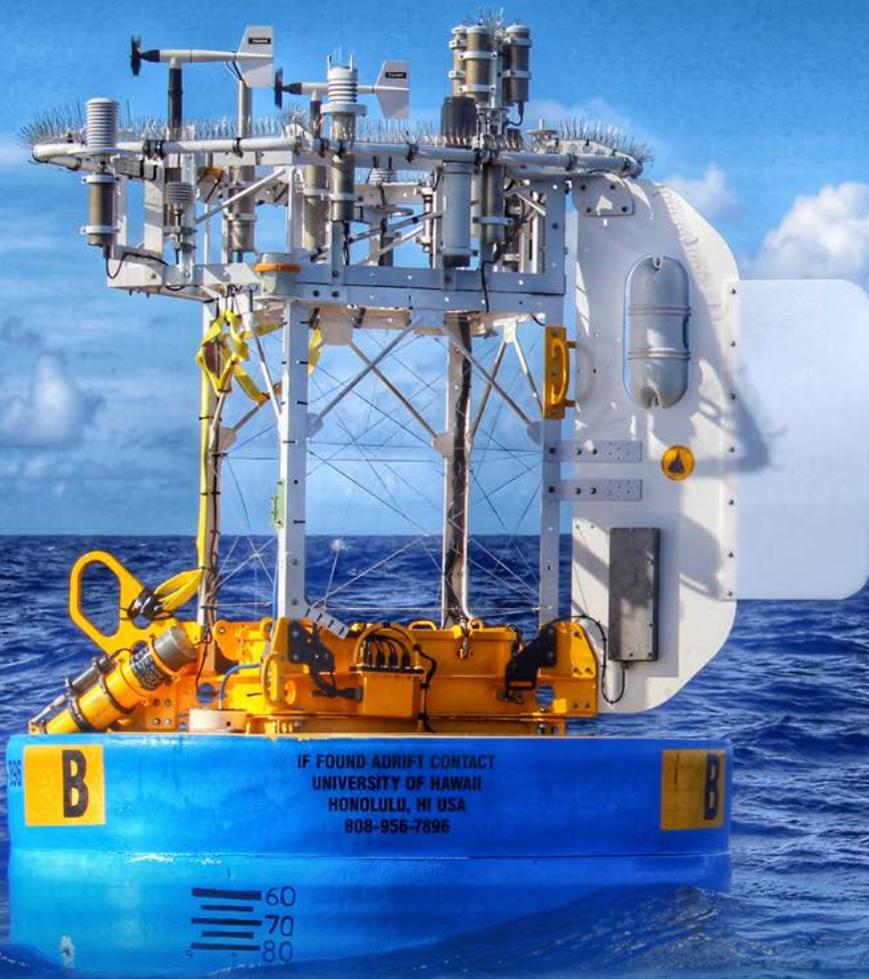


OceanSITES

TAKING THE PULSE OF THE GLOBAL OCEAN



Continuous measurements
from the open ocean in real time

Our Earth and Oceans

OceanSITES is watching... measuring... and looking forward.

Every year billions of tons of carbon emissions flood into the atmosphere and dissolve into the ocean. Warm air billows from tropical waters, turning thunderstorms into raging hurricanes. Fish stocks seeking cold ocean waters retreat toward the poles. Arctic ice thins each summer, burying the salty northern oceans under a layer of fresh water.

As the world reacts to a changing ocean, scientists are working hard to find explanations and to predict what else lies in store. Thanks to the explosive pace of modern technology, many of the right tools are now in their hands. Satellites watch the sea surface; Argo floats measure temperature and salinity as a function of depth every 10 days or so as they drift. OceanSITES seeks to add the capability to sample at key, fixed locations from the sea surface to the sea floor every few minutes for sustained, long periods of many years.

The major challenge remaining in sampling the ocean is also one of the most basic: the ocean is immense, inaccessible and always in motion. Tracking the key variables important to climate, ocean chemistry and fisheries as they change over days to seasons and decades and as they change in response to episodic events like storms is a long-time goal that is only now coming within reach.

Seventy percent of the Earth is covered by oceans. At present fewer than 300 permanent deep-water observatories report air and sea conditions for the entire world's oceans. Europe alone, at only 1/35th the size, has about 10 times that many weather stations on land.

It's a critical challenge, because when it comes to shaping our planet, the open ocean is a far more powerful force than dry land. The ocean's global influence extends from regulating climate, to feeding the

fish that feed the world, to carrying the storms and tsunamis that threaten our mariners and coastlines.

Monitoring the entire ocean over long time periods is an ambitious proposal. The OceanSITES team—more than 100 scientists from two dozen nations—are at the forefront of making the work economically feasible. To deliver the maximum possible data out of each station, OceanSITES scientists will:

- Secure long-term support for existing OceanSITES stations;
- Upgrade stations with new sensors to record a host of physical, chemical and biological variables, enabling cross-discipline studies;
- Install new stations in key regions of the globe to collect long-term records for the first time;
- Collect observations centrally in common format and distribute publicly from two Global Data Assembly Centers (GDACS)
- Refine existing sensors and develop new platforms to usher in continuous surface measurements in even the most brutal sea conditions.

By studying key regions, OceanSITES scientists unravel puzzles for the entire ocean. Long-term observations at these sites give researchers the background they need to recognize complex patterns amid the ocean's immense variability.

are Changing

OceanSITES*

are long-term buoy and ship stations that measure many aspects of the ocean's surface and depths using advanced sensors and satellite telemetry. Since 1999, an international science team has shared data and costs in order to capitalize on the enormous potential of these instruments. The growing network now consists of about 60 surface and more than 200 subsurface OceanSITES monitoring the global ocean.

A Host of Sensors

OceanSITES stations offer stable platforms from which to deploy a wide range of instruments. Variables measured include:

Meteorology

- Precipitation
- Wind speed and direction
- Air and sea-surface temperature
- Humidity
- Barometric pressure
- Solar and infrared radiation
- Surface waves

Climate

- Air-sea fresh water exchange
- Air-sea heat exchange
- Air-sea gas exchange
- Wind stress

Physical oceanography

- Current speed and direction
- Water temperature
- Salinity

Transport of water

- Volume of open ocean currents

Biogeochemistry

- Nutrients
- Organic sediments
- Dissolved inorganic carbon
- Oxygen
- Chlorophyll
- Acidity (pH)

Carbon cycle

- Carbon dioxide pressure in air and water

Biology

- Phytoplankton
- Zooplankton
- Fish stocks
- Ambient noise

Geophysics

- Seismic movements
- Magnetism

*Ocean Sustained Interdisciplinary Timeseries Environment observation System

The next great leap in understanding our planet's ocean will come from measuring more of it, more precisely, and for longer periods than ever before.



OceanSITES covers the ocean from whitecaps to bedrock

Oceanographers' questions: What happens when the wind and sea trade heat, water and momentum? Does the ocean effect weather, including droughts and floods? Can sea level rise and flooding by the ocean be predicted? How much carbon dioxide goes into the Ocean? How are fish stocks changing and why?



Answering those interrelated questions requires tools to match. That's the rationale behind the Global Ocean Observing System, an international effort to study the ocean by coordinating observations from satellites, drifters, ships, and fixed reference stations, including OceanSITES.

Satellites watch the entire globe but can't see below the surface. Drifters follow ocean currents, some sampling at the sea surface and some diving every week or so to collect profiles, usually to 2,000m depth. Roughly every decade, teams onboard research ships lower instrumentation to collect full depth profiles of ocean properties.

OceanSITES buoy and ship stations complete the picture by focusing on the ocean at key fixed locations around the globe. At these locations they continuously measure a suite of variables along a single column, which can range from the sea surface to the sea floor. Sampling is rapid, as fast as every minute, and

repeat deployments allow records at fixed sites to extend for many years.

The long-term data let scientists factor out everyday variation and detect other phenomena (see box). As the planet moves, we get regular changes like sunrise, sunset, tides and seasons. These recurring patterns dominate the signal on any ocean graph, obscuring subtler trends. To look past the noise requires the perspective of a long time series.

Climate and ocean-researchers work with wide-coverage satellite, ship-based, and drifter data, but they need fixed reference points that add key information about sea surface and ocean variability with time and depth. OceanSITES sustained observations, recorded by sensors calibrated before and after each deployment that sample as often as once per minute for many years are a cornerstone for documenting the ocean, improving ocean models, and providing ground-truth for satellite observing.



In the open ocean, what do you measure?

OceanSITES give scientists long-term data about basic ocean processes. Those same data stations give us immediate insight on a suite of globally important phenomena:



Weather forecasts predict where **HURRICANES** will go, but we need ocean data to predict how punishing they will be when they arrive.



Large-scale **CLIMATIC FLUCTUATIONS** like El Niño change weather patterns, threaten crops and cause floods and droughts.



Burgeoning human populations demand ever more from **DECLINING FISHERIES**. Managing the stocks starts with measuring ocean productivity at the base of the food chain.



Some of our global **CARBON EMISSIONS** get locked away in open ocean currents. We need to know how much the waters can hold, and for how long.



TUNAMIS travel at deadly speeds. The key to safety is rapid detection and early warning.

Milestones in Ocean Observations

OceanSITES is part of a long history of oceanic exploration. Technological advances along with our need to preserve and protect ocean resources makes sustained support of OceanSITES an important choice for our future.

1500 Lighthouse keepers in Europe begin accruing continuous records of coastal ocean conditions.

1855 Matthew Fontaine Maury publishes *The Physical Oceanography of the Seas*, the first textbook in oceanography, after spending 30 years studying ships' logs and ocean currents.

1876 After 4 years, the HMS Challenger finishes the first oceanographic research voyage. The final report takes 50 volumes and 20 years to write.

1900 On the Albatross, Alexander Agassiz maps unknown parts of the Pacific, sampling the sea floor and water column along the way.

1925-27 Georg Wüst explores the Atlantic aboard the Meteor, mapping deep currents, salinity and temperature in unprecedented detail.

1940 Ships in the Ocean Weather Station program begin collecting continuous data from 46 spots in the open ocean. The program lasts until 1980, when satellite imagery replaces it.

1960s-70s First subsurface moorings, then surface moorings begin to appear in the open ocean.

1972 The GEOSECS voyages begin. Over 6 years, researchers make the first maps of radioisotopes in the Atlantic, Pacific and Indian oceans.

1978 NASA launches satellites equipped with Advanced Very High Resolution Radar (AVHRR). The digital sensors record global weather patterns and sea surface temperature.

1982 Devastating El Niño weather causes \$13 billion in damages and spurs governments to build a long-term buoy array across the equatorial Pacific.

1990 Scientists and ships from 30 nations pitch in for the World Ocean Circulation Experiment, (WOCE), a decade-long effort to map ocean circulation.

1991 UNESCO forms the Global Ocean Observing System to promote international work on ocean observatories.

1999 St. Raphael, France: oceanographers envision a global system of "Eulerian observatories," eventually renamed "OceanSITES."

2000 The first of 3,000 Argo drifters is set loose in the water worldwide. They ride ocean currents and report upper-ocean conditions to satellites every 10 days.

2004 The devastating Indian Ocean Tsunami highlights the need for improved tsunami warning.

2011 OceanSITES begins an effort to collect sustained time series of temperature and salinity in the deep ocean. The goals are to better understand the deep ocean and provide the data needed to improve ocean models and their simulation of the deep ocean. Funds are raised to create a pool of shared temperature and salinity recorders for placement on existing OceanSITES stations.

By recording data over the long term, OceanSITES stations let scientists distinguish natural patterns of ocean variability from new changes to the ocean.

Putting eyes in the ocean

Advanced technology makes the ocean visible

OceanSITES moorings are anchored to the sea floor and stay in place for a year or more between maintenance visits. During that time. Their cargo of instruments collects and stores a large volume of observations.

Moorings with surface buoys are able to transmit observations back to shore via satellites. Meteorological and other observations at the sea surface are often transmitted and available in close to real time. Some moorings also send data from ocean instruments up the mooring cable, making observations from the ocean interior available for sending via satellite.

Instruments on moorings without a surface buoy record their observations inside their instruments. At some subsurface OceanSITES moorings, these data can be collected by acoustic data telemetry, allowing the observations to be collected by hydrophones lowered from ships or mounted on ocean gliders, which in turn can transmit the observations to researchers on shore.

Scientists choose from sensors like the ones drawn here and use surface or subsurface moorings, research ships, or drifters and robotic vehicles.



Meteorological sensors atop the surface buoy provide data to improve weather forecasts, predictions of storms and waves, and calculation of the exchange of heat, freshwater, momentum, carbon dioxide, and other properties between the air and ocean. The self-reliant buoys carry batteries for power; some have solar panels as well. Satellite transmitters send data to shore and GPS is used to track buoy location.

Current meters record current speed, direction, temperature and salinity to produce a motion picture of flow and mixing in the water column.

Acoustic Doppler current profilers emit high-pitched pings and measure their echoes to calculate current speed at regular intervals in the water column.

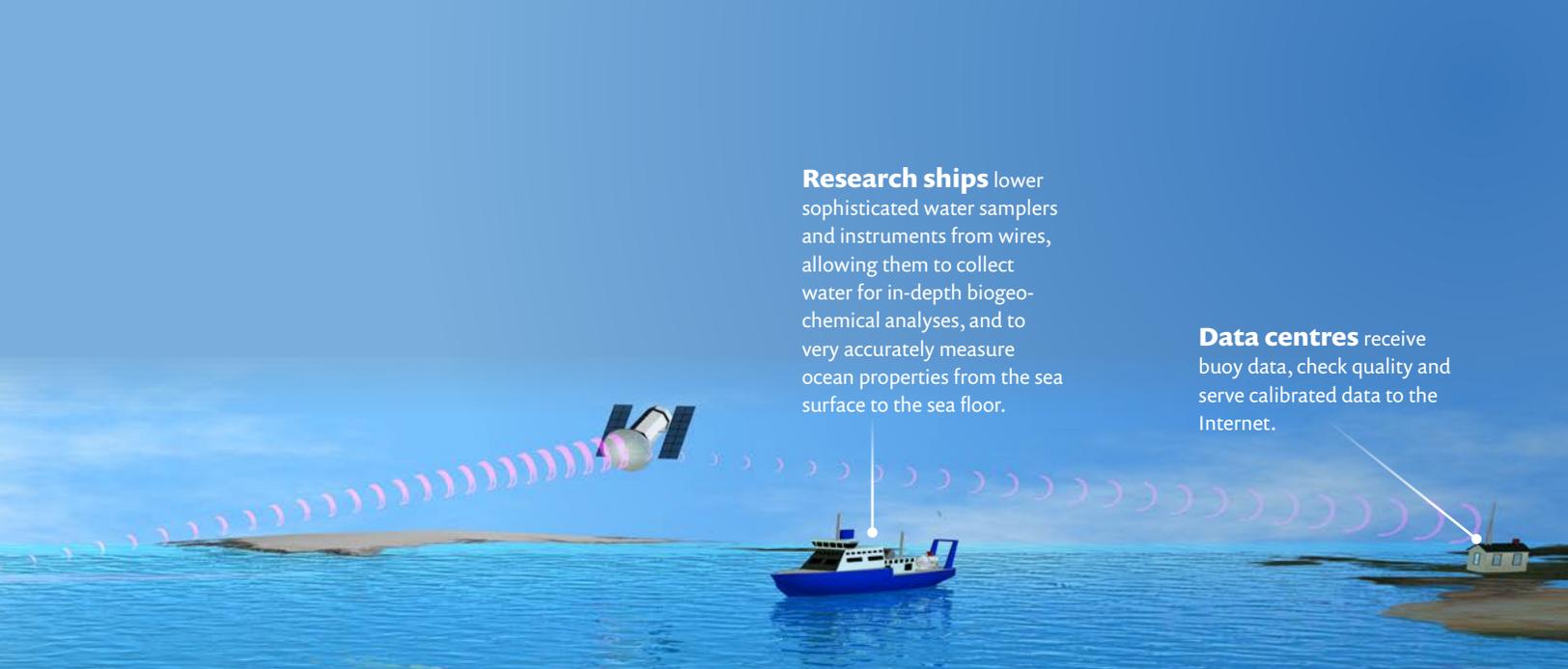
Other systems record dissolved oxygen, light levels, photosynthetic activity and nutrients like nitrogen, phosphorus and silica.

Engineers build an **S-bend** in the mooring line to reduce the tension between anchor and buoy during heavy seas.

Bottom pressure recorders can sense the pressure from a passing tsunami wave, then beam a warning to a surface buoy.

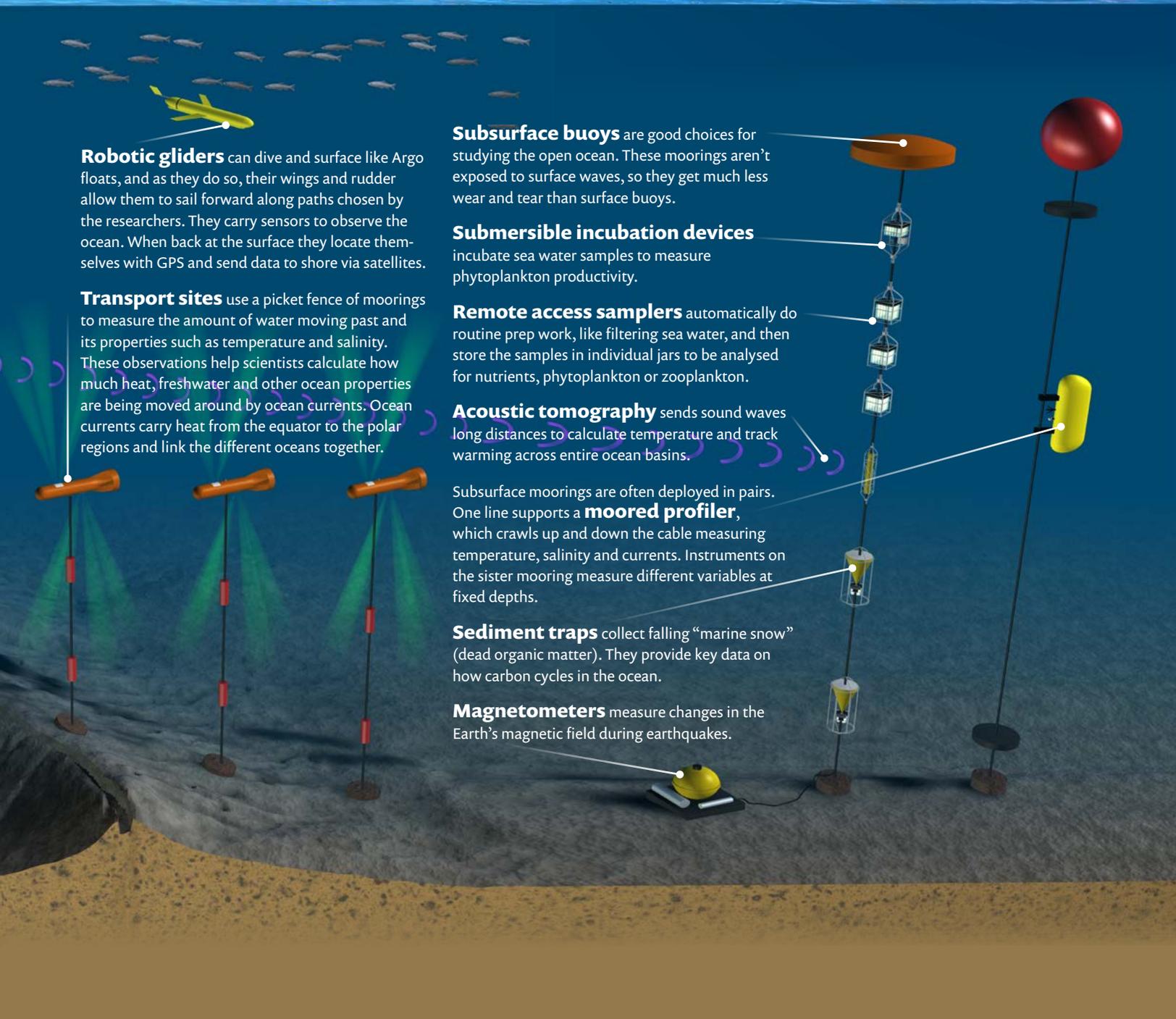
Seismometers measure earthquakes in the sea floor.





Research ships lower sophisticated water samplers and instruments from wires, allowing them to collect water for in-depth biogeochemical analyses, and to very accurately measure ocean properties from the sea surface to the sea floor.

Data centres receive buoy data, check quality and serve calibrated data to the Internet.



Robotic gliders can dive and surface like Argo floats, and as they do so, their wings and rudder allow them to sail forward along paths chosen by the researchers. They carry sensors to observe the ocean. When back at the surface they locate themselves with GPS and send data to shore via satellites.

Transport sites use a picket fence of moorings to measure the amount of water moving past and its properties such as temperature and salinity. These observations help scientists calculate how much heat, freshwater and other ocean properties are being moved around by ocean currents. Ocean currents carry heat from the equator to the polar regions and link the different oceans together.

Subsurface buoys are good choices for studying the open ocean. These moorings aren't exposed to surface waves, so they get much less wear and tear than surface buoys.

Submersible incubation devices incubate sea water samples to measure phytoplankton productivity.

Remote access samplers automatically do routine prep work, like filtering sea water, and then store the samples in individual jars to be analysed for nutrients, phytoplankton or zooplankton.

Acoustic tomography sends sound waves long distances to calculate temperature and track warming across entire ocean basins.

Subsurface moorings are often deployed in pairs. One line supports a **moored profiler**, which crawls up and down the cable measuring temperature, salinity and currents. Instruments on the sister mooring measure different variables at fixed depths.

Sediment traps collect falling "marine snow" (dead organic matter). They provide key data on how carbon cycles in the ocean.

Magnetometers measure changes in the Earth's magnetic field during earthquakes.

Tracking Global Ocean Processes

The ocean and air constantly trade heat, water and chemistry

In 1958, Charles Keeling began to measure the concentration of carbon dioxide at the Moana Loa observatory, and the well-known red line to the right showing how the concentration has increased is now known as the “Keeling Curve”. The goal of OceanSITES is to collect such long, continuous records from the surface and interior of the ocean at key locations and to document and reveal variability in the ocean and in its interaction with the atmosphere.

Ocean change can be imperceptible without decades of precise time-series measurements. Yet, it is clear from observing deep ocean waters, which are blanketed from seasonal, year to year and other transients changes in the surface waters, that the oceans provide vital evidence that our planet is warming. Sampling the ocean also provides evidence of how to predict ocean impacts weather and climate and thus society.

The 1990s saw the realization of the multi-national TAO array, a system of more than 70 stations spanning the entire breadth of the tropical Pacific. Just three years after its completion, the array paid off. Climatologists predicted impacts of the severe 1997–98 El Niño six months in advance. California alone saved more than \$1 billion.

Climate work has focused on the equatorial oceans because they are a major engine in Earth’s climate machine. Tropical waters soak up enough energy each day to keep a high-output light bulb burning for every meter of ocean surface in all directions. Ocean currents born in the tropics carry heat toward the poles and trade it back into the cooler atmosphere along the way.

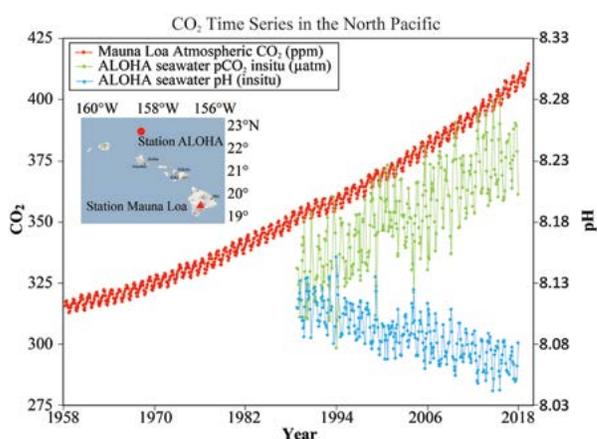
Now, climate scientists are turning their attention to the cold, stormy seas of the north and south. The moorings that enable year-long buoy deployments in the tropics can’t stand up to the high winds, waves, and icing found at higher latitudes. Building on the success of equatorial buoys, OceanSITES scientists are engineering new surface buoys that will be deployed in the challenging northern and southern oceans.

Heat isn’t the only commodity that ocean and air trade back and forth. Billions of tons of carbon dioxide dissolve into the ocean from the atmosphere every year. At select OceanSITES stations, scientists are now measuring the net transfer of carbon and other elements between the two systems.

When carbon dioxide dissolves into the ocean, it stops adding to greenhouse warming. (Perhaps up to almost half of the world’s carbon dioxide emissions find their way into the ocean each year.) But ocean circulation also in some locations brings carbon-dioxide-rich water to the surface, where the gas enters the atmosphere. For scientists to know the net effect, they need precise measurements collected over years.

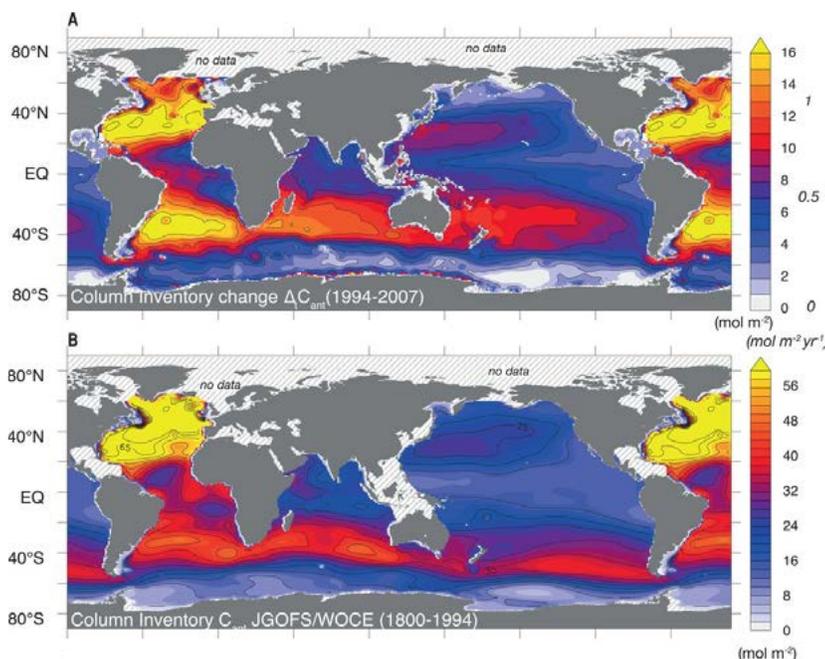
As well as simply dissolving into ocean water, carbon dioxide can enter the ocean when tiny plants and animals use the carbon to grow. As they die and sink, the carbon in their bodies falls to the sea floor. Biologists are now using OceanSITES to measure the rate at which these creatures grow, die and settle out.

By tracking plankton growth at these reference stations, biologists are also learning about the staple food of the ocean. Phytoplankton numbers promise to be crucial data for researchers assessing commercial fisheries. Giving scientists the ability to know key variables from across the spectrum of ocean sciences—all measured simultaneously—is part of the power of the OceanSITES program.



Near Hawaii, ship-based sampling has been used to collect observations of the amount of carbon dioxide in the ocean and of the pH of the seawater. Land-based observations of carbon dioxide in the atmosphere (in red) have been made atop Mauna Loa since 1958 and have shown carbon dioxide increasing in the atmosphere. The shipboard sampling shows carbon dioxide in the ocean (in green) is also increasing. As carbon dioxide enters the ocean, it leads to an increase in the acidity of the seawater, which is shown by the decrease in the pH of seawater (in blue) with time. The shipboard sampling is carried out at Station ALOHA as part of the Hawaii Ocean Time Series program.

Data: Mauna Loa (ftp://aftpcmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) ALOHA (http://hahana.soest.hawaii.edu/hot/products/HOT_surface_CO2.txt) Ref: J.E. Dore et al., 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proc Natl Acad Sci USA* **106**:12235-12240



A recent study of the amount of man-made or anthropogenic carbon dioxide stored in the upper 3,000 m of the ocean yielded three maps for the global ocean. Map A shows the change between 1994 and 2007. Map B shows how much was present in 1994.

Gruber, N., D. Clement, B.R. Carter, R.A. Feely, S. van Heuven, M. Hoppema, M. Ishii, R.M. Key, A. Kozyr, S. Lauvset, C. Le Monaco, J.T. Mathis, A. Murata, A. Olsen, F.F. Perez, C.L. Sabine, T. Tanhua, and R. Wanninkhof (2019): The oceanic sink for anthropogenic CO₂ from 1994 to 2007. *Science*, 363(6432), 1193–1199, doi:10.1126/science.aau5153

To understand the climate in any one location, scientists must calculate four crucial air-sea exchange rates: water, heat, momentum and carbon dioxide. For OceanSITES surface stations, measuring these variables is just part of the daily routine.

Global ocean studies require

OceanSITES includes 300 sites maintained by investigators in more than 20 countries

When an ocean research question has a global scope or spans a broad region of disciplines, OceanSITES has relevant experts already at the table. Investigators from more than 20 countries work to obtain the funds needed to build and maintain the current 60 surface and 240 subsurface moorings and ship-based sites that comprise the OceanSITES program.

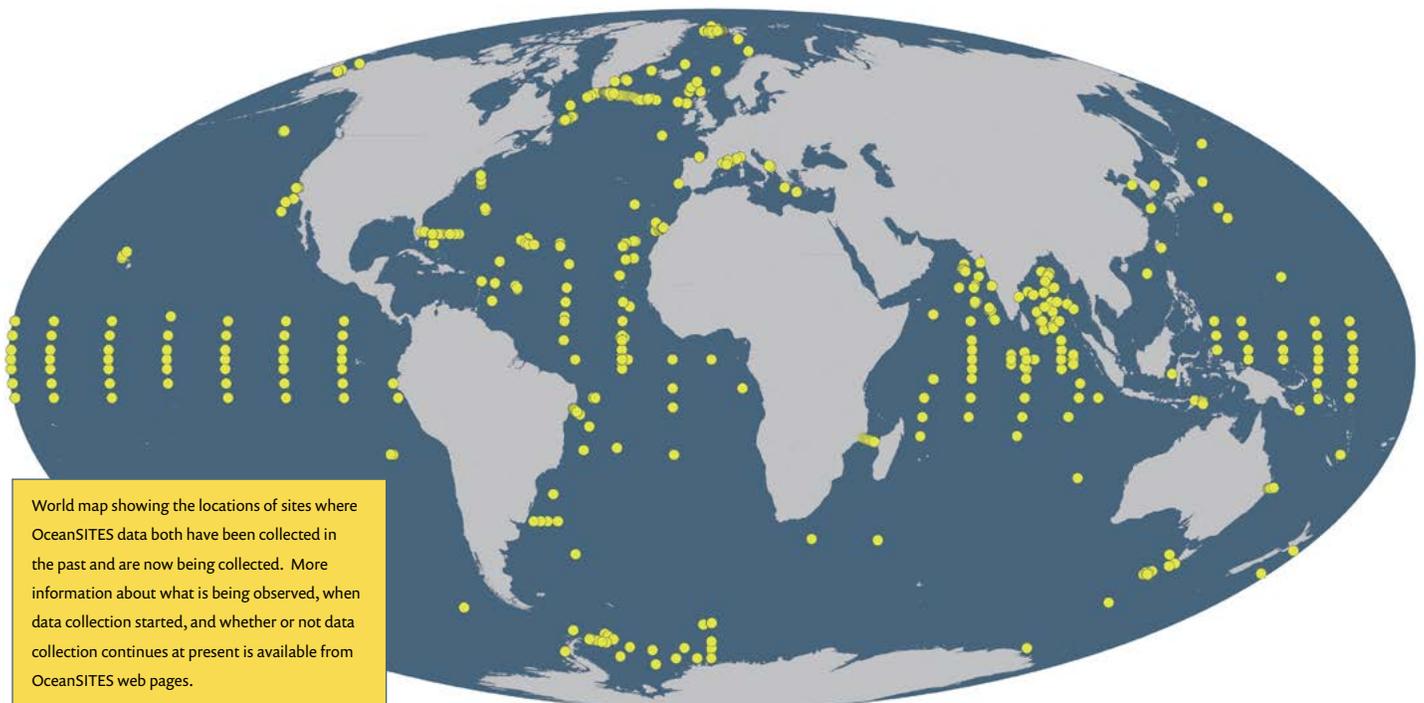
OceanSITES research contributes to larger projects like UNESCO's Global Ocean Observing System (GOOS) and the Global Earth Observing System of Systems (GEOSS). Guidance is provided by the Climate Variability and Predictability project (CLIVAR) of the World Climate Research Program (WCRP), the Partnership for Observation of the Global Oceans (POGO) and the Ocean Observations Panel for Climate (OOPC).

The OceanSITES data management team aims at distributing quality-controlled data in a common

format with all the needed supporting information. Lead scientists submit calibrated data to local data centers; and all data are stored at two Global Data Assembly Centers (GDACS), which make them freely available. The OceanSITES Steering Committee and Data Team work to establish and maintain best practices and standards for collecting long, sustained observations of the ocean at fixed locations.

Technical challenges still complicate the goal of long-term, open-ocean measurements (see What's so complicated?, at right). But OceanSITES engineers are solving these problems as they invent the next wave of ocean technology. The technologies for moorings continues to improve, and more diverse instruments measuring more multidisciplinary ocean properties are becoming available.

Ocean observation is moving beyond only physical properties such as temperature, salinity, and



global partnerships

currents, towards long-term records of dozens of variables illuminating also the biology, chemistry, ecology, and biogeochemistry of the oceans. As we track the ways our planet is changing, research teams need data precise enough to inform global models of climate change, life in the ocean, and the impacts of the ocean on human society. OceanSITES is an indispensable part of the ocean observing system needed to meet these needs.

Ocean observation is moving beyond spot estimates of basic physical properties, toward long-term records of dozens of variables. OceanSITES is an indispensable part of the campaign.

Lower left, Recovery of the NOAA Ocean Climate Station Papa mooring during the June 2011 Canadian Fisheries and Ocean Line P cruise aboard the CCGS John P. Tully. Photo by Keith Ronnholm. Lower right, WHOI Technician Amy Simoneau, MATE Intern Arianna Johns, and University of Miami technician Adam Houk handling a buoy during Agulhas mooring recovery aboard Research Vessel *Knorr* in 2013. Photo by Valery Lyman.

What's so complicated?

about measuring a column of water and air in the open ocean, 5 km deep or more and totally at the mercy of open-ocean weather?

Radio silence. Space communication is easy: Colour pictures of Saturn's moons reach Earth in about 90 minutes. But just a metre of ocean water stops radio and radar dead.

Very long cables. Just sinking a mooring line is a major undertaking. The rope, chain and cable can be 5 km long, weigh 10 tons and take up much of a ship's deck.

Slimy instruments. For some reason, ocean life loves new instruments. While OceanSITES has nothing against sea creatures, "biofouling" is a major cause of instrument failure.

No elbow room. OceanSITES engineers have to pack dozens of sensors onto each station. And they also have to find room for backups, spare batteries and prototypes of next-generation equipment.

Needles in a haystack. OceanSITES platforms carry radar reflectors so ships can avoid them—and stay clear of the water the buoy is measuring.

Gremlins in the data. OceanSITES data are freely shared to the world. Before that happens, data managers and technicians spend hours calibrating sensors, checking the quality of the data, and then organising and formatting the data stream. They also prepare the supporting information about what was measured and how it was measured so that users understand the data.



OceanSITES—succeeding in its mission and key role

OceanSITES is an international program working to observe the open ocean, document its physical, chemical, and biological structure and variability, discover new knowledge about the ocean, and make those data and that knowledge publicly available. The program employs a global array of sampling stations recording diverse measurements from the sea surface to the sea floor. The rugged, technologically advanced stations are regularly refreshed, allowing scientists to compile long-term observations of the ocean in key regions of the globe. Success for OceanSITES will be the collection and open sharing of long, ongoing time series measurements from those key fixed ocean sites and the use of those time series to define variability and change in the ocean, quantify and illuminate the ocean's role in the earth system, drive improvements to numerical models and predictions, anchor and calibrate remote sensing of the ocean, and provide the means to assemble and validate gridded data fields at the ocean surface and in its interior. The ocean is variable; and, as a result, detecting and describing decadal and longer time scale variability with confidence depends directly on the length of the time series being analyzed. Confidence in doing so increases directly with the length of the record, and to succeed OceanSITES thus needs to maintain sites as ongoing, sustained observing platforms.

OceanSITES coordinates the open ocean time series activities for the Global Ocean Observing System (<https://www.gooscean.org>). We are part of the Observations Coordination Group (OCG) that oversees all ocean observing components and provides technical support related to GOOS. One of the key activities is representation of the OceanSITES national organizations and the observing technology in the OceanOPS (former JCOMMOPS) metadatabase. OceanSITES collection of long time series at fixed sites complements the other components of GOOS that collect data from ships and from drifting platforms. The OceanSITES time series sites with their fast sampling rates and often with high vertical resolution and diverse multidisciplinary instrumentation make a unique contribution to GOOS. To answer requests from colleagues working to improve numerical models, some OceanSITES

scientists have merged data from successive deployments to make long, continuous time series, some running longer than 10 years.

OceanSITES data are provided in NetCDF data format with supporting metadata. These data are served by two Global Data Assembly Centres (GDACS), one at Coriolis at Ifremer in Brest, France and one at the National Data Buoy Center (NDBC) in the United States. At Ifremer, access is via

- Ifremer FTP: <ftp://ftp.ifremer.fr/ifremer/oceansites/>
- Ifremer THREDDS Catalog: <http://tds0.ifremer.fr/thredds/CORIOLIS-OCEANSITES-GDAC-OBS/CORIOLIS-OCEANSITES-GDAC-OBS.html>

At NDBC, access points are:

- NDBC OceanSITES Web Page: <http://dods.ndbc.noaa.gov/oceansites>
- NDBC FTP: <ftp://data.ndbc.noaa.gov/data/oceansites/>
- NDBC THREDDS Catalog: <http://dods.ndbc.noaa.gov/thredds/catalog/oceansites/catalog.html>

OceanSITES has a Steering Team made up of the leads for all the sites. The Steering Team has an Executive Committee and two co-Chairs, listed at <http://www.oceansites.org/contact.html>. The OceanSITES Data Management Team works to maintain the common OceanSITES NetCDF data format and supporting metadata for each site. OceanSITES invites scientists planning to maintain or now maintaining open ocean time series collection sites to browse the OceanSITES web site to find out requirements for being an OceanSITES and contact information to reaching out to the Steering Team to inquire about becoming an OceanSITE. Any questions about OceanSITES are also invited as are examples of the use of data from OceanSITES. OceanSITES is interested in fostering growth by adding sites in key locations to improve knowledge of the ocean, by adding instrumentation to increase multidisciplinary sampling, and by aiding new investigators to develop and maintain sites.