THE AVATARS OF THE ARCTIC ICE PACK AND SOLAR ACTIVITY

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Since the 1990s, a wave of panic has been stirred up by the IPCC, threatening us with cataclysmic warming of the Arctic Ocean, with its impact on the climate via the disappearance of the ice pack**.** The IPCC relies on a low variability of Total Solar Irradiance (PMOD, ΔTSI≈ 0.1 Wm-^{2}/century) if **solar forcing has only contributed 0.05 Wm-^{2} since 1850,** relegating the sun to a minor role (Soon et al. 2024).

The main reason for the summer melting of ice and snow is the presence of the sun, and therefore its various energy contributions: radiation, solar wind and the magnetic field arriving at the ground and ocean surface. It is important to note that the melting season begins when the temperature rises above -5˚C. However, the annual cycle of the Arctic ice pack clearly depends on changes in insolation over the year and therefore on our position in the current 11-year solar cycle (Schwabe) (Figure 1). When the first rays of sunlight reach the edge of the pack ice after winter, the ice begins to melt, slowly at first, then more rapidly, until the minimum extension of the sea ice is reached between the end of August and the beginning of September, when the cold nights restart the freezing cycle. At the end of winter, it can be 1.5 to 2 metres thick, with a possible layer of snow on top (30 to 50 cm in the Arctic). The action of pack ice already begins in cold temperate contexts and may therefore have been active very early in the Cenozoic era. There is perennial pack ice, which consists of ice several years old and up to 5 m thick (excluding pressure ripples), and annual pack ice, which varies in thickness and lifespan depending on the polar or regional context. The buoyancy of the pack ice is due to the difference in density between the ice and the water, particularly if it is salty: the less dense ice is subject to Archimedes' buoyancy and therefore **does not contribute to the rise in sea level.**

In addition to the direct insolation factor, the ice cover is also modified by **the influx of warm water from the North Atlantic Drift, which warms the Arctic atmosphere in the northern extension of the Gulf Stream. This heat was stored at the surface of the inter-tropical ocean during periods of high solar activity (Van Vliet-Lanoe 2024 SCE)**

and reached the northern hemisphere (NH) at the end of 2024 via the thermohaline circulation.

So, two main factors are currently superimposed to understand the extension of the ice pack: the advance of solar cycle 25, with a first exceptional maximum in 2023 (SCE, 2024) and a second, at the end of 2024 (Figure 1 A). The mechanism that transfers planetary and lunar signals for changes in sea-ice extent seems to be the solar wind, which provides a magnetic shield for the Earth in addition to geomagnetic disturbances (Solenheim et al., 2020).

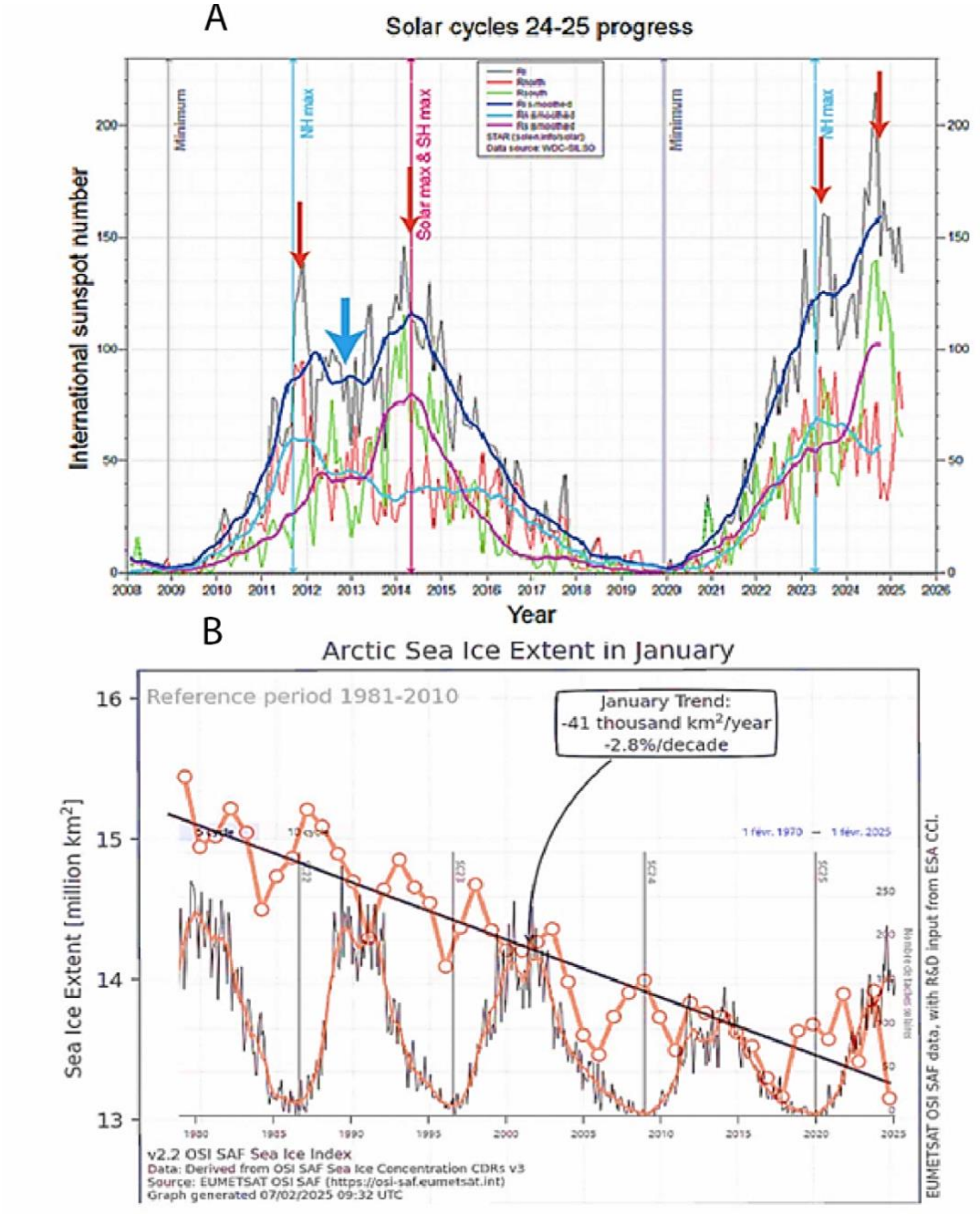

Figure 1: A) Evolution of solar cycles 24 and 25 with double maxima (Solen info) 2012(blue arrow) is a particularly cold winter. B) Comparison of annual changes in sea ice from 1980 to

2025 (EU Meteosat). Note a decline in sea ice that seems almost parallel to the intensity of the solar cycles (Solen info) except for cycle 25.

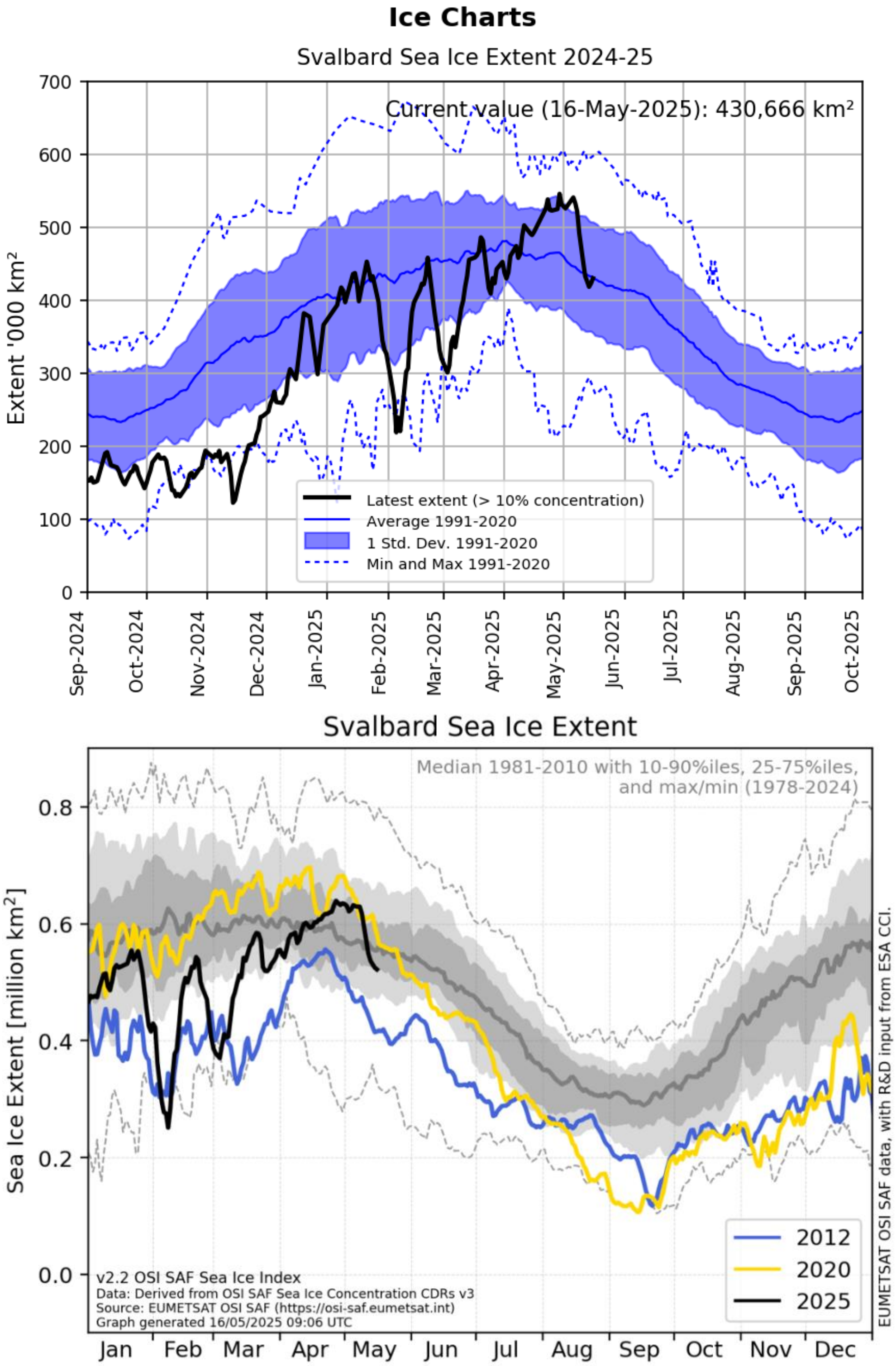

Figure 2: Recent changes (2025) in the pack ice around Spitzbergen (https://cryo.met.no/en/sea-ice-index), showing a delay in pack ice expansion during periods of high solar activity and heat input via the North Atlantic Drift (NAD).

The increase in the solar wind produces a pressure that slows down the Earth's rotation and speeds up the trade winds in the tropics. It also transfers electrical energy to the ring current in the Earth's magnetosphere. This magnetising current accelerates the rotation of the Earth's solid core. To maintain angular momentum, the Earth's fluid outer mantle rotates more slowly, with a delay of around 100 years. In addition, geomagnetic storms, triggered by coronal mass ejections (CMEs), penetrate deep into the Earth's atmosphere and change the pressure pattern in the Arctic. This effect is particularly noticeable during solar minima, when the magnetic shield is reduced and the outgoing radiation is greater, leading to local cooling in the Arctic. The transition to a potentially deep and long solar minimum during the current century should lead to a modest cooling of the Arctic and a southward re-extension of the pack ice.

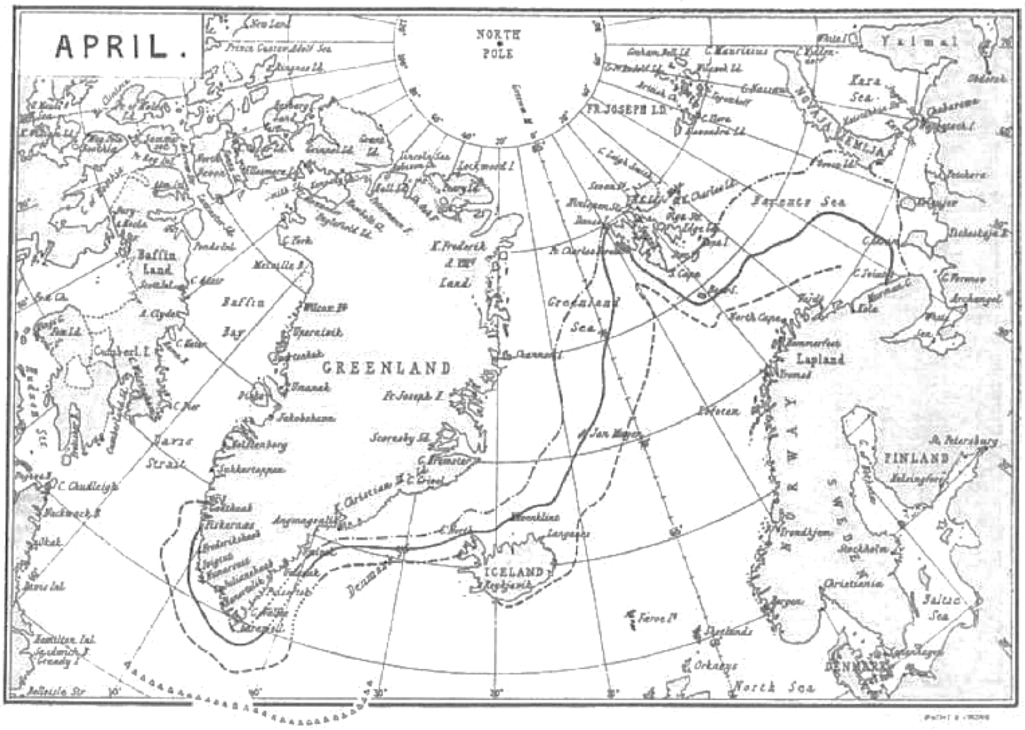

Figure 3: Map of the extent of the pack ice in April 1917 (solid line) and 1911 (dotted line). The rise of the North Atlantic Current (NAC) pushed the pack ice eastwards (Barents Sea) and towards the NW of Spitsbergen. Source: Danish Meteorological Institute.

Sea ice in the winter of 2024-2025 (Figure 2A) persisted over most of the Arctic, but with a delay in the area warmed by the North Atlantic Drift (Gulfstream Extension or NAC), the west coast of Spitsbergen and the Barents Sea as far as New Zemble (Figure 3). The Gulf of St. Lawrence remained virtually ice-free and the ice in the Sea of Okhotsk was significantly reduced. Only the East Greenland Sea had a near-average ice extent during the winter. However, the ice extent in the Bering Sea accelerated from the end of February to the end of March, reaching a value close to the 1981-2010 average and extending late in the season. The most obvious example is the gradual increase in the ice pack around Spitsbergen since December (Figure 2), after the passage of the second solar maximum of cycle 25 at the end of 2024. This situation partially explains the observed shift in cyclonic low circulations over the zone between 35° and 42° N, accompanied by heavy precipitation induced by localised warming of the intertropical ocean since the first peak in solar activity in 2023. This confirms that the primary forcing of ice pack extension and all that follows from it is under the control of the solar energy input. The evolution of the solar polar magnetic field throughout a sunspot cycle makes it possible, to a certain extent, to predict the extent of the next cycle and the intensity of the peak of the current cycle.

Pack ice forms on the surface of the ocean in winter, when the temperature of the sea water falls below -1.8°C, depending on its salinity, and the sea freezes over. At the end of winter, the ice can be 1.5 to 2 metres thick, with an additional layer of superficial snow (30 to 50 cm in the Arctic). There is **perennial pack ice**, which consists of ice that is several years old and can be up to 5 metres thick (excluding pressure ripples), and **annual pack ice,** which varies in thickness and lifespan depending on the polar or regional context. Annual pack ice is known as young ice. Perennial pack ice changes colour with age and is often referred to as old ice. The ice crystals form a soup, frazil ice, which will eventually form a mass. This is young ice. Freezing continues under the already frozen interface. It is important to note that as the ice crystallises, it expels or excludes cold brine, which changes the temperature and density of the underlying water. This water then sinks to the ocean floor. Pack ice therefore plays an important role in ocean circulation and the planet's climate.

The ice will continue to thicken almost every winter. The various types of ice will evolve over time, recrystallising because of the persistence of a capillary liquid film between the crystals, rising from the underlying liquid. Conversely, when the surface snow melts, freshwater seeps through the pack ice and recrystallises at its base, so recent ice can be found under old pack ice.

This phenomenon of exclusion occurs extensively during the formation of pack ice. When a layer of sea water cools to its freezing point, its density increases and it sinks to the bottom, bringing less salty water to the surface. The freezing point is then at a lower concentration of salts than seawater, often around -2°C . The higher the rate of freezing and the rougher the sea, the more salt is excluded from sea ice.

In summer, polar waters are relatively "warm" at +2 or +3°C. So, when the pack ice breaks up or has **an opening, called a polynya**, it absorbs incident radiation, which is relatively weak given the obliquity of the sun in the polar zone. The **re-emission of heat will therefore mainly take the form of vaporisation**, given the very low tension of water vapour at low temperatures. One of the consequences is the presence of **very low clouds or fog over ice-free waters and a high albedo,** despite the disappearance of the ice, **limiting the direct heating of outcropping seawater.**

BIOLOGICAL IMPLICATIONS

In the North Atlantic, the effects of the southward expansion of the pack ice will have significant consequences for ocean bioproduction from around 2040 according to the models, if the warming continues, which is far from certain. Cod, which disappeared from the Loftoten Islands in the 1980s (Cruickshank, 1985), reappeared regionally after the winter of 2012-2013. Drift ice probably disappeared during the early Holocene at the time of maximum insolation (Gersonde and de Vernal 2013; Detlef et al. 2023).

Arctic marine ecosystems underwent significant reconfigurations in response to climatic and environmental changes during the Holocene (Schreiber et al. 2025). There is a close correlation between traces of marine mammals in Atlantic sediments and the break-up (pack ice) of the high Arctic Ocean at the beginning of the Holocene. Air temperature and changes in sea ice cover are important drivers of change in marine communities over time. During the Holocene (8000 BP), a period when the climate was significantly warmer than today, northward shifts in the distribution of temperate and low-arctic marine mammal species were associated with complete summer deglaciation of the North Atlantic. Major oceanographic changes have recently propagated through several trophic levels in the coastal zones of south-east Greenland (Heide-Jørgensen, et al., 2023). The amount of drift ice exported from the Fram Strait and transported by the East Greenland Current has decreased considerably over the last two decades, and summer sea ice has virtually disappeared since 2003. The subsequent 20-year period with little or no coastal sea ice is unique in the 200 years of ice observations in the region, and the change in regime is also evident in the volume of ice exported through the Fram Strait since 2013. Over the same period, the temperature of the East Greenland Current (the coldest) south of 73.5° N has risen considerably (> 2°C) since 1980. On the other hand, the warm Irminger Current, which brings warm salty water from the Gulf Stream to the NE of Iceland, has become warmer since 1990 with an influx of warm water carrying boreal species to the south and subarctic capelin and cetaceans further north, as during almost all Dansgaard Oeschger events. Pack ice acts as an insulator between the ocean and the atmosphere. It reflects around 60% between 0.4 and 0.8 µm. In the Arctic, 70% of the solar irradiance received is in the range 0.4-0.9 µm, 14% between 0.9-1.1µm and the rest mainly between 1.1 and 1.4 µm. Because its temperature is still slightly negative in summer, ice mainly absorbs and reflects incident radiation. In winter, it is mainly an IR emitter, but in very small proportions given the very negative temperatures (<-20°C).

The pack ice is also transparent to UV and visible light: in spring, photosynthetic algal flora develops at its base, turning it brown and thus reducing its albedo. The summer extension of the ice pack is therefore inversely controlled by insolation, particularly during periods of high obliquity of the Earth's axis of rotation (at the end of interglacial periods) and in connection with the eccentricity of the Earth's orbit. **When snow covers the ice, the albedo of the pack ice is almost identical to that of fresh snow. Its presence limits evaporation from the ocean and therefore the ocean's heat and precipitation input in winter**. On the other hand, it emits IR radiation and encourages significant regional cooling of the overlying atmosphere: the ice-free ocean absorbs 90% of the incident energy, while the snow-free pack ice already reflects 70%.

Its primary role is therefore to provide thermal protection: in the Arctic winter, the temperature above the pack ice generally reaches -30°C, or even lower, while the temperature of the sea water at its base is only -2°C. On the other hand, many micro-organisms colonise the pack ice sensu-stricto - on the surface, - in the lower zone of ice accumulation, or - in the summer surface melt pools. These are diatoms and various types of algae (dinoflagellates, cyanobacteria). Their accumulation colours the old ice and reduces its albedo. Pack ice is also translucent and, when it is not too thick (annual ice), allows planktonic photosynthesis under its base. In spring, well before the thaw, the waters enriched in mineral salts by the exclusion process during the crystallisation of the ice and by the first continental melt waters, rich in ferrous iron phosphate, nitrates and silica, see the appearance of teeming life just under the pack ice near the presence of ice-free waters: the "ice edge spring bloom". This biological "explosion" easily explains the richness of the pelagic and coastal biotopes in the Arctic, fed by both sunlight and the salts excluded by the crystallisation of seawater into ice. In summer, this bio-productivity shifts towards ice-free waters and peaks when daylight becomes continuous.

Diatoms also produce specific organic molecular tracer, as the IP25s biomarker, which make it possible to reconstruct the extent of the pack ice in marine sediments, over and above those found in historical sources.

The creep and drift of pack ice from foreshore areas allows certain species to migrate to the littoral zone outside their normal geographical range. This is the case for *Spartina grass* on the east coast of Canada. Pack ice and drifting icebergs also allow sporadic migration of animal species that are poor swimmers, such as polar foxes and mustelids. During the Holocene, before the arrival of the Vikings, the only known non-marine mammal in Iceland was the polar fox, while traces of mustelids have been fossilised during the Last Interglacial. Nevertheless, Upper Palaeolithic man was the first to reach North America by following the edge of the pack ice, seeing the shaping of his flint artefacts (Folson versus Solutrean, ca 20 ka BP and later).

In contrast to these mechanical actions, ice floes and especially ice foot efficiently protect coastlines from the impact of storm waves, currents and biological agents for much of the year. In Arctic regions, the ice hinders the action of waves and currents for 8 to 11 months. Wave heights are often limited, and periods of effective swell are infrequent in the Arctic seas. In the North Atlantic, where cyclonic lows can rise in latitude during winter, storms play a very important role: the Barents Sea may be the coldest of the Arctic seas, but it is also the roughest (Loset et al., 1999). The rise in storms over the Arctic is mechanically more efficient than a rise in sea level in explaining perched beaches (outside glacio-isostasy), coastal retreat and the melting of coastal permafrost (Van Vliet-Lanoe et al., 2014). At Shismaref, on the north-west coast of Alaska, the upwelling of cyclonic storms caused the ice foot to disappear early, allowing the erosion of a coastal spit formed around 1000 AD (see USGS).

PACK ICE AND THERMOHALINE CIRCULATION: THE INDIRECT PACEMAKER OF OUR CLIMATE

The Thermohaline Circulation (THC) is superficial and managed by three main factors: evaporation in the intertropical zone and the Mediterranean, a superficial cooling of salt water as it approaches the poles, and the formation of brine by the exclusion of salts under the Arctic and Antarctic ice packs. These factors combine with the warming of surface waters and evaporation in the inter-tropical zones, controlled directly by insolation. This warming by solar UV rays affects the upper 200 metres of the ocean. It is in this intertropical zone that the highest levels of atmospheric water vapour have been observed (see 2023, the first maximum of solar cycle 25, Earth Observatory).

The oversalted water, weighed down by the exclusion of salts during the crystallisation of the pack ice, accumulates at the bottom of the oceans, where it circulates alongside its surface counterpart, **the North Atlantic Deep Water (NADW) circulation**. The more salt-rich the surface water arriving in the Arctic, the easier it is for deep water to form. This phenomenon becomes more pronounced during periods of high solar activity, at the same time as evaporation increases in the intertropical zone and in the Mediterranean. **Its richness in dissolved salts generates fertility when it rises to the surface to form an upwelling thanks to the action of winds and surface marine currents.**

The water desalinated by crystallisation and the summer melt form a light surface layer that floats on the ocean surface and will stratify the water at high latitudes. This will push back the underlying cold brine plunge zone to lower latitudes and the circulation will slow down, deflected eastwards during the cooling period by Coriolis. The Arctic zone, deprived of warm surface water, will begin to cool and a desalination pack ice may form again, increasing the albedo and reaccelerating the thermohaline circulation. Certain climatic events, such as Dansgaard-Oeschger (DO) warming, may be controlled by such feedback.

In addition to direct sunlight, the melting of the pack ice is therefore mainly caused by the arrival of 'warm' surface water brought in by NAC and the upwelling of storms (polar front upwelling) that break it up. This explains the exceptional melting of the Arctic ice pack in 2007, 10 years after the Super Nino of 1997-98. The activity of the Arctic gyre explains the rest: when the current becomes stronger, in the context of a positive Arctic Oscillation (AO), it expels the old, multi-year, thick, salt-depleted ice along the east coast of Greenland like a centrifuge. As the annual ice is thinner (< 2 m), this melts much more easily.

On the other hand, the waters transported by the Gulf Stream in the North Atlantic, warmed by solar activity, contribute to the NAC that extends it, with an energy input that is greater in summer over the Arctic (polar night in winter). This effect can then be counterbalanced at the surface of the ocean, particularly along the east coast of Greenland, by the inflow of fresh water linked to the melting of glaciers and permafrost, but also, as has been the case for the last fifteen years or so, by the melting of the very old ice pack, expelled from the Arctic Ocean by the functioning of the N polar gyre.

When the desalinated or iceberg melt zone extends too far southwards, these masses of freshwater thwart the initial mechanism of the thermohaline circulation, which does not disappear, but slows down very sharply and its activity is more limited in terms of extension in latitudes. This can be explained very well by the nature of the currents, which are not a "quiet river" at the surface of the ocean, but a series of eddies with a slow global propagation. During the last Glacial Maximum, the North Atlantic plunged to the north-west of Ireland.

For our regions, this mechanism of surface desalination limits the rise in latitude of the warm Gulf Stream current and periodically leads to a marked cooling of the climate. But given the permanence of the Coriolis force, the THC has never stopped and will never stop in the current context of the distribution of continental masses.

INSOLATION, CLIMATE AND PACK ICE

During the periods when the Quaternary glaciation began, storms developed between 40 and 70°N with an intertropical ocean that was still warm, in contrast to the marked cooling of the Arctic. **The North Atlantic ice caps suffered from a lack of precipitation at the start of the (cold) stages due to aridity caused by the seasonal extension of the pack ice. The delayed fall in sea level is the result of ice storage in permafrost and pack ice, which has led to a decrease in $\delta^{18}O$ values in seawater ($\delta^{18}Osw$) and limited the development of the ice caps (Van Vliet-Lanoë et al., 2024).**

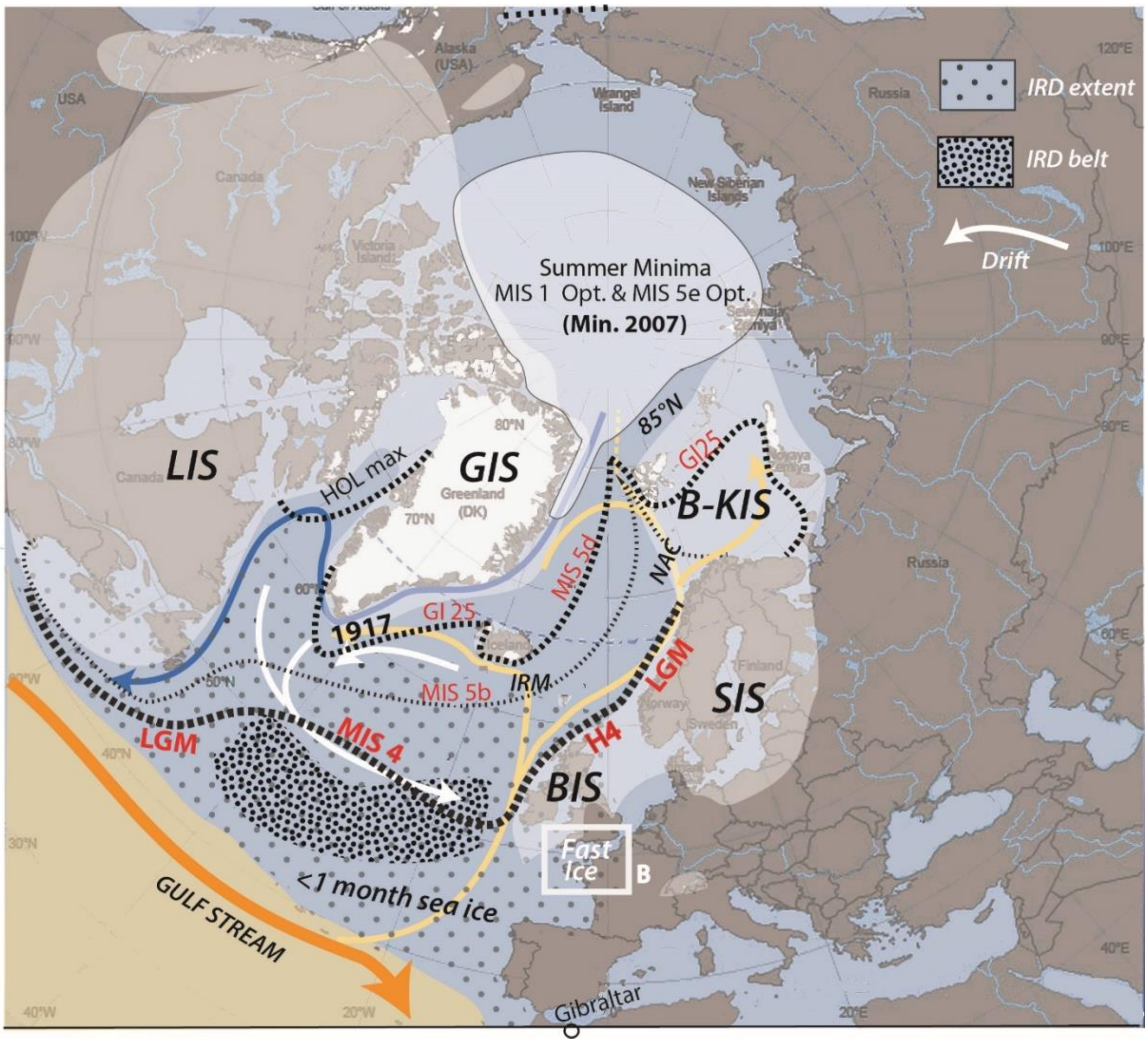

Figure 4: Extent of sea ice and IRD (boulders) released into the North Atlantic by icebergs (adapted from de Vernal et al., 2006; Gersonde and de Vernal, 2013). The dense dashed field corresponds to the Ruddiman iceberg release belt. The blue line indicates the East Greenland Current. The dotted black lines show the extent of the sea ice in winter 1917 (see Figure 3). The LGM glacial maximum (23 ka) and the MIS 4 sea ice extent (<75 ka). IRM: Irminger Current. LIS:

Laurentide Ice Cap; SIS: Scandinavian Ice Cap; B-KIS: Barents-Kara Ice Cap (Van Vliet-Lanoë et al., 2024).

The major ice sheets along the North Atlantic (Laurentide or LIS; Scandinavia or SIS) gradually expanded, especially from isotope stage 4 (MIS 4; 75-70 ka BP) following a resumption of evaporation and summer precipitation (snow) associated with the cyclical restoration of thermohaline circulation during Dansgaard-Oechger (DO) events, alternating with the extension of multi-year sea ice (Wary et al., 2017). Around 40-25 ka BP, it was the floating ice shelves that melted first, destabilising the ice caps edges, sometimes in association with rapid apparent rises in sea level (10 to 20 m). This led to an NAC, destabilised several times, rising towards the Fram Strait in summer or under the Arctic pack ice in winter. Early glacial storage was reduced at the start of the DO warming events, characterised by climatic conditions like those of today. An apparent paradox is that **the current warming recorded in the stratum of Atlantic water under the Arctic ice pack has been perceptible since the early 1990s, whereas the significant thinning of the ice has continued, particularly since the high insolation of 1930-1945 (solar cycles 17-18).** This suggests that the extension of the Arctic ice pack is more complex than previously thought (Mörner et al., 2020), a DO-type mechanism, characterised by the arrival in the Arctic of a NAC warmed by increased insolation from the intertropical zone, as in 2023, which has already been mentioned by many researchers since the 1990s, notwithstanding the IPCC.

If we look at the longer term, the process that led to the formation of ice caps and ice shelves during MIS 4 (75-70 ka BP), mainly in the high latitudes of the HN (Kukla and Gavin, 2004), a period during which the role of precipitation was clearly more important in relation to a marked orbital obliquity (Ruddiman and MacIntyre, 1981). During the last glaciation), the surface of annual sea ice underwent a sudden retraction during the rapid construction of the true ice caps at MIS 4. (Maffezzoli et al., 2019). The North American Ice Sheet (LIS) appeared in northern Canada from 119 ka BP, but its southward extension was delayed until 75 ka (Stokes et al., 2012), because the presence of persistent pack ice reducing precipitation along the northwest Atlantic. This event corresponds to the true start of the fall in sea level, the maximum extension of multi-year sea ice and ice-rich permafrost (Van Vliet-Lanoë et al., 2024). From 58 ka onwards (Wary et al., 2017), DO warming was responsible for pulsed reactivations of the NAC, particularly in summer (Polyakov et al., 2017, Ezat et al 2014), which provided moisture necessary for the growth of the Scandinavian Ice Sheet (SIS). The maximum extent of the multi-year ice pack is reached after the LGM (from 27 to 15 ka), with the rise in insolation from 17 ka (Waelbroeck et al., 2014).

CONCLUSION

Winter drift ice spread into the NH during the Late Pleistocene, south of a potential pack ice boundary between that of MIS 4 and these of the LGM, reaching as far as Spain and possibly Gibraltar during the LGM for drift ice only (de Vernal et al., 2006; Gersonde and de Vernal, 2013). In the north, DO episodes along the NAC track (Wary et al., 2017) allowed the formation of a few large polynyas (ice-free zones) in the summer boarded by a multi-year pack ice. This restored precipitation and enabled the late summer development of the Scandinavian ice cap. The southern edge of the sea ice at the LGM was probably constrained by a retracted Gulf Stream around 40° N (towards North Carolina), which persisted throughout the last glaciation (Ezat, et al., 2014). The Gulf Stream probably never shifted to lower latitudes in response to stronger trade winds at the LGM (solar and orbital forcing). Consequently, only icebergs and drifting ice crossed the ocean towards Gibraltar at that time. Coastal fast ice developed in winter along the ice-free coasts of western Europe as far south as Brittany from the first cooling of the Last Interglacial (119- 116 ka; Van Vliet-Lanoe et al., 2024).

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