# OCE/MPO 603 Introduction to Physical Oceanography

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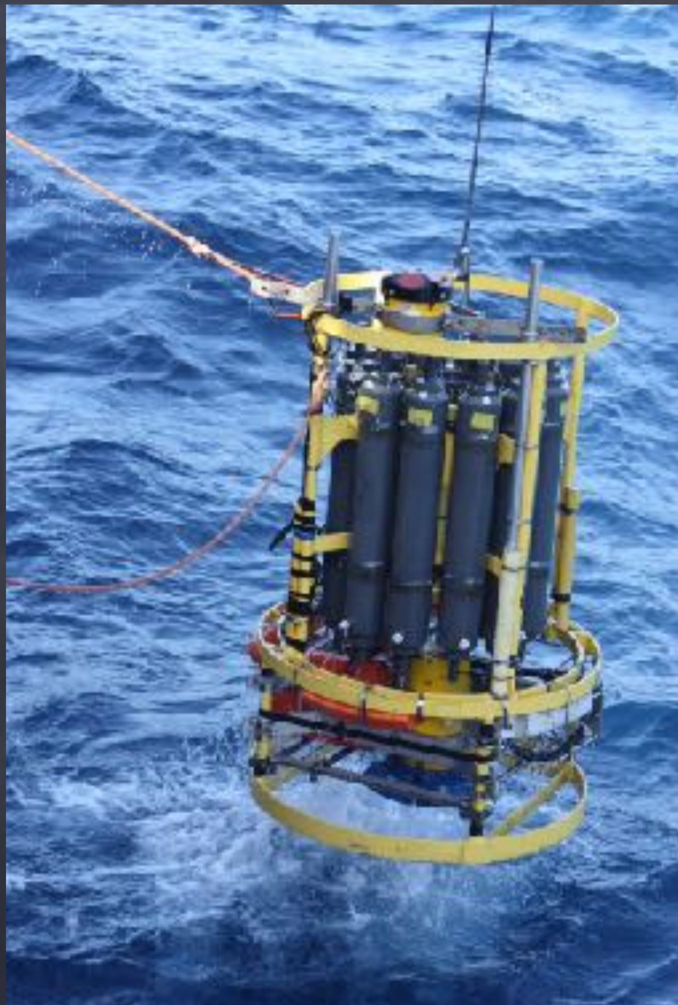
Room MSC 328

# My background and research

- born in United Kingdom
- PhD at National Oceanography Centre, Southampton, UK
- Postdoc at LDEO, Columbia University, NY
- Postdoc at Scripps Institution of Oceanography, UCSD, CA
- Assistant to Full Professor at RSMAS

# My background and research

- Western boundary current structure, variability, and transport
- Circulation of the western Indian Ocean, including Somali Current and Agulhas Current systems
- Ocean observations: velocity, temperature, salinity, sound speed
- Global thermohaline / overturning circulation
- The role of the ocean, in particular the Agulhas System, in climate and climate change

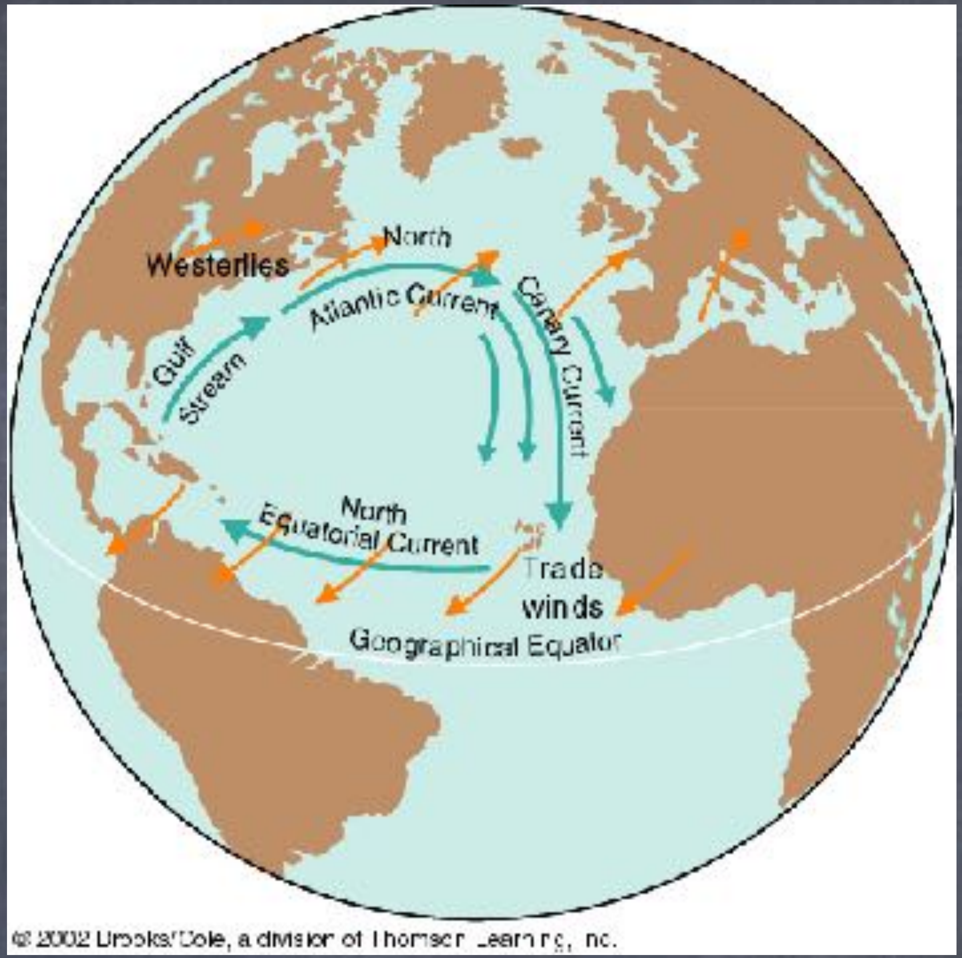




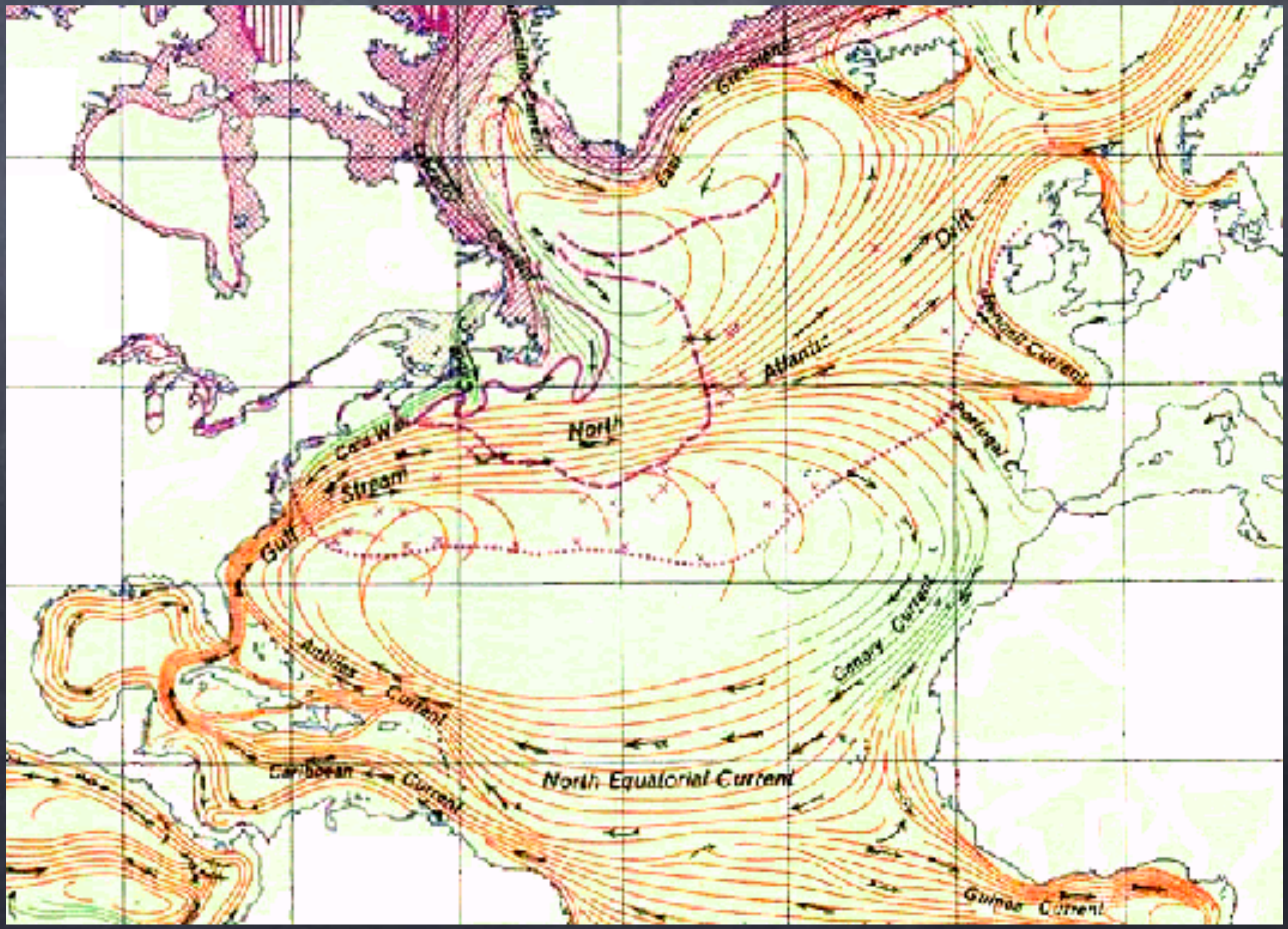

# Some important concepts about the Ocean and Oceanography

- Oceanography is a relatively young science. Pretty much everything that was known about the physical oceans could be written in one book back in 1942 (The Oceans: Sverdrup, Johnson, and Fleming)
- The theory of the wind-driven ocean (Sverdrup, Stommel, Munk) came about in 1950.

The wind stress and the rotation of the planet produce an ocean current to the right of the wind in the northern hemisphere




This creates a gyre with a narrow, fast western boundary current



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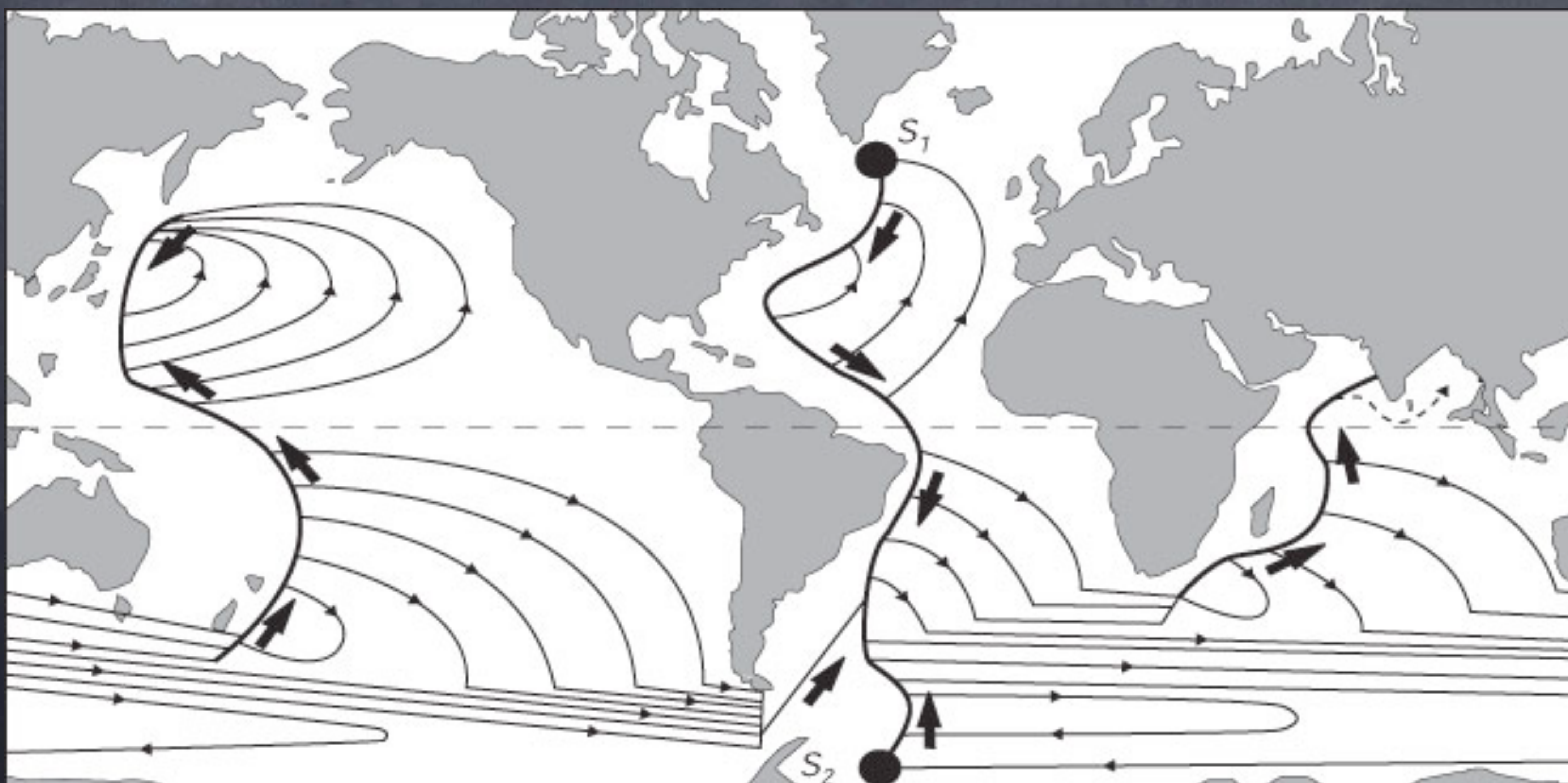
- The theory of the deep circulation (Stommel) came about in 1958 and is still being refined today.

The global abyssal circulation largely results from deep convection and sinking of surface waters in the North Atlantic and in the Weddell Sea (black circles) and upwelling of deep waters through the thermocline (aided by topography) elsewhere in the world's oceans (Stommel 1958).



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- Full-depth profiles of ocean density (giving water mass and flow characteristics) were made possible with the invention of the CTD (Brown, Hamon) in 1955.

# Conductivity-Temperature-Depth (CTD)

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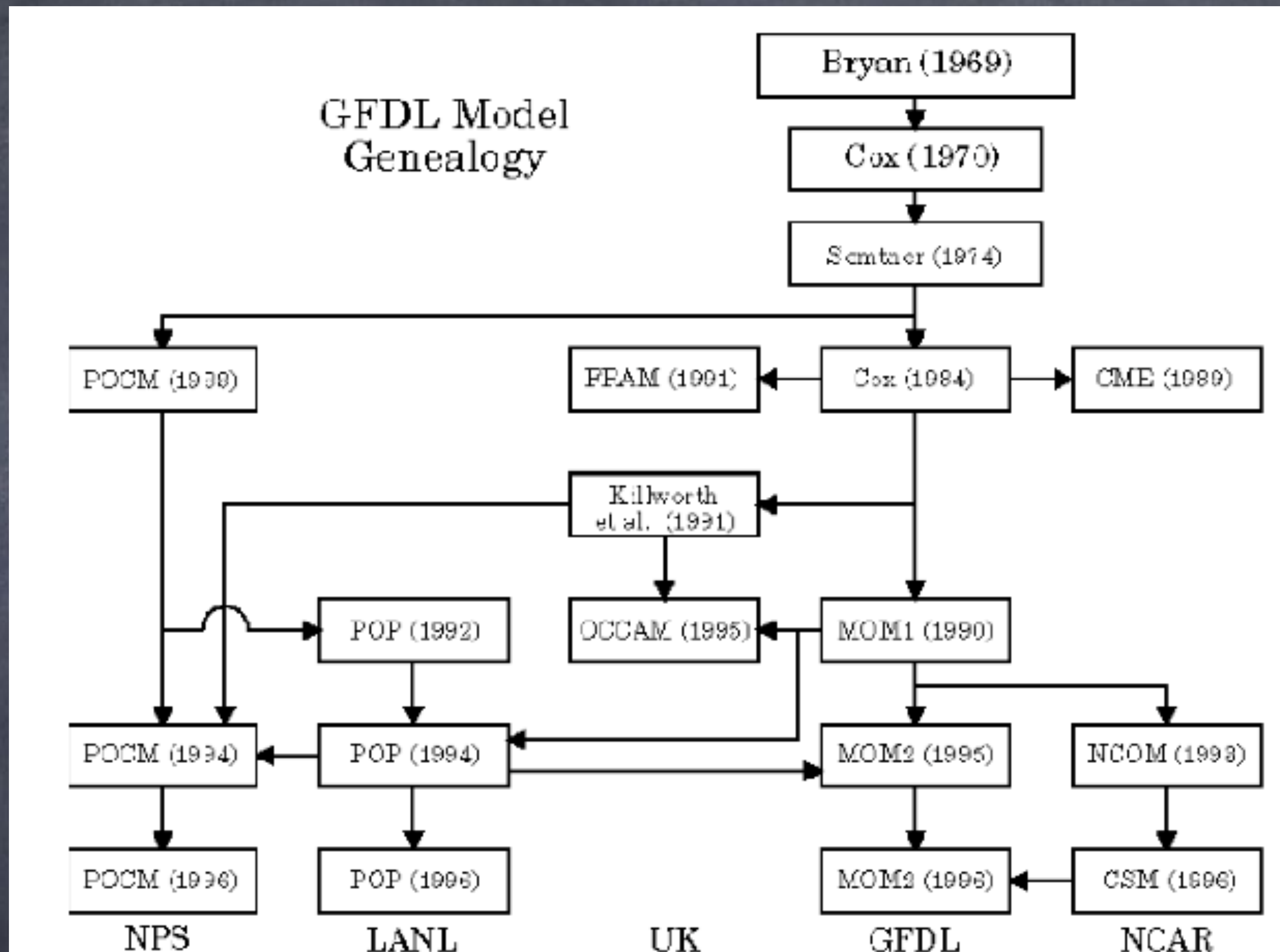
- The first numerical ocean model (Bryan, Cox) was in 1969.

# Many of today's ocean and climate models can be traced back to Bryan and Cox's model




MOM4 (2006) → CESMX.Y.Z

MOM4 (2006) → MOM5 (2012) → MOM6 (development)

MOM4 (2006) → CM2.X (climate model, contributed to IPCC 2007, 2013)

# Some important concepts about the Ocean and Oceanography II

- Measurements with global coverage began when SeaSat was launched in 1978 to monitor SST, waves, sea ice, wind speed and direction. But measurements restricted to the surface.

SEASAT

In 1978, NASA's Jet Propulsion Laboratory built an experimental satellite called SEASAT to test a variety of oceanographic sensors including imaging radar, altimeters, radiometers, and scatterometers.

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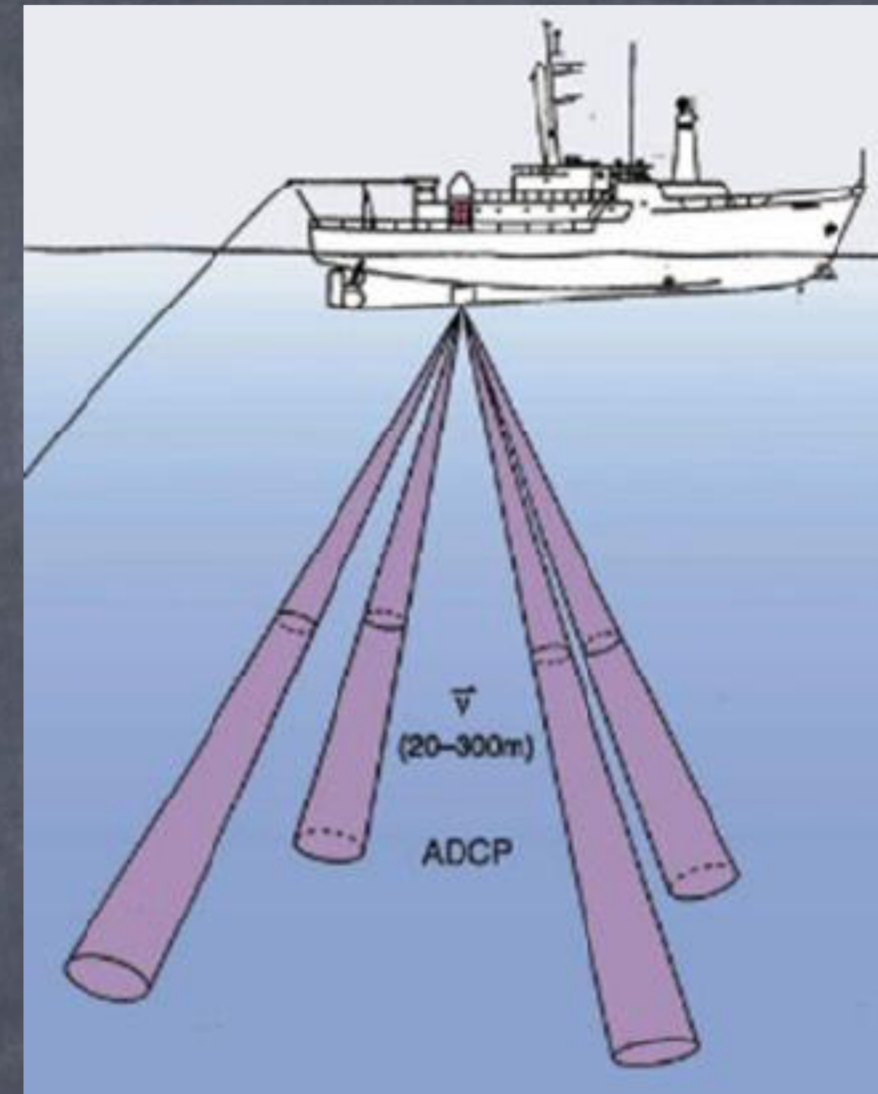
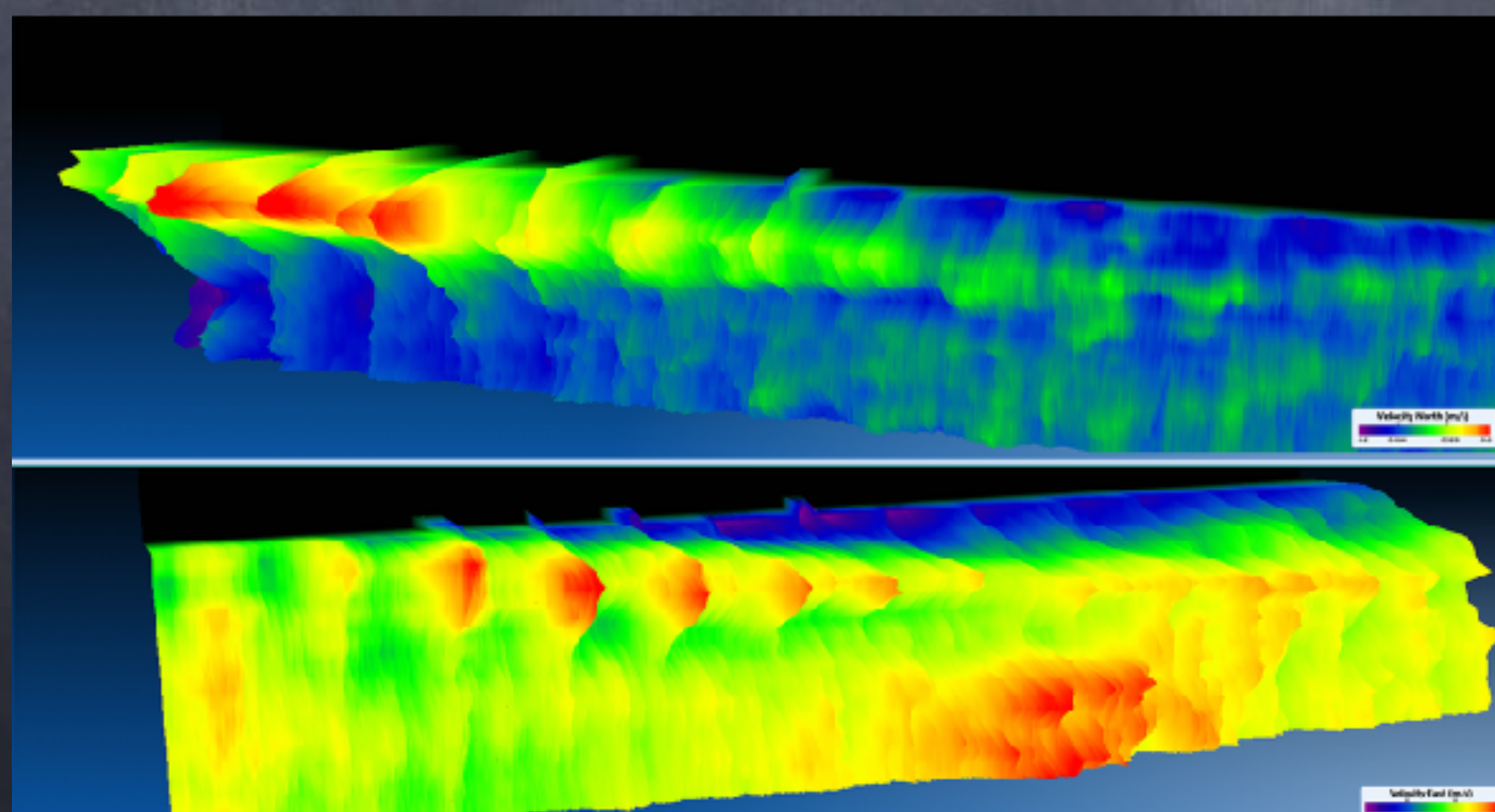
- Direct measurements of ocean velocity from moving ships were made possible in 1980 (Joyce, Pinkel), through the invention of an acoustic current meter. Full depth profiles after 1990.


(20–300m)
ADCP



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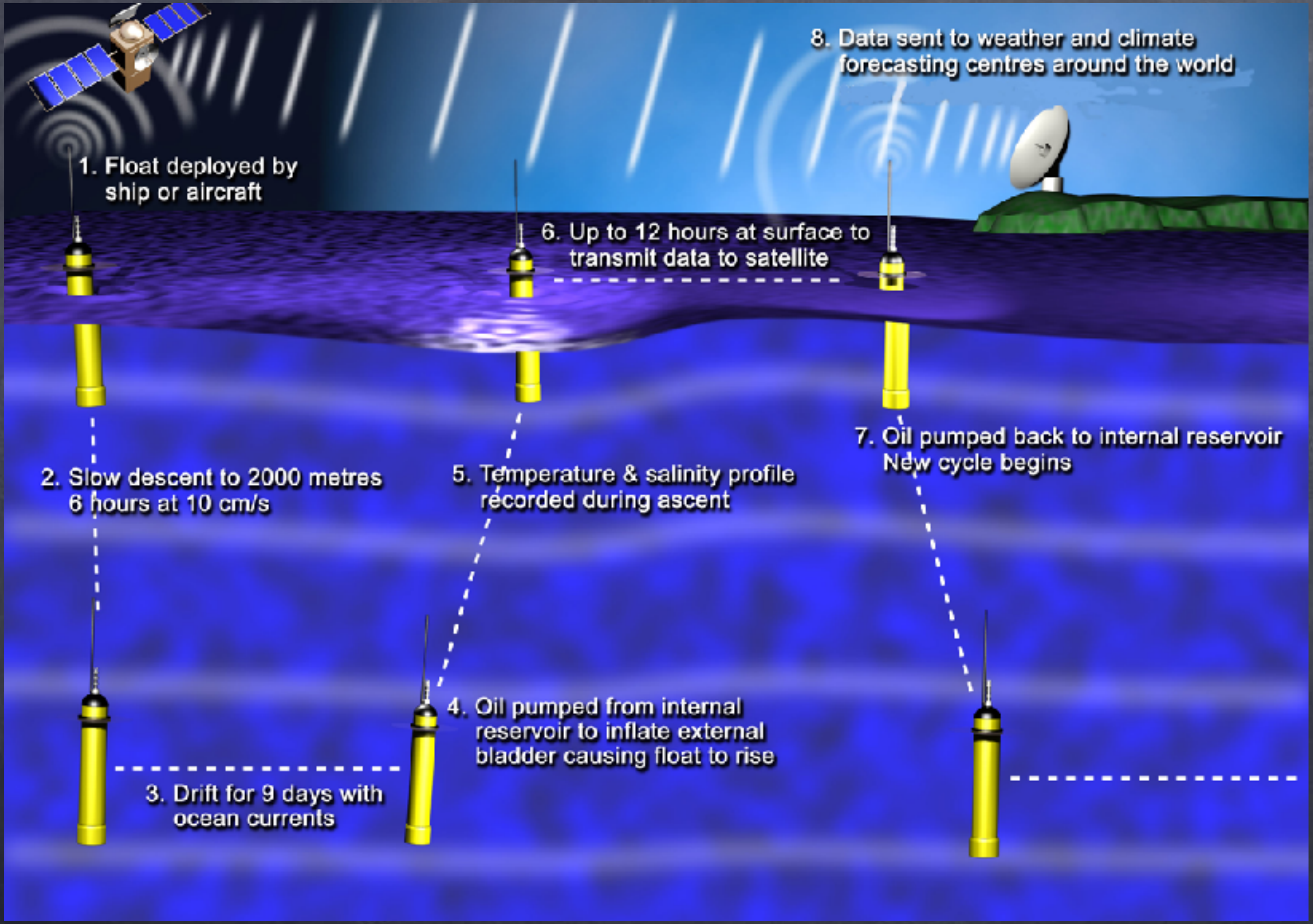
- In 1992 a pop-up float was developed that could be satellite-tracked (ALACE - Davis, Webb), leading to the profiling float.


1. Float deployed by ship or aircraft
2. Slow descent to 2000 metres 6 hours at 10 cm/s
3. Drift for 9 days with ocean currents
4. Oil pumped from internal reservoir to inflate external bladder causing float to rise
5. Temperature & salinity profile recorded during ascent
6. Up to 12 hours at surface to transmit data to satellite
7. Oil pumped back to internal reservoir New cycle begins
8. Data sent to weather and climate forecasting centres around the world

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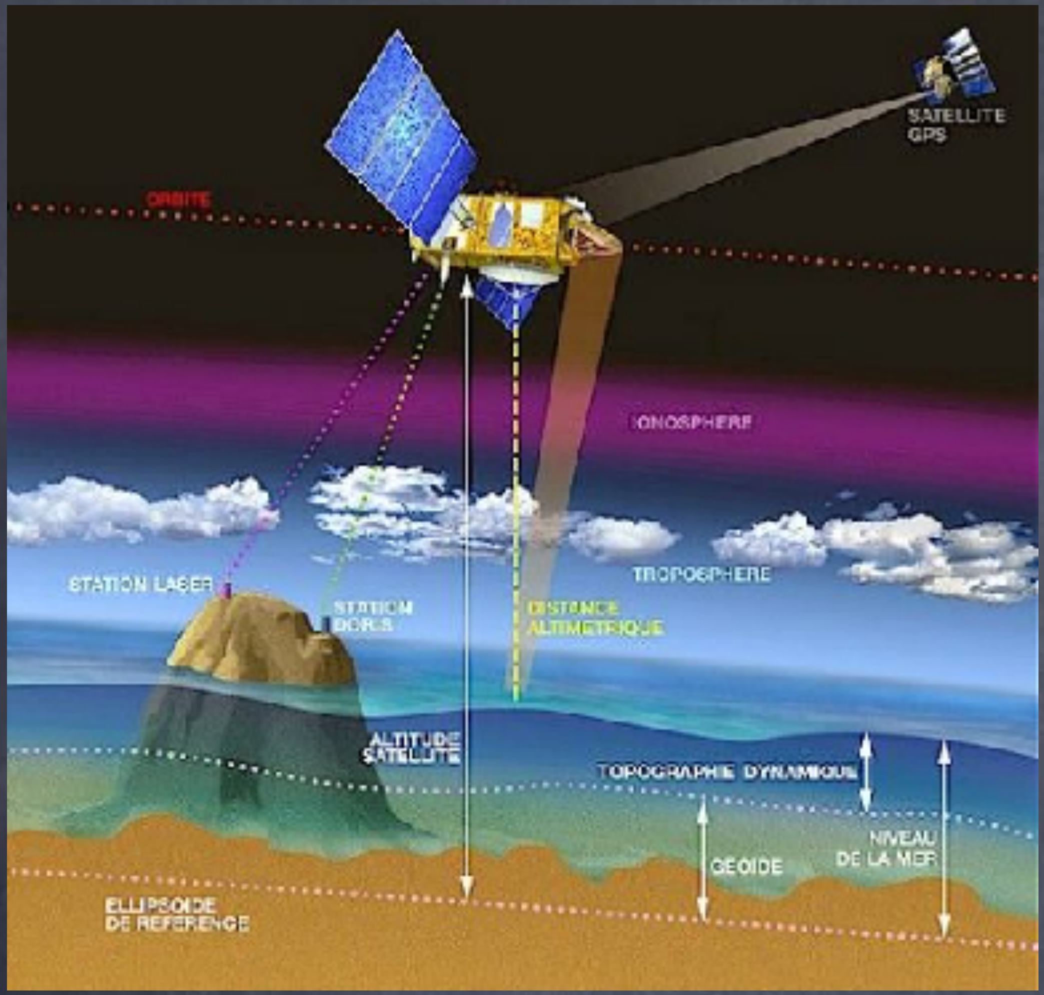
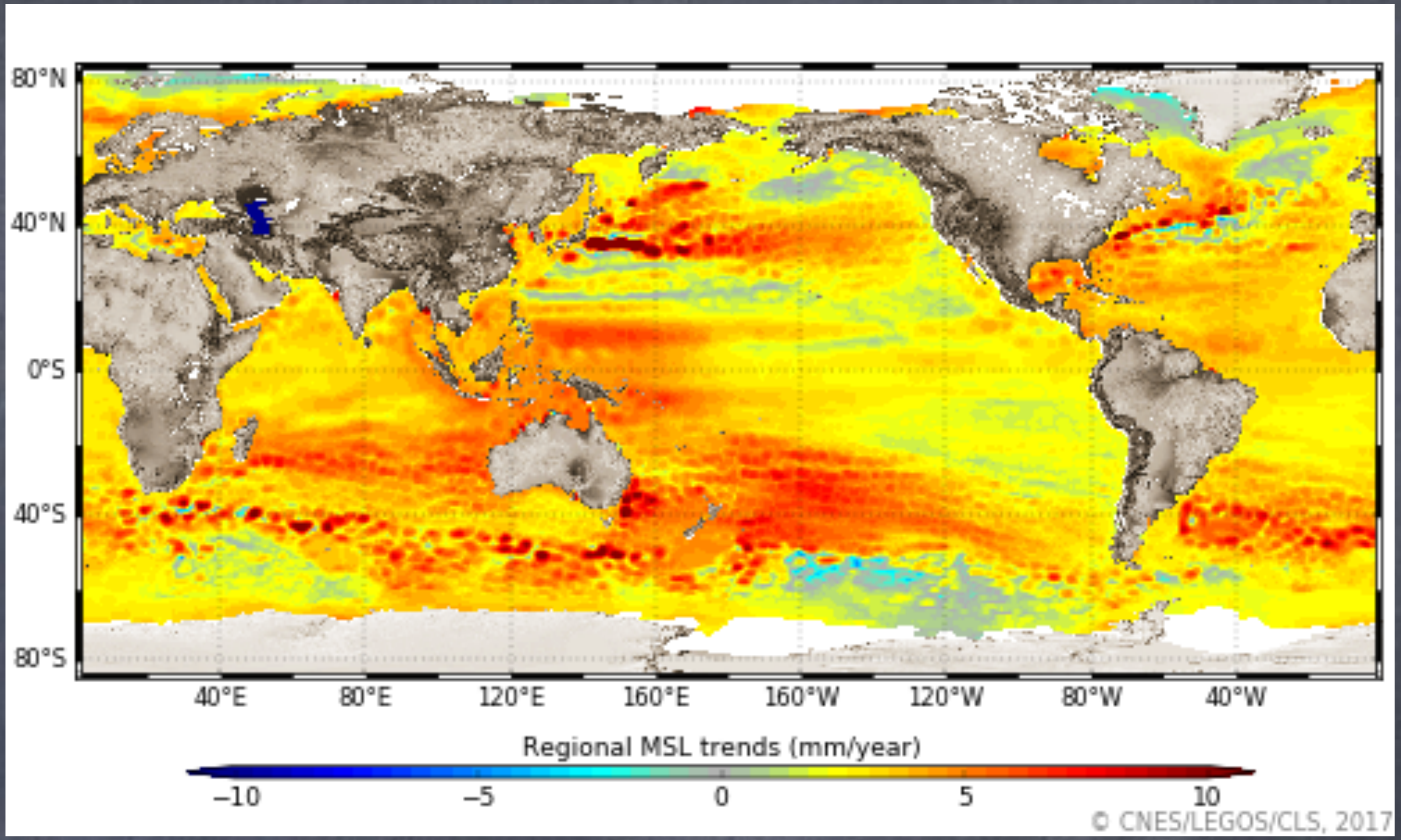
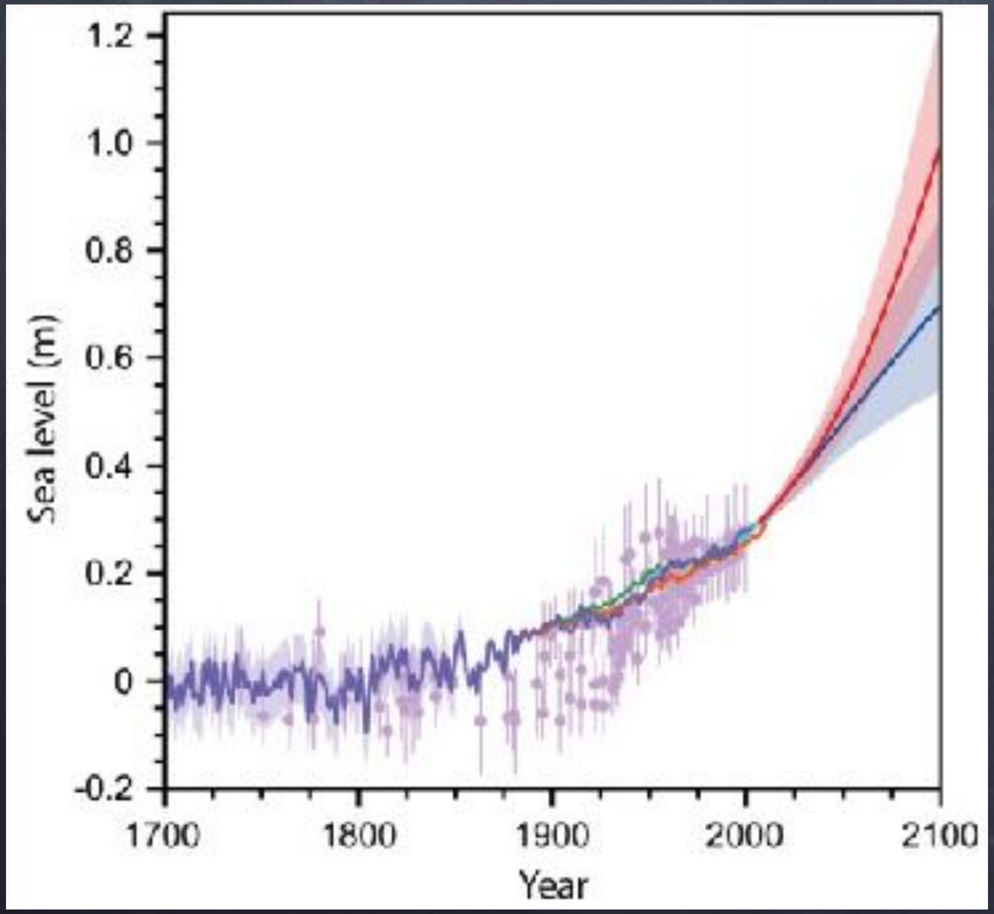
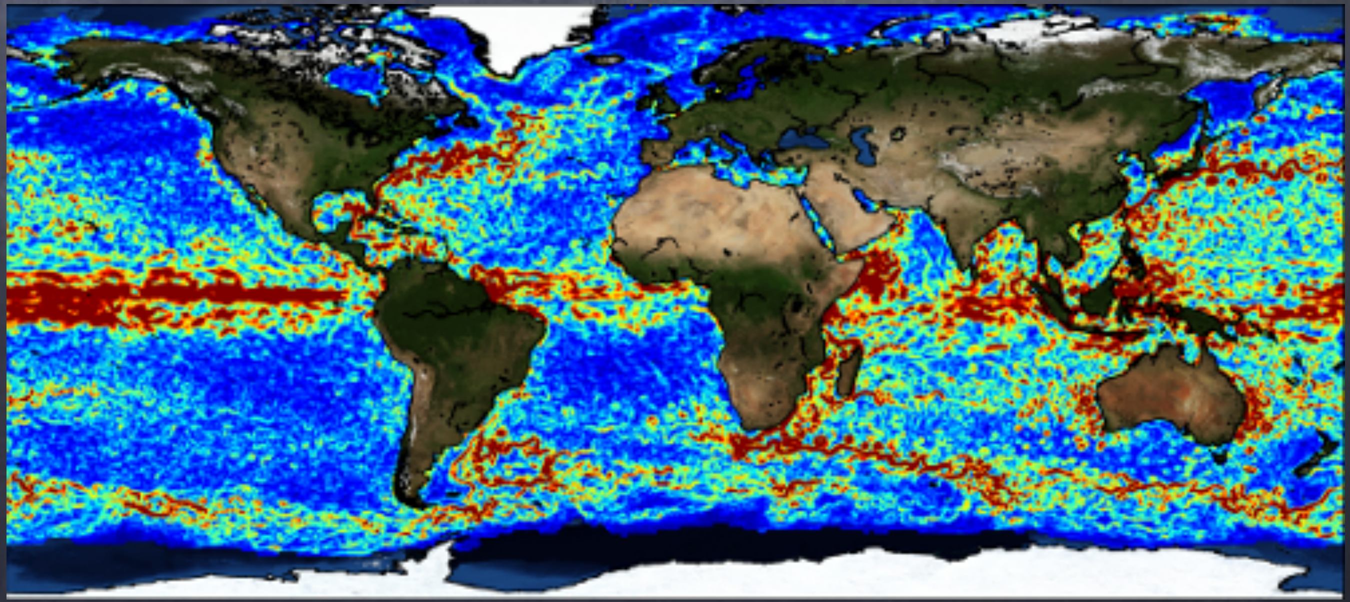
- 1992- launch of TOPEX-Poseidon which can measure sea surface height, **geostrophic currents**, waves, and tides, is still revolutionising our understanding of ocean dynamics and sea level rise.


SATELLITE
GPS
ORBITE
IONOSPHERE
TROPOSPHERE
STATION LASER
STATION
DORIS
DISTANCE
ALTIMETRIQUE
ALTITUDE
SATELLITE
TOPOGRAPHIE DYNAMIQUE
GEOIDE
NIVEAU
DE LA MER
ELLIPSOIDE
DE REFERENCE


80°N
40°N
0°S
40°S
80°S
40°E
80°E
120°E
160°E
160°W
120°W
80°W
40°W
Regional MSL trends (mm/year)
−10
−5
0
5
10
© CNES/LEGOS/CLS, 2017


1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
Sea level (m)
1700
1800
1900
2000
2100
Year



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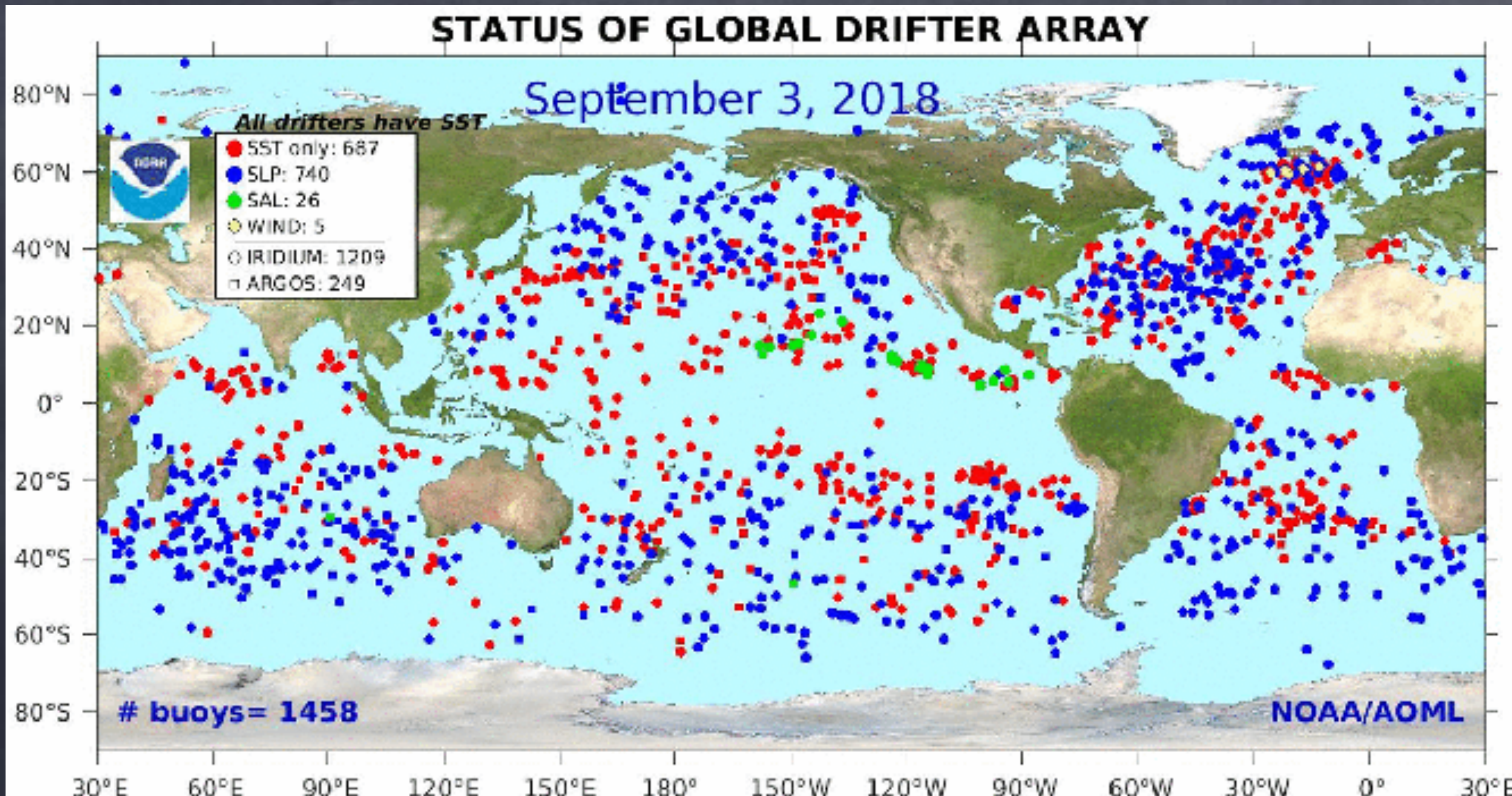
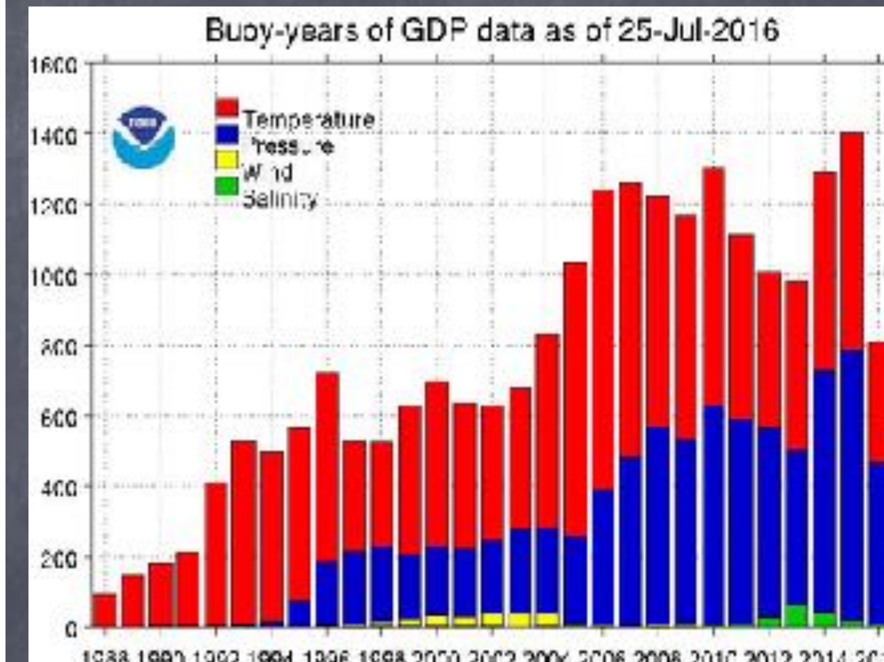
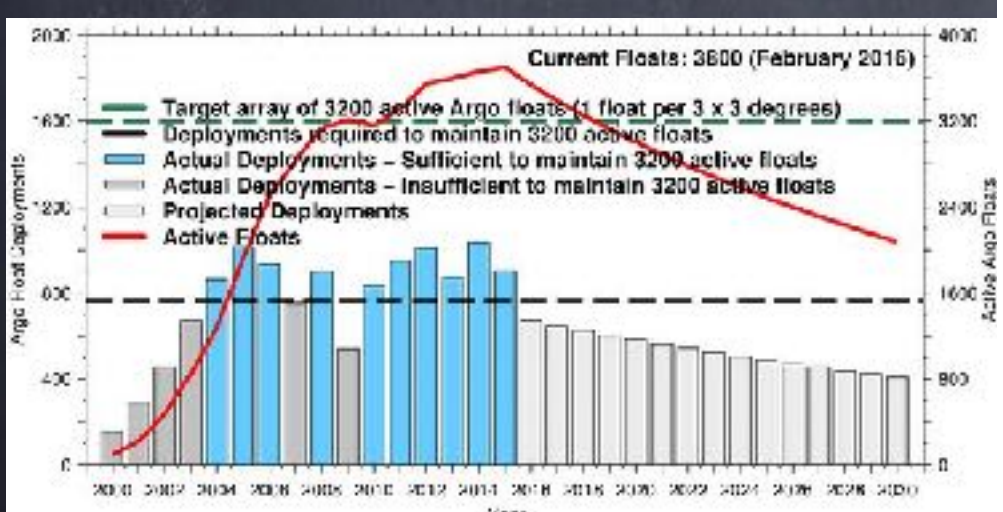
- Global drifter and ARGO arrays reached density circa 2004 (Niiler, Roemmich): A new era of global ocean observation.

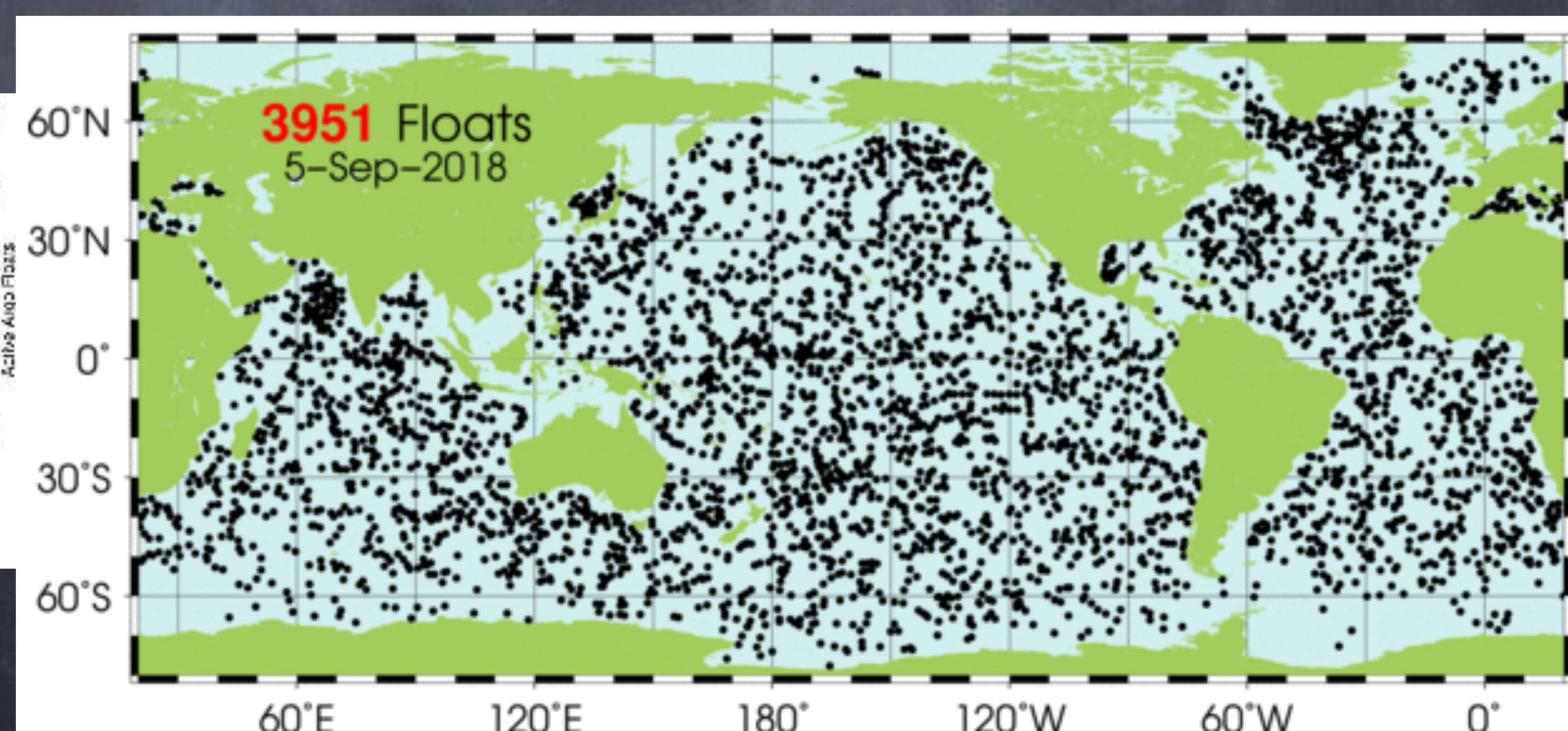
http://www.aoml.noaa.gov/phod/dac/index.php




http://www.argo.ucsd.edu



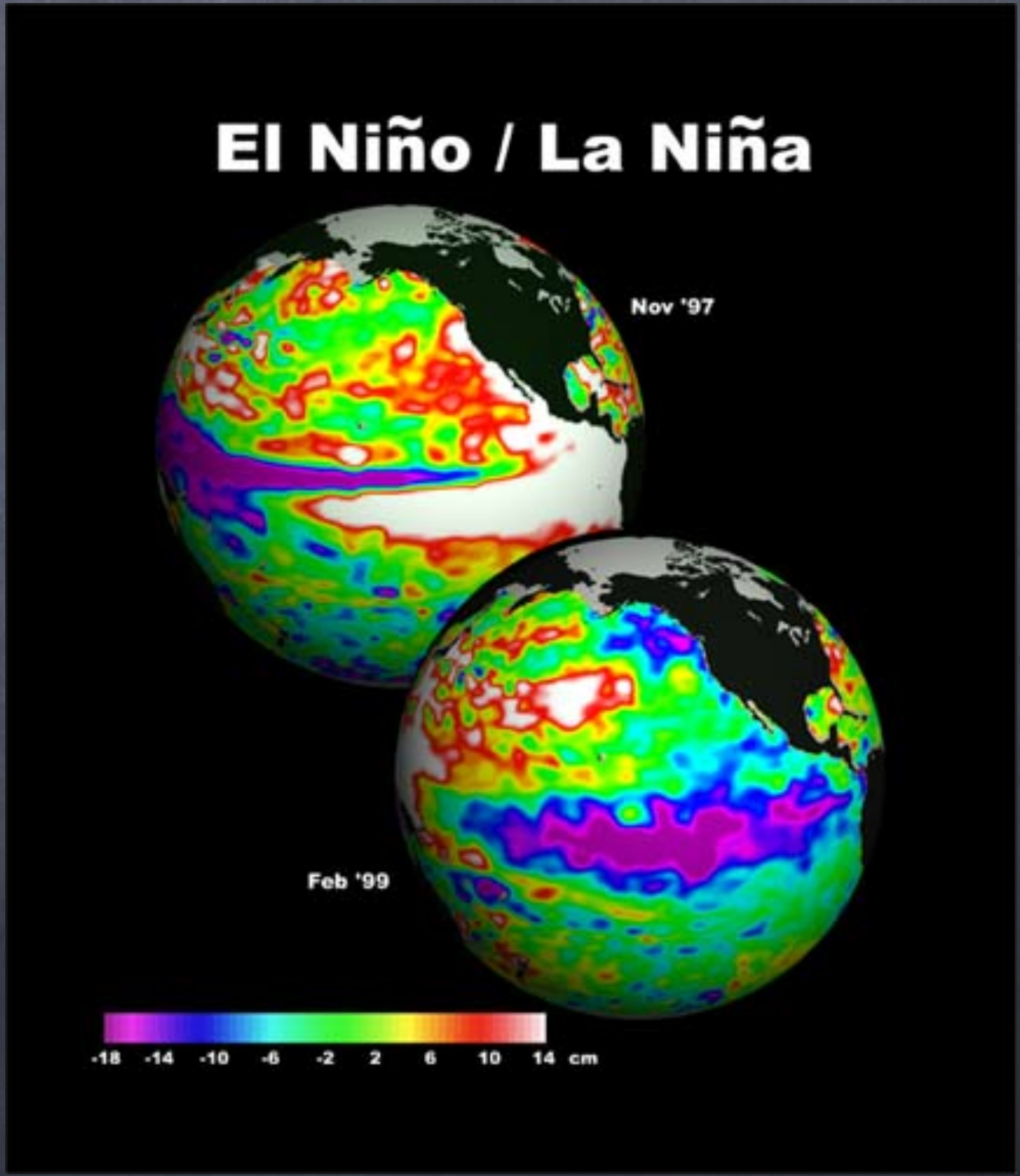
# A few more important concepts about the Ocean and Oceanography

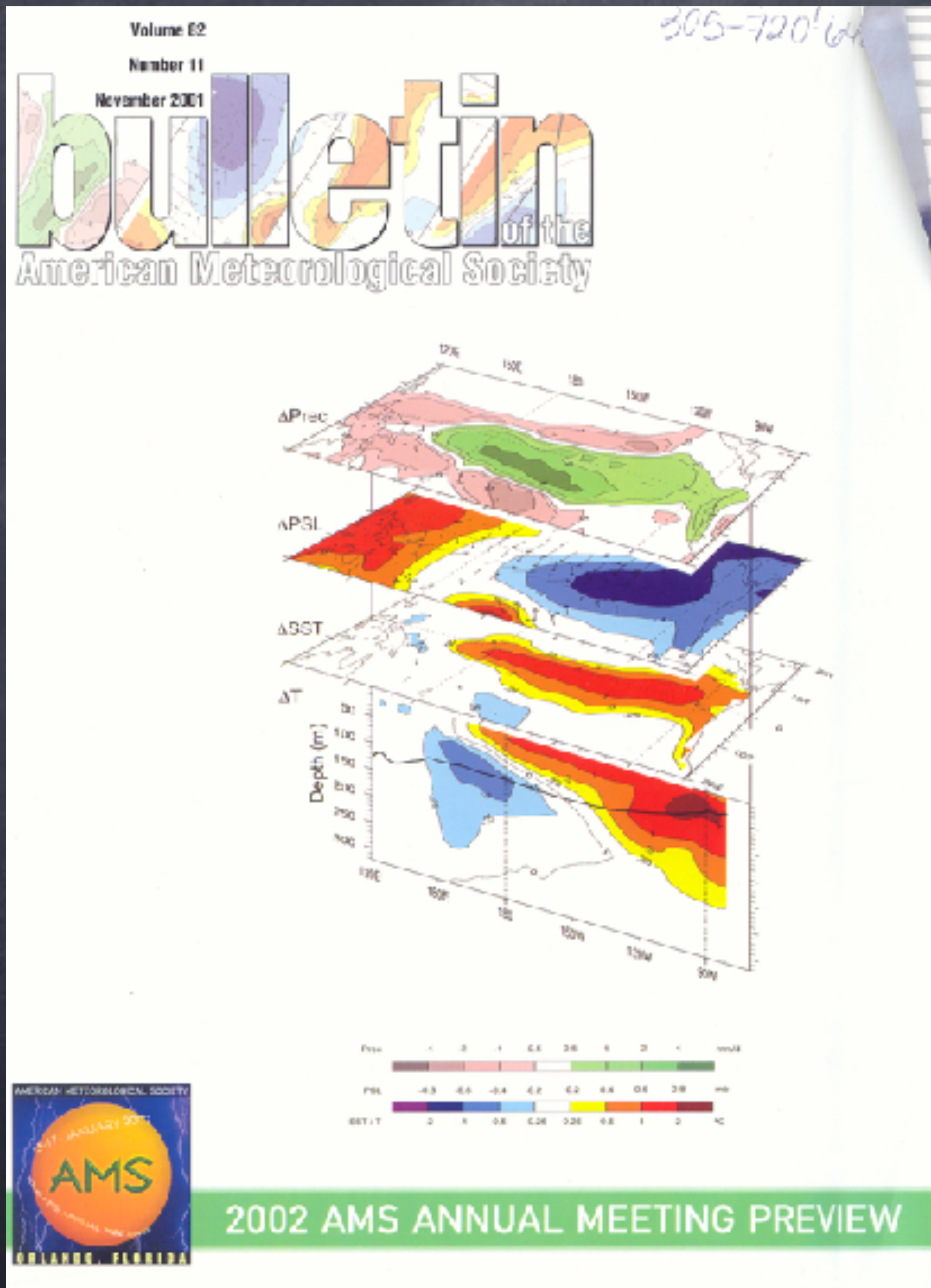
- The ocean is not well known.
- We can now describe the time-average circulation of the ocean fairly well, but have only begun to describe its variability.
- The equations describing a turbulent ocean subject to chaotically variable winds and uneven solar forcing on a rotating planet are complex and unsolvable (without simplifying assumptions). Observations are essential for understanding the ocean.
- Lack of observations and sampling errors are insurmountable in oceanography and can lead to misleading concepts.
- Oceanographers are relying more and more on large data sets from satellites, floats, and moorings and less and less on observations collected from ships.

The ocean is an integral part of the climate system

# Many climate modes are driven by coupled Ocean-atmosphere feedbacks

1. El Nino-Southern Oscillation (ENSO)
2. North Atlantic Oscillation (NAO)
3. Pacific Decadal Oscillation (PDO)
4. Indian Ocean Dipole (IOD)
5. SubAnnular Mode (SAM)




Volume 82
Number 11
November 2001
bulletin of the American Meteorological Society
ΔPrec
ΔPSL
ΔSST
ΔT
Depth (m)
AMS
2002 AMS ANNUAL MEETING PREVIEW


'El Meaño' responsible for disasters, benefits in world's weather
El Nino rules world grain markets
El Nino has 'absolutely crazy' effect on business
Cold Winter On the Way? Some Bet On It
COMMODITIES
El Nino gets the blame for weirdness
Energy prices plunging
Consumers, economy benefit as oil supply surpasses demand
Crops may survive El Nino
Meteorologist sees weather woes ahead
El Nino KOs artichokes
Volume 80
Number 9
September 1999
bulletin of the American Meteorological Society
El Nino gave blizzard much of its strength
Mild weather helps to build job growth
2 die as storms pummel coasts
El Nino a wild card for vacation plans
Clinton visits twister-torn Florida; 3 still missing
LET'S BLAME IT ON EL NINO!
El Nino-charged rain pounds California
El Nino is coming! It'll drown California! It'll ruin the Olympics! It'll kill seals! It's already making everybody weird!
And Exactly What Isn't El Nino's Fault?

# Atlantic Multi-decadal Oscillation (AMO)

Driven by variability of the Atlantic Meridional Overturning Circulation? Linked to sea ice?



## Atlantic Climate Pacemaker for Millennia Past, Decades Hence?

An unsteady ocean conveyor delivering heat to the far North Atlantic has been abetting everything from rising temperatures to surging hurricanes, but look for a turnaround soon

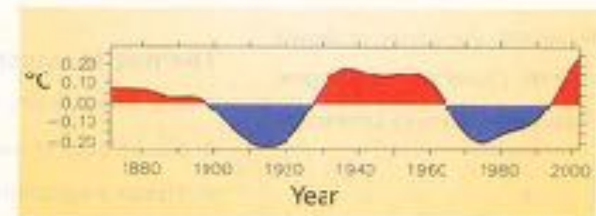
Benjamin Franklin knew about the warm Gulf Stream that flows north and east off the North American coast, ferrying more than a petawatt of heating power to the chilly far North Atlantic. But he could have had little inkling of the role that this ponderous ocean circulation has had in the climatic vicissitudes of the greater Atlantic region and even the globe.

With a longer view of climate history and long-running climate models, today's researchers are tying decades long oscillations in the Gulf Stream and the rest of the ocean conveyor to long-recognized fluctuations in Atlantic sea-surface temperatures. These fluctuations, in turn, seem to have helped drive the recent revival of Atlantic hurricanes, the drying of the Sahel in the 1970s and '80s, and the global warming of the past few decades, among other climate trends.

The ocean conveyor "is an important source of climate variability," says meteorologist James Hurrell of the National Center for Atmospheric Research in Boulder, Colorado. "There's increasing evidence of the important role oceans have played in climate change." And there are growing signs that the conveyor may well begin to slow on its own within a decade or two, temporarily cooling the Atlantic and possibly reversing many recent climate effects. Greenhouse warming will prevail globally in both the short and long terms, but sorting out just what the coming decades of climate change will be like in your neighborhood could be a daunting challenge.

Researchers agree that the North Atlantic climate machine has been revving up and down lately (*Science*, 16 June 2000, p. 1984). From recorded temperatures and climate proxies such as tree rings, researchers could see that temperatures around the North Atlantic had risen and fallen in a roughly 60- to 80-year cycle over the past few centuries. This climate variability was dubbed the Atlantic Multidecadal Oscillation (AMO). Ocean observations suggested that a weakening of the ocean conveyor could have cooled the Atlantic region and even the entire Northern Hemisphere in the 1950s and '60s, and a subsequent strengthening could have helped warm it in the 1980s and '90s. But the records were too short to prove that the AMO is a permanent fixture of the climate system or that variations in the conveyor drive the AMO.

Taking the long view, climate modeler Jeff Knight of the Hadley Centre for Climate Prediction and Research in Exeter, U.K., and colleagues analyzed a 1400-year-long simulation on the Hadley Centre's HadCM3 model, one of the world's leading climate models. The simulations included no changes in climate drivers such as greenhouse gases that could force climate change. Any changes that appeared had to represent natural variations of the model's climate system.



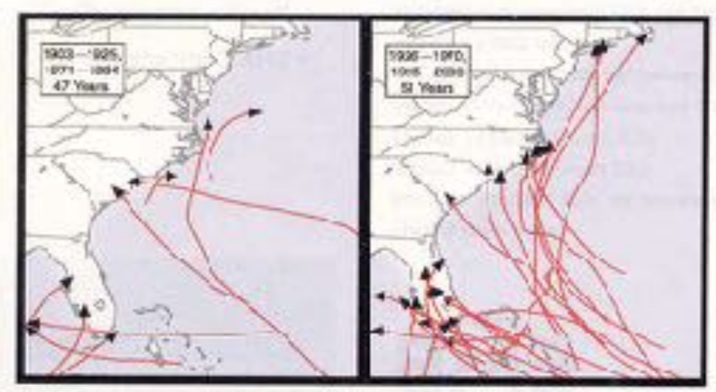

**Wobbly ocean.** North Atlantic temperatures have wavered up and down at a roughly 60- to 80-year pace.

At April's meeting of the European Geosciences Union in Vienna, Austria, Knight and colleagues reported that the Hadley Centre model produces a rather realistic AMO with a period of 70 to 120 years. And the model AMO persists throughout the 1400-year run, they note, suggesting that the real-world AMO goes back much further than the past century of observations does. The model AMO also tends to be in step with oscillations in the strength of the model's conveyor flow, implying that real-world conveyor variability does indeed drive the AMO.

Such strong similarities between a model and reality "suggest to me it's quite likely" that the actual Atlantic Ocean works much the same way as the model's does, says climate modeler Peter Stott of the Hadley Centre unit in Reading, who did not participate in the analysis. Hadley model simulations also support the AMO's involvement in prominent regional climate events such as recurrent drought in North East Brazil and in the Sahel region of northern Africa, as well as variations in the formation of tropical Atlantic hurricanes, including the resurgence of such hurricanes in the 1990s.

On page 115, climate modelers Rowan Sutton and Daniel Hodson of the University of Reading, U.K., report that they could simulate the way relatively warm, dry summers in the central United States in the 1930s through the 1960s became cooler and wetter in the 1960s through 1980s. All that was needed was to insert the AMO pattern of sea-surface temperature into the Hadley atmospheric model. That implies that the AMO contributed to the multidecadal seesawing of summertime climate in the region.

If the Hadley model's AMO works as well as it seems to, Knight and his colleagues argue, it should serve as some guide to the future. For example, if North Atlantic temperatures track the conveyor's flow as well in the real world as they do in the model, then the conveyor has been accelerating during the past 35 years—not beginning to slow, as some signs had hinted (*Science*, 16 April 2004, p. 371). That acceleration could account for about 10% to 25% of the global warming seen since the mid-1970s, they calculate, meaning that rising greenhouse gases haven't been warming the world quite as fast as was thought.



**Bad warmth.** The AMO's warm years favor more U.S. hurricanes (*right*).

Judging by the 1400-year simulation's AMO, Knight and colleagues predict that the conveyor will begin to slow within a decade or so. Subsequent slowing would offset—although only temporarily—a "fairly small fraction" of the greenhouse warming expected in the Northern Hemisphere in the next 30 years. Likewise, Sutton and Hodson predict more drought-prone summers in the central United States in the next few decades.

But don't bet on any of this just yet. The AMO "is not as regular as clockwork," says Knight; it's quasi-periodic, not strictly periodic. And no one knows what effect the

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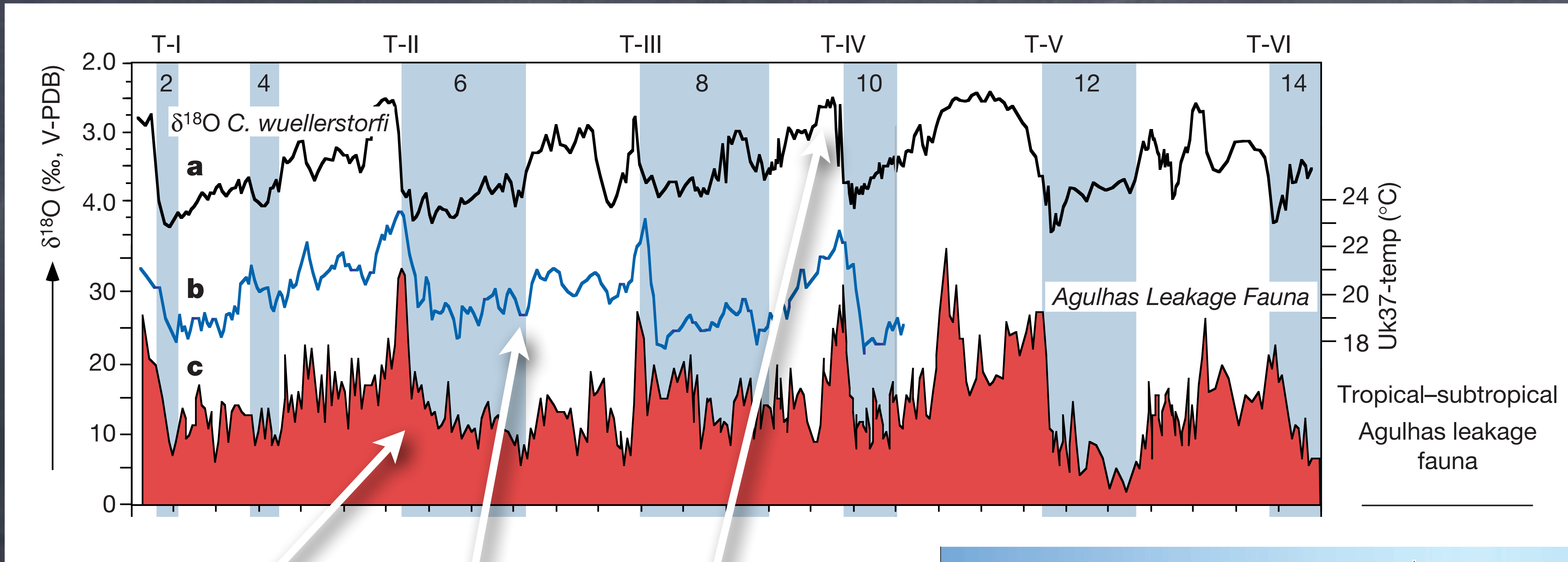
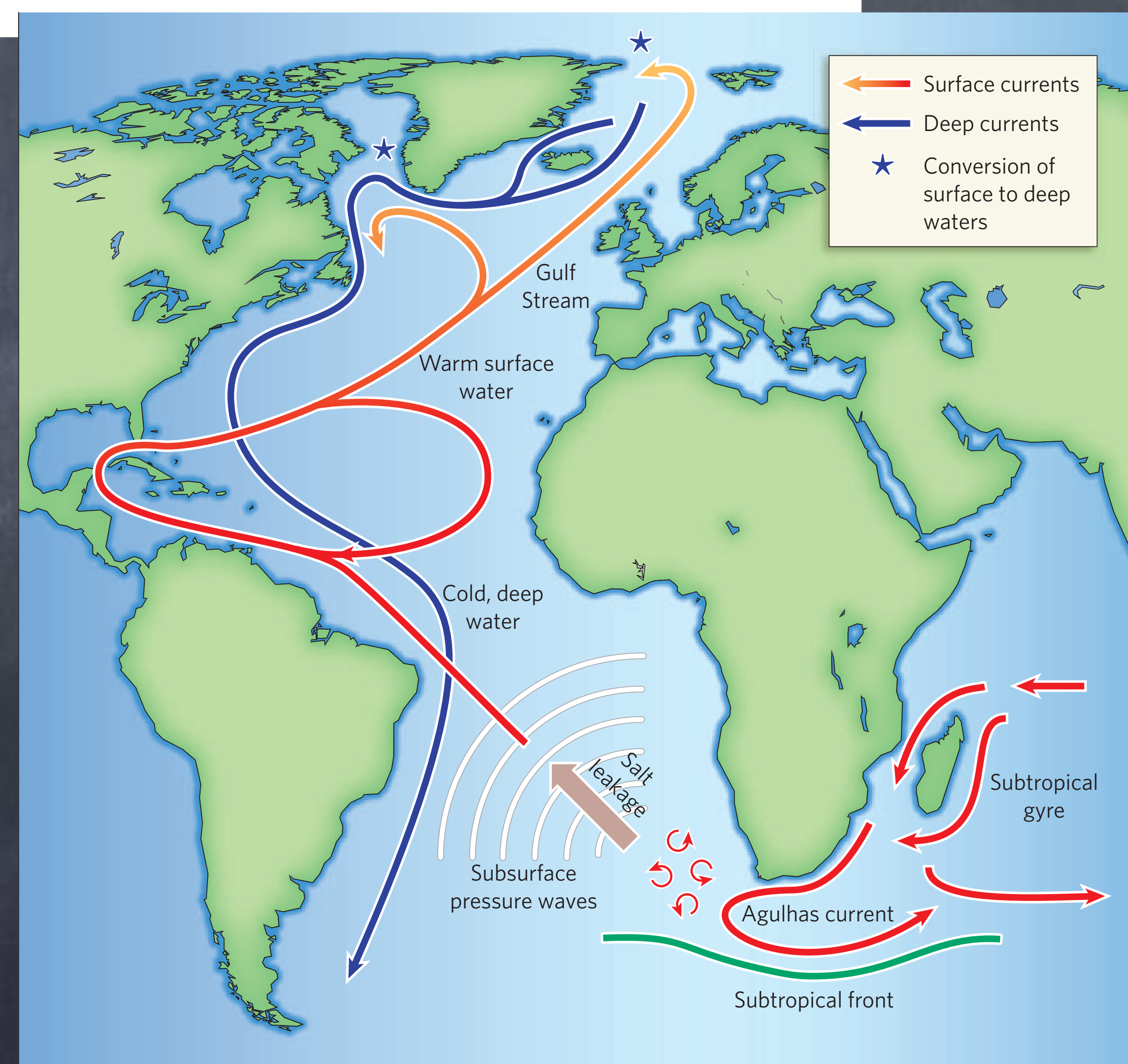



Agulhas "leakage"

ice volume

sea surface temperature




Agulhas Current/leakage implicated in rapid glacial terminations

The ocean helps to regulate global warming, through uptake of anthropogenic heat and $CO_2$

- but will it continue to do so?