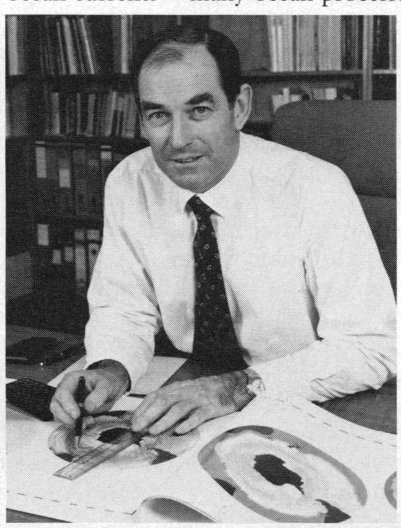
Supercomputer Voyages to the Southern Seas

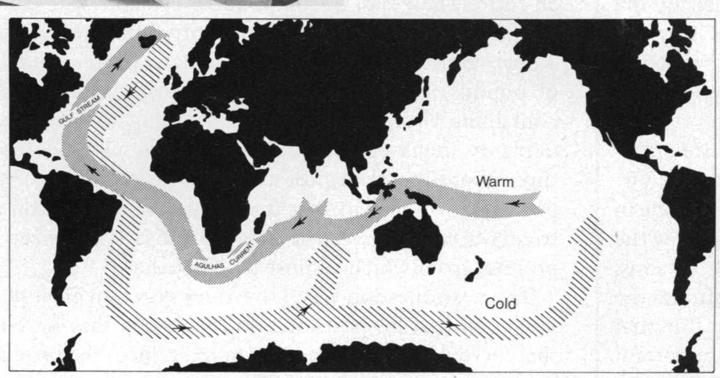
A model of ocean circulation in the Southern Hemisphere helps explain Britain's warm winters—and much more

London—ASK ANY ENGLISH SCHOOLCHILD why an overcoat is enough to keep you warm in London in the middle of January (mean temperature +41°F) while across the Atlantic, at exactly the same latitude (51.5°N), you need to dress like an Eskimo (mean temperature in Labrador -13°F) and you will get the standard answer: because of the Gulf Stream drift, carrying warm water across the Atlantic to Britain's shores from Florida. That answer has been good for at least 2 centuries, ever since the invention of the chronometer enabled Major James Rennell to begin measuring ocean currents accurately and plot the course of the Gulf Stream. But, alas, from now on, that answer would win only half a point.


PROFESSIONAL IMAGES

Heat driver. *Without Agulhas current carrying heat from the Indian Ocean into the Gulf stream, "Europe might have a different climate," says David Webb.*

The traditional view of the Gulf Stream has been changed by the publication this month of a new oceanographic atlas of the southern oceans, summarizing data from a massive supercomputer model of the southern oceans. The news is that Londoners should not only thank Florida for their mild winters; they should also show some gratitude to the ferocious Agulhas current off South Africa. That current drives warm water from the Indian Ocean around the tip of South Africa, generating enormous swirling eddies (see color picture and map) that, the model suggests, carry gigantic quantities of heat up through the Atlantic and into the Gulf Stream. "If it weren't for the current and these eddies most of the heat would stay in the Indian Ocean, or be swept around Antarctica. Europe might have a different climate," says David Webb, coordinator of the project, known as the Fine Resolution Antarctic Model (FRAM).



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If that weren't surprise enough, the FRAM model has also revealed that surface ocean currents are affected by underwater mountain ranges—even though these are all at least 2 kilometers below the surface. And there are likely to be many more unexpected findings lurking within the data—the key thing is that the model at last provides a realistic, accessible picture of the southern oceans.

"This is the first time that a model of the southern ocean currents has been created that agrees closely with the observations of those who work at sea," Webb says. With the model in hand, researchers can now begin to tackle the underlying physics of many ocean processes. And even more important, the model provides a step toward the ultimate goal of a simulation of the entire oceans and atmosphere—one that will make accurate, long-term climate prediction possible.

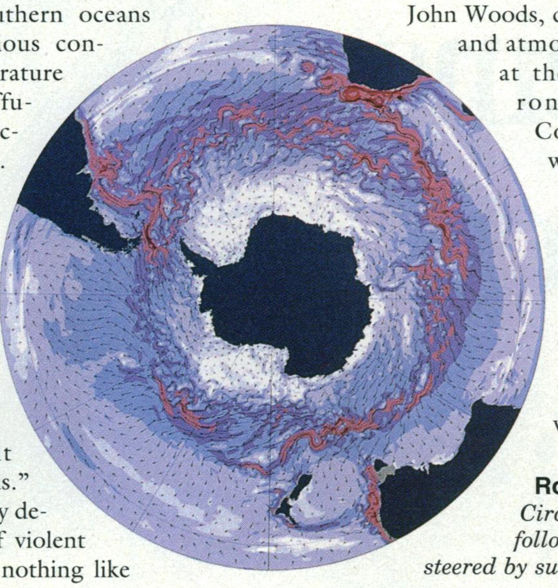
For the British group, based at the Institute of Oceanographic Sciences in Surrey, there is also an extra thrill in publishing the atlas: They feel they've stolen a march on their American colleagues who are working on the Community Modelling Effort (CME) at the National Center for Atmospheric Research in Boulder, Colorado. CME is putting together a very similar model of the Atlantic Ocean. "We got the best deal by choosing the Southern Ocean....We have made much faster progress," says an exuberant Webb.

That is not quite how the Americans see it. "The FRAM team has done fine work, it is extremely important and I have a high regard for them," says Bill Holland, leader of the CME. "However, I would dispute that they are ahead of us. We've taken a different approach. Rather than making an atlas on preliminary findings we have been giving away the raw data to many different research groups around the world." Both groups started work in 1986, but Holland says, "Our part of the ocean has quite important climatic implications for America and Europe so we are focusing more on the role of this numerical ocean in climate. The FRAM team has focused more on basic dynamic issues about how the ocean works in that part of the system. Anyway, Holland stresses, "It is not a competition." Efforts made by both FRAM and CME will eventually combine in a world ocean model.

That goal is still a long way off because modeling the ocean is very much more difficult than modeling the atmosphere. Key features in the sea are much smaller than those in the atmosphere. A climate modeler worrying about regions of high or low pressure can think in scales of 500 to 1000 kilometers; an ocean modeler has to deal with features such as the Gulf Stream that are only 50 kilometers wide. Colossal computing power is needed to handle such fine detail. "These calculations are among the largest ever done on a computer anywhere," says Holland. "The ocean is very difficult to simulate. The events are very small scale and there are an extremely large number of grid points."

A supercomputer model of the oceans works just like the kind of mechanical universe envisaged by Descartes: Start with the known position of all the particles in the universe, let their interactions be governed by Newton's laws, and the future then unfolds at the speed with which the supercomputer can calculate all their interactions. The ocean may not be as big as the universe, but the scale is still immense: Even with 20 million data points, FRAM still only samples the vastness of the southern oceans at points 27 kilometers apart on average. And even using a CrayX-MP supercomputer, the model can run only 50 times as fast as reality—a solid week of computer time is needed to model a year's change in the oceans.

Even more difficult is knowing at what point to start the model going. The FRAM team began by putting in the known topography of the southern oceans, plus the observed values of temperature, wind speed, and salinity as far as they were known from a hundred years of patchy data collection in the southern oceans (along with various constants for temperature and salinity diffusion, bottom friction and so on). "It was an obvious approach," says Peter Killworth, one of the FRAM coordinators, "it worked for the Americans modeling the North Atlantic—but it didn't work for us." The model quickly developed a pair of violent eddies that were nothing like those seen in the ocean.



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Round and round. *Circumpolar Current follows tortuous path, steered by subsurface features.*

A kinder, gentler approach was tried next. They started with the oceans as a uniform cold, motionless fluid, added sunshine, rainfall, and wind, and as the model ran, nudged it toward the real values of temperature and salinity in the deep ocean. Now in its 16th model year, the supercomputer has been generating the full complexity of the ocean for 6 model years but with one massive advantage over the real thing—the model oceans can be stopped at any time and vast quantities of data read out.

The model shows that, as expected, currents in the Southern Ocean are driven by the wind, and they flow round and round Antarctica. But what has never been seen in field observations is that this Circumpolar Current follows a very tortuous path, steered by features deep below the surface of the ocean, and breaking into a series of intense jets where it passes through the Pacific-Antarctic Ridge in the South Pacific. The strongest jet is at the Udintsev Fracture Zone, where a current almost four times as big as the Gulf Stream is forced through a gap less than 100 kilometers wide. The jets cause eddies, which had been seen by the U.S. Geosat satellite. The model showed no sign of any heat being transported southwards out of the Pacific through the Drake passage at the tip of South America, as many oceanographers had predicted. Instead, heat from the Pacific goes via the Indian Ocean and the Agulhas current.

The new ocean features seen in the FRAM model are a delight for oceanographers. One FRAM snapshot creates more information than oceanographers have ever collected in the ocean itself. "We squeezed far more out of the model than we could out of the oceans—we found intense currents, steady ones and weak ones. Some of the currents have never been seen before," says John Woods, director of marine and atmospheric sciences at the Natural Environment Research Council (NERC), which funded FRAM. But discovering new currents is just the beginning—the problem is then to explain the physics of why they arise, whether in the model or the real ocean.

"The model is so comprehensive that to analyze the data is just as difficult as to analyze real observations, in some ways even harder," says Kristofer Döös, a Swedish oceanographer who came to Britain to join FRAM. "Often people hold up these multicolored pictures from the computer like a Picasso and imply that the task is finished, but it is only when the simulation is over that the real work starts," he says. Killworth agrees: "With FRAM we have been able to see much more clearly what is happening but our ability to explain it is only just beginning." To make progress, individual researchers may spend years analyzing a single slice of data from the FRAM or CME models.

In spite of the torrent of data it generates, the FRAM model cannot answer all the questions oceanographers have about the Southern Ocean. Still finer resolution is required. "We need points close enough to pick up small-scale features that would show more clearly what is happening and help explain how it came about," says Killworth. Sometimes the picture it produces is horribly regular. "Something is right, something is wrong," says Killworth. The strengths of the currents generated by FRAM are sometimes out by as much as 30%, but when the resolution is increased, accuracy improves, suggesting a more detailed model would produce even better results. Finer detail is also needed to model the topography of the sea bed. FRAM uses smoothing techniques to cope with the steep gradients of undersea mountain ranges, but these can create false currents.

Webb's team wants to extend its work to cover the oceans of the world, but even with today's supercomputers such a program would take 3 years to run! NERC should have a new supercomputer within the next couple of years, but Webb reckons that it will be the end of the decade before machines 1000 times more powerful than existing models are available. Only then will they have sufficient number-crunching power for routine research using fine-resolution models of global circulation.

A number of British university researchers are helping analyze the FRAM data. Says Webb: "One team is looking at what determines the current strength and others are making detailed comparisons of model and observational data. An important area of investigation is to discover how currents find their way over mountain ranges from valley to valley. In addition to the circulation of heat and water, the flow of nutrients will also be examined."

FRAM's data are being used to design observational cruises in the Southern Ocean from British research ships starting in 1992-93, as part of the World Ocean Circulation Experiment (WOCE). This 40-nation collaborative effort, begun last year, aims to create the first coherent survey of world oceans using data from satellites, ships, and buoys. WOCE routes that have already been agreed for data gathering will not change, but FRAM data will influence the locations where readings are taken. This is because FRAM has shown how localized and intense the key currents might be—measurements just 20 kilometers away from an area of strong flow can yield a substantially inaccurate result.

"There have already been major advances in our view of the ocean since these data were produced," says Webb. "In future it will change our thinking on what happens to pollutants, how water mixes and how force gets transmitted down into the deep ocean. Until we got to this scale, models were in the dream world and did not have credibility."

Further advances in computer modeling are expected to be rapid. In 10 years time, FRAM will look like the Model T Ford does today, says Peter Saunders, a researcher working on the model. The mass of new data from WOCE will provide a strong reality check on the modelers' efforts, so that by the end of the decade, researchers on both sides of the Atlantic should be ready for the next modeling challenge: joining ocean to atmosphere. ■ JANE BIRD

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