

Computer modeling in physical oceanography from the global circulation to turbulence

Only with the recent generation of powerful supercomputers can more realistic ocean models be constructed to show oceanic circulation over many scales of motion—such as global, basin and mesoscale.

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In a computational science, there can come a time when enough raw computational power is available to lift the science to a new level of fundamental understanding. Particularly in various subdisciplines of fluid dynamics, the complexity of the physical problems to be solved establishes a benchmark—a minimum need in computer resources. It is only recently that sufficient computing power has become available to allow significant leaps in the understanding of important phenomena. The rapid increase has been extraordinary over the last several decades, with a 10-fold increase in the speed of computations in the 1970s and a 25-fold increase in the 1960s.¹ Today's supercomputer is a thousand times more powerful than those in existence in the early 1960s, when the first ocean model calculations were done.

Up to now, we have had to restrict the "realism" of global-circulation models severely because of the great range of scales, both in space and in time. Now, however, we are at the juncture where computing power allows the numerical integration of the four-dimensional geophysical fluid dynamics equations (see the box on page 56) and will let us work on developing—over the next decade—more adequate models capable of very realistic simula-

tions of the large-scale ocean circulation system.

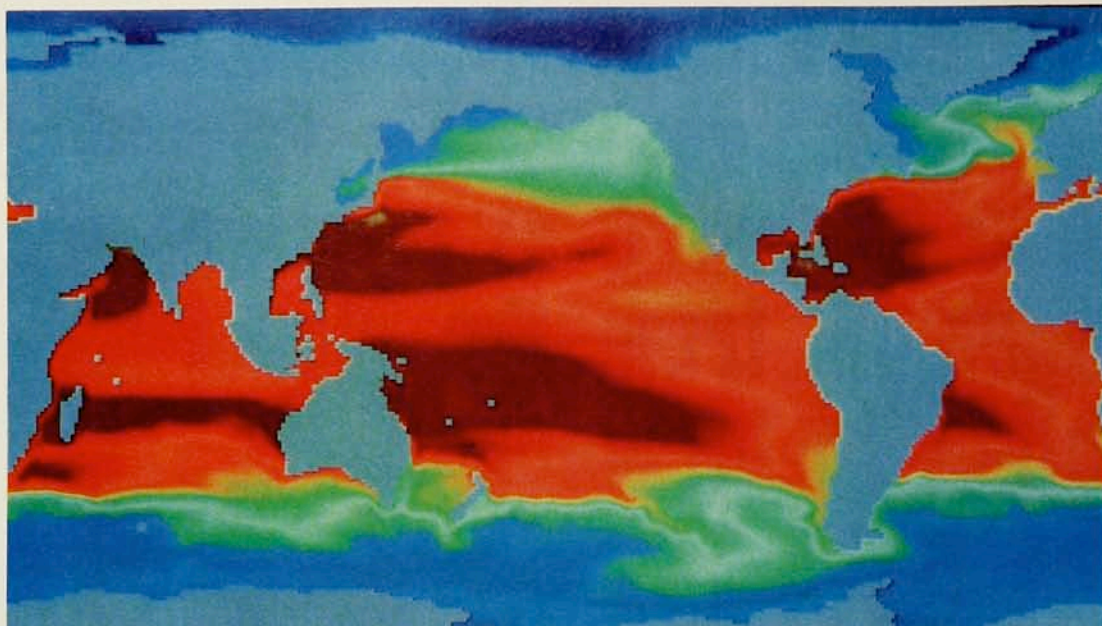
The ocean circulation problem concerns the motion of a rotating stratified fluid on a sphere (the Earth). In a rotating coordinate system a particle experiences a deflection at right angles to the direction of motion—the Coriolis effect. Also the complex boundaries introduced by the continents break up the global ocean circulation pattern into horizontally recirculating gyres (vast rotating flows established by wind forcing) in individual basins that are interconnected by meridionally overturning recirculation cells. Thin boundary layers such as the Gulf Stream, processes associated with ice formation in the Arctic and Antarctic regions, special behavior near the Equator due to the fact that the vertical component of the Coriolis force goes to zero there, thermohaline convection, and complex atmospheric fluxes of momentum, heat and fresh water at the sea surface all play a role. (The box on page 54 defines many of the technical terms we use in this article.) In addition, the ocean is inherently turbulent.

Instabilities in the fluid flow regimes established by large-scale winds and buoyancy forcing lead to intensely energetic eddies that mix and stir the fluid vigorously. Both its momentum and its vorticity are turbulently mixed, as are the temperature and salinity distributions that combine to give rise to density variations. Several factors—

the Coriolis effect, and the stratification set up by equator-to-pole heating and cooling patterns and by evaporation and precipitation at the ocean surface—affect the ocean parameters to produce narrow (100 km wide) boundary layers on the western sides of ocean basins, which are 50 to 150 times wider. The natural scales of the most energetic eddies, set by the rotation and stratification, are also about 100 km. Thus, due to the very high resolution and long time integration required, a very large numerical computation is needed to include the entire spectrum of motions from the scale of the energetic eddies—called the oceanic mesoscale—up to basin scales or even global scales of motion. This kind of calculation was not possible until the recent generation of supercomputers became available. Even now the computational limitations make such calculations just barely possible.

The time scales for adjustment of oceanic properties are important as well. As in many geophysical systems, a wide variety of interesting phenomena are linked in the ocean, from salt fingers, with centimeter motion scales and time scales that might be counted in minutes or hours, up to the global motions, with time scales of centuries, that control aspects of the Earth's climate. In addition, the ocean is itself interacting with other components of the climate system that have their own intrinsic time scales: the atmosphere,

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Temperature field in January at a depth of 225 meters (the fifth level of an 18-level model), from a global model of the oceanic general circulation. Deep reds represent temperatures of 24 °C and deep blues are -2 °C. Land masses are shown in a uniform gray. Note the strong thermal contrasts across the western boundary currents, which penetrate eastward along the poleward edges of the midlatitude gyres in all of the major ocean basins. (Courtesy of Michael Cox.) Figure 1

with periods of days, and glacial-interglacial effects due to the Earth's orbit, with time scales of tens of thousands of years.

We know we cannot include this entire range of interesting and relevant space and time scales in a single calculation. But do we need to know the details of those not included? Probably not. We do need to be able to describe their gross effects, if any, upon the scales of interest. We can assess what these effects are by constructing a hierarchy of models with different but overlapping resolutions.

We should say something about what kind of computer resources such a model of the ocean circulation requires and why this kind of modeling is a worthwhile scientific endeavor. A typical large-scale numerical ocean model might consist of finite difference equations representing the momentum, heat and salt balances in a single ocean basin such as the North Pacific. The equations must predict the time evolution of the horizontal and vertical structure of the fluid flow as well as the temperature and salinity within this domain, given the wind stresses and buoyancy forcing at the sea surface. The grid or cell size in such calculations is crucial for understanding, for example, how typical 100-km-scale ocean eddies influence basin-scale circulation. This calculation could require 10-km resolution in a 10 000-km ocean, or 1000 grid points in each of the two horizontal dimensions. The requirements in the vertical direction are not as demanding, but one might need 10 or 20—or even 50—layers to treat adequately the time evolution of vertical structure in the flow. Both physical

and numerical considerations set the size of the time step in such finite difference models. Typically, the time step is a fraction of a day, perhaps even as small as tens of minutes. Thus an ocean simulation of, say, the seasonal cycle of an ocean basin like the North Pacific, in a model that explicitly includes mesoscale eddies, can take hundreds (or even thousands!) of computer hours on present-day supercomputers.

Why should the physical oceanographer want to tackle such vast computational problems? The answer lies in the ocean's enormous importance in problems of climate and climatic change, in fisheries and other marine activities such as maritime commerce and warfare, and as the last repository of human-generated refuse.

The natural variability of the climate system has always played a major role in governing humanity's well-being. In recent times we have initiated a series of changes in the climate system that could lead to catastrophic consequences. Thus it is incumbent on us to develop an adequate understanding of the reasons for such changes in order to predict and control them, and perhaps even to prevent them from becoming a problem.

Global ocean models

The Earth's climate—and our adaptation to it—is a consequence of a complex coupling among various land processes, vegetation, glaciers and sea ice, the atmosphere and the global ocean. The whole is driven by the solar radiation—both its amount and its variation—most notably from the seasonal cycle, but also from the complicated variations in the Earth's orbit

and in the orientation of its spin axis on very long (astronomical) time scales. The habitability of the planet's various regions is directly determined by the manner in which the complete system adjusts to this incoming radiation, but in an intricate way that we still know only vaguely.

Numerical models of the atmospheric component of the climate system have been under development for nearly 40 years. John von Neumann singled out atmospheric modeling as a computational problem big enough and complex enough for the first digital computer, ENIAC, then a newly emerging tool for the scientific community. Phillip Thompson has given an eloquent description of the early days of numerical weather prediction.² Since then atmospheric models have become important operational tools in numerical weather forecasting. One can also examine the response of the atmosphere's general circulation to factors that might contribute to climatic changes. Important problems now being examined include:

- ▶ The reasons for glacial-interglacial climate behavior
- ▶ The potential for a greenhouse effect due to the rapid burning of fossil fuels and the release of CO₂
- ▶ The potential for irreversible changes due to our release of other trace gases.

The concept of a *general* circulation is valuable. Not only the mean flow but also the fluctuations in the circulation are critical elements in determining the nature of the climate response. Thus there is a need to determine and understand the whole set of space and time scales that character-

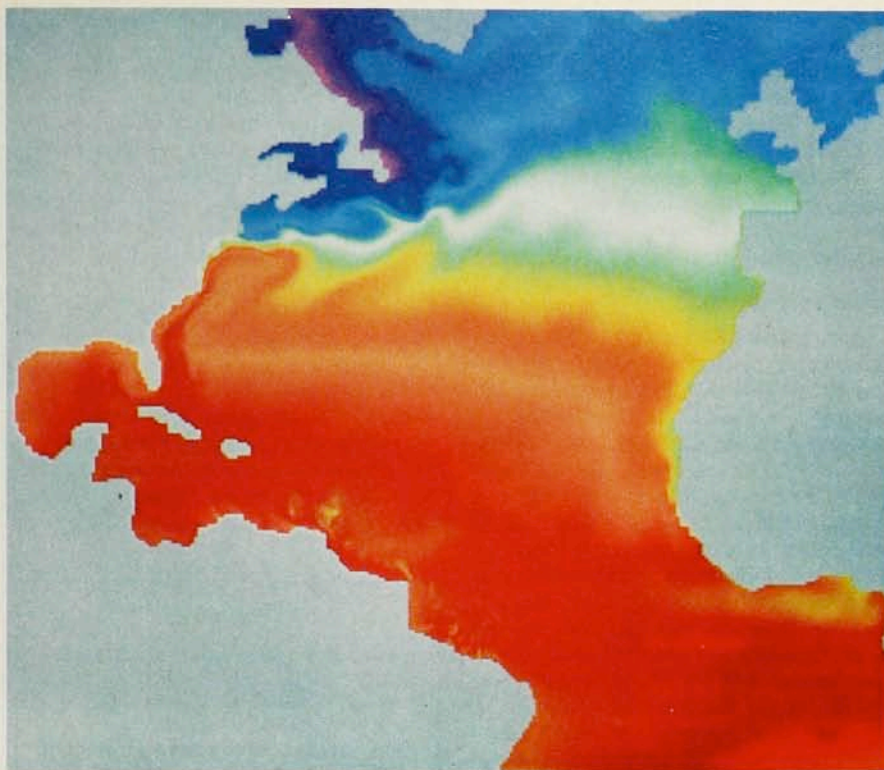
ize the behavior of the climate system, not just the longest and largest scales. General circulation will recur as a theme throughout our discussion of the development and application of ocean models.

Numerical ocean models have a somewhat shorter history of development than atmospheric models. The first three-dimensional basin-scale calculations were carried out in the late 1960s,^{3,4} and by the early 1970s such models were being extensively exploited. Global ocean calculations began in the early 1970s at the Geophysical Fluid Dynamics Lab in Princeton⁵ and at UCLA.⁶ These calculations had rather coarse resolution, and could represent only the broad structure of the three-dimensional flow. The supercomputer of that day was a Univac 1108, a machine about as powerful as a present-day low-end minicomputer. Many hundreds and even thousands of computer hours were needed to complete those pioneering calculations.

Such calculations, run without feedback coupling to the atmosphere, were not truly climate calculations but rather were designed to begin to develop an understanding of the complex, time-averaged ocean circulation, including the meridional overturning and inter-hemispheric exchange processes that together are responsible for the basic structure of the water masses—the three-dimensional distributions of temperature, salinity and other chemical properties—and the circulation patterns that characterize the global ocean. In these calculations the atmospheric wind forcing and the thermohaline (or buoyancy) forcing at the ocean surface were taken from observations rather than derived from an atmospheric model. Soon a coupled model followed.

In the mid-1970s, state-of-the-art atmospheric and ocean models enabled the first coupled model calculations of a single interacting system.⁷ Such calculations spawned numerous new modeling difficulties, stemming both from inadequate knowledge of the physical processes at the ocean-atmosphere boundary and from the disparate time and space scales in the two components. Globally the atmosphere's important transient events typically occur on time scales of days and on space scales on the order of 1000 km; the ocean responds on time scales of decades to hundreds of years on a global scale. Such vast differences have led to new asynchronous approaches to the coupling of such systems calling for an even greater need for very large computer resources.

Recently, Michael Cox (at the National Oceanic and Atmospheric Ad-



Sea surface temperature from an eddy-resolving model of the North Atlantic Ocean. The temperature is about 28 °C in the tropics (deepest reds) and 0 °C in the Labrador Sea (dark blue). Note the transport of warm water to northern latitudes by the Gulf Stream along the coast of North America. The domain is 15° S–65° N in latitude and 100° W–14° E in longitude. The horizontal resolution is one-third of a degree and there are 20 vertical levels. Approximately 1.4 million grid points were used in the calculation. The surface wind and thermohaline forcing are seasonal. Special boundary conditions at the north and south ends of the basin connect the circulation, temperature and salinity fields to the globally observed fields.

Figure 2

ministration's Geophysical Fluid Dynamics Laboratory) has carried out the most complete and best resolved global ocean calculation to date. The model, with 44 vertical layers, has a horizontal resolution of 1.2° in longitude and 1.0° in latitude. The ocean is mechanically driven by seasonal wind forcing, and the fluxes of heat and fresh water at the sea surface are determined by observed seasonally varying values of temperature and salinity. The ocean circulation is determined by a time integration of the equations of motion from initial conditions for a time equivalent to 10 000 years, until the deep ocean has come to equilibrium and the upper ocean is in a complete seasonal equilibrium. Comparisons with observed distributions of temperature and salinity and with seasonal heat storage show good first-order agreement with the real ocean, although a number of important problems associated with various mixing processes arise. And still better resolution is clearly needed. Figure 1, which shows the January temperature field at a depth of 225 meters, typifies the predictions that such a model can give. A

complex of pathways for horizontal and vertical heat transport, which are driven by time-dependent seasonal heating and cooling at the sea surface, determine the structure shown in the figure. The meridional transport of heat in the various ocean basins associated with this thermal field and with the three-dimensional circulation is poleward—with important consequences for the Earth's climate.

As these global ocean models were developed, the oceanographic community realized that much of the variability in energy in the ocean occurs on the relatively small "mesoscale," for which typical space and time scales are 100 km and 1 month. Limitations on computer resources prevented the global models from having sufficient resolution to include explicitly the effects of such eddies. Instead the models were parameterized with simple mixing lengths. But about this time new models of ocean circulation began to be developed that were restricted to single ocean basins but had very high horizontal resolution. (These eddy-resolved general-circulation models will be discussed in the next section.) The ocean-

modeling community concluded that a hierarchy of models would be absolutely essential to elucidating the important processes spanning:

- ▶ The global and climate scales
- ▶ The oceanic mesoscale
- ▶ The even finer-scale processes responsible for the mixing and dissipation events that govern the high-wavenumber end of the velocity spectrum.

Basin-scale models

During the 1970s many observations demonstrated that the oceanic mesoscale is extraordinarily energetic. Numerical models and theoretical studies have established that much of this mesoscale energy comes from hydrodynamic instability of large-scale current systems similar to those calculated in the coarse-resolution global models. However, mesoscale eddies did not spontaneously arise in those models, because they did not contain enough resolution—and were too dissipative. New model studies offered much higher resolution, but only on a restricted part of the globe, often a small, idealized ocean basin. Such models showed that extensive regions of typical oceanic circulation gyres would be unstable and that the emerging eddy field created its own equilibrium among mean currents, the eddy field and dissipation. The concept of a relatively slow-moving, laminar ocean was fundamentally changed to one in which vigorous turbulence as well as stratification and rotation plays a fundamental role. The general-circulation viewpoint, namely that the circulation statistics are crucial descriptors of the complex processes in the geophysical fluid, an idea long present in meteorology, has now come to ocean circulation theory and modeling as well.

Because of the need for very high resolution in ocean models that seek to capture the essence of the instability mechanisms that produce mesoscale processes, the computational expense is high. In early studies of mesoscale processes in basin-scale problems, trading sophisticated physics for better resolution in the model was an obvious compromise. Eddy calculations were first done for small, idealized basins with simplified physics. These primitive-equation models had only a few vertical layers. Even simpler eddy models followed. For the scales of motion involved, one could assume that the dynamics were strongly geostrophic—striking a near balance between Coriolis and pressure forces in the horizontal momentum equations.⁸ Because they filter out the faster gravity waves that play little role in midlatitude mesoscale processes, these so-called quasigeostrophic models can be

an order of magnitude less costly in computer time than the more complete, global models developed earlier, at least for problems of comparable size.

Recently the oceanographic community has been planning a global observation and modeling program for the 1990s, when several oceanographic satellites will be in space providing global synoptic observations. This World Ocean Circulation Experiment will be under the auspices of the National Science Foundation. In anticipation of the modeling needs of WOCE, the modeling community is beginning a sequence of model developments and studies to provide a sophisticated global- and basin-scale modeling capability with eddy-resolving general-circulation models. First calculations are

already under way for a North Atlantic model that extends from 65° N latitude to 15° S latitude, driven by realistic wind and surface thermohaline forcing. The model, with 20 vertical layers, has initially a horizontal resolution of one-third of a degree in describing the time-evolving velocity, temperature and salinity fields. An instantaneous depiction of these fields will exceed 5 million words of data, and many such depictions will be required to describe adequately the statistics of the model solution. Such a model will be run at this resolution for 25 years or so of simulated ocean time to gain accurate statistics for the mesoscale eddy activity over many replications of the seasonal forcing cycle. Figure 2 shows a preliminary picture of the surface temperature field in an early stage of the calculation. The scales of the large-scale flow and of the narrow Gulf Stream are apparent here. Approximately 1200 hours on a Cray X-MP using a single processor will be needed for this one calculation. Within the next few years, it is likely that the community will need to double this resolution, leading to an increase by a factor of 8 in computer cost, and will be interested in extending the one-third of a degree calculation to the global domain to better determine the physical behavior of the system at the finest resolvable scales of motion.

For some purposes, even higher-resolution models will be needed to treat satisfactorily especially energetic regions of the flow or to make special studies of local processes. Such studies can be carried out with the development of regional models with open boundaries. Figure 3 shows a regional model of the Gulf Stream obtained using a quasigeostrophic model with 14-km horizontal resolution. The Gulf Stream enters the domain as a western boundary current, separates from the North American continent at Cape Hatteras and meanders vigorously as it flows northeastward. The Stream is so unstable that its meanders often deepen enough to detach and form the Gulf Stream rings. These rings are important in the transport of water properties such as temperature, salinity and assorted chemical species across the Stream, warm rings moving north into cold waters and cold rings moving south into the Sargasso Sea. (See the section below on coherent structures for further discussion of such isolated features in the ocean.)

In a sense the computer cost of the increase in resolution in such models is partially offset by the reduced domain size. In fact all of the model studies discussed here are calculations at the limits of computer time availability.

Glossary

Geostrophic flow—a hypothetical horizontal flow in which there is an exact balance between the pressure gradient term and the Coriolis term.

Gulf Stream meanders—transient north-south deflections of the Gulf Stream as it flows eastward from the North American coast at Cape Hatteras into the North Atlantic.

Gulf Stream rings—intense vortices that arise from the pinching off of Gulf Stream meanders.

Mesoscale eddies—the relatively small-scale (~50 km) eddies that arise due to hydrodynamic instabilities of the larger-scale flow. These eddies can be as energetic as the time-averaged flow in much of the oceanic domain.

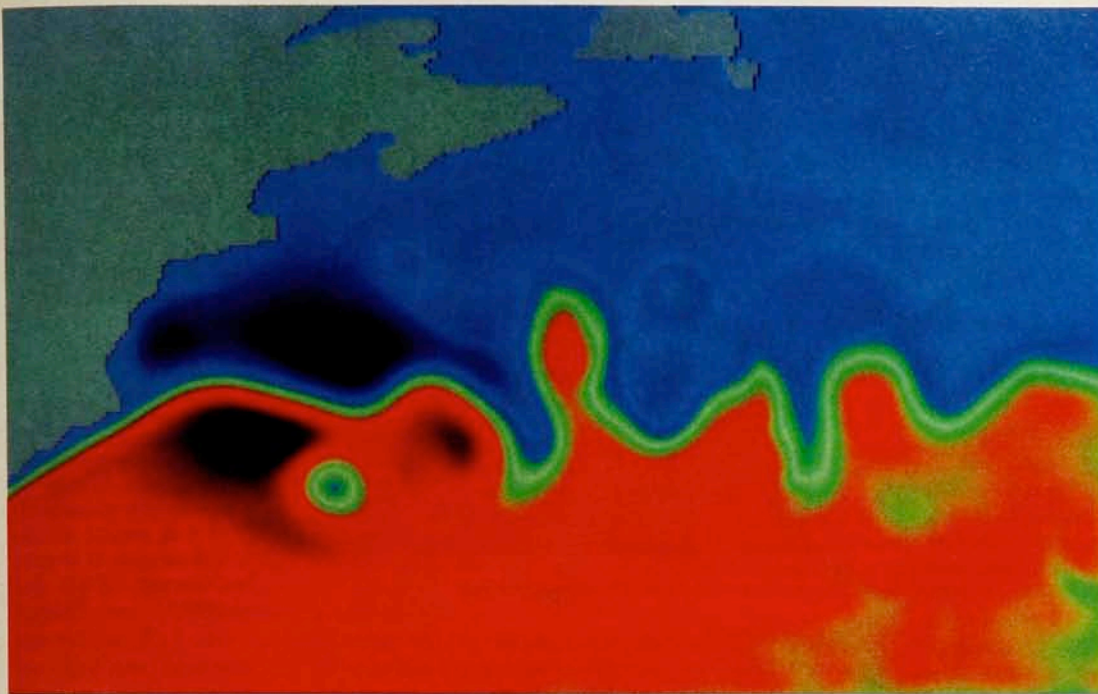
Ocean gyres—the horizontal rotational circulations that make up the large-scale flow in individual ocean basins.

Primitive equations—the equations of motion derived from the Navier-Stokes equations when the fluid flow is assumed to be hydrostatic and Boussinesq. In the latter approximation density is assumed constant except in the hydrostatic pressure term. The primitive equations (see the box on page 56) include an enhanced coefficient of viscosity to parameterize the influence of motions smaller than the numerical grid can describe.

Quasigeostrophic equations—the equations of motion derived from the primitive equations when the fluid flow is assumed to be strongly geostrophic. These equations have gravity waves filtered out, allowing larger time steps than in the primitive equations.

Sub-mesoscale coherent vortices—very small-scale vortical flows in which a geostrophic or centrifugal balance exists between the core density or pressure anomalies and the circular flow around the core.

Thermohaline—pertaining to the combined effects of temperature and salinity that contribute to density variations in the ocean fluid.



Regional model of the Gulf Stream, based on the quasigeostrophic equations of motion. The domain is 25°N – 50°N in latitude and 80°W – 40°W in longitude. The instantaneous pressure field depicted is due to variations in the height of the ocean's surface. Red represents the subtropical gyre (positive height) and dark blue the subpolar gyre (negative height). The sea surface is about 2.3 meters lower north of the Stream than south. Note the vigorous meandering and ring formation—important elements in the region's dynamics. Figure 3

Very large computational power is necessary to carry out such studies systematically.

Eddies, waves and turbulence

The ocean circulations resolvable in the class of models described above are not complete and self-consistent physical systems with dissipation due only to molecular kinetics (the collisions between molecules in the fluid). To achieve dynamic and thermodynamic equilibrium with model solutions at all close to real ocean circulations, one must greatly enhance the dissipation rates over those due to the actual transport coefficients of seawater (that is, the conductivities for heat and salt and the fluid viscosity). Such properties of the enhanced transport coefficients as spatial anisotropy and differences among the conductivities and viscosity need to be chosen correctly because the models are highly sensitive to them.

Finding the correct forms of transfer from the larger scales to the molecular ones (where dissipation must occur in the real ocean) involves an additional—much more varied—class of ocean models. These models are distinguished by their attention to smaller-scale processes, with the global- and basin-scale circulation superimposed in some *ad hoc* fashion.

As we suggested in the previous section, basin-scale models have their smallest resolved spatial scales within the mesoscale range. Do the enhanced model diffusivities match the actual transfer involving the nearly geostro-

phic motions on smaller mesoscales, where planetary rotation and stable density stratification continue to have significant effects? The transfer properties of geostrophic turbulence vary with physical quantity and spatial orientation. Kinetic and potential energy are transferred toward larger scales, while the differences in velocity and temperature gradients are transferred toward smaller scales. Variations in tracers are transferred toward smaller scales along surfaces of constant density, but little transfer occurs across these surfaces. (Tracers are quantities conserved following the fluid motion, such as compensating fluctuations of heat and salt that do not influence density.)

On even smaller scales, planetary rotation ceases to be important and geostrophic balance no longer holds. Yet ocean currents continue to be anisotropic because of stable density stratification, with vertical velocities typically weaker than horizontal ones. In a stably stratified fluid, the motions tend to be of two types: stratified turbulence and internal gravity waves. When the stratification is strong (that is, when the vertical gradient of density is large), these two types of motions interact only weakly. Stratified turbulence has many properties in common with geostrophic turbulence; the difference is that a local centrifugal force replaces the Coriolis force in balancing horizontal pressure gradients. One important difference is a tendency toward transfer of kinetic energy to smaller vertical scales.⁹ Gravity waves are

generated primarily by atmospheric forcing at the sea surface and propagate throughout the ocean. Except where they steepen and break, which tends to occur where local stratification is weak or current shear is large, these waves transfer momentum vertically much more efficiently than they do heat or salt. Breaking, however, induces isotropic turbulence and efficient transfer of all quantities to the scales of molecular dissipation; a hypothesis requiring further testing, partly through model studies, is that breaking is sufficiently widespread to make this transfer mechanism an important one in the general circulation.¹⁰ Also, where interactions with larger-scale currents generate gravity waves directly, as in flow past topographic relief or in the adjustment of a pressure field to an impulsive current, the induced transfer can be significant. For example, the transfer over topography is a drag force analogous to aerodynamic drag.

Finally, at even smaller scales, turbulent motions can be isotropic and efficient in transferring energy to molecular scales. Where the local turbulence is not strong, transfers at even the smallest scales can be anomalous because of motions induced by different conductivities for heat and salt, a process known as double diffusion or salt fingering. The present evidence is that much of the middle of the ocean supports salt fingering and that the resulting vertical transfer of heat and salt is important in the general circulation.¹¹

Locations on the periphery of the ocean have distinct mixing and trans-

fer properties. Atmospheric forcing causes formation of an upper-surface boundary layer where the density and tracer fields are well mixed. There are also boundary layers adjacent to the solid earth on the bottom and sides, where a major fraction of the oceanic kinetic energy is dissipated. Much of the vertical transfer of density and tracers may occur in the side boundary layers, in competition with the interior mechanisms of internal wave breaking and salt fingering.¹²

No single model calculation, of course, can span all these processes. Nor does the study of any of them require the full generality of the compressible Navier-Stokes equations. A hierarchy of approximate equation sets serves as the basis for numerical models: quasigeostrophic, balanced (including centrifugal forces), primitive and Boussinesq. By selecting from within this hierarchy a model no more complex than necessary, and by focusing on only a few small-scale processes at a time, one can calculate the sequence of oceanic transfer mechanisms. Ocean-

The primitive equations

The numerical model discussed herein is similar to that described by Kirk Bryan⁴ and will not be discussed in detail. The important simplifications are the hydrostatic assumption, in which the vertical equation of motion is a balance between the gravitational force acting on the fluid and the vertical pressure gradient; the Boussinesq assumption, in which density variations are neglected but not the effect of gravity; and an approximate treatment of small-scale mixing processes by eddy diffusion. Let $\mathbf{V}$ be the horizontal velocity vector with components (u, v) , let w be the vertical velocity component and let ∇ be the horizontal grad operator. Then the equations (with partial differentiation indicated by subscripts) governing the model are

$$\mathbf{V}_t + (\mathbf{V} \cdot \nabla) \mathbf{V} + w \mathbf{V}_z + (2\Omega + \lambda) \sin \theta \mathbf{k} \times \mathbf{V} = -\nabla(p/\rho_0) + C \mathbf{V}_{zz} + \mathbf{G}$$

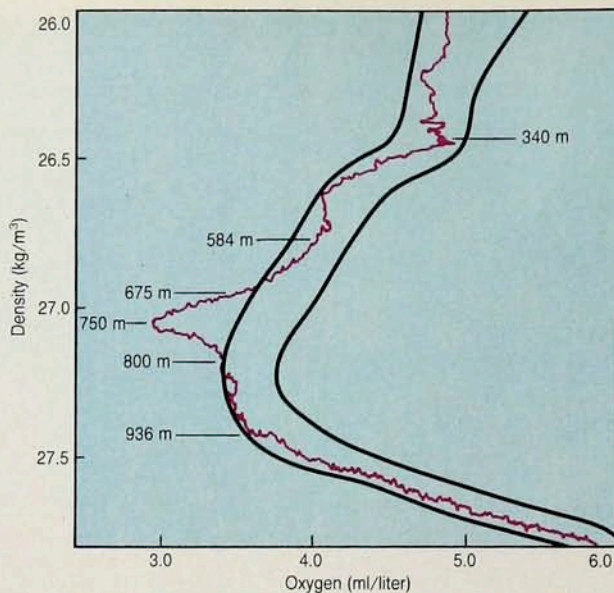
$$\rho g = -p_z$$

$$w_z + \nabla \cdot \mathbf{V} = 0$$

$$T_t + \mathbf{V} \cdot \nabla T + w T_z = K T_{zz} + A \nabla^2 T$$

$$S_t + \mathbf{V} \cdot \nabla S + w S_z = K S_{zz} + A \nabla^2 S$$

where θ is latitude; λ is the angular velocity relative to the rotating coordinate system (λ is longitude); Ω is the angular rotation of the Earth; T and S are the temperature and salinity (salt content) fields; ρ is the density; p is the pressure field; K and A are the eddy coefficients of turbulent mixing for heat and salt in the vertical and horizontal directions, respectively; C is the coefficient of vertical eddy viscosity; $\mathbf{k}$ is the unit vector along the z axis; and $\mathbf{G}$ is a horizontal body force due to lateral turbulent mixing.



Density vs dissolved oxygen (both of which are approximately invariant along a fluid trajectory) from a vertical profile through the core of a sub-mesoscale coherent vortex centered at a depth of 750 m. Dashed lines mark the ± 2 standard deviation envelope of climatological variability at this site in the western North Atlantic. (Adapted from S. C. Riser, W. B. Owens, H. T. Rossby, C. C. Ebbsmeyer, *J. Phys. Oceanogr.* **16**, 572, 1986.) Figure 4

ographers are quite optimistic about the plausibility of such calculations, and consequently about the prospects for piecing together correct evaluations of the smaller-scale transfers in the general circulation of the ocean.

Coherent structures

An example of the smaller-scale processes being modeled is coherent structures in turbulence. These are localized circulation patterns that can spontaneously emerge from complex initial conditions or forcing, are long-lived and can control the flow evolution even though they are spatially sparse, that is, intermittent. Underlying the coherent structure is a stationary solution of the nonlinear, conservative equations of motion; in the presence of forcing, perturbations and dissipation of limited amplitudes, the structures are kept within a domain of attraction about the underlying solution by the dynamical processes associated with spontaneous emergence.

The classical coherent structure in the ocean is a Gulf Stream ring. (See figure 3.) A nearly circular vortex with a radius of 75–100 km and a vertical profile decaying from the surface on a scale of about 1 km, such a ring is created when a large-amplitude meander of the Gulf Stream breaks. Once formed a ring usually persists and moves about until it is altered by close contact with another ring, the Stream or the continental boundary; a typical ring lifetime is many months. Other major currents spawn analogous rings.

Coherent structures also exist on smaller scales in the ocean. A widespread class, with spatial dimensions a factor of 10 smaller than rings, are

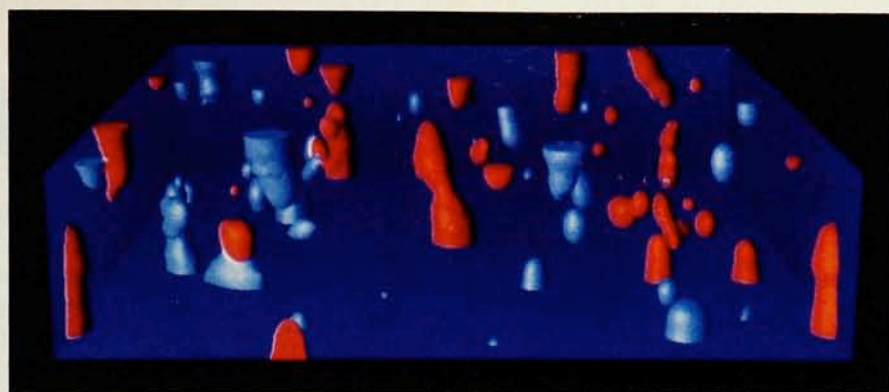
called sub-mesoscale coherent vortices.¹³ These are formed when nonconservative mixing events are followed by development of a vortical circulation in geostrophic or centrifugal balance with the core density and pressure anomaly. Sub-mesoscale coherent vortices can have lifetimes of many years, during which the larger-scale flow can transport them far from their generation sites. Since such circulations entrap the water mass within the core, the chemical-tracer properties can be quite anomalous for the new locations, given the mean geographical variation of chemical properties in the ocean. (See figure 4.) Eventually the coherent vortices must be destroyed, and then their chemical contents are no longer protected from diffusion by other ocean currents. This illustrates the potential for structured turbulence to have temporal nonuniformity and spatial nonlocalness in its mixing behavior.

The coherent structures in geostrophic (or stratified) turbulence are amenable to modeling. In fact, they are three-dimensional generalizations of the coherent structures in a purely turbulent two-dimensional flow, which is of course easier to calculate in numerical models.¹⁴ These coherent structures are intense, localized, axisymmetric concentrations of the vorticity (by definition equal to the curl of velocity). In an initial-value problem with broadband, random initial conditions and small viscosity, a coherent vortex develops by gathering the vorticity in its neighborhood and by resisting the straining deformations that induce both rapid vorticity transfers to small scales and rapid alterations of flow pattern in other regions of the

flow. As it emerges, a vortex in two-dimensional turbulence tends toward an axisymmetric shape about a central vorticity extremum. In geostrophic turbulence the preferred shape is axisymmetric about an axis aligned with the rotation axis and gravitational force; along the axis the vortex has a finite extent set by the strength of the stratification and the rotation rate. (See figure 5.) The profiles of vorticity with horizontal radius and height can be quite varied within broad limits set by the stability of the solutions. The vortices are persistent and usually move passively with the large-scale velocity field. However, when two or more vortices come close to one another, the mutually induced deformations are quite strong, and the outcome can be either nearly elastic—in which case the structures after interaction are the same as before—or wholly inelastic and irreversible. A common example of the latter is the merger of two vortices spinning in the same direction into a single vortex. Cumulatively such close interactions are non-conservative, so that weaker and smaller vortices tend to be destroyed and partially absorbed by stronger ones. Following such interactions the surviving vortices return to symmetry and alignment. Hence the field of vortices becomes increasingly sparse or intermittent.

The development of coherent vortices in geostrophic turbulence significantly reduces the rates of energy transfer between larger and smaller scales compared with flow configurations with comparable energy distributions but without vortices.¹⁵ For a given fluid domain and viscosity value, the number of vortices is a finite number much smaller than the truncation number of the Fourier series required to represent the same flow adequately. During typical intervals when individual vortices move passively, one can use a reduced description of the local circulation and its effect on other (distant) vortices. However, even a reduced model of invariant vortices (called point vortices) has chaotic solutions with limited predictability.¹⁶ Coherent vortices are of course more complex than point vortices during close interactions. Nevertheless some reduction in the number of degrees of freedom seems plausible in a flow with coherent structures, and this may offer a more tractable basis for a theory of turbulence in such circumstances.

Thus one can make the following hypothesis: Coherent structures may arise in many, or even most, regimes of turbulence, and an understanding of the dynamics of such structures may lead to a deeper understanding of



Surfaces of constant magnitude for the vertical component of vorticity in geostrophic turbulence. Red indicates a positive value of the vorticity and blue a negative value. This solution is from a Galerkin (Fourier transform) quasigeostrophic model with 192×192 horizontal and 32 vertical quadrature points. Equivalent oceanic physical dimensions for the domain would be approximately $100 \text{ km} \times 100 \text{ km} \times 5 \text{ km}$. On the basis of such solutions it is hypothesized that the ocean has a similar vorticity structure on a horizontal scale of a few kilometers. The elapsed time since the random initial state corresponds to fluid near the emergent coherent structures having made many circulation cycles about them. The computational time is about 40 single-processor hours on a Cray X-MP.

Figure 5

turbulence and its transfer. This is an exciting direction of research—and computer model solutions will be essential.

Conclusion

We have tried to give something of the flavor of the development of general-circulation models of the ocean, from global scales down to small-scale processes suspected of contributing, albeit indirectly, to the global circulation. There are two messages here. The first is that the availability of large computing resources dedicated to the development of such models has been and will continue to be vital if these methods are to reach full capability. Second, it has been necessary to develop a hierarchy of models, models whose computational costs are roughly equivalent but which still allow us to look at the vast range of space and time scales relevant to oceanic circulation. Presumably this situation will continue in the future, except that with increasing computer power we should be able to fully couple realistic atmosphere-ocean-ice models of the climate system, achieve mesoscale resolution in global models and develop superfine-resolution models of regional domains that explicitly include turbulent cascade processes.

Our understanding of the oceanic component of the climate system will also continue to grow rapidly. For the first time the models have a realism that makes systematic and careful comparisons with observations both useful and necessary. The models have gone beyond their early beginnings as simple extensions of idealized theories to make the link with the real world. At the same time the observational oceanographer has been busily acquir-

ing and developing the necessary tools to observe the ocean synoptically and to telemeter back these data for testing and inclusion in numerical models. The synergism involved and the rapid progress already apparent make this a truly exciting time in ocean research.

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