side of the PECAD architecture in figure 1

582   represent the periodic global estimates used to inform official USDA forecasts. These products are provided to the

583   agricultural market, including farmers; agribusiness; commodity traders and researchers; and federal, state, and local

584   agencies. In addition to CADRE, other automated components include two features providing additional types of

585   information. The FAS Crop Explorer (middle of diagram) is a feature on the FAS Web site since 2002 (Kanarek, 2005).

586   Crop Explorer offers near-real-time global crop condition information based on satellite imagery and weather data from

587   the CADRE database and NASA/GIMMS. Thematic maps of major crop growing regions show vegetation health,

588   precipitation, temperature, and soil moisture. Time-series charts show growing season data for agro-meteorological

589   zones. For major agriculture regions, Crop Explorer provides crop calendars and crop areas. Through Archive Explorer,

590   PECAD provides access to an archive of moderate- to high-resolution data, allowing USDA users (access is controlled

591   by user name and password) to search an image database.

592

593   **3. Potential Future Use and Limits**

594   The most recent enhancements to PECAD/CADRE have included the integration and evaluation of MODIS,

595   Topex/Poseidon, and Jason-1 products (NASA, 2006a). Figure 2 summarizes the Earth system models, Earth

596   observations data, and the CADRE DBMS and characterizes their outputs. Several planned Earth observations missions

597   anticipated when this image was prepared (indicated in italics) show how PECAD/CADRE could incorporate new

598   opportunities, including those with additional land, atmosphere, and ocean observations. These would include space-

599   based observations of atmospheric carbon dioxide (CO_2) from the Orbiting Carbon Observatory (OCO) and

600   measurement of global sea surface salinity (Aquarius) to improve understanding of the links between the water cycle,

601   climate, and the ocean. Other opportunities for enhancing PECAD/CADRE could include improvements in predictive

602   modeling capabilities in weather and climate (National Aeronautics and Space Administration, 2006a).

603   In a recent evaluation report for PECAD, NASA has acknowledged that one of the largest technology gaps in

604   meeting PECAD requirements is the design of NASA systems for research purposes rather than for operational uses

605   (NASA, 2004a). PECAD analysts require dependable inputs, implying the use of operational systems that ensure

606   continuous data streams and that minimize vulnerability to component failure through redundancy. The report also

607   emphasizes that PECAD requires systems that deliver real-time or near-real-time data. Many NASA missions have

608   traded timeliness for experimental research or improvements in other properties of the information delivered.

609   Additionally, the report identifies several potential Earth science data streams that have not yet been addressed,

610   including water balance, the radiation budget (including solar and long wave radiation flux), and elevation, and

611   expresses concern about the potential continuity gap between Landsat 7 and the Landsat Data Continuity Mission.

612   A 2006 workshop convened at the United Nations Food and Agriculture Organization (FAO) by the Integrated

613   Global Observations of Land (IGOL) team identified priorities for agricultural monitoring during the next 5 to 10 years

614   as part of the emerging GEOSS. In summary, the meeting called for several initiatives including the following (United

615   Nations Food and Agriculture Organization, 2006):

616   (1) the need for an international initiative to fill the data gap created by the malfunction of Landsat 7;

617   (2) a system to collect cloud-free, high resolution (10 to 20 m) visible, near-infrared, and shortwave infrared

618   observations at 5 to 10-day intervals;

619   (3) workshops on global agricultural data coordination and on integrating satellite and *in situ* observations;

620   (4) an inventory and evaluation of existing agro-meteorological data sets to identify gaps in terrestrial networks, the

621   availability of data, and validation and quality control in order to offer specific recommendations to the World

622   Meteorological Organization to improve its database;

623   (5) funding to support digitizing, archiving, and dissemination of baseline data; and

624   (6) an international workshop within the GEOSS framework to develop a strategy for "community of practice" for

625   improved global agricultural monitoring.

626   A recent study by the National Research Council (NRC) of the use of land remote sensing expressed additional

627   concerns about present limits on the usefulness of Earth observations in agricultural assessment) (National Research

628   Council, 2007). These include data integration, communication of results, and capacity to use and interpret data.

629   Specifically, the NRC identified these concerns:

630   (1) inadequate integration of spatial data with socioeconomic data (locations and vulnerabilities of human populations

631   and access to infrastructure) to provide information that is effective in generating response strategies to disasters or

632   other factors influencing access to food or impairing agricultural productivity;

633   (2) a lack of communication between remote sensing mission planners, scientists and decision makers to ascertain what

634   types of information enable the most effective food resource management; and

635   (3) shortcomings in the acquisition, archiving, and access to long-term environmental data and development of capacity

636   to interpret these data, including maintaining continuity of satellite coverage over extended time frames, providing

637   access to affordable data, and improving capacity to interpret data.

638

639   **4. Uncertainty**

640   Two aspects of PECAD provide means of validation and verification of crop assessments. One is the maturity

641   of PECAD as a decision support system. Over the years, it has been able to benchmark, validate, verify, and then

642   selectively incorporate additional data sources and automated decision tools. An example of the systems engineering

643   review associated with a decision to incorporate Poseidon and Jason data, for example, is offered in a detailed NASA

644   study (NASA, 2004b).

645   Another example demonstrates how data product accuracy, delivery, and coverage are tested through

646   validation and verification during the process of assimilating new data sources, as well as to ascertain the extent to

647   which different data sources corroborate model outputs (Kaupp *et al.,* 2005). Essential considerations included

648   enhanced repeatability of results, increased accuracy, and increased throughput speed.

649   Another significant aspect of resolving uncertainty in PECAD is its extensive use of a convergence

650   methodology to assimilate information from regional field analysts and other experts. PECAD seeks to provide accurate

651   and timely estimates of production, yet must accommodate physical and biological influences (e.g., weather or pests),

652   the fluctuations in agricultural markets, and developments in public policy impacting the agricultural sector (Kaupp *et*

653   *al.,* 2005). The methodology brings a large amount of additional information to the PECAD forecasts, well beyond the

654   automated outputs of the decision support tools. This extensive additional analysis may not fully correct for, but

655   certainly mitigates, the uncertainty inherent in the data and modeling at the early stages. Figure 3, a simplified version

656   of Figure 1, shows the step represented by the analyses that take place during this convergence of information in

657   relation to the outputs obtained from the decision support tools and their data inputs. Figure 4 further describes the

658   nature of information included in the convergence methodology in addition to the outputs of the data and automated

659   decision support tools. Official reports, news reports, field travel, and attaché reports are additional inputs at this stage.

660   The process is described as one in which, "while individual analysts reach their conclusions in different ways, giving

661   different weight to various inputs, analysts join experts from the USDA's Economic Research Service and National

662   Agricultural Statistics Service once a month in a 'lock-up.' In this setting, the convergence of evidence approach is fully

663   realized as analysts join together in committee formed by (agricultural) commodity. Final commodity production

664   estimates are achieved by committee consensus" (NASA, 2004a, p. 4).

665   The convergence methodology is at the heart of analysis and the final step prior to official world agricultural

666   production estimates and suggests that uncertainty inherent in data and automated models at earlier stages of the

667   analysis are "scrubbed" in a broader context at this final stage.

668

669   **5. Global change information and PECAD**

670   The relationship between climate and agriculture is complex. Agriculture is not only influenced by a changing

671   climate, but agricultural practices themselves are a contributory factor through emissions of greenhouse gases and

672   influences on fluxes of carbon through photosynthesis and respiration. In short, agriculture is both a contributor to and a

673   recipient of the effects of a changing climate (Rosenzweig, 2003).

674   At present, PECAD is not directly used to address these dimensions of the climate-agriculture interaction.

675   However, many of the data inputs for PECAD are climate-related, thereby enabling PECAD to inform understanding of

676   agriculture as a "recipient" of climate-induced changes in temperature, precipitation, soil moisture, and other variables.

677   If reliable climate change prediction of temperature, precipitation, soil moisture, and other necessary variables become

678   available, then these variables can be used as input to PECAD and the results may be used to provide long-range

679   planning of agricultural practices. In addition, spatial and geographic trends in the output measures from PECAD have

680   the potential to contribute to understanding of how the agricultural sector is responding to a changing climate.

681   The output measures of PECAD also can serve to inform understanding of agriculture as a "contributor" to

682   climate changes. For example, observing trends in PECAD's measures of production and composition of crops can shed

683   light on the contribution of the agriculture sector to agricultural soil carbon sequestration.

684

685   *The effects of a changing climate on agricultural efficiency as measured by PECAD:*

686

687   PECAD relies on several data sources for agro-meteorological phenomena that affect crop production and the quality of

688   agricultural commodities. These include data that are influenced by climate (e.g., precipitation, temperatures, snow

689   depth, and soil moisture). The productivity measures from PECAD (yield multiplied by area) are also influenced by

690   climate-induced changes in these data.

691   In addition, the productivity measures of PECAD can be indirectly but significantly affected by possible

692   climate-induced changes in land use. Examples of such changes include the reallocation of land from food production to

693   biomass fuel production or from food production to forestry cultivation as a means of carbon sequestration. In all of

694   these cases, Earth observations can contribute to understanding climate-related effects on agricultural efficiency

695   (National Research Council, 2007). Much of the research to integrate Earth observations into climate and agriculture

696   decision support tools is relatively recent; for example, in FY05, NASA, and USDA began climate simulations using

697   GISS GCM ocean temperature data and also completed fieldwork for verification and validation of a climate-based crop

698   yield model (NASA, 2006b). The UN FAO has begun to coordinate similar research on integrating Earth observations

699   and decision support systems to study possible effects of changing climate on food production and distribution (e.g., see

700   United Nations Food and Agriculture Organization, no date).

701

702   *The effects of agricultural practices and efficiency on climate:*

703

704   In addition to consideration of the effects of climate on agriculture, the feedback from agricultural practices to climate

705   has also been a topic of study (e.g., see http://www.fao.org/NES/1997/971201-e.htm, accessed April 2007). The crop

706   assessments and estimates from PECAD, by revealing changes in agricultural practices, could play a role as early

707   indicators to inform forecasting future agricultural-induced effects on climate. The Agricultural Research Service within

708   USDA and NASA have undertaken research using Earth observation data to study scale-dependent Earth—atmosphere

709   interactions, suggesting that significant changes in regional land use or agricultural practices could affect local and

710   regional climate (NASA, 2001).

711

712   **Figure 1: The PECAD Decision Support System: Data Sources and Decision Support Tools** (Source:

713   Kaupp and coauthors, 2005, p. 5).

714
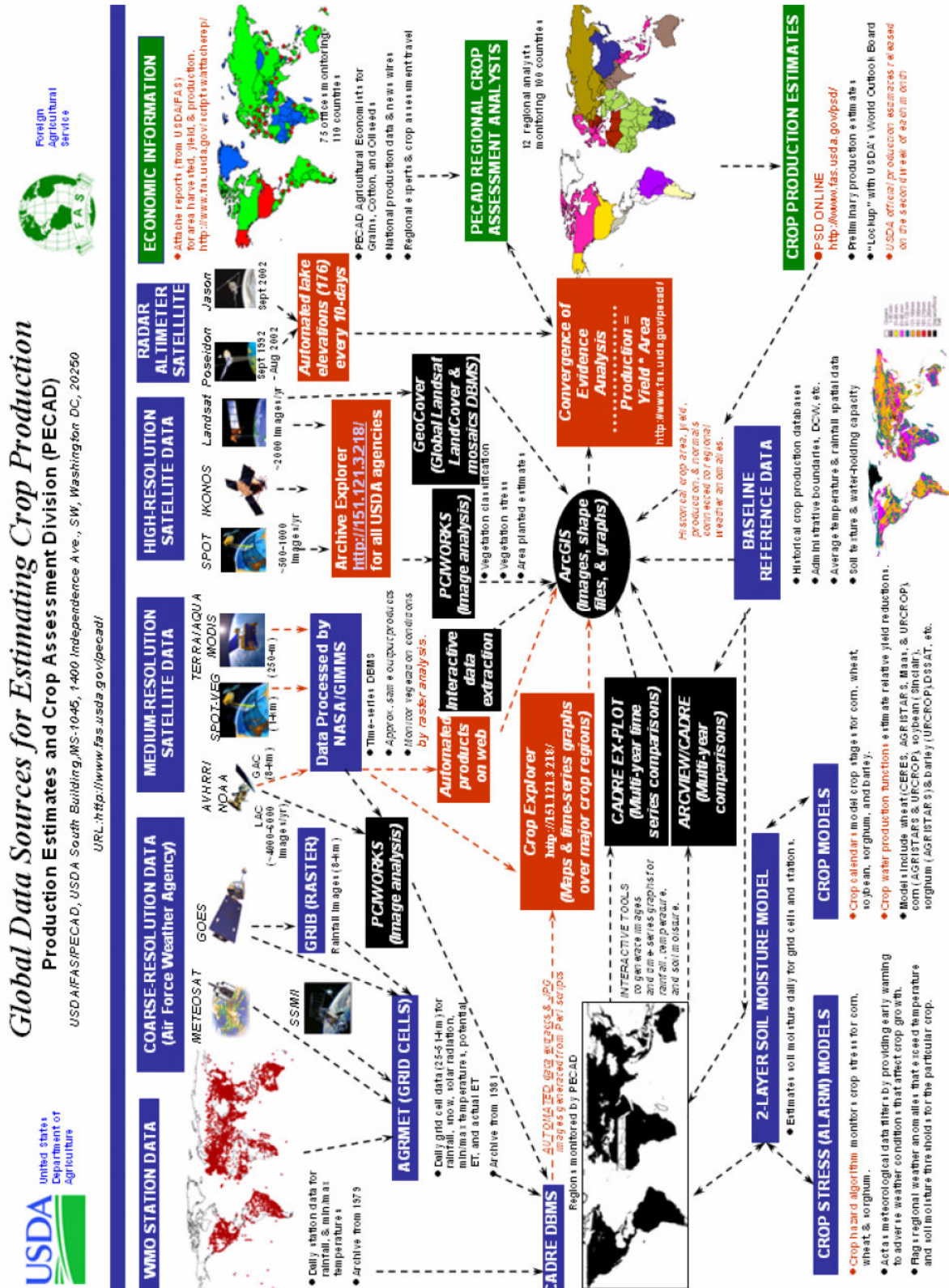
715   **Figure 2. The PECAD Decision Support System: Earth System Models, Earth Observations, Decision**

716   **Support Tools, and Outputs** (Source: National Aeronautics and Space Administration, 2006a, p. 32).

717
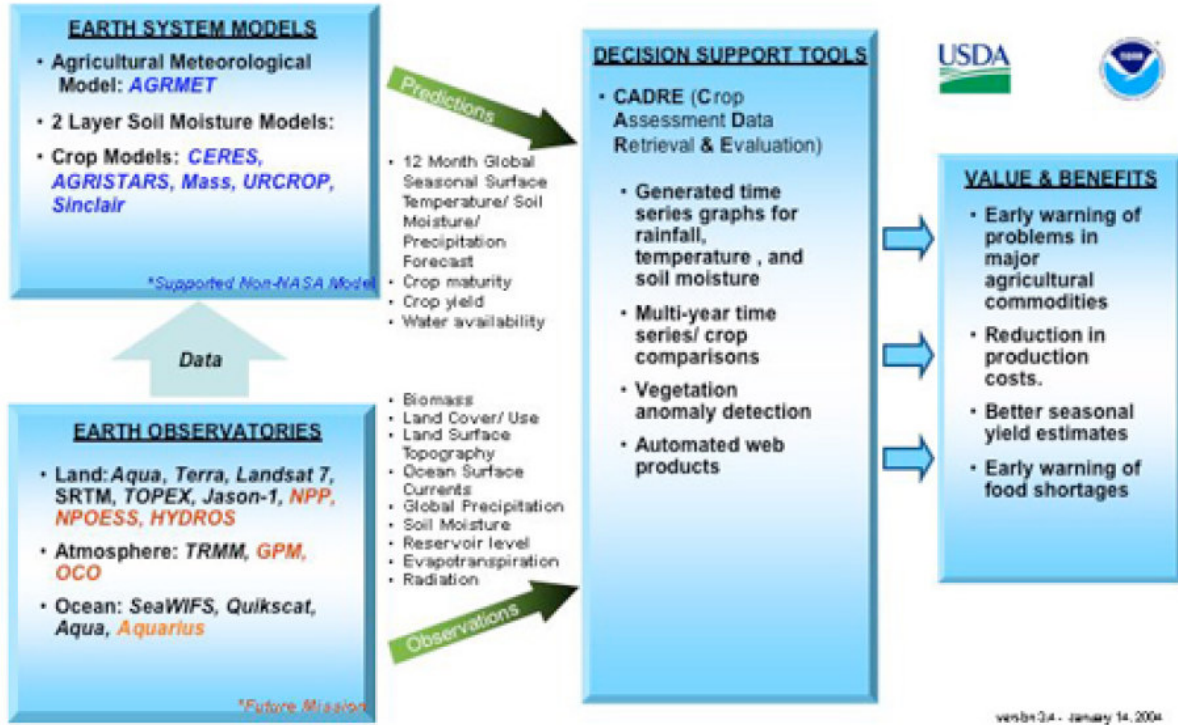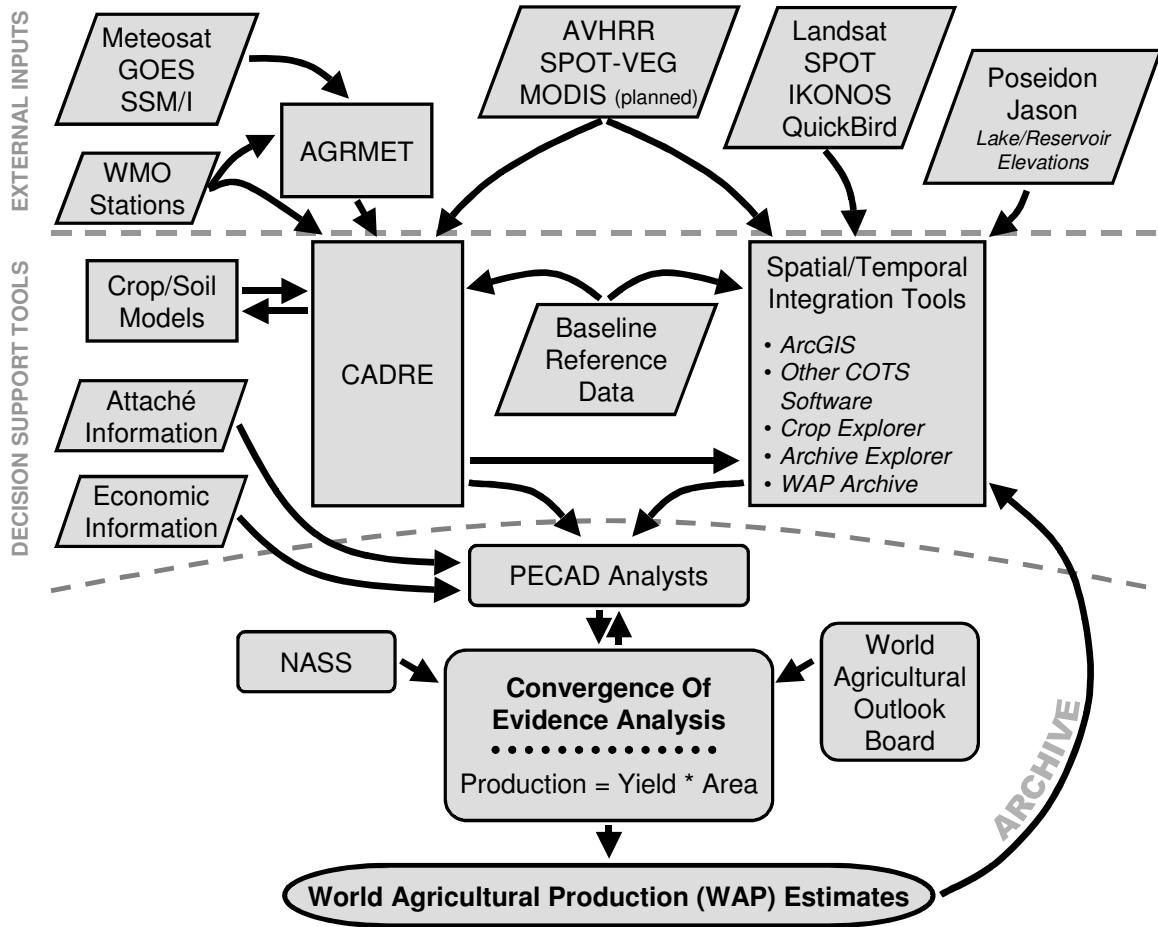
Figure 3: The PECAD Decision Support System: The Role of Convergence of Evidence Analysis (Source: National Aeronautics and Space Administration, 2004a, p. 8).

FAS Attaché
Reports

FAS Remote
Sensing Analysis

**FAS
Economic
Analysis**

FAS Analysis
of Weather Data

FAS Field Travel

Official Country
Reports & Int'l
News Services

USERS
USDA Policymakers
U.S. Ag Producers
USDA Publications

Commodity Price
Discovery

Commodity Price
Adjustment
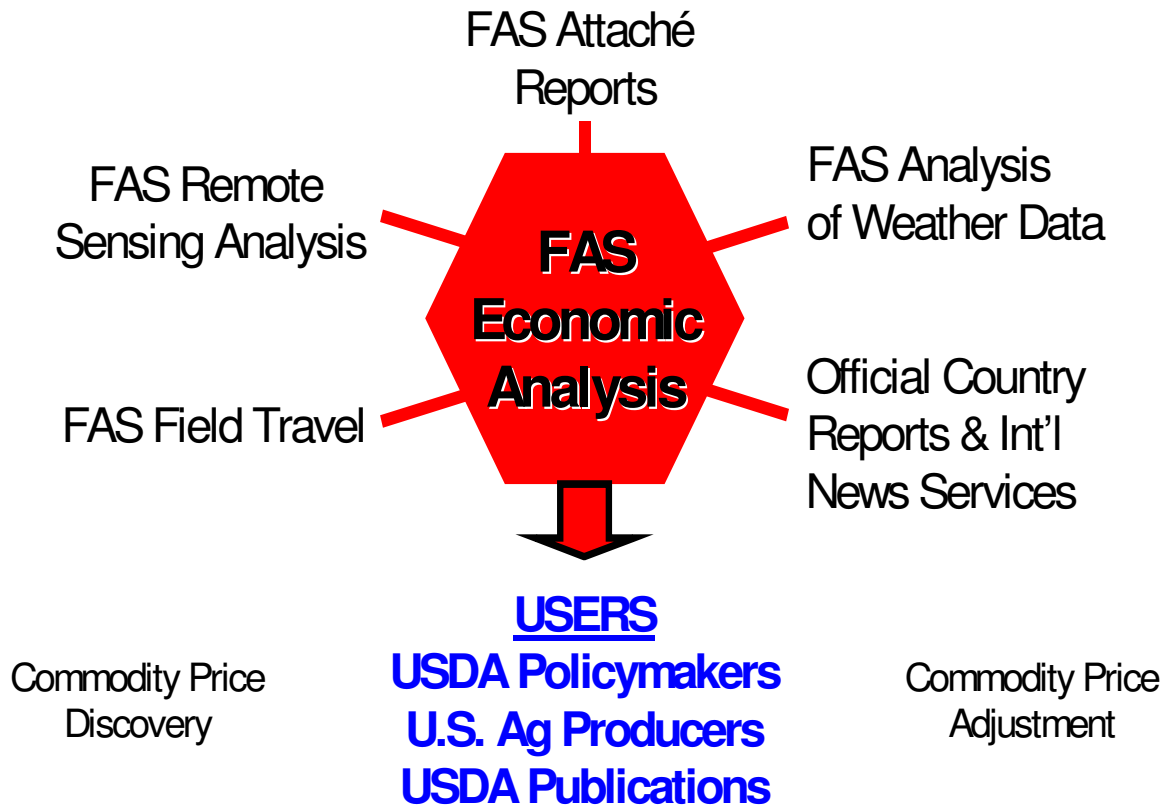
From: http://www.fas.usda.gov/pecad/remote/overview/frame_OV.htm

722   **Figure 4: The PECAD Decision Support System: Information Sources for the Convergence of Evidence Analysis**

723   (Source: National Aeronautics and Space Administration, 2004a, p. 5).

724   # Chapter 2

725

726   ## Decision Support for Air Quality

727   (Use of CMAQ as a Decision Support Tool for Air Quality to Climate Change)

728   **Lead Author: Daewon W. Byun**

729

730   **1. Introduction**

731   Our ability to understand and forecast the quality of the air we breathe, as well as our ability to understand the

732   science of chemical and physical atmospheric interactions, is at the heart of models of air quality. The quality of air is

733   affected by and has implications for the topics presented in our other chapters. Air quality is affected by energy

734   management and agricultural practices, for instance, and is a major factor in public health. Models of air quality also

735   provide a means of evaluating the effectiveness of air pollution and emission control policies and regulations.

736   While numerous studies examine the potential impact of climate change on forests and vegetation, agriculture,

737   water resources, and human health (examples are found in Brown *et al.,* 2004; Mearns, 2003; Leung and Wigmosta

738   1999; Kalkstein and Valimont 1987), attempts to project the response of air quality to changes in global and regional

739   climates have long been hampered by the absence of proper tools that can transcend the different spatial and temporal

740   scales involved in climate predictions and air quality assessment and by the uncertainties in climate change predictions

741   and associated air quality changes.

742   One of the popular modeling tools to study air quality as a whole, including tropospheric ozone, fine particles,

743   toxics, acid deposition, and visibility degradation is the US Environmental Protection Agency's (EPA) Community

744   Multiscale Air Quality (CMAQ) modeling system. CMAQ has as its primary objectives to (1) improve the ability of

745   environmental managers to evaluate the impact of air quality management practices for multiple pollutants at multiple

746   scales, (2) enhance scientific ability to understand and model chemical and physical atmospheric interactions

747   (http://www.epa.gov/asmdnerl/CMAQ/, and (3) guide the development of air quality regulations and standards and to

748   create state implementation plans. It has been also used to evaluate longer-term pollutant climatologies as well as short-

749   term transport from localized sources, and it can be used to perform simulations using downscaled regional climate

750   from global climate change scenarios listed in IPCC (2000). Various observations from the ground and from *in-situ*,

751   aircrafts, and satellite platforms can be used at almost at every step of the processing of this Decision Support System

752   (DSS) for air quality.

753   Although there are significant effects of long-range transport, most of the serious air pollution problems are caused

754   by meteorological as well as chemical processes and their changes at regional and local areas, at scales much smaller

755   than those resolved by global climate models (GCM), which are typically applied at a resolution of several hundred

756   kilometers. Current-day regional climate simulations, which typically employ horizontal resolutions of 30 to 60 km, are

757   insufficient to resolve small-scale processes that are important for regional air quality, including low-level jets, land-sea

758   breezes, local wind shears, and urban heat island effects (Leung *et al.,* 2006). In addition, climate simulations place

759   enormous demands on computer storage. As a result, most climate simulations only archive a limited set of

760   meteorological variables, the time interval for the archive is usually 6 to 24 hours (e.g., Liang *et al.,* 2006), and some

761   critical information required for air quality modeling is missing.

762   The interaction and feedback between climate and air chemistry is another issue. Climate and air quality are linked

763   through atmospheric chemical, radiative, and dynamic processes at multiple scales. For instance, aerosols in the

764   atmosphere may modify atmospheric energy fluxes by attenuating, scattering, and absorbing solar and infrared

765   radiation, and may also modify cloud formation by altering the growth and droplet size distribution in the clouds. The

766   changes in energy fluxes and cloud fields may, in turn, alter the concentration and distribution of aerosols and other

767   chemical species. Although a few attempts have been made to address these issues, our understanding of climate

768   change is based largely on modeling studies that have neglected these feedback mechanisms.

769   The impact of climate change on air emissions is also of concern. Changes in temperature, precipitation, soil

770   moisture patterns, and clouds associated with global warming may directly alter emissions, including biogenic

771   emissions (e.g., isoprene and terpenes). Isoprene, an important natural precursor of ozone, is emitted mainly by

772   deciduous tree species. Emission rates are dependent on the availability of solar radiation in visual range and are highly

773   temperature sensitive. Emissions of terpenes (semi-volatile organic species) may induce formation of secondary organic

774   aerosols. The accompanying changes in the soil moisture, atmospheric stability, and flow patterns complicate these

775   effects, and it is difficult to predict whether climatic change will eventually lead to increased degradation of air quality.

776   This chapter discusses how CMAQ is used as the DSS for studying climate change impact on air quality addressing

777   the focus areas required by the *SAP 5.1 Prospectus*: (1) observational capabilities used in the DSS, (2) agencies and

778   organizations responsible, (3) characterization of interactions between users and the DSS information producers, (4)

779   sources of uncertainties with observation and the decision support tools, and (5) description of the relation between the

780   DSS and climate change information.

781

782

783   **2. Description of CMAQ**

784   The US EPA CMAQ modeling system (Byun and Ching, 1999; Byun and Schere, 2006) has the capability to

785   evaluate relationships between emitted precursor species and ozone at urban/regional scales (Appendix W to Part 51 of

786   40CFR: Guideline on Air Quality Models in "http://www.epa.gov/fedrgstr/EPA-AIR/1995/August/Day-09/pr-

787   912.html"). CMAQ uses state-of-the-science techniques for simulating all atmospheric and land processes that affect the

788   transport, transformation, and deposition of atmospheric pollutants. The primary modeling components in the CMAQ

789   modeling system include (1) a meteorological modeling system (e.g., The Fifth-Generation NCAR/Penn State

790   Mesoscale Model, MM5) or a Regional Climate Model (RCM) for the description of atmospheric states and motions,

791   (2) inventories of man-made and natural emissions of precursors that are injected into the atmosphere, and (3) the

792   CMAQ Chemistry Transport Modeling (CTM) system for the simulation of the chemical transformation and fate of the

793   emissions. The model can operate on a large range of time scales from minutes to days to weeks as well as on numerous

794   spatial (geographic) scales ranging from local to regional to continental.

795   The base CMAQ system is maintained by the U.S. EPA. The Center for Environmental Modeling for Policy

796   Development (CEMPD), University of North Carolina at Chapel Hill (UNC), is contracted to establish a Community

797   Modeling and Analysis System (CMAS) (http://www.cmascenter.org/) for supporting community-based air quality

798   modeling. CMAS helps development, application, and analysis of environmental models and helps distribution of the

799   DSS and related tools to the modeling community. The model performance has been evaluated for various applications

800   (e.g., Zhang *et al.,* 2006; Eder *et al.,* 2006; Tong and Mauzerall, 2006; Yu *et al.,* 2007). Table 1 lists Earth observations

801   (of all types-remote sensing and *in situ*) presently used in the CMAQ DSS.

802   Within this overall DSS structure as shown in Table 1, CMAQ is an emission-based, three-dimensional (3-D) air

803   quality model that does not utilize daily observational data directly for the model simulations. The databases utilized in

804   the system represent typical surface conditions, and demographic distributions. An example is the EPA's Biogenic

805   Emissions Land Use Database, version 3 (BELD3) database (http://www.epa.gov/ttn/chief/emch/biogenic/) that

806   contains land use and land cover as well as the demographic and socioeconomic information. At present the initial

807   conditions are not specified using observed data even for those species routinely measured as part of the controlled

808   criteria species listed in the National Clean Air Act and its Amendments (CAAA) in an urban area using a dense

809   measurement network. This is because of the difficulty in specifying the multi-species conditions that satisfy chemical

810   balance in the system, which is subject to the diurnal evolution of radiative conditions and of the atmospheric boundary

811   layer as well as temporal changes in the emissions that reflect constantly changing human activities.

812   The main output of the CMAQ and its DSS is the concentration and deposition amount of atmospheric trace gases

813   and particulates at the grid resolution of the model, usually at 36 km for the continental United States (CONUS)

814   domain, and 12 km or 4 km for regional or urban scale domains. The end users of the DSS want information on the

815   major scientific uncertainties and our ability to resolve them subject to the information on socioeconomic context and

816   impacts. They seek information on the implications at the national, regional, and local scales and on the baseline and

817   future air quality conditions subject to climate change to assess the effectiveness of current and planned environmental

818   policies. Local air quality managers would want to know if the DSS could help assess methods of attaining current and

819   future ambient air quality standards and evaluate opportunities to mitigate the climate change impacts. Decision makers

820   would ask modelers to simulate the air quality in the future for a few plausible variations in the model inputs that

821   represent plausible climate scenarios of regional implications. Through sensitivity simulations of the DSS with

822   different assumptions on the meteorological and emissions inputs, the effectiveness of such policies and uncertainties in

823   the system can be studied. The results can be also compared with the historic air quality observations with similar

824   ambient conditions to validate predictions of the DSS.

825

826   **3. Potential Future Uses and Limits**

827   Although one of the major strengths of CMAQ is its reliance on the first principles of physics and chemistry, a few

828   modeling components, such as cloud processes, fine scale turbulence, radiative processes, etc., rely on

829   parameterizations or phenomenological concepts to represent intricate and less-well known atmospheric processes. The

830   present limitations in science parameterizations and modeling difficulties will continuously be improved as new

831   understanding of these phenomena are obtained through various measurements and model evaluation/verification. The

832   development of the chemical mechanism, Carbon Bond 05 (CB05), which recently replaced CB-4 is a case in point.

833   The reliability of the CMAQ simulation result is subject to quality of the emission inputs, both at the global and

834   regional scales, which depend heavily on socio-economic conditions. Because such estimates are obtained using

835   projection models in relevant socio-economic disciplinary areas, their accuracy must be scrutinized when used for the

836   decision-making process. The CMAQ DSS users/operators may not always have domain expertise to discern the

837   validity of such results.

838   CMAQ needs to have the ability to utilize available observations to specify more accurately the critical model

839   inputs, although they have been chosen based on best available information and experience currently. A data assimilation

840   approach may be used to improve the system performance at different processing steps.

841

842   Table 1. Input data used for operating the CMAQ-based DSS.

843   <<footnotes: PNNL, UIUC, NCEP, EPA, USGS, NASA>>

844   PNNL: Pacific Northwest National Laboratory

845   UIUC: University of Illinois at at Urbana-Champaign

846   NCEP: National Center for Environmental Prediction

847   EPA: Environmental Protection Agency

848   USGS: US Geological Survey

849   NASA: National Astronautics and Space Agency

850

851   For example, research has been undertaken to use satellite remote sensing data products together with high-

852   resolution land use and land cover (LULC) data to improve the land-surface parameterizations and boundary layer

853   schemes in the RCMs (e.g., Pour-Biazar *et al.,* 2007). Active research in chemical data assimilation (e.g.,

854   Constantinescu *et al.,* 2007a and b) is currently conducted with models such as STEM-II (Carmichael *et al.,* 1991) and

855   Goddard Earth Observing System (GEOS)-Chem (Bey *et al.,* 2001) , which utilize both *in situ* and satellite observations

856   (e.g., Sandu *et al.,* 2005; Kopacz *et al.,* 2007; Fu *et al.,* 2007). Because of the coarse spatial and temporal resolutions of

857   the satellite data collected in the 1960s through the 1980s, and gas measurements through the launch of EOS Aura in

858   2004, most research in this area has been performed with global chemistry-transport models. As the horizontal

859   footprints of modern satellite instruments reach the resolution suitable for regional air quality modeling, these data can

860   be used to evaluate and then improve the bottom-up emissions inputs in the regional air quality models. However, they

861   do not provide required vertical information. The exception is occultation instruments, but these do not measure low

862   enough in altitude for air quality applications. In-*situ* and remote sensing measurements from ground and aircraft

863   platforms could be used to augment the satellite data in these data assimilation experiments.

864   Utilization of the column-integrated satellite measurements in a high-resolution 3-D grid model like CMAQ poses

865   serious challenges in distributing the pollutants vertically and separating those within and above the atmospheric

866   boundary layer. Because similar problems exist for the retrieval of meteorological profiles of moisture and temperature,

867   experiences in including these can be adapted for a few well-behaved chemical species. A data assimilation tool can be

868   used to improve the initial and boundary conditions using various in *situ* and satellite measurements of atmospheric

869   constituents. At present, however, an operational assimilation system for CMAQ is not yet available, although prototype

870   assimilation codes have recently been generated (Hakami, *et al.,* 2007; Zhang *et al.,* 2007). Should these data

871   assimilation tools become part of the DSS, various conventional and new satellite products, including Tropospheric

872   Emission Spectrometer (TES) ozone profiles, Geostationary Operational Environmental Satellites (GOES) hourly total

873   ozone column (GhTOC) data, Ozone Monitoring Instrument (OMI) total ozone column (TOC), The Cloud-Aerosol

874   Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (http://www-calipso.larc.nasa.gov/) attenuated

875   backscatter profiles, and OMI aerosol optical thickness (AOT) data can be utilized to improve the urban-to-regional

876   scale air quality predictions.

877   Because of the critical role of the RCM as the driver of CMAQ in climate change studies, RCM results for the long-

878   term simulations must be verified thoroughly. To date, evaluation of the RCM has been performed for the air quality

879   related operations only for relatively short simulation periods. For example, the simulated surface temperature, pressure,

880   and wind speed must be compared to surface observations to determine how well the model captures the mean land-

881   ocean temperature and pressure gradients, the mean sea breeze wind speeds, the average inland penetration of sea

882   breeze, the urban heat island effect, and the seasonal variations of these features. Comparisons with rawinsonde

883   soundings and atmospheric profiler data would determine how well the model reproduces the averaged characteristics of

884   the afternoon mixed layer heights and of the early morning temperature inversion, as well as the speed and the vertical

885   wind shears of the low-level jets. In addition to these mesoscale phenomena, changes in other factors can also alter the

886   air pollution patterns in the future and need to be carefully examined. These factors include the diurnal maximum,

887   minimum, and mean temperature; cloud cover; thunderstorm frequency; surface precipitation and soil moisture patterns;

888   and boundary layer growth and nocturnal inversion strength.

889   As demonstrated in global model applications, satellite measured biomass burning emissions data should be utilized

890   in the regional air quality modeling (e.g., Duncan *et al.,* 2003; Hoelzemann, *et al.,* 2004). Duncan *et al.* (2003)

891   presented a methodology for estimating the seasonal and interannual variation of biomass burning, designed for use in

892   global chemical transport models using fire-count data from the Along Track Scanning Radiometer (ATSR) and the

893   Advanced Very High Resolution Radiometer (AVHRR) World Fire Atlases. The Total Ozone Mapping Spectrometer

894   (TOMS) Aerosol Index (AI) data product was used as a surrogate to estimate interannual variability in biomass burning.

895   Also Sprackclen *et al.* (2007) showed that the wildfire contribution to the interannual variability of organic carbon

896   aerosol can be studied using the area-burned data and ecosystem specific fuel loading data. A similar fire emissions

897   data set at the regional scales could be developed for use in a study of climate impact on air quality. For retrospective

898   application, a method similar to that used by the National Oceanic and Atmospheric Administration's (NOAA) Hazard

899   Mapping System (HMS) for Fire and Smoke (http://www.ssd.noaa.gov/PS/FIRE/hms.html) may be used to produce a

900   long-term regional scale fire emissions inventory for climate impact analysis.

901

4. Uncertainty

903   The CMAQ modeling system as currently operated has several sources of uncertainty in addition to those

904   associated with some of the limits described in the previous section. In particular, when CMAQ is used to study the

905   effects of climate change and air quality, improvements in several areas are necessary to reduce uncertainty. First, the

906   regional air quality models employ limited modeling domains and, as such, they are ignorant of air pollution events

907   outside the domains unless proper dynamic boundary conditions are provided. Second, because the pollutant transport

908   and chemical reactions are fundamentally affected by the meteorological conditions, improving both the global climate,

909   regional climate models, and the downscaling methods by evaluating and verifying physical algorithms that have been

910   implemented with observations as necessary in order to improve the system's overall performance. Third, the basic

911   model inputs, including land use/vegetation cover descriptions and emissions inputs must be improved. Fourth, the

912   model representativeness issues, including grid resolution problems, compensating errors among the model components,

913   and incommensurability of the model results compared with the dimensionality of the measurements (i.e., inherent

914   differences in the modeled outputs that represent volume and time averaged quantities to the point or path-integrated

915   measurements), as discussed in Russell and Dennis (2000) and NARSTO (2000), need to be addressed.   These factors

916   are the principal cause of simulation/prediction errors.

917   Although the models incorporated in this DSS are first-principle based environmental models, they have difficulties

918   in representing forcing terms in the system, in particular, the influence of the earth's surface, long-range transport, and

919   uncertainties in the model inputs such as daily emissions changes due to anthropogenic and natural events. There is

920   ample opportunity to reduce some uncertainties associated with CMAQ through model evaluation and verification using

921   current and future meteorological and atmospheric chemistry observations. Satellite data products assimilated in the

922   global chemical transport models (GCTM) could provide better dynamic lateral boundary conditions for the regional air

923   quality modeling (e.g., Al-Saddi, *et al.,* 2005). Additional opportunities to reduce the model uncertainty include

924   comparison of model results with observed data at different resolutions, quantification of effects of initial and boundary

925   conditions and chemical mechanisms, application of CMAQ to estimate the uncertainty of input emissions data, and

926   ensemble modeling (using a large pool of simulations among a variety of models) as a means to estimate model

927   uncertainty.

928   A limitation in CMAQ applications, and therefore a source of uncertainty, has been the establishment of initial

929   conditions. The default initial conditions and lateral boundary conditions in CMAQ are provided under the assumption

930   that after spin-up of the model, they no longer play a role, and in time, surface emissions govern the air quality found in

931   the lower troposphere. Song *et al.* (2007) showed that the effects of the lateral boundary conditions differ for different

932   latitudes and altitudes, as well as seasons. In the future, dynamic boundary conditions can be provided by fully

933   integrating the GCTMs as part of the system. Several research groups are actively working on this, but the simulation

934   results are not yet available in open literature. A scientific cooperative forum, the Task Force on Hemispheric Transport

935   of Air Pollution (http://www.htap.org/index.htm), is endeavoring to bring together the national and international

936   research efforts at the regional, hemispheric, and global scales to develop a better understanding of air pollution

937   transport in the Northern Hemisphere. This task force is currently preparing its 2007 Interim Report addressing various

938   long-range transport of air pollutant issues (http://www.htap.org/activities/2007_Interim_Report.htm). Although the

939   effort does not directly address climate change issues, many of findings and tools used are very relevant to

940   meteorological and chemical downscaling issues.

941   Ultimately, CMAQ should consider all the uncertainties in the inputs. The system's response may be directly

942   related to the model configuration and algorithms (e.g., structures, resolutions, and chemical and transport algorithms),

943   compensating errors, and the incommensurability of modeling nature, as suggested by Russell and Dennis (2000).

944

945   **5. Global Change Information and CMAQ**

946   CMAQ could be used to help answer several questions about the relationship between air quality and climate

947   change. For instance:

948

949   1) How will global warming affect air quality in a region?

950   2) How will land use change due to climate, urbanization, or intentional management decisions affect air quality?

951   3) How much will climate change alter the frequency, seasonal distribution, and intensity of synoptic weather patterns

952   that influence pollution in a region?

953   4) How sensitive are air quality simulations to uncertainty in wildfire projections and to potential land management

954   scenarios?

955   5) How might the contribution of the local production and long-range transport of pollutants differ due to different

956   climate change scenarios?

957   6) Will future emissions scenarios or climate changes affect the frequency and magnitude of high pollution events?

958   To provide answers to these questions, CMAQ will rely heavily on climate-change-related information. In addition

959   to the influence of greenhouse gases and global warming, other forcing functions include population growth, land use

960   changes, new emission controls being implemented, and new energy sources to be available to replace the existing high-

961   carbon sources. Different scenarios can be chosen either to study potential impacts or to estimate the range of

962   uncertainties of the predictions. The two upstream climate models, GCMs and RCMs, generate the climate change data

963   that drive a GCTM and CMAQ. Both the GCMs and RCMs are expected to represent future climate change conditions

964   while simulating historic climate conditions that can be verified with comprehensive datasets such as the NCEP

965   Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, CO, from their Web site,

966   http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html   The meteorology simulated by the climate models represents

967   conditions in future year scenarios, reflecting changing atmospheric conditions. Furthermore, emissions inputs used for

968   the GCTM and CMAQ must reflect the natural changes and/or anthropogenic developments related to climate change

969   and other factors (e.g., population growth and geographical population shifts due to climate change).

970   In recent years, the EPA Science to Achieve Results (STAR) program has funded several projects on the possible

971   effects of climate change on air quality and on ecosystems. A majority of these projects have adopted CMAQ as the

972   base study tool. Figure 1 provides a general schematic of the potential structure of a CMAQ-based climate change DSS.

973   The figure shows potential uses of CMAQ for climate study; most climate-related CMAQ applications are not yet

974   configured as fully as indicated in the figure.

975   The projects linking CMAQ and climate study have used upstream models and downstream tools, including those

976   identified in Table 2. Related projects that use regional air quality models other than CMAQ are also listed. For the

977   GCMs, NCAR Community Climate Model (CCM) (Kiehl *et al.,* 1996), NASA Goddard Institute for Space Studies

978   (GISS) model (e.g., Hansen *et al.,* 2005), and NOAA Geophysical Fluid Dynamics Laboratory (GFDL) CM2 (Delworth

979   *et al.,* 2006) are the most popular global models for providing meteorological inputs representing climate change events.

980   A recent description for the GISS model can be found in Schmidt *et al.* (2006) (http://www.giss.nasa.gov/tools/) and for

981   the CCM in Kiehl *et al.* (1996) (http://www.cgd.ucar.edu/cms/ccm3/). A newer version of the CCM was released on

982   May 17, 2002 with a new name—the Community Atmosphere Model (CAM) (http://www.ccsm.ucar.edu/models/atm-

983   cam). The model is described in Hurrell *et al.* (2006).

984

985   Table 2. An illustrative example of the potential uses of the models and upstream and downstream tools for a CMAQ-

986   based Climate Change Impact Decision Support System.

987   <footnote: WRF-ARW, WRF-NMM, SLEUTH>>

988

989   As shown in Table 2, for climate change studies, CMAQ is linked with upstream models such as a global climate

990   model (GCM), a global tropospheric chemistry model (GTCM), and a regional climate model (RCM) to provide

991   emissions sensitivity analysis, source apportionment, and data assimilation to assist policy and management decision-

992   making activities, including health impact analysis. Certain EPA STAR projects (Hogrefe *et al.,* 2004 and 2005;

993   Knowlton *et al.,* 2004; Civerolo *et al.,* 2007) have utilized the CMAQ-based DSS to assess whether climate change

994   would influence the effectiveness of current and future air pollution policy decisions subject to the potential changes in

995   local and regional meteorological conditions.

996   Other EPA STAR projects employ global climate change information from a GCM. For example, Tagaris *et al.*

997   (2007) and Liao *et al.* (2007a,b) use the results of GCM simulation with the well-mixed greenhouse gases—CO2, CH4,

998   N2O, and halocarbons—updated yearly from observations for 1950 to 2000 (Hansen *et al.,* 2002) and for 2000 to 2052

999   following the A1B SRES scenario from the Intergovernmental Panel on Climate Change (IPCC 2001).   The simulation

1000   used ozone and aerosol concentrations in the radiative scheme fixed at present-day climatological value provided in

1001   Mickley, *et al.* (2004).

1002

1003   To resolve the meteorological features affecting air pollution transport and transformation at a regional scale, the

1004   coarse scale meteorological data representing the climate change effects derived from a GCM are downscaled using an

1005   RCM. An RCM is often based on a limited-domain regional mesoscale model, such as MM5, the Regional

1006   Atmospheric Modeling System (RAMS), Eta, and WRF/ARW or WRF/NMM. An alternative method for constructing

1007   regional scale climate change data is through a statistical downscaling, which evaluates observed spatial and temporal

1008   relationships between large-scale (predictors) and local (predictands) climate variables over a specified training period

1009   and domain (Spak *et al.,* 2007). Because of the need to use a meteorological driver that satisfies constraints of dynamic

1010   consistency (i.e., mass and momentum conservations) for regional scale air quality modeling (e.g., Byun, 1999 a and b),

1011   the CMAQ modeling system relies exclusively on the dynamic downscaling method.

1012   Regional chemistry/transport models, like CMAQ, are better suited for regional air quality simulations than a

1013   GCTM because of the acute air pollution problems that are managed and controlled through policy decisions at specific

1014   geographic locations. Difficulty in prescribing proper boundary conditions (BC), especially in the upper troposphere, is

1015   one of the deficiencies of CMAQ simulations of air quality (e.g., Tarasick *et al.,* 2007; Tang *et al.,* 2007). Therefore,

1016   one of the main roles of the global CTM is to provide proper dynamic boundary conditions for CMAQ to represent

1017   temporal variation of chemical conditions that might be affected by the long-range transport of pollution (e.g., particle

1018   from large-scale biomass burnings) from outside the regional domain boundaries (Holloway, *et al.,* 2002; In *et al.,*

1019   2007). The contemporary EPA funded projects on climate change impact on air quality mainly use two 3-D GCTM

1020   models: the NASA/Harvard GEOS-Chem (Bey *et al.,* 2001) and the National Center for Atmospheric Research (NCAR)

1021   Model of Ozone and Related Chemical Tracers (MOZART) (Brasseur *et al.,* 1998; Horowitz *et al.,* 2003).

1022   The GEOS-Chem model (http://www-as.harvard.edu/chemistry/trop) is a global model for predicting tropospheric

1023   composition. The model was originally driven by the assimilated meteorological observation data from the GEOS of the

1024   NASA Global Modeling and Assimilation Office (GMAO). GEOS-Chem has been used as community assessment

1025   models for NASA Global Model Initiative, climate change studies with the NASA/GISS GCM, chemical data

1026   assimilation of tropospheric gaseous and aerosol species at NASA GMAO, and regulatory models for air pollution, in

1027   particular providing long-range transport information for regional air quality models. Long-term retrospective studies

1028   are possible with the GEOS data, which are available from 1985 to present at horizontal resolution of 2 degrees

1029   (latitude) by 2.5 degrees (longitude) until the end of 1999 and 1 degrees by 1 degrees afterward. For climate studies, the

1030   NASA GISS GCM meteorological outputs are used instead. Emission inventories include a satellite-based inventory of

1031   fire emissions (Duncan *et al.,* 2003) with expanded capability for daily temporal resolution (Heald *et al.,* 2003) and the

1032   National Emissions Inventory for 1999 (NEI 1999) for the US with monthly updates in order to achieve adequate

1033   consistency with the CMAQ fields at the GEOS-Chem/CMAQ interface.

1034   MOZART (http://gctm.acd.ucar.edu/mozart/models/m3/index.shtml) is built on the framework of the Model of

1035   Atmospheric Transport and Chemistry (MATCH) that can be driven with various meteorological inputs and at different

1036   resolutions such as meteorological reanalysis data from the National Centers for Environmental Prediction (NCEP),

1037   NASA GMAO, and the European Centre for Medium-Range Weather Forecasts (ECMWF). For climate change

1038   applications, meteorological inputs from the NCAR CCM3 are used. MOZART includes a detailed chemistry scheme

1039   for tropospheric ozone, nitrogen oxides, and hydrocarbon chemistry, semi-Lagrangian transport scheme, dry and wet

1040   removal processes, and emissions inputs. Emission inputs include sources from fossil fuel combustion, biofuel and

1041   biomass burning, biogenic and soil emissions, and oceanic emissions. The surface emissions of NOx, CO, and NMHCs

1042   are based on the inventories described in Horowitz *et al.* (2003), aircraft emissions based on Friedl (1997), and lightning

1043   NOx emissions that are distributed at the location of convective clouds.

1044   GCTMs are applied to investigate numerous tropospheric chemistry issues, involving gases – CO, CH_4, OH, NOx,

1045   HCHO, and isoprene– and inorganic (sulfates and nitrates) and organic (elemental carbons, organic carbons)

1046   particulates. Various *in situ*, aircraft, and satellite-based measurements are used to provide the necessary inputs, to

1047   verify the science process algorithms, and to perform general model evaluations. They include vertical profiles from

1048   aircraft observations as compiled by Emmons *et al.* (2000), multiyear analysis of ozonesonde data (Logan, 1999), and

1049   those available at the Community Data Web site managed by the NCAR Earth and Sun Systems Laboratory (ESSL)

1050   Atmospheric Chemistry Division (ACD); and multiyear surface observations of CO reanalysis (Novelli *et al.,* 2003).

1051   Current and previous atmospheric measurement campaigns are listed in Web pages by NOAA Earth Systems Research

1052   Laboratory (ESRL), http://www.esrl.noaa.gov/; NASA, Tropospheric Integrated Chemistry Data Center, http://www-

1053   air.larc.nasa.gov/; and NCAR ESSL (Earth and Sun Systems Laboratory) Atmospheric Chemistry Division (ACD)

1054   Community Data, http://www.acd.ucar.edu/Data/. These observations are used to set boundary conditions for the slow

1055   reacting species, including CH_4, N_2O, and CFCs, and to evaluate other modeled species, including CO, NOx, PAN,

1056 HNO_3, HCHO, acetone, H_2O_2, and non-methane hydrocarbons. In addition, several satellite measurements of CO, NO_2,

1057   and HCHO from the Global Ozone Monitoring Experiment (GOME), The SCanning Imaging Absorption SpectroMeter

1058   for Atmospheric CHartographY (SCIAMACHY), and OMI instruments have been used extensively to verify the

1059   emissions inputs and performance of the GCTM.

1060   The grid resolutions used in the studies discussed above are much coarser than those used in the air quality models

1061   for studying emission control policy issues, such as evaluating state implementation plans (SIP). SIP modeling

1062   typically utilizes over 20 vertical layers at around 4-km horizontal grid spacing to reduce uncertainties in the model

1063   predictions near the ground and around high-emission source areas including urban and industrial centers. Although

1064   Civerolo *et al.,* (2007) applied CMAQ at a higher resolution, the duration of the CMAQ simulation was far too short a

1065   time scale to evaluate the regional climate impacts in detail.

1066   One of the additional key limitations of using the CMAQ for climate change studies is that the linkages between

1067   climate and air quality and from the global scale to regional scale models are only one-way (i.e.., no feedback). Jacob

1068   and Gilliland (2005) stated that one-way assessment of the global change scenarios would be less useful for projection

1069   of air pollutant emissions because the evolution of regional air quality policies were not accounted for in these

1070   storylines. Also, to represent the interactions between atmospheric chemistry and meteorology, such as radiation and

1071   cloud/precipitation microphysics, particulates and heterogeneous chemistry, a two-way linkage must be established

1072   between the meteorology and chemistry models. An on-line modeling approach as implemented in WRF-chem is an

1073   example of such a linkage, but still there is a need to develop a link between the global and regional scales. A multi-

1074   resolution modeling system such as demonstrated by Jacobson (2001 a, b) might be necessary to address the true

1075   linkage between air pollution forcing and climate change and to provide the urban-to-global connection.

1076   In addition, there would be significant benefits to linking other multimedia models describing subsoil conditions,

1077   vegetation dynamics, hydrological processes, and ocean dynamics, including the physical/chemical interactions between

1078   the ocean micro-sublayer and atmospheric boundary layer to an air quality model. To generate such a megamodel under

1079   one computer coding structure would require handling of extremely different state variables in each multimedia model

1080   with substantially different data. Furthermore, interactions among the multimedia models need multidirectional data

1081   inputs, quality assurance checkpoints, and the decision-support entries. A more generalized on-line and two-way data

1082   exchange tools currently being developed under the Earth System Modeling Framework (ESMF)

1083   (http://www.esmf.ucar.edu/) may be a viable option.

1084   Observations not only represent the real changes in the climate but also provide a fundamental database to verify

1085   various modeling components in the DSS. The meteorological reanalysis data are available both in regional and global

1086   scales, but similar atmospheric chemistry database for air quality is lacking. An ozone database from ozonesonde

1087   system and other *in situ* measurements are useful for global scale studies. But for regional air quality studies, the

1088   availability of such measurements representing urban and local conditions in long-term is limited. Satellite or other

1089   remote sensing platform observations may provide additional data sources to build an atmospheric chemistry reanalysis

1090   database at global and regional scales, but theses observations are mainly limited to ozone and aerosols. Such chemical

1091   reanalysis database can be utilized to study long-term air quality trends; to evaluate science process components in the

1092   air quality models, emissions, and other model inputs and configurations; and to improve model predictions through

1093   data assimilation approaches.

1094

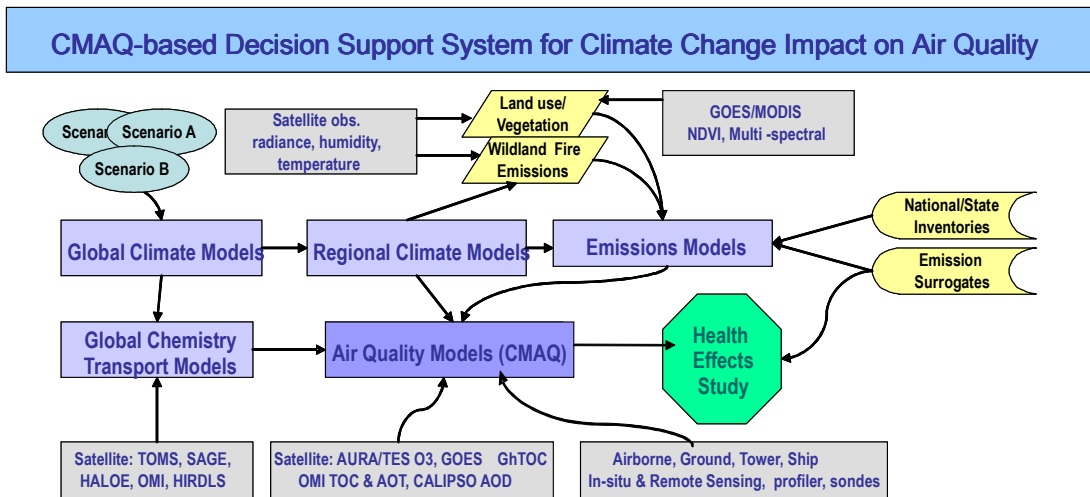1095   Figure 1. Configuration of CMAQ-based Decision Support System for climate change impact study

Figure 1. Configuration of CMAQ-based Decision Support System for climate change impact study

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1097   Table 1. Input data used for operating the CMAQ-based DSS.

Data Set	Type of Information	Source	Usage
Regional climate model output	Simulation results from a regional climate model (RCM) used as a driver for CMAQ modeling; processed through meteorology-chemistry interface processor (MCIP)	RCM modeling team; PNNL, UIUC, NCEP, EPA, and universities	Regional climate characterization, driver data for air quality simulations, and emissions processing
Land use, land cover, subsoil category, and topography data; topography for meteorological modeling	Describes land surface conditions and vegetation distribution for surface exchange processes	Various sources from USGS, NASA, NCEP EPA, states, etc.	Usually the data are associated with RCM's land surface module; need to be consistent with vegetation information, such as BELD3 if possible
Biogenic emissions land use database version 3 (BELD3)	Land use and biomass data and vegetation/tree species fractions	EPA	Processing of biogenic emissions; used to provide activity data for county-based emission estimates; now also used for land surface modeling in RCM
Air emissions inventories: national emissions inventories (NEI) and state/special	Amount and type of pollutants into the atmosphere. Includes: - Chemical or physical identity of pollutants - Geographic area covered - Institutional entities	EPA, regional program organizations (RPO), states and local government, and foreign governments	Preparation of model-ready emission inputs; perform speciation for the chemical mechanism used; used to evaluate "top-down" emissions (i.e.,

inventories; often called as "bottom-up" inventories	- Time period over which the emissions are estimated - Types of activities that cause emissions		from inversion of satellite observations though air chemistry models)
Chemical species initial and boundary conditions	Clean species concentration profiles initial input and boundary conditions used for CMAQ simulations; originally from observations from clean background locations	EPA (fixed profiles), GEOS-Chem (Harvard & Univ. Houston), MOZART (NCAR); dynamic concentrations with diurnal variations (daily, monthly or seasonal)	CMAQ simulations; fixed profiles are used for outer domains where no significant emissions sources are located
AQS/AIRNow	Near real-time (AIRNow) and archived datasets (AQS) for ozone, PM, and some toxics species	Joint partnership between EPA and state and local air quality agencies	Measurement data used for model evaluations; report and communicate national air quality conditions for

1098

1099   Table 2. An illustrative example of the potential uses of the models and upstream and downstream tools for a CMAQ-

1100   based Climate Change Impact Decision Support System.

Component	Functions	Model Name: Owner	Users
Global climate models (GCM)	Performs climate change simulations over the globe for different SRES climate scenarios. Typical resolution for a long-term (50 yearr) simulation is at 4º x 5º latitude and longitude	Community Climate Model (CCM): NCAR Goddard Institute for Space Studies (GISS) GCM: NASA CM2: Geophysical Fluid Dynamics Laboratory (GFDL) of NOAA	Climate research institutes, universities, and government institutions
Global chemistry transport models (GCTM)	Computes global scale chemical states in the atmosphere; uses same resolution as GCM	GEOS-Chem: NASA, Harvard University MOZART: NCAR (ESSL/Atmospheric Chemistry Division)	Global chemistry research organizations, universities, and government institutions
Regional climate models (RCM)	Simulates regional scale climate and meteorological conditions downscaling the GCM output; for US application ~36 km resolution used	MM5-based: NCAR, PNNL, UIUC, and others; the weather research and forecasting (WRF) model - advanced research WRF (WRF-ARW) core based: NCAR, UIUC Eta-based: NCEP (before June, 2006) The WRF- nonhydrostatic mesoscale model (WRF-NMM) core based: NCEP (after June,	Regional climate research groups, universities, and government institutions

		2006)	
Regional air quality models (AQM)	Performs air quality simulations at regional and urban scales at the same resolution as the RCM	Community multiscale air quality (CMAQ): EPA Comprehensive air quality model with extensions (CAMx): Environment WRF-Chem: NOAA/NCAR STEM-II: University of Iowa	Regional, state, and local air quality organizations; universities; private industries; and consulting companies
Downstream tools for decision support	Performs additional computations to help decision support, such as sensitivity and source apportionment studies, exposure studies	CMAQ/DDM: GIT CMAQ/4Dvar: CalTech/VT/UH Stochastic human exposure and dose simulation (SHEDS): EPA Total risk integrated methodology (TRIM): EPA	Universities and consulting companies
Upstream tools for representing climate change impacts on input data	Performs additional computations to generate model inputs that affect simulations	Land surface models SLEUTH: USGS, UC Santa Barbara (captures urban patterns) CLM (community land model): NCAR (used for RCM and biogenic emission estimates after growth)	Universities and consulting companies

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DELIVERABLE ONE: REPORT ON THE DST(S) FOR YOUR NATIONAL APPLICATIONS AREA

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Climate Change Science Program

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Uses and Limitations of Observations, Data, Forecasts, and Other Projections in

Decision Support for Selected Sectors and Regions

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Chapter 3. "Decision Support System for Assessing Hybrid Renewable Energy Systems"

1112

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1. Introduction

The national application area addressed in this chapter is the deployment of renewable energy technologies. Renewable energy technologies are being used around the world to meet local energy loads, to supplement grid-wind electricity supply, to perform mechanical work such as water pumping, to provide fuels for transportation, to provide hot water for buildings, and to support heating and cooling requirements for building energy design. Numerous organizations and research institutions around the world have developed a variety of decision-support tools to address how these technologies might perform in a most cost-effective manner to address specific applications. This chapter will focus on one specific tool, known as the Micropower Optimization Model, Hybrid Optimization Model for Electric Renewables (HOMER), that has been under consistent development and improvement at the US Department of Energy's National Renewable Energy Laboratory and is used extensively around the world.

1129

1130   HOMER relies heavily on knowledge of the renewable energy resource available to the technologies being analyzed.

1131   Renewable energy resources, particularly for solar and wind technologies, are highly dependent on weather and climate

1132   phenomena, and are also driven by local microclimatic processes. Given the absence of a sufficiently dense ground

1133   network of reliable solar and wind observations, we must rely on validated numerical models, empirical knowledge of

1134   microscale weather characteristics, and collateral (indirect) observations derived from Earth observations, such as

1135   reanalysis data and satellite-borne remote sensors, to develop reliable knowledge of the geospatial characteristics and

1136   extent of these resources. Thus, the Decision Support System (DSS) described in this chapter includes HOMER as an

1137   end-use application and is described in the context of the renewable energy resource information required as input, as

1138   well as some intermediate steps that can be taken to organize these data, using Geographic Information Systems (GIS)

1139   software, to facilitate the application of HOMER.

1140

1141

1142

1143   2a. Description of the HOMER DSS

1144

1145   The HOMER DSS described in this chapter consists of three main components: (1) the renewable energy resource

1146   information required to estimate technology performance and operational characteristics, (2) (optional) organization of

1147   the resource data into a GIS framework so that the data can be easily imported into the decision support tool, and (3)

1148   NREL's Micropower Optimization Model known as HOMER, which ingests the renewable resource data for

1149   determining the optimal mix of power technologies for meeting specified load conditions at specified locations. This

1150   section describes each of these components separately. Although climate-based Earth observational data are primarily

1151   relevant only to the first component, some related Earth observation information could also be associated with the

1152   second and even the third component. Furthermore, it will be apparent that the first component is of major importance

1153   in the successful use of the HOMER DSS.

1154

1155   Although HOMER handles a number of power technologies, we will focus our attention in this chapter on solar and

1156   wind technologies and the resources required to run these technologies.

1157

1158

1159   Solar and Wind Resource Assessments

1160

1161   The first component of the HOMER DSS is properly formatted, reliable renewable energy resource data. The significant

1162   data requirements for this component are time-dependent measurements of wind and solar resources, as well as Earth

1163   observational data and data from numerical models, to provide the necessary spatial information for these resources,

1164   which can vary significantly over relatively small distances due to local microclimatic effects. Because of this natural

1165   variability, it is necessary to examine these energy resources geospatially in order to determine optimal siting of

1166   renewable energy technologies; alternatively, if a renewable energy technology is sited at a specific site in order to meet

1167   a nearby load requirement (such as a solar home system), it is necessary to know what the resource availability is at that

1168   location, since microclimatic variability may make even nearby data sources irrelevant.

1169

1170   Examples of the products derived from the methodologies described below can be found for many areas around the

1171   world. One significant project that has recently been completed is the Solar and Wind Energy Resource Assessment

1172   (SWERA) Project, which provided high-resolution wind and solar resource maps for 13 countries around the world.

1173   SWERA was a project funded by the Global Environment Facility and was cost-shared by several technical

1174   organizations around the world: NREL; the State University of New York at Albany, the NASA's Langley Research

1175   Center, and the USGS/EROS Data Center in the U.S.; Riso National Laboratory in Denmark; the German Aerospace

1176   Institute (DLR); the Energy Resources Institute (New Delhi, India); and the Brazilian Spatial Institute (INPE) in Sao

1177   Jose dos Campos, Brazil. The United Nations Environment Programme (UNEP) managed the project. Besides the

1178   solar and wind resource maps and underlying data sets, a variety of other relevant data products came out of this

1179   program. All of the final products and data can be found on the SWERA archive, hosted at the UNEP/GRID site,

1180   collocated with the USGS/EROS data center in Sioux Falls, South Dakota (http://swera.unep.net).

1181

1182   For wind resource assessments, NREL's approach, known as Wind Resource Assessment Mapping System (WRAMS)

1183   relies on mesoscale numerical models such as MM5 or Weather Research and Forecasting (WRF), which can provide

1184   simulations of near-surface wind flow characteristics in complex terrain or where sharp temperature gradients might

1185   exist (such as land-sea contrasts). Typically, these numerical models use available weather data, such as the National

1186   Climatic Data Center's Integrated Surface Hourly (ISH) data network and National Center for Atmospheric Research-

1187   National Centers for Environmental Protection (NCAR-NCEP) reanalysis data as inputs. In coastal areas or island

1188   situations NREL's wind resource mapping also relies heavily on SeaWinds data from the Quickscat satellite to obtain

1189   near-shore and near-island wind resources. WRAMS also relies on Global Land Cover Characterization (GLCC) 1-km

1190   and Regional Gap Analysis Program (ReGAP) 200-m land cover data, as well as Moderate Resolution Imaging

1191   Spectroradiometer (MODIS) data from the Aqua and Terra Earth Observation System satellites, to obtain information

1192   such as percent of tree cover and other land use information. This information is used not only to determine roughness

1193   lengths in the numerical mesoscale models but also to screen sites suitable for both wind and solar development in the

1194   second component of the HOMER DSS.

1195

1196   The numerical models are typically run at a 2.5-km resolution. However, wind resource information is often reported at

1197   the highest resolution at which a digital elevation model (DEM) can provide. Globally this has traditionally been 1-km

1198   resolution; however, in some cases in the US 400-m DEM data are available. Furthermore, the Shuttle Radar Topology

1199   Mission has now been able to provide users with a

1200   90-m DEM for much of the world. Thus, additional steps are needed beyond the 2.5-km resolution model output to

1201   depict wind resources at the higher resolutions offered by these DEM's. This can be accomplished by using a

1202   secondary high-resolution mesoscale model, empirical methods, or both. For example, with NREL's WRAMS

1203   methodology, GISD-based empirical modeling tools have been developed to modify results from the numerical models

1204   that appear to have provided unreliable results in complex-terrain areas.

1205

1206   The numerical models generally provide outputs at multiple levels above the ground. The WRAMS methodology

1207   provides values at a single specified height above the ground, nominally 50 m, or near the hub-height of modern-day

1208   large wind turbines (although with the recent advent of larger and larger wind turbines, hub heights are approaching 100

1209   m, so this standard height designation is changing). Where measured data are used to assess wind resources, a simple

1210   "power law" relationship is used to extrapolate the measured data to the desired height (Elliott *et al.,* 1987), i.e.

1211

1212 $V_R/V_a = (Z_R/Z_a),^{\alpha}$ (1)

1213

1214   where α, the power law coefficient, is normally assumed to be 1/7, V_R is the wind speed at reference height Z_R

1215   (nominally, 50 m), and V_a is the wind speed at the measurement height Z_a.

1216

1217   The output of the WRAMS methodology is typically a value of wind power density at every grid-cell representative of

1218   an annual average (in order to produce monthly values, the procedure outlined above would have to be repeated for each

1219   month of the year). For mapping purposes, a classification scheme has been set up that relates a "wind power class" to

1220   a range of wind power densities. The classification scheme ranges from 1 to >7, and applies to a specific height above

1221   ground.   Normally, for grid-connected applications, a wind power class of 4 or above is best, while for small wind

1222   turbine applications where machines can operate in lower wind speeds, wind power class of 3 or above is suitable. Of

1223   course, the wind maps are not intended to identify sites at which large wind turbines can be installed, but rather are

1224   intended to provide information to developers on where they might most effectively install wind measurement systems

1225   for further site assessment. The maps also provide a useful tool for policy makers to obtain reliable estimates on the

1226   total wind energy potential for a region.

1227

1228   Other well-known approaches besides NREL's WRAMS methodology are also used to produce large-area wind

1229   resource mapping. For example, Riso National Laboratory calculates wind speeds within 200 m above the Earth's

1230   surface using the Karlsruhe Atmospheric Mesoscale Model (KAMM),. Although KAMM also uses NCEP/NCAR

1231   reanalysis data, the model is based on large-scale geostrophic winds, and simulations are performed for classes of

1232   different geostrophic wind. The classes are weighted with their frequency to obtain statistics for the simulated winds.

1233   The results can then be treated as similar to real observations to make wind atlas files for the Wind Atlas Analysis and

1234   Application Program (WAsP), which are employed to predict local winds at a much higher resolution than KAMM can

1235   provide. WAsP calculations are based on wind data measured or simulated at specific locations and includes a complex

1236   terrain flow model, a roughness change model, and a model for sheltering obstacles. More on WAsP can be found at

1237   http://www.wasp.dk/.

1238

1239   Due to the scarcity of high-quality, ground-based solar resource measurements, large-area solar resource assessments in

1240   the US have historically relied on the analysis of surface National Weather Service cloud cover observations. These

1241   observations are far more ubiquitous than solar measurements, and allowed NREL to develop a 1961 to 1990 National

1242   Solar Radiation Database for 239 surface sites. However, more recently in the US more and more reliance has been

1243   placed on GOES visible channel data to obtain surface reflectance information that can be used to derive high-resolution

1244   (~10-km) site-time specific solar resource data (see for example Perez, *et al.,* 2002). In fact, this approach has become

1245   commonplace in Europe, using Meteosat data. And the NASA Langley Research Center has recently completed a 20-

1246   year worldwide 100-km resolution Surface Solar Energy Data set derived from International Satellite Cloud

1247   Climatology Project data, which is derived from data collected by all of the Earth's geostationary and polar orbiting

1248   satellites (http://eosweb.larc.nasa.gov/sse).

1249

1250   The use of satellite imagery for estimating surface solar resource characteristics over large areas has been studied for

1251   some years, and Renné *et al.* (1999) published a summary of approaches developed around the world. These satellite-

1252   derived assessments require good knowledge of the aerosol optical depth over time and space, which can be obtained in

1253   part from MODIS and Advanced Very High Resolution Radiometer (AVHRR) data from polar orbiting environmental

1254   satellites. The assessments provide information both on Global Horizontal Irradiance (GHI), which is useful for

1255   estimating resources available to flat plate collectors such as photovoltaic panels or solar water heating systems, and

1256   Direct Normal Irradiance (DNI), which is needed for determining the resources available to solar concentrators that

1257   track the sun.

1258

1259   Besides NREL and NASA, other organizations perform similar types of high-resolution solar resource data sets. For

1260   example, the German Space Agency (DLR) has been applying similar methods to Meteosat data for developing solar

1261   resource maps and data for Europe and northern Africa. DLR was also involved in the SWERA project and applied

1262   their methodologies to several SWERA countries.

1263

1264

1265   Geospatial Toolkit

1266

1267   Recently, NREL has begun to format the solar and wind resource information into GIS software-compatible formats,

1268   and has incorporated this information, along with other geospatial data relevant to renewable energy development, into

1269   a Geospatial Toolkit (GsT). The GsT is a stand-alone, downloadable, and executable software package that allows the

1270   user to overlay the wind and solar data with other geospatial data sets available for the region, such as transmission

1271   lines, transportation corridors, population (load) centers, locations of power plant facilities and substations, land use and

1272   land form data, terrain data, etc. Not only can the user overlay various data sets of their choosing, there are also simple

1273   queries built into the toolkit, such as the amount of "windy" land (e.g. Class 3 and above) available within a distance of

1274   10-km of all transmission lines (minus specified exclusion areas, such as protected lands). The GsT developed at NREL

1275   makes use of the Environmental Science and Research Institute's (ESRI) MapObjects software, although other

1276   platforms, including on-line, Web-based platforms, could also be used.

1277

1278   In a sense, the GsT is a DSS, since it allows the user to manipulate resource information with other critical data relevant

1279   to the deployment of renewable energy technologies to assist decision makers in identifying and conducting preliminary

1280   assessments of possible sites for installing these systems and supporting renewable energy policy decisions. However,

1281   up to now NREL has only prepared GsT's for a few locations: the countries of Sri Lanka, Afghanistan, and Pakistan;

1282   Hebei Province in China; the state of Oaxaca in Mexico; and the state of Nevada in the US. By the time of publication

1283   of this chapter, additional toolkits may also be available. As with the resource data, all toolkits developed by NREL are

1284   available for download from NREL's Web site. Those toolkits developed under the SWERA project are also available

1285   from the SWERA Web site.

1286

1287   HOMER: NREL's Micropower Optimization Model

1288

1289   The primary decision support tool that makes up the DSS being described here is HOMER, NREL's Micropower

1290   Optimization Model. HOMER is a computer model that simplifies the task of evaluating design options for both off-

1291   grid and grid-connected power systems for remote, stand-alone, and distributed generation applications. HOMER's

1292   optimization and sensitivity analysis algorithms allow the user to evaluate the economic and technical feasibility of a

1293   large number of technology options and to account for variation in technology costs and energy resource availability.

1294   HOMER can also address system component sizing and the adequacy of the available renewable energy resource.

1295   HOMER models both conventional and renewable energy technologies:

1296   **Power sources**:

1297   • solar photovoltaic

1298   • wind turbine

1299   • run-of-river hydropower

1300   • Generator: diesel, gasoline, biogas, alternative and custom fuels, co-fired

1301   • electric utility grid

1302   • microturbine

1303   • fuel cell

1304   **Storage**:

1305   • battery bank

1306   • hydrogen

1307   **Loads**:

1308   • daily profiles with seasonal variation

1309   • deferrable (e.g., water pumping and refrigeration)

1310   • thermal (e.g., space heating and crop drying)

1311   • efficiency measures

1312

1313   In order to find the least cost combination of components that meet electrical and thermal loads, HOMER simulates

1314   thousands of system configurations, optimizes for lifecycle costs, and generates results of sensitivity analyses on most

1315   inputs. HOMER simulates the operation of each technology being examined by making energy balance calculations for

1316   each of the 8,760 hours in a year. For each hour, HOMER compares the electric and thermal load in the hour to the

1317   energy that the system can supply in that hour. For systems that include batteries or fuel-powered generators, HOMER

1318   also decides for each hour how to operate the generators and whether to charge or discharge the batteries. If the system

1319   meets the loads for the entire year, HOMER estimates the lifecycle cost of the system, accounting for the capital,

1320   replacement, operation and maintenance, and fuel and interest costs. The user can obtain screen views of hourly energy

1321   flows for each component as well as annual costs and performance summaries.

1322

1323   This and other information about HOMER are available on NREL's Web site: http://www.nrel.gov/homer/. The Web

1324   site also provides extensive examples of how HOMER is used around the world to evaluate optimized hybrid renewable

1325   power systems to meet load requirements in remote villages. Figure 1 shows a typical example of an output graphic

1326   available from HOMER.

1327

1328   In order to accomplish these tasks, HOMER requires information on the hourly renewable energy resources available to

1329   the technologies being studied. However, typically hour-by-hour wind and solar data are not available for most sites.

1330   Thus, the user is requested to provide monthly or average information on solar and wind resources; HOMER then uses

1331   an internal weather generator to provide the best estimate of a simulated hour-by-hour data set, taking into consideration

1332   diurnal variability if the user can provide an indication of what this should be. However, these approximations

1333   represent a source of uncertainty in the model. For those locations where a GsT is available, the GsT offers a

1334   mechanism for the user to easily ingest data from the toolkit into HOMER for the specific location of interest. However,

1335   since the toolkit contains only monthly solar and wind data, the limitations described above still apply. More

1336   information on the weather generator can be found in the HOMER Help files.

1337

1338   The HOMER developers have implemented various methods to facilitate access to reliable resource data that provide

1339   some of the input for simulations. For example, a direct link with the NASA SSE data site enables the user to download

1340   monthly and annual solar data from any location on Earth. The 100-km resolution NASA data have become a

1341   benchmark of solar resource information, due to the high quality of the modeling capability used to generate the data,

1342   the fact that the SSE is validated against numerous ground stations, and the fact that it is global in scope and now covers

1343   a 20-year period. However, the data set is still limited by a somewhat coarse resolution and no validation in areas where

1344   ground data do not exist. The procedures used to generate the SSE also have problems where land-ocean interfaces

1345   occur, and in snow-covered areas.

1346

1347   Linking HOMER to higher-resolution regional solar data sets would likely improve these uncertainties somewhat, but in

1348   general these data sets are also limited to monthly and seasonal values. However, since these methods rely on

1349   geostationary satellite data that provide frequent imagery of the Earth's surface, an opportunity exists to produce hourly

1350   time series data for up to several years at a 10-km resolution. This option will require significant data storage and

1351   retrieval capabilities on a server, but such a possibility now exists for future assessments.

1352

1353   Wind data available to HOMER is also generally limited to annual and at best monthly values. The standard HOMER

1354   interface allows the user to also designate a Weibull "k" value if this information is available. The Weibull k is a

1355   statistical means of defining the frequency distribution of the long-term hourly wind speeds at a location; this value can

1356   vary substantially depending on local terrain and microclimatic conditions. HOMER also has a provision for the user to

1357   designate the diurnal range of wind speeds and the timing when maximum and minimum winds occur. This

1358   information then provides improved simulation of the hour-by-hour wind values. The difficulty is that there may be

1359   applications where even these statistical values are not known to the user and are not available from the standard wind

1360   resource maps produced for a region, but this limitation may not be critical and requires further study to determine the

1361   impact on model output uncertainties.

1362

1363   2b. Access to the HOMER DSS

1364

1365   HOMER was originally developed and has always been maintained by the National Renewable Energy Laboratory.

1366   The model can be downloaded free of charge from NREL's Web site at http://www.nrel.gov/homer/default.asp. The

1367   user is required to register, and registration must be updated every six months. The Web site also contains a variety of

1368   guides for getting started and using the software.

1369

1370   Resource information required as input to HOMER is generally freely available at the Web sites of the institutions

1371   developing the data. These institutions also generally maintain and continuously update the data. For example,

1372   renewable energy resource information can be found in several places on NREL's Web site, such as http://rredc.nrel.gov

1373   or www.nrel.gov/GIS. NASA solar energy data, which can be easily input to HOMER, is available at

1374   http://eosweb.larc.nasa.gov/sse. In fact, there is a specific feature built into HOMER that automatically accesses and

1375   inputs the SSE data for the specific location that the model is analyzing. Wind and solar resource data for the 13

1376   SWERA countries can be found at http://unep.swera.net. This Web site is currently undergoing expansion and

1377   upgrading by the USGS/EROS Data Center in Sioux Falls, SD, and will eventually become a major clearing house for

1378   resource data from around the world in formats that can be readily ingested into tools such as HOMER.

1379

1380   2c. Definition of HOMER information requirements

1381

1382   The ideal input data format to HOMER is an hourly time series of wind and solar resource data covering a complete

1383   year (8,760 values). In addition, the wind data should be representative of the wind turbine hub height that is being

1384   analyzed within HOMER. Unfortunately data sets such as these are seldom available at the specific locations for which

1385   HOMER is being applied. More typically, the HOMER user will have to identify input data sets from resource maps

1386   (even within the GsT, the resource data are based on what is incorporated into the map, which, in the case of wind, may

1387   represent only a single annual value).   Because monthly and annual mean data are more typically available, HOMER

1388   has been designed to take monthly mean wind speeds (in m/s) and monthly mean solar resource values (in kw-h/m^2-

1389   day). In the case of wind, HOMER also allows for the specification of other statistical parameters related to wind speed

1390   distributions and diurnal characteristics. Furthermore, if the wind data available for input to HOMER do not represent

1391   the same height above the ground as the wind turbine's hub height being analyzed, HOMER has internal algorithms to

1392   adjust for this. The user must specify the height above the ground for which the data represent, and a power law

1393   conversion adjusts the wind speed value to the hub height of the specific wind turbine being analyzed. HOMER then

1394   utilizes an internal weather generator that takes the input information and creates an hour-by-hour data profile

1395   representing a one-year data file. Then, HOMER calculates turbine energy output by converting each hourly value to

1396   the energy production of the machine using the manufacturer's turbine power curve.

1397

1398   Besides the mean monthly wind speeds, the statistical parameters required by HOMER to generate the hourly data sets

1399   include the following:

1400

1401   • The altitude above sea level (to adjust for air density, since turbine performance is typically rated at sea level);

1402   • The Weibull k value, which typically ranges from 1.5 to 2.5, depending on terrain type;

1403   • An auto-correlation factor, which is a measure of how strongly the wind speed in 1 hour depends (on average)

1404   on the wind speed in the previous hour (these values typically range from 0.85 to 0.90);

1405   • A diurnal pattern strength, which is a measure of how strongly the wind speed depends on the time of day

1406   (values are typically 0.0 to 0.4); and

1407   • The hour of the peak wind speed (over land areas this is typically 1400 to 1600 local time)

1408

1409   In the US as elsewhere, wind resource maps often depict the resource in terms of wind power density, in units of watts-

1410   m^{-2} rather than in wind speeds. In this case, the wind power density must be converted back to a mean wind speed. The

1411   relationship between wind power density (P) and wind speed (v) is given as follows:

1412

1413 $P = \frac{1}{2}\rho \sum_i v_i^3,$ (2)

1414

1415   where ρ is the density of the air and i is the individual hourly wind observation. Since the frequency distribution of

1416   wind speed over the period of a year or so follows a Weibull distribution shape, the wind power density can be

1417   converted back to a wind speed if the "k" factor in the Weibull distribution is known, as well as the height above sea

1418   level of the site (to determine the air density).

1419

1420   2d. Access to and use of the HOMER DSS among the federal, state, and local levels

1421

1422   Because of the easy access to HOMER and to the related resource assessment data products, the HOMER DSS is freely

1423   available to all government and private entities in the US and worldwide. Thousands of users from all economic sectors

1424   are using HOMER to evaluate renewable energy technology applications, particularly for off-grid use.

1425

1426   2e. Variation of the HOMER DSS by geographic region or characteristic

1427

1428   A key feature of HOMER is the evaluation of specific renewable energy technologies and related energy systems for

1429   different regions and for different applications. The HOMER model contains information on renewable energy

1430   technology characteristics; however, these characteristics, such as power curves of difference wind turbine models,

1431   generator fuel curves, and other factors are not affected by location. Because of the location-specific dependency of

1432   resource data, use of data that is not representative of the specific region of analysis will introduce additional

1433   uncertainties in the model results. Thus, the user should evaluate the accuracy and relevancy of any default information

1434   that is built into HOMER, or any resource data chosen as input to HOMER before completing the final analyses.

1435

1436   **3. Observations used by the HOMER DSS now and of potential use in the future**

1437

1438   This section focuses on the Earth observations (of all types, from remote sensing and *in situ*) used or of potential use in

1439   the HOMER DSS.

1440

1441   3a. Kinds of observations being used

1442

1443   In the previous section we provided a description of the renewable energy resource assessment related to solar and wind

1444   technologies that are required as input to HOMER when these technologies are being modeled. As noted in that section,

1445   developing this resource information requires the use of a variety of Earth observations. In this section we list out these

1446   observations for each resource category, as well as other types of observations relevant to the HOMER DSS.

1447

1448   <u>Wind Resources</u>

1449

1450   The ideal observational platform for obtaining reliable wind resource data to be input into HOMER would be calibrated

1451   wind speed measurements from a meteorological tower installed at the location of interest. These measurements should

1452   be obtained at the hub height of the wind turbine being modeled, should be of sufficient sampling frequency to provide

1453   hourly measurements, and should be of sufficient quality and duration to result in at least one full year of continuous

1454   measurements. Although measurements of this quality are typically necessary at project sites where significant

1455   investments in large grid-connected wind turbines are anticipate, and where a decision has already been made to

1456   implement a large-scale project, it is extremely rare that this level of observation is available for most HOMER

1457   applications, where the user is examining potential applications for proposed projects. Thus, some indirect means to

1458   establish wind characteristics at a proposed site, such as extrapolating wind resource measurements available from a

1459   nearby location or developing a wind resource map such as described in Section 2, is required. The major global data

1460   sets typically used by NREL for wind resource assessment are summarized in table 1.

1461

1462   More discussion on some of these data sets is provided below.

1463

1464   <u>Surface Station Data</u>

1465

1466   In the US, as well as in most other countries, the main source of routine surface wind observations would be

1467   observations from nearby national weather stations, such as those routinely maintained to support aircraft operations at

1468   airports. These data can be made available to the user from the National Climatic Data Center (NCDC) in the form of

1469   the Integrated Surface Hourly (ISH) data set. This database is composed of worldwide surface weather observations

1470   from about 20,000 stations, collected and stored from sources such as the Automated Weather Network (AWN), the

1471   Global Telecommunications System (GTS), the Automated Surface Observing System (ASOS), and data keyed from

1472   paper forms (see, http://gcmd.nasa.gov/records/GCMD_C00532.html).

1473

1474   Satellite-Derived Ocean Wind Data

1475

1476   Ocean wind data can be obtained from the SeaWinds Scatterometer (see http://manati.orbit.nesdis.noaa.gov/quikscat/)

1477   mounted aboard NASA's Quick Scatterometer (QuickSCAT) satellite. QuickSCAT was launched on June 19, 1999 in a

1478   sun-synchronous polar orbit. A longer-term ocean winds data set is available from the Special Sensor

1479   Microwave/Imager (SSM/I) data products as part of NASA's Pathfinder Program. The SSM/I geophysical dataset

1480   consists of data derived from observations collected by SSM/I sensors carried onboard the series of Defense

1481   Meteorological Satellite Program (DMSP) polar orbiting satellites (see

1482   http://www.ssmi.com/ssmi/ssmi_description.html#ssmi). An example of how Scatterometer data were used in support

1483   of a wind resource assessment in Pakistan is provided in figure 2 (see also

1484   http://www.nrel.gov/international/rr_assess_pakistan.html). Airborne or space borne Synthetic Aperture Radar systems

1485   can also provide information on ocean wind data, although these data are not commonly used for this purpose in the US,

1486   since Scatterometer data products are more readily and freely available.

1487

1488   Reanalysis Upper Air Data

1489

1490   The US reanalysis data set was first made available in 1996 to provide gridded global upper air and vertical profiles of

1491   wind data derived from 1,800 radiosonde and pilot balloon observations stations (Kalnay, *et al.* 1997). The reanalysis

1492   data were prepared by NCAR-NCEP and can be found at http://www.cdc.noaa.gov/cdc/reanalysis/. An early analysis of

1493   the data set (Schwartz, George, and Elliott, 1999) showed that for wind resource assessments the dataset was a

1494   promising tool for gaining a more complete understanding of vertical wind profiles around the world but that

1495   discrepancies with actual radiosonde observations still existed. Since that time, continuous improvements have been

1496   made to the NCAR-NCEP dataset, and it is has become an ever-increasingly important data source for contributing to

1497   reliable wind resource mapping activities.

1498

1499   Digital Terrain Data

1500

1501   Digital Elevation Models (DEM) have been accessed from the USGS/EROS data center. These models consist of a

1502   raster grid of regularly spaced elevation values that have been derived primarily from the USGS topographic map series.

1503   The USGS no longer offers DEMs, and for the US these can now be accessed from the National Elevation Dataset

1504   (http://ned.usgs.gov/). The Shuttle Radar Topographic Mission (SRTM) offers much higher resolution terrain data sets,

1505   which are now beginning to be used in some wind mapping exercises. These are also being distributed by USGS/EROS

1506   under agreement with NASA (http://srtm.usgs.gov/).

1507

1508   Digital Land Cover Data

1509

1510   Land cover data are used to estimate roughness length parameters required for the mesoscale meteorological models

1511   used in the wind mapping process. Data from the Global Land Cover Characterization dataset provide this information

1512   at a 1-km resolution (see http://edcsns17.cr.usgs.gov/glcc/background.html). The Moderate Imaging Spectroradiometer

1513   (MODIS) is used to obtain global percent tree cover values at a spatial resolution of 0.5 km (Hansen, *et al.,* 2003).

1514   Existing natural vegetation is also being mapped at a 200-m resolution as part of the USGS Regional Gap Analysis

1515   program. Gap analysis is a scientific method for identifying the degree to which native animal species and natural

1516   communities are represented in our present-day mix of conservation lands (Jennings and Scott, 1997).

1517

1518   Solar Resources

1519

1520   As with wind, the ideal solar resource data set for incorporation into HOMER would be data derived from a quality,

1521   calibrated surface solar measurement system consisting of a pyranometer and a pyrheliometer that can provide a

1522   continuous stream of hourly data for at least one year. Such data are seldom available at the site for which HOMER is

1523   being applied. Although interpolation to nearby surface radiometer data sets can be accomplished with reasonable

1524   reliability, we usually resort to an estimation scheme to derive an *in-situ* data set. The solar resource assessments that

1525   NREL and others undertake make use of several different observational datasets, such as ground-based cloud cover

1526   measurements, satellite-derived cloud cover measurements, or the use of the visible channel from satellite imagery data.

1527   The major global data sets used for solar resource assessments are summarized in table 2.

1528

1529   More discussion on some of these data products is described below.

1530

1531   World Radiation Data Center

1532

1533   Since the early 1960s the World Radiation Data Center, located at the Main Geophysical Institute in St. Petersburg,

1534   Russia, has served as a clearinghouse for worldwide solar radiation measurements collected at national weather stations.

1535   The WRDC is under the auspices of the World Meteorological Organization. A Web-based data set was developed by

1536   NREL in collaboration with the WRDC and can be accessed at http://wrdc-mgo.nrel.gov/. This data archive covers the

1537   period 1964 to1993. For more recent data, the user should go directly to the WRDC home page at

1538   http://wrdc.mgo.rssi.ru/.

1539

1540   Aerosol Optical Depths (AOD)

1541

1542   After clouds, atmospheric aerosols have the greatest impact on the distribution and characteristics of solar resources at

1543   the Earth's surface. However, routine *in-situ* observations of this parameter have only recently begun. Consequently, a

1544   variety of surface-based and satellite-based observations are used to derive the best information possible of the temporal

1545   and spatial characteristics of the atmospheric AOD. The most prominent of the surface data sets is the AERONET

1546   (http://aeronet.gsfc.nasa.gov/), a network of automated multiwavelength sun photometers located around the world.

1547   This network also has links to other networks, where the data may be less reliable. AERONET data can be used to

1548   provide ground-truth data for different satellite sensors that have been launched on a variety of sun-synchronous

1549   orbiting platforms since the 1980s, such as the Total Ozone Mapping Spectrometer (TOMS), the Advanced Very High

1550   Resolution Radiometer (AVHRR), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Multi-Angle

1551   Imaging Spectroradiometer (MISR), the latter two mounted on NASA's Terra satellite. As noted by Gueymard (2003)

1552   determination of AOD from satellite observations is still subject to inaccuracies, particularly over land areas, due to a

1553   variety of problems such as insufficient cloud screening or interference with highly reflective surfaces. The Global

1554   Aerosol Climatology Project (GACP), established in 1998 as part of the NASA Radiation Sciences Program and the

1555   Global Energy and Water Experiment (GEWEX), has as its main objectives to analyze satellite radiance measurements

1556   and field observations in order to infer the global distribution of aerosols, their properties, and their seasonal and

1557   interannual variations and to perform advanced global and regional modeling studies of the aerosol formation,

1558   processing, and transport (http://gacp.giss.nasa.gov/).

1559   Other sources of aerosol optical depth data include the Global Ozone Chemistry Aerosol Transport (GOCART) model

1560   (http://code916.gsfc.nasa.gov/People/Chin/gocartinfo.html) which is derived from a chemical transport model. An

1561   older dataset, the Global Aerosol Dataset (GADS), which can be found at http://www.lrz-

1562   muenchen.de/~uh234an/www/radaer/gads.html, is a theoretical data set providing aerosol properties averaged in space

1563   and time on a 5^0 x 5^0 grid. (Koepke, *et al.,* 1997).

1564   Other Renewable Energy Resources

1565   Although the scope of this chapter focuses on wind and solar energy resources, it is evident that many of the Earth

1566   observation data sets listed above can apply to other renewable energy resources as well. For example, hydropower

1567   resources can be determined by analysis of high resolution DEM data, along with knowledge of the rainfall amounts

1568   over specific watersheds and the land use characteristics of these watersheds. Biomass resource assessments can be

1569   enhanced through use of MODIS data as well as other weather-related data, and through evaluation of MODIS and

1570   AVHRR data to determine the Normalized Vegetation Index (NVI).

1571   3b. Limitations on the usefulness of observations

1572

1573   In the absence of direct solar and wind resource measurements at the location for which HOMER is being applied, the

1574   observations described in Section 3a, when used in the wind and solar resource mapping techniques described in

1575   Section 2, will together provide useful approximations of the data required as input to HOMER. However, the

1576   observations all have limitations in that they do not explicitly provide direct observation of the data value required for

1577   the mapping techniques but only approximations based on the use of algorithms to convert a signal into the parameter of

1578   interest. These limitations for some of these data sets can be summarized here:

1579

1580   Surface Station Data: These are generally not available at the specific locations at which HOMER would be applied, so

1581   interpolation is required. Furthermore, they generally do not have actual solar measurements, but rather proxies for

1582   these measurements (i.e., cloud cover). The wind data are generally collected at 10 m above the ground or less, and the

1583   anemometer may not be in a well-exposed condition. When the station observations are derived from human

1584   observations, they represent samples of a few minutes duration every 1 or 3 hours; therefore, many of the observations

1585   are missing. For those stations that have switched from human observations to Automated Surface Observation Stations

1586   (ASOS), the means of observation have changed significantly from the human observations, representing a

1587   discontinuity in long-term records. Occasionally, the location of the station is changed without changing the station ID

1588   number, which can also cause a discontinuity in observations. Similarly, equipment changes can cause a discontinuity in

1589   observations

1590

1591   Satellite-Derived Ocean Wind Data: These data are not based on direct observation of the wind speed at

1592   10 m above the ocean surface, but rather from an algorithm that infers wind speeds based on the wave height

1593   observations provided by the scatterometers or Synthetic Aperture Radar

1594

1595   Satellite-Derived Cloud Cover and Solar Radiation Data: These data sets are derived from observations of the

1596   reflectance of the solar radiation from the Earth-atmosphere system. Although it could be argued that this method does

1597   provide a direct observation of clouds, the solar radiation values are determined from an algorithm that converts

1598   knowledge of the reflectance observation, the incoming solar radiation at the top of the atmosphere, and the

1599   transmissivity characteristics of the atmosphere to develop estimates of solar radiation.

1600

1601   Aerosol Optical Depth: Considerable research is underway to improve the algorithms used to convert multi-spectral

1602   imagery of the Earth's surface to aerosol optical depth. The satellite-derived methods have additional shortcomings

1603   over land surfaces, where irregular land-surface features make application of the algorithms complicated and uncertain.

1604

1605

1606   3c. Reliability of the observations

1607

1608   For those observations that provide inputs to the solar and wind resource data, their reliability can vary from parameter

1609   to parameter. Generally all of the observations used to produce data values required for solar and wind assessments

1610   have undergone rigorous testing, evaluation, and validation. This research has been undertaken by a variety of

1611   institutions, including the institutions gathering the observations (e.g., NASA and NOAA) as well as the institutions

1612   incorporating the observations into resource mapping techniques (e.g., NREL). Many of the satellite-derived

1613   observations of critical parameters will be less reliable than *in-situ* observations; however, satellite-derived observations

1614   must still be used due to the scarcity of *in-situ* measurement stations.

1615

1616   3d. What kinds of observations could be useful in the near future

1617

1618   All of the observations currently available will continue to be of critical value in the near future. For renewable energy

1619   resource mapping, improved observations of key weather parameters (wind speed and direction at various heights above

1620   the ground and over the open oceans at higher and higher spatial resolutions, improved ways of differentiating snow

1621   cover and bright reflecting surfaces from clouds, etc.) will always be of value to the renewable energy community.

1622   New, more accurate methods of related parameters such as aerosol optical depth would result in improvements in the

1623   resource data. All of these steps will lead to improvements in the quality of outputs from renewable energy decision

1624   support tools such as HOMER.

1625

1626   **4. Uncertainty**

1627

1628   Application of the HOMER DSS involves a variety of input data types, all of which can have a level of uncertainty

1629   attached to them. HOMER addresses uncertainties by allowing the user to perform sensitivity analyses for any

1630   particular input variable or combination of variables. HOMER repeats its optimization process for each value of that

1631   variable and provides displays to allow the user to see how results are affected. An input variable for which the user has

1632   specified multiple values is called a sensitivity variable, and users can define as many of these variables as they wish.

1633   In HOMER, a "one-dimensional" sensitivity analysis is done if there is a single sensitivity variable, such as the mean

1634   monthly wind speed. If there are two or more sensitivity variables, the sensitivity analysis is "two" or "multi-

1635   dimensional." HOMER has powerful graphical capabilities to allow the user to examine the results of sensitivity

1636   analyses of two or more dimensions. This is important for the decision maker, who must factor in the uncertainties of

1637   input variables in order to make a final judgment on the outputs of the model.

1638

1639   The amount of uncertainty associated with resource data is largely dependent on how the data are obtained and on the

1640   nature of the analysis being undertaken. For some types of analyses, very rough estimates of the wind resource would

1641   be sufficient; for others, detailed hourly average data based on surface measurements would be necessary. Quality *in-*

1642   *situ* measurements of wind and solar data in formats suitable for renewable energy applications over a sufficient period

1643   of time (one year or more) can have uncertainties of less than ±3% of the true value. However, when estimation

1644   methods are required, such as the use of Earth observations and modeling and empirical techniques, uncertainties can be

1645   as much as ±10% or more. These uncertainties are highest for shorter-term data sets, and are lower when annual

1646   average values are being used, since throughout the year errors in the estimation methods have a tendency to

1647   compensate among the individual values.

1648

1649   Based on wind turbine and solar technology operating characteristics, it is possible that the error in estimating a

1650   renewable energy system performance over a year is roughly linear to the error in the input resource data. For example,

1651   for wind energy systems, even though the power of the wind available to a wind turbine is a function of the cube of the

1652   wind speed, it turns out that the turbine operating characteristics, where turbines typically do not provide any power at

1653   all until a certain threshold speed is reached, and then the power output increases linearly with wind speed until the

1654   winds are so high that the turbine must shut down. This results in an annual turbine power output that is roughly linear

1655   to the mean annual wind speed for certain mean wind speed rangers. This would mean that, in some cases, an

1656 uncertainty in the annual wind or solar resource of ±10% results in an uncertainty of expected renewable energy

1657 technology output of approximately ±10%.

1658

1659

1660 **5. Global change information and the HOMER DSS**

1661

1662 This section expands the discussion of the HOMER DSS to include the relationship of HOMER and its input data

1663 requirements with global change information

1664

1665 5a. Reliance of HOMER DSS global change information

1666

1667 As shown in the previous section, a number of observations that provide information on global change are also used in

1668 either direct or indirect ways as input to HOMER. These observations related primarily to the renewable energy

1669 resource information that is required for HOMER applications. Renewable energy system performance is highly

1670 dependent on the local energy resources available to the technologies. The extent and characteristics of these resources

1671 is driven by weather and local climate conditions, which happens to be the primary area in which Earth observational

1672 systems monitoring climate change are addressing. Thus, as users seek access to observations to support renewable

1673 energy resource assessments, they will invariably be seeking certain global change observational data.

1674

1675 Specifically, users will be seeking global change data related to atmospheric properties that support the assessment of

1676 solar and wind energy resources, such as wind and solar data, and atmospheric parameters important for estimating

1677 these data. For example, major data sets used in solar and wind energy assessments include long-term reanalysis data,

1678 climatological surface weather observations, and a variety of satellite observations from both active and passive

1679 onboard remote sensors.

1680

1681 Key factors in affecting the choice of these observational data are their relevance to conducting reliable solar and wind

1682 energy resource assessment, their ease of access, and low or no cost to the user. The extensive list of observational data

1683   being used in the assessment of renewable energy resources represents strong leveraging of major, taxpayer-supported

1684   observational programs that are geared primarily for global change assessment.

1685

1686   There is also an important consideration regarding the potential influence of long-term climate change on the renewable

1687   energy resources that are used as input into HOMER. Through the Intergovernmental Panel on Climate Change there

1688   has been a significant improvement in the reliability and spatial resolution of General Circulation Models (GCM) used

1689   to estimate the impacts of greenhouse gas emissions on climate change. As weather patterns change under changing

1690   climate conditions, wind and solar energy resources at a specific location can also change over time. The GCM results

1691   indicate that these renewable energy resources can be measurably different 50 to 100 years from now than today in

1692   specific locations and regions. These changes may have a noticeable impact on the results of HOMER simulations in

1693   the future; however, significant uncertainties exist in GCM results. Until these uncertainties are reduced sufficiently,

1694   implementation of GCM results will produce unreliable HOMER simulations.

1695

1696   5b. How the HOMER DSS can support climate-related management decision-making among US government agencies

1697

1698   Although HOMER was not intentionally designed to be a climate-related management decision-making tool, the

1699   HOMER DSS has attributes that can support these decisions. For example, as we explore mechanisms for mitigating

1700   the growth of carbon emissions in the atmosphere, the HOMER DSS can be deployed to evaluate how renewable energy

1701   systems can be used cost-effectively to displace energy systems dependent on fossil fuels. Clearly, the science results

1702   and global change data and information products coming out of our reanalysis and satellite-borne programs are of

1703   critical importance to HOMER for supporting this decision-making process. Given that the pertinent observational data

1704   sets have been developed primarily by federal agencies, these data sets tend to be freely available or available at a

1705   relatively small cost, given the costs involved in making the observations in the first place. However, as we have noted

1706   in previous sections, the use of global change observations as input to the resource assessment data required by

1707   HOMER is not the optimal choice of data; ideally, *in-situ* (site-specific) measurements of wind and solar data relevant

1708   to the technologies being analyzed would be the most useful and accurate data to have for HOMER, if they were

1709   available.

1710   Figure 1: Example of HOMER output graphic. The column on the left provides a diagram showing the load

1711   characteristics and the types of equipment considered to meet the load. The optimal system design graphic shows the

1712   range within specified diesel fuel prices and wind energy resources for which various system types are most economical

1713   (e.g., a wind/diesel/battery system becomes the most optimal configuration to meet the load requirement for wind

1714   speeds greater than 5 m/s and fuel costs at 0.45 to 0.75$/l.

1715
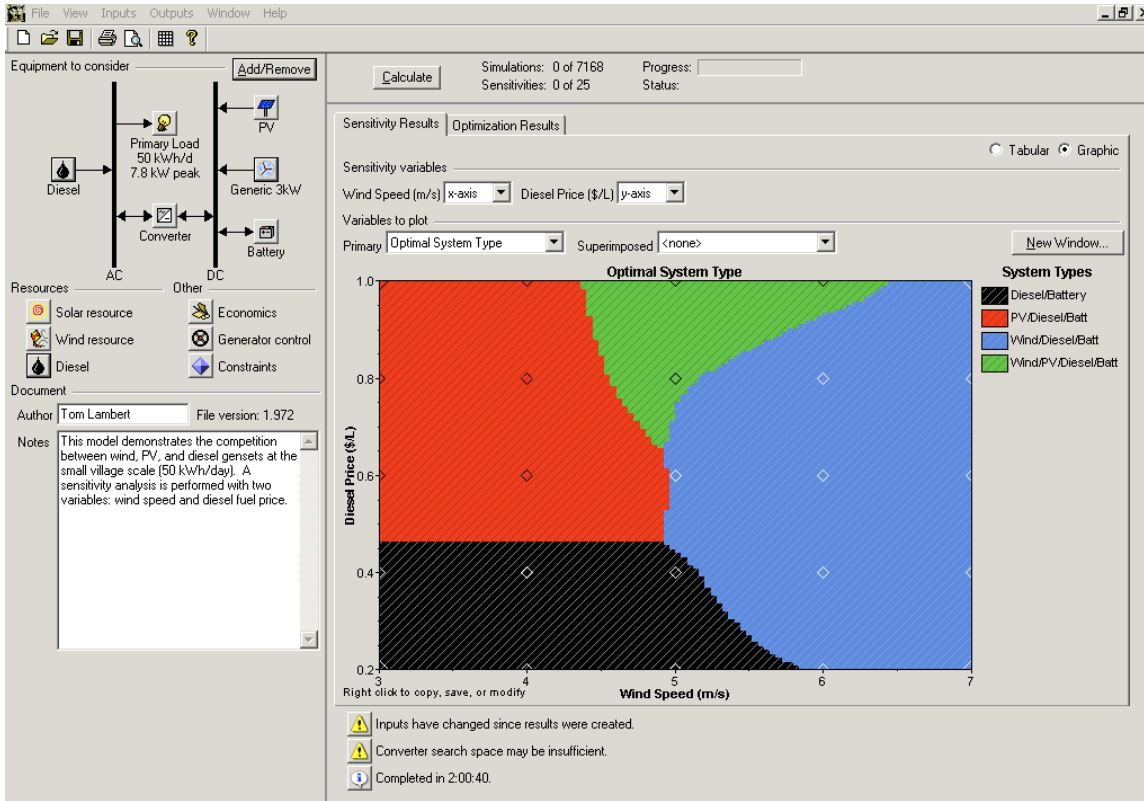
1716

1717

1718   Figure 2. Example of ocean wind resource assessment output for the offshore regions of Pakistan. These data were

1719   derived from the SeaWinds scatterometer aboard NASA's QuickSCAT satellite. The assessment provides estimated

1720   mean annual wind speeds at 10-m above the ocean surface, averaged over the period 1988 to 2002.

1721

1722

Pakistan Wind Speed (m/s) – 1988 to 2002
0.25°Grid   PRODUCT 109 SSMI   SatCode 63
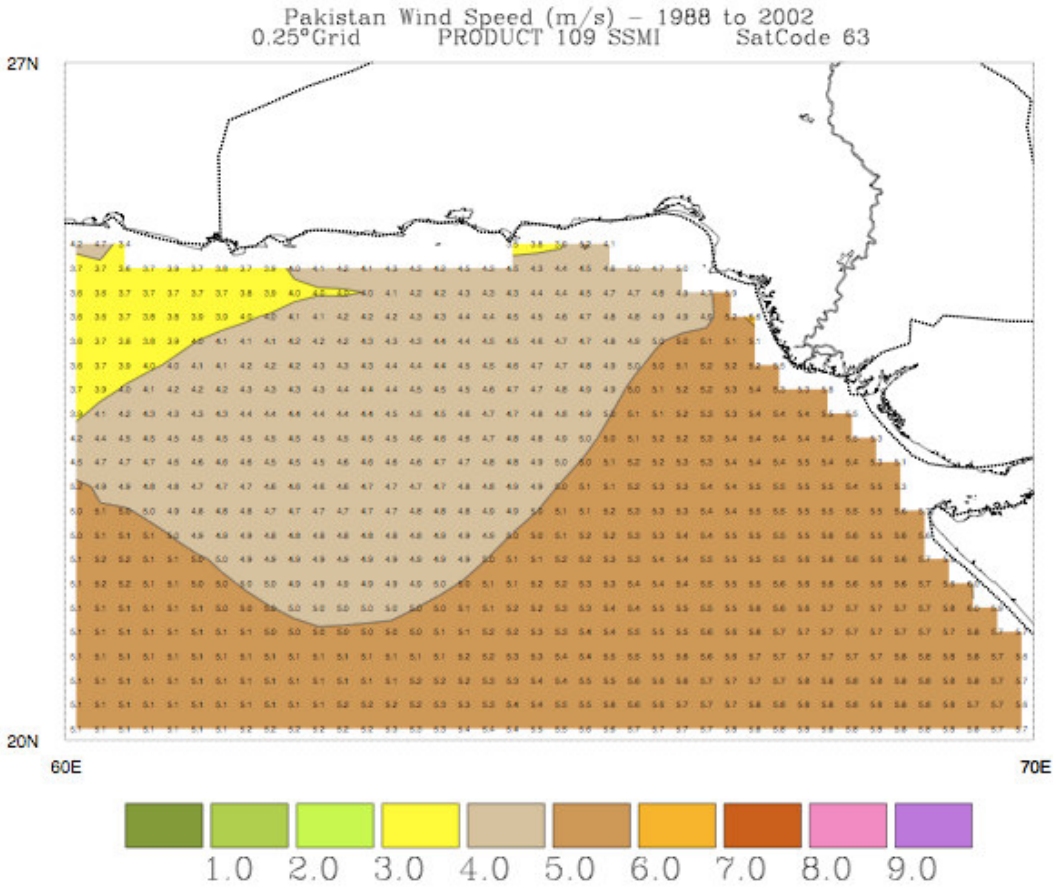
1723

1724   Table 1: Major Global Data Sets Used by NREL for Wind Resource Assessment

1725

Data Set	Type of Information	Source	Period of Record
Surface station data	Surface observations from more than 20,000 stations worldwide	NOAA/NCDC	Variable up to 2006
Upper air station data	Rawinsonde and pibal observations at 1,800 stations	NCAR	1973–2005
Satellite-derived ocean wind data	Wind speeds at 10 m above the ocean surface gridded to 0.25^0	NASA/JPL	1988–2006
Marine climatic atlas of the world	Gridded (1.0^0) statistics of historical ship wind observations	NOAA/NCDC	1854–1969
Reanalysis upper air data	Model-derived gridded (~200-km) upper air data	NCAR-NCEP	1958–2005
Global upper air climatic atlas	Model-derived gridded (2.5^0) upper air statistics	NOAA/NCDC	1980–1991
Digital geographic data	Political, hydrograph, etc.	ESRI	N/A
Digital terrain data	Elevation at 1-km spatial resolution	USGS/EROS	N/A
Digital land cover data	Land use/cover and tree cover density at 0.5-km resolution	NASA/USGS	N/A

1726

1727   Table 2: Major global data sets used for solar resource assessments

1728

1729

Data Set	Type of Information	Source	Period of Record
Surface station data	Surface cloud observations from more than 20,000 stations worldwide	NOAA/NCDC	Variable up to 2006
World Radiation Data Center	Surface radiation observations from over 1,000 stations worldwide	WRDC, St. Petersburg	1964–1993
Satellite imagers	Imagery from the visible channel of geostationary weather satellites, 1-km resolution	NASA/NOAA	1997– present
International Satellite Cloud Climatology Project	Used in the 1^0 global surface solar energy meteorological data set	NASA/SSE	1983–2003
AERONET	Observations of aerosol optical depth from around the world	NASA/Goddard	Variable depending on station
GACP	Aerosol optical depths (generally over oceans) at 1^0 x 1^0 from AVHRR data	NASA	1981–2005
MODIS, MISR, TOMS	Aerosol optical depth	NASA	Variable since

			1980s
GOCART	Aerosol optical depth for turbid areas	NASA	March 30-May 3, 2001
GADS	Aerosol optical depth derived from theoretical calculations and proxies		Compilation of Measurements & Models
Digital geographic data	Political, hydrography, etc.	ESRI	N/A
Digital terrain data	Elevation at 1-km spatial resolution	USGS/EROS	N/A
Digital land cover data	Land use/cover and tree cover density at 0.5-km resolution	NASA/USGS	N/A

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Chapter 4

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Decision Support for Public Health

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1. **Introduction**

Public health is an approach to protect and improve the health of community members by preventive

medicine, health education, control of communicable diseases, application of sanitary measures, and

monitoring of environmental hazards (http://www.answers.com/topic/public-health?cat=health). This overall

task is achieved by assessing and monitoring populations at risk to identify health problems and establishing

priorities, to formulate policies to solve identified problems and to ensure populations have access to

appropriate care, including health promotion, disease prevention, and evaluation of care. During the past

century, the notable public health achievements as identified by the US Centers for Disease Control and

Prevention (CDC) include vaccinations and treatments against infectious diseases, injury prevention strategies,

reduced occupational exposures to toxins, improved food and water safety, decreases in childhood and

maternal mortality, and safer water sources. Thus, many of the key issues related to public health are

incorporated in previous chapters in this report, though they may not be characterized as public health.

Regardless, public health may represent a key factor in problem solving under climate change situations.

Many of the anticipated public health consequences of climate change are due to the influences of temperature

and precipitation patterns, as well as land cover with consequences for the affected human communities. For

example, changes in the availability of food resources and the quality of drinking water are anticipated to

directly affect nutritional status, the spread of communicable infectious agents, and the impacts of poor air

quality on vulnerable populations and in extreme situations the creation of "environmental refugees"

(Huntingford *et al.,* 2007).

1758   Because public health is an important outcome component of decision support tools (DST) involving air

1759   quality, water management, energy management and agricultural efficiency issues, it was decided to focus on a

1760   unique public health aspect of DST/DSS by examining infectious disease systems. Infectious diseases remain

1761   a significant burden to populations both globally, as well as within the US. Some of these, such as syphilis and

1762   measles involve a relatively simple dynamic of the human host population and the parasite—be it a virus,

1763   bacterium, or other micro-organism. These diseases, therefore, tend to be influenced by social behavior and

1764   the ability to provide resources and of health education to significantly alter human behavior. However, other

1765   disease systems include additional species for their successful transmission—either wildlife species that

1766   maintain the micro-organism (zoonoses) or there are insect or arthropod vectors that serve to transmit the

1767   parasites either among people or from the wildlife to people (vector-borne diseases).

1768   Some of the most significant diseases globally are vector-borne or zoonotic diseases. Examples include

1769   malaria and dengue. In addition, many newly recognized (i.e., emerging) diseases either are zoonoses, such as

1770   SARS, or appear to have been derived from zoonoses that became established in human populations (e.g.,

1771   HIV). Changes in rates of contact between component populations of these disease systems alter the rates of

1772   infectious disease (Glass 2007). Many of these changes come about through activities involving the movement

1773   of human populations into areas where these pathogen systems normally occur or they can occur because

1774   people introduce materials with infectious agents into areas where they were not known previously (Gubler et

1775   al. 2001). The introduction of West Nile virus from its endemic area in Africa, the Middle East, and Eastern

1776   Europe into North America and its subsequent spread across the continent is a recent example. The impacts of

1777   the virus on wildlife, human, and agricultural production are an excellent example of the economic

1778   consequence of such emergent disease systems.

1779   More recently, attention has focused on the potential impact that climate change could have on

1780   infectious disease systems, especially those with vector or zoonotic components (e.g., Gubler *et al.,* 2001).

1781   Alterations in climate could impact the abundances or interactions of vector and reservoir populations, or the

1782   way in which human populations interact with them (Gubler, 2004). In addition, there is speculation that

1783   climate change will alter the locations where disease systems are established, shifting the human population

1784   that is at risk from these infectious diseases (e.g., Brownstein *et al.,* 2005a; Fox, 2007)

1785   Unlike many of the other applications in this report where Earth observations and modeling are of

1786   growing importance, the use of Earth observations by the public health community has been sporadic and

1787   incomplete. Although early demonstrations showed their utility for identifying locations and times that vector-

1788   borne diseases were likely to occur (e.g., Linthicum *et al.,* 1987; Beck *et al.,*1997), growth of their application

1789   has been comparatively slow. Details of the barriers to implementation include the need to "scavenge" data

1790   from Earth observation platforms, as none of these are designed for monitoring disease risk. This is not an

1791   insurmountable problem and in fact, only few applications for Earth observations have dedicated sensors.

1792   However, disease monitoring requires a long history of recorded data to provide information concerning the

1793   changes in population distribution and the environmental conditions associated with outbreaks of disease.

1794   Detailed spectral and spatial data need to be of sufficient resolution and the frequency of observations must be

1795   high enough to enable identification of changing conditions (Glass 2007). As a consequence, many DSTs

1796   undergoing development have substantial integration of Earth observations but lack an end-to-end public

1797   health outcome, particularly when focusing on infectious diseases. Therefore, the Decision Support System to

1798   Prevent Lyme Disease (DDSPL) supported by the CDC and Yale University was selected to demonstrate the

1799   potential utility of these systems within the context of climate change science. Lyme disease is a vector-borne,

1800   zoonotic bacterial disease. In the US it is caused by the spirochete, *Borrelia burgdorferi,* and it is the most

1801   common vector-borne disease with tens of thousands of reported cases annually (Piesman and Gern 2004).

1802   Most human cases occur in the Eastern and upper Mid-West portions of the US, although there is a secondary

1803   focus along the West Coast of the country. In the primary focus, the black-legged tick (or deer tick), of the

1804   genus *Ixodes,* is most often found infected with *B. burgdorferi.*

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1807   **2.   Description of DDSPL**

1808   The diverse ways in which Lyme disease presents itself in different people has made it a public health

1809   challenge to ensure that proper priorities are established, to formulate policies to solve the problem, and to

1810   ensure that populations have access to appropriate care. The CDC uses DDSPL to address questions related to

1811   the likely distribution of Lyme disease east of the 100th meridian, where most cases occur (Brownstein *et al.,*

1812   2003). This is done by identifying the likely geographic distribution of the primary tick vector (the black-

1813   legged) tick in this region. DDSPL uses field reports of the known distribution of collected tick vectors, as

1814   well as sites with repeated sampling without ticks as the outcome space. DDSPL uses satellite data, and

1815   derived products such as land cover characteristics, and census boundary files and meteorological data files to

1816   identify the best statistical predictor of the presence of black-legged ticks within the region. Land cover is

1817   derived from multi-date Landsat TM imagery and 10-m panchromatic imagery.

1818   DDSPL combines the satellite and climate data with the field survey data of *Ixodes* ticks sampled at

1819   locally sampled sites throughout the region (Brownstein *et al.,* 2003) or from rates of reported cases of Lyme

1820   disease (Brownstein *et al.,*2005b) in spatially explicit statistical models to generate assessment products of the

1821   distribution of the tick vector or human disease risk, respectively. These models are validated by field surveys

1822   in additional areas and the sensitivity and specificity of the results determined (figure 1). Thus, the DDSPL is

1823   primarily a DST for prioritizing the likely geographic extent of the primary vector of Lyme disease in this

1824   region (figures 1 and 2). It currently stops short of characterizing the risk of disease in the human population

1825   but is intended to delimit the area within which Lyme disease (and other diseases caused by additional

1826   pathogens carried by the ticks) might occur (Figure 2). Researchers at Yale University are responsible for

1827   developing and validating appropriate analytical methods to develop interpretations that can deal with many of

1828   the challenges of spatially structured data, as well as the acquisition of Earth science data that are used for

1829   model DDSPL predictions. The distinction between the presence/abundance of the tick vector and actual

1830   human risk relies on the effects of human population abundance and behavioral heterogeneity (e.g., work or

1831   recreational activity) that can alter the contact rate between the tick vector and susceptible humans. However,

1832   such detailed human studies (especially behavioral heterogeneity) are typically not available (Malouin *et al.,*

1833   2003). In Brownstein *et al.* (2005b) analysis, they found that although the entomological risk (the abundance

1834   of infected ticks) increased with landscape fragmentation, the human incidence of Lyme disease decreased,

1835   thus indicating there is a complex relationship between the landscape, the population of ticks, and the human

1836   response resulting in the health outcome.

1837

1838   **3.   Potential Future Use and Limits**

1839   Future use of DDSPL depends to a great extent on public health policy decisions exterior to the DST. The

1840   perspective of the role that Lyme disease prevention rather than treatment of diseased individuals will play is a

1841   key aspect of the importance that DDSPL will experience. For example, studies have shown that even in Lyme

1842   disease endemic regions, risk communication often fails to reduce the likelihood of infection (Malouin, *et al.,*

1843   2003). In principle, policy makers may decide that it is more cost effective to provide improved treatment

1844   modalities rather than investing in educational programs that fail to reduce disease burden. Alternatively, the

1845   development of vaccines is time consuming, costly, and may have additional risks of unacceptable side effects

1846   that affect the likelihood that this would be a policy choice. Thus, depending on policy decisions and the

1847   effects of alternative interventions, the DDSPL might be used to forecast risk areas for educational

1848   interventions, to inform health care providers in making diagnoses, or to plan mass vaccination campaigns.

1849   Currently, the removal of the licensed Lyme disease vaccine from the general public has eliminated this as

1850   a strategy to reduce the disease burden. The apparent lack of impact of targeted education also makes this a

1851   less likely strategy. Thus, the extent to which treatment modalities rather than prevention of infection will drive

1852   the public health response in the near future will play a major role in the use of DDSPL. However, even if the

1853   decision is made to focus on treatment of potentially infected individuals, DDSPL may still be useful by

1854   identifying regions where disease risk may be low, helping health care workers to focus clinical diagnoses on

1855   alternate causes.

1856   Presuming that the DST continues to be used, the need for alternative/improved Earth science data to

1857   clarify environmental data for DDSPL such as land cover, temperature, and moisture regimes is currently

1858   uncertain. The present system reports a sensitivity of 88 percent and specificity of 89 percent—generally

1859   considered a highly satisfactory result. Sensitivity and specificity are considered the two primary measures of a

1860   method's validity in public health analyses. Sensitivity in the DDSPL model refers the to expected proportion

1861   of times (88 percent) that ticks would be found when field surveys were conducted at sites that the DDSPL

1862   predicted they should occur. Specificity refers to the proportion of times (89 percent) that a survey would not

1863   be able to find times at sites where the DDSPL excluded them from occurring. These two measures provide an

1864   estimate of the "confidence" the user can have in the DST prediction (Selvin 1991). These analyses extended

1865   geographically from the East Coast to the 100th meridian and were validated by field sampling for the presence

1866   of *Ixodes* ticks at sites throughout the region.

1867   Typically, patterns of weather regimes appear to have a greater impact on distribution than more

1868   detailed information on land cover patterns. However, some studies indicate that fragmentation of forest cover

1869   and landscape distribution at fairly fine spatial resolution can substantially alter patterns of human disease risk

1870   (Brownstein *et al.,* 2005b). These results also suggest that human incidence of disease may, in some areas of

1871   high transmission, be decoupled from the model constructed for vector abundance, reemphasizing the

1872   distinction between a key component (the vector) and actual human risk. When coupled with the stated

1873   accuracy of the DDSPL in identifying vector distribution, this would suggest that future efforts will probably

1874   require an additional model structure that includes sociological/behavioral factors of the human population that

1875   puts it at varying degrees of risk. An additional limit of the DDSPL is that it does not explicitly incorporate

1876   human health outcomes in its analyses. In part, this reflects a public health infrastructure issue that limits

1877   detailed information on the distribution of human disease to (typically) local and state health agencies. For

1878   example, confidentiality of health records, including detailed locational data, such as home addresses, are often

1879   shielded in the absence of explicit permission. This makes establishing the relationship between monitored

1880   environmental conditions and human health outcomes difficult. One solution is to aggregate data to some

1881   jurisdictional level. However, this produces the well know "ecological fallacy" in establishing relationships

1882   between environmental factors and health outcomes (Selvin 1991). With appropriate planning or the

1883   movement of the technology into local public health agencies, these challenges could be overcome. Some

1884   localized data (e.g., Brownstein *et al.,* 2005b) of human health outcomes have been used to evaluate the utility

1885   of DDSPL and indicate that there is good potential for the DSS to provide important information on local risk

1886   factors.

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1889   **4.   Uncertainty**

1890   Uncertainty in decision making from DDSPL is based on the results of statistical analyses in which

1891   standard statistical models with spatially explicit components, such as autologistic intercepts of logistic

1892   models, are used to account for spatial autocorrelation in outcomes. The statistical analyses are well-supported

1893   theoretically. Typical calibration approaches involve model construction followed by in-field validation.

1894   Accuracy of classification is then assessed in a sensitivity-specificity paradigm.

1895   However, little attention is paid in the current model to assessing uncertainty in the environmental data

1896   obtained from remotely sensed (or even *in situ*) monitors of the environment. For example, most of the

1897   derivative data, such as land cover, may change with population growth and development. In addition, the use

1898   of average environmental conditions provide an approximate characterization of local edaphic conditions that

1899   may affect the abundance of the the tick vectors.

1900   Whether these are the primary sources of "error" in the sensitivity and specificity results (although these

1901   are considered excellent results) of the DDSPL is not addressed and is an area the public health applications

1902   need to consider in future applications. Alternatively, there are biological reasons for the errors in the model,

1903   including the interaction of climatic factors and tick activity that may be responsible for sites predicted to have

1904   ticks that were not found to have them. To resolve some of the biological/environmental issues, validation is

1905   ongoing.

1906   There also are a number of public health issues that affect the certainty of the DDSPL (and any DST)

1907   that are extrinsic to the system or tool. Accuracy in clinical diagnoses (both false positives and negatives), as

1908   well as reporting accuracy can affect the evaluation of the tool's utility. Currently, this is an issue of serious

1909   contention and forms part of the rationale for focusing on accurately identifying the distribution of the primary

1910   tick vector, as an integral step in delimiting the distribution of the disease and evaluating needs for the

1911   community.

1912

1913   **5.   Global Change Information and DDSPL**

1914   The relationship between climate and public health outcomes is complex. It is affected both by the

1915   direction and strength of the relationship between climatic variability and the component populations that make

1916   up a disease system, as well as the human response to changes in disease risk (Gubler 2004).

1917   The DDSPL is one of the few public health DSTs that has explicitly evaluated the potential impact of

1918   climate change scenarios on this infectious disease system. Assuming that evolutionary responses of the black-

1919   legged tick, *B. burgdoferi* and the reservoir zoonotic species remains little changed under rapid climate change,

1920   Brownstein *et al.,* (2005a) evaluated anticipated changes in the distribution and extent of disease risk.

1921   This analysis used the basic climate-land cover suitability model developed for DDSPL and selected the

1922   Canadian Global Coupled Model (CGCM1) under two historically forced integrations. The first with a 1

1923   percent per year increase in greenhouse gas emissions and the second with greenhouse gas and sulfate aerosol

1924   changes, resulted in a 4.9 and 3.8° Celsius increase in global mean temperature by the year 2080. Near (2020),

1925   mid (2050) and farpoint (2080) outcomes were evaluated (Figure 3). The choice of CGCM1 was based on the

1926   Intergovernmental Panel on Climate Change criteria for vintage, resolution, and validity (Brownstein *et al.,*

1927   2005a).

1928   Extrapolation of the analyses suggest that the tick vector will experience a significant range expansion

1929   into Canada but will also experience a likely loss of habitat range in the current southern portion of its range

1930   (figure 3). This loss of range is thought to be due to impact of increased temperatures causing decreased

1931   survival in ticks when they are off their feeding hosts. It also is anticipated that its range will shift in the central

1932   region of North America – where it is currently absent. When coupled with the anticipated continued human

1933   movement to more southern portions of the country, the numbers of human cases are expected to show an

1934   overall small decrease.

1935   These long-range forecasts disguise a more dynamic process with ranges initially decreasing during near

1936   and mid-term timeframes. This range reduction is later reversed in the long-term producing the overall pattern

1937   described by the authors. The impact in range distribution also produces an overall decrease in human disease

1938   risk as suitable areas move from areas of primary human concentration to areas that are anticipated to be less

1939   well populated.

1940   Thus, DSS similar to those developed for Lyme disease have the potential for providing both near- and

1941   far-term forecasts of potential infectious disease risk that are so important for public health planning. In

1942   addition, detailed studies (e.g. Brownstein *et al.,* 2005b) provide public health agencies with important

1943   information on drivers of human risk that have been difficult to obtain by other means. As a consequence,

1944   DSS using remotely sensed data sources either in part or whole have the potential to significantly improve the

1945   health of communities.

1946   The primary challenges for the Earth science community involve understanding the needs of the public

1947   health community for the appropriate data at the appropriate spatial, temporal, and spectral scales. This will

1948   involve understanding a historically entrenched set of methodologies for interpreting health data and

1949   establishing causal relationships between inputs (environmental data) and outputs (health outcomes). In

1950   addition, there is the challenge of performing these tasks in the presence of limited resources for a community

1951   that has little cultural understanding of both the strengths and limitations of the data derived from these
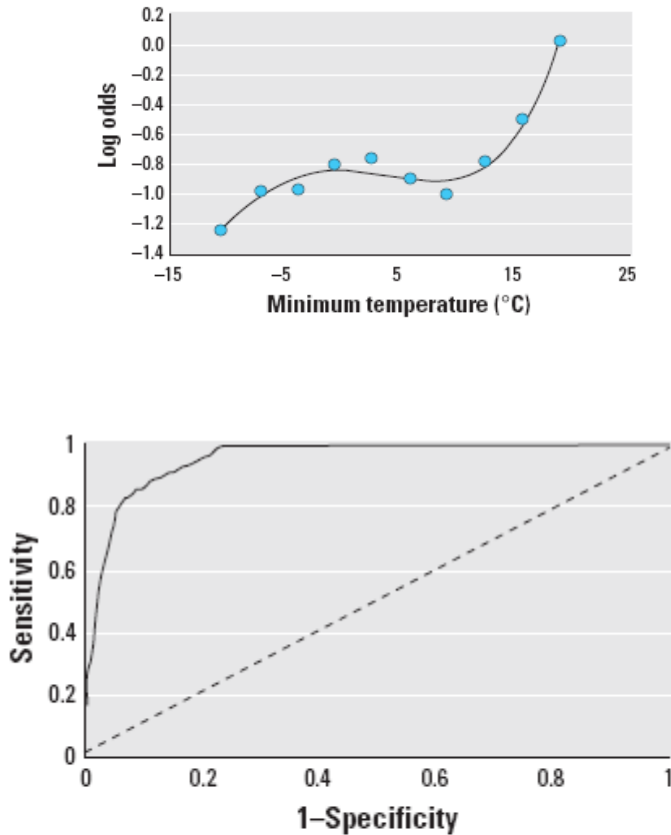
1952   sources.

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Figure 1. Relationship between the occurrence of black-legged tick presence at a site and minimum temperature (top) and evaluation of model (bottom). From Brownstein et al. 2003 Env. Hlth Perspect. **Top Panel:** Log odds plot for relationship between *I. Scapularis* population maintenance and minimum temperature (T). Minimum temperature showed a strong positive association with odds of an established *I. Scapularis* population. According to good-ness of fit testing, the relationship was fit best by a fourth order polynomial regression ($R^2 = 0.97$) Log odds = $0.0000067^4 + 0.00027^3 - 0.0027T^2 + 0.0002T - 0.8412$.
Bottom Panel: ROC Plot describing the accuracy of the auto logistic model. This method graphs sensitivity versus 1-specificity over all possible cutoff probabilities. The AUC is a measure of overall fit, where 0.5 {a 1:1 line} indicates a chance performance {dashed line}. The plot for the auto logistic model significantly outperformed the chance model with an accuracy of 0.95 {p<0.00005}.

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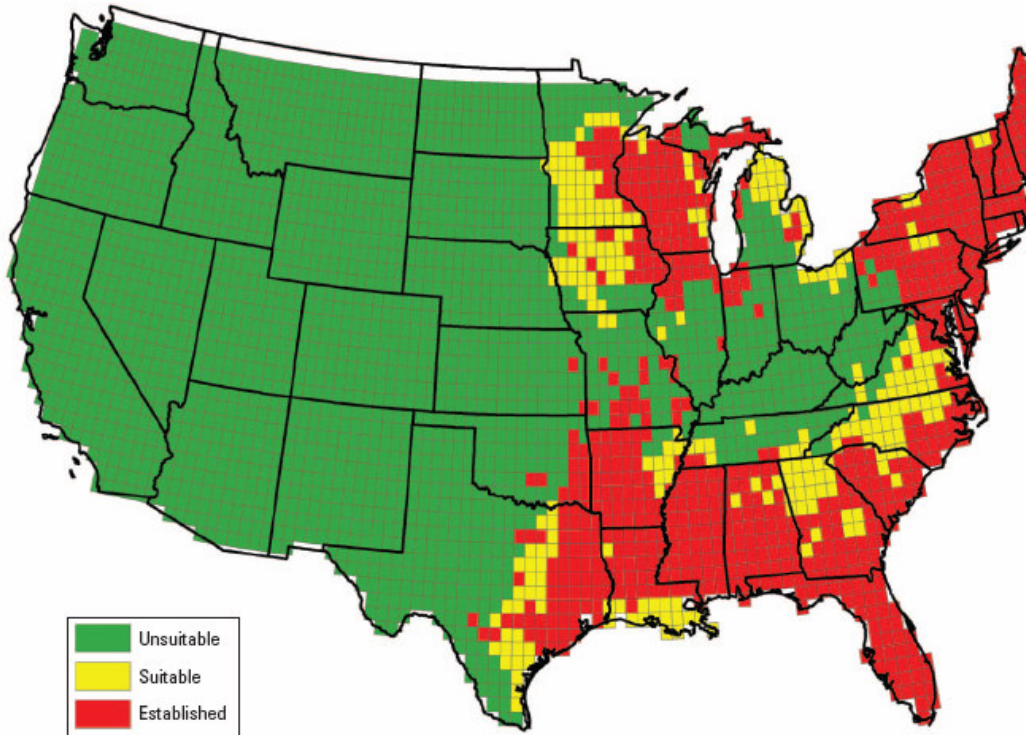
Figure 2. Forecast geographic distribution of the black-legged tick vector east of the 100th meridian in the United States for DSSPL. From Brownstein et al (2003) Envr. Hlth. Perspect. 2a. New distribution map for *I. Scapularis* in the United States. To determine whether a given cell can support *I. Scapularis* populations, a probability cutoff point for habitat suitability from the auto logistic model was assessed by sensitivity analysis. A threshold of 21% probability of establishment was selected, giving a sensitivity of 97% and a specificity of 86%. This cutoff was used to reclassify the reported distribution map {Dennis et al. 1998}. The auto logistic model defined 81% of the reported locations {n=427} as established and 14% of the absent areas {n=2,327} as suitable. All other reported and absent areas were considered unsuitable. All areas previously defined as established maintained the same classification.

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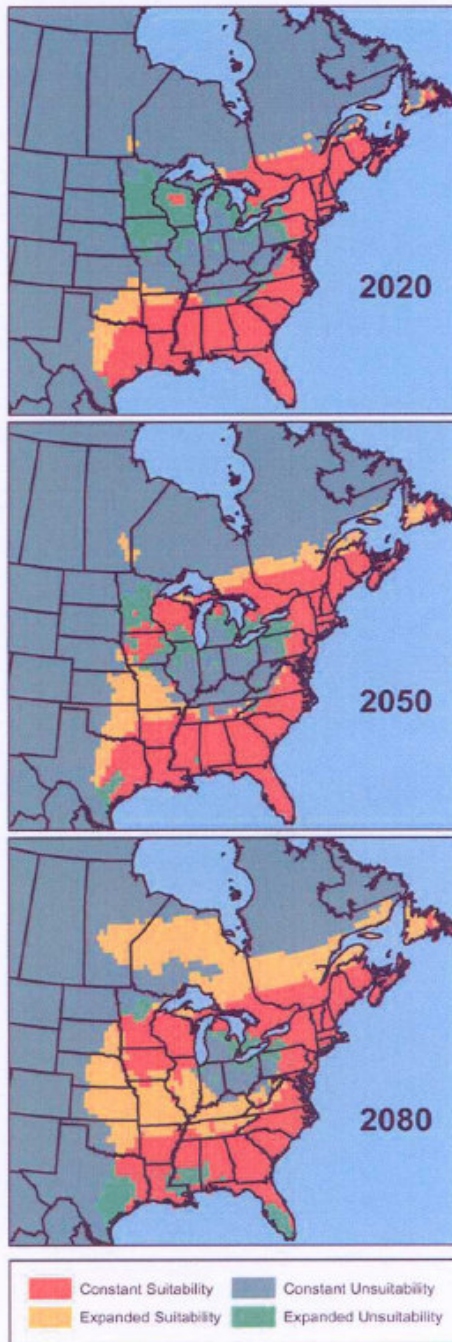
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Figure 3. Forecast change in black-legged tick distribution in Eastern and Central North America under climate change scenarios using DSSPL. From Brownstein et al (2005a) EcoHealth

1965   **Climate Change Science Program**

1966

1967   **Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected**

1968   **Sectors and Regions**

1969

1970   **Chapter 5. "Decision Support for Water Resources Management"**

1971

1972   **Holly C. Hartmann**

1973   **Department of Hydrology and Water Resources, The University of Arizona**

1974

1975

1976   **1. Introduction**

1977   Water resource managers have long been incorporating information related to climate in their decisions. The

1978   tremendous, regionally ubiquitous, investments in infrastructure to reduce flooding (e.g., levees and reservoirs) or

1979   assure reliable water supplies (e.g., reservoirs, groundwater development, irrigation systems, water allocation, and

1980   transfer agreements) reflect societal goals to mitigate the impacts of climate variability at multiple time and space

1981   scales. As the financial, political, social, and environmental costs of infrastructure options have become less tractable,

1982   water management institutions have undergone comprehensive reform, shifting their focus to optimizing operations of

1983   existing projects and managing increasingly diverse, and often conflicting, demands on the services provided by water

1984   resources (Bureau of Reclamation [BOR], 1992; Beard, 1993; Congressional Budget Office, 1997; Stakhiv, 2003;

1985   National Research Council [NRC], 2004). Governments have also made substantial investments to improve climate

1986   information and understanding over the past decades through satellites, *in situ* measuring networks, supercomputers,

1987   and research programs. National and international programs have explicitly identified as an important objective

1988   ensuring that improved data products, conceptual models, and predictions are useful to the water resources management

1989   community (Endreny et al., 2003; Lawford et al., 2005). Although exact accounting is difficult, potential values

1990   associated with appropriate use of accurate hydrometeorologic predictions generally range from the millions to the

1991   billions of dollars (e.g., National Hydrologic Warning Council, 2002). There are also non-monetary values associated

1992   with more efficient, equitable, and environmentally sustainable decisions related to water resources.

1993   Droughts, floods, and increasing demands on available water supplies continue to create concern, and even

1994   crises, for water resources management. Many communities have faced multiple hydrologic events that were earlier

1995   thought to have low probabilities of occurrence (e.g., NRC, 1995), and long-term shifts in streamflows have been

1996   observed (Lettenmaier et al., 1994; Lins and Slack, 1999; Douglas et al., 2000), leading to questions about the relative

1997   impacts of shifts in river hydraulics, land use, and climate conditions.

1998   Until the last two decades, climate was viewed largely as a collection of random processes, and this paradigm

1999   informed much of the water resource management practices developed over the past 50 years that persist today.

2000   However, climate is now recognized as a chaotic process, shifting among distinct regimes with statistically significant

2001   differences in average conditions and variability (Hansen et al., 1997). As instrumental records have grown longer and

2002   extremely long time-series of paleoclimatological indicators have been developed (Ekwurzal, 2005), they increasingly

2003   belie one of the fundamental assumptions behind most extant water resources management—stationarity. Stationary

2004   time series have time-invariant statistical characteristics (e.g., mean or variance), meaning that different parts of the

2005   historical record can be considered equally likely. Within the limits posed by sampling, statistics computed from

2006   stationary time series can be used to define a probability distribution that will also then faithfully represent expectations

2007   for the future (Salas, 1993).

2008

2009   Further, prospects for climate change due to global warming have moved from the realm of speculation to

2010   general acceptance (Intergovernmental Panel on Climate Change [IPCC] 1990, 1995a, 2001a, 2007). The potential

2011   impacts of climate on water resources, and their implications for management, have been central topics of concern in

2012   climate change assessments (e.g., EPA, 1989; IPCC, 1995b, 2001b; National Assessment Synthesis Team, 2000; Gleick

2013   and Adams, 2000; Barnett *et al.,* 2004). These studies are becoming increasingly confident in their conclusions that the

2014   future portends statistically significant changes in hydroclimatic averages and variability.

2015   There has been persistent and broad disappointment in the extent to which improvements in hydroclimatic

2016   science from large-scale research programs have affected resource management practices in general (Pielke, 1995,

2017   2001; NRC, 1998a, 1999a) and water resource management in particular (NRC, 1998b, 1999b,c). For example,

2018   seasonal climate outlooks have been slow to be entered into the water management decision processes, even though

2019   they have improved greatly over the past 20 years (Hartmann et al., 2002a, 2003). Water mangers have been even more

2020   resistant to incorporating notions of hydrologic non-stationarity in general and climate change in particular in decision

2021   processes. Until recently, hydrologic analysis techniques have been seen as generally sufficient (e.g., Matalas, 1997;

2022   Lins and Stakhiv, 1998), especially in the context of slow policy and institutional evolution (Stakhiv, 2003). However,

2023   an inescapable message for the water resource management community is the inappropriateness of the stationarity

2024   assumption in the face of climate change.

2025   Several ongoing efforts are leading the way forward to establish more effective ways of incorporating climate

2026   understanding and earth observations into water resources management (Pulwarty, 2002; Office of Global Programs,

2027   2004; NASA, 2005). While diverse in their details, these efforts seek to link hydroclimatological variability, analytical

2028   and predictive technologies, and water management decisions within an end-to-end context extending from

2029   observational data through large-scale analyses and predictions, uncertainty evaluation, impacts assessment,

2030   applications, and evaluations of applications (e.g., Young, 1995; Miles et al., 2000). Some end-to-end efforts focus on

2031   cultivating information and management networks; designing processes for recurrent interaction among research,

2032   operational product generation, management, and constituent communities; and developing adaptive strategies for

2033   accommodating climate variability, uncertainty, and change. Other end-to-end efforts focus on the development of

2034   decision support tools (DST) that embody unique resource management circumstances to enable formal and more

2035   objective linkages between meteorological, hydrologic, and institutional processes. Typically, end-to-end DST

2036   applications are developed for organizations making decisions with high-impact (e.g., state or national agencies) or

2037   high-economic value (e.g., hydropower production) and that possess the technical and managerial abilities to efficiently

2038   exploit research advances (e.g., Georgakakos et al, 1998, 2004, 2005; Georgakakos, 2006). If linked to socioeconomic

2039   models incorporating detailed information about the choices open to decision-makers and their tolerance for risk, these

2040   end-to-end tools could also enable explicit assessment of the impacts of scientific and technological research advances.

2041   This chapter describes a river management DST, RiverWare, which facilitates coordinated efforts among the

2042   research, operational product generation, and water management communities. RiverWare emerged from an early and

2043   sustained effort by several federal agencies to develop generic tools to support the assessment of water resources

2044   management options in river basins with multiple reservoirs and multiple management objectives (Frevert et al., 2006).

2045   RiverWare was selected for use as a case study because it has been used in a variety of settings, by multiple agencies,

2046   over a longer period than many other water management DSTs. Furthermore, RiverWare can explicitly accommodate a

2047   broad range of resource management concerns (e.g., flood control, recreation, navigation, water supply, water quality,

2048   and power production). RiverWare can also consider perspectives ranging from day-to-day scheduling of operations to

2049   long-range planning and can accommodate a variety of climate observations, forecasts, and even climate change

2050   projections. RiverWare can incorporate hydrologic risk, whereby event consequences and their magnitudes are mediated

2051   by their probability of occurrence, in strategic planning applications and design studies, which can offer a way forward

2052   for decision makers reluctant to shift away from use of traditional, stationarity-based, statistical analysis of historical

2053   data (Lee, 1999; Davis and Pangburn, 1999).

2054

2055   **2. Description of RiverWare**

2056   RiverWare is a software framework used to develop detailed models of how water moves and is managed

2057   throughout complex river basin systems. RiverWare applications include physical processes (e.g., streamflow, bank

2058   storage, and solute transport), infrastructure (e.g., reservoirs, hydropower generating turbines, spillways, and diversion

2059   connections), and policies (e.g., minimum instream flow requirements and trades between water users) (Zagona et al.,

2060   2001, 2005). At a minimum, RiverWare applications require streamflow hydrographs as input for multiple locations

2061   throughout a river system. While hydrographs can be generated within the DST, they can also be input from other

2062   sources, with the latter approach being especially important in advanced end-to-end assessments. Detailed discussion of

2063   the role of observations and considerations of global change using RiverWare are discussed in later sections. RiverWare

2064   can be applied to address diverse water management concerns, including real-time operations, strategic planning for

2065   seasonal to interannual variability in water supplies and demands, and examining impacts of hydrologic non-

2066   stationarity. Because infrastructure, management rules, and policies can be easily changed, RiverWare also allows

2067   examination of alternative options for achieving management objectives over short-, medium-, and long-term planning

2068   horizons.

2069   RiverWare was developed by the University of Colorado-Boulder's Center for Advanced Decision Support for

2070   Water and Environmental Systems (CADSWES) in collaboration with the BOR, Tennessee Valley Authority, and the

2071   Army Corps of Engineers (Frevert et al., 2006). CADSWES continues to develop and maintain the RiverWare software,

2072   as well as offer training and support for RiverWare users (see http://cadswes.colorado.edu). According to CADSWES,

2073   RiverWare is used by more than 75 federal and state agencies, private sector consultants, universities and research

2074   institutes, and water districts, among others.

2075

2076   *Example Applications*

2077   Consistent with the intent of its original design, the use of RiverWare varies widely, depending on the specific

2078   application. An early application was its use for scheduling reservoir operations by the Tennessee Valley Authority

2079   (Eshenbach et al., 2001). In that application, RiverWare was used to define the physical and economic characteristics of

2080   the multi-reservoir system, including power production economics, to prioritize the policy goals that governed the

2081   reservoir operations and to specify parameters for linear optimization of system objectives. In another application,

2082   RiverWare was used to balance the competing priorities of minimum instream flows and consumptive water use in the

2083   operation of the Flaming Gorge Reservoir in Colorado (Wheeler et al., 2002).

2084   While day-to-day scheduling of reservoir operations is more a function of weather than climate, the use of

2085   seasonal climate forecasts to optimize reservoir operations has long been a goal for water resources management.

2086   RiverWare is being implemented for the Truckee-Carson River basin in Nevada to investigate the impact of

2087   incorporating climate outlooks into an operational water management framework that prioritizes irrigation water

2088   supplies, interbasin diversions, and fish habitat (Grantz et al., 2007). Another example application to the Truckee-

2089   Carson River using a hypothetical operating policy indicated that fish populations could benefit from purchases of water

2090   rights for reservoir releases to mitigate warm summer stream temperatures resulting from low flows and high air

2091   temperatures (Neumann et al., 2006).

2092   RiverWare has also been used to evaluate politically charged management strategies, including water transfers

2093   proposed in California's Quantification Settlement Agreement and the BOR's Inadvertant Overrun Policy, maintaining

2094   instream flows sufficient to restore biodiversity in the Colorado River delta, and conserving riparian habitat while

2095   accommodating future water and power development in the BOR Multiple Species Conservation Program (Wheeler et

2096   al., 2002). RiverWare also played a key role in negotiations by seven western states concerning how the Colorado River

2097   should be managed and the river flow should be distributed among the states during times of drought. The BOR

2098   implemented a special version of the RiverWare model of the Colorado River and its many reservoirs, diversions, and

2099   watersheds (Jerla, 2005). The model was used to provide support to the Basin States Modeling Work Group Committee

2100   over an 18-month period, as they assessed different operational strategies under different hydrologic scenarios,

2101   including extreme drought (U.S. Department of Interior, 2007).

2102

2103   *Implementation*

2104   RiverWare requirements are multi-dimensional. A specific river system and its infrastructure operating policies

2105   are defined by data files supplied to RiverWare. This allows incorporation of new basin features (e.g., reservoirs),

2106   operating policies, and hydroclimatic conditions without users having to write software code. Utilities within RiverWare

2107   enable users to automatically execute many simulations, including accessing external data or exporting results of model

2108   runs. Users can also write new modules that CADSWES can integrate into RiverWare for use in other applications. For

2109   example, in an application for the Pecos River in New Mexico, engineers developed new methods and software code for

2110   realistic downstream routing of summer monsoon-related flood waves (Boroughs and Zagona, 2002). RiverWare is

2111   implemented for use on Windows or Unix Solaris systems, as described in the requirements document

2112   (http://cadswes.colorado.edu/PDF/RiverWare/RecommendedMinimumSystemsRequirements.pdf).   An   extensive

2113   manual is also available (http://cadswes.colorado.edu/PDF/ReleaseNotes/ RiverWareHelp.pdf).

2114   RiverWare applications can be implemented by any group that can pay for access, both in terms of finances

2115   and educational effort. Development of RiverWare applications requires a site license from CADSWES. Significant

2116   investment is required to learn to use RiverWare as well. CADSWES offers two 3-day RiverWare training courses, an

2117   initial class covering general simulation modeling, managing scenarios, and incorporating policy options through rule-

2118   based simulation, and a second class covering rule-based simulation in more detail, creating basin policies, and

2119   examining water policy options. Costs for the original license, annual renewals, technical support, and training require

2120   several thousand dollars. The costs of licensing and learning RiverWare mean that small communities and civic groups

2121   are unlikely to implement their own applications for assessing water management options. Rather, large agencies with

2122   technical staff or the financial means to fund university research or consultants are the most frequent users of

2123   RiverWare. The agencies then mediate the access of stakeholders to assessments of water management options through

2124   traditional public processes (e.g., U.S. Department of Interior, 2007). Conflicts may arise in having academic research

2125   groups conduct analyses funded by stakeholder groups, with inherent tensions between the open publication of research

2126   required by academia and the limited access to results required by strategic negotiations among interest groups.

2127

2128   **3. Current and Future Use of Observations**

2129   The specific combination of observations used by a RiverWare application depends on both the decision

2130   context and the use of other models and DSTs to provide input to RiverWare that more comprehensively or accurately

2131   describes the character, conditions, and response of the river basin system. Figure 1 illustrates the information flow

2132   linking observations, RiverWare, other models and DSTs, and water management decisions; it shows that RiverWare

2133   has tremendous flexibility in the kinds of observations that could be useful in hydrologic modeling and river system

2134   assessment and management. The types of observations that may ultimately feed into RiverWare applications also

2135   depend on the timescale of the situation.

2136   A detailed discussion of the role of satellite observations in RiverWare applications and selected input models

2137   and DSTs (e.g., the BOR's ET Toolbox and Precipitation Runoff Modeling System [PRMS]) is given by the

2138   "Evaluation Report for AWARDS ET Toolbox and RiverWare Decision Support Tools" (Hydrological Sciences

2139   Branch, 2007). Briefly, RiverWare can use a combination of observations from multiple sources, including satellites,

2140   products derived from land-atmosphere or hydrologic models, and combinations of both. Satellite observations can

2141   assist models in estimating evapotranspiration, precipitation, snow water equivalent, soil moisture, groundwater storage

2142   and aquifer volumes, reservoir storage, and water quality, among other variables. Measurements from sensors aboard a

2143   variety of satellites are being considered for their usefulness within DST contexts and their impacts on reducing water

2144   management uncertainty, including the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor aboard the

2145   Earth Observing System (EOS) Terra and Aqua satellites, Landsat TM data, Advanced Spaceborne Thermal Emission

2146   and Reflection Radiometer (ASTER), Shuttle Radar Topography Mission (SRTM), Advanced Microwave Scanning

2147   Radiometer–EOS (AMSR-E), Gravity Recovery and Climate Experiment (GRACE), and Tropical Rainfall Mapping

2148   Mission (TRMM), among others. Future and planned satellites with hydrologically relevant sensors and measurements

2149   include CloudSAT, the Global Precipitation Mission (GPM), and the National Polar-Orbiting Operational

2150   Environmental Satellite (NPOESS). Use of these observations can be enhanced by assimilating them into land surface

2151   models to produce spatially-distributed estimates of snowpack, soil moisture, evapotranspiration, energy fluxes, and

2152   runff, which then provide inputs to RiverWare to base a more comprehensive assessment of river basin conditions. The

2153   land surface models include the Community Land Model (CLM), Mosaic, Noah, and VIC, among others, supported by

2154   NASA's Land Data Assimilation System (LDAS) and Land Information System (LIS) (NASA, 2006a).

2155   NASA has several pilot projects specifically focused on assessing the impact of satellite observations in a

2156   variety of hydrologic models and DSTs as they feed into RiverWare applications (NASA, 2005, 2006b, 2007). For

2157   example, one project is comparing Terra and Aqua MODIS snow cover products for the Yakima-Columbia River basins

2158   with land-based snow telemetry measurements, testing their use for LIS simulations that also use the North American

2159   LDAS, connecting assimilated snow data with the Modular Modeling System (MMS) Precipitation-Runoff Modeling

2160   System (PRMS), and then supplying the simulated runoff as inputs to RiverWare. Another project on the Rio Grande

2161   River basin is assessing MODIS and Landsat data to improve evapotranspiration estimates generated by the BOR DST,

2162   the Agricultural Water Resources Decision Support (AWARDS) ET Toolbox, which then provides water demand time

2163   series to RiverWare. While application of specific hydrologic models and observations depend on the specific

2164   RiverWare application, significant processing of both model and observations are required and can be resource

2165   intensive (e.g., calibration and aggregation/disaggregation).

2166   Operational scheduling of reservoir releases depend on orders of water from downstream users (e.g., irrigation

2167   districts) that are largely affected by day-to-day weather conditions as well as seasonally varying demands. In these

2168   cases, the important observations are the near real-time estimates of conditions within the river basin system (e.g., soil

2169   moisture or infiltration capacity), which affect the transformation of precipitation into runoff into the river system,

2170   relative to constraints on system operation (e.g., reservoir storage levels or water temperatures at specific river

2171   locations). Meteorological prospects are mediated by those placing the water orders or through short-term weather

2172   forecasts that may affect operations when the system is near some constraint (e.g., flood flows when reservoir levels are

2173   near peak storage capacity). In these situations, the important observations are recent extreme precipitation events and

2174   their location, which may be provided, separately or in some combination, by *in situ* monitoring networks, radar, or

2175   satellites.

2176   For mid-range applications, such as strategic planning for operations over the next season or year, outlooks of

2177   total seasonal water supplies are routinely used in making commitments for water deliveries, determining industrial and

2178   agricultural water allocation, and carrying out reservoir operations. In these applications, it is also important for water

2179   managers to keep track of the current state of the watershed. Such observations are often used as input to one of the

2180   many independent hydrologic models that can provide input to a specific RiverWare application. In these situations, the

2181   important observations are those that provide boundary or forcing conditions for the independent hydrologic models,

2182   including snowpack moisture storage, soil moisture, precipitation (intensity, duration, and spatial distribution), air

2183   temperature, humidity, winds, and other meteorological conditions.

2184   For long-term planning and design applications, observations are less important because the effects of recent

2185   conditions have less impact on long-term outcomes than future meteorological uncertainty, or even institutions at multi-

2186   decadal time scales. In these applications, accurate representation of anticipated natural hydroclimatological variability

2187   is important. In many western U.S. applications, observed streamflows are adjusted to remove the effects of reservoir

2188   management, interbasin diversions, and water withdrawals. The adjusted flows, termed "naturalized flows." may be

2189   used as input to RiverWare applications to assess the impact of different management options. Use of naturalized flows

2190   is fraught with problems. A central issue is poor monitoring of actual human impacts, especially withdrawals,

2191   diversions, and return flows (e.g., from irrigation). Alternative approaches include the use of proxy streamflows (e.g.,

2192   from paleoclimatological indicators) or output from hydrologic modeling studies (Hartmann, 2005). For example,

2193   Tarboton (1995) developed hydrologic scenarios for severe sustained drought in the Colorado River basin based on

2194   streamflows reconstructed from centuries of tree-ring records; the scenarios were used in an assessment of management

2195   options using a precursor to the current RiverWare application to the Colorado River system.

2196   The usefulness of the observations used within RiverWare depends on the specific implementation, as well as

2197   the quality of the information itself. For example, one direct use of climate information for long-term planning includes

2198   hydrologic and hydraulic routing of "design storms" of various magnitudes and likelihoods, with the storms based on

2199   analyses of the available instrumental record (Urbanas and Roesner, 1993). However, those instrumental records have

2200   often been too short to adequately express climate variability and resulting impacts, regardless of the specific DSTs

2201   used to do the hydrologic or hydraulic routing. In short- and mid-range forecasting applications, the use of observations

2202   is mediated by the hydrologic model or DST that transforms weather and climate into streamflows, evaporative water

2203   demands, and other hydrologic processes. In these situations, from an operational perspective, the stream of

2204   observational inputs must be dependable, without downtime or large data gaps, and data processing, model simulation,

2205   and creation of forecast products must be fast and efficient. The usefulness of observations may be limited by other

2206   issues as well. The water resources management milieu is complex and diverse, and climate influences are only one

2207   factor among many affecting water management policies and practices. Factors limiting the use of observations or

2208   subsequent hydrologic model input to RiverWare for actual water management include lack of familiarity with the

2209   available information, disconnects between the specific information available (e.g., variables and spatiotemporal scales)

2210   and their relevance to decision makers, skepticism about the quality and applicability of information, conservative

2211   decision preferences due to accountability for poor consequences, and institutional impediments such as the inflexible

2212   nature of many multi-jurisdictional water management agreements (Changnon, 1990; Kenney, 1995; Pulwarty and

2213   Redmond, 1997; Pagano et al., 2001, 2002; Jacobs, 2002; Jacobs and Pulwarty, 2003; Rayner et al., 2005).

2214

2215

2216   **4. Uncertainty**

2217   The reliability of observations for driving hydrologic models that may provide input to RiverWare applications

2218   is the subject of much ongoing research. The hydrologic models, because they incompletely describe the physical

2219   relationships among important watershed components (e.g., vegetation processes that link the atmosphere and different

2220   levels of soil and surface and groundwater interactions), are themselves the subject of much research to determine their

2221   reliability. Streamflow and other hydrologic variables are intimately responsive to atmospheric factors, especially

2222   precipitation, that drive a watershed's behavior; however, errors in precipitation estimates are often amplified in the

2223   hydrologic response (Oudin et al., 2006).

2224   Obtaining quality precipitation estimates is a formidable challenge, especially in the western U.S. where

2225   orographic effects produce large spatial variability and where there is a scarcity of real-time precipitation gage data and

2226   radar beam blockage by mountains. In principal, outputs from atmospheric models can serve as surrogates for

2227   observations, as well as providing forecasts of meteorological variables that can be used to drive hydrologic models.

2228   One issue in integrating atmospheric model output into hydrologic models for small watersheds (<1000 km^2) is that the

2229   spatial resolution of atmospheric models is lower than the resolution of hydrologic models. For example, quantitative

2230   precipitation forecasts (QPF) produced by some atmospheric models may cover several thousand square kilometers, but

2231   the hydrologic models used for predicting daily streamflows require precipitation to be downscaled to precipitation

2232   fields for watersheds covering only tens or hundreds of square kilometers. One approach to produce output consistent

2233   with the needs of hydrologic models is to use nested atmospheric models, whereby outputs from large scale but coarse

2234   resolution models are used as boundary conditions for models operating over smaller domains with higher resolution.

2235   However, the error characteristics of atmospheric model products (e.g., bias in precipitation and air temperature) also

2236   can have significant effects on subsequent streamflow forecasts. Bias corrections require knowledge of the

2237   climatologies (i.e., long-term distributions) of both modeled and observed variables.

2238   Although meteorological uncertainty may be high for the periods addressed by streamflow forecasts, accurate

2239   estimates of the state of watershed conditions prior to the forecast period are important because they are used to

2240   initialize hydrologic model states, with significant consequences for forecast results. However, watershed conditions

2241   can be difficult to measure, especially when streamflow forecasts must be made quickly, as in the case of flash flood

2242   forecasts. One option is to continuously update watershed states by running the hydrologic models continuously and by

2243   using inputs from recent meteorological observations and/or atmospheric models. Regardless of the source of inputs,

2244   Westrick et al. (2002) found it essential to obtain observational estimates of initial conditions to keep streamflow

2245   forecasts realistic; storm-by-storm corrections of model biases determined over extended simulation periods were

2246   insufficient. Recent experimental end-to-end forecasts of streamflow produced in a simulated operational setting (Wood

2247   et al., 2001) highlighted the critical role of quality estimates of spring and summer soil moisture used to initialize

2248   hydrologic model states for the eastern U.S.

2249   Where streamflows may be largely comprised of snowmelt runoff, quality estimates of snow conditions are

2250   important. The importance of reducing errors in the timing and magnitude of snowmelt runoff are especially acute in

2251   regions where a large percentage of annual water supplies derive from snowmelt runoff, snowmelt impacts are highly

2252   non-linear with increasing deviation from long-term average supplies, and reservoir storage is smaller than interannual

2253   variation of water supplies. However, resources for on-site monitoring of snow conditions have diminished rather than

2254   grown, relative to the increasing costs of errors in hydrologic forecasts (Davis and Pangburn, 1999). Research activities

2255   of the NWS National Office of Hydrology Remote Sensing Center (NOHRSC) have long been directed at improving

2256   estimates of snowpack conditions through aerial and satellite remote sensing (Carroll, 1985). However, the cost of aerial

2257   flights prohibits routine use (T. Carroll, NOHRSC, personal communication, 1999), while satellite estimates have

2258   qualitative limitations (e.g., not considering fractional snow coverage over large regions) and have not found broad use

2259   operationally.

2260   Multiple techniques exist to more accurately represent the uncertainty inherent in understanding and predicting

2261   potential hydroclimatic variability. Stochastic hydrology techniques use various forms of autoregressive models to

2262   generate multiple synthetic streamflow time series with statistical characteristics matching available observations. For

2263   example, in estimating the risk of low flows for the Sacramento River Basin in California, the BOR (Frevert et al.,

2264   1989) generated 20 one-thousand-year streamflow time series matching selected statistics of observed flows (adjusted to

2265   compensate for water management impacts on natural flows); the non-exceedance probabilities of low flows were

2266   computed by counting the occurrences of low flows within 1- through 10-year intervals for all 20 one-thousand-year

2267   sequences. The U.S. Army Corps of Engineers (1992) used a similar approach to estimate flood magnitudes with return

2268   periods exceeding 1,000 years, using Monte Carlo sampling from within the 95% confidence limits of a Log Pearson III

2269   distribution developed by synthesizing multiple streamflow time series.

2270   The ability to automatically execute many model runs within RiverWare, including accessing data from

2271   external sources and exporting model results, facilitates using stochastic hydrology approaches for representing

2272   uncertainty. For example, Carron et al. (2006) demonstrated RiverWare's capability to identify and quantify significant

2273   sources of uncertainty in projecting river and reservoir conditions, using a first-order, second-moment (FOSM)

2274   algorithm that is computationally more efficient than more traditional Monte Carlo approaches. The FOSM processes

2275   uncertainties in inputs and models to provide estimates of uncertainty in model results that can be used directly within a

2276   risk management decision framework. The case study presented by Carron et al. (2006) evaluated the uncertainties

2277   associated with meeting goals for reservoir water levels beneficial for recovering endangered fish species within the

2278   lower Colorado River.

2279   With regard to RiverWare applications concerned with mid-range planning and use of hydrologic forecasts, at

2280   the core of any forecasting system is the predictive model, whether a simple statistical relationship or a complex

2281   dynamic numerical model. Advances in hydrologic modeling have been notable, especially those associated with the

2282   proper identification of a model's parameters (e.g., Duan et al., 2002) and the development of models that consider the

2283   spatially distributed characteristics of watersheds, rather than treating entire basins as a single point (Grayson and

2284   Bloschl, 2000). Conceptual rainfall-runoff models offer some advantages over statistical techniques in support of long-

2285   range planning for water resources management. These models represent, with varying levels of complexity, the

2286   transformation of precipitation and other meteorological forcing variables (e.g., air temperature and humidity) to

2287   watershed runoff and streamflow, including accounting for hydrologic storage conditions (e.g., snowpack, soil moisture,

2288   and groundwater). These models can be used to assess the impacts and implications of various climate scenarios by

2289   using historic meteorological time series as input, generating hydrologic time series, and then using those hydrologic

2290   scenarios as input to RiverWare. This approach enables consideration of current landscape and river channel conditions,

2291   which may be quite different than recorded in early instrumental records and which can dramatically alter a watershed's

2292   hydrologic behavior (Vorosmarty et al., 2004). Furthermore, the use of multiple input time series, system

2293   parameterizations, or multiple models, enables a probabilistic assessment of an ensemble of scenarios. The Hydrological

2294   Ensemble Prediction Experiment (HEPEX) (Schaake et al., 2007) aims to address the unique challenges of expressing

2295   uncertainty associated with ensemble forecasts for water resources management.

2296   An additional concern for mid- and long-range planning is that, as instrumental records have grown longer,

2297   they often show trends (e.g., Baldwin and Lall, 1999; Olsen et al., 1999; Andreadis and Lettenmaier, 2006) or persistent

2298   regimes (i.e., periods characterized by distinctly different statistics) (e.g., Angel and Huff, 1995; Quinn, 1981, 2002),

2299   with consequences for estimation of hydrologic risk (Olsen et al., 1998). Observed regimes and trends can have multiple

2300   causes, including climatic changes, watershed and river transformations, and management impacts (e.g., irrigation

2301   return flows and trans-basin water diversions). These issues enter into RiverWare applications directly through the use

2302   of naturalized flows, which are notoriously unreliable. For example, in assessments of water management options on the

2303   San Juan River in Colorado and New Mexico, the reliability of naturalized flows was considered to be affected by the

2304   inconsistent accounting of consumptive uses between irrigation and non-irrigation data, use of reservoir evaporation

2305   rates with no year-to-year variation, neglecting time lags in the accounting of return flows from irrigation to the river,

2306   errors in river gage readings that underestimated flows in critical months, and the lack of documentation of diversions

2307   that reduce river flows as well as subsequent adjustments to data used to compute naturalized flows.

2308

2309   **5. Global Change Information and RiverWare**

2310   *Climate Variability*

2311   Decision makers increasingly recognize that climate is an important source of uncertainty and potential

2312   vulnerability in long-term planning for the sustainability of water resources (Hartmann, 2005). With the appropriate

2313   investment in site licenses, training of personnel, implementation for a specific river system, and assessment efforts,

2314   RiverWare is capable of supporting climate-related water resources management decisions by U.S. agencies. However,

2315   technology alone is insufficient to resolve conflicts among competing water uses. Early in the development of

2316   RiverWare, Reitsma et al. (1996) investigated its potential role as a DST within complex negotiations between

2317   hydroelectric, agricultural, and flood control interests. Results indicated that while DSTs can help identify policies that

2318   can satisfy specific management requirements and constraints, as well as expand the range of policy options considered,

2319   they are of limited value in helping decision makers understand interactions within the river system. Furthermore, the

2320   burdens of direct use by decision makers of a DST that embodies a complex system are significant; a more useful

2321   approach is to have specialists support decision makers by making model runs and presenting the results in an iterative

2322   manner. This is the approach used by the Bureau of Reclamation in the application of RiverWare to support interstate

2323   negotiations concerning the sharing of Colorado River water supply shortages during times of drought (Jerla, 2005; U.S.

2324   Department of Interior, 2007).

2325   From the perspective of mid-range water management issues, the use of forecasts within RiverWare

2326   applications constitutes an important pathway for supporting climate-related decision making. Each time a prediction is

2327   made, science has an opportunity to address and communicate the strengths and limitations of current understanding.

2328   Each time a decision is made, managers have an opportunity to confront their understanding of scientific information

2329   and forecast products. Furthermore, each prediction and decision provides opportunities for interaction between

2330   scientists and decision makers and for making clear the importance of investments in scientific research. Perceptions of

2331   poor forecast quality are a significant barrier to more effective use of hydroclimatic forecasts (Changnon, 1990; Pagano

2332   et al., 2001, 2002; Rayner et al., 2005); however, recent advances in modeling and predictive capabilities naturally lead

2333   to speculation that hydroclimatic forecasts can be used to improve the operation of water resource systems.

2334   Great strides have been made in monitoring, understanding, and predicting interannual climate phenomena

2335   such as the El Nino-Southern Oscillation (ENSO). This improved understanding has resulted in long-lead (up to about a

2336   year) climate forecast capabilities that can be exploited in streamflow forecasting. Techniques have been developed to

2337   directly incorporate variable climate states into probabilistic streamflow forecast models based on linear discriminant

2338   analysis (LDA) with various ENSO indicators, (e.g., the Southern Oscillation Index [SOI]) (Peichota and Dracup, 1999;

2339   Piechota et al., 2001). Recent improved understanding of decadal-scale climate variability also has contributed to

2340   improved interannual hydroclimatic forecast capabilities. For example, the Pacific Decadal Oscillation (PDO) (Mantua

2341   et al., 1997) has been shown to modulate ENSO-related climate signals in the West. Experimental streamflow

2342   forecasting systems for the Pacific Northwest have been developed based on long-range forecasts of both PDO and

2343   ENSO (Hamlet and Lettenmaier, 1999). In the U.S., the Pacific Northwest, California, and the Southwest are strong

2344   candidates for the use of long-lead forecasts because ENSO and PDO signals are particularly strong in these regions and

2345   each region's water supplies are closely tied to accumulation of winter snowfall, amplifying the impacts of climatic

2346   variability.

2347   While many current water management decision processes use single-value deterministic approaches,

2348   probabilistic forecasts enable quantitative estimation of the inevitable uncertainties associated with weather and climate

2349   systems. From a decision maker's perspective, probabilistic forecasts are more informative because they explicitly

2350   communicate uncertainty and are more useful because they can be directly incorporated into risk-based calculations.

2351   Probabilistic forecasts of water supplies can be created by overlaying a single prediction with a normal distribution of

2352   estimation error determined at the time of calibration of the forecast equations (Garen, 1992). However, to account for

2353   future meteorological uncertainty, new developments have focused on ensembles, whereby multiple possible futures

2354   (each termed an ensemble trace) are generated; statistical analysis of the ensemble distribution then provides the basis

2355   for a probabilistic forecast.

2356   Changnon (2000), Rayner et al. (2005), and Pagano et al. (2002) found that improved climate prediction

2357   capabilities are initially incorporated into water management decisions informally, using subjective, ad hoc procedures

2358   on the initiative of individual water managers. While improvised, those decisions are not necessarily insignificant. For

2359   example, the Salt River Project, among the largest water management agencies in the Colorado River Basin and primary

2360   supplier to the Phoenix metropolitan area, decided in August 1997 to substitute groundwater withdrawals with reservoir

2361   releases, expecting increased surface runoff during a wet winter related to El Nino. With that decision, they risked

2362   losses exceeding $4 million in an attempt to realize benefits of $1 million (Pagano et al., 2002). Because these informal

2363   processes are based in part on confidence in the predictions, overconfidence in forecasts can be even more problematic

2364   than lack of confidence, as a single incorrect forecast that provokes costly shifts in operations can devastate user

2365   confidence in subsequent forecasts (e.g., Glantz, 1982).

2366   The lack of verification of hydroclimatic forecasts is a significant barrier to their application in water

2367   management, but it is not easy to resolve with traditional research efforts, because the level of acceptable skill varies

2368   widely depending on the intended use (Hartmann et al., 2002a; Pagano et al., 2002). Information on forecast

2369   performance has rarely been available to, and framed for, decision makers, although hydrologic forecasts are reviewed

2370   annually by the issuing agencies in the U.S (Hartmann et al., 2002b). Hydrologic forecast verification is an expanding

2371   area of research (Franz et al., 2003; Hartmann et al., 2003; Bradley et al, 2004; Pagano et al., 2004; Kruger et al., 2007),

2372   but much work remains and could benefit from approaches developed within the meteorological community (Welles et

2373   al., 2007). Because uncertainty exists in all phases of the forecast process, forecast systems designed to support risk-

2374   based decision making need to explicitly quantify and communicate uncertainties from the entire forecast system and

2375   from each component source, including model parameterization and initialization, meteorological forecast uncertainty at

2376   the multiple spatial and temporal scales at which they are issued, adjustment of meteorological forecasts (e.g., through

2377   downscaling) to make them usable for hydrologic models, implementation of ensemble techniques, and verification of

2378   hydrologic forecasts.

2379

2380   *Climate Change*

2381   From the perspective of long-range water management issues, the potential impacts of climate change on water

2382   resources, and their implications for management, are central topics of concern. Estimates of prospective impacts of

2383   climate change on precipitation have been mixed, leading, in many cases, to increasing uncertainty about the reliability

2384   of future water supplies. However, where snow provides a large fraction of annual water supplies, prospective

2385   temperature increases dominate hydrologic impacts, leading to stresses on water resources and increased hydrologic

2386   risk. Higher temperatures effectively shift the timing of the release of water stored in the snowpack "reservoir" to earlier

2387   in the year, reducing supplies in summer when demands are greatest, while also increasing the risk of floods due to rain-

2388   on-snow events. While not using RiverWare, several river basin studies have assessed the risks of higher temperatures

2389   on water supplies and management challenges. The near universal analytical approach has been one of sensitivity

2390   analysis (Lettenmaier, 2003):

2391   1) downscaling outputs from a dynamic general circulation model of the global land-atmosphere-ocean system to

2392   generate regional- or local-scale meteorological time series over many decades,

2393   2) using the meteorological time series as input to rainfall-runoff models to generate hydrologic time series,

2394   3) using the hydrologic scenarios as input to water management models, and

2395   4) assessing differences among baseline and change scenarios using a variety of metrics.

2396   Early assessments of warming impacts on large river basins generally showed extant water management systems to

2397   be effective for all but the most severe scenarios (Hamlet and Lettenmaier, 1999; Lettenmaier et al., 1999), with a

2398   notable exception being the Great Lakes system where increased lake heat storage was tied to loss of ice cover,

2399   increased winter lake evaporation, lower lake levels, and potential failure to meet Lake Ontario regulation objectives

2400   under extant operating rules (Croley, 1990; Hartmann, 1990; Lee et al., 1994; Lee et al., 1997; Sousounis et al., 2000;

2401   Lofgren et al., 2002).

2402   Extensive detailed studies of the ability of existing reservoir systems and operational regulation rules to meet water

2403   management goals under changed climates are fairly recent (e.g., Saunders and Lewis, 2003; Christensen, et. al, 2004;

2404   Payne et. al, 2004; VanRheenan et. al, 2004; Maurer, 2007). However, there is a rapidly growing literature on broad

2405   considerations of climate change in water resources management (Frederick et al., 1997; Gamble et al., 2003;

2406   Lettenmaier, 2003; Loomis et al., 2003; Snover et al., 2003; Stakhiv, 2003; Ward et al., 2003; Vicuna et al., 2007).

2407   Some (Matalas, 1997) that contend that existing approaches are sufficient for water resource management planning and

2408   risk assessment because they contain safety factors; however, an inescapable message for the water resource

2409   management community is the inappropriateness of the stationarity assumption in the face of climate change. While

2410   precipitation changes may remain too uncertain for consideration in the near term, temperature increases are more

2411   certain and can have strong hydrologic consequences.

2412   Cognitively, climate change information is difficult to integrate into water resources management. First, within

2413   the water resources engineering community, the stationarity assumption is a fundamental element of professional

2414   training. Second, the century timescales of climate change exceed typical planning and infrastructure design horizons

2415   and are remote from human experience. Third, even individuals trying to stay up-to-date can face confusion in

2416   conceptually melding the burgeoning climate change impacts literature. Assessments are often repeated as general

2417   circulation and hydrologic model formulations advance or as new models become available throughout the research

2418   community. Furthermore, assessments can employ a variety of techniques for downscaling. Transposition techniques

2419   (e.g., Croley et al., 1998) are more intuitive than the often mathematically complex statistical and dynamical

2420   downscaling techniques (e.g., Clark et al., 1999; Westrick and Mass, 2001; Wood et al., 2002; Benestad, 2004).

2421   GCMs and their downscaled corollaries provide one unique perspective on long-term trends related to global

2422   change. Another unique perspective is provided by tree-ring reconstructions of paleo-streamflows, which, for example,

2423   indicate that in the U.S. Southwest droughts over the past several hundred years have been more intense, regionally

2424   extensive, and persistent than those reflected in the instrumental record (Woodhouse and Lukas, 2006). Decision makers

2425   have expressed interest in combining the perspectives of paleoclimatological information and GCMs. While some

2426   studies have linked instrumental records to paleoclimatological information (e.g., Prairie, 2006) and others with GCMs

2427   (e.g., Christensen and Lettenmaier, 2006), few link all three (an exception is Smith et al., 2007).

2428   Conceptual integration of climate change impacts assessment results in a practical water management context

2429   is complicated by the multiplicity of scenarios and vague attribution of their prospects for occurrence, which depend so

2430   strongly on feedbacks among social, economic, political, technological, and physical processes. For decision makers, a

2431   critical issue concerns the extent to which the various scenarios reflect the actual uncertainty of the relevant risks versus

2432   the uncertainty due to methodological approaches and biases in underlying models. The difficulties facing decision

2433   makers in reconciling disparate climate change impact assessments are exemplified by the Upper Colorado River Basin,

2434   where reductions in naturalized flow by the mid-21st century have been estimated to range from about 45% by Hoerling

2435   and Eischeid (2007), 10 to 25% by Milly et al (2005), about 18% by Christensen et al. (2004), and about 6% by

2436   Christensen and Lettenmaier (2006). Furthermore, using the difference between precipitation and evapotranspiration as

2437   a proxy for runoff, Seager et al. (2007) suggest an "imminent transition to a more arid climate in southwestern North

2438   America."

2439   However, in the face of circumstances nearing or exceeding the effectiveness of existing management

2440   paradigms, individuals can become more cognizant of the need to consider climate change. In the U.S. Southwest, over

2441   1999–2004, Lake Powell levels declined faster than previously considered in scenarios of extreme sustained drought

2442   (e.g., Harding et al., 1995; Tarboton, 1995), from full to only 38% capacity in November 2004 (BOR, 2004). Resource

2443   managers, policymakers, and the general public are now actively seeking scientific guidance in exploring how

2444   management practices can be more responsive to the uncertainties associated with a changing climate.

2445

Observations

Land Observations
Precipitation
Wind
Humidity
Snow water equivalent

Satellite Observations
Surface Temperature: Terra, Aqua, GOES
Precipitation: TRMM, Aqua, GOES
Soil Moisture: Aqua, TRMM, NPOESS
Snow cover: Aqua, Terra
Snow quantity: Aqua
Groundwater: GRACE
Land use/cover: Terra, Aqua, Landsat
Surface radiation: GOES, Terra, Aqua, ASTER

Radar & Airborne Observations
Precipitation
Snow water equivalent

Input Models/DSTs

Supply Models
NWSRFS
MMS PRMS

Integrated Models
GCMs: NEP ETA
Land Surface Models: Noah, MOSAIC, VIC, Catchment, CLM2, SWAT
In-stream water quality: QUAL2E
Watershed loading and transport: HSPF

Demand Models
AWARDS ET Toolbox

RIVERWARE

Impacts Models/DSTs
Economic
Vulnerability
Environmental

Decisions

Day-to-day Operations

Management, Strategic Planning
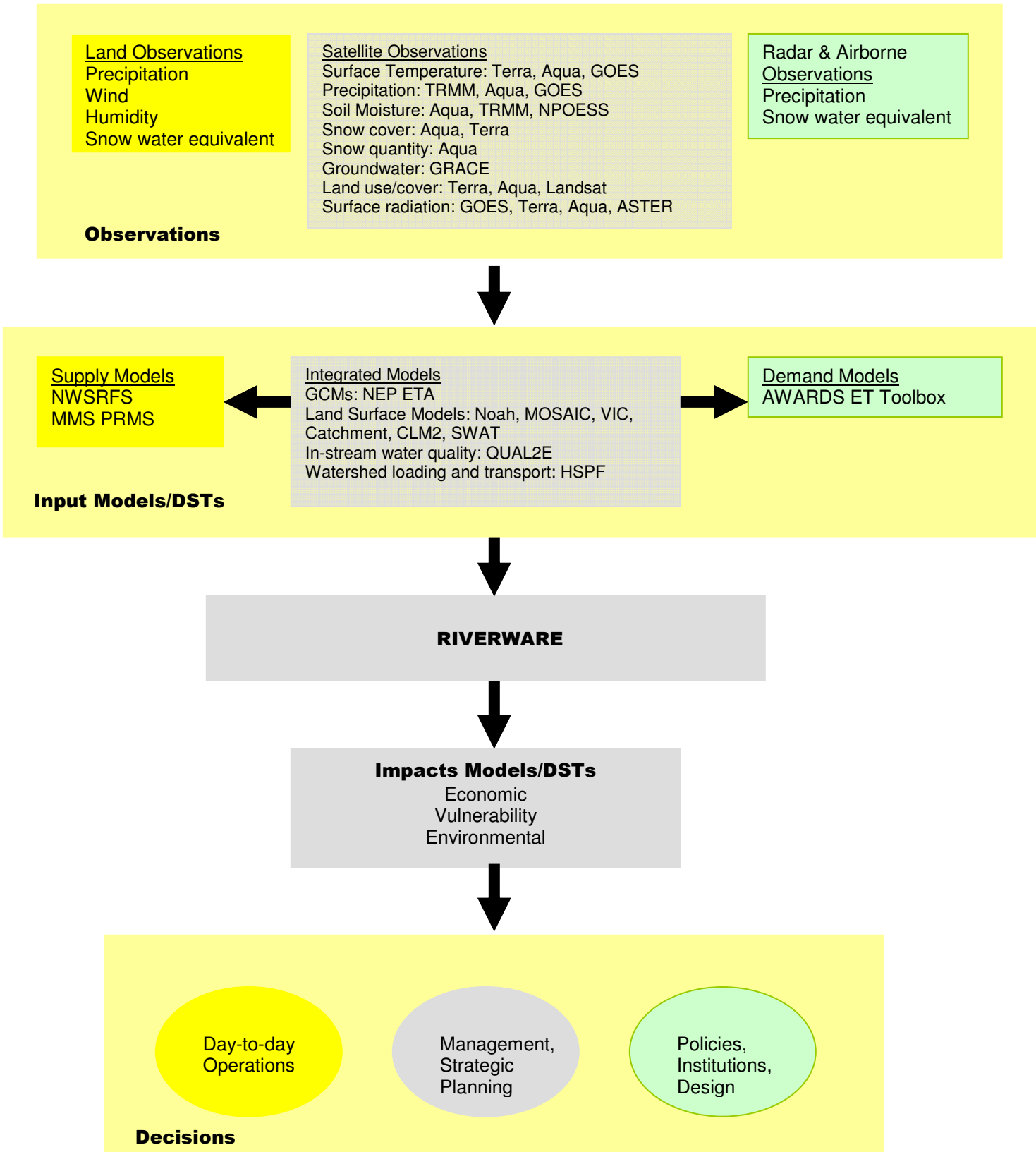
Policies, Institutions, Design

Figure 1: Illustration depicting the flow of information

Appendix A

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3265   **APPENDIX B**

3266   **List of Figures by Chapter**

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3270   **Chapter 1:**

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3280   **Chapter 2:**

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3292   **Chapter 4:**

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3294   **Figure 1:** Relationship between the occurrence of black-legged tick presence at a site and minimum

3295   temperature (top) and evaluation of model (bottom)..

3296   **Top Panel:** Log odds plot for relationship between *I. Scapularis* population maintenance and minimum

3297   temperature (T).

3298   **Bottom Panel:** ROC Plot describing the accuracy of the autologistic model.

3299   **Figure 2**: Forecast geographic distribution of the black-legged tick vector east of the

3300   100[th]meridianin the United States for DSSPL.

3301   **Figure 3**: Forecast change in black-legged tick distribution in Eastern and Central North   America under

3302   climate change scenarios using DSSPL

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3304   **Chapter 5:**

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3306   **Figure 1:** Illustration depicting the flow of information

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3309   **Appendix C**

3310   **Glossary, Acronyms, Symbols & Abbreviations**

3-D	Three-dimensional
ACD	Atmospheric Chemistry Division
AERONET	Aerosol RObotic NETwork
AgRISTARS	Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing
AI	Aerosol Index
AOD	Aerosol Optical Depths
ASOS	Automated Surface Observation Stations
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AWN	Automated Weather Network
BC	Boundary Conditions
BELD3	Biogenic Emissions Land Use Database version 3
CAAA	Clean Air Act and its Amendments
CAM	Community Atmosphere Model
CAMx	Comprehensive Air quality Model with Extensions
CBv	Carbon Bond V
CCSP	Climate Change Science Program
CDC	Disease Control and Prevention
CEMPI	Center for Environmental Modeling for Policy Development
CENR	Committee on Environment and Natural Resources Research
CH4	Methane
CM2	Climate Model 2
CMAQ	Community Multiscale Air Quality

CMAS	Community Modeling and Analysis System
CNES	Centre National d'Etudes Spatiales
CO₂	Carbon Dioxide
CONUS	Continental United States
CTM	Chemistry Transport Modeling
DDSPL	Decision Support System to Prevent Lyme disease
DEM	Digital Elevation Models
DG	Distributed generation
DLR	German Aerospace Center (DLR) (German: Deutsches Zentrum für Luft- und Raumfahrt e.V.)
DMSP	Defense Meteorological Satellite Program
DSSs	Decision Support Systems
DSTs	Decision Support Tools
ECMWF	European Centre for Medium-Range Weather Forecasts
EPA	Environmental Protection Agency
ESMP	Earth System Modeling Framework
ESRI	Environmental Science and Research Institute
ESRL	Earth Systems Research Laboratory
ESSL	Earth and Sun Systems Laboratory
EUTMETSAT	European Organization for the Exploitation of Meteorological Satellites
FAS	Foreign Agricultural Service
GACP	Global Aerosol Climatology Project
GADS	Global Aerosol Dataset
GCM	Global Climate Model
GCTM	Global Chemistry Transport Models
GEO	Group on Earth Observations
GEOS	Goddard Earth Observing System
GEWEX	Global Energy and Water Experiment
GFDL	Geophysical Fluid Dynamics Laboratory

GhTOC	HourlyTotal Ozone Column
GIS	geographic information system
GISS	Goddard Institute for Space Studies
GLCC	Global Land Cover Characterization
GMAO	Global Modeling and Assimilation Office
GOCAT	Global Ozone Chemistry Aerosol Transport
GOES	Geostationary Environmental Operational Satellite
GOME	Global Ozone Monitoring Experiment
GsT	Geospatial Toolkit
GTCM	Global Tropospheric Chemistry Model
GTS	Global Telecommunications System
HMS	Hazard Mapping System
HOMER	Hybrid Optimization Model for Electric Renewables
IGOL	Integrated Global Observations of Land
INPE	Brazilian Spatial Institute
IPCC	Intergovernmental Panel on Climate Change
ISH	Integrated Surface Hourly
KAMM	Karlsruhe Atmospheric Mesoscale Model
kw	Kilowat
h	Hour
m	Meter
LACIE	Large Area Crop Inventory Experiment
LULC	Land Use and Land Cover
MATCH	Model of Atmospheric Transport and Chemistry
MCIP	Metorology-Chemistry Interface Processor
MIST	Multi-Angle Imaging Spectroradiometer
MM5	Mesoscale Model Version 5
MODIS	Moderate Resolution Imaging Spectroradiometer

MOZART	Model of Ozone and Related Chemical Tracers
N2O	Nitrous oxide
NASA	National Aeronautics and Space Administration
JPL	Jet Propulsion Laboratory
SSE	Surface meteorology and Solar Energy
USGS	US Geological Survey
NCAR	National Center for Atmospheric Research
NCAR- NCEP	National Center for Atmospheric Research-National Centers for Environmental Protection
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NSTC	National Science and Technology Council
OCO	Orbiting Carbon Observatory
OMI	Ozone Monitoring Instrument
AOT	aerosol optical thickness
TOC	Total Ozone Content
P	Wind Power Density
PECAD	Production Estimate and Crop Assessment Division
CADRE	Crop Condition Data Retrieval and Evaluation system
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
RCM	Regional Climate Model
ReGAP	Regional Gap Analysis Program
RPOs	Regional Program Organizations
SAP	Synthesis and Assessment Product
SHEDS	Stochastic Human Exposure and Dose Simulation

SIP	State Implementation Plans
SPOT	Systeme Pour L'Observation de la Terre
SRTM	Shuttle Radar Topographic Mission
SSE	Surface meteorology and Solar Energy
SSM/I	Special Sensor Microwave/Imager
SSMR	Scanning Multichannel Microwave Radiometer
STAR	Science to Achieve Results
SWERA	Solar and Wind Energy Resource Assessment
TES	Tropospheric Emission Spectrometer
TOMS	Total Ozone Mapping Spectrometer
TOMS	Total Ozone Mapping Spectrometer
TRI,	Total Risk Integrated Methodology
U.S.	United States
UIUC	Unknown Sent email to Daewon
UNC	University of North Carolina at Chapel Hill
UNEP	United Nations Environment Programme
USDA	Department of Agriculture
EROS	Earth Resources Observation Systems
USWRP	United States Weather Research Program
V	Wind Speed
WAsP	Wind Atlas Analysis and Application Program
WRAMS	Wind Resource Assessment Mapping System
WRDC	World Radiation Data Centre
WRF	Weather Research and Forecasting

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