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calization, cloning, and identification of genes make it invaluable for studying insecticide resistance phenotypes. For example, *Drosophila* genetic studies led to the first identification of a point mutation in a protein (the γ-aminobutyric acid–gated chloride channel in nerve membranes) that confers target site insensitivity to cyclodienes (*7*). *Drosophila* genetics also played a key role in the characterization of two other major target site mechanisms identified in insects: acetylcholinesterase insensitivity to organophosphates and carbamates (*8*) and knockdown resistance to pyrethroids (*9*). Daborn *et al.* (*1*) provide another elegant example of how this species can be exploited to benefit both basic and applied research on insecticide resistance. To take full advantage of the *Drosophila* model, it needs to be tested through access to genomics data for species of more direct practical concern. The amount of genome sequence available is changing rapidly. The whole genome sequence of *Anopheles gambiae*—the primary vector of malaria—has recently been completed (*10*), and rumors abound of sequencing projects involving crop pests and other disease vectors, either in progress or close to completion. Provided completion of these projects yields publicly accessible data, the opportunities for investigating the homology, origins, and organization of resistance traits at the molecular level, and for comparing these traits across a broad range of taxa, will be very exciting indeed.

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10. The complete *Anopheles gambiae* genome sequence is freely available at ftp://ftp.ncbi.nih.gov/genbank/genomes/Anopheles_gambiae. An initial annotation of the sequence can be found at www.ensembl.org/Anopheles_gambiae.

PERSPECTIVES: CLIMATE

The Ocean's Role in Atlantic Climate Variability

Martin Visbeck

Large climatic variations during the ice ages have been linked to changes in the circulation of the Atlantic Ocean (*1*). During the last 10,000 years, we have enjoyed a more stable climate with comparatively mild century-scale fluctuations (*2*). Today, a substantial part of the global year-to-year climatic variability is caused by the El Niño–Southern Oscillation in the Pacific Ocean (*3*).

The Pacific is three times as wide along the equator as the Atlantic and can effortlessly influence climate around the globe. The influence of the Atlantic is less wide-ranging but can nevertheless be substantial, especially if its circulation changes. One part of the international research program CLIVAR (Climate Variability and Predictability) is beginning to shed light on the mechanisms and predictability of Atlantic climate variability (*4*).

Air-sea interactions in the tropical Atlantic cause substantial year-to-year variability in the amount and timing of rainfall along the east coast of South America from Brazil to the Caribbean in boreal spring (March to May) and in western sub-Saharan Africa in boreal fall (August to September). These regions are near the Intertropical Convergence Zone (ITCZ), where very warm surface temperatures cause rapid, high-reaching cloud formation associated with strong precipitation (see the figure). Changes in the location of the warmest surface temperature cause north-south displacements of the ITCZ and substantial regional rainfall variability (*5*).

In the equatorial Atlantic, changes in the north-to-south temperature distribution cause most of the observed ITCZ variability. This is quite different from the Pacific, where El Niño is associated with changes in the west-to-east surface temperature. Atlantic surface-temperature anomalies just north of the Equator can be triggered by El Niño, as well as by changes in the strength of the trade winds associated with the North Atlantic Oscillation (NAO) (see below). Changes in large-scale ocean circulation may also alter tropical temperature gradients and thus modulate the location and strength of the Atlantic ITCZ. With rapid progress in the understanding of tropical Atlantic variability (TAV), prospects are good for improved seasonal-to-interannual rainfall predictions in the tropical Atlantic.

Atmospheric variability in the extratropical Northern Hemisphere winter (December through March) is dominated by the NAO (*6*, *7*). When the NAO is in its positive phase, low-pressure anomalies over Iceland and the Arctic combine with high-pressure anomalies across the subtropical Atlantic to produce stronger-than-average westerly winds across the mid-latitudes (see the figure). During this phase, climate is colder and drier than average over the northwest Atlantic and the Mediterranean, whereas conditions are warmer and wetter than average in northern Europe and the eastern United States.

Extensive climate impacts have been documented for the NAO (*4*), and scientists speculate about its interaction with global warming (*8*). The phase of the NAO appears to be largely driven by atmospheric weather noise, with changes in ocean sea-surface temperatures having only a moderate effect on the NAO (*9*). However, the NAO causes extensive changes in the surface wind field, which in turn strongly affect upper-ocean temperatures and circulation (*10*).

Surface temperatures and wind-driven currents change within days, whereas the basin-scale ocean circulation takes up to a decade to fully adjust to changes in atmospheric conditions (*11*). This constant game of oceanic catch-up leads to marked decadal variability in ocean properties forced by month-to-month atmospheric variability (*12*).

Seasonal or longer term prediction of the NAO would have enormous socioeconomic impacts: Who would not like to know a few months in advance when ski conditions in the Alps will be best, or what the price for hydroelectric energy in Norway and Turkey might be? But recent studies are not optimistic about the accuracy of seasonal-to-interannual NAO forecasts (*4*, *9*).

The Atlantic Ocean helps to mediate the imbalance in net radiation between the tropics (where more heat is received by the Sun) and the polar regions (where more heat is radiated into space). It does so through ocean currents that transport warm water from the tropical Atlantic to the subpolar Arctic region (see the figure).

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But the atmosphere is the largest contributor of heat, with warm air rising in the tropical ITCZ and moving poleward from there. On a global scale, the combined atmospheric and ocean circulations transport 6×10^{15} W northward at ~30°N and a similar amount southward at ~30°S (*13*).

The North Atlantic is the largest ocean contributor, with a heat transport of 1.3×10^{15} W at 30°N. This is 25% of the total northward heat transport and is carried by the warm surface currents—North Brazil Current, Florida Current, Gulf Stream, and North Atlantic Current—from south to north. Most of the heat is released to the atmosphere north of ~30°N; a small fraction of the heat leaves the Atlantic ocean northward, among other effects keeping Norway's west coast free of ice.

Modes of climate variability in the Atlantic sector. The figure shows the path and strength of winter storms depending on the sign of the NAO; the location of tropical rainfall (determined by the ITCZ); and the transport of ocean currents (MOC). Blue arrows: cold, deep currents; red arrows: warm surface currents.

Continued heat loss from the ocean to the atmosphere cools the surface waters. On its northward journey, the ocean's surface mixed layer becomes denser and finally sinks to great depths in the Greenland Sea, Labrador Sea, and Irminger Sea to form the cold return flow—the North Atlantic Deep Water—that flows south along the western boundary of the Atlantic at a depth of 1500 to 2000 m (*14*). This large-scale Atlantic overturning circulation moves about 15 million metric tons of water per second in a conveyor-belt–like circulation (*1*). Observational campaigns such as that during WOCE (World Ocean Circulation Experiment) have provided reasonable estimates of the Atlantic meridional overturning circulation (MOC) strength during the 1990s, but little is known observationally about how it varies with time (*14*).

The CLIVAR and GOOS (Global Ocean Observing Systems) programs aim to install an ocean observing and synthesis system that can, among other things, produce monthly estimates of the strength of the Atlantic MOC and associated poleward heat transport. Such an ocean-monitoring system, like those we have for the atmosphere, relies heavily on the optimal combination of data (satellite and in situ) and models to provide the desired basin-scale analysis (*15*). Once established, it will be the centerpiece for assessing climate change in the Atlantic sector and the database from which to initialize predictive models of future climate variability and change (*16*).

Substantial progress has been made in understanding individual parts of the global climate system. In the tropics, two-way interactions between ocean and atmosphere have proven to be essential, and some aspects of large-scale tropical climate anomalies, such as El Niño and the tropical Atlantic variability, are predictable. Much less is known about the influence of land-surface changes—such as increased desertification and deforestation—on these phenomena. It is becoming increasingly clear that the land surface influences the ITCZ and its variability, especially in the Atlantic and Indian Oceans.

Outside of the tropics, air-sea interactions seem to be more like a one-way street: Changes in the atmosphere cause reactions in the ocean–sea ice system. Here, the ocean plays a different role:

Changes in ocean circulation and mixing will affect the amount of CO_2 and other pollutant gases that get dissolved into the ocean and removed from the atmosphere. Thus, the ocean's ability to provide a long-term sink can be strongly modulated by the state of the climate system and its variability (*17*).

How will human-induced climate change affect the NAO (*6–8*)? And what does a changing climate mean for the ocean's ability to absorb CO_2? Answering such questions requires a detailed understanding of the ocean's mean and variable circulation and of many aspects of the ocean's ecosystem (*18*). Complex interactions may yet be discovered between climate and ecosystems. Some might turn out to be predictable on seasonal, interannual, or longer time scales, providing benefits to human society.

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