FOAM: Expanding the Horizons of Climate Modeling

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Abstract:

We report here on a project that expands the applicability of dynamic climate modeling to very long time scales. The Fast Ocean_Atmosphere Model (FOAM) is a coupled ocean-atmosphere model that incorporates physics of interest in understanding decade to century time scale variability. It addresses the high computational cost of this endeavor with a combination of improved ocean model formulation, low atmosphere resolution, and efficient coupling. It also uses message-passing parallel processing techniques, allowing for the use of cost-effective distributed memory platforms. The resulting model runs over 6000 times faster than real time with good fidelity and has yielded significant results.

Keywords:

massively parallel, distributed memory, message passing, scientific supercomputing, climate, meteorology, oceanography, hydrology

Introduction

Climate modeling consistently has been among the most computationally demanding applications of scientific computing, and an important initial consumer of advances in scientific computation. We report here on the Fast Ocean-Atmosphere Model (FOAM), a new coupled climate model that continues in this tradition by using a combination of new model formulation and parallel computing to expand the time horizon that may be addressed by explicit fluid dynamical representations of the climate system.

Climate is the set of statistical properties that emerges at large temporal and spatial scales from well-known physical principles acting at much smaller scales. Thus, successfully representing such large-scale climate phenomena while specifying only small-scale physics is an extremely computationally demanding endeavor. Until recently, long-duration simulations with physically realistic models have been infeasible. Through improvements in model formulation and in computational efficiency, however, our work breaks new ground in climate modeling.

Our progress in model formulation has been based on a new, efficient representation of the world ocean. Success in this endeavor has further directed our efforts to establishing the minimum spatial resolution that can be considered a successful representation of the earth's climate for the purposes of understanding decade to century variability.

Our work on computational efficiency has focused on developing a coupled model that can execute efficiently using message passing on massively parallel distributed-memory computer systems. Such systems have proved powerful and cost-effective in those applications to which they can effectively be applied.

The result of this work is a coupled model that can sustain a simulation speed of 6,000 times faster than real time on a moderate-sized parallel computer, while representing coupled atmosphere-ocean dynamical processes of very long duration which are of current scientific interest. In this important class of application, we have obtained a significant cost performance advantage relative to leading contemporary climate models. We believe that the achieved throughput in terms of wall clock time is the highest of any coupled general circulation model to date.

FOAM has already been used to obtain significant scientific results. Modes of variability with time scales on the order of a century have been identified in the model. These results provide a basis for observational and theoretical studies of climate dynamics that may permit climatologists to observe and explain such phenomena.

The rest of this paper is organized as follows. We first briefly review the state of the art in general circulation models. Then, in Sections 3 and 4, we describe the FOAM design approach and the FOAM model, respectively. In Section 5 we describe our experience running the model and in Section 6 we discuss scientific results. We conclude in Section 7.

General Circulation Models

Models which are intended to explicitly represent the fluid dynamics of an entire planet starting from the equations of fluid motion are known as general circulation models (GCMs). In the case of the earth, there are two distinct but interacting global scale fluids, and hence three classes of GCM: atmospheric GCMs, oceanic GCMs, and coupled ocean-atmosphere GCMs.

GCM calculation is essentially a time integration of a first-order-in-time, second-order-in-space weakly nonlinear set of partial differential equations. As is typical in such problems, the system is represented by a discretization in space and time. The maximum time step of this class of computational model is approximately inversely proportional to the spatial resolution, while the number of spatial points is inversely proportional to its square. Hence, the computational cost, even without increases in vertical resolution which may be required, is roughly proportional to the inverse cube of the horizontal spacing of represented points.

Since planets are large and the scale of fluid phenomena is small, representation in GCMs is quite coarse, typically on a grid scale of hundreds of kilometers. Nevertheless, on the order of 10^{10} floating point operations are required at a typical modest resolution to represent the flow of the atmosphere for a single day. The calculations are further complicated by the necessity to represent other physical processes that are inputs into the fluid dynamics, such as radiative physics, cloud convective physics, and land surface interactions in atmospheric models, as well as atmospheric forcing and equations of state in oceanic models.

Despite these daunting constraints, atmospheric and oceanic GCMs that succeed in representing the broad features of the earth's climate have been available for about two decades [3, 36]. Continuing refinement and demonstrable progress have been evident in intervening years [26, 34]. These GCMs have a remarkable range of applications, which can usefully and neatly be divided into two classes--those within and those outside the limits of dynamic predictability set by the chaotic nature of nonlinear fluid dynamics.

In the first class of model, predictions or representations of specific flow configurations are sought. Weather models are the best known such applications, but there are operational ocean models and research models of both the ocean and atmosphere systems that fall into this class.

In the second class are climate applications, where the duration of the simulation is longer than the predictability of the instantaneous flow patterns. Here, the interest is in representing the statistical properties of the flow rather than its instantaneous details. Since prediction of specific fluid dynamical events is replaced by studies of the statistics of such events, much longer durations must be calculated. Meaningful climate statistics emerge after some years while the limit of dynamic predictability is at most tens of days. Hence, the cost at a given spatial resolution is at least two orders of magnitude greater for climate applications than for applications that simulate individual events within the limits of dynamic predictability. As a result, for a given spatial resolution and set of represented physical processes, climate modeling is intrinsically a much more computationally demanding application than weather modeling. Furthermore, additional physics may be required in climate applications that may be left out of weather models.

In order to understand the implications of past or future simulated climates at particular locations, as well as to represent the global dynamics more accurately, the push in climate modeling has been toward higher spatial resolution as more computational resources become available. Still, integrations of climate models for about a century have represented the maximum attainable until very recently.

A second push has been towards coupled models. There is a rough symmetry between atmosphere and ocean in that each provides an important boundary condition for the other. Early long-duration models studied the ocean or atmosphere in isolation, using observed data for the other boundary condition. Efforts to link models of the two systems into a coupled model have been frustrated by the independent and, until recently, mutually inconsistent representations of the physics of the air-sea boundary [33]. Substantial progress in this area has been reported recently, particularly at the National Center for Atmospheric Research (NCAR) [15]. Our project benefits directly from this progress.

Interest in coupled modeling applications has been intense because there are variations in climate at all time scales, many of which are poorly understood. Such phenomena cannot be represented by either atmospheric or oceanic GCMs. The coupling between atmosphere and ocean, as well as with land and ice processes in some applications, thus becomes critical. Additionally, longer simulations are required than in more established climate modeling approaches, since the time constants of the relevant processes are much longer, on the order of decades.

Finally, there is enormous practical and theoretical interest in transient climate responses to rapid changes in atmospheric conditions, such as changes in atmospheric concentrations of radiatively active (''greenhouse'') gases and aerosol (airborne fine dust) distributions. A few such runs have been performed [24], but in these cases it is difficult to separate intrinsic climate variability from variability in response to the changes in atmospheric composition. To address this question rigorously would require ensembles of similar runs, again multiplying the requisite computational resources substantially. Thus, calculations of ten thousand years requiring on the order of 10^{16} floating point operations are of immediate interest, even at the modest resolutions currently used for climate models.

Design Strategies for FOAM

The principal objective of the FOAM modeling effort is to study the long-duration variability of the climate system. Variations in deep ocean circulation are believed to be the dominant mechanism for climate changes on long time scales. In turn, these variations are forced by the spectrum of atmospheric phenomena, each individual event of which occurs on much shorter time scales, and which in turn are the direct effect of phenomena which, while mostly well understood, occur on time scales of minutes. It is this need to address processes occurring at multiple time scales that leads to the high computational cost of climate models and that motivates the FOAM project focus on improving model performance.

One measure of simulation performance is ‘‘model speedup,’’ i.e., simulated time per wall clock time. We have adopted as our objective a speedup of 10,000 for a model capable of representing deep ocean dynamics using a fully bidirectionally coupled ocean-atmosphere model. This level of performance as our goal would makes thousand-year simulations practical on a routine basis.

We adopted several strategies to approach this goal. The simplest of these strategies is the sacrifice of spatial resolution for expansion of available simulated time. Since computational cost is directly proportional to simulation duration, but roughly proportional to the inverse cube of the horizontal spacing, simulated duration can be extended greatly by using the lowest resolution that captures the phenomena of interest.

Investigations revealed that it was important to maintain a reasonable resolution within the ocean, due to the relatively small scale of important ocean dynamics. However, we determined that a coarse representation of the atmosphere is sufficient to represent multidecadal coupled variability. In conventional coupled models, approximately equal amounts of time are spent in the ocean and atmosphere; hence, reducing atmosphere resolution can make a large difference to overall performance only if we are able to speed up the ocean simulation performance in some other way. This observation led us to adopt as a principal algorithmic focus the improvement of the ocean model efficiency in terms of the number of computations required per unit of simulated time. As we describe below, we were successful in this endeavor; this success allowed for an excellent scaling of coupled performance from the use of a low atmospheric resolution, since the ocean part of the model now accounts for only a small fraction of the resources used.

A second strategy was to use established representations of system physics. As far as possible, we did not endeavor to participate in the ongoing improvement of representation and parameterization of the many relevant physical processes of the climate system. Our objective was not to improve the representation of climate but to expand the applicability of those representations.

A third strategy was to use massively parallel distributed-memory computing platforms, that is, computing platforms built of relatively large numbers of processing units, each with a conventional memory and high speed message links to other processors. This type of computer is well-suited to fluid dynamics applications, where low-latency, high-bandwidth exchanges are necessary, but in a predictable sequence and thus subject to direct tuning. The distributed-memory architecture avoids the hardware complexity of shared-memory configurations, improving cost per performance and providing a straightforward hardware upgrade path.

A fourth component of our approach was to use the standard Message Passing Interface (MPI) [9] to implement interprocessor communication. The use of MPI not only facilitates the design of the communication-intensive parts of the model, but also enhances our ability to run on a wide variety of platforms. While the coupled model has to date been run only on IBM SP platforms, both the ocean and atmosphere models have been benchmarked on a variety of machines. As processors continue to improve, migration to commercial mass market platforms connected by commodity networks may further improve cost efficiency.

The fifth element of our strategy was to design an independent piece of code, the ‘‘coupler,’’ to link pre-existing atmosphere and ocean models. This structure minimized the changes required for those already tested pieces of software. The coupler also includes a water runoff model, representing river flows and thus allowing for a closed hydrological cycle.

Efficiency and parallel scalability, that is, the ability to make optimal use of large numbers of processors, were paramount in these design efforts. The development of model physics was avoided by this project, in that the relevant algorithms, with the important exception of the new surface hydrology routines, were imported without modification. This incremental approach allowed us to focus our attention on the computationally demanding issues of the fluid dynamics and parallelization.

Components of FOAM

As noted above, FOAM comprises an atmosphere model, ocean model, and coupler. We describe each of these components in turn.

The FOAM Atmosphere Model

The atmospheric component of FOAM is derived from the PCCM2 version of the NCAR Community Climate Model (CCM2) [11] plus, as we explain below, selected components from CCM3. PCCM2 is functionally equivalent to CCM2, but has been adapted to support efficient execution on massively parallel distributed-memory computers [6].

Parallelization of GCMs is generally accomplished by a one- or two-dimensional decomposition of the spatial domain into subregions and assignment of those subregions to distinct processors. The parallelization process for CCM is complicated by the fact that some of the computation is performed in a spectral transform space. The spectral transform approach has useful properties from a numerical methods point of view (avoiding aliasing, accurate differentiation) at the cost of some complexity in sequential implementation. In a parallel implementation, however, it also introduces a need for global communication [8]. PCCM2 addresses these issues by incorporating parallel spectral transform algorithms developed at Argonne and Oak Ridge National Laboratories [6, 8] that support the use of several hundred or more processors, depending on model resolution. Additional modifications involved the semi-Lagrangian representation of advection and techniques for load balancing [6].

Calculations in the third, vertical dimension, particularly those representing radiative transfer, are tightly coupled, so there is relatively less advantage to a vertical decomposition. As a result, the physics processes in CCM2, which occur entirely in vertical columns, are represented without any information exchange between processors. Thus no changes to the relevant code were needed.

The principal modification to PCCM2 to support its use in FOAM was to replace the lower boundary condition routine with new code responsible for transferring data to the coupler and hence to the ocean model. As we noted above, FOAM uses a low-resolution atmosphere. The vertical coordinate is a hybrid of a terrain following coordinate and pressure, with 18 vertical levels. We use a 15th order rhomboidal (R15) horizontal resolution; this corresponds to 40 latitudes arranged in a Gaussian distribution centered on the equator and 48 longitudes for an average grid size of 4.5 degrees of latitude and 7.5 degrees of longitude. FOAM uses a 30 minute time step and the recommended values for the diffusion coefficient given by [41] for an R15 CCM2.

After we began building the coupled model, a new implementation of the Community Climate Model has been released. The radiative and hydrologic changes to the physics from CCM2 to CCM3, described in detail by [18], have since been implemented in FOAM. The bulk of the code of FOAM, including the remainder of the physics, remains that of CCM2. Details can be found in [11].

The radiation parameterization used in the FOAM atmosphere model is based on PCCM2 [11, 2, 16] but includes the CCM3 additions and improvements [18, 17]. Several other CCM3 innovations have also been incorporated in FOAM. In CCM2, all types of moist convection were handled by the simple mass flux scheme developed by [10]; in CCM3, and FOAM, this scheme is used in conjunction with the deep convection parameterization of [43]. The evaporation of stratiform precipitation is also now included. The boundary layer model of CCM2 has been modified as described by [40]. Finally, the surface fluxes over the ocean are now calculated using a diagnosed surface roughness which is a function of wind speed and stability [18].

The FOAM Ocean Model

FOAM uses the parallel ocean model developed at the University of Wisconsin - Madison by Anderson and Tobis [1]. The dynamics of this model are similar to those of the Modular Ocean Model developed by the Geophysical Fluid Dynamics Laboratory [29]. As with PCCM2, the focus of our work was not in new representations of the ocean's physical properties but in efficient implementation for message-passing parallel platforms.

The ocean model uses the vertical mixing scheme of [30] but with a steeper Reynolds number dependency consistent with the observational analysis of [31]. The revised mixing values appear to improve the tropical Pacific SST field by reducing the model cold bias in the west equatorial Pacific.

A simple, unstaggered Mercator 128 x 128 point grid is used, yielding a discretization of approximately 1.4 degrees latitude by 2.8degrees longitude. Spatial mode splitting on the grid is prevented through the use of a ∇^4 numerical dissipation. A spatial filter similar to the sort used in atmospheric models [42] is used to maintain numerical stability in the Arctic. The topography used is somewhat tuned to preserve basin topology at the represented resolution but is not smoothed.

The vertical discretization is with height, with a stretched vertical coordinate maximizing resolution in the upper layers. For the runs reported here, a sixteen layer version was used. The central importance of the surface thermodynamics in the coupling process and the objective of a minimal computational load led to this choice in preference to an isopycnal model.

Three separate techniques are used to speed the performance of the ocean model. Unlike in some ocean models, the free surface is explicitly represented, but its dynamics are artificially slowed, an approach which has been shown to make little difference to the internal motions [37, 38]. In addition, the still relatively fast, and therefore difficult to represent, free surface is modeled as a separate two-dimensional system coupled to the internal ocean in a way that correctly reproduces the free surface while allowing a much longer time step in the internal ocean [19]. Finally, that time step itself is used only for the calculation of the fastest parts of the internal dynamics, while yet a longer step is used for diffusive and advective processes.

We believe that the combination of these techniques yields the most computationally efficient ocean model in existence. That is, for a given resolution, we believe that this model requires fewer floating point operations to integrate the ocean for a given time than any other model. When compared with other state-of-the-art ocean models, this improvement corresponds to roughly a tenfold increase in the amount of simulated time represented per unit of computation.

We have benchmarked the ocean code at 128 x 128 resolution on 64 SP2 nodes running at over 105,000 times real time. The ocean model also scales well to higher resolutions, and other applications beside long-term climate modeling are anticipated.

The FOAM Coupler

The separately developed atmosphere and ocean models are integrated into a functioning whole by a set of routines called the coupler. The coupler is essentially a model of the land surface and atmosphere-ocean interface. The coupler also handles the calculation of fluxes between the ocean and atmosphere, organizes the exchange of information between them, and calls a new parallel river model for routing the runoff found by the hydrology model to the oceans.

The land surface in FOAM (and in CCM2) is represented by a four-layer diffusion model with heat capacities, thicknesses and thermal conductivities specified for each layer. Soil types vary in the horizontal direction, with 5 distinct types derived from the vegetation data of [25]. Roughness lengths and albedos for two different radiation bands are also specified.

The fluxes of latent and sensible heat and momentum between the land and the atmosphere are calculated using the bulk transfer formulas with stability dependent coefficients from CCM2 summarized by [11]. Between the ocean and the atmosphere, the new bulk transfer formulas of CCM3 are used [18]. These are also stability dependent but do not assume a constant roughness length.

The hydrology in FOAM is a simple box model after [23] and [4]. This model was an option in early versions of CCM2 and was also present in CCM1 [42]. Precipitation is added to a 15 cm soil moisture box or to the snow cover, if the ground and lowest two atmosphere levels are below freezing. The soil moisture is used to calculate a wetness factor D_w used in the latent heat flux calculation. (D_w equals 1 for land ice, sea ice, snow covered and ocean surfaces.) Evaporation removes water from the box and any excess over 15 cm is designated as runoff and sent to the river model. Snow cover modifies the properties of the upper soil layer for purposes of the albedo and surface temperature calculations. Snow melt is calculated and added to the local soil moisture. Snow depths greater than 1 m liquid water equivalent are also sent to the river model to mimic the near-equilibrium of the Greenland and Antarctic ice sheets.

Because fresh water cycling may be of interest in the phenomena to be studied by the model, and also to avoid long-term ocean salinity drift, a closed hydrological cycle is implemented by the coupler, with a simple explicit river model that results in a finite fresh water delay and a set of point sources (river mouths) for continental runoff. This strategy enables the model to represent phenomena that involve coupling between variations in continental rainfall and delayed resultant variations in ocean salinity, in turn affecting weather patterns through altered sea surface temperatures resulting from altered ocean circulation.

The river model is based on the work of Miller et al. [27]. A similar implementation is also used in the coupled model of Russell et al. [32]. First a river flow direction is set for each land pointi. Although this can be automated by processing the topography file, in practice many of the river directions had to be set by hand so that the resulting basin boundaries resemble the observed.

The flow F in cubic meters per second out of a cell is $F = V \cdot u/d$, where V is the total river volume equal to the local runoff plus the sum of the flow from up to seven of the eight neighboring cells, u is an effective flow velocity which is taken as a constant 0.35 meters per second [27], and d is the downstream distance. Precipitation and evaporation do not act directly on the river water and the temperature of the river water is not taken into account. *V* for an ocean point near the coast is then calculated as the sum of the outflow from neighboring land points and converted back to a flux by dividing by the area of that ocean point. This river freshwater flux is then added to the local precipitation and evaporation rates to form the total freshwater flux at that point and close the hydrologic cycle.

The temperature of the sea ice is determined by treating it as another soil type. The sea surface may continue to lose heat by conduction with the lowest ice layer so a clamp on temperature is imposed by the ocean model at -1.92 degrees Celsius. Sea ice roughness and albedos are prescribed. For the hydrologic cycle, the formation of sea ice is treated as a flux of 2 m of water out of the ocean. The stress between the ice and the atmosphere is arbitrarily divided by 15 before passing to the ocean model.

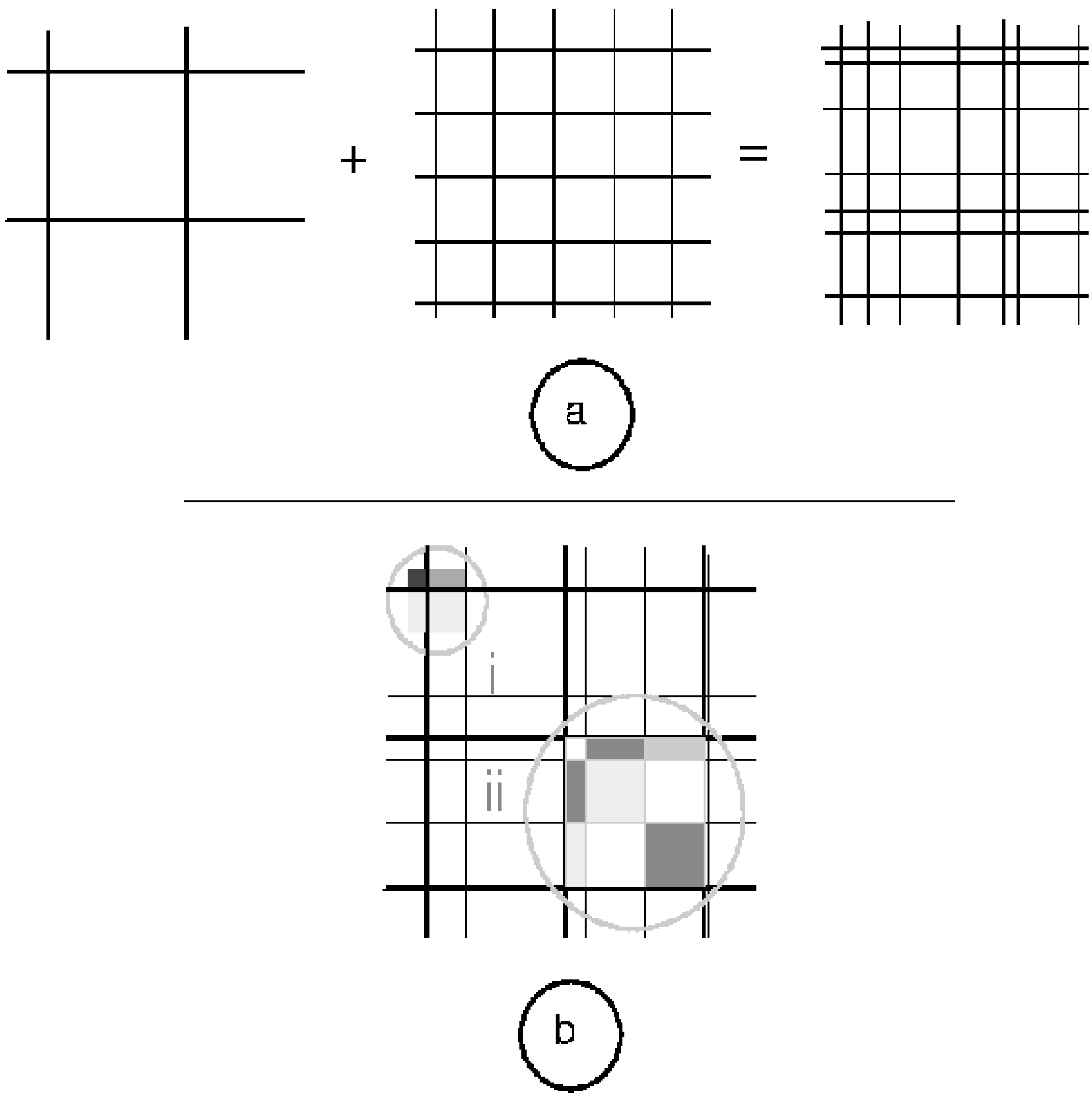

Figure 1: FOAM coupler tiles (see text)

The problem of representing atmosphere-ocean interactions is complicated by the fact that these two components are represented on different spatial grids. Couplers must represent these fluxes consistently in both domains. FOAM handles this in a simple but highly efficient way, as illustrated in Figure 1. The model represents the globe as being divided into two grids, one for the atmosphere and another for the ocean. A third decomposition of the surface is constructed by laying one grid on top of the other, as shown schematically in Figure 1(a). The atmosphere/ocean exchanges, which depend on the properties of both, are calculated for each piece of this overlap grid and are then averaged for passing back to the ocean (Figure 1(b), region i) and atmosphere (Figure 1(b), region ii) exchanges. No effort is made to interpolate all state variables to a single grid, thus greatly simplifying the task of maintaining consistent representations on both grids.

Running FOAM

We used FOAM to perform a series of long-duration simulations with the goal of determining whether a low resolution atmosphere could yield a reasonable representation of coupled ocean-atmosphere phenomena. We found that the coarse R15 atmospheric resolution sufficed to yield a realistic ocean circulation. Although R15 is an extremely coarse resolution (48 latitudes and 40 longitudes), it still requires approximately 16 times as much processor time as our ocean with 128 x 128 resolution on IBM SP platforms. This difference in execution time is attributable to the relatively complicated atmospheric physics code and to the efficiency of our ocean model. Accordingly, we typically run on 17 or 34 nodes, with 1 or 2 of those processors, respectively, dedicated to the ocean. To optimize inter-processor communication, the coupler runs on the same nodes as the atmosphere.

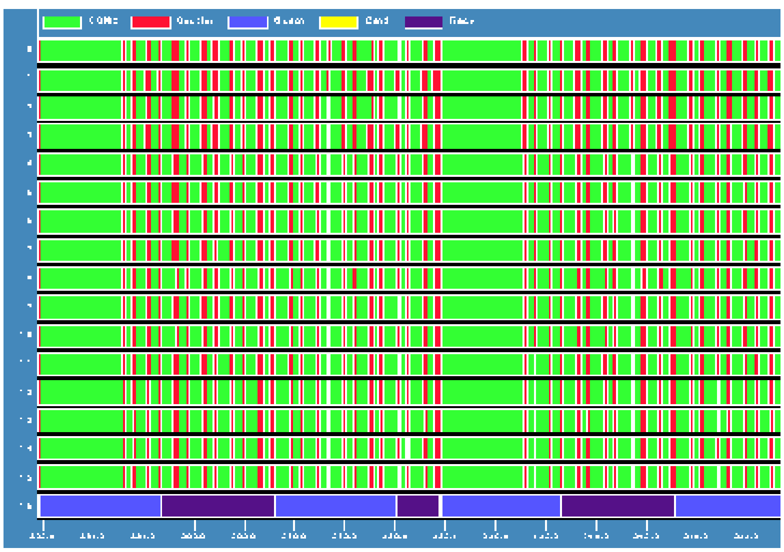

Figure 2: Time allocation for a typical FOAM run. Horizontal axis is labelled in seconds. Each bar represents a single SP processor. Green sections represent atmosphere calculations, red: coupler code, blue: ocean, and purple: idle time.

Figure 2 shows the allocation of computational resources as a function of time for a typical 17 node run performing the calculations for one simulated day. The bulk of the computation is allocated to the atmosphere implementation. The ocean time step is six hours, so the ocean is called four times per simulated day. The faster atmospheric dynamics must be represented on a half-hour time step, called 48 times. Twice per day, the radiative properties of the atmosphere are recalculated, yielding particularly long atmosphere steps.

All atmosphere nodes must integrate synchronously, as their results are dependent on results of neighboring processors. This is seen by the simultaneous exit of all atmosphere processors from the coupler routine, which handles all communication. The fact that all processors do not enter the coupler at the same time indicates imperfect load balancing in the atmosphere calculations, typically because cloud distributions are not uniform. It is seen that one ocean processor has no difficulty keeping up with 16 atmosphere processors, but that it can not keep up with 32.

We are still tuning the code for performance. To date, our best performance has been approximately 6,000 times real time in a run on 68 nodes of an IBM SP2 using 120 MHz P2SC Power PC symmetric multiprocessors. However, because of some constraints on the domain decomposition used in low resolution applications of PCCM2, this is a poor scaling from our production runs. We have seen almost linear scaling on 8, 16, and 32 atmosphere processors, which is what we normally use. We typically achieve peak performance faster than 4,000 times real time on 34 nodes. (This lack of scaling to 68 nodes is due to limitations in the spatial decomposition technique as applied to the low atmosphere resolution we use.)

In practice, with the production of large output files and the sharing of the platform with other users, we are producing results over months of real time at over 2,000 times real time and have established that we can scale this up significantly with the availability of additional resources at contemporary levels of technology. We are hopeful that even better results may be obtained as the platform configuration is tuned for scientific applications. We are also investigating parallelization of the input and output to further increase our efficiency.

The performance of FOAM can be compared directly to the NCAR CSM coupled model which accomplishes only a third of FOAM's maximum throughput using 16 nodes of a Cray C90 [39]. Our principal time advantages are in the extremely effective ocean code and in the reduced resolution of the atmosphere, which remains adequate to capture decadal ocean variability.

A further advantage of FOAM lies in the lower cost and complexity of the distributed memory systems on which FOAM is executed. While determining the true cost of supercomputers is difficult, we estimate that the cost per unit of performance of FOAM is already more than ten times better than that of other current models of the same phenomena.

Results and Refinements

Initial simulation results with FOAM, performed with CCM2 physics, were somewhat discouraging. In particular, the tropical Pacific, an important region for climate variability because of the strong phenomenon known as El Nino, was poorly represented. A more detailed representation of ocean mixing processes helped only slightly.

Near this point in the development of our model, NCAR released a new version of their Community Climate Model, CCM3 [18]. We were fortunate in that the software interfaces to updated physics routines were largely unchanged. We found that including the new CCM3 moisture physics into our model vastly improved its representation of the tropical Pacific [14].

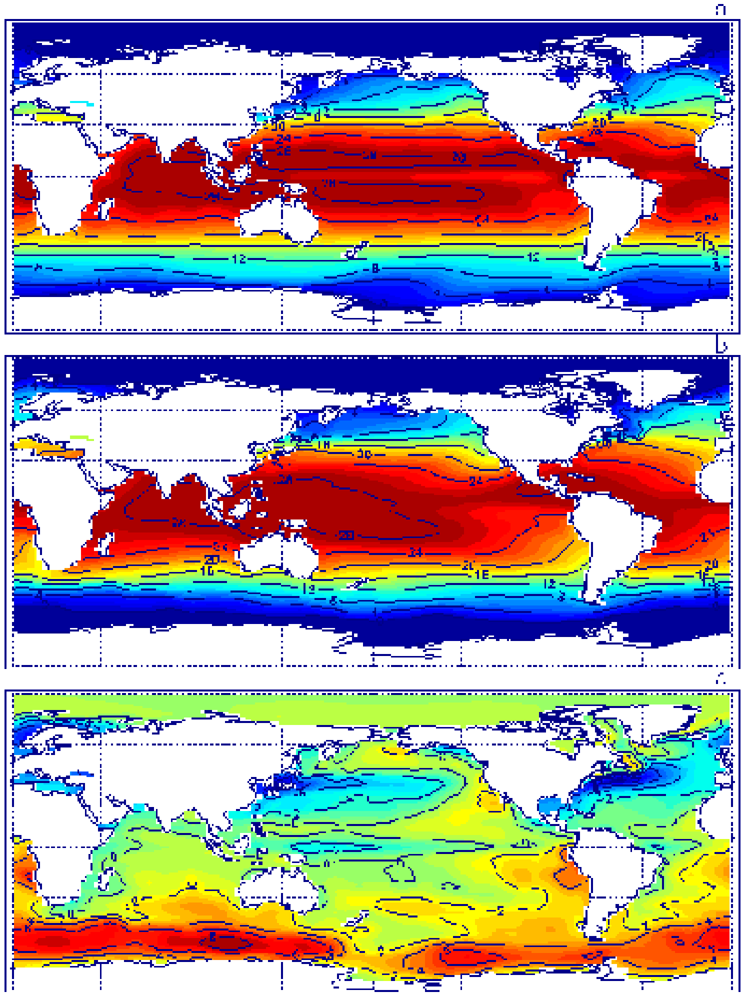

Figure 3: Sea surface temperature patterns (degrees C): (a) FOAM output (b) observations (see text), and (c) model minus observations.

Annual average sea surface temperature as modeled by FOAM improved with CCM3 moisture physics is shown in Figure 3(a). For comparison, observational data [35] is shown in Figure 3(b) and the difference between the true and modeled fields is shown in Figure 3(c). The broad features of the temperature field are captured, though the tight gradients in western boundary currents such as the Gulf Stream and the Kuroshio are somewhat smeared.

Except in the Antarctic Ocean, the results are comparable to those obtained with higher resolution atmospheres, less efficient ocean models, and more expensive computational platforms. The errors in the Antarctic are attributable to the crude representation of sea ice that we currently use. Updating this part of the model is currently a high priority. The otherwise good agreement indicates that we are capturing the large scale features of ocean circulation.

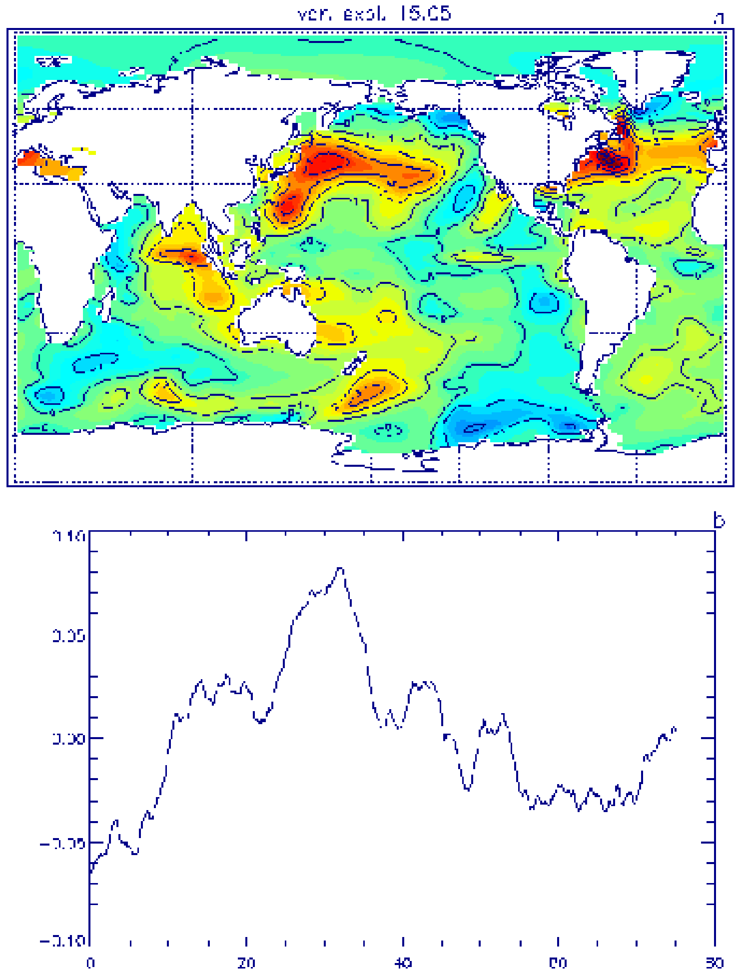

Figure 4: Two basin variability. Scales are arbitrary, but their product is anomaly sea surface temperature amplitude as a function of space and time, degrees C: (a) spatial pattern, and (b) temporal pattern

We have now successfully run the model for over 500 simulated years, and our first results regarding low frequency variability of the coupled system are emerging. Figure 4 shows a pattern (obtained by VARIMAX rotation of empirical orthogonal function decomposition) that accounts for fully 15 percent of 60 month low-pass filtered variance in sea surface temperature. The associated time series is also shown, indicating the long time scale of this phenomenon. This correlation between North Atlantic and North Pacific, until recently unanticipated, corroborates recent model and observational results by Latif and Barnett [20, 21].

Conclusions

The FOAM project has accomplished a substantial improvement in the performance that can be achieved by coupled climate models, without sacrificing physical realism. While reducing atmosphere resolution, it maintains a good representation of the ocean. The result is that the model is able to identify and study phenomena of interest on decadal and century time scales, and has succeeded in replicating recent model and observational results. In addition, the model is able to exploit parallel computer systems that offer improved cost performance relative to the vector supercomputers that have traditionally been used for such simulations.

Given these successes, FOAM may now be used for its intended purpose, to implement very long simulations for studying variability on the longest time scales. Currently, we are performing these simulations on multicomputers such as the IBM SP.

In the longer term, we intend to examine the feasibility of using PC clusters to improve cost performance yet further. We also hope to exploit high-speed networks to expand the utility of the model, by enabling remote browsing of the large datasets generated by FOAM [12], hence making these datasets more accessible to the community, and by using remote I/O techniques [7] to enable seamless execution on remote computers, with files maintained at a central location.

Since von Neumann used a weather model as his first test case of scientific computing [28, 5] leading developments of scientific computing platforms have been put to some of their earliest tests by meteorological applications [13, 22]. This will continue to be the case for the foreseeable future. The vast nature of the physical system will allow it to make use of whatever resources become available. The ultimate goal of very high resolution, very long duration, and very complete models remains far in the future. In the meantime, the FOAM project will endeavor to continue to provide the first glimpses of climate variability on the longest time scales.

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