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PERSPECTIVES: OCEANOGRAPHY

What Is the Thermohaline Circulation?

Carl Wunsch

The discussion of today's climate and its past and potential future changes is often framed in the context of the ocean's thermohaline circulation. Widespread consequences are ascribed to its shutdown and acceleration—a deus ex machina for climate change.

But what is meant by this term? In interdisciplinary fields such as climate change, terminological clarity is of the essence; otherwise, what everyone thinks they understand may in fact be a muddle of mutual misunderstanding. Only if one can define the circulation, can its controlling factors be sensibly discussed.

A reading of the literature on climate and the ocean suggests at least seven different, and inconsistent, definitions of the term "thermohaline circulation":

1) the circulation of mass, heat, and salt;

2) the abyssal circulation;

3) the meridional overturning circulation of mass;

4) the global conveyor, that is, the diffusely defined gross property movements in the ocean that together carry heat and moisture from low to high latitudes;

5) the circulation driven by surface buoyancy forcing;

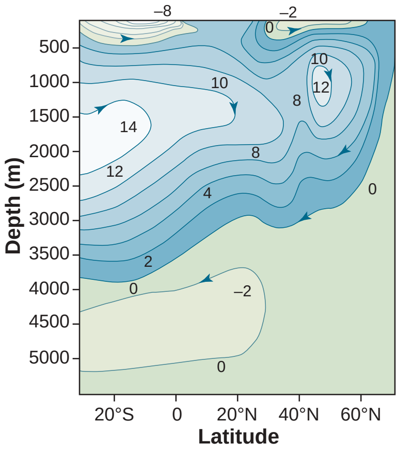
6) the circulation driven by density and/or pressure differences in the deep ocean; and

7) the net export, by the North Atlantic, of a chemical substance such as the element protactinium.

These different usages present important conceptual issues. For example, the deep ocean is in a near-equilibrium state, and it is not possible, without an intricate calculation, to determine if the density/pressure differences drive the flow field, or the reverse. Some authors claim to be able to separate the fraction of the flow derived from density field gradients from that caused by the wind field (definition 6). But the density gradients are set up primarily by the wind.

For present purposes, I define the ocean circulation as that of its mass. The fluxes of mass affect the movements of all other properties, such as heat, salt, oxygen, carbon, and so forth (*1*, *2*), all of which differ from each other. For example, the North Atlantic imports heat, but exports oxygen. It seems most sensible to regard the thermohaline circulation as the circulation of temperature and salt. However, because the three-dimensional (3D) distributions and surface boundary conditions of temperature and salt are different, it should come as no surprise that one must separate the thermal circulation from the salt (or freshwater) circulation.

What drives the ocean's mass circulation? The upper layers of the ocean are clearly wind-driven, involving such major features as the Gulf Stream and the Circumpolar Current. A large body of observational, theoretical, and modeling literature supports the inference that the mass fluxes in the top several hundred meters of the ocean are directly controlled by the wind stress (the force per unit area exerted by the wind on the ocean).



Meridional overturning circulation (MOC) in the North Atlantic. This figure shows volume fluxes in units of 10^6 m^3/s, obtained by integrating zonally across the basin in a general circulation model constrained to observations (*3*). The northward near-surface flow includes the Gulf Stream and other dominantly wind-controlled elements. Yellow regions are areas of counterclockwise flow; in reddish regions the flow is clockwise. Regions of downward motion near 30°N and 60°N are associated with strong heat losses to the atmosphere. The subsequent flows are, however, determined largely by the global wind distribution.

If the flow is integrated zonally in the ocean (see the figure), one notices what is best called a meridional overturning circulation (MOC) (*3*). Features such as the Gulf Stream are not evident, but the Gulf Stream dominates the mass flux in the upper ocean and is clearly part of the MOC (*1*). Circulations at high latitudes generally contain a downward mass flux at high latitudes that is associated, at least loosely, with regions of severe heat loss to the atmosphere. In these regions, the fluid becomes dense and convectively unstable; the downward flux and subsequent lateral flow thus appear to be driven by thermal and evaporative forcing from the atmosphere. The ocean seems to act like a heat engine, in analogy to the atmosphere.

Some authors apparently think of this convective mode of motion as the thermohaline circulation. But results of the past few years suggest that such a convectively driven mass flux is impossible. There are several lines of argument. The first goes back to Sandström (*4*), who pointed out that when a fluid is heated and cooled at the same pressure (or heated at a lower pressure), no significant work can be extracted from the flow, with the region below the cold source becoming homogeneous.

The ocean is both heated and cooled effectively within about 100 m of the sea surface, but almost everywhere else it has a finite stable stratification. Returning the downwelling mass flux upward across the stable stratification requires a finite amount of work, manifested as the turbulent mixing carrying dense fluid across the density gradient. The only possible sources of this work are tidal stirring and the wind field (*5*, *6*).

Furthermore, the work done on the ocean circulation by the net heating and cooling, and evaporation and precipitation, reduces the system's potential energy (*7*). Paparella and Young (*6*) have shown that a convective mode of motion cannot generate the turbulence required to carry the MOC across the stable stratification. Laboratory-scale theories indicate that in the absence of intense turbulence at depth, the deep ocean would be unstratified (*8*)—in accord with more elaborate oceanographic models (*9*) and in conflict with what is observed.

The conclusion from this and other lines of evidence is that the ocean's mass flux is sustained primarily by the wind, and secondarily by tidal forcing. Both in models and the real ocean, surface buoyancy boundary conditions strongly influence the transport of heat and salt, because the fluid must become dense enough to sink, but these boundary conditions do not actually drive the circulation.

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The ocean is thus best viewed as a mechanically driven fluid engine, capable of importing, exporting, and transporting vast quantities of heat and freshwater. Although of very great climate influence, this transport is a nearly passive consequence of the mechanical machinery. When Stommel (*10*) first introduced the term "thermohaline circulation" in a box model, he explicitly provided a source of mechanical energy in the form of mixing devices. These devices disappeared in subsequent discussions and extensions of this influential model.

For past or future climates, the quantity of first-order importance is the nature of the wind field. It not only shifts the near-surface wind-driven components of the mass flux, but also changes the turbulence at depth; this turbulence appears to control the deep stratification. The wind field will also, in large part, determine the regions of convective sinking and of the resulting 3D water properties. Fluxes and net exports of properties such as heat and carbon are determined by both the mass flux and spatial distribution of the property, and not by either alone.

Tidal motions were different in the past than they are today, owing to lower sea level during glacial epochs, and moving continental geometry in the more remote past. The consequent shifts in tidal flow can result in qualitative changes in the oceanic mixing rates, and hence in the mass and consequent property fluxes.

The term "thermohaline circulation" should be reserved for the separate circulations of heat and salt, and not conflated into one vague circulation with unknown or impossible energetics. No shortcut exists for determining property fluxes from the mass circulation without knowledge of the corresponding property distribution.

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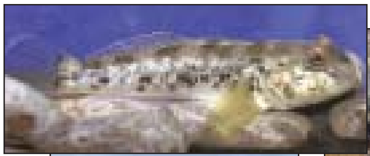
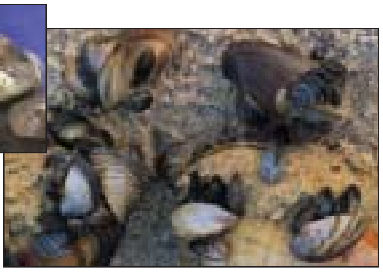
PERSPECTIVES: CONSERVATION BIOLOGY

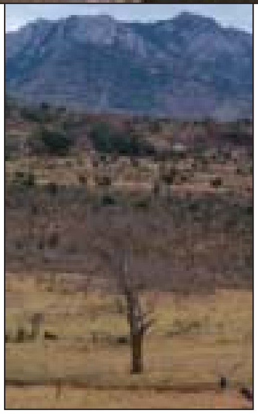
Predictive Ecology to the Rescue?

Isabelle M. Côté and John D. Reynolds

The recently released *Red List of Threatened Species*, compiled by the World Conservation Union, lists one quarter of the world's mammalian species as threatened with extinction, along with 12% of birds and between 20 and 30% of fishes, reptiles, and amphibians (*1*). The *Plan of Implementation* approved at the World Summit on the Environment held in Johannesburg in September affirms the goal of achieving by 2010 a significant reduction in the rate of biodiversity loss. What role can conservation biologists play in addressing this biodiversity crisis, and where are we to begin? There is no point in planning long-term, detailed investigations into the ecology of every species that may be under threat. We have neither the time nor the resources to do this for the vast majority of species that we know to be endangered, let alone the countless other organisms whose conservation status has not yet been assessed. We need simple ecological rules of thumb that can be applied broadly to help prioritize conservation action and funding. Two papers in this issue, by Kolar and Lodge on page 1233 (*2*) and by Lens *et al.* on page 1236 (*3*), demonstrate that such rules of thumb may well exist.







Aliens and altered landscapes. **(Top)** A round goby fish (*Neogobius melanostomus*) and a zebra mussel (*Dreissena polymorpha*). Both species originate from the Black Sea and Caspian basins and are thought to have been introduced to the Great Lakes of North America from the ballast waters discharged by trans-Atlantic ships. Both are prolific breeders, insatiable feeders, and aggressive competitors for space. These characteristics have put these two species at a competitive advantage relative to native species. **(Bottom)** The Taita Hills forest ecosystem of southeast Kenya is part of the Eastern Arc biodiversity hotspot, which is home to a wide variety of endemic plants and animals. Years of deforestation for conversion to agriculture have transformed the formerly dense forest into a patchwork of more or less degraded fragments.

Kolar and Lodge (*2*) tackle the issue of introduced species that rank as a major cause of extinction threat in many parts of the world. Why do some introduced species flourish whereas others fail? Species that are ecological generalists (that is, they tolerate a broad range of environmental conditions) and produce many offspring quickly are expected to be robust invaders (*4*). Yet, there have been few attempts to test this hypothesis. Kolar and Lodge take on the challenge with their investigation of alien fish species in the Great Lakes of North America (see the figure). Construction of canals in the 19th century and of the St. Lawrence Seaway some 50 years ago inadvertently opened a floodgate of alien species introductions into the Great Lakes. Species such as the sea lamprey (*Petromyzon marinus*) and, more recently, the zebra mussel (*Dreissena polymorpha*) have wrought economic and ecological havoc. Clearly, the ability to predict the establishment and impact of such species before their introduction could have led to stricter control measures.

These investigators compared the characteristics of alien fish species that became established or failed to spread, that spread quickly or slowly, and that became a nuisance or had little ecological or economic impact. As expected, at all stages of the invasion process successful species tended to have wide temperature or salinity tolerance and rapid life histories (although the speed at which they spread was, surprisingly, related to slower growth rates). Armed with these results, the authors predicted the likelihood of invasion of fish species native to the Black Sea, Caspian Sea, and surrounding watersheds,

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