ENVIRONMENTAL SCIENCE COMPUTING

The primary purpose of computing in the environmental sciences is to ellucidate the properties of the atmosphere and ocean and the processes that influence the evolution of the physical environment in time and space. This is accomplished by collecting observations, displaying and visualizing information, and numerically diagnosing and predicting the environment. To this end, a variety of special computing requirements and applications have been developed specifically for the environmental sciences, which must address problems ranging from long-term climate assessments to the immediacy of observing and predicting small-scale weather phenomena, such as tornadoes. This range of problems requires the long-term collection and storage of a wide range of parameters that describe the physical environment (observations) and the rapid collection and use of observations and information for assessing and predicting the environment in real time. Because of this range of problems in environmental science, computing tools have evolved into flexible applications capable of meeting many requirements and highly specialized applications aimed at a single environmental problem.

Computing in the environmental sciences is logically divided into three primary areas. First, the numerical simulation or modeling of environmental systems is a major area of computing in the environmental sciences. In this application of computers to environmental science, equations governing some aspect of the physical system are numerically solved to predict and depict the atmosphere or ocean. Perhaps most advanced in this application of computing is the numerical prediction of weather done routinely at numerous national centers and various universities. The second major use of computers in the environmental sciences is for visualizing complex four-dimensional data sets. In this application, observations and numerical model results are displayed using both tailored and generic computer graphics and visualization programs. This ranges from generating simple graphical products to three-dimensional animations of dynamic or structural properties of the atmosphere or ocean. The third area of computing in the environmental sciences focuses on collecting observations from environmental sensors or instruments of various types. In this application, individual electronic sensor or instrument signals are collected locally or over a wide area as part of a network of observations for use by environmental scientists. Simple systems for electronically logging these observations on a computer disk to elaborate real-time data collection systems over broad geographic domains have been designed to address this aspect of computing in environmental science.

Background and Theoretical Considerations

The requirements of environmental science for real-time environmental monitoring and prediction, the collection, display, and communication of geographically distributed information, the long-term storage of a wide range of environmental observations, and other factors combine differently to uniquely influence the development of specialized environmental computing applications in each of the three primary areas. For example, the computing constraints and challenges imposed in the area of numerical prediction are rather different from those in the area of observation collection over a broad network. Consequently, it is useful to examine the requirements and theoretical basis for each of the three areas individually.

NUMERICAL MODELING

An important goal in many areas of environmental science is to predict the future state of the atmosphere and ocean or some related aspect of the physical environment, such as river flow or air pollution concentration. Predictions or forecasts of the physical environment are often done by utilizing an appropriate set of governing equations that are solved to obtain the time-dependent behavior of the environment. Analytic solution of the governing equations is generally not feasible because of their coupled, nonlinear nature. Consequently, numerical solutions are typically obtained through specially developed computer software, which are numerical models of the atmosphere, ocean, or other environmental system. For example, numerical models are routinely used worldwide to predict weather, ocean temperature and waves, and to assess the dispersion of various atmospheric pollutants. Each type of numerical model differs in its computational details but the basic approaches for constructing and operating these computer models are rather similar.

To illustrate the specific approach by which computers are used to numerically model the environment, the approach taken to model the atmosphere is used as an example. The theoretical basis by which computers are used to numerically solve the equations governing the atmosphere is described by Haltiner and Williams (1) and is relatively simple to understand. The following are a complete yet simplified set of equations that govern the dynamics and thermodynamics of the atmosphere:

$$\frac{\partial u}{\partial t} = -\boldsymbol{V} \cdot \nabla u + \frac{1}{\rho}\frac{\partial p}{\partial x} + fv + F_x$$

$$\frac{\partial v}{\partial t} = -\boldsymbol{V} \cdot \nabla v + \frac{1}{\rho}\frac{\partial p}{\partial y} - fu + F_y$$

$$\frac{\partial Z}{\partial p} = \frac{-1}{\rho g}$$

$$\frac{\partial T}{\partial t} = -\boldsymbol{V} \cdot \nabla T + \omega\left(\frac{\kappa T}{p}\right) + \dot{Q}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0$$

$$p = \rho R T$$

where $\boldsymbol{V}$ is the three-dimensional wind vector (u, v, ω) in the coordinate system (x, y, p), T is the absolute air temperature, Z is the geopotential height, F_x,F_y are x and y components of surface friction, ρ is air density, $\dot{Q}$ represents diabatic heating processes, t is time, and f, κ, and R are various constants. These equations are the so-called primitive equations which are derived from the basic conservation principles of physical variables, such as momentum, thermodynamic energy, and mass. Although the exact form of these equations differs slightly in specific applications, they embody the important principles governing atmospheric flows and illustrate the basic application in many numerical prediction models. Note that the variables appear multiple times in multiple equations, which results in their coupled, nonlinear character.

The numerical solution to these equations is carried out by transforming the derivatives into finite differences, mapping continuous distributions of atmospheric structures to a discrete grid, and specifying an initial state from which the model is integrated forward in time. The transformation of the basic equations containing various spatial derivatives into a discretized, finite-difference representation is a standard practice in numerical analysis. The primary difference between standard numerical analysis and formulating numerical model equations is in the representation of physical processes not directly measured. For example, the release of latent heat during condensation of water in a convective cloud must be approximated because direct measurements of liquid water in clouds are generally not available. Approximations of various physical processes are typically done to produce a set of equations that can be solved using information actually measured.

The next step in obtaining a numerical solution is to map the continuously distributed atmosphere to a grid covering the geographic region of interest. Mathematically, this simply means that the model equations are solved on a discrete grid of points. Physically, this discretization of the atmosphere implies a definite physical distance between the grid points, which sets a minimum resolvable length scale for the model. The physical spacing (grid distance) can be decreased within the constraints imposed by computer memory and desired geographic coverage. Generally, large geographic domains have larger distances between model grid points and smaller domains have relatively close separation of grid points. The size of the numerical grid strongly influences the computational time required to integrate the model over a specified forecast period. Consequently, numerous factors must be balanced against each other to produce numerical models that produce solutions of some accuracy over a geographic domain of interest in a specified time.

The next crucial aspect in this process is that to integrate these equations forward in time, the initial state of the environment must be obtained on the grid being used for numerical computations. Obtaining this initial state of the atmosphere or ocean depends on collecting observations and transforming them into a three-dimensional depiction of the initial state of the atmosphere or ocean. This transformation of direct measurements of the environment into gridded depictions of the atmosphere or ocean is done through a process called data assimilation, which, as described by Daley (2), may be as simple as mathematical interpolation or as complex as spatial fitting using the governing equations as weak or strong constraints. This data assimilation process is a highly specialized application of various mathematical concepts in computer software tailored to this specific environmental science problem.

Although numerical prediction is a major area of computing in the environmental sciences, calculating individual terms in the model equations or other more simplified equations is often done to gain insight into particular physical processes and to improve our understanding of the environment. This application of computing is to perform numerical diagnosis on either gridded numerical model output or directly on observations of the environment. This aspect of computer applications to environmental science provides a strong link to display and visualization applications that are specifically targeted at environmental problems and often contain appropriate diagnostic equations as part of the display and visualization software.

DISPLAY AND VISUALIZATION REQUIREMENTS

Although numerically solving the predictive or diagnostic equations for the atmosphere or ocean is of great interest in environmental science, computers perform their greatest role in environmental science by displaying observations, numerical model results, and other environmental information in an interpretable visual form. Environmental information comes in three basic primary forms for visualization: gridded numerical fields output from a model or data assimilation system; raw observations taken at specific points in space; and images of remotely sensed observations covering entire geographic areas. These basic kinds of data provide different types of information ranging from uniform three-dimensional distributions (gridded volume data), to scattered point samples in three dimensions, and to planar representations of three-dimensional information (two-dimensional images). Each basic type influences how it is typically displayed.

Fundamental to the display of environmental science information is the need to convey three- and four-dimensional geographic relationships among multiple parameters. For example, point measurements of surface air temperature and winds over the continental United States are used to define storm systems and fronts. In oceanography, the sea surface temperature is determined in part by the distribution and strength of surface currents and the surface wind. And in air pollution, the low-level air flow, the tendency for vertical mixing (stratification), and the distribution of pollution sources combine to determine the transport and concentration of pollutants. Information on the required variables to understand the atmosphere or ocean come from point measurements, images, and numerical model output. Consequently, the geo-

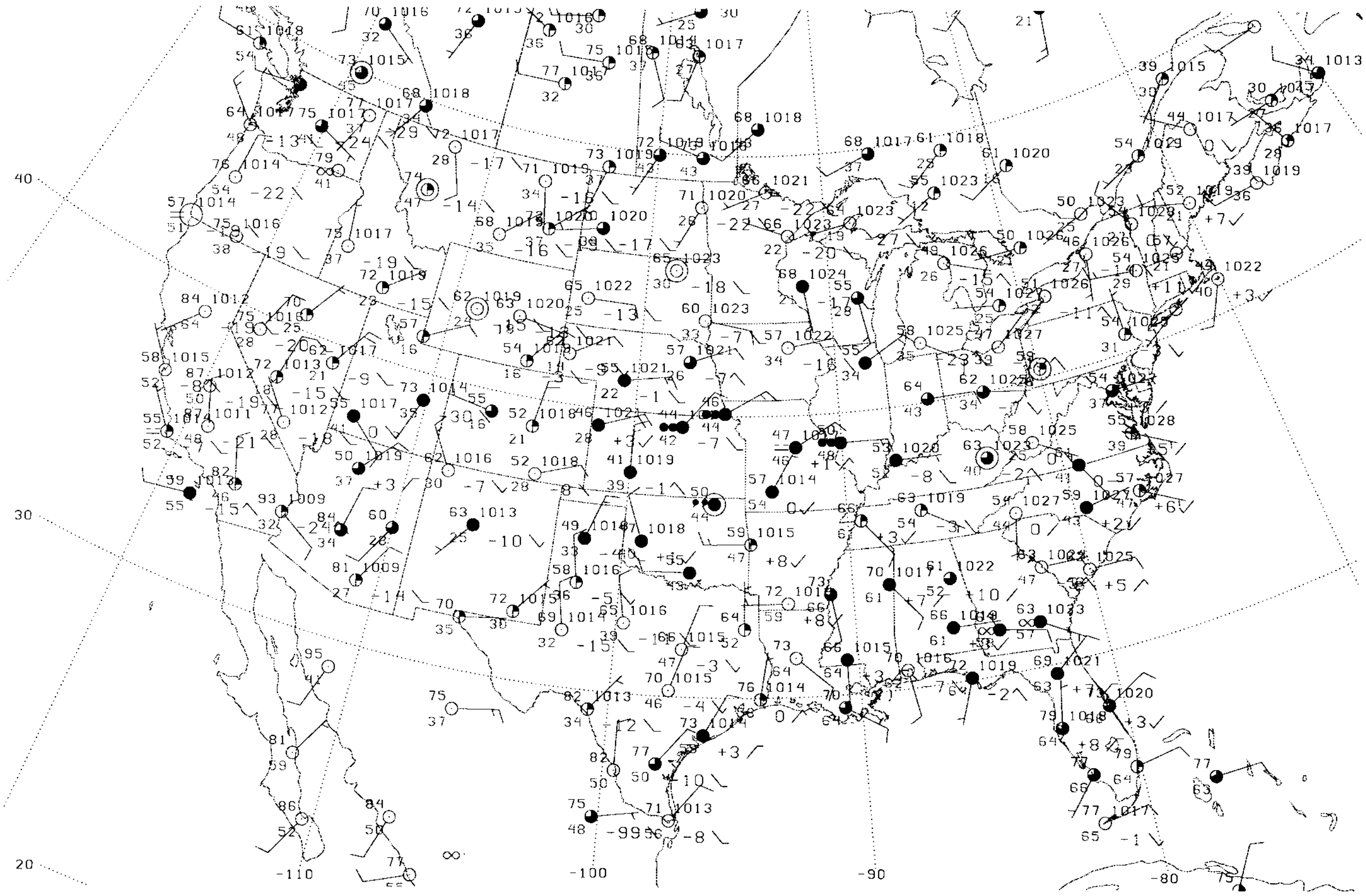

Figure 1. Map of the United States with weather observations plotted. Station plots consist of a circle that is filled based on cloud cover observations, a wind barb showing wind direction and speed, weather symbols for rain, fog, haze, etc., a pressure tendency trace, and numerical values for the temperature, dewpoint temperature, sea-level pressure, and pressure change.

graphic and multiparametric relationships are crucial aspects of environmental science display and visualization software.

The geographic information needed to properly relate observations or numerical predictions to physical locations on the earth is typically handled by placing observations or model output on a geographic map. The map is rendered by drawing appropriate geographic features, such as continental outlines, state boundaries, or latitude and longitude lines using a mathematically prescribed cartographic projection (3). Lambert conformal projections, Mercator projections, polar stereographic projections, and others are widely used to generate a geographic background upon which environmental data are displayed. Data sets may occur in one map projection but need to be accurately displayed in another map projection. Thus appropriate map transformations are a part of many specialized display systems and a comprehensive code base for map transformations is available from the US Geological Survey (USGS).

Geographically scattered, point measurements are common in the environmental sciences and displaying this type of information is a fundamental requirement for environmental scientists. For example, weather observations consisting of temperatures, winds, cloud cover and heights, visibilities, etc. are routinely taken at airports around the world. Although reports are used individually for some purposes, collecting these reports over a region provides a more complete depiction of the weather conditions. Display systems are challenged to depict the multiple parameters in a geographic display that can be interpreted by meteorologists. Figure 1 shows a plotted weather map, on which the various types of observations are plotted as text or symbols in a specified configuration around the marker indicating the station location on a geographic map. To a trained meteorologist, observational plots of this type are easily interpreted and provide a wealth of environmental information. Much more simplified versions of this observational plotting is used in some other environmental science applications, but the weather map is perhaps the most developed use of this display approach.

Although point measurements like weather observations lend themselves to simple plots on a suitable map, other types of environmental observations, such as satellite images and radar volume scans must be displayed in different forms. Figure 2 shows a satellite image, which is essentially a photograph taken in a specific wavelength band (visible light in this case). The image consists of a block of individual picture elements (pixels) that are mapped to a color table by the magnitude of the light received by the satellite. This image is displayed in its inherent map projection on which the earth becomes a distorted disk produced by the downward looking camera. The image displays cloud information over a broad area of the earth. An appropriate map overlay is crucial to provide needed geographic information. Sometimes images are remapped into a preferred map projection compatible with other types of environmental information. Depicting and interpreting the spatial structure seen in the image is crucial in using images in the environmental sciences. In Fig. 2, the white areas represent clouds, and other areas represent clear air. In other types of images, color mapping is used to highlight features of importance. For example, infrared wavelength images are used to extract ocean surface temperature distributions by appropriate color mapping to highlight this aspect of the image. Radar volume scans from a fixed location also produce images but over a small region compared to satellites. Color mapping to highlight structure in the image and some form of geographic referencing are also used for these types of images.

Numerical model output or mathematically interpolated point measurements provide the richest two- or three-dimen-

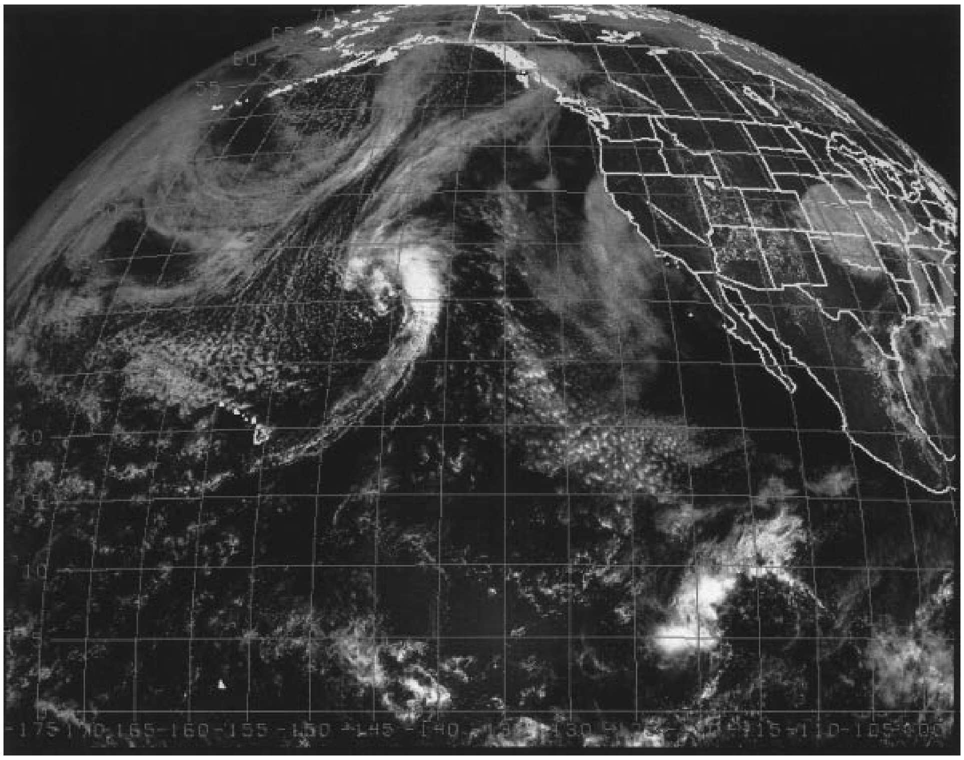

Figure 2. Satellite image of the western United States and Pacific Ocean regions. Image is in visible light and clouds appear as white areas on the image.

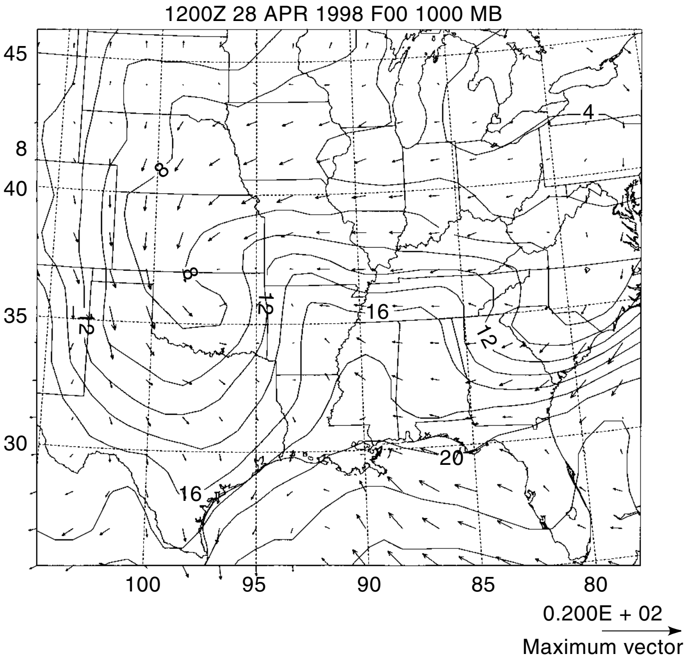

Figure 3. Plot of numerical model grid over the southeastern United States showing temperature contours in degrees Celsius and scaled wind vectors (arrows) where the length is proportional to speed.

sional environmental data sets available for display and visualization. The spatial completeness of this type of data allows for a wide range of display types, such as contouring, vector maps, isosurfaces, and three-dimensional volume representations. Because of the computational completeness of numerical model data, the key element dictating the visual form for displaying this data is the information content required by a certain user or group of users. Each of the various display forms emphasize unique aspects of the environmental data, which may or may not contribute to the ease of interpretation by the environmental scientist.

Contour maps provide a highly quantitative means for displaying two-dimensional geographic spatial relationships in environmental data. Figure 3 illustrates a contour plot of the air temperature obtained from a numerical model of the atmosphere. The locations and magnitudes of the relative warm and cold spots are immediately evident as are the regions of strongest horizontal temperature gradient. This basic structure supplies the geographic relationships needed to interpret the possible evolution of the environment. Also shown in Fig. 3 is a scaled vector plot of the winds whose vector length is proportional to the wind speed. Scaled vector plots, streamlines, and wind barb plots provide two-dimensional structural information about vector fields similar to that provided by contour plots for scalars. The high wind regions and the basic flow directions are easily located over the geographic region. As illustrated by the dynamic equations in the previous section, the tendency for the wind to blow across lines of temperature partially determines the temporal evolution of the temperature. This thermal advection ($-\boldsymbol{V} \cdot \nabla T$) is easily identified using a contour map with the wind vectors plotted on top as shown in Fig. 3. Contour maps and scaled vector plots or wind barb plots provide direct quantitative information about the environment whereas other types of visual displays are not as easily interpreted quantitatively.

The three-dimensional nature of the atmosphere or ocean requires displays capable of illuminating the three-dimensional spatial structure. Direct volume rendering (4), isosurfaces (5), vector objects (6), and other techniques (7) meet these needs. For example, in meteorology the position of the strongest upper level divergence relative to the low-level moisture distribution is important in determining where thunderstorms may form. This information is obtained from multiple horizontal contour plots but is more easily illustrated in a three-dimensional display. Figure 4 depicts isosurfaces of the divergence and convergence of the horizontal wind. The coupling of upper level divergence to low-level convergence imposed by mass continuity is evident in Fig. 4. This vertical coupling and the vertical and horizontal structure are very well illustrated by this or similar three-dimensional displays. However, a major disadvantage of these types of displays are the difficulty by which quantitative information is quickly discerned by the user. Some environmental information is very instructive when viewed in three dimensions whereas other information is quite meaningless without easily discernible quantitative values.

The need to display the temporal aspects of environmental science problems have resulted in additional specialized software, which is described later in this article. Specific features in displays of fundamental parameters or complex derived variables undergo tremendous time evolution. For example, the cloud distribution around an extratropical low pressure system evolves from a relatively linear feature to a rotating comma-shaped cloud over a broad area as the storm develops. This evolution is related to storm dynamics and structure

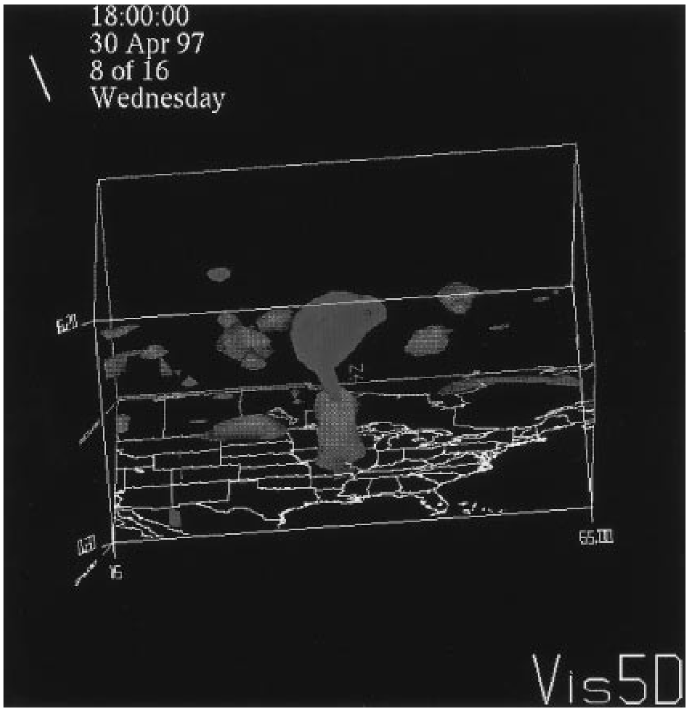

Figure 4. Three-dimensional perspective of the Eastern United States showing isosurfaces of horizontal divergence (green) and convergence (purple). Plot is generated using VIS5D.

which are related to the time tendencies in the atmosphere that occur over a few hours to a few days. Looping or animation technologies are typically used to illustrate these kinds of evolutions. These animations generally consist of a series of still frames separated by some reasonable time increment to provide a more or less smooth evolution of the features of interest. For example, a series of satellite images may be separated by as little as a few minutes to depict detailed cloud evolution, whereas larger scale atmospheric analyses are effectively looped using six hour time steps.

INSTRUMENTATION AND DATA COLLECTION

The third major area of specialized use of computers in environmental science is for making and distributing observations or measurements of the environment. Instrument manufacturers and designers utilize various techniques to convert raw analog electronic signals from sensors into environmentally relevant measurements. Electronic signal processing is a highly specialized application of electronics engineering for environmental measurements that range from simple temperature measurements to derived velocity measurements using the Doppler shift of various radar, sound, or light signals. Electronic signal processing is specific to individual instruments but all instruments eventually return a digital signal called the environmental measurement or observation.

Environmental observations are typically collected over some geographic area of interest. Observation sites are usually collections of numerous individual sensors or instruments whose observations are collected by a data logger or computer at the observation site. Geographically distributed observations are achieved by deploying suites of instruments at numerous observing sites. This distribution of observing sites may be achieved through the collection efforts of a single agency or researcher but is often achieved by multiple agencies and/or researchers, such as that coordinated by the World Meteorological Organization (WMO) (8). Observations from the geographically distributed sites must be collected centrally as a complete set of observations for optimum use by environmental scientists. This is an observing network consisting of a number of observing sites and types of instruments or measurements. The collection of multiple observations in an observing network is an important area using computers in environmental science, especially meteorology.

The collection and redistribution of multiple observations represents a mix of specialized computing and data communications systems. Because there is a need in environmental science for real-time observation and prediction, considerable effort has gone into developing data exchange networks and data exchange formats to allow compact and rapid transfer of data. Most developed is the meteorological observing network which takes data collected world wide and distributes these observations to numerical modelers, weather forecasters, and other users. The operational network uses specialized reporting standards and the Global Telecommunications System to distribute these environmental observations worldwide (9).

Local observational networks developed for specific purposes or for a particular environmental science area are common. These local networks often use phone lines, dedicated Internet lines, radio links, and satellite communications to collect observations over the network. For example, many air quality agencies maintain a network of local observing sites to monitor pollutants and other meteorological conditions. These observations are collected via modem dial-up or radio links to provide these data to the agency for its own use. The sophistication and timeliness of the data collection in these local networks is dictated by use requirements and resources.

Beyond the data collection step, archival of environmental data is a very important area to support research and to conduct longer term studies, such as climate monitoring. Archival methods range from cataloging files of observations, images, and numerical model output to highly developed database systems using relational database technology (10,11). A very significant challenge in archiving of environmental data is the volume of data sets, particularly satellite images, radar observations, and numerical model output. The volume poses challenges to relational database systems and typically necessitates off-line storage media, such as tapes.

Software and Computer Systems

The variety of environmental science problems and the requirements for numerical modeling, display and visualization, and observation collecting have resulted in a wide collection of software tailored to environmental science. The following sections describe some of this software and the approaches for meeting the various environmental science needs highlighted in the previous section. Most environmental science computing is done using specialized software installed on a variety of standard computer hardware ranging from personal computers (PCs) to high-end, large-scale computers (Cray C-90s). Specialized hardware in environmental science computing is largely limited to specific instrumentation where the needs are more limiting. In fact the trend in recent years has been to make environmental software portable to most types of computing hardware.

NUMERICAL MODELING

The application of numerical models in environmental science is quite widespread and covers a broad range of problems. The importance of this application of computers to environmental science can be seen by the number and type of models in use, each of which represents a piece of specialized environmental science software. Table 1 lists a selection of some common environmental numerical models and their intended application. Most mature in the application of numerical modeling to environmental science is the numerical prediction of the atmosphere and ocean routinely carried out in various operational centers around the world. Some of these numerical models are listed in Table 1 with their associated parent organizations. Operational application of these numerical weather prediction models (13) consists of running these models routinely (typically twice a day) utilizing the plethora of available meteorological observations. The resultant forecasts are distributed to a wide user community of weather forecasters and atmospheric scientists. These operational models are computationally efficient and robust, so that numerical instabilities rarely arise and forecasts that extend 48 to 240 h or beyond in time are obtained within a few hours after the model is initiated on the computer. To support these large computational problems, most operational weather fore-

Table 1. Numerical Models in Environmental Science

Model	Developer of Model	Use
ETA Model	National Centers for Environmental Prediction (NCEP)	Operational weather forecasts
Medium-range forecast model	National Centers for Environmental Prediction (NCEP)	Operational weather forecasts
Nested-grid model	National Centers for Environmental Prediction (NCEP)	Operational weather forecasts
NOGAPS, Navy Operational Global Atmospheric Prediction System	Fleet Numerical Meteorological and Oceanographic Center (FNMOC)	Operational weather forecasts
NORAPS, Navy Operational Regional Atmospheric Predicton System	Fleet Numerical Meteorological and Oceanographic Center (FNMOC)	Operational weather forecasts
COAMPS, Coupled Ocean and Atmospheric Prediction System	Naval Research Laboratory (NRL)	Operational weather forecasts
MM5, Penn State/NCAR Mesoscale Model	National Center for Atmospheric Research (NCAR)	Research and quasi-operational weather forecasts
RAMS, Regional Atmospheric Modeling System	Colorado State University	Research and quasi-operational weather forecasts
ARPS, Advanced Regional Prediction System	University of Oklahoma	Research and quasi-operational weather forecasts
UAM, Urban Airshed Model	Environmental Protection Agency	Air quality research
WAM, Wave Model	European Center for Medium Range Weather Forecasting (ECMWF)	Operational ocean wave forecasts

cast centers utilize high-end, large-scale computing hardware, such as the Cray C-90 or comparable systems. Other types of atmospheric models include climate models, photochemical pollution models, cloud models, and dispersion models.

Ocean modeling is also carried out routinely (14) for a variety of research applications (15). The ocean models listed in Table 1 represent examples of the types of ocean modeling being done. Full-physics ocean models are computationally comparable to their atmospheric counterparts but typically have less observational information from which to be initiated. Other types of ocean models are wave and swell models and ocean mixed-layer models, which focus on a more specific aspect of ocean prediction.

Although the output from models for research or local use poses no special computing problems, the output from operational models must be delivered to appropriate users in some form. Given the size of the numerical grids, graphical products have been the primary means by which operational centers deliver model forecasts to users. Now this is typically accomplished through WWW displays available for public viewing (16). However, the gridded output is also delivered to some users, such as National Weather Service offices and university researchers, for local processing to perform needed diagnostic and graphical analysis. The dissemination of the raw model output from operational forecast centers is handled by packing the output as much as possible into compressed forms to be subsequently delivered through a variety of computer network distribution systems (17).

DISPLAY AND VISUALIZATION SOFTWARE

A relatively large selection of display and visualization software supports a variety of environmental science applications. Display and visualization software can be divided into two basic classes: rudimentary graphics software and high-level applications software. Rudimentary graphics software is primarily aimed at software developers who build specific environmental applications from the basic graphics routines. Although this graphics software is generally useful in a wide range of applications beyond environmental science, some rudimentary packages are aimed directly at environmental science problems. NCAR Graphics (18) is one of the most well-known graphics packages used in the atmospheric and oceanic sciences by research scientists capable and willing to develop their own computer codes. A large body of special purpose display packages developed by individual scientists or by groups of scientists has been built from base level display packages, such as NCAR Graphics. This body of software is largely undocumented in the literature but freely shared among scientists through direct contact. High-level applications software are aimed directly at environmental scientists and have been developed by larger institutional development efforts and commercial interests. Table 2 lists some of the common high-level environmental display and visualization software. This software is often tailored to specific data sets and user needs that have relatively wide applicability.

As suggested in Table 2, a large body of environmental display software exists and the differences between the various software packages resides primarily in their user interface and the breadth of input data that is easily accepted. For example, in two-dimensional display systems, the Gempak (19) Analysis and Rendering Program (GARP) has a relatively simple interface and the displays a wide range of meteorological data stored in a standard directory and file structure. This system displays gridded model data as contours or vectors (where appropriate), meteorological observations as station plots, and satellite or radar imagery. These displays can be overlaid to make composite charts, which allow cross-checking environmental information and validating of models against observations or satellite imagery. Display can also be animated over a time loop when multiple time periods are available. The package includes a zoom capability using a rubber-banding approach, which adds additional observations

Table 2. Environmental Science Display and Visualization Software

Software Package	Developer	Use
NCAR Graphics	National Center for Atmospheric Research	General graphics
GL/Open GL	Silicon Graphics Inc.	General graphics
MATLAB	The Mathworks	General computation and graphics
GEMPAK/GARP	NASA/UCAR	Two-dimensional weather graphics
WXP	University of Illinois	Two-dimensional weather graphics
GrADS	University of Maryland	Two-dimensional weather graphics
Ferrett	NOAA PMEL	Two-dimensional weather graphics
VIS5D	Space Science and Engineering Center (SSEC) of the University of Wisconsin-Madison	Three-dimensional weather graphics
Vtk	Visualization Toolkit	Three-dimensional graphics
IBM Data Explorer	IBM	Three-dimensional graphics
AVS	Advanced Visual Systems	Three-dimensional graphics
SLVG	University of California, Santa Cruz	Three-dimensional weather graphics
Environmental WorkBench	SSESCO	Three-dimensional weather graphics
LAPS	NOAA FSL	Two- and three-dimensonal weather graphics

to the display as the domain size decreases and uncluttered space becomes available. This allows the meteorologist to look at larger scales and then focus on the smaller scale features of interest. On the other hand, some packages incorporate probe tools, have an easier method for performing diagnostics, and handle specialized data types. The key element in these two-dimensional display packages is that the technology is definitely user-driven and the basic capabilities are similar.

Three-dimensional display software, such as the Local Analysis and Prediction System (LAPS) (20), VIS5D (21), the systems developed by the Santa Cruz Laboratory for Visualization and Graphics (SLVG) (22,23), the Visualization Toolkit, or others listed in Table 2 are more different in capability and user interface than the predominantly two-dimensional packages. Most packages generate graphical objects like isosurfaces, three-dimensional streamlines, and perspective views of two-dimensional objects, like contours or vectors. Data ingestion often requires more manipulation, and these packages rarely include environmental diagnostic computational capability. Because the visualization in three dimensions requires a three-dimensional volume of data, these packages are most suited for use with numerical model data. However, some packages, such as LAPS and SLVG, have attempted to allow more integrated displays of observations, satellite images, and three-dimensional renditions of model data. This is an area of great potential in the environmental sciences that has been hampered because the use of visualization software by scientists is not easy and making quantitative interpretations of the graphical objects is difficult.

Images and image analysis software is another area of environmental science software. In its simplest form, satellite and other images are displayed on an appropriate geographic background using a color mapping for the pixels. This is the level of image analysis in most combined display packages, such as GARP. In more extensive packages, the color map, pixel transformation and values, or other image aspects are extracted or manipulated for a particular application. For example, the NOAA polar-orbiting satellite measures infrared (IR) radiation emitted by the ocean surface which can be extracted into a sea surface temperature (SST) analysis. Image analysis software removes clouds that obscure the view of the ocean surface and turn the emitted radiation into an appropriate temperature. Numerous other types of image analysis algorithms included in some image analysis software packages, have been developed and are used to determine aerosol distributions, ocean color which is related to biological processes, cloud motions, and vertical temperature structures.

The most active area of specialized display applications today is associated with WWW products. In their simplest form, many web images in the environmental sciences are simply created by one of the common display packages mentioned previously and then are linked in a hypertext markup language (HTML) document. However, some interactive packages are beginning developing where the display can be constructed by the web browser. One example of this activity is to install the needed display software, like VIS5D, as a web browser plug-in and then develop interface tools to send commands to the display program. Other approaches are to utilize software on the host system to display desired products constructed by the user. The web interface brings a new set of environmental data users who require more easily interpretable products.

DATA COLLECTION AND MANAGEMENT SOFTWARE

Beyond individual instruments and their attendant software, environmental data collection over a wide area is a major piece of environmental computing. At the root level, data collection is primarily a set of message passing and parsing software that sends and retrieves data from an instrument or data source. Standard networking procedures are typically used for the message passing but specialized software has been developed to handle the volume of message traffic from a worldwide observing network. The Unidata-developed Local Data Manager (LDM) (25) provides a model of this activity where a data stream is delivered over a network and then parsed into individual data files based on the data type. Similar software is embedded in many real-time meteorological data processing systems, such as Advanced Weather and Image Processing System (AWIPS) (26). The typical approach is to place the messages into files for use by display or other software.

Database systems are being used to manage both archived and real-time observations in environmental science. Archival data fit well into the software structure of most relational database systems and this has been utilized in several efforts in environmental science. The Master Environmental Library (MEL) project (27) of the Naval Research Laboratory is one archive system that contains a large cross section of environmental data. Data stored in this system can be retrieved for subsequent analysis and research. More problematic has been the application of this technology to real-time use. The Real-time Environmental Information Network and Analysis System (REINAS) project (28) at UCSC was directed specifically at this problem and has developed a working, real-time, data management system using relational database technology. A key problem to be solved was inserting high frequency, high volume data into the database system. The REINAS approach uses a logging system to provide a buffer between the data collection and the database insertion, which can fall behind the data collection. This logging allows for real-time use of data even if it is not yet written in the database.

FUTURE DIRECTIONS

The primary factors that drive the future of environmental science computing are the increases in numerical modeling capability and the closer union of models, observations, and display systems. The primary impediments to advances in numerical modeling that reduce the size and sophistication of numerical models are the memory size and speed of high-end computers. As these increase, the size of computational domains will no doubt increase as will the computational sophistication in the physical representation in models. To provide timely solutions, very fast number-crunching machines are needed. Another impediment to the accuracy of the numerical models is the availability of smaller scale observations. In the future it is likely that observational capabilities will increase, which will require data assimilation software capable of inserting this information into numerical models. Present trends are to perform 4-D variational analysis which involves inverting a matrix that scales by the number of observations. Consequently, computational speed and memory again become the primary impediments.

Another area of future development is in end-to-end forecast systems, in which the collection of observations, numerical modeling, and visualization are linked in a single system (possibly distributed). The REINAS system is one example of this type of system on a small scale. As this approach to collecting, managing and working with environmental data becomes more widespread, the number of observations, the size of the database, and the sophistication of the models will increase.

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