This project, code-named *Viento*, is a collaborative effort that combines the science of meteorology with the emerging discipline of scientific visualization and innovative satellite networking approaches to study air-lake interactions in the Lake Erie region (ref. 5). This is accomplished by coupling a mesoscale atmospheric model with lake circulation and wave models using NASA's Advanced Communications Technology Satellite (ACTS) satellite network connection, and providing a sophisticated Graphical User Interface (GUI) that supports the visualization and the subsequent analysis of the output of these models. The project involves meteorologists, oceanographers, network researchers and computer scientists located at the The Ohio State University/Ohio Supercomputer Center (OSC), the National Center for Atmospheric Research (NCAR), and the National Oceanographic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL). The coupled system consists of the Penn State University/NCAR three-dimensional, non-hydrostatic mesoscale model MM5 (running simultaneously on a Cray Y/MP 8E at OSC and a Cray J90 at NCAR), and a three-dimensional coastal circulation model and wave model of the Great Lakes Forecasting System, GLFS (running on the Cray J90 at NCAR). This will be the first time that both a coastal circulation model and wave models will be two-way coupled to a mesoscale atmospheric model for study of an inland water body.

The system (see figure 1) is constructed using a distributed supercomputer configuration at NCAR and OSC, with monitoring and evaluation of the computation by expert scientists at GLERL, using the ACTS Gigabit Satellite Network (GSN). Boundary conditions (e.g. surface heat and momentum fluxes, wave heights and direction, lake surface temperatures) are exchanged in real-time via ACTS. Communication between the supercomputers, the ACTS High Data Rate (HDR) ground stations at NCAR and OSU, and the Silicon Graphics 1

1The Advanced Computing Center for the Arts and Design

2The Department of Engineering, etc.

3The Ohio Academic Resources Network
Inc (SGI) Crimson VGXT high-performance graphic workstations at the three sites is achieved using off-the-shelf high-bandwidth network HiPPI and ATM channels. Data exchange between GLERL and the two other sites is accomplished using a terrestrial T3 network. The computational modules communicate with each other and with the visualization software using Parallel Virtual Machine (PVM), which will use TCP/IP as the underlying transport mechanism.

ACTS allows for real-time collaboration and visualization between scientists at GLERL, NCAR and OSU/OSC. This collaboration includes audio and video channels and a sharable whiteboard through the use of existing protocols and the SGI and Sun Microsystems workstations. The original focus of this project was to conduct simulation experiments designed to:

1) examine the impact of spatial and temporal varying lake-surface water temperatures and wave conditions on surface winds and lake-effect snow bands
2) examine the effect of mesoscale atmospheric conditions on the lake's thermal structure, circulation, surface waves and water levels
3) study the impact of techniques of interactive collaboration using visualization and audio/visual channels on scientific teams in disparate locations
4) study the approaches and techniques of integrating high speed, high performance computers with data communications channels built around satellite transmission.

INTRODUCTION

Over the years numerous observational and modeling studies have shown the importance of air-sea interactions in the evolution of both atmospheric and oceanic/lake phenomena. The particular focus of this project is the influence of air-sea interaction on selected atmospheric and lake phenomena in the Great Lakes region. From the atmospheric perspective, many studies have documented the effects of surface water temperature of the individual lakes on lake-effect snow bands (refs. 16, 13, and 10) as well as the cumulative effect of all the lakes on the movement and intensification of low and high pressure centers (refs. 16 and 20). From the lake perspective, its circulation, thermal structure, waves, and water level fluctuations are critically dependent on the wind stresses and surface heat fluxes that drive lake dynamics (refs. 4, 6 and 17).

In order to represent air-sea interaction properly in a numerical modeling study of the above phenomena, it is clear that a coupled lake-atmospheric model is necessary. Of major importance is the correct representation of the heat, moisture and momentum fluxes, which in turn depend critically on the physics of the mixed layers above and below the air-sea interface, and also on the physics of the interface itself. Furthermore, the modeling system must be run at a resolution that is fine enough to capture the scale of the phenomena being studied (e.g., lake-effect snow bands may be as narrow as a few kilometers). To this end, we set out to couple high-resolution, three-dimensional atmospheric and lake models in a two-way interactive mode. A key component of that coupling is a surface wind wave model, which explicitly predicts the roughness of the air-sea interface. To date, coupled modeling systems in the Great Lakes have consisted of a one-dimensional energy balance lake model and a hydrostatic mesoscale atmospheric model (refs. 2 and 12). This project represents the first time that both coastal circulation and wave models are two-way coupled to a mesoscale atmospheric model for an inland water body. Similar but separate two-way coupled ocean circulation/atmosphere and ocean wave/atmosphere mesoscale models have been used for coastal ocean studies (refs. 11 and 7).
This coupling project draws on scientific expertise and supercomputer resources at distant locations. For this reason, it is being sponsored by NASA and the Advanced Research Projects Agency (ARPA) as a project that can demonstrate the usefulness of NASA's Advanced Communications Technology Satellite (ACTS) (refs. 15 and 23). By making use of ACTS' high-data-rate transmission capability (620 megabits/second), scientists are able to (1) run interacting numerical models at widely separated supercomputing locations, (2) instantly visualize output from the running models at all participating sites, and (3) interact with each other in real time through video conferencing technology.

The Viento Project involves meteorologists, oceanographers and computer scientists located at the National Center for Atmospheric Research (NCAR) in Boulder, CO; NOAA's Great Lakes Environmental Research Laboratory in Ann Arbor, MI; and The Ohio State University/Ohio Supercomputer Center in Columbus, OH. The expertise and supercomputer facilities at these three locations are brought together by ACTS to develop the coupled mesoscale atmosphere-lake prediction system for the Lake Erie region. The coupled system consists of the Penn State University/NCAR three-dimensional, non-hydrostatic mesoscale meteorological model (ref. 8) and the three-dimensional circulation model and wave model used in the Great Lakes Forecasting System (ref. 18).

**HARDWARE CONFIGURATION**

The overall system consists of the Cray supercomputers at both NCAR and OSC running the simulation models; Silicon Graphics Inc workstations at all three sites for visualization and analysis of the models; a Sun Microsystems workstation at all three sites that supports the audio/video/whiteboard collaboration between the scientists; and the ACTS and its necessary HDR groundstations at NCAR and OSC — GLERL is connected via a DS-3 terrestrial line between Columbus and Ann Arbor. The hardware components of the OSC system are displayed in figure 2.

At the OSC site, the Synchronous Optical Network (SONET) output from the electronics in the HDR trailer is carried over fibre lines to the OSC Kinnear Road Center (KRC), where the SONET/HiPpi conversion is done in a specialized hardware interface called the LANL box developed at Los Alamos National Laboratories. The HiPpi signal passes through a Network Systems, Inc PS-32 HiPpi switch that connects the Cray, the HDR and the ATM interface, which is called a GigaRouter®, made by NetStar, Inc. The signal is then passed over a single mode fibre channel from KRC to a Fore Systems ASX-200 ATM switch for distribution to the scientific workstations at The Advanced Computing Center for the Arts and Design (ACCAD). The Fore switch includes an NM-155 SONET OC-3c network module which is connected to a Fore VMEbus ATM computer interface and a high performance Sbus ATM interface in the SGI and Sun computers, respectively. The ATM switch also contains a DS-3 Network interface for distribution of the signal over a leased line to the GLERL facilities in Michigan.

Hardware tests of the LANL box were done at NCAR, where they first utilized a long link emulator (LLE) made by BBN to test the signal connection. Loopback tests were then conducted using the HDR groundstation at NCAR and the ACTS. Once the hardware was tested, one of the LANL boxes was sent to OSC. Loopback tests using the OSC groundstation were conducted, followed by end to end tests between NCAR and OSC. At the same time, NCAR and OSC network engineers were busy with network performance testing and fine-tuning the rest of the system components.
SOFTWARE DESCRIPTION

The software configuration can be divided into four basic components:

• the lake and atmospheric simulation models,
• the visualization environment,
• the collaboration channel, and
• the software communications interface.

The Simulation Models

The code which comprises the coupled atmosphere-lake model consists of three components: a mesoscale atmospheric model covering North America and coastal circulation and wave models for Lake Erie. The mesoscale model is the nonhydrostatic version of the PSU/NCAR mesoscale meteorological model MM5. The coastal circulation is a version of the Princeton coastal ocean model while the wave model is a version of the GLERL-Donelan parametric wave model. The wave and circulation models are currently used in the Great Lakes Forecasting System (GLFS) at Ohio State and run on OSC's Y-MP.

MM5 uses four domains, each at successively finer resolution: 54, 18, 6 and 2 km. GLFS uses the output from the 2 km domain and then feeds back the computational results to MM5 for the next time step. In the ACTS experiments, the MM5 domains are distributed with executables running simultaneously on the Y-MP at NCAR and also the Y-MP running at OSC. The finest resolution MM5 domain will be run at OSC along with the lake circulation and wave models. (See figure 3)

MM5 consumes approximately 97 percent of the total CPU time used by the coupled simulations. Initial performance data is available for MM5 in the form of output from perftrace. The model is optimized to run on a Cray Y-MP, taking advantage of its multi-tasking capability. The performance data, provided in full on the following pages, shows the code is dominated by vectorized operations, obtaining 134.6 MFLOPS overall. Parallel efficiency (as an average of CPUs used) is 83.5 percent. As development continues, these numbers are improving slightly.

The Visualization Environment

The visualization environment development has been driven by the desire to have representations of relevant and appropriate computational results available to scientists at all three sites, and to have a user interface that will allow these scientists to interactively select the variables in the models that they want rendered. For example, the individuals at NCAR may want to view the wind velocity predictions, while the scientists at Ohio State and GLERL might be interested in the boundary conditions related to water temperatures and the resulting predictions for the currents. Since collaboration will be taking place for the entire coupled system, the visualizations being rendered at one site are simultaneously available at the other sites because of the satellite interface.
The Explorer\textsuperscript{4} visualization system was chosen as the infrastructure because of the flexibility offered in this system for customizing the visualization stream due to the open data-flow architecture. The visualization personnel at ACCAD have created a set of modules for capturing the output of the models via the DM, filtering them as necessary, and rendering various variables (see appendix 1 for a list of variables that can be rendered in this system). The resulting 3D visualizations are then rendered on the local machine and distributed by means of a “RenderRemote” over the satellite to the other sites. Once they are resident at the other sites, the scientists there have full interactive control for viewing the visualization, such as pan/zoom, rotation, etc.

*** Steve - we probably need a little bit more about explorer and renderremote***

Figure 4 shows an example of the visualization screen on the workstation at NCAR or OSC. In the lower left is the graphical user interface which is used to select variables and adjust the display parameters. In the lower right is a visualization display window showing the currently selected variable (in this case, ground temperature) along with a color map legend and text label. Up to ten variables, which can be either scalar or vector variables, can be displayed simultaneously. Behind the gui and display window is the Explorer map editor which shows the currently invoked programs or modules in the data-flow paradigm and the connections between them which combine to create the image in the display window. The scientists at GLERL can see all of the display windows that are being displayed at the other two sites, but don’t have access to the user interface which allows them to select an arbitrary variable for visualization. They can see the status windows, and can use the collaboration channel to request of one of the other sites to select the desired variable.

Additionally, the visualization includes a system status window, an example of which is shown in figure 5. In this case, in the upper right is the MM5 status window from the Cray at NCAR, showing surface air temperature plotted as a series of contours with a legend and text annotation, which shows the current time-step. In the lower right is a similar status window from the Cray in Ohio, showing the lake model computation with surface temperature plotted as a series of contours. Both status windows are displayed automatically as each new timestep is generated by the computational models. These status windows are sent over the satellite to all three sites. The status window is another Explorer pipeline using a pre-selected variable and are annotated with pertinent information regarding the domain and timestep to allow the scientist to assess the current viability of the model as well as the operational status of the satellite and the supercomputers. The DM automatically sends the computational results for that variable at each timestep.

The Collaboration Channel

The intent of this project is to demonstrate the viability of collaborative computing between separate sites using ACTS. Part of this formula includes the ability for the scientists involved in the experiment to easily and effectively communicate with each other. This communication is provided by the collaboration channel. This channel allows for distribution of video and audio feeds between all sites, and includes a collaborative “whiteboard” on which the experimenters can draw, highlight text, point to salient features, cut and paste images and text, and other information sharing actions that increase the productivity of the team (see figure 6).

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\textsuperscript{4}Explorer is a product of Silicon Graphics Inc
The video software is mbone
*** expand with a short description and a footnote for attribution ***

The whiteboard is Collage.
*** expand with a short description and a footnote for attribution ***

The Software Communications Interface

The computational modules communicate with each other and with the visualization software using Parallel Virtual Machine (PVM) from Oak Ridge National Laboratory with optimizations for the Cray Y-MP provided by Cray, along with a hand-coded socket library developed specifically for this project at OSC and NCAR. Both solutions use TCP/IP as the underlying transport mechanism, with the TCP protocol modified to allow for the exceptionally high latency resulting from the use of a satellite connection. The models run simultaneously on both Crays, writing via PVM to PVM memory on the other machine. A "data receiver" program (also running on each Cray) reads PVM memory and writes to SSD (fast data cache) area.

Interaction between the models running on the separate Crays, and between the visualization components is controlled with the use of a protocol called the Data Manager (DM). Written by NCAR and OSC personnel, the DM is a simple file passing protocol which indicates to the visualization software that a new timestep from one of the models is now available. This data is retrieved from the SSD on the Crays and is written to a Network File System (NFS) disk. All of the system components have access to the DM in order to get relevant information regarding the computational model and variables for visualization (see figure 3.)

USER INTERFACE

The GUI, developed by visualization experts at The Advanced Computing Center for the Arts and Design at Ohio State and scientists at NCAR was designed to allow scientists at all three sites to efficiently identify and gather appropriate data being calculated by the coupled models in order to visualize it on the screens of the workstations (see figure 7.)

The GUI allows a user to select variable(s), domain, and a vertical coordinate system (for three-dimensional data). It allows a user to add a map background to current display in order to orient the resulting computational visualization, selectively save a snapshot of the display to an external PostScript file, and to make a time dependant movie of the display's contents, as a timestep-by-timestep animation. This can be viewed interactively, or saved on disk to provide a documentation of the experiment in progress.

There are four components of the GUI:
• a pair of scrolling windows containing names of variables and their particular display options, with checkboxes next to each variable name for selection of that variable for display
• linked buttons (radio buttons) allowing the user to select (a) variable domain, and (b) vertical
coordinate system
• linked buttons (radio buttons) allowing the user to suspend and resume delivery of data from
  the Data Manager
• unlinked buttons (checkboxes) allowing the user to add a map background, save the display
to an external PostScript file, and save the display to an external SGI movie

The GUI has ten data output ports, each of which is capable of writing a 3D curvilinear lattice.
When the user selects a variable from one of the two scrolling lists (one for MM5, one for lake data), the
variable is assigned to an available port, and an Explorer pipeline is created which links that particular
port to the Render module. This pipeline contains modules appropriate for the selected display method,
to transform the curvilinear 3D lattice into a geometry suitable for display in the Render module.

When the user changes the display method of a selected variable, the existing pipeline for that
variable is destroyed and a new pipeline is created. For example, assume that a user is looking at a
variable as an isosurface and wishes to look at it as a contour plot. The appropriate checkbox is selected,
and the GUI notifies the DM. At the completion of the next timestep, the DM sends the new variable
data file from the Cray to the SGI, and writes a file containing the timestep number. This "OK file" will
have a naming format similar to that of the variable data file, and is polled by the GUI. When the "OK
file" for a particular variable data file is noticed, the GUI constructs the appropriate variable data file
name and reads the data file, removes the "OK file," and adjusts the visualization map.

The list of active variables is used by the Data Manager to pass to the GUI only the data
requested by the scientist. If he/she selects the "Pause..." checkbox in the GUI, the DM is sent an empty
list — indicating to the DM that no data is to be sent to the GUI until further notice. This functionality
exists to allow the user to study the currently displayed data or to reload old data into the GUI.

CONCLUDING REMARKS

A coupled atmospheric-lake mesoscale modeling system has been developed by scientists at OSU,
NCAR, and GLERL to study air-sea interactions in the Great Lakes region. The system is part of the ACTS
demonstration project, and consists of a three-dimensional, nonhydrostatic atmospheric model, a three-dimensional
lake circulation model and a surface wave model. The coupled system is run on a distributed supercomputer
configuration involving OSC and NCAR. The system is used to investigate the effect LSTs and wave conditions
have on the marine planetary boundary layer (MPBL) and mesoscale atmospheric phenomena in Lake Erie region,
as well as the effect of MPBL on lake storm surges, circulation, waves and thermal structure.

The scientific results of this project have provided better understanding, simulation and visualization of
the complex air-lake interactions present in the Great Lakes region. In addition, the technical knowledge gained
from this project will assist in the development and future implementation of coupled lake-atmosphere mesoscale
forecast systems for the region, similar to the coupled system being developed by the U. S. Navy for military use in
coastal ocean regions around the world (refs. 9 and 11). The results also provide evidence of the applicability of
ACTS technologies to atmospheric and lake modeling and scientific collaboration.
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REFERENCES

7. Doyle, J. D., 1994: Coupled ocean wave/atmosphere mesoscale model simulations of cyclogenesis. Submitted to Tellus,