Watching the oceans for signs of climate change


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Summertime sea ice (here) may become a much rarer sight in the future

The International Year of Physics will also enter the record books as one of climate extremes. The year 2005 saw the most hurricanes ever in the Atlantic sector, including one with the lowest surface pressure ever recorded, which left thousands of dead in their wake in North and Central America. In the Arctic Ocean, northern summertime sea ice cover was a record low and rainfall in the Indian state of Maharashtra during the monsoon a record high. The Amazon forest, source of the world's strongest-flowing river, is experiencing its worst drought in recorded history. The five warmest years on record are now 1998, 2002, 2003, 2004 and 2005. All of these climate events have a link to the ocean.

It is scientifically impossible to link any one extreme event to global climate change but the ongoing trend confirms that global change is under way. The Intergovernmental Panel on Climate Change (IPCC), which is charged with assessing climate research, stated in 2001 that 'the balance of evidence' suggested a human influence on climate. Recent scientific studies, which will feed into the Panel's next report in 2007 (*see back page*), reinforce this evidence, key pieces of which come from the oceans.

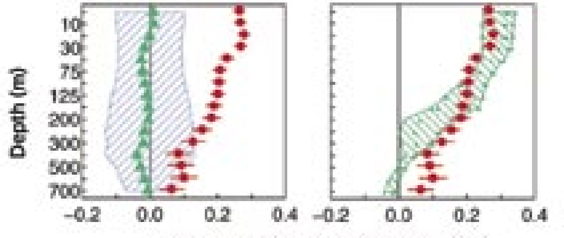
The oceans cover more than 70% of the globe. A major part of the climate system, they interact with the atmosphere and land. In the climate system, the oceans are unique for their high capacity to store heat: compared to air, seawater absorbs four times as much energy per kilogram in heating up one degree Celsius – and water is about 800 times denser than air at the surface. The heat energy contained in the top 3 m of the oceans is therefore equivalent to that contained in the entire atmosphere. This makes the oceans a key pathway for the transport of heat in the climate system.

Observations of the subsurface ocean have a fairly short history, beginning only in earnest after the Second World War and being concentrated in zones of high shipping traffic like the North Atlantic. But this history is now long enough to calculate trends in subsurface temperatures over vast expanses of ocean with a reasonable degree of scientific confidence.

The subsurface ocean is a good place to look for clear evidence of human-induced climate change. A change in the forcing of the climate system, such as that introduced by greenhouse gasses, forces the entire climate system to find a new balance, with a warmer Earth radiating more heat to space to compensate. The oceans are the major absorber of this extra heat. Since the subsurface oceans are less 'noisy' than the surface, which is affected by weather and the seasons, they have the clearest signals of long-term changes in the climate.

© NASA/SVS

Warm ocean waters fuel hurricanes and the waters were unusually warm in the tropical Atlantic in 2005. Hurricane Katrina is shown here, on 27 August 2005, in a satellite cloud image super-imposed on a map of the sea surface temperature



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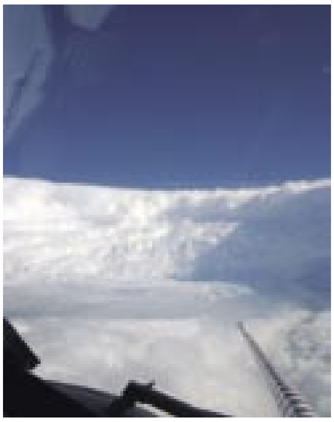
The panel on the left shows the average (green triangles) and range (blue hatching) of climate models reproducing natural climate variability over hundreds of years without inclusion of the human effect. The panel on the right shows the variability of a climate model run with the full history of human input of greenhouse gases (green hatching and dots); the red dots in each panel are averages over the North Atlantic of changes in ocean temperature over the past 40 years. The surface waters have warmed the most, by about 0.25°C. The panel on the right is a far better match to the observations than the panel on the left and excellent evidence of human influence on climate

Conclusive evidence from the oceans

In an article published in *Science* in July 2005, Tim Barnett and his colleagues showed that the observed patterns of ocean warming over the past 40 years could not be explained by natural variability but instead were a good match with the climate predictions incorporating the human effect on climate (*see figure*), findings which disagree with measurements taken elsewhere.

The study has helped to boost scientific confidence in the ability of modern land–ocean–atmosphere climate models to simulate climate change. In large part, the scientific debate over whether human activity has provoked climate change is over. Exactly how it will change remains a question.

Even if the human emissions of greenhouse gases were to stop today, the global climate would keep changing for decades to come, due to the level of greenhouse gases currently in the atmosphere and the thermal inertia of the climate system. The climate will stabilize again only when the Earth heats up enough or greenhouse gases get absorbed into other parts of the climate system. The oceans have absorbed about 50% of historical greenhouse gas production, with potentially dramatic effects on ocean ecosystems (see *page 41*).

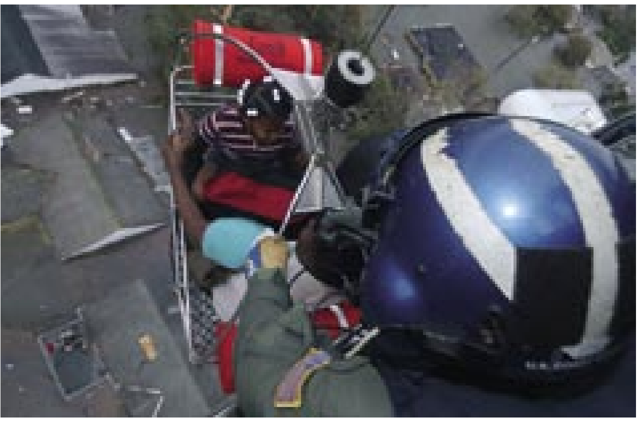

© NOAA

Too close for comfort. This view from the cockpit of the ring of thunderstorms surrounding the eye of Hurricane Katrina (known as an eyewall) was captured aboard a NOAA hurricane hunter aircraft a day before the powerful storm came crashing ashore. The heaviest rain and strongest winds are found in the eyewall, whose energy comes from heat from the ocean

Climate impacts driven from the ocean

Since the oceans are a major reservoir of heat in the climate system, prediction of short-term climate variations – those felt over days or months – is highly dependent on the interaction between the ocean and atmosphere. The climate records achieved this year are best understood using models that include the physics of ocean circulation. It is the extremes in rainfall and temperature which most affect humans, provoking floods, landslides, drought and shifts in the seasons which affect food production and tourism.

A record-breaking hurricane season


© K. Niemi/US XCoast Guard Digital

The fierce winds and extreme low pressure of Hurricane Katrina forced enormous storm surges, flooding a territory half the size of France. They breached a number of the levees protecting the coastal city of New Orleans, built mostly below sea level. Over 1 million people had to be evacuated, like the children in this photo, and more than 1200 people lost their lives. It is estimated that reconstruction will cost the USA over US$100 billion.

Unusually warm ocean conditions in the tropical Atlantic in 2005 contributed to the strength of hurricanes during the hurricane season, the most damaging season in recorded history. Hurricane Katrina last August devastated the US Gulf Coast (*see images*). Rainfall associated with Hurricane Stan in early October triggered severe flooding and landslides that killed up to 2000 people in Guatemala and other countries in Central America. Seven of the 14 hurricanes that formed were major and three were of the highest strength[12]. Meteorologists ran out of names for Atlantic hurricanes for the first time, resorting to the Greek alphabet and ending with Hurricane Epsilon.

The strong winds of a hurricane evaporate enormous quantities of water vapour from the ocean surface. The evaporation is strongest over ocean water with the greatest heat reserves. Climate change models incorporating hurricanes show an increase in the intensity of hurricanes – but not in their number – as the oceans warm. The debate is still ongoing as to whether the current warming of the tropical Atlantic is due to climate change or natural variability but global warming has already led to an increase in ocean temperatures.

A parched Amazon

While Central and North America flooded, the Amazon forest was experiencing its worst-ever recorded drought. Lakes and lagoons have dried up, river channels are no longer navigable, farming and fishing have been disrupted, the delicate tropical rain forests are burning, and stagnant water left


© Ana Cristina Vieira Folha

A dry mangrove swamp in Bragança, Brazil, in early 2005. The Amazon is experiencing severe drought, also due to the warm tropical Atlantic

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[12] *Category Five, with winds in excess of 249 km/hr*

in riverbeds is causing disease-carrying mosquitoes to proliferate. The same warming of the tropical Atlantic is thought to be to blame, as greater evaporation and rising air over the ocean has forced the air to descend over the Amazon, displacing the rains.

Monsoons driven by ocean heat

A similar balance of ocean and land evaporation drives the monsoon, a periodic wind which can be likened to a very strong sea breeze. The strongest of the monsoons occurs over the northern Indian Ocean, with the winds blowing from the southwest during one half of the year and from the northeast during the other half.

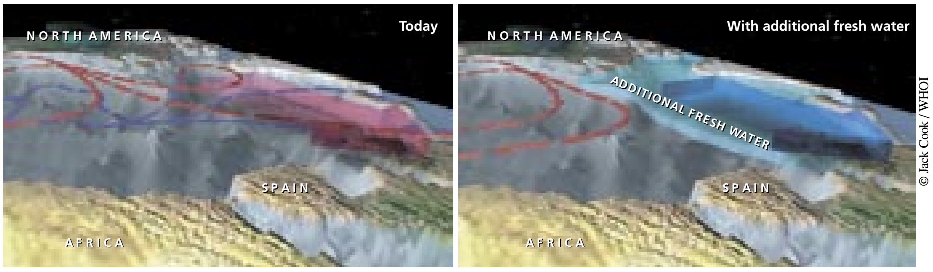
Tropical monsoon rainfall is driven by the difference in the heat capacity of the oceans and land. In summer under strong sunshine, the temperature on land rises much more quickly than the temperature at the sea surface. The warm air over land rises, drawing moist air from over the oceans inland and feeding strong rainfall. Both the amount of heat stored in the ocean and the difference in temperature between ocean and land affect the intensity of monsoons.

Melting ice and rising seas

The oceans are of course central to sea-level rise caused both by the expansion of warming oceans and the melting of glaciers (*see box, p. 10*) and ice caps. The global average sea level has been increasing by about 2 mm per year. But the increase is not entirely uniform; as the climate changes, the average winds and ocean circulation have also changed, creating localized changes in sea level.

How will things change in the future? Will there be stronger hurricanes across the tropics? How likely is it that Europe will cool? Will disappearing sea ice finally open the fabled Northwest Passage to shipping? Will Tuvalu disappear beneath the waves? Will the mighty Amazon be reduced to a trickle? And could the climate change suddenly? (*see box on facing page*)

The ocean conveyor belt



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Left: the warm surface water of the North Atlantic flows northward (red lines), replacing the southbound flow of cold, deep water (blue lines). This transports heat northward, warming the winds blowing eastward over Europe (large red arrow). A large addition of freshwater from melting land ice (right) would prevent seawater from sinking in the North Atlantic. The northward oceanic heat transfer could then stop, making the winds blowing over Europe much cooler, despite global warming (large blue arrow)

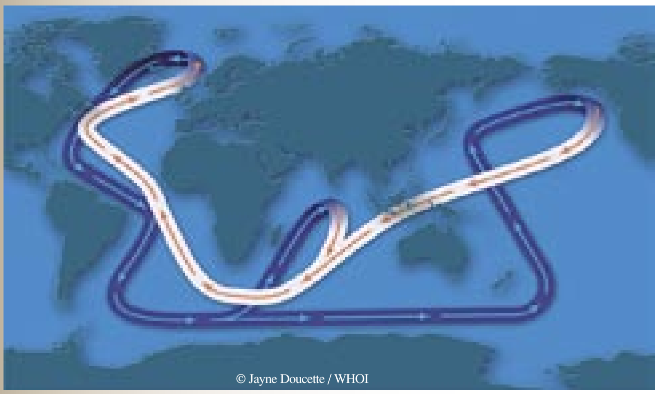
The average temperature between the equator and the poles differs because of the tilt of the Earth's surface relative to the sun. However, this difference is much weaker than one would expect. This is because the oceans and atmosphere carry heat to the poles, ensuring a more comfortable balance (for humans at least), by cooling temperatures at the equator and warming them at the poles.

The ocean transports about half of this heat via shallow and deep currents collectively known as the ocean conveyor belt (thermohaline circulation, see figure). One of the busiest ocean highways is the wind-driven Gulf Stream and North Atlantic Current, which warms Europe to its east. These surface currents transport tens of millions of cubic metres of warm tropical water northwards every second. Since mid-latitude weather systems generally move from west to east, New York in the USA is cooler than Naples in Italy, even though they are the same distance from the equator.

Evaporation to the atmosphere leaves behind saltier and cooler (and therefore denser) water. The waters below the upper layer everywhere in the world are filled with the densest cold and salty waters, formed mostly in the polar North Atlantic by extreme winter evaporation and heat loss; most of the sub-surface ocean is just a few degrees above freezing.

Carried in deep southward flows away from its source and, eventually, over thousands of years, spreading to the other oceans, the wind and tides bring this deep water back to the surface. There it is warmed by the sun and freshened by rain. Eventually, the water heads back to the poles again in the surface ocean to repeat the cycle.

Climate models with scenarios of human-induced change nearly all show that the ocean conveyor belt will slow down as the climate warms.



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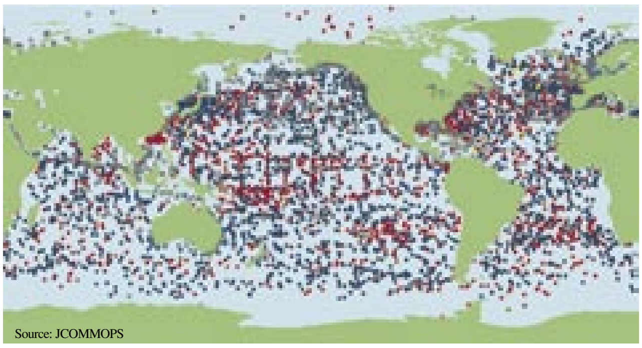
The path followed by the ocean conveyor belt

The World Climate Research Programme

The Intergovernmental Oceanographic Commission (IOC) of UNESCO, along with its partners the World Meteorological Organization (WMO) and the International Council for Science (ICSU), sponsors a World Climate Research Programme (WCRP) that tries to answer these questions. Its major goal is to determine both the limits of predictability of the climate system and the human influence on climate.

Published articles stemming from climate research within the WCRP make the main contribution to the body of knowledge periodically assessed by the IPCC.



Source: JCOMMOPS

Towards global coverage: in situ *platforms observing the ocean in October 2005, which produce data available in real time. These data come mainly from Argo floats (dark blue), ships of opportunity (light grey, light blue and yellow), fixed moorings and drifting buoys (red). The seasonally ice-covered oceans pose technical problems that are yet to be surmounted*

One continuing difficulty for scientists is how to separate human-induced climate change from natural climate variability. In fact, climate variability itself appears to be changing, with more extreme swings outside the realm of ‘normal’ weather. This in itself is an indication of climate change. The WCRP’s Climate Variability and Predictability project is helping us to better predict and model the extremes in climate, on time scales ranging from days to months to years ahead.

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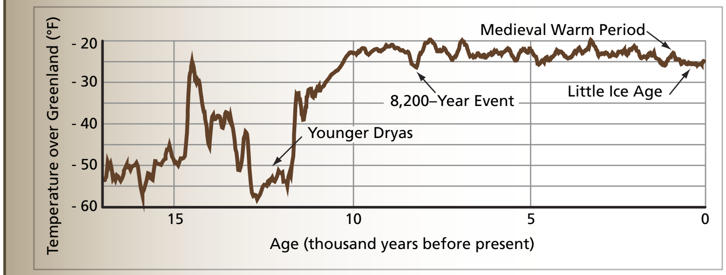
The aftermath of severe monsoon flooding in Mumbai, India, on 26 July 2005, when 1 m of rain fell in less than 24 hours, almost doubling the city’s previous record. The resulting flooding and landslides took more than 1000 lives. The strength of the monsoon is dependent on the ocean heat content in the Indian Ocean, along with other factors like the phase of El Niño in the Pacific

Could the climate change suddenly?

Studies of past climate from fossils and ice cores show that the climate system has made sudden jumps in the past.

The most recent climate jump occurred at the end of the last ice age, about 12 000 years ago, as humans were settling the American continent and, elsewhere, first began to farm. The melting North American ice sheets suddenly released a large amount of fresh water into the North Atlantic. Fresh water is less dense than salt water, so the normal formation of deep water in the polar North Atlantic stopped abruptly (see *The ocean conveyor belt*). The consequence was the collapse of the thermohaline circulation, causing average temperatures in the North Atlantic region to plummet by 5°C in less than a decade.

Some scientists fear that the melting of the Greenland ice cap could lead to a similar freshening of the North Atlantic and a climate jump. A great exaggeration of that scenario was recently at the heart of a Hollywood disaster film. What then is the threshold for abrupt climate change? Our present-day climate models are not yet skilled enough to tell us. But the consequences of a sudden jump in climate to ecosystems and to human society would most likely be catastrophic.



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Ice cores extracted from the 3km-thick Greenland ice sheet show several sudden shifts in climate in the past, within periods as short as a decade. Most dramatic was the Younger Dryas period, when average temperatures in the North Atlantic region dropped abruptly and remained cold for 1300 years before rapidly warming again[13]

There are already signs of a slowdown in part of the ocean conveyor. Only last month, scientists revealed that the deep southward flow of cool water in the North Atlantic, measured by five expeditions over five decades, had dropped by 30% between 1957 and 2004[14]. Should we put this down to a cycle of natural variability, or is this drop indicative of a longer-term change in the ocean conveyor? Only time – coupled with sustained observation – will tell.

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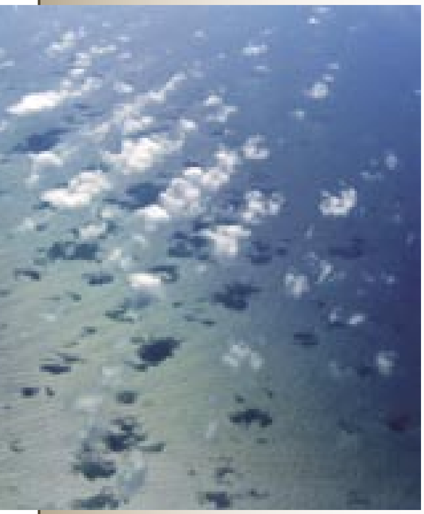
[13] *All the figures from the Woods Hole Oceanographic Institution are reproduced, with kind permission, from the brochure* Abrupt climate change: should we be worried?, *put together for the Davos Economic Forum in Switzerland in 2003: www.whoi.edu/institutes/occi/currenttopics/ct_abruptclimate.htm*

[14] *These findings were published by Harry Bryden and colleagues in the 1 December 2005 issue of* Nature

Give and take: competing climate feedbacks

Scientists who grapple with trying to understand the complex climate system have found a simple way to describe the patterns of interaction that they observe: as feedbacks. Feedbacks can either reinforce the current state of the climate system or lead it to run away.

An example of a stabilizing feedback (called a negative feedback) is the interaction between solar radiation, the sea surface temperature, and clouds in the tropics. The ocean warms from solar heating, warming and humidifying the atmosphere above. The strong winds of a hurricane evaporate enormous quantities of water vapour from the ocean surface. Energy from the latent heat released when this vapour then condenses into raindrops is injected into the storm, further increasing its strength. These clouds shield the ocean surface, which cools. In this way, the climate system creates a natural barrier to endless heating of the ocean. The opposite is also true: cooler oceans mean fewer clouds and more solar radiation reaching the surface. A negative feedback moves things towards an equilibrium.



Convective clouds in the tropics cast shadows over the warm ocean below

An example of a runaway feedback (called a positive feedback) is the interaction between solar radiation and ice in the polar regions. Ice is a very efficient reflector of sunlight, bouncing a significant fraction of its energy back into space. If the ice melts and is replaced by darker ocean or land surfaces, less sunlight is reflected, heating the surface. The heating will further melt ice. It is this which makes the polar regions particularly sensitive to climate change.

The balance of feedbacks, and whether a positive feedback can temporarily gain the upper hand over the stabilizing negative feedbacks, describes the evolution and natural variability of the climate.

The best-known interaction of climate feedbacks involving the ocean is El Niño, a temporary shift of the warmest waters in the tropical Pacific towards the east, with patterns of atmospheric uplift and rainfall following, bringing drought to Indonesia and Australia, excessive rainfall to Peru and Ecuador, and changed storm patterns over much of the globe.

Will El Niño change as the global climate changes? Many scientists believe it will or that it already has but predicting El Niños remains a difficult task.

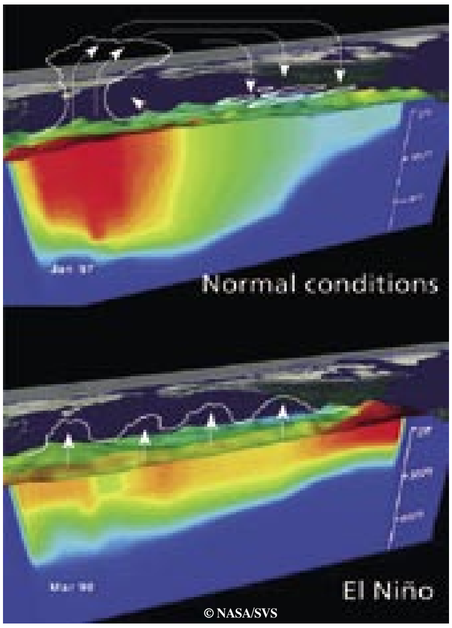
© ESA

Satellites provide global coverage of the oceans and are a key element of GOOS. This is an artist's impression of the European SMOS satellite, which will measure surface salinity from 2007 onwards

Observing the oceans to understand them

The IOC of UNESCO and its flagship programme, the Global Ocean Observing System (GOOS), make up the UN arm responsible for sustained global ocean observations. An IOC group of experts, the Ocean Observations Panel for Climate (OOPC), helps to define the standards and goals of the global climate component of GOOS and the tools for monitoring and evaluating the system.

Through a joint technical commission with the WMO for oceanography and marine meteorology (JCOMM), the IOC is also actively coordinating these global networks through an *in situ* (in the water) platform support centre (JCOMMOPS) located in Toulouse, France, which continually monitors the thousands of floats, ships and fixed moorings transmitting oceanographic data.



© NASA/SVS

A slice of temperatures the Pacific ocean, cut east–west at the equator and looking northwards, as visualized from the tropical array of fixed moorings in the Pacific. Normally, air rises over a pool of the warmest water in the western Pacific (top image), drawing the surface winds from the east that maintain this warm pool by piling up warm water. During an El Niño event (bottom image), something weakens the surface winds, which allows the warm water to slump eastward. The centres of rising air follow eastward, further weakening the surface wind and allowing the warm water to slump further, a positive feedback. The result is a change in the tropical Pacific on the ocean side and global changes in the atmospheric circulation

Satellites: scratching the surface

Ocean satellite missions have revolutionized oceanography; they are critical for global coverage of surface temperature, ocean eddies (the sea's weather systems), surface wind and ocean colour as an indicator of biological activity.

The oceans pose a serious impediment to satellite observations however. As the conductivity of salt water makes them almost impervious to electromagnetic radiation, only the skin of the ocean is visible from space. To observe the global oceans fully, measurements need to be taken in the oceans themselves, from different types of autonomous platforms and research ships.


© Canada DFO–MPO

An Argo profiling float being deployed from the Canadian coast guard ship John P. Tully in the Gulf of Alaska

Robotic sentinels of the deep

The most rapidly growing of these *in situ* networks is the Argo profiling float network. Argo floats are robotic, self-contained oceanographic measuring devices that park in the deep ocean, 2 km below the surface. Changing their buoyancy once every 10 days by shifting oil out to an external bladder, they rise to the surface. On the way up, they collect information on temperature and salinity (some also measure oxygen), which they then transmit by satellite at the surface.

By the end of 2005, the four-year old Argo project had seeded the oceans with more than 2000 floats, two-thirds of its way to its initial goal of 3000 floats, roughly one per every 100 000 km^2. When the batteries fail after about four years, the floats cannot rise to the surface. Most will eventually sink to the bottom. Argo floats are widely distributed in the world's oceans, thanks to the coordinated efforts of more than 20 participating countries. In some areas, the floats are now returning more information on the subsurface ocean in one year than can be found in the entire historical database before Argo.

A modern message in a bottle

Inspired by shipwreck survivors who sometimes cast messages sealed in a bottle to the waves, US scientist and statesman Benjamin Franklin used message-carrying bottles in the mid-1700s to compile an atlas of currents off the east coast of North America.


© NOAA

One of 70 fixed moorings in the tropical Pacific which monitor and forecast El Niño events within the global ocean observing system. The last El Niño event occurred in 2002–2003

In 1929, German scientists released a message that could be read without breaking the bottle in the South Indian Ocean. It was read and re-released a number of times. Caught up in the strong circumpolar current, it had travelled more than 25 000 km by 1935.

Today, a modern equivalent of these messages in a bottle – surface drifting buoys – ply the surface currents of the world, transmitting their electronic reports of surface temperature, currents and often barometric pressure. These buoys provide a ground truth for satellite estimates of the sea surface temperature and are the best witnesses of ocean surface currents, themselves driven by winds and ocean eddies. They also improve weather forecasts by reporting on the surface pressure.

The scientific goal set by OOPC for the surface drifting buoy network was to have one in every 300 000 km^2 box of ocean, or 1250 in total. That goal was reached in September 2005, when Global Drifter 1250 was launched at a special ceremony held in conjunction with the Second Session of JCOMM in Halifax, Canada. It is the first of the *in situ* global ocean observing networks to reach the goal it was designed for, a major milestone.

But scientists can't just declare victory and go home; the drifting buoy network needs constant replenishing as floats fail and drift out of regions of current divergence. Moreover, the planned global *in situ* ocean observation network of floats, profilers, moorings, sea level gauges and volunteer and research ships is currently only about 55% complete.


© NOAA

A message in a bottle: Global Drifter 1250, symbolically completing the first component of GOOS, is deployed in September 2005 in Canadian waters

© UNESCO/IOC

A training course in ocean data management at the IOC's International Oceanographic Data and Information Exchange (IODE) programme office in Oostende, Belgium. These courses build countries' capacities to participate in, and benefit from, ocean observing systems

Scientists hitch a ride on the oceans

The M/V Skogafoss, a 100 m-long container freighter, sets sail monthly from the port of Reykjavik, in Iceland, carrying containers full of frozen fish to North America. It returns two weeks later, repeating this voyage year in and year out. It navigates the most northerly regular ship route in the North Atlantic, dodging icebergs flowing southward in the Labrador Current well into spring.

The Skogafoss is also a volunteer observing ship. It regularly launches radiosondes (atmospheric profilers) from an automated laboratory mounted on a rear deck. It has automatic systems recording surface meteorology and sea surface temperature, as well as atmosphere and ocean carbon measurements. Once every few hours, the officer on duty steps out onto one of the bridge wings, loads an expendable bathythermograph (XBT) into a launcher and pulls the trigger. The XBT drops into the ocean and measures a profile of temperature, sending back its data on an unspooling length of copper wire thinner than a human hair. These observations are a key part of the global system and are coordinated through JCOMM's Ship Observations Team. The captain and the shipping company provide their services for free, volunteering their time and space aboard the ship.

This is a real boon for scientists, as a modern research vessel is extremely expensive to run. Paying for fuel, maintenance, three round-the-clock shifts of officers, engineers and sailors adds up, to the tune of US$ 20 000–50 000 per day. These volunteer ships of opportunity are also a major deployer of Argo and surface drifting floats, filling holes in the observational network as they open up.

Global information for local decisions

The global component of GOOS was designed for climate monitoring, forecasting and research but it also helps to improve weather and marine prediction. Ocean data (now coming from nearly 70 countries) is managed and disseminated globally in a coordinated fashion and turned into ocean and climate models and other products. The IOC has also taken on a strong role in the coordination of global ocean natural hazard warnings, in particular as regards tsunamis. The observing platforms that feed into the warning systems are often the same: moored buoys and tide gauges are used in both the climate and tsunami observing systems. The IOC is working to maximize the synergies between the two systems.

Raw ocean data are of interest to scientists but may be incomprehensible to government officials and other decision-makers responsible for addressing climate change, managing fisheries or sailing safely. GOOS and the WCRP are working to develop ocean and climate models that can provide more targeted information for decision-making.

Long-term foresight in short supply

The global oceans that cover such a large portion of our Earth belong to all nations collectively – but very few people live on the oceans. Whereas nearly every country, rich or poor, has a national meteorological agency charged with observing and forecasting the atmosphere, very few have national oceanography agencies with a mandate to observe the oceans and even fewer a mandate to observe the global ocean.

The ocean observing network has been built on the sustained work of research oceanographers. But this poses its own problems; for example, subsurface current meters have been monitoring part of the thermohaline circulation in the Atlantic (see *The ocean conveyor belt*) for over a decade but a number will not be renewed because the national research agencies are keen to fund something new. There is no-one however to fill the gap once this monitoring ceases.

This lack of commitment by the world's governments to sustained observations of the oceans is shortsighted. In the face of slow political action to change mounting human production of greenhouse gases, it is clear that climate will continue to change and that this change may even accelerate.

Scientific observations and research are needed to help us understand how regional climate will change, to improve predictions about shorter-term changes in the local climate, to improve our poor understanding of how ocean chemistry and ecosystems may change and to equip governments and citizens of the world with better knowledge to help them in making decisions about the future.

Humans have generated an unprecedented perturbation in the Earth's climate. In facing the consequences, we need to be as informed as possible.

Albert Fischer[15]

For details: http://ioc.unesco.org/iocweb/climate-Change; a.fischer@unesco.org

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[15] *UNESCO–IOC Programme Specialist and physical oceanographer*