OCEAN CIRCULATION AND ITS ROLE IN GLOBAL CLIMATE

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Summary Heat- and water transports by the atmosphere- and ocean circulations are principal elements of global climate. Natural variability and human-induced emissions combine to create active patterns of climate change which are not reflected in overall averages like global mean-surface temperature. Some of these patterns are well-known, like el Nino/Southern Oscillation cycles and the North Atlantic Oscillation; others are less familiar and may be abrupt: the 30-year decline in salinity of the northern Atlantic, invasion of the Arctic by warm Atlantic waters, and the rise and subsequent decade-long decline in the subpolar North Atlantic circulation, and the pattern of global heat content and upper ocean salinity increase in the subtropics.

Dynamical elements of Rossby-wave theory, jet dynamics, stratified spin-up, and rotating convection seem to be important. We also describe a new invention, the Seaglider, with which we are patrolling the cold northern oceans to examine the structure of abruptly changing climate.

DYNAMICAL STRUCTURE

Natural fluid dynamics of Earth's oceans, atmosphere and the atmospheres of planets involves classical Navier-Stokes dynamics as a subset of the larger problems in which layered density stratification and planetary rotation are important. Thus one has classic surface gravity waves, buoyant convection, three-dimensional turbulence and the problem of 'stirring and mixing' embedded in motions of larger scale and very different force balances. An organizing principle for this field is energy: the ultimate source in the sun's radiation, its absorption and re-radiation as long-wave infrared radiation, and the two-fluid problem of thermal convection, complicated by phase-change of water and augmented by buoyancy production from dissolved salts in the oceans. The expansion/contraction work cycle takes place in meridional overturning circulations which then drive the principle horizontal winds and currents of the general circulation.

What makes this story so interesting is the ten decades of length-scale spanning the interesting fluid dynamics: from O(1mm) to 10^5 km which could in principal at least ten schools of geophysical fluid dynamics, each attending to a different aspect of flow and waves. The problem is made more tractable by the trapping of energy at fairly large scale by the effect of Earth's rotation. Coriolis effects combined with the strong layering of the stratified fluid prevent massive disintegration of the flows we see on weather maps and ocean charts: paraphrasing Geoffrey Taylor, who first recognized this trapping effect, 'large-scale rotating fluid motions are non-turbulent' in the sense that the bulk of the kinetic- and potential energy is prevented from cascading to fine scales where explicit frictional dissipation can occur. The stiffness imparted to a fluid by rotating it is a surprising effect, and it appears in surprising places (another example being the liquid core of the Earth, where Taylor columns are almost certainly present, sitting adjacent to the solid core, and strongly involved in generating the magnetic field: evidence being that the radial magnetic field has two maxima in northern Canada and Asia rather than at the expected site for a dipole, the rotational pole).

Current research problems in ocean-atmosphere dynamics emphasize particularly the stationary and transient features of the circulation: classically this would be the 'time-mean circulation' and the 'energy-containing eddies or waves' yet we now recognize the vital activity in time-scales ranging beyond seasons, from decades to centuries. Both natural and human-induced variability of climate occurs at these scales. Dynamicists like to believe that potential-vorticity dynamics plays a role in all of these regimes, although augmenting these with study of energy, thermodynamics and radiation of the ocean-atmosphere, is also necessary.

In this lecture the emphasis will be on the observed structure of one or two strong features of the ocean-atmosphere problem, in particular an aspect of the stationary-wave circulation of the atmosphere known as 'storm tracks', their variability known as the 'North Atlantic Oscillation', and the dynamics of the subpolar circulation of the ocean. The first question we address is the oceanic contribution to climate. In the basic heat- and fresh-water transport of the climate system, the strength of sunshine in the tropics and its weakness near the poles requires a poleward heat transport. This has three principal components: atmospheric thermal-energy transport by winds (known as 'sensible heat-transport'), oceanic thermal-energy transport, and a combined ocean-atmosphere mode, transporting freshwater and hence latent thermal energy. The three have comparable amplitudes and their sum peaks at about 5 x 10^{15} watts; 5 petawatts. While it is a source of continuing controversy, the most recent observations, properly interpreted, show that the oceanic fraction is indeed substantial, particularly in the Atlantic and contributes to the warming of northern Europe.

One of the expected consequences of global warming is a strengthening of the global water cycle: the evaporation from the oceans, precipitation, freezing, thawing and spatial transport that gives color to the Earth, as seen from outer space. There are now several independent observations suggesting that this is happening. One of these is the decline in oceanic salinity, from top to bottom, in the northern Atlantic Ocean over the past 30 years. The difficult problem facing us is that there are many possible reasons for this decrease in salinity. The 'modes' of variability of the climate system, mentioned above, have been strongly energized during the late 20th Century, and these alone can cause decadal climate shifts, with or without human intervention and the greenhouse effect. We will show 'portraits' of the North Atlantic Oscillation and discuss its dynamical roots.

Fluid dynamics contributes by providing simple idealized models of this variability. Rossby wave dynamics sets the stage, in the presence of global mountain barriers and ocean-land thermal contrast. We will describe the variety of Rossby waves and wake instabilities generated in the westerly winds, and how the storm tracks connecting sub-tropics and Arctic depend on this structure. The 'potential vorticity elasticity' that enables Rossby-wave dynamics works only at large horizontal scales; small-scale yet still geostrophic turbulence readily shreds the potential vorticity field leading to non-classical wavenumber dependence of turbulent mixing. Though dynamical modelling provides an essential tool for progress (complementing the all-encompassing simulations of global numerical models), the major climate shifts of the past few years are not yet resolved.

A good example of the mixture of causes at work is the circulation of the subpolar Atlantic Ocean, which is driven by both wind-stress and cooling in the harsh wintertime. Using the remarkable altimetry measurements from satellites we have found that this cyclonic gyre, which fills the ocean from Labrador to Ireland and Scandavia, has declined in strength steadily over the years since observations began (1992 for the TOPEX/Poseidon satellite). Yet this circulation had accelerated to a high intensity in 1992-1993 by a century-long maximum in driving by the cold, Arctic winds flowing from Canada, so that it may now be returning to 'normal'. Dynamical ideas point to convective forcing as being responsible for this decadal change in circulation, rather than wind-stress. Indeed, the 'beta-plume' solutions of Rossby-wave dynamics are circulations controlled by the basic potential vorticity field (in turn determined by sea-floor topography and Earth's rotation). These show that the short-time response to shifting winds is orthogonal to the basic circulation gyres and hence wintertime cooling rather than wind-stress is likely the driving effect.

A very few key measurements have had great impact on climate studies: examples are Charles Keeling's carbon dioxide measurements at Mauna Loa, Hawaii, and a handful of decades-long weather-ship observations of both ocean and atmosphere. Observations of three-dimensional circulations must be sustained in time long enough to observe the 10- to 100-year timescales. Modern oceanography is maturing, thanks both to basic studies in geophysical fluid dynamics and remarkable new observational methods, which now give us the hope of sustained, yet detailed observation: examples are orbiting satellites measuring sea-surface height variability, surface circulation, surface temperature and ice cover globally and *in situ* observations of chemical tracers and dynamically active temperature, salinity and velocity by autonomous undersea vehicles.

We launched two such vehicles, known as Seagliders, offshore of west Greenland in October 2003. These gliding vehicles move at about 20 km per day across the oceans, diving to 1000m while profiling the ocean with horizontal resolution of about 3 km. At the time of this writing each Seaglider has produced more than 1500 km long sections, while 'phoning home' three times per day (at which time the data is transmitted and course changes can be made). The vehicles, developed by Charles Eriksen at University of Washington, promise to give oceanography the kind of three-dimensional data matched to the oceans' complexity.

The accelerating pace of global change is affecting more 'variables' than temperature, winds and rainfall. In danger of being caught off balance, the science community needs to respond with observational strategies that can overcome the difficulty of the 'baseline': the mean state of past climate means less and less as we climb the exponentials of change, and the implicit linearization of our models and thinking about past baselines daily becomes less and less valid.

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