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Turbulent paradox beneath the ice

Turbulence in the Arctic Ocean causes melting of sea ice. Surprisingly the ice melts slower than theory suggests. This is caused by the impact of sea salt.

As part of his PhD thesis, Thomas Keitzl and his supervisors Juan Pedro Mellado and Dirk Notz solved the mystery of turbulent mixing of heat and salt underneath sea ice. They were able to identify the transport equilibrium that determines the freezing temperature and the ice melt rate. Facilitated by the latest high performance computers, they used high-resolution three-dimensional simulations to examine in detail the turbulence underneath ice.

We know turbulence from travelling by plane, when we get a funny feeling in the stomach. But what is turbulence? Turbulence indicates the chaotic motion in fluids, although there is no generally accepted definition. Turbulence is essential for the efficient mixing of air in the atmosphere, water in the ocean and milk in our coffee. In the case of our bad-weather flight, the air masses mix so wildly that they carry the plane with them. We feel the resulting unpredictable acceleration. Rarely do we perceive turbulence as consciously as in an aircraft, but turbulence is not uncommon. For example it plays an important role for the bottom evolution of Arctic sea ice.

Water masses of different densities mix underneath the Arctic sea ice. The nature of the mixing process contributes significantly to the transport of heat: If turbulence is the driving factor for the mixing, a lot of heat can be transported towards the ice. In that case, the ice melts quicker than when the mixing takes place only by molecular motion. The situation under the ice is particularly interesting because turbulence does not only transport heat in this environment. Just as turbulence in the sky moves the aircraft, the water transports an additional property affecting the melting: sea salt.

The effect of salt on ice can be well observed in winter, for example, when large amounts of salt are distributed on the roads. The salt lowers the freezing temperature of the water. At the same ambient temperature as before, the ice turns liquid and the road becomes ice-free again. The same is true for the Arctic: If turbulence under the ice transports particularly saline water towards the ice, its freezing temperature changes, and it ablates at a lower water temperature. The salt dissolves the ice.

The turbulent transport of heat and salt towards the sea ice has the same effect: the ice melts and dissolves. Upon dissolution and melting, a very thin layer of melt water forms under the ice. Paradoxically, the two mechanisms interfere with each other. If the ice dissolves due to the salt transport, this thin layer is very cold and protects the ice from the heat transport. If the ice melts due to the heat transport, the thin layer has very little salt and protects the ice from the salt transport. The paradox gets solved by the fact that the turbulent mixing of heat and salt creates a heat-salt transport equilibrium. This transport equilibrium determines the freezing temperature and thus the melt rate. Therefore, scientists must know the transport equilibrium if they want to predict the melt rate.

Since this interplay of heat and salt occurs in the very thin layer directly underneath the sea ice, it has not yet been possible to directly measure the transport equilibrium. The inhospitable environment, a desert of ice, does not make it easier for the scientists. Therefore, they use certain tricks. Instead of measuring the interplay directly under the ice, scientists work with laboratory experiments or indirectly derive the transport equilibrium from other measurements. As a result, the transport equilibrium and the melt rate have been only vaguely known until now.

Thomas Keitzl and his supervisors used a new method, which was facilitated by the latest high-performance computers. Instead of drilling holes into the Arctic ice and measuring on-site, they used three-dimensional simulations of the turbulence under the ice.

Turbulence simulations allow a correct representation and quantification of the fine processes in the very thin layer directly underneath the ice. While measurements in the laboratory and in the field usually only provide a single measured property (e.g. temperature), the simulation provides the complete spatio-temporal evolution of all simulated properties (e.g. flow velocity and -direction, temperature- and salt transport).

Turbulence simulations have advantages and disadvantages On the one hand, a single simulation represents not only a single but a multitude of measurements of all parameters at the same time. On the other hand, the simulations require a certain minimum resolution and hence enormous computing capacities. The supercomputer JUQUEEN in Jülich, Europe's second fastest supercomputer, has these computing capacities. For a single simulation, 8196 processor cores calculate for a week. This means that a computer with a single processor core would have had to calculate continuously for about 200 years, since the beginning of the 19th century, to present the results today.

Working with the simulations, the scientists proceeded in two steps. As a first step it was ensured that the simulations represent reality. For this purpose they simplified the physical system and compared the simulation results with laboratory experiments. Instead of the turbulence underneath sea ice, they analyzed the turbulence under the ice sheet of a freshwater lake. In order to study the thin layer under the ice, the scientists varied the temperature of the ice-covered lake by several tens of degree. Laboratory experiment and simulation agreed with each other. As a by-product of this first step, they made a remarkable discovery: It has been known how much energy is needed to melt ice for a quarter of a millennium, but how fast it melts remained unknown. For the ice-covered fresh water lake, the scientists now found the formula that correctly describes the melt rate. Formula, laboratory result and simulation correspond to each other.

In the second step, salt was included in the simulation. In this way, the scientists made a discovery that explains the previous uncertainty in the transport equilibrium. Contrary to what was generally believed, the equilibrium varies with the distance to the ice. It is constant only in the very thin layer directly below the ice. Measurements of the salt transport so close beneath the ice were previously impossible. This explains why field measurements carried out too far away from the ice yielded incorrect assessments. Keitzl, Mellado and Notz conclude that turbulence creates a transport equilibrium in which heat transport (compared to salt transport) is about three times as efficient as previously assumed. As a result, the salinity of the thin layer is lower.

This means that the freezing temperature of ice has so far been underestimated, and that the melt rate was overestimated. This is by no means an all-clear signal for the melting ice caps in the Arctic and Antarctic because, in addition to heat transport in the ocean, the melt rates depend on many other factors. The atmosphere, for example, also has an influence on the development of sea ice. The results of Thomas Keitzl and his supervisors allow a better understanding of the oceanic contribution to sea ice development and a more detailed representation in future climate models.

Publications:

Keitzl, T., Mellado, J.-P. & Notz, D. (2016). Impact of thermally driven turbulence on the bottom melting of ice. Journal of Physical Oceanography, 46, 1171-1187, doi:10.1175/JPO-D-15-0126.1

Keitzl, T., Mellado, J.-P. & Notz, D. (2016). Reconciling heat flux and salt flux estimates at a melting ice-ocean interface. Journal of Geophysical Research - Atmospheres, 121, 8419-8433, doi:10.1002/2016JC012018

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