Antarctic krill *Euphausia superba*. The formation of large aggregations through rapid reproduction appears to be a common strategy for taking advantage of favorable conditions. Dense populations are sometimes further concentrated by wind or current action, or are transported close to the coast from their normal habitats farther offshore. The combination of rapid growth and advection can cause the sudden appearance of swarms of medusae, ctenophores, or salps in coastal waters. Although these blooms may sometimes have serious or even catastrophic effects on other organisms, including fisheries or human activities, they are a natural part of the life histories of the species, and not events for which remedial action is needed, or even possible. Gelatinous zooplankton are normal components of virtually all planktonic ecosystems. They are among the most common and typical animals in the oceans, whose biology and ecological roles are now becoming better understood.

See also

Plankton. Zooplankton Sampling with Nets and Trawls.

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GENERAL CIRCULATION MODELS

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Introduction

A general circulation model (GCM) of the ocean is nothing more than that – a numerical model that represents the movement of water in the ocean. Models, and more particularly, numerical models, play an ever-increasing role in all areas of science; in geophysics broadly, and in oceanography specifically. It was perhaps less the early advent of supercomputers than the later appearance of powerful personal workstations (tens of megaflops and megabytes) that effected not only a visible revolution in the range of possible computations but also a more subtle, less often appreciated, revolution in the very nature of the questions that scientists ask, and the answers that result.

The range of length scales and timescales in oceanography is considerable. Important dynamics, such as that which creates 'salt fingers' and hence influences the dynamically significant profile of density versus depth, takes place on centimeter scales, while the dominant features in the average circulation cascade all the way to basin scales of several thousand kilometers. Timescales for turbulent events, like waves breaking on shore, are small fractions of seconds, while at the opposite end, scientists have reliably identified patterns in the ocean with characteristic evolution times of order several decades.[1]

Most simply, a 'model' is no more than a mathematical description of a physical system. In the case of physical oceanography, that description includes the following elements:

- The momentum equation ($F = m\dot{v}$, but expressed in terms appropriate to a continuous medium), or often in its place a derivative form, the 'vorticity equation'.
- An equation to express the principle of mass conservation.
- A heat equation, which describes the advection (carrying by the fluid) and diffusion of temperature.
- A similar 'advection–diffusion' equation for salinity.
- An equation of state, which relates the pressure to the density.

[1] It is useful to distinguish extrinsic evolution times, which span geologic time, from intrinsic variation, which characterizes an isolated ocean and atmosphere, thus neglecting such secular influences as orbital variation, change in the earth's rotation rate, variation in the solar constant, etc. Although not all causes of variability have been identified, it is possible that even documented evolution over thousands of years may reflect the latter, intrinsic, variability.

Although it may, after the fact, sound obvious, it took scientists many years to appreciate the full role of rotation – which enters Newton's law through a latitude dependent Coriolis force – in generating the observed large scale circulation of ocean.

Elements of these equations can become quite complicated. For example, momentum in the upper ocean is imparted by a complex, not yet fully understood, process of wind–wave interaction. One has to choose whether to represent the action of the wind kinematically, which means that the spatial and temporal variability of the wind must be given beforehand, or dynamically, in which case we must solve not only the set of equations above, but a similar set that describes the simultaneous evolution of the atmosphere. Clearly the dynamical case is the more 'realistic' of the two, but the price is a substantially more involved computation.

It is issues such as these that force one to a choice that often pits understanding and intuition on the one hand against verisimilitude and complete dynamical consistency on the other. As the common aim of most large-scale models is to generate results of maximum realism, it usual that the models are frequently corrected, or 'steered', on the fly by extensive use of data assimilation. It is not merely a matter of slight refinement: no large-scale model (GCM) is yet sufficiently robust that it can be used for forecasting without considerable input of such observationally derived constraints; in the oceanic component, for example, the need to force model agreement at depth by continuously 'relaxing' the solution to the smoothed data of the Levitus atlas (a world-wide compendium of data from many sources, smoothed and interpolated onto a regular grid). How much of this fragility is because of explicit defects (faulty 'subgrid scale modeling' and explicit omissions in the physics e.g., neglect of wave breaking) and how much is due to discrete numerical implementation inconsistent with plausible continuous equations remains an open question.

Their limitations notwithstanding, large numerical models are one vital means by which we grapple with questions about global warming and a host of other environmental issues that affect the way that both we and future generations will live.

Models in Theory and Practice

Historically, computers were initially so limited that the questions posed were often, in effect, slight extensions of preexisting analytic queries. To that extent, such studies continued to conform (at least in principle) to what we may identity as four basic building blocks of most theories, which, in aiming to describe physical reality become subject to constraints. Classical modes to which physical laws are found to conform generally[2] include the following.

- *Expression in quantity, extent, and duration*. The language that offers itself as encompassing all distinct physical conditions and all meaningful physical relations is fundamentally that of mathematics. As others before and since, the great mathematician Eugene Wigner too had a stab at explaining what, in an eponymous essay, he termed 'the unreasonable effectiveness of mathematics in the physical sciences'. It remains a conundrum.
- *Confinement of form*. This attains its purest expression in the Platonic view that mathematical entities are not invented, but discovered, and as such have a prior, if not physical, existence. In extension to physical theories, it corresponds to the belief that there is some true, ultimate, equation association with any natural phenomenon. One important respect in which this idea must be tempered in application to fluids is the mathematical demonstration that a variety of different microscopic laws for interaction may all yield the same generic macroscopic law applicable to behavior at large space scales or timescales. If one's aim is solely to understand the latter, then although for a given problem we might presume that there is indeed a precise, if complicated, microscopic law, one's effort might more profitably be spent understanding the passage to the large-scale limit.
- *Falsifiability*. Implicit in the progress of science is the idea that one makes and then tests hypotheses. But unlike in mathematics, in the physical sciences we cannot show the hypothesis is correct, only that it is wrong. A hypothesis is never vindicated, instead we reach a tentative conclusion of not proven wrong (yet!). While it may stimulate conjecture, and have other worthy ends, the idea of introducing artificial parameters for the express purpose of manufacturing close agreement with reality is nonetheless formally antithetical to the paradigm of testing independent, quantitative predictions.
- *Backward compatibility*. As with confinement of form, the idea of compatibility achieves a purity in mathematics that is not to be expected of the

[2] We speak gently here, since to insist that those four are always either necessary or sufficient would require that we introduce a theory about theories: a metatheory. But we have no notion of how rigorously to evaluate such ideas!

> physical sciences. Each new bit of mathematics must fit perfectly into the entire edifice of results already discovered (or invented, as you will). Commonly, though not without exception, in the physical sciences, newer theories are seen to encompass the older theories as special or limiting cases. We speak, for example, of the 'classical limit' as a means of recovering prerelativistic or prequantum results. Indeed, it is only in light of Einstein's theory of special relativity that we can understand the limitations of Newton's law, which we now understand more fully as not a law, but a limiting approximation. Oceanography has families of theories, each nesting one within the next, like a series of oceanographic Matryoshka dolls, the innermost of which is often the theory of 'quasigeostrophy,' which dates from the 1950s.

The unavoidable adoption and resulting sensitivity of GCMs to *ad hoc* parameterizations (e.g., subgrid scale modeling) or necessity set them apart from the traditional pursuit of the scientific method. This distinction was (presciently) appreciated at least by the early 1960s and it changes, or ought to change, one's view of such models as rigorous arbiters of precise truths. And yet while it is true that numerical experiments with GCMs are merely suggestive rather than truly predictive of future evolution of the ocean, the sheer lack of experimental data, to say nothing of the lack of a control, means that theoretical ideas are often assessed on the basis of their success in explaining strictly numerical experiments.

As computers became more powerful it was natural to press for the most realistic model runs possible. And, because the growth in computing power was increasingly realized through distributed[3] as well as mainframe (super), computing, the school of 'kitchen sink' models, which started as a specialized branch off the mainstream of oceanography – largely limited in participation to those in close physical proximity to two or three central machines – became a powerful tributary in its own right: an autonomous discipline within oceanography, which naturally began to evolve its own criteria for relevance.

Limits on Numerical Models

We spoke of two sources of error common to large numerical models: difficulties in numerical implementation, and poorly modeled or unrepresented physical processes. In this section we consider specific instances of each, starting with an abstract mathematical point of view. But note that if we could with the wave of hand dispense with these two issues (which one supposes are in principle tractable), the fact that we do not know the exact physical state of the ocean inevitably increases the uncertainty of the results. Moreover, even were we given that exact state at some instant in time, the intrinsic and spontaneous genesis of disorder in such a physical system must forever constrain our predictive power.

There are two key mathematical features of the basic momentum (or vorticity) equation which bear comment: conservation and dissipation. The nonlinear term is fundamental to the initiation and sustenance of turbulence and by itself strictly conserves energy. (Other terms introduce explicit dissipation.) In addition, in two dimensions the term conserves 'enstrophy' (the square of the vorticity) and in three, both 'circulation' and 'helicity' (the dot-product of velocity and vorticity). While one might hope for all such conservation properties to be preserved in numerical implementations, some large models, often those based on curvilinear – as opposed to Cartesian – coördinates – manage only to conserve energy.

Beyond the conserved quantities associated with the nonlinear term, which include the energy and, in general, the so-called 'Noether invariants,' there is a more subtle property associated with the exact (continuous) equation: its associated 'multisymplectic geometry.' Recent mathematical advances make it possible for a discrete numerical model to preserve such structure exactly, though as yet such improvements have not been incorporated into any working GCM. Is it quantitatively important that we do so when basic fluid processes, such as convection, are as yet only crudely modeled? Until the experiment is tried, no one can say. But it is pertinent to note that a similar (that is, 'symplectic') refinement is critical for a numerical solution of sufficient accuracy that one can decide whether planetary orbital motions are chaotic on astronomical timescales.[4]

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[3] Both virtually, through high speed and increasingly transparent networks, and physically, through desktop workstations of considerable power.

[4] On dissipation, a deep, though perhaps insufficiently appreciated, mathematical result is that the solution of a parabolic, dissipative system quickly collapses onto a finite-dimensional 'attractor'. This is remarkable. If you think of assigning a point to every one of N molecules of water in the ocean, and tracking the velocity and position of each, the associated 'phase space ' – just a record of that evolution – has dimension $6N$. Because the momentum equation is derived on the basis that water is an infinitely divisible continuum, strictly we need to imagine that N approaches infinity. Nonetheless, even in that infinite-dimensional phase space, it remains true that the solution confines itself to only a finite, if quite large, portion.

Finally, strictly speaking, not only ambitious models, but even more confined 'process' models, rest upon a not yet wholly secure foundation: it is still an open research question whether the basic equation of fluid mechanics (the Navier–Stokes equation) is itself 'globally well-posed' in three dimensions.[5] (It is widely believed to be so, but belief comes cheap. A proof, however, is worth one million dollars(!) – one of seven prizes in a competition recently announced by the Clay Mathematics Institute.)

Even overlooking such foundational matters on which mainly mathematicians would cavil about numerical models, the last three of the four principles above are often violated in more apparent ways in the application and development of present-day models. We illustrate this divergence from traditional norms with a few representative examples to emphasize the sometimes causal (not casual!) link between models and 'reality.' In delineating the borders of the known, the unknown, and the unknowable, it is important to discriminate between deduction and rationalization as competing processes for exploring and explaining those borders.

- Although GCM simulations with a viscosity approaching that of water are at present inconceivable, at least as a thought experiment it is worth bearing in mind that those are the numerical results we would in principle compare against observation to assess a given model.[6] Short of that, GCMs use various formulations that ostensibly mimic the dynamical effects of the unresolved scales of motions. In the simplest instance, this amounts to choosing a numerical viscosity several orders of magnitude larger than that of sea water. But often the value is dictated by purely heuristic numerical considerations: it is set at a threshold value, any decrease below which leads to rapid numerical blowup. It cannot be said to be satisfactory feature that a basic parameter is set not by independent dynamical considerations but for stability reasons, and those pertaining solely to the discrete form of the equations. (The solution to the continuous equation would not blow up!) At times, not only the coefficient, but the actual form of the diffusive operator is adjusted. As above, usually the motivation is intrinsically numerical, so it is not surprising that a catalogue of the various choices shows some, for example, that create artificial sources (or sinks) of vorticity in the flow. Others, subject to the given boundary conditions, do not make mathematical sense in a region where the fluid depth tends to zero (like Atlantic City).

Oceanographers, unfortunately, do not have the luxury of extensive laboratory measurements from which their dissipative parameterizations can be calibrated. A program of direct observation in particular regions where dissipation is thought to be significant is just getting under way. While such measurements will help reveal deficiencies in present formulations, the largest GCMs will probably rely on a solely heuristic approach for some time to come.

- An important, but numerically unresolved, process in the ocean is that of convection, which typically occurs at small scales in, for example, localized regions of intense surface cooling. The overall thermal structure of the ocean is sensitive to this, a means by which 'bottom water' is formed; a cold, relatively less salty mass that constitutes the deep Atlantic, for example. Because the horizontal resolution is too coarse to encompass the sinking motions, various schemes have been devised to mimic that effect. It has been shown that one of the most common of these leads paradoxically to unacceptable physical (and mathematical) behavior as resolution is improved; it has no verifiable correspondence to a realizable physical process. The temptation with a model that has been extensively tuned to give plausible answers for other observables is to leave well enough alone. Unhappily, a model with one or more such elements whose limits are ill-defined or nonexistent must inevitably produce end results whose errors are typically an opaque mix of effects: some physical, some numerical, some mathematical. In such circumstances, the program of falsifiability of the physical components is apt to be fatally compromised.

The point is not that one should immediately dispense with all *ad hoc* parametrizations; excepting those that are simply mathematically ill-posed from the outset, theorists generally do not have better alternatives to suggest. But one should always bear in mind the degree to which numerical simulations are sensitive to these components, and seek independent ways in which to constrain their parameters, in isolated settings that test the limits of prediction against known measurements or, failing

[5] Hadamard introduced the notion of ill-posedness of partial differential equations. A problem is well-posed when a solution exists, is unique, and depends continuously on the initial data. It is ill-posed when it fails to satisfy one or more of these criteria.

[6] There is a curious division among physical oceanographers as to whether the large-scale flow we observe is, in the end, actually sensitive to the precise value of the viscosity of sea water. Predictably, there are two camps: yes and no.

that, at least against fully converged, adequately resolved simulations of a local or regional character. If, within the acceptable parameter range identified, it is found that the original model no longer gives adequate large-scale predictions, then there are more basic problems to be addressed.

Summary

From the numerical side, no computer improvements that can be seen on the horizon seem likely to make reasonably ambitious GCMs accessible to rigorous and extensive parametric and numerical exploration, a prerequisite to their complete understanding. From the mathematical side, it seems to be our fundamental ignorance about turbulence that most severely restricts the range of our grasp, leaving us with an often painfully narrow range of computations to which theoretical remarks can be significantly addressed. For these structural reasons, the gulf between theory and much numerical modeling will probably continue to widen for the foreseeable future, and thus there may grow to be—indeed some would say it already exists—a division akin to C.P. Snow's 'Two Cultures'.

All the cautions about GCMs notwithstanding, they have become an integral part of the study of physical oceanography. With due regard for the novel capacities and limitations of numerical models, such scientific progress as we do make will more and more often hinge upon judicious computation.

See also

Deep Convection. Double-diffusive Convection. Forward Problem in Numerical Models. Thermohaline Circulation. Wind Driven Circulation.

Further Reading

The literature on ocean modeling is not yet productive of definitive treatises, in large measure because the field is yet young and rapidly evolving. Thus in lieu of textbooks or similar references, the reader is directed to the following series of articles.

For some predictions on the perennially intriguing issue of what improvements in large-scale modeling may be driven by plausible increases in computing speed with massively parallel machines see

Semtner A (2000) Ocean and climate modeling. *Communications of the ACM* 43 (4): 81–89.

For a look back at the history of one of the single most influential models in physical oceanography, see A.J. Semtner's Introduction to 'A numerical method for the study of the circulation of the World Ocean', which accompanies the reprinting of Kirk Bryan's now classic 1969 article of the title indicated. This pair appears back-to-back, beginning on page 149, in *Journal of Computational Physics*, (1997) 135 (2).

General readers may wish to consult the following succinct review, accessible to a broad audience:

Semtner AJ (1995) Modeling ocean circulation. *Science* 269 (5229): 1379–1385.

Finally, for those readers desiring a more in depth appreciation of modeling issues and their implications for specific features of the large scale circulation, consult the careful review

McWilliams JC (1996) Modeling the oceanic general circulation. In: Lumley JL, Van Dyke M, Read HL (eds) *Annual Review of Fluid Mechanics*, Vol. 28, pp. 215–248, Palo Alto, CA: Annual Reviews.

GEOMAGNETIC POLARITY TIMESCALE

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Introduction

Dating and time control are essential in all geoscientific disciplines, since they allow us to date, and hence correlate, rock sequences from widely different geographical localities and from different (marine and continental) realms. Moreover, accurate time control allows to understand rates of change and thus helps in determining the underlying processes and mechanisms that explain our observations. Biostratigraphy of different faunal and floral systems has been used since the 1840s as a powerful correlation tool giving the geological age of sedimentary rocks. Radiometric dating, originally applied mostly to igneous rocks, has provided numerical ages; this method has become increasingly sophisticated and can now—in favorable environments—also be used on various isotopic decay systems in sediments. We are concerned with the application of magnetostratigraphy: the recording of