The wind: an efficient amplifier of glacial climate changes

Studying past climatic events helps understanding the interactions between atmosphere, ocean and continents. Through its history, Earth experienced abrupt climate changes, and those that occurred during the last ice age in particular are of high interest to climatologists. These so-called Dansgaard–Oeschger (DO) events were associated with rapid Greenland warmings of up to 16°C within a few decades are were followed by a progressive cooling lasting several centuries. They occurred every 1,000 to 2,000 years between 30,000 and 60,000 years before present.

Climate evolution in Greenland for the last 100,000 years as shown by the isotope ratio $\delta^{18}O$, a good indicator of air temperature. DO events (numbers) are absent from the most recent interglacial period (Holocene).

It is generally well accepted that the Atlantic Meridional Overturning Circulation (MOC) is somehow involved. This large-scale circulation results from seawater density differences and cannot be dissociated from the wind-forced circulation. It can be described as a surface northward flow (Gulf Stream and North Atlantic Drift) and a returning deep southward flow. Its variations cannot explain alone the large temperature variations observed during the last ice age. In fact their effect on high latitude climate is strongly amplified by sea-ice, and particularly by the feedback effect of its reflecting power (albedo). If the ocean transports more heat northward in the Atlantic Ocean, Arctic sea ice melts. Surface water in the Arctic then absorbs more solar radiations and warms up, thereby amplifying the initial sea ice melting.

While the ice-albedo feedback is well understood, much less is known about the influence of atmospheric feedbacks through which surface winds can alter sea ice distribution and thus influence the response of surface air temperature to a change in the strength of the Atlantic MOC.

This study consisted in a simulation of the ocean-ice-atmosphere coupled system designed to improve our understanding of the influence of atmospheric circulation changes on both the stability of the coupled system and the abrupt millennial variability observed in Greenland records. The scientists compared the results of numerical simulations where winds were allowed to interact with the climate and where they followed a constant seasonal cycle independent of the climatic and oceanic conditions. They used an ocean-ice-atmosphere coupled model whose complexity is intermediate between conceptual models and the highly complex models used to make climate predictions over the 21st century.
The model geometry is that of an idealized ocean basin whose dimensions are similar to those of the Atlantic Ocean. A periodic channel is opened in southern subpolar latitudes to represent the Antarctic Circumpolar Current. Space is divided by a 2° horizontal spherical grid and by a vertical grid of 19 layers whose thickness varies from 50 m at the surface to 450 m at the bottom. This idealized framework (both in geometry and physics) is necessary to cope with the long time-scales involved. Using a general circulation coupled model of the kind used for 21st century climate predictions would require computer resources that are much beyond what presently exists. This approach is also justified by the fact that parameter sensitivity analyses are necessary to establish causal relationships between different physical processes in a complex coupled system, an approach that is currently not tractable using climate prediction models.

Model geometry. Arrows show the main features of the circulation generated in the basin.

The main experience consisted in cooling the climate system over a very long period (100,000 years), with or without considering the interaction between wind and climate; other simulations were performed to refine the analysis. A first result is that, at intermediate climates, MOC looses its stability and exhibits very strong millennial-scale oscillations whose structure in space and time is similar to observed DO events.

MOC strength (in Sverdrups, $1 \text{ Sv} = 10^6 \text{ m}^3 \text{s}^{-1}$) during the simulated progressive cooling, with (red) or without (blue) considering the interaction between wind and climate.
The simulation also agrees with analysis of paleoclimate archives from Greenland ice cores that have suggested that abrupt millennial-scale climate transitions during the last ice age developed only for cooling rates associated with intermediate ice-sheet sizes. The model also shows that the interaction between wind and climate increases the amplitude of the oscillations and shifts their domain of existence towards colder climates.

Through which mechanisms this wind-climate interaction increases the amplitude of abrupt millennial-scale variability? Whereas the ice-albedo positive feedback is well understood, the processes involving atmosphere, ocean and sea ice interact in a highly complex way within a chain of physical processes that is generally difficult to establish. In the present case however, the authors have been able to identify the causal relationships at play. Results show that the effect of the wind-climate interaction combines with the ice-albedo feedback to increase the amplitude of millennial oscillations: a new positive feedback loop emerges within the coupled system. This is through its effect on sea ice export that the interaction between wind and climate is able to amplify the atmospheric response to a change in ocean circulation.

Mechanisms of positive feedback between atmosphere (beige), ice (green) and ocean (purple), and involving either albedo (left) or the interaction between wind and climate (right). The signs on the arrows are linked with the impact of an anomaly of one variable on the anomaly of the following one.

The second effect of the interaction between wind and climate is to shift the domain of existence of abrupt millennial variability towards colder climates. To understand this, it is necessary to consider not the variability of the coupled system but rather its stability. Atlantic MOC stability stems from the northward oceanic heat transport: if the circulation weakens, the north-south temperature gradient increases and drives the circulation back on track. Weakening of this regulator causes the instability of the circulation to occur and (under certain conditions) abrupt millennial-scale climate oscillations to emerge. The numerical simulations show that the interaction between wind and climate strengthens this negative temperature-circulation feedback: the oscillation window thus shifts towards colder climates because of the higher stability of circulation with respect to the "coolness" of the climate.
This study shows that the interaction between wind and climate can significantly alter the properties of abrupt millennial-scale climate variability as observed during the last glacial period in Greenland ice cores. The robustness of this result will have to be evaluated in coupled models of increasing complexity and of course checked against future reconstructions of glacial climates.

The paper

The authors
This work was conducted in collaboration by researchers of the Laboratoire de physique des océans (LPO) of IUEM and of the Climate Change Research Centre (University of New South Wales, Sydney, Australia).

The journal
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