PERSPECTIVES: CLIMATE

Open Windows to the Polar Oceans

Peter Lemke

The sea ice cover on the polar oceans reflects up to 80% of the solar radiation reaching its surface back into space and so plays a major role in climate change by affecting Earth's temperature. In contrast, the open ocean only reflects 10% of the solar energy and absorbs the rest. Thus, an increase in the sea ice cover cools Earth's surface, thereby promoting further advances in sea ice; retreating sea ice warms Earth's surface, promoting further retreats in sea ice. This positive feedback is believed to be the main reason for the polar amplification of the warming observed in climate model scenarios for the 21st century (*1*, *2*).

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The polar sea ice is not a large, solid lid but is broken into floes of various size and thickness by tides, surface waves, and variable winds. Sea ice motion due to winds and ocean currents varies irregularly on small scales and is organized in large-scale drift patterns like the Arctic Transpolar Drift Stream, which carries water and ice from Siberia across the pole and down the east coast of Greenland. Large holes in the sea ice, called polynyas, may persist for years, through mechanisms that are not well understood. On page 1697 of this issue, Holland (*3*) suggests an interesting new mechanism for the formation of the largest polynya ever observed.

Short-term, local divergent sea ice drift creates short-lived (hours to days) long, narrow channels of open water called leads, which are about 100 m wide and up to several kilometers long. Larger, rounder features called polynyas evolve during large, long-term divergences. Their sizes vary from a few hundred meters to several hundred kilometers, and they may persist for weeks to years. In wintertime, leads and polynyas amount on average to about 5% of the ice-covered area.

There are two types of polynyas (see the figure). Coastal polynyas are created and maintained by divergent sea ice drift due to steady offshore winds. Open ocean polynyas are created and maintained by divergent sea ice drift and the heat stored in the ocean, which is supplied to the surface layers, thus preventing the formation of sea ice.

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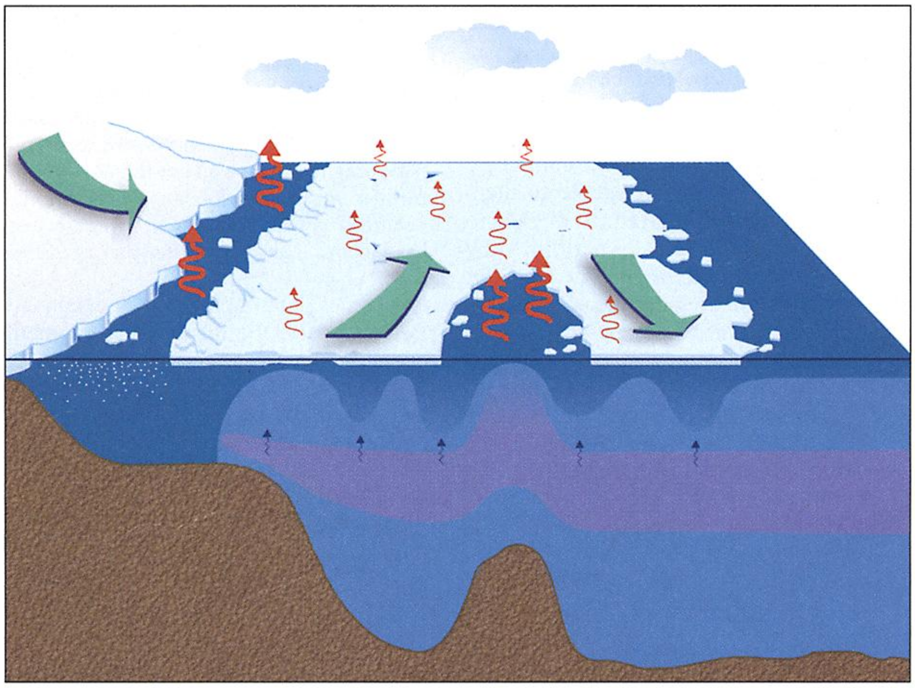
In polynyas (and leads), the ocean is in direct contact with the cold atmosphere. Polynyas are therefore open windows to the polar ocean that allow enhanced exchange of heat, water vapor, and other gases, such as CO_2, between ocean and atmosphere. The heat flux from the ocean to the atmosphere in a polynya may exceed 500 W m^{-2}, compared with 30 W m^{-2} over the adjacent sea ice.

In coastal polynyas, where the water is shallow, the ocean quickly cools down to the freezing point at all depths. The heat supplied to the atmosphere then originates only from the latent heat of fusion of the continuous production of sea ice (*4*). During sea ice formation, oceanic salt is released into the water because it is not incorporated into the ice crystals. This salt increases the local density of the ocean water, which therefore sinks to deeper layers of the ocean. Coastal polynyas therefore represent important sources of dense deep and bottom water, which ventilate the abyss and drive the oceanic global conveyor belt (*5*).

In open ocean polynyas, the supply of oceanic heat is less restricted. Therefore, large amounts of sensible heat (the amount of energy necessary to change a liquid to a vapor at constant temperature and pressure) from deeper ocean layers are lost to the atmosphere and little ice is created. The substantial cooling of the ocean water can lead to deep convection, which homogenizes the ocean waters to great depths and produces deep water in the open ocean. Consequently, both types of polynyas have a large influence on global ocean circulation and on Earth's climate.

There are two prerequisites for open ocean polynya formation and maintenance: Heat stored in deeper ocean layers must easily be transferred to the surface during convection, and a divergent sea ice drift must prevent the ice from entering the polynya and melting inside. Melting sea ice consisting mostly of fresh water would stabilize the oceanic stratification and disconnect the surface from the deeper ocean. The divergent sea ice drift during the initial stages of polynya formation may originate from divergent winds or ocean currents.

The largest polynya ever seen was the Weddell Polynya, an open ocean polynya the size of Great Britain that was observed by satellite remote sensing from 1974 to 1976 during three consecutive winters (*6*). Unfortunately, no in situ observations were carried out during that time. Deep-water



Breaking the lid. Sea ice acts as an insulating lid that effectively reduces the communication between atmosphere and ocean. But sea ice cover is not continuous. Near the coast, offshore winds may create coastal polynyas; in the open ocean, divergent sea ice drift with large upward heat fluxes may lead to open ocean polynyas. Salt rejection from the forming ice and strong heat fluxes in the polynyas create deep and bottom waters, which drive the global thermohaline circulation of the ocean.

properties in the Weddell Sea were, however, different before and after the occurrence of the polynya (*7*). Explanations concerning its formation and maintenance are mostly based on meteorological and oceanographic arguments and on numerical experiments with coupled sea ice–ocean models.

The location of the Weddell Polynya in the mid-1970s and areas of low ice concentrations in later years suggest a strong influence of Maud Rise, a topographical feature on the sea floor (seamount) that modifies ocean currents and tides. In Holland's model (*3*), the seamount sheds cyclonic eddies when the ocean current from the northwest interacts with the seamount. Cyclonic eddies at the northeast flank of Maud Rise then apply a divergent stress to the sea ice, increasing the amount of open water within the pack ice despite a deeper thermocline (*8*). In contrast, convergent motion in an anticyclonic eddy southwest of Maud Rise provides a closed ice cover despite the shallow thermocline.

Modeling studies have also shown that tidal motion modified by bottom topography may reduce sea ice concentration substantially (*9*). These high-resolution ocean models can identify structures in the coupled ice-ocean fields that are difficult to observe directly. They thereby help to advance our understanding of polynya-forming processes. But despite this new information, it remains a mystery why the large Weddell Polynya appeared during three consecutive winters in the 1970s but has never appeared since.

References and Notes

1. J. F. B. Mitchell, T. C. Johns, J. M. Gregory, S. F. B. Tett, *Nature* **376**, 501 (1995).
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3. D. M. Holland, *Science* **292**, 1697 (2001).
4. S. D. Smith, R. D. Muench, C. H. Pease, *J. Geophys. Res.* **95**, 9461 (1990).
5. W. S. Broecker, *Oceanography* **4**, 79 (1991).
6. F. Carsey, *Mon. Weather Rev.* **108**, 2032 (1980).
7. A. L. Gordon, *J. Phys. Oceanogr.* **8**, 600 (1978).
8. The thermocline is the region of strong vertical temperature contrast in the ocean at the base of the surface mixed layer (typically at a depth of 50 m in summer and 100 to 200 m in winter). The thermocline separates the surface layer from the deeper layers of the ocean. In sea ice–covered oceans, the mixed layer is cold (–2°C) and less saline, whereas the deeper layers are a few degrees warmer and a little saltier. In polar oceans, the thermocline indicates the depth where the warm waters are.
9. A. Beckmann, R. Timmermann, A. F. Pereira, C. Mohn, in preparation.

PERSPECTIVES: CHEMICAL PHYSICS

Single-Molecule Spectroscopy Comes of Age

Anne Myers Kelley, Xavier Michalet, Shimon Weiss

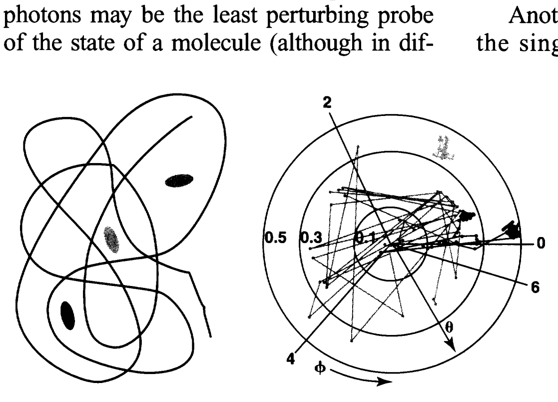
In the summer of 1999, researchers working in the field of single-molecule biophysics gathered for a 1-week workshop in the French town of Tours (*1*). Sensing the birth of a new discipline, the participants termed the workshop "the Woodstock of single molecules," but their enthusiasm was mainly about future promise: It was clear that a considerable amount of work would be required to extend and validate methodologies originally developed for solids at cryogenic temperatures (*2*) to materials and biological systems (*3*).

In April of this year, a symposium at the American Chemical Society Meeting in San Diego (*4*) demonstrated that single-molecule spectroscopy is beginning to deliver on its promise. Chemists, physicists, and biologists gathered for nearly 60 talks on topics as diverse as low-temperature dynamics of single-dye molecules embedded in crystals (M. Orrit, Bordeaux I University), optical tracking of the entry of individual viruses into live cells (C. Bräuchle, Ludwig-Maximilian-University, Munich), single-photon light sources from single molecules (W. E. Moerner, Stanford University) (*5*), polymer conformations and dynamics (P. Barbara, University of Texas, Austin; R. Dickson, Georgia Tech) (*6–8*) and the mechanisms of single enzymatic motors (K. Thorn, University of California, San Francisco; K. Kinosita Jr., Keio University; T. Yanagida, Osaka University) (*9*, *10*). The broad range of topics illustrates the power of optical approaches for studying single molecules or molecular assemblies. Very few talks emphasized methodologies but rather concentrated on the new scientific knowledge being gained, demonstrating that single-molecule spectroscopy is reaching maturity (*11*).

One reason for the burgeoning interest in single-molecule optical techniques is that photons may be the least perturbing probe of the state of a molecule (although in different power regimes, lasers can be used to exert a substantial force on atoms, molecules, and beads). Different spectroscopic signatures can be used, of which fluorescence is the most popular because of its inherent sensitivity. Fluorescence studies can be performed on biomolecules that have intrinsic fluorophores, such as photosynthetic light-harvesting complexes (J. Schmidt, Leiden University) or enzymes containing flavin cofactors (S. Xie, Harvard University). More often, however, a fluorescent moiety is attached to the species under study by genetic engineering such as tagging with green fluorescent protein (Thorn; T. Schmidt, Leiden University), by targeted chemical functionalization as in site-specific protein labeling (P. Lu, Pacific Northwest National Laboratory), or by chemical modification of DNA or RNA bases (S. Chu, Stanford; M. Ishikawa, Joint Research Center for Atom Technology, Tsukuba).

Another powerful spectroscopic tool at the single-molecule level is Raman (T. Basché, University of Mainz) or surface-enhanced Raman scattering (M. Käll, Chalmers University of Technology; S. Nie, Indiana University; L. Brus, Columbia University). Raman spectra contain more detailed information about molecular structure than fluorescence spectra and can, for the most active surface-enhanced sites, provide photon count rates competitive with fluorescence (K. Kneipp, Massachusetts Institute of Technology).

The most fundamental reason for the excitement about single-molecule spectroscopy is that ensemble studies give only an average picture of the properties exhibited by individual molecules that are not identical.



Single-molecule dynamics in polymers. Orientational trajectories of three dye molecules embedded in poly(methyl methacrylate) are probed with wide-field single-molecule optical microscopy (*6*). The different orientational dynamics of the different molecules illustrate the heterogeneity observed within polymer hosts even 80°C below the glass transition temperature. The cartoon shows how differences in local free volume might give rise to these differences in rotational mobility.

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