If Rain Falls On the Ocean—

Does It Make a Sound?

Fresh Water's Effect on Ocean Phenomena

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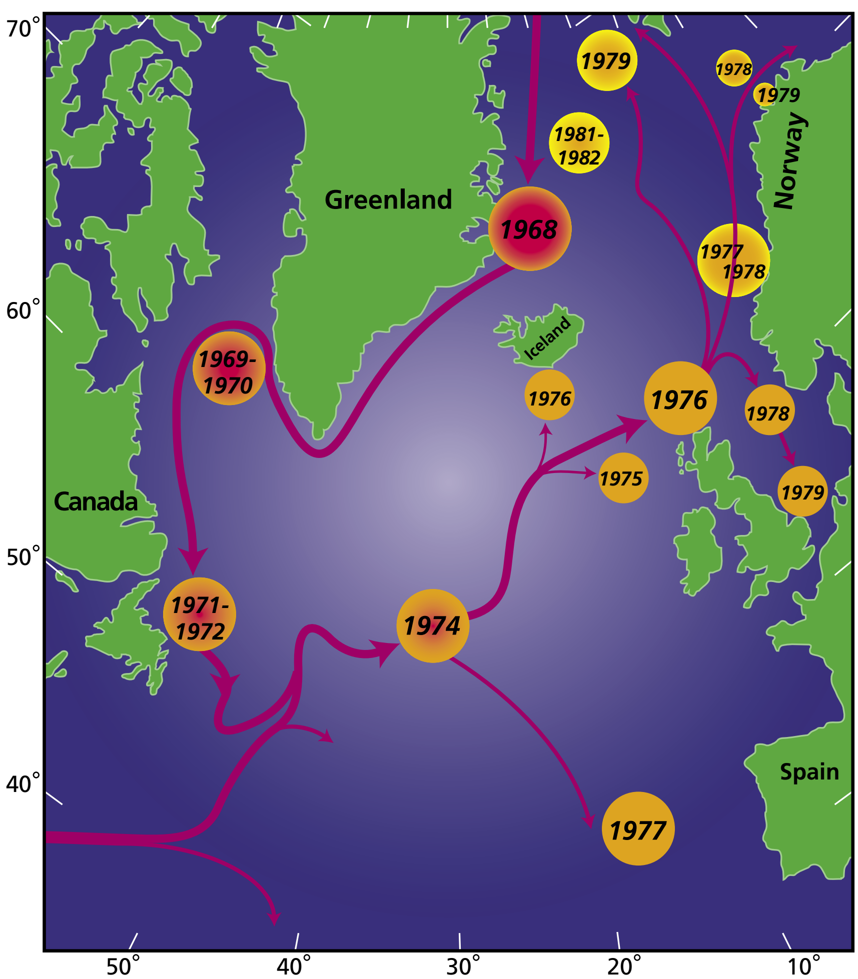
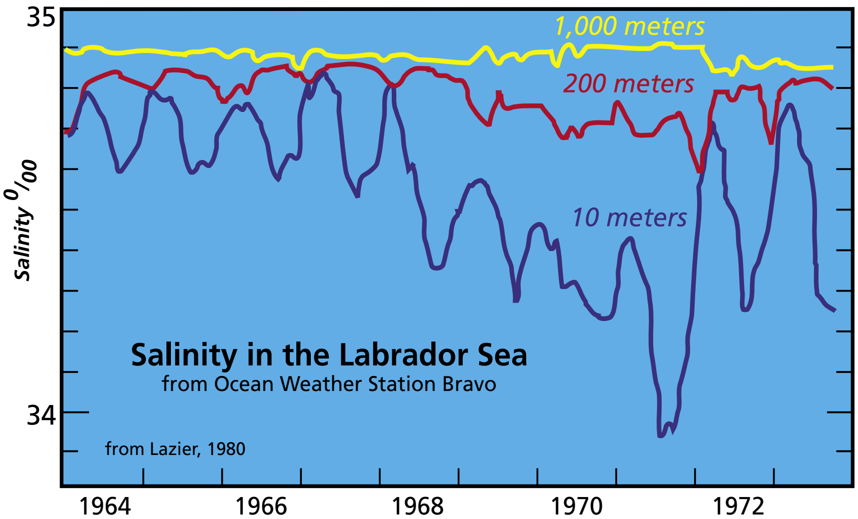
As with similar questions about a tree in the forest or a grain of sand on the beach, it may be hard to imagine that a few inches of rain matters to the deep ocean. After all, the ocean's average depth is around 4 kilometers and only 1 to 5 centimeters of water are held in the atmosphere at any one time. But it does matter, in part because the ocean is salty. The effect of rain diluting the salts in the ocean (or evaporation concentrating them) can be greater than the effect of heating (or cooling) on the density of seawater.

It also matters because rainfall and evaporation are not evenly distributed across and among ocean basins—some regions continuously gain water while others continuously lose it. This leads to ocean current systems that can be surprisingly strong. The processes of evaporation and precipitation over the ocean are a major part of what is called "the global water cycle;" indeed, by all estimates, they dominate the water cycle over land by factors of ten to a hundred. The addition of just one percent of Atlantic rainfall to the Mississippi River basin would more than double its discharge to the Gulf of Mexico.



The Great Salinity Anomaly, a large, near-surface pool of fresher-than-usual water, was tracked as it traveled in the subpolar gyre currents from 1968 to 1982.

As discussed previously in Oceanus, our knowledge of the water cycle over the ocean is extremely poor (see the Spring 1992 issue). Yet we now realize that it is one of the most important components of the climate system. One of the significant pieces of evidence for this comes from a description of the "Great Salinity Anomaly" put together by Robert Dickson (Fisheries Laboratory, Suffolk, England) with other European oceanographers. The Great Salinity Anomaly (GSA) can be characterized as a large, near-surface pool of fresher water that appeared off the east coast of Greenland in the late 1960s (see figure at left). It was carried around Greenland and into the Labrador Sea by the prevailing ocean currents, in the counterclockwise circulation known as the subpolar gyre. It hovered off Newfoundland in 1971–72 and was slowly carried back toward Europe in the North Atlantic Current, which is an extension of the Gulf Stream. It then completed its cycle and was back off the east coast of Greenland by the early 1980s, though reduced in size and intensity by mixing with surrounding waters.



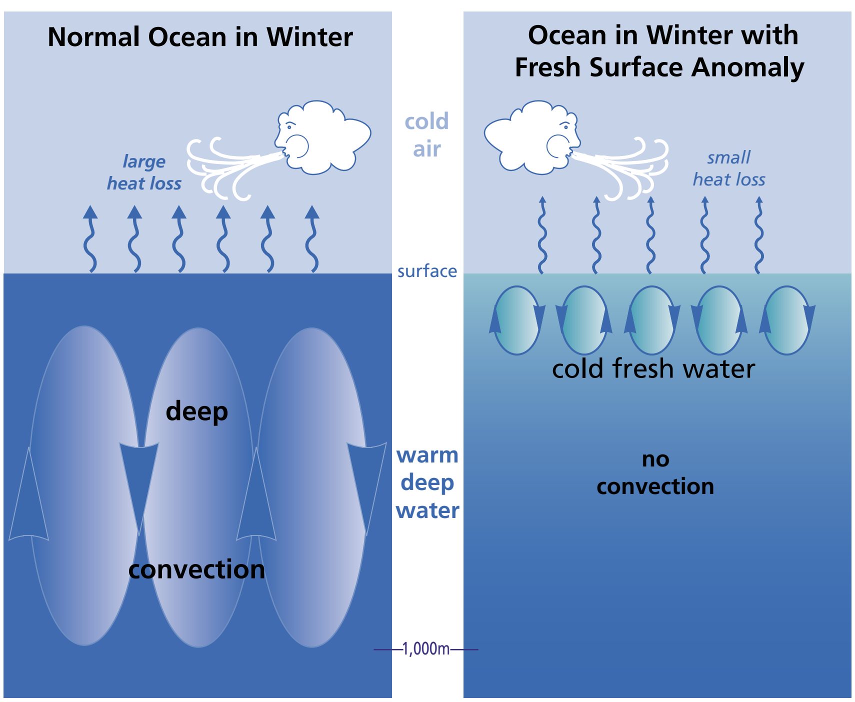
Salinity as a function of time at 10 meters, 200 meters, and 1,000 meters depth as recorded at Ocean Weather Station Bravo (see map on page 10) in the Labrador Sea. Deep convection is possible when the salinity difference between shallow and deep water is small. This normally occurs every winter. However, from 1968 to 1971, the presence of the fresh, shallow, Great Salinity Anomaly prevented deep convection. Unfortunately, Weather Station Bravo is no longer maintained. Scientists will need to use new technology like the PALACE float (see Box overleaf) in order to reestablish such time series. Such data is essential for understanding the role of freshwater anomalies in the climate system.

The origin of the Great Salinity Anomaly is thought to lie in an unusually large discharge of ice from the Arctic Ocean in 1967. Its climatic importance arises from the impact it had on ocean–atmosphere interaction in the areas it traversed.

The GSA derives its climate punch from the strong effect of salinity on seawater density, with salty water being considerably denser than fresh water. That is, these northern waters normally experience strong cooling in the winter, which causes the surface water to sink and mix with deeper waters. This process, called deep convection (see figure below), is a way for the ocean to release heat to the atmosphere, heat that then helps to maintain a moderate winter climate for northern Europe.

However, when the GSA passed through a region, the surface waters became so fresh and light that even strong cooling would not allow it to convect into the deeper waters. Thus, the deep water remained isolated from the atmosphere, which could not extract as much heat as usual from the ocean. The GSA acted as a sort of moving blanket, insulating different parts of the deep ocean from contact with the atmosphere as it moved around the gyre. Its impact in the Labrador Sea has been particularly well documented (see "Labrador Sea" article on page 24). When the surface waters were isolated from deep waters, they became cooler. Changing sea surface temperature patterns can affect atmospheric circulation, and may possibly reinforce a poorly understood, decades-long variation in North Atlantic meteorological conditions known as the North Atlantic Oscillation (see box on page 13). For it is the ocean that contains the long-term memory of the climate system. By comparison, the atmosphere has hardly any thermal inertia. It is difficult to imagine how the atmosphere alone could develop a regular decadal oscillation, but the advection of freshwater anomalies by the ocean circulation could be an important key to this climate puzzle.

Unfortunately, we have no ready means of detecting freshwater pulses like the GSA. While surface tempera-



Deep convection is a key component of the ocean's role in Earth's climate. Strong winter cooling of surface waters causes them to become denser than water below them, which allows them to sink and mix with deeper water. This process releases heat from the overturned water to the atmosphere and maintains northern Europe's moderate winter climate. The Great Salinity Anomaly interrupted this process as its pool of fresher water prevented convection.

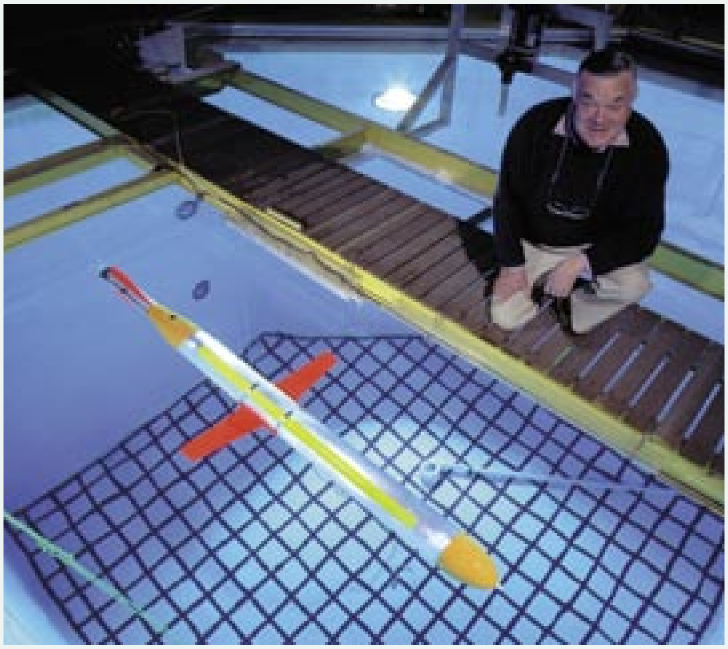
ture can be observed easily from space, surface salinity, so far, cannot. The salinity variations important for oceanography require high precision and accuracy, so there is no quick and inexpensive method of measurement. We have had to rely on careful analysis of sparse historical records from mostly random and unrelated surveys gleaned from several nations to piece the GSA's story together. But how many other "near-great" salinity anomalies have we missed because the signal was not quite large enough? Is there a systematic way to monitor salinity so that we know years in advance of another GSA's approach?

In addition to variability within an ocean basin, we would like to understand the large differences in salt concentration among ocean basins. (see figure on next page) For example, the Pacific Ocean is significantly fresher than the Atlantic and, because

ALACE, PALACE, Slocum

A Dynasty of Free Floating Oceanographic Instruments

Autonomous diving floats have been developed by Doug Webb of Webb Research, Inc. in Falmouth, MA, in conjunction with Russ Davis of the Scripps Institution of Oceanography. The Profiling Autonomous LAgrangian Circulation Explorer (PALACE) is a free float that drifts with the currents at a selected depth, much like a weather balloon drifts with the winds. At preset time intervals (typically one or two weeks) it pumps up a small bladder with oil from an internal reservoir, which increases its volume, but not its mass, and causes it to rise to the surface. On the way up it records temperature and salinity as a function of depth. Once at the surface it transmits the data to a satellite system that also determines its geographical position. The drift at depth between fixes provides an estimate of the "Lagrangian" velocity at that time and place (as opposed to "Eulerian" measurements of the velocity past a fixed point. These names derive from 18th century mathematicians who originated these ways of looking at fluid flows).



Doug Webb was photographed on a catwalk above a test tank used to put the Slocum glider through its paces.

The basic technology of the float has been used for several years in the nonprofiling ALACE, which simply provides velocity information. Hundreds of ALACES have been successfully deployed in the Pacific and Indian Oceans. A program to release a large number of PALACES in the Atlantic is just getting underway.

The use of the ALACE as a platform for salinity measurements is not without problems. The slow rising motion, and low power available, limit the type of sensor that can be deployed. The problem of sensor drift due to biological fouling may be severe in some regions, and methods to prevent fouling are just being developed. However, because the float spends most of its life in a deep and climatically stable water mass, not subject to near-surface atmospheric variations, we should be able to compensate for any drifts.

But the fact that these floats move around is something of a drawback if the objective is to monitor ocean temperature and salinity. That is, in the long run, we would rather that they stayed put and measured the properties in one place. Such a task could be achieved if the float were capable of gliding horizontally and turning as it rose. The horizontal displacement achieved could be directed to maintain one position, with each excursion compensating for the drift caused by ocean currents. With Navy funding, Webb, Davis, and Breck Owens (WHOI) are currently working on such a gliding float (see photo).

All these floats depend on batteries to power the electronic sensors, the pump that varies ballast, and the transmitter that sends data to the satellite. The battery life is around two years, depending on the frequency of profiling and transmitting. One way to extend its life is to use the ocean's vertical temperature differences to run a simple heat engine. Doug Webb has another type of float with such a propulsion system. It uses a waxy material that expands it is lighter, stands about half a meter higher. This height difference drives the flow of Pacific water into the Arctic through the Bering Strait. The salinity difference between these two major oceans is thought to be caused by the transport of water vapor across Central America: The trade winds evaporate water from the surface of the Atlantic, carry it across Central America, and supply rainfall to the tropical Pacific. This water loss is the major cause of the Atlantic's greater saltiness and its propensity to form deep water. The extra rainfall on the Pacific makes it fresher and prevents deep convection. How does this atmospheric transport vary with time? Since salinity is a good indicator of the history of evaporation or precipitation, perhaps if we had sufficient data, we could see changes in the upper ocean salt content of the two oceans that reflect variations in atmospheric transports. How

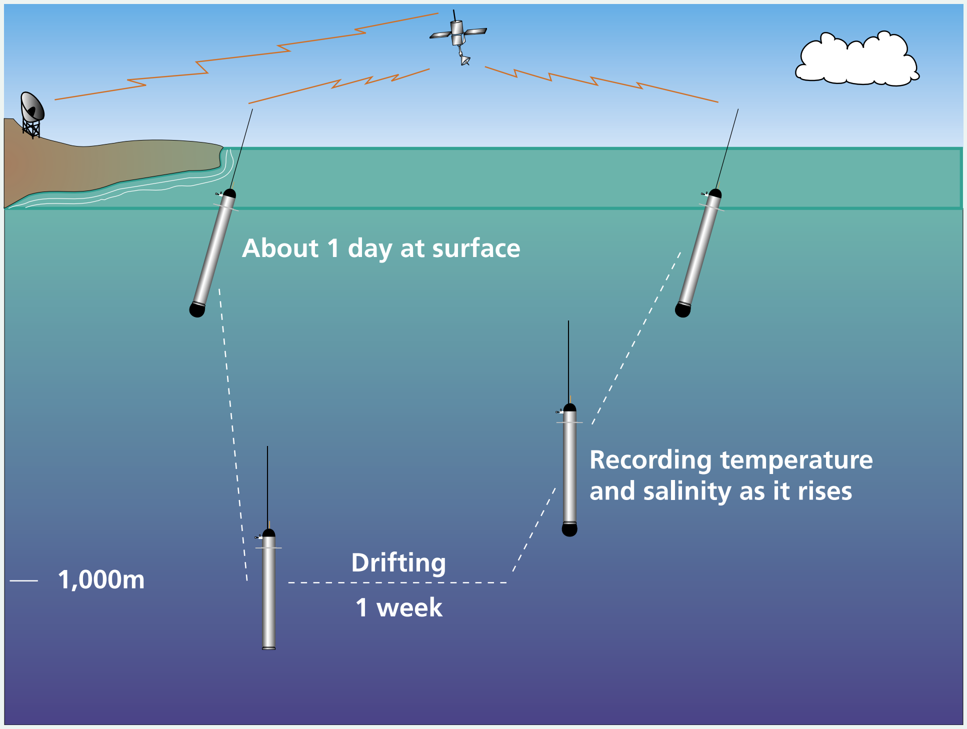
when it melts at around 50 degrees, a temperature the float encounters at several hundred meters depth on each trip to and from the surface. This expansion is used to store energy to pump ballast when needed. Use of this "free" energy for propulsion reduces the load on the batteries and extends the life of the float. The thermal ballasting engine has been tested extensively in the lab and recently deployed off Bermuda in a nongliding float, where it performed over 120 depth cycles.

Doug Webb's dream is to marry the thermal engine with the glider, and thus make a long-lived, roving (or station-keeping) autonomous profiler possible. Years ago he described the technical possibilities to the late Henry Stommel, who developed a vision of how such an instrument might be deployed in large numbers around the globe (see Oceanus, Winter 1989/90). They called the instrument Slocum, with the idea that it could circumnavigate the globe under its own power, like New Englander Joshua Slocum, the first solo sailor to perform that feat. The Internet could allow scientists to monitor Slocum data from their home laboratories around the world.

Sarah Zimmerman

MIT/WHOI Joint Program student Steve Jayne holds an ALACE (Autonomous LAgrangian Circulation Explorer) float aboard R/V Knorr during a 1995–1996 (yes, Christmas at sea) cruise for the World Ocean Circulation Experiment in the Indian Ocean.

If we deploy enough Slocums, their data should be as valuable for predicting global climate on seasonal to decadal time scales as satellites and weather balloons are for forecasting the daily weather. Indeed, one of Slocum's key attractions is that it is inexpensive enough to deploy in large numbers. Per-profile costs for both temperature and salinity are expected to be $50 or less, once a mature system is operating—vastly cheaper than anything possible using ships. A globe-spanning array of 1,000 Slocums would cost less than a new ship, yet provide an unprecedented view into the internal workings of the global ocean. —Ray Schmitt



During a data collection and reporting cycle, a PALACE (Profiling Autonomous LAgrangian Circulation Explorer) float drifts with the current at a programmed depth, rises every week or two by inflating the external bladder (recording temperature and salinity profiles on the way up), spends a day at the surface transmitting data, then returns to drift at depth by deflating the bladder.

many years does it take for salinity anomalies in the tropical Atlantic to propagate to high-latitude convection regions and affect the sea-surface temperature there? What is the impact on the atmospheric circulation?

These and other climate problems will continue to perplex us until we make a serious attempt to monitor salinity on large space and time scales. One approach would be to maintain ships in certain places to sample the ocean continually. A modest effort along these lines was made after World War II when weather ships were maintained at specific sites by several nations (see following article). The data they collected provide nearly the only long time-series measurements available from deep-ocean regions. However, the weather ships are all but gone; there is only one now, maintained seasonally by the Norwegians. Today's satellites provide information on approaching storm systems, but, unfortunately, they cannot tell us what we need to know about ocean salinity distributions.

It now appears that new technology will provide the key to the salinity monitoring problem, at a surprisingly modest cost. The Box on pages 6 and 7 describes how we might obtain temperature and salinity profiles from data collected by autonomous diving floats. It should be quite feasible to deploy an array of these station-keeping "Slocums" that would intercept and monitor the progress of the "Great Salinity Anomalies" of the future. In the next two years, a large number of profiling ALACE (precursor to the Slocum) floats will be deployed in the Atlantic in a preliminary test of the general concept. In addition to measuring temperature and salinity, Slocums might some day measure rain. It turns out that rain falling on the ocean does make a sound, and work is underway to record that sound with hydrophones and develop algorithms to convert the measured sound level to rain rates.The remaining technical obstacles to development of a globe-spanning array of station-keeping Slocums are small. The only thing lacking is a strong societal commitment to the support of such fundamental research on the climate system of the earth.

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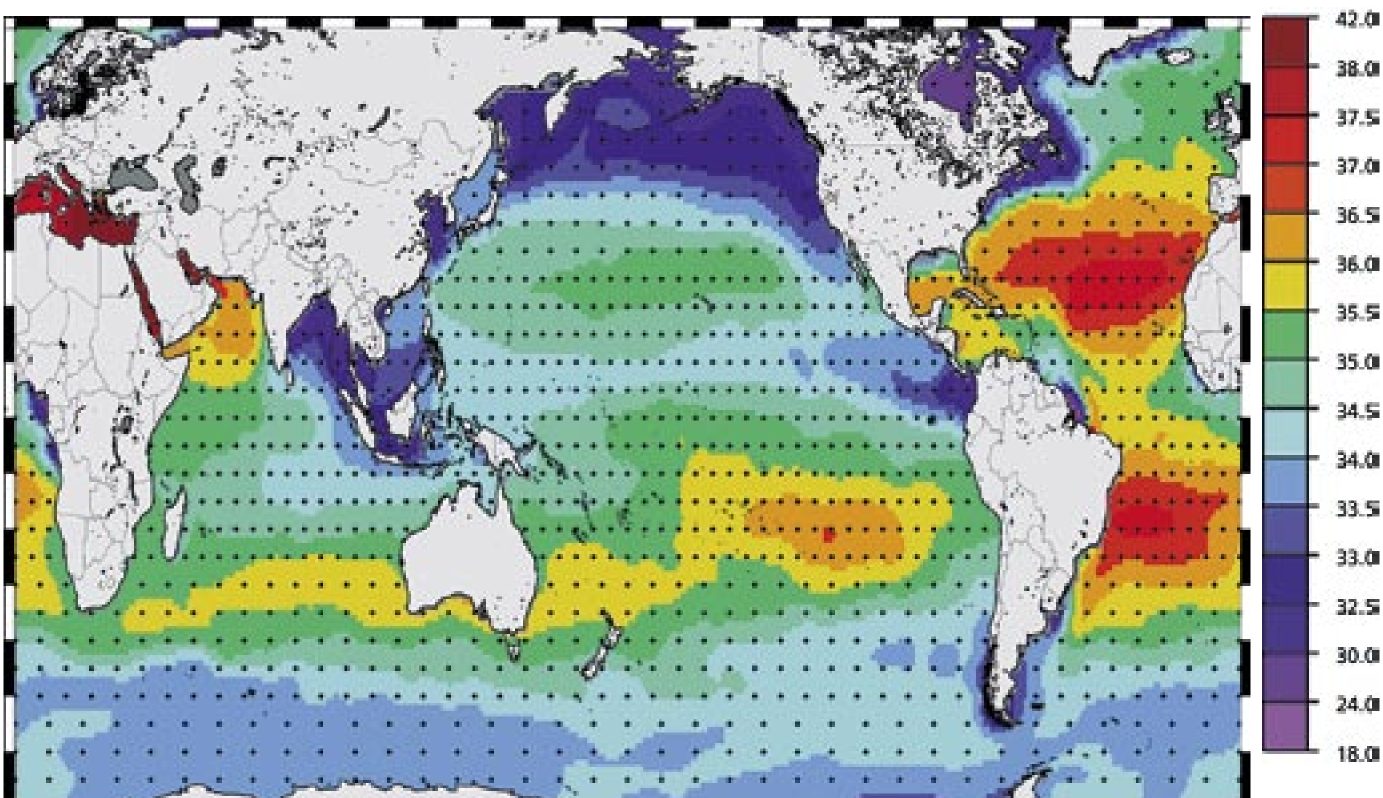
Most of Ray Schmitt's career has been focused on very small-scale processes in the ocean related to mixing by turbulence and "salt fingers." However, he has been driven toward studies of the global-scale hydrologic cycle by a desire to contribute to improved weather and climate prediction, so that he can better plan to take advantage of the rare good weather in Woods Hole.



The average surface salinity distribution in the global ocean, as compiled from many individual ship measurements, mostly during this century. The figure also shows the approximate coverage obtainable with an array of about 1,000 Slocums or PALACES. These would resolve the large scale features of the salinity field and provide completely new information on its variability with time. The array would be an early warning system for the Great Salinity Anomalies of the future.