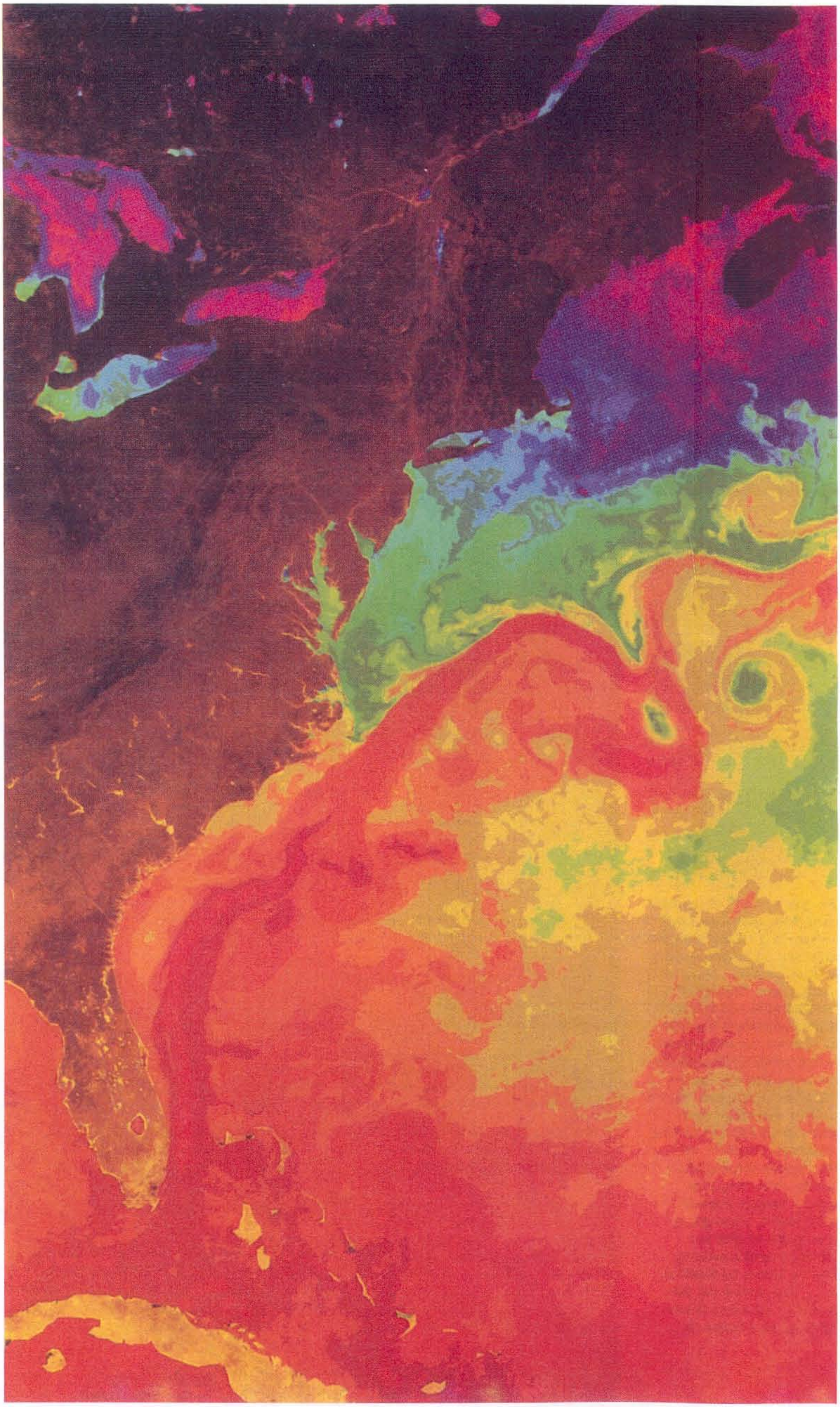
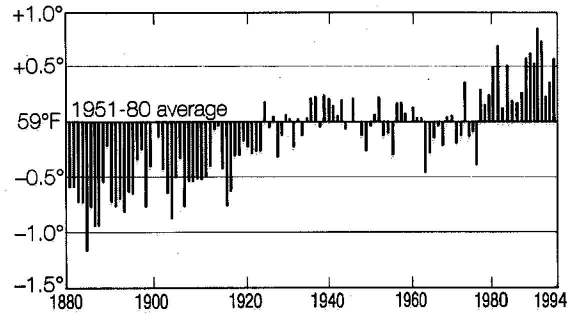


The Ocean and Climate: Observations from Space

by Lee-Lueng Fu



Left: This infrared image, taken by a meteorological satellite, provides a colorized view of the sea surface temperature in the North Atlantic. The Gulf Stream (deep red at 25°C) flows up along the southeastern coast of the United States, bringing warm water from the tropics. Veering out to sea at Cape Hatteras, it mixes with the cooler waters offshore (blue is 10–16°C and magenta is 2–9°C).
Above, right: Globally averaged temperatures over the past 115 years show a net increase of about 1°F.

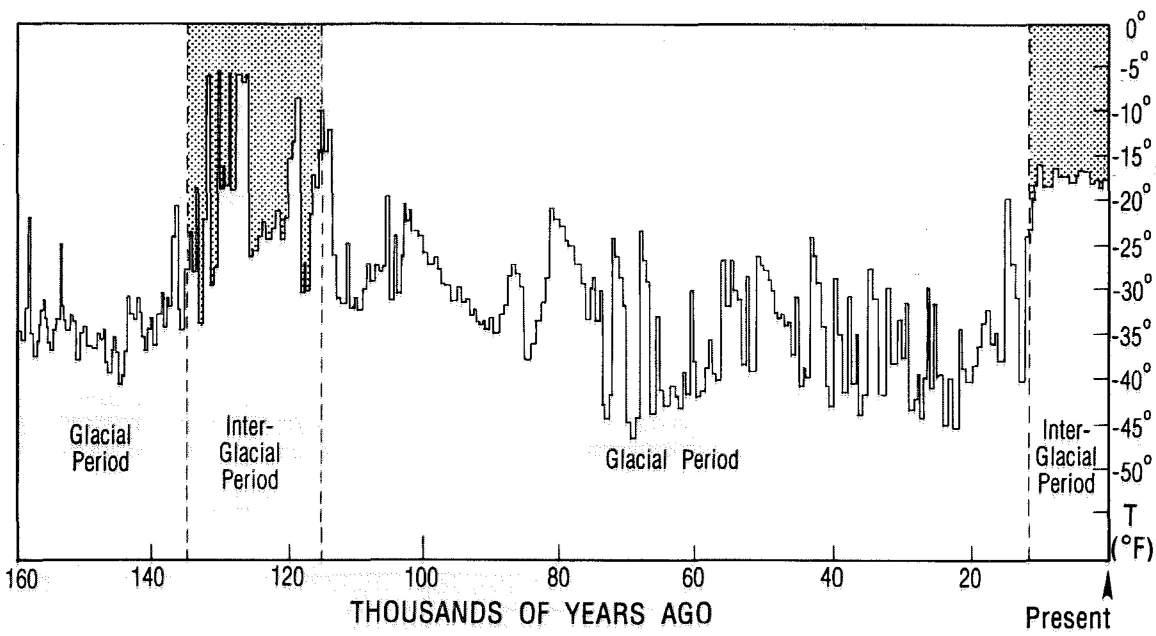
Eight hundred miles above the earth, a satellite named TOPEX/POSEIDON is observing the sea surface with radar, studying the ocean's currents and how they change with time. From this vantage point, all the world's oceans are in the satellite's view within a very short period of time. The radar can see through clouds, day and night, under all weather conditions, detecting even small movements of water to a high degree of accuracy. Now you're probably wondering: Why are ocean currents so important? And why do we bother to fly a satellite to study them?

The short answer is that we want to decipher the ocean's role in global climate change. Climate is long-term weather averaged over a season, a year, a decade, or even longer. It's not about rain or shine tomorrow, or even two weeks from now. It's about whether next winter will be warm or cold, dry or wet; it's about whether we're going to have frequent El Niño conditions in the next five years; and it's about the extent of global warming in the next 50 years. The ocean is the key to our understanding of climate and ultimately to our ability to predict it.

First, let's consider some realities of climate change, both at present and in the past. The Southern California floods this past winter were blamed on the returning El Niño in the Pacific. El Niño (named for the Christ child because its first noticeable effect usually comes around Christmas, when it causes warm currents to appear along the west coast of Central and South America) is an unusual warming of the tropical Pacific Ocean. The warm ocean alters the path of the jet stream in the upper atmosphere, which then changes the weather patterns all around the world. El Niño usually occurs once every three to five years, but lately the Pacific Ocean doesn't seem to be able to shake off a lingering condition that has prevailed for three winters in the past four years.

Many experts believe that this increased frequency of El Niños is caused by global warming, because the tropical ocean–atmosphere system is most sensitive to warming. As you can see from the record of temperatures averaged globally (above), there has been a net increase of about 1 degree Fahrenheit over the past hundred years. Half of this increase occurred in the 1980s, making it the warmest decade in this record. The warmest year was 1990, and after that came a few years of cooling caused by the eruption of Mount Pinatubo, which sent volcanic dust into the upper atmosphere, blocking sunshine. But the heat came back in 1994, making that the fifth warmest year of the century. This warming trend is believed to be a direct consequence of the buildup of carbon dioxide in the atmosphere, mostly due to the burning of fossil fuels, over the past hundred years or so.

An apparent result of this rising temperature is the increased frequency of severe weather—such as the deep freeze experienced in the eastern United States in the winter of 1994—despite the fact that that year as a whole was the fifth warmest year on record. Are we entering an unusual period of time, with three El Niños in four years as well as the warmest summer and the coldest winter in the same year? The answer depends on what we are comparing it to. In the



A 160,000-year temperature record from a Greenland ice core shows that temperatures over the past 10,000 years, during which human civilization developed, have been warm and stable. This was not so in earlier times, however, and frequent, sudden temperature swings were the rule. The temperatures here—from -5° down to -55°F —may seem a bit chilly (this *is* Greenland, after all), but other evidence indicates that the pattern of these fluctuations was typical of the whole planet.

ancient past, frequent abrupt climate change was actually the rule rather than the exception. A record of Greenland's temperature over the past 160,000 years, obtained from an ice core drilled more than 3,000 meters into the Greenland ice sheet, shows an interesting history over geological time. From the chemical properties of the ice, scientists can determine the temperature of the air when the ice was formed; other evidence suggests that these fluctuations were not just a local characteristic, but typical of the entire globe.

As you can see from the graph above, temperatures have been relatively warm and stable for the past 10,000 years, over which human civilizations flourished. The rest of the record, before the last 10,000 years, is characterized by frequent and abrupt change. This tells us that global temperature swings of more than 10 degrees Fahrenheit could happen in a period as short as 20 years, which is quite alarming. This record raises many questions: Why have the temperatures of the past 10,000 years been so stable? How long are we going to enjoy this present stability? What would trigger the instabilities and rapid climate swings that were so common in the past?

The answers to all these questions have a great deal to do with the ocean. The ocean is the flywheel of the climate engine, because it is the biggest repository for key elements of climate change such as water, heat, and carbon dioxide. The giant currents of the ocean transport these elements from one ocean to another, from the equators to the poles. They also control their exchange with the atmosphere, which ultimately affects the earth's climate and therefore our own lives. A few facts about the ocean will help illustrate its power and influence. The upper three meters of the ocean (of its average depth of 4,000 meters) stores the same amount of heat as does the entire atmosphere. The heat transport of the North Atlantic Ocean is a hundred times the man-made energy production of the entire world. And 99 percent of all the carbon dioxide that has ever existed in the atmosphere now resides in the sediments at the bottom of the ocean.

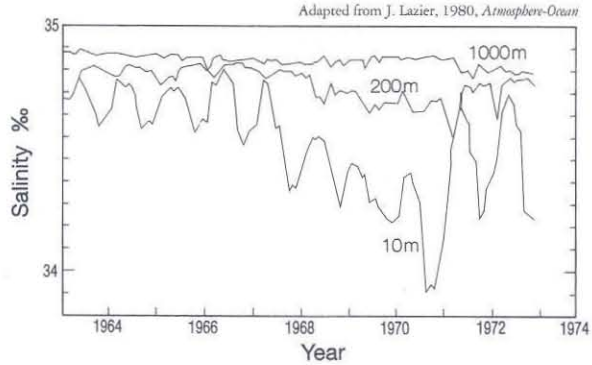
Let's focus first on heat transport, shown as a conveyor belt in the schematic diagram on the opposite page. This is an overly simplistic picture of a highly complex process, including only one of many important components. The warm surface water brings heat from low latitudes all the way to the northern North Atlantic, where it transfers the heat to the atmosphere. Then the water gets cold and heavy, begins to sink to the deep ocean, and returns to the tropics, where the cycle begins again. The efficiency of this conveyor belt controls the climate, especially in the northern hemisphere. The faster the water sinks in the north, the more efficient the belt, and the warmer the climate. Conversely, if the water sinks slowly in the north, the efficiency decreases, and the climate becomes colder. That was indeed the case during the Ice Ages.

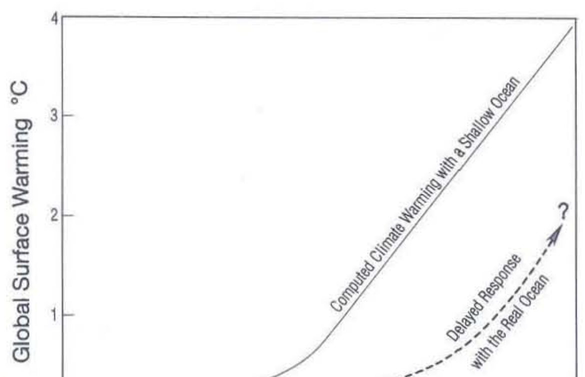
The rate at which water sinks in the north is controlled by the ocean's temperature and salt content. The salt content may be the real key to the switch of this conveyor belt. If the water is too fresh, it's not heavy enough to sink. The salinity, in turn, is controlled by many things, including the patterns and the rate of ocean

Below: The heat transport system of the ocean is like a conveyor belt. Currents of warm surface water bring tropical heat to the North Atlantic, where it's exchanged with the atmosphere. The now-cooler water sinks, returns to the tropics, and begins the cycle anew.

Right (top): The drop in salinity (shown here in parts per thousand) of an area in the North Atlantic threatened to disrupt the heat-transport conveyor belt in the late sixties. Usually, wintertime sinking of surface water leaves the salinity well mixed and fairly equal at 10 m, 200 m, and 1,000 m below the surface. But between 1968 and 1971 surface water was quite fresh all year round, indicating that the sinking process had mysteriously stopped. Right (bottom): Based on the record of carbon dioxide since 1850, this model predicted a 2°C rise in temperature by the year 1990. It has actually risen only 0.6°C. This might be a delayed response due to the ocean's high heat capacity.

Adapted from J. Lazier, 1980, *Atmosphere-Ocean*



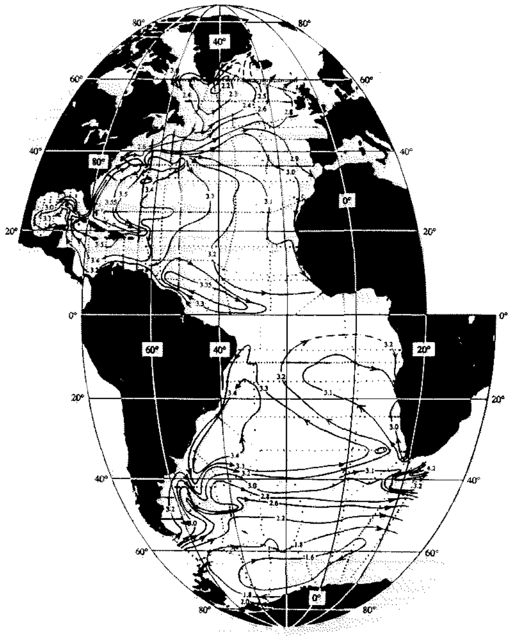


currents, the mixing, the precipitation and evaporation and, perhaps most important, the formation and melting of the ice in the region. These processes are all interrelated, making the conveyor belt potentially prone to instabilities and rapid changes.

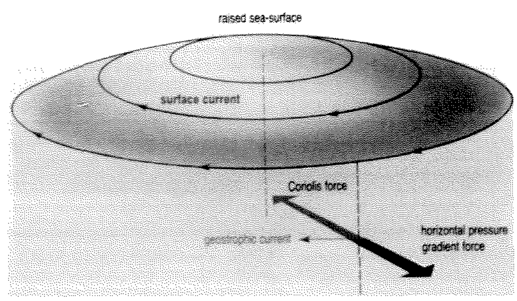
An alarming event in the Labrador Sea (in the western corner of the northern North Atlantic) in the late sixties illustrates this delicate balance. The graph in the middle at left shows the salinity at three levels: 10 meters (that's almost surface water), 200 meters, and 1,000 meters. The salinity increases with depth, so the surface water is fresher. At the beginning of the record in 1964 the temperature is low enough and the salinity high enough during the winter, so that the water sinks to mix the upper water column, making the salinity almost the same at all three levels. This wintertime convection process suddenly disappeared between 1968 and 1971, probably due to a temporary increase in unusually fresh water input to the region from the Greenland Sea to the north. You can see that during wintertime the ocean was still stratified; the salinity varied at the different depths, and the sinking process stopped. The extent of the event was small, and it had no significant effects on climate, but it was alarming nonetheless. We don't know the complete story of this incident. In order to diagnose such a problem you need to know what's going on in the entire North Atlantic and its overlying atmosphere for a long period of time, and at that time we didn't have that knowledge. Even now we don't yet have the observations and understanding required to predict whether a full-blown shutdown of the conveyor belt, possibly bringing the Ice Age back, is likely or not in the near future. This is because the actual process of oceanic heat transport is far more complicated than the schematic diagram indicates. It involves currents of very complex, three-dimensional structures, which are difficult to construct in a computer model. Current climate models usually treat the ocean as a shallow swamp and describe an oversimplified coupling with the atmosphere. When they try to make predictions, more often than not these models fail.

One model, using a very shallow ocean, predicted global temperature from 1850 to 2050, based on the recorded and projected levels of carbon dioxide. This model (left) predicted the temperature over the past 100 years to increase by 2 degrees C, but the actual temperature increase was quite small—0.6 degrees C, or about 1 degree F. We know from this that the current climate models don't work, because they cannot reproduce what we observe has happened. It may

Right: Before satellites, oceanographers could draw only very simple diagrams of the circulation of the ocean's currents from instruments placed in the ocean itself.
Far right: The balance (called the geostrophic current) between the Coriolis force (from the earth's rotation) and the horizontal pressure created by an ocean current pushes the water up into a hump. A current's speed can be calculated from the slope of the hump, or, in other words, the shape of the sea surface elevation.



From J. Reid, 1994, *Progress in Oceanography*

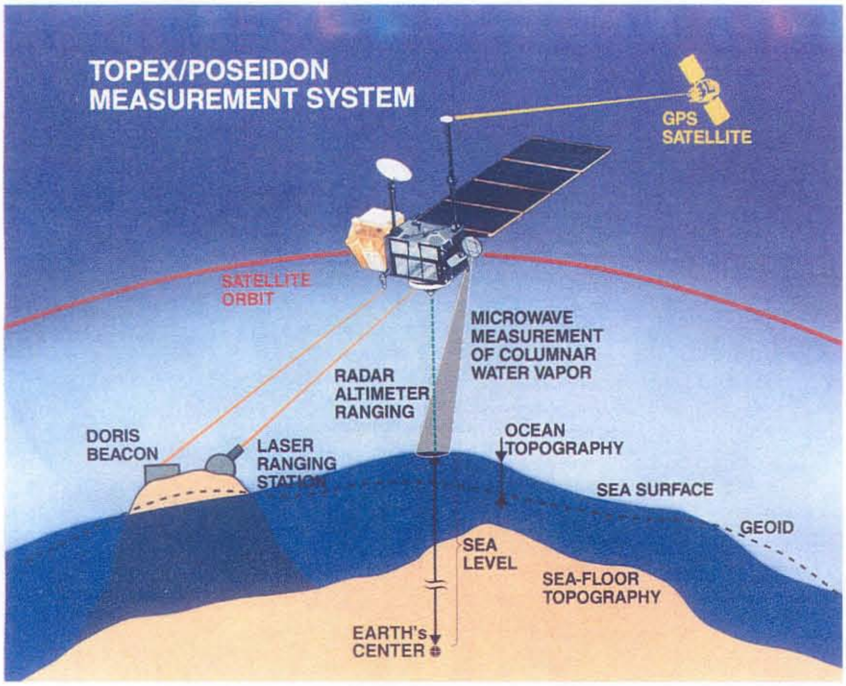


be that the response to global warming is delayed because of the high heat capacity of the real ocean, but the kind of model that could incorporate this complexity doesn't yet exist. A major reason for the slow development of ocean models is the lack of adequate global observations. In the past we learned about the ocean from piecemeal data taken from ships—ships that take months to cross the ocean at the speed of a bicycle. And during this time the ocean is constantly changing.

Using sparse data taken in different seasons, in different years, and with the radical assumption that the ocean doesn't change, oceanographers have been trying to draw ocean circulation diagrams for the past hundred years. An example is shown above. The resulting picture is inevitably distorted or much too smoothed out, but it has proven useful for a *qualitative* climatological description. In fact, most of our knowledge of the ocean circulation has been obtained this way. But for a *quantitative* analysis of a very complex system like climate, it is totally inadequate. It can't come anywhere near the spatial scale of the infrared image of the sea surface temperature in the North Atlantic taken from space, shown on page 2. The temperature reflects the pattern of ocean currents to some extent; you can see the Gulf Stream and the eddies that surround it. Every week this current system changes. To resolve the ocean currents in both space and time, you would have to sample the ocean every 50 kilometers. A rough calculation suggests that you would need 200,000 permanent stations in the ocean in order to do adequate sampling for quantitative analysis. This is out of the question. Satellites turn out to be the only way to study the global ocean at the required resolution.

Rough seas sometimes have waves several meters high; how are you going to determine mean sea level of rough seas to within a few centimeters?

But what can we observe about ocean currents from space? Although sea surface temperature is easy to detect using infrared sensors, the relationship between this temperature and the currents is not straightforward. We need three-dimensional ocean currents to solve climate problems, but sea surface temperature doesn't reveal much information about what's going on below the surface. So we use a radar altimeter to measure the shape of the sea surface. This approach is based on a simple principle that can be explained with an analogy to a cup of coffee. If you stir coffee in a cup, circularly, it will create a depression in the surface. Smart undergraduate physics students can calculate the velocity of the coffee everywhere in the cup just by looking at the shape of the surface, because there's a balance of forces between the pressure (caused by the depression in the surface) and the centrifugal force (caused by the circular velocity of the coffee). The only difference in the ocean is that the balance is between the pressure force (caused by the currents we want to measure) and the Coriolis force, a force that is exerted on every moving object in a rotating frame. If you roll a marble on the floor of a merry-go-round, for example, the marble cannot roll straight; it has to deflect either to the left or to the right, depending on which direction the merry-go-round is rotating. Similarly, in the rotating frame of the earth currents are deflected to the right in the northern hemisphere and to the left in the southern hemisphere until the



TOPEX/POSEIDON's radar altimeter bounces pulses off the sea surface, measuring the distance between the satellite and the sea surface. By subtracting that distance from the radial orbit height (the distance from the satellite to the earth's center) you can calculate the sea level. Then the geoid (the influence of gravity on sea level) has to be subtracted from the sea level to obtain ocean topography. To pick up a signal of a couple of inches, the satellite also has to compensate for water vapor, using a microwave radiometer, and to establish its own position in space within a couple of inches, using lasers, the DORIS microwave system, and the global positioning system.

Coriolis force is balanced by the pressure force.

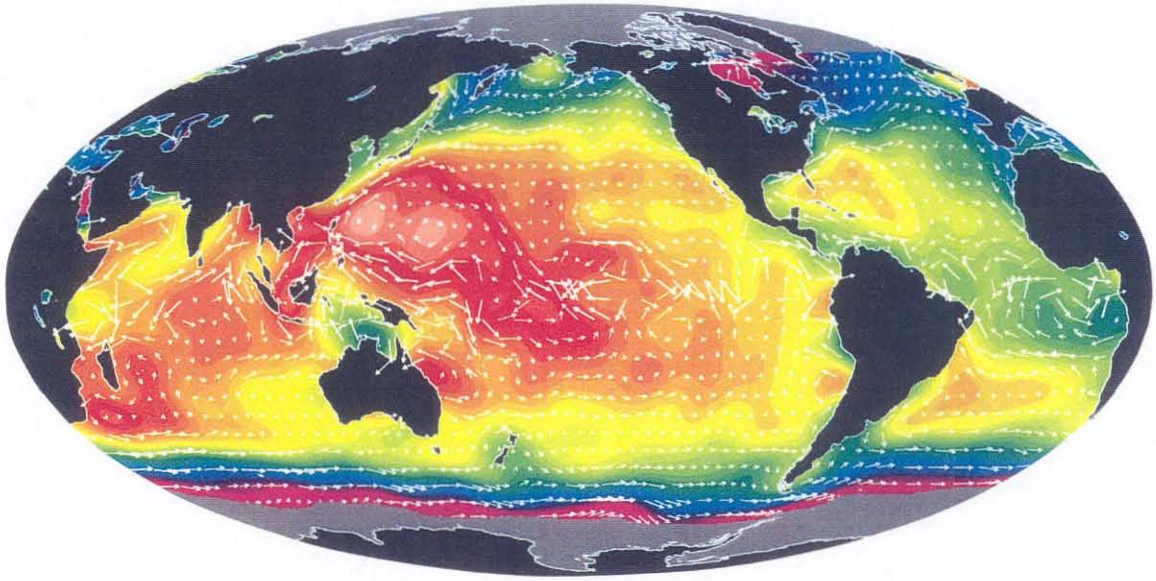
So the combination of the current's pressure and the Coriolis force pushes the sea up into a mound or a dip, and scientists can calculate the current's speed from the mound's, or dip's, slope. This sea surface elevation is to oceanographers what air pressure is to meteorologists; a map of the sea surface elevation is the equivalent of a map of surface pressure. Just as from the lows and highs on the surface pressure chart, meteorologists can tell you the wind speed and direction, with a chart of sea surface elevation oceanographers can tell you the speed and direction of ocean currents, not only at the surface, but at depths with the aid of a model, which I'll discuss later.

Measuring the shape of the sea surface elevation from space is also based on a simple principle. A radar altimeter on the satellite sends radar pulses to the surface of the sea, which bounces the pulses back. We can measure the round-trip travel time of the pulse and calculate the distance between the radar and the sea surface. But what we really want to know is the elevation of the sea surface relative to the center of the earth, so we have to know the precise height of the satellite, called the radial orbit height. Then we subtract the distance we measured with the altimeter from the radial orbit height to get the sea level relative to the center of the earth. Ocean currents do not actually control the shape of the sea level. The most important force is the earth's gravity field: variations in gravity caused by uneven density distributions in the earth's crust create sea level changes of hundreds of meters in different parts of the ocean. The ocean currents deflect the sea surface from the gravity surface (which we call the geoid) by only two meters, or 1 percent of the total variation of the sea level. It's this 1 percent that we're looking at. Temporal changes in ocean currents, which is what we're *really* interested in, create a change of only 10 to 20 centimeters—10 percent of the total 1 percent signal. So, to measure global changes in ocean currents, we have to be able to measure the sea level to within a few centimeters, or a couple of inches. That's a challenge. Rough seas sometimes have waves several meters high; how are you going to determine the mean sea level of rough seas to within a few centimeters?

In the early eighties two groups of scientists and engineers (one from France and the other from the United States) believed this could be done. They eventually joined forces and proposed a mission called TOPEX/POSEIDON. TOPEX, for "ocean topography experiment," was the original name of the U.S. mission; the French scientists named their mission after the Greek god of the sea. The two governments approved the mission in 1987, and the satellite was launched in 1992 by a French Ariane rocket. The satellite contains several instrument systems: one of them, the radar altimeter, sends pulses to measure the range to the sea surface. Because of the rough seas, it sends thousands of pulses every second to average out the wave effects. Tides, on the other hand, which move the sea surface up and down by about one meter, are quite easy to deal with, because the frequencies of the tides are well known. The satellite's orbit, which determines how the ocean is sampled in time, was planned so that the tides could be determined precisely by the satellite and removed from the signal.

Many things interfere with this signal; for example, the free electrons in the upper atmosphere and the water vapor in the lower atmosphere slow it down. To correct for the first we send the pulses in two radio frequencies. Because the delay is a function of frequency, if we combine these two frequency measurements, we can retrieve the signal's delay and make corrections for the electron effects. To correct for the second, a radiometer measures the total water vapor content of the atmosphere. Actually, only a tiny portion of the atmosphere has water vapor, but it's enough to slow down the signal and we have to correct for it.

We also need to know where the satellite is in space to within a few centimeters. We have three systems to do that job. One is traditional laser range finding, which uses the round-trip travel



This map from TOPEX/POSEIDON data represents the average relief of the ocean topography from September 1992 to September 1993. With the geoid (the large variation caused by gravity) removed, the variation covers a range of two meters, from the lowest (magenta and blue) near Antarctica, to the highest (red and pink) in the western Pacific, which stands about half a meter higher than the Atlantic. The Pacific's larger size allows the winds room to raise the western Pacific and create the highest sea surface elevation. Calculated currents are shown by the white arrows (each arrow is about 10 cm/sec). Gyres, the large recirculating cells in the western ocean basins, are part of the permanent system of circulation—the climatology of the ocean.

time of light to determine the distance between the satellite and the laser station. A second system, called DORIS, consists of an antenna that receives microwave signals from a ground network of beacons. From the change of the frequency due to the motion of the satellite (the Doppler effect) you can determine its velocity. The third system is the global positioning system, which has many applications, including determining the position of tanks to within a few meters during the Persian Gulf war. That was good enough for the military, but we have to determine the center of mass of the satellite, which is about the size of a Greyhound bus, within about an inch.

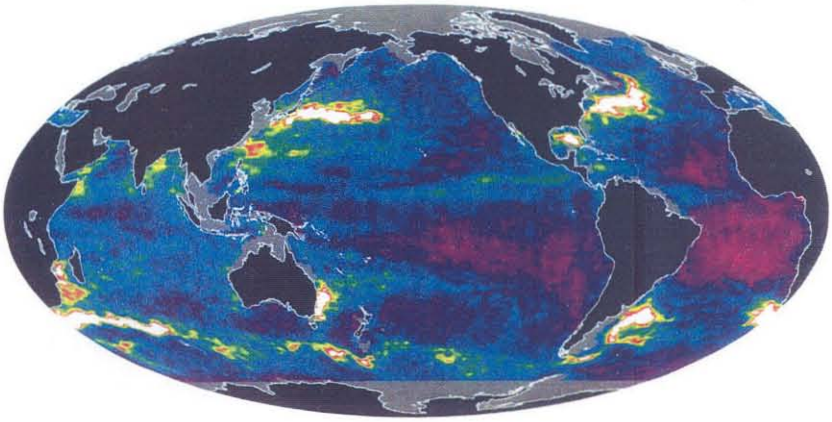
Satellite radar altimetry began with SEASAT, launched by JPL in 1978. The uncertainty of SEASAT's radial orbit height was one meter, so it couldn't resolve (nor could the satellites that followed it) the changing part of the ocean's large-scale signal, which is about 10–20 centimeters. With TOPEX/POSEIDON we achieved a measurement accuracy of better than five centimeters for the first time, and were able to resolve the changing sea surface elevation at even the largest scales.

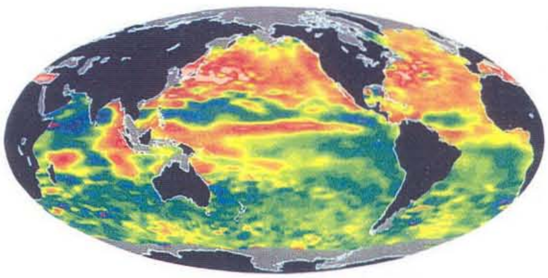
Every 10 days the satellite makes measurements along exactly the same ground track, so that we can compare one cycle's measurement with the next and then determine precisely how the ocean changes with time. The moment we got our first map from the satellite was very exciting; it was the first snapshot of the ocean's currents from space. No more waiting for months for a ship to cross the ocean just to collect one single section of the ocean. Now, in 10 days we could have it all. The amount of data contained in one 10-day record is equivalent to all the data collected over the past 100 years. The map above shows, in false color, the relief of the ocean topography, which covers a range of two meters. And every 10 days we get a map like this. They all show basically similar features—the semipermanent systems analogous to such features as the Aleutian low and the Siberian high in the atmosphere. The gyres, the large circulating systems of water on the western sides of the ocean basins, are permanent ocean systems, although their details change.

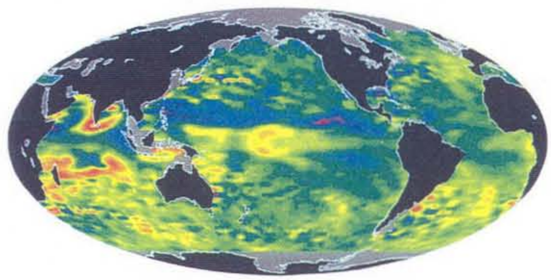
When we remove the average elevation, as calculated from the first year's data, what is left is the temporal change. Then we average that for each season to get the deviation, or the change of the sea level from its mean, during the four different seasons. The scale here, in the maps at right, is no longer two meters, but ranges from minus 15 to plus 15 centimeters. It is these small changes in the ocean that carry the signal for climate consequences.

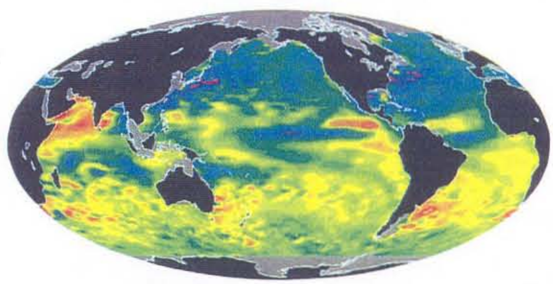
Sea level changes inherently with the seasons. The highest sea level occurs in the fall because it takes time to heat the ocean. After a whole summer's heating of the sea surface, the heat content reaches a maximum in the fall, and thermal expansion raises the sea level to its highest point. And, conversely, after a whole winter's cooling, the lowest sea level occurs in spring. Again, the maximum seasonal change occurs in the western part of the ocean, because of the rotation of the earth. If the earth rotated the other way, you

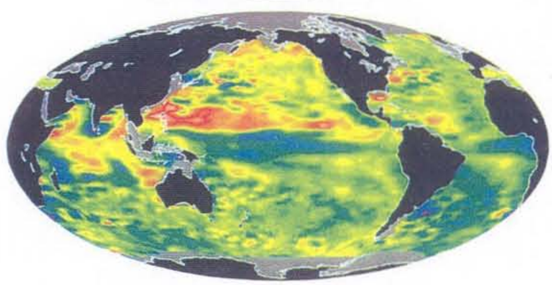
The map at right illustrates a year's summary of random fluctuations of ocean currents—the ocean's storms. Magenta (0 to 5 cm) and blue (10 cm) represent the most stable regions of the ocean, while the red (20 cm) and white (30 cm) show areas of turbulence and instability, most notably the warm Kuroshio current off Japan and the Gulf Stream in the North Atlantic.







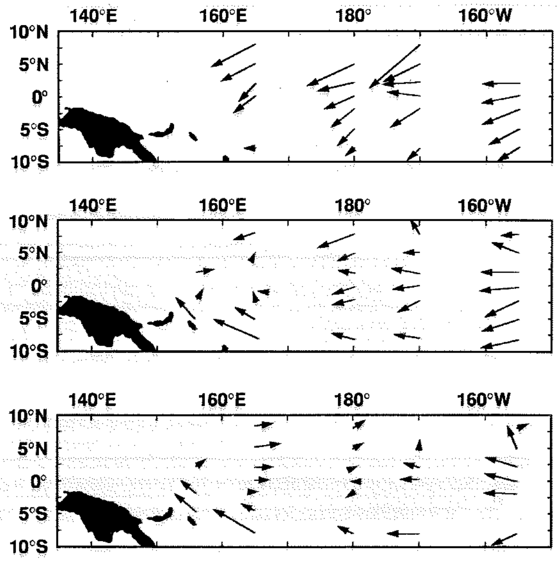




Averaged for season, the TOPEX/POSEIDON data show a deviation from the mean sea surface height of from –15 cm (magenta) to +15 cm (pink); yellow-green means zero change, and red is +10 cm. After a summer's heating, the highest sea surface elevation occurs in the fall (top); then the surface cools off in winter and reaches its lowest point in spring before starting to warm up again in summer (bottom). The highest seasonal change occurs in the western part of the oceans because of the earth's rotation. Greater land mass in the northern hemisphere makes for greater variation.

would see the gyres and the highest seasonal variation on the eastern side of the ocean. Note, too, that the southern hemisphere has a similar seasonal change, but its intensity is much lower. This is because there is less land in the southern hemisphere to provide the severe cold air that blows out from the continental interiors during the winter and cools the oceans in the northern hemisphere. The southern hemisphere contains mostly ocean, creating a steadier climate with less seasonal change.

In addition to seasonal change, the ocean has its own weather. In the atmosphere weather consists of random fluctuations of air flow; the ocean weather is random fluctuations of ocean currents. These are the ocean's storms. A summary of a year's observations shows, in the map above, the typical magnitudes of sea surface change resulting from ocean storms. The range from red to white represents about 20 centimeters. Off Japan you can see the famous Japan Current (the Japanese call it the Kuroshio, which means "black current"), which is the ocean's version of the atmospheric jet stream. It has a lot of the same turbulence and instability as the jet stream. Typically this causes a 20–30 centimeter change in this region's sea level, but the maximum can be as high as one or even two meters from very severe storms. This is also the case in the Gulf Stream region and in the Antarctic Circumpolar Current. Ocean storms are much smaller than atmospheric storms, with a diameter of 50–100 kilometers, as opposed to the 1,000-plus kilometers of atmospheric storms. So, to resolve all these ocean storms in a giant



Wind patterns in the El Niño of 1994 show the trade winds blowing strongly westward in April (top), pushing the warm surface water to the western Pacific (that's New Guinea at lower left). In July (middle) the winds started to grow disorganized in the west, and by October (bottom) had reversed direction.

computer model, we have to have a much higher spatial resolution than the atmospheric models have.

In addition to seasons and weather, the oceans also have unusual events on larger scales of space and time. One is the famous El Niño phenomenon, which we in Southern California have become very familiar with in recent years. In a normal December, the strong trade winds, blowing westward, push the warm surface water against the western boundary of the Pacific Ocean. The air rises in the warm western Pacific, and the rainfall comes down in Indonesia and Australia. If most of the warm water is pushed westward, the cold water has to come up to compensate for it, welling up along the west coast of South America and bringing the nutrients that make for good fishing here in a normal season.

During an El Niño year, the trade winds weaken and even reverse direction. (The trades are controlled by an inherent oscillation mechanism between the atmosphere and the ocean, which is caused by the sea surface temperature.) So this huge mass of warm water in the western Pacific is no longer pressed against the ocean boundary and begins moving eastward. As it does so, it sends a large number of wave pulses called Kelvin waves after Lord Kelvin, the British scientist who first studied them. These waves send a signal back east, changing the internal density structure of the ocean, and allowing the warm water to continue on its path. As the warm water moves eastward, it occupies the entire tropical ocean, and as the tropical Pacific Ocean warms up, convection occurs in the middle of the Pacific. Then torrential rain falls in places like the Christmas Islands and the Marshall Islands; Indonesia and Australia experience severe drought. Australia is experiencing its fifth year now of drought due to a lingering El Niño.

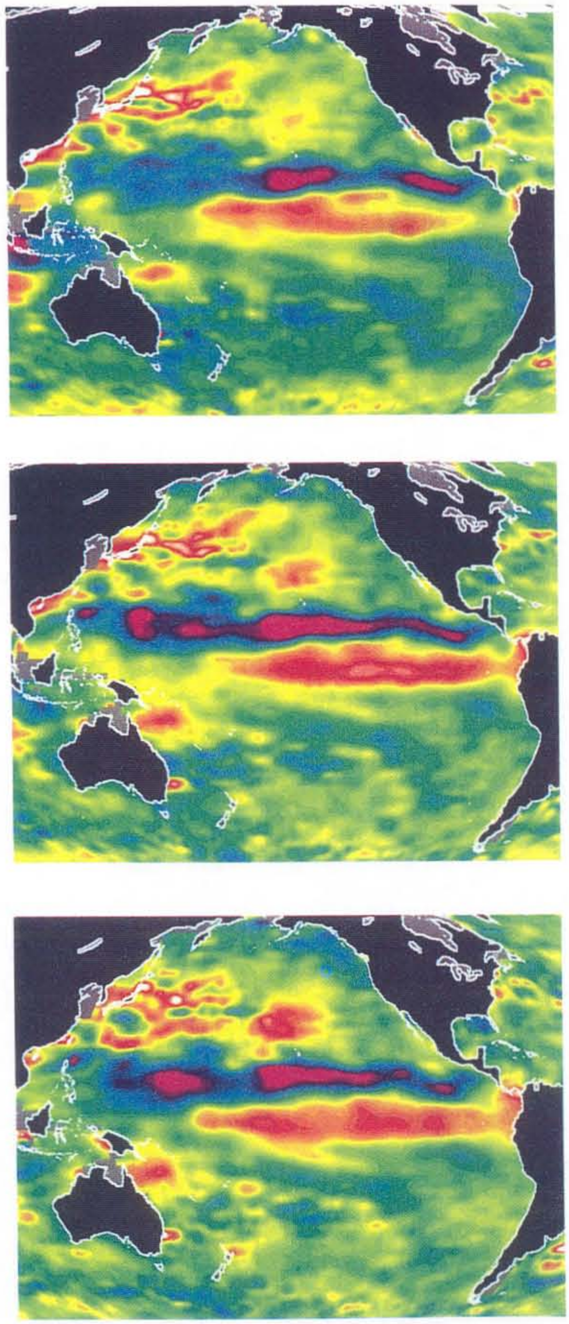
At left you can see the progression of events that led to the heavy rains in California this past winter. The wind, reported from an array of buoys on the equator in the Central Pacific, was normal in April 1994. The trade winds were blowing strongly westward. In July the trade winds in the western part of the ocean became disorganized, and in October they changed direction. This is the classic sequence leading to El Niño. Last April, when the trade winds were blowing strongly, the highest sea level (15 to 20 cm above normal) occurred in the western Pacific because the wind was piling up the warm water there (see cover). Cold water welled up along the South American coast. After the disorganized wind in July, the warm water in the western Pacific moved to the east (opposite page) in the form of Kelvin waves in the late fall—four pulses of them, the largest in November—setting the stage for the heavy rains we experienced in January. As late as January, these conditions were still lingering, but by March they were beginning to disperse.

As the currents bring the warm water to the colder part in the east, they feed the heat to the atmosphere, changing the path of the atmosphere's jet stream. During normal times, the jet stream's path goes across America's northern states and brings the winter storms along with it. When El Niño occurs, the warm sea surface temperature diverts the jet stream to the south, bringing heavy rainfalls to California and the Gulf States, as well as relatively warm winters to the northeastern states.

On a larger scale, there's another phenomenon with far vaster potential effects than El Niño, and that is the mean sea level variations in response to global warming. There are two causes of sea level increase. One is thermal expansion: when temperature rises, the ocean occupies a greater volume. Over the past hundred years sea level has risen 15 cm for about a half degree C of temperature rise. Most computer models predict about three degrees (ranging from 1.5 to 4.5°C) of warming under the scenario of doubling of carbon dioxide in the atmosphere by the end of the next century. If we extrapolate this linearly, we get about one meter of sea level rise.

In the past we had to rely on tide gauges sparsely distributed around the ocean. Since many oceanic phenomena such as El Niño can

On a larger scale, there's another phenomenon with far vaster potential effects than El Niño, and that is the mean sea level variations in response to global warming.

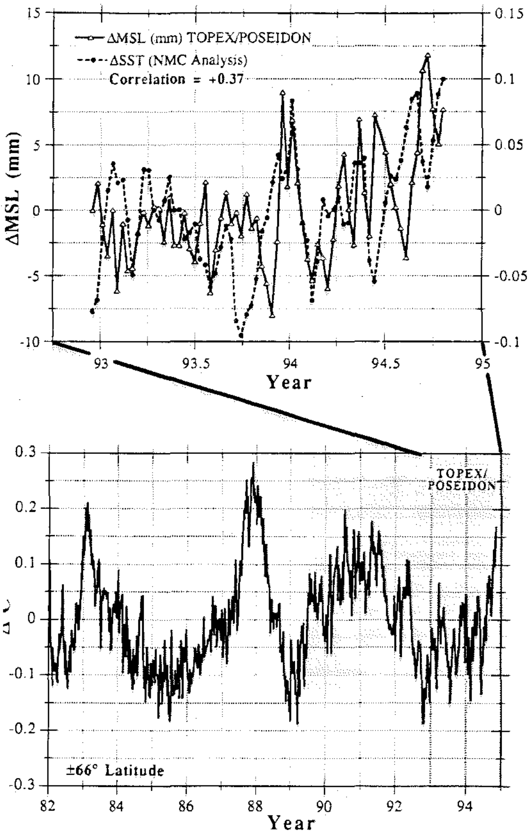


In TOPEX/POSEIDON's measurements of sea surface height, the development of the El Niño during the fall of 1994—October (top), November (middle), and December (bottom)—is clearly visible. Yellow-green represents normal height, shading below normal through blue to magenta (–15 cm), and above normal through yellow, red (+10 cm), to white (+15 cm). When the trade winds reversed in October, warm water pulses moved eastward in the succeeding months, hitting Central and South America, diverting the jet stream, and ultimately bringing heavy rains to California.

create a large local sea level change, the average measurement from such gauges can be distorted. But when we have a satellite giving us half a million observations in just one 10-day cycle, we have a much more accurate measurement of mean sea level rise. If the predicted one-meter sea level rise is correct, it will create enormous problems worldwide. About 3 percent of the earth's land, which is home to about 20 percent of the world's population, will be affected. Dams to hold back the sea would cost hundreds of billions of dollars. But because there's a large element of uncertainty about these predictions for sea level rise, it's an urgent task to obtain a reliable measurement of the sea level trend to determine whether it will be disastrous or relatively benign. Actually, most of the models predict that we will have about a half meter increase in the sea level, even with 3 degrees of temperature increase.

The effects of thermal expansion pale, however, in comparison to the second phenomenon, and that is the melting of ice, in particular the potentially unstable West Antarctic ice sheet, creating a sea level rise of up to five to six meters. Most climatologists assure us that this won't happen in the near future, because the upwelling of cold deep water surrounding Antarctica shields the ice sheet to some extent from the heat of the low latitudes. But there's still a big uncertainty there, which underscores the importance of having a reliable way to monitor sea level rise.

On the following page is the record of mean sea level based on two years of TOPEX/POSEIDON data. You can see a linear trend, with quite a lot of fluctuation, showing about a six-millime-



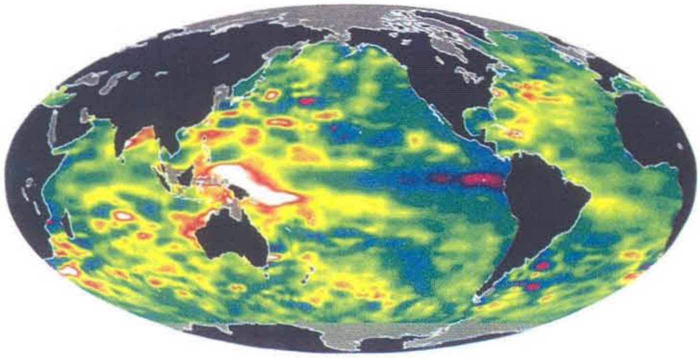
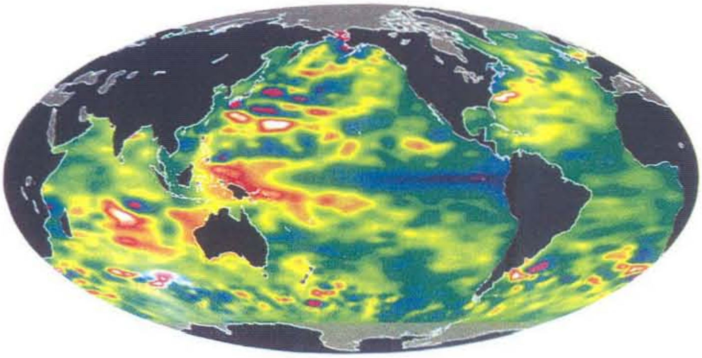
The top graph shows how the change in mean sea level (left axis) follows the change in mean sea surface temperature. The solid line comes from TOPEX/POSEIDON observations over the past two years, and the dotted line is the temperature (right axis in degrees Celsius). The upward trend may not indicate global warming but may be only a transitory expression of El Niño. Over a longer term (lower graph) temperature peaks have corresponded to the El Niños in 1982–83 and 1986–87. (Courtesy of S. Nerem of NASA Goddard Space Flight Center.)

ter sea level rise over this period. The other curve is the mean sea surface temperature in the ocean for the same period of time. You can see that the sea level follows the temperature. In those two years temperature rose about 0.15 of a degree C, but we need to compare this with a longer record to get some perspective on what it means. If we look at the past 10 years, we see that most of the fluctuation in sea surface temperature corresponds to El Niños: 1982–83, the biggest El Niño ever recorded, and 1986–87. So with a short record like this we have to be very cautious; what we see here may not be a long-term trend, but simply a temporary fluctuation caused by El Niño. On the other hand, it's reassuring to have proof that the mean sea level does correspond to the temperature. This lends a lot of credence to the measurements from space. But we will need a long-term record to give us an indicator of how fast sea level is really rising as a result of temperature change.

Now that we have our first global ocean observing system, how are oceanographers going to put this wonderful data stream to work to help improve climate prediction? Meteorologists' methods of weather forecasting make a good comparison here. A successful weather forecast needs three elements: weather satellites, a sophisticated computer model, and a ground network of weather stations. For climate prediction we now have satellite observations of the ocean. Fortunately, in the past five years, parallel to the development of satellite technology, computer technology has also taken off. Massively parallel computing allows oceanographers to resolve all the ocean storms in the system for the first time. We can now produce a credible picture of global ocean circulation just through number crunching. (Compare the computer-model map on the inside back cover with the similar infrared image shown on page 2.)

We can also compare TOPEX/POSEIDON maps and computer models of the intensity of ocean storms, of seasonal change, and of yearly change after subtraction of seasonal fluctuations. The most interesting comparison is that of the yearly, or interannual, change—the change in a particular month from one year to the next. At left on the opposite page is TOPEX/POSEIDON's observations in the difference of the sea level in April 1993 and 1994 (1994 minus 1993). In 1994 you can see the buildup of El Niño and a much higher sea level in the western Pacific than in the same month a year earlier. The map next to it on the right was produced by a state-of-the-art model, and shows very high correlation with the actual observations. So we know now that this interannual change, this climate change in the ocean, can be simulated by a model very well. There are differences between the observations and the models, but the similarities are encouraging, and the differences also tell us that we need to combine these two technologies to achieve an optimal description of the ocean.

But can we just let these models run, to make predictions? The answer is no, because the ocean model, like the atmospheric model, is highly nonlinear; it has a chaotic character. A chaotic system is characterized by the fact that it takes only an infinitesimal change in the initial conditions of a prediction to arrive at entirely different results. That's the famous butterfly effect: a butterfly flapping its wings in the jungles of Brazil sets off an unexplainable chain

The left-hand map—a comparison of the difference in sea level height in April 1994 and April 1993 (1994 minus 1993) from TOPEX/POSEIDON data—shows the obvious buildup of the 1994 El Niño. Again, zero is yellow-green, going up to yellow (5 cm), red (10 cm), and white (15 cm). The corresponding trough of lower-level magenta and blue can be seen off the coast of South America. The map on the right, which was constructed from a state-of-the-art model, shows a very good correlation.

of events in the atmosphere that produces a storm in China a week later. So, no matter how accurate your model is, you can't just let it run by itself. You will always need observations to adjust the model via a technique called data assimilation, originally used by meteorologists. Like meteorologists, oceanographers depend on fresh data to keep their forecasts on track as well, so that they don't drift away over time.

Now we have global observations and a credible model, so we can assimilate satellite data and make predictions. But we still need the third element—a ground network of in situ observations, to produce reliable three-dimensional pictures of the circulation structure (rather than the shallow swamp that was the basis for earlier models). This is crucial in order to calculate the heat transport and make a correct prediction about the conveyor belt. So we also need to have deep-ocean observations to validate our computer calculations constrained by satellite observations. If it's consistent—great. If there are discrepancies, then we know where to concentrate our ocean observations. We don't have to populate the ocean with a hundred thousand stations, but only need to place them in a few strategic locations—those where the satellite and the model can't reproduce the real features. So in parallel with TOPEX/POSEIDON, we have a field campaign involving 40 nations around the world, called the World Ocean Circulation Experiment. A large number of different types of instruments have been deployed in the ocean over the past three years, an activity that will continue in the years to come. This experiment will provide a framework in which we can combine these observations with those from the satellite and the computer models to define a global climate prediction system. It will rely heavily on models and satellite data, with a minimum requirement of measurement in the sea, but it's the combination of all three of these things that should make a breakthrough in better climate prediction in the years to come.

TOPEX/POSEIDON will probably fly for another three or four years or possibly longer. Ocean climate study, however, is a long-term commitment. The phenomena we need to observe exceed the life cycle of a single mission, and we're not going anywhere unless we obtain at least a 15- or 20-year record. Realizing this, the United States and France are planning to continue precision altimetry measurement into the next century as part of NASA's Mission to Planet Earth. We're entering an era, a very exciting one, in which our investment in space will pay off with the knowledge for predicting the future of our own planet and helping us to prepare for inevitable change. □

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