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SCIENTIFIC DEVELOPMENT OF A MASSIVELY PARALLEL OCEAN CLIMATE MODEL

Progress Report for 1992-93 and
Continuing Request* for 1993-94

to

CHAMMP

(Computer Hardware, Advanced Mathematics, and Model Physics)

A Program of the U.S. Department of Energy

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PROGRESS:

During the second year of CHAMMP funding to the PIs, progress has been made in the proposed areas of research, as follows:

- **Investigation of the Physics of the Thermohaline Circulation**

Major numerical experiments were conducted to investigate the sensitivity of global ocean circulation and its associated transports of heat and salt to changes in high-latitude buoyancy forcing and in wind forcing.

An experiment had been designed to improve the continued production of water masses in areas of known deep-water formation. At the same time, almost all of the deep and abyssal regions of the world ocean were free from earlier restoring to observed values of temperature and salinity. This 'convective forcing' experiment was run on the National Center for Atmospheric Research (NCAR) Y-MP/864 for two additional years to complete a five-year sensitivity study. A suite of analysis programs, already converted to run on the NCAR Unix-based computers, was applied in order to make comparisons with published results of the earlier experiment (Semtner and Chervin, 1992). The outcome was an improved representation of the global thermohaline circulation, as well as enhanced levels of eddy energy, particularly in the deep and abyssal waters. The results were dramatically illustrated in a two-hour videotape of temperature, salinity, surface height, and particle trajectories, in basin-by-basin closeups, as produced at the Naval Postgraduate School (NPS) by Shirley Isakari and Michael McCann. This "Video Atlas of Global Ocean Circulation" was distributed upon request to over 100 scientists throughout the world. Additional quantitative results are being prepared for publication by Semtner and Chervin.

To examine the dependence of simulated ocean currents and heat transports on the improving observations of wind forcing, two ten-year experiments have been conducted at NCAR using monthly climatological and monthly 1980-89 wind stresses of the European Centre for Medium-Range Weather Forecasts (ECMWF). The computer time for these efforts was provided at no cost by the Model Evaluation Consortium for Climate Assessment (MECCA). The impact on the thermohaline circulation of wind variations has been analyzed, and major variations in oceanic heat transport are found to occur from changes in wind stress. For example, seasonal maxima of global oceanic transport reach 7 PW during strong El Niños, but the net heat transport

by eddies is much smaller at such times. Annual-mean heat transports for individual basins typically vary by a factor of two between the maximum and minimum over ten years. These results bring into question some of the assumptions and estimates of observational oceanographers for heat transport across standard latitudes in the various ocean basins. In particular, deep flows fluctuate much more rapidly than expected and large western boundary transports take place in very thin ribbons. These results are being prepared for publication by Robert Chervin and Anthony Craig. Also, a 40-minute videotape of the integrations by Isakari and McCann includes comparisons of model surface temperatures and sea-surface heights with those observed from satellites.

- **Examination of Resolution Effects on Ocean General Circulation**

A major upgrade of the global model was made during the second year of CHAMMP support. A free-surface formulation developed by Killworth et al. (1991) was successfully implemented in the model. This new feature provides full scalability of the barotropic part of the ocean calculation with expected increases in grid resolution. Such a method permits direct assimilation of satellite altimeter data; it also allows the use of unsmoothed coastlines and bathymetry, as earlier demonstrated by Smith et al. (1991).

A new configuration of the grid of the global model was designed to be much more adequate for eddy resolution than the earlier $1/2^\circ$ model. Grid spacing in latitude was allowed to vary with a cosine-of-latitude factor, so that the grid was locally square everywhere. A choice of longitudinal grid spacing of $2/5^\circ$ then led to an overall average grid spacing of $1/4^\circ$. The horizontal resolution of the model thereby exceeded that of earlier regional ocean modeling efforts (the U.K. Fine Resolution Antarctic Model and the U.S./German Community Modeling Effort), especially in high latitudes where enhanced resolution is most needed. In addition, the varying grid of the model allows subgrid-scale viscosity and diffusion to be decreased significantly at high latitudes relative to grids with fixed latitudinal spacing.

A full-scale production capability was developed in order to use the CRAY Y-MP/864 at NCAR under NSF cosponsorship of global ocean modeling. Many upgrades in model design were incorporated into the Parallel Ocean Climate Model by Chervin and Craig, in order to maximize the use of the multiple processors, the solid-state disk, the history-tape archival system, and the restart capability. The resulting model now sustains 1.2 gigaflops while running 2–3 hours per night in a dedicated

machine environment and producing a full suite of history tapes, restart tapes, and visual output.

The new model with $1/4^\circ$ grid size on average was started using a fast robust-diagnostic initialization to interpolated output from the end of the convective forcing run. Then ECWWF monthly winds of 1985–88 were prepared for use; to date, integration through 1986 has been completed. The results are very encouraging, in that eddy kinetic energy in the Antarctic Circumpolar Current approaches realistic values, and the major low latitude currents such as those through the Indonesian Archipelago are very well represented. Some spectacular regional animations of free-surface height, temperature, salinity, and barotropic speed have already been made to illustrate phenomena. Now the integration has entered a two-year period where Geosat altimetric observations are available for quantitative comparison. Following the completion of this 1987–88 phase, a repeat of this phase will be conducted with ongoing assimilation of the Geosat height data, in order to give a better estimate of ocean circulation during this time period, as well as the net contribution of mesoscale eddies to the three-dimensional viscosity and diffusivity of the real ocean. Many of these planned integrations and analyses will be handled by Robin Tokmakian, an experienced oceanographer who has just replaced Michael McCann on the project.

• Development of a Massively Parallel Ocean Climate Model

At this time last year, it appeared that the Connection Machine 5 with 1024 processors would be operational relatively soon at the Los Alamos National Laboratory (LANL). Therefore, our hope was to have a production model running there by now. However, delays in delivery of the high-speed chips, plus additional slowdowns of both hardware and software nature, have postponed a production effort on the CM-5 at LANL. Nevertheless, Smith, Malone, and Dukowicz have progressed to a more general Parallel Ocean Program (POP) that should perform at ten times the speed of the CRAY Y-MP/8 on the full CM-5. In anticipation of using this resource in collaboration with the Los Alamos team, we have continued to interact with them on issues of computational and physical importance.

Some activities of a collaborative nature include Chervin's participation in a CM-5 class at LANL and his attendance at the Second Annual Ocean Predictability Workshop, Semtner and McCann's analysis of CM-200 output using the Ocean Processor at NCAR, Smith's visit to the Postgraduate School to install his implicit free-surface method in the Parallel Ocean Climate Model, Isakari's planned June visit to

LANL to make arrangements for collaboration using the CM-5, and joint discussions at the JASON Review in La Jolla and the CHAMMP Science Team meeting in Monterey.

- **Some Other Related Activities**

Semtner attended the Aspen Global Change Institute in August 1992 and a meeting of the Numerical Experimental Group for the World Ocean Circulation Experiment in September at Devizes, England. An invited talk was given at each meeting.

Semtner gave a talk on Indian Ocean modeling at Rutgers University during an October meeting of the US WOCE Working Group on Numerical Modeling. He gave a seminar the next day at the NOAA Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey.

Chervin and Semtner helped to organize a JASON Review in La Jolla, and they presented talks on various aspects of global ocean modeling at that meeting in October 1992.

Chervin began serving on the Program Committee for Supercomputing '93, to be held in Portland, Oregon, 15-19 November 1993.

Chervin and Semtner presented results of their global simulations with ECMWF winds at a MECCA meeting in January 1993 at NCAR.

Chervin and Semtner gave invited talks at a meeting of the U.S. Science Steering Committee of the World Ocean Circulation Experiment, February 1993 in Dallas.

A paper entitled "Including Eddies in Global Ocean Models" was published in *EOS* of 2 February 1993, as well as in *Geophysics News* 1992 and in *The Earth in Space*, all publications of the American Geophysical Union. Authors were Semtner and Chervin.

Semtner and Chervin gave talks at the Fourth International Conference on Southern Hemisphere Meteorology and Oceanography, March 1993, in Hobart, Australia.

A *SCIENCE* article entitled "Ocean-in-a-Machine Starts Looking Like the Real Thing" highlighted the global modeling effort. It was written by Richard Kerr for the 2 April 1993 issue of the magazine.

Chervin was an invited visitor and consultant on parallel computing for the Earth System Science Center of Pennsylvania State University in April.

Anthony Craig paid a collaborative visit to the NPS in April 1993 to interact with CHAMMP investigators there.

Chervin attended a meeting of the Data Management Working Group for the World Ocean Circulation Experiment, April 1993, in Corvallis, Oregon.

Isakari and McCann provided videotape material and high-quality graphical products to many international science projects upon request.

THIRD-YEAR PLANS:

During the next year, we plan to continue running and analyzing the thermohaline sensitivity experiments discussed above. We plan to defer any research on improving surface ocean processes (such as sea-ice and surface mixed-layer physics) to an extension proposal, in order to accelerate progress toward a massively parallel ocean climate model.

The main focus of our effort over the next year will be to conduct an eddy-resolving global simulation at dramatically high resolution on the CM-5, in collaboration with Smith, Malone, and Dukowicz. With their expertise in advanced mathematics and parallel computing, as well as our own in conducting large ocean simulations, we can achieve a successful simulation, including interpreting and publishing the results. Everyone is committed to demonstrating that long-term, eddy-resolving, global ocean calculations can be done on massively parallel machines.

We have put a lot of thought into the choice of an experiment that would also help to achieve a major goal of our research—to determine the resolution required for valid ocean modeling in climate research. On the basis of evidence from satellite altimeter measurements, it is clear that the primary length scale of energy containing ocean eddies (which mix heat, salt, and momentum in complex ways) is the local radius of deformation. This parameter varies from about $1/3^\circ$ of latitude spacing in the subtropics to about $1/10^\circ$ in very high latitudes. It is possible to configure a relatively efficient model whose grid size is less than the local radius of deformation at almost all latitudes, by continuing to use an ocean model that allows the latitudinal grid spacing in kilometers to be the same as that of the longitudinally converging meridians. Conveniently, one can choose $1/4^\circ$ spacing near the equator and converge to a $1/12^\circ$ grid at 72° —all without decreasing the timestep much from that for a

uniform $1/4^\circ$ grid. However, the effective (or average) grid spacing of such a model is $1/6^\circ$.

Following the above approach should allow us to decide quickly on the optimal resolution for ocean climate simulations. In the meantime, a global simulation with $1/6^\circ$ average grid spacing will provide an unprecedented view of the ocean general circulation with relatively well-resolved eddies. It will be a major contribution to physical oceanography and, more generally, to geophysical fluid dynamics and climate research. Therefore, our main objective during year three is to carry out such an experiment.

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