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The 21st-century Arctic environment: accelerating change in the atmospheric, oceanic and terrestrial spheres

Earth's climate system transfers excess heat energy from the equatorial regions to the polar regions, where there is a perpetual energy deficit. It is therefore perhaps unsurprising that the effects of further accumulating heat energy, consequent upon increasing anthropogenic GreenHouse Gas (GHG) emissions, should manifest early and strongly in the Arctic, compared to the globe as a whole. Yet the Arctic also possesses distinctive environmental characteristics that act as strong, positive feedbacks on atmospheric warming. In fact, the Arctic is almost uniquely susceptible to rapid change brought about through climate warming from both natural and anthropogenic sources. The aim of this commentary is to outline recent and probable future environmental changes in the Arctic. It commences with a consideration of rates of change through the satellite era in air temperatures, sea ice extent, snow cover and the state of balance of the Greenland Ice Sheet. This is subsequently set against fluctuations over previous centuries and millennia. From this observational basis, the commentary moves on to consider factors which particularly amplify rates of change in high northern latitudes, before addressing further feedbacks which may become important, and how Arctic changes may proceed up to the year 2100.

KEY WORDS: Arctic, climate change, Arctic amplification, sea ice, permafrost, cryosphere

Introduction: rapid, accelerating, exceptional change

The Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC, 2013) states that multiple lines of evidence support very substantial Arctic warming since the mid-20th century. The mean, annual surface air temperature over the Arctic land surface has increased by about 2°C since the mid-1960s. Positive temperature anomalies (values above the 1971–2000 mean) were seen throughout the central Arctic in the first decade of the 21st century (Overland et al., 2012). Such temperatures are exceptional on a timescale of many centuries. Proxy temperature records from Arctic latitudes indicate that atmospheric cooling was underway 2000 years ago, probably attributable to an orbitally-driven reduction in summer insolation (Kaufman et al., 2009). This cooling trend was reversed during the 20th century (Figure 1), with four of the five warmest decades of the past two millenia occurring between 1950 and 2000. Climate simulations show that the majority of this recent temperature increase can be explained by GHG emissions, with near-zero statistical probabilities that natural climate variability could account for observed trends (Fyfe et al., 2013).

Probably the best-known manifestation of Arctic change is the strong decline in sea ice extent, which has exceeded 500,000 km² or 4% per decade since 1979, compared to the 1979–2000 mean. However, the decline in September (the month when the annual minimum extent is reached) has been greater than 800,000 km² or almost 12% per decade, with particularly strong losses caused by unfavourable weather effects superimposed on this trend in 2007 and 2012: the extent at the end of the summer of 2012 was only half the long-term average (NSIDC 2012). Whilst above this downward trend, ice extent in 2013 was still the sixth-lowest value observed since 1979. At the same time, the thickness of the remaining ice has also decreased strongly. Combined satellite and submarine data indicate a thinning rate of 0.6 m per decade in the central Arctic over 1980–2008 (Kwok and Rothrock, 2009). Furthermore, 'multi-year' ice, which has accumulated over several seasons and is significantly thicker and more robust than 'first-year' ice, was 75% of the cover in 1988, but only 45% in 2010. The circulation in the Arctic Ocean basin moves ice counter-clockwise and out into the North Atlantic; almost all ice now is 1–2 years old, with thicker, 4–5 year-old ice having been almost entirely removed (Maslanik et al.,

2011). The thinning of the residual ice cover is an important positive feedback, as ice loss can continue rapidly even during relatively moderate melt seasons.

Reconstruction of long-term sea-ice extent via proxy records, in marine and coastal sediments, allows comparison of recent trends with historical ones (Figure 2), confirming that the recent, late-summer decline is exceptional, apparently unmatched over at least the last few thousand years, and unexplainable by any known natural variabilities (Polyak et al., 2010). The most plausible explanation for the decline remains the inflow of warmer Atlantic water to the Arctic Ocean, which is consistent with anthropogenically-forced warming (Kinnard et al., 2011). IPCC (2013) states that, globally, it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century. For the Arctic specifically, the equivalent statement is that it is likely that there has been an anthropogenic contribution to the very substantial warming in the same period. The lower certainty for the Arctic results from a lesser body of observational evidence, consequent upon the difficulties of operating long-term monitoring programmes in a remote and characteristically inhospitable region. Day et al. (2012) used a General Circulation Modelling (GCM) approach to find that no more than 30% of the sea ice decline from 1979–2010 could be attributed to the natural cycles of the Atlantic Multidecadal Oscillation (AMO) and Arctic Oscillation (AO). Likewise, Stroeve et al. (2011) noted that in 2009–2010, the AO was in a state which should have favoured a large sea-ice extent: that 2010 was actually a year of low sea ice extent instead likely reflects anthropogenic influence.

Sometimes overlooked, given the dramatic changes to sea ice, is that the snow cover of the northern hemisphere in general is also in significant long-term decline (Figure 3). June snow cover extent (a month in which snow is largely confined to the Arctic) is now decreasing at a faster rate (18% per decade) than September sea ice extent (12% per decade) (Derksen and Brown 2012; Jeffries and Richter-Menge, 2013). 2012 was the fifth consecutive year of record low Eurasian snow cover.

The Greenland Ice Sheet (GrIS) is much the largest ice mass in the Arctic, and a repository for some 11% of the global glacier ice mass. Its melt extent has been increasing steadily over the satellite era. In an eye-catching event in July 2012, detected by independent satellites, some 97% of the entire ice surface of the Greenland Ice Sheet, from its low-lying coastal margins to its high-altitude interior, experienced some surface melting for a few days, a situation which was

unprecedented in more than 30 years of satellite observations (NASA, 2012). Typically, about half of the surface of the GrIS experiences at least some summer melting. However, this proportion has been steadily and significantly increasing (Fettweis et al., 2011): recent melt extent is unprecedented in the last 50 years, with the 2000s' melt area being about twice that of the 1980s. This increase has not been offset by any increase in the rate of precipitation or decrease in the rate of iceberg calving. Overall therefore, the average rate of ice loss from the GrIS has very likely substantially increased from 34 Gt yr⁻¹ over the period 1992–2001, to 215 Gt yr⁻¹ over 2002–2011 (IPCC, 2013). The consequences of this change are transmitted globally through the influence of the GrIS on sea levels.

Changes in the snow and ice systems of the Arctic are generally cumulative, with strong links across the seasons and years. For instance, satellite observations of the GrIS in 2011 revealed that its surface was darker compared to the 2000–2006 average (Box et al., 2013). Successive years of high melt, removing increasing areas of surface snow, were responsible, exposing bare ice and allowing dust and soot to accumulate. Even where snow survives year-on-year, temperature-driven changes in the size and shape of snow grains cause further darkening (Box et al., 2012). The darker surface is less reflective to solar radiation, causing more solar energy to be absorbed, thus favouring further melting in a positive feedback process, expanded upon below.

The importance of Arctic Amplification

The Arctic is warming at least twice as fast as the global average (ACIA, 2005; Jeffries and Richter-Menge, 2013; Figure 4). Atmospheric warming in high northern latitudes is amplified by several, strong, positive feedback mechanisms. First, the Arctic troposphere (the lowermost layer of the atmosphere) is relatively thin: only about half as deep as the equatorial troposphere. Therefore, a given amount of energy will be more effective in warming the Arctic atmosphere, other factors being equal. Second, the cover of perennial and seasonal snow and ice on the land and ocean surfaces of the Arctic acts as an energy sink: inputs of atmospheric energy are consumed in first raising this snow and ice to the melting temperature, and then in converting it from solid to liquid (latent-heat absorption). Only when the snow and ice cover has been removed, with the consumption of large amounts of atmospheric

energy, can the temperature of the surface and its overlying air be raised. As the extent of snow and ice decreases, the efficiency of this energy sink decreases: less energy is consumed in melting, so more is available to raise surface temperatures. Similarly but to a lesser extent, the presence of impermeable permafrost beneath the Arctic land surface leads to poor drainage, meaning that soils are often waterlogged in summer, keeping the supply of water for evaporation high, which also consumes atmospheric energy. This is also an effect which diminishes as permafrost degrades and Arctic soils become more freely-draining.

Third, but most importantly, the loss of snow and ice, particularly over the ocean, greatly reduces the albedo, or reflectivity, of the Earth's surface. Over fresh snow, the reflection of solar radiation is extremely efficient, with 90% or more of incoming energy returned back to space. Over open ocean water however, this figure falls to around 10%. Therefore, as snow and particularly sea ice diminish in area, the albedo of the surface decreases, more atmospheric energy is absorbed, more snow and ice melts, and albedo is further decreased: a highly effective, positive-feedback on atmospheric warming. Pistone et al. (2014) quantified the effectiveness of this feedback in an analysis of 30 years of satellite microwave data, finding that the decline in Arctic albedo yielded atmospheric forcing equivalent to 25% of that due to CO₂ emissions in the same period. Snow-free Arctic land surfaces are more efficient reflectors than the ocean, but they too are becoming less efficient as warming contributes to vegetation growth, and bare ground or tundra vegetation gives way to shrubs and trees (Epstein et al., 2013; Xu et al., 2013; Figure 5). Atmospheric black carbon particles (soot, derived from various sources including forest fires, diesel or wood combustion, oil and gas flaring) can accumulate on snow or ice surfaces and further contribute to the lowering of albedo (AMAP, 2011). The fallout of black carbon is at a maximum in the Arctic in late winter, and models suggest that this may be increasing spring snowmelt rates by 20–30% (Flanner et al., 2007).

The potential for positive feedbacks

Permafrost (perennially frozen ground) is believed to contain up to 1700 Gt of carbon: about four times more than all the carbon emitted by human activity in modern times. The upper 3 m of permafrost is estimated to hold as much carbon as all known coal

reserves (Tarnocai et al., 2009). If that permafrost were to thaw and soils became waterlogged, soil microbes could convert the carbon into methane (CH₄). If the soils instead drained, the carbon would be respired into the atmosphere as carbon dioxide (CO₂). Much uncertainty currently surrounds the potential for these processes to occur and at what rates, but it is clear that permafrost is thawing over wide areas. Since the 1990s, the thickness of the seasonally-thawing surface ground layer (the active-layer) has increased in the Eurasian Arctic, Siberia, Chukotka, Svalbard and Greenland (Romanovsky et al., 2012).

Permafrost soils bordering the Arctic Ocean contains as much shallow carbon as all the world's temperate and tropical forests, grass and shrubland ecosystems and agricultural land combined. Reduced sea-ice cover is now exposing Arctic coastlines to greater wave action and accelerated coastal erosion compared to previous decades. Coastal erosion at Yedoma, northern Siberia, is currently believed to destabilise about 44 Mt of permafrost carbon each year, of which about two thirds becomes atmospheric CO₂ (Vonk et al., 2012). As yet, there is no direct evidence that either Arctic emissions of CH₄, or the net carbon balance, are changing over the Arctic as a whole (Bruhwiler and Dlugokencky, 2012), but reducing the uncertainty surrounding these processes is a key scientific priority, given the potential magnitude of the associated feedback. IPCC (2013) states that it is virtually certain that Arctic permafrost extent will decrease as atmospheric temperature increases through the 21st century, by about 80% for a business-as-usual scenario. Lawrence et al. (2008) predict that annual permafrost carbon emissions could eventually equate to 15–35% of today's annual anthropogenic emissions. A potentially even more significant feedback is associated with methane in the seabed of the Arctic Ocean, notably off the coast of Siberia. Sub-sea clathrate (a form of water ice that contains large amounts of methane within its crystal structure) is estimated to contain 1400 Gt of methane, which is a much more powerful GHG than CO₂. These clathrates remain stable under a combination of high pressure and low temperature, but are thought to become vulnerable as sea ice retreats and ocean temperatures increase.

21st-century prospects

IPCC (2013) state, with very high confidence, that the Arctic will warm more rapidly than the global mean over the 21st century. As it does so, Arctic sea ice will continue

to diminish in extent and volume, and Northern Hemisphere spring snow cover will continue its decline, particularly in spring, when the albedo feedback is particularly effective. The pathway sea ice decline ultimately follows depends sensitively on the magnitude and rate of GHG emissions, but even for a future scenario envisaging aggressive, early decarbonisation, more than a 40% reduction in September sea ice extent by the end of the 21st century is predicted. At the time of the previous IPCC assessment report in 2007, models were significantly under-estimating the rate of sea-ice decline: progress has been made since, and current rates of decline can now be simulated with greater confidence, but much uncertainty remains with respect to specific GHG scenarios and decade-to-decade variability. It is generally agreed, however, that significant September sea ice is unlikely to remain by the end of the 21st century, and most probably not even by 2050 under a business-as-usual scenario. The spring snow cover decrease under the same conditions is projected to be a less dramatic, but still highly-significant, 25%.

The Arctic is particularly sensitive to the effects of black carbon: the deposition of soot on snow and ice has a much greater impact than its presence in the atmosphere, which is more important in mid-latitudes (Sand et al., 2013). Greater controls on air pollution have recently contributed to reduced black carbon emissions from industrialised northern countries (AMAP, 2011), but if significant oil and gas extraction goes ahead, such emissions would increase within the Arctic itself. It has been suggested that black carbon emissions from increased Arctic shipping may increase five-fold by 2030 (Corbett et al., 2010). Russian President Vladimir Putin has already declared an intention to transform the Northern Sea Route into a globally-important shipping lane by 2020, with a 40-fold increase in traffic (Corell et al., 2013).

In considering the 21st-century evolution of the Arctic environment, it is important to bear three main issues in mind. First, the Representative Concentration Pathway (RCP) 8.5 scenario used for the IPCC (2013) report to provide an upper limit on climate projections is not a worst-case scenario, but a business-as-usual one (and has been referred to as such in this commentary). As reported by the International Energy Agency (IEA), about 80% of the power stations likely to be in use in 2020 are either already built or currently under construction, which means a commitment to continued emissions from these power plants, which will be responsible for about 30% of global CO₂ emissions (IEA, 2012). This means that

decarbonisation must be very early and very aggressive in order to avoid the most pessimistic predictions which have been reviewed in this commentary.

Second, it should not be assumed that warming, by ameliorating the Arctic, will necessarily “improve” its environment or ecosystem. For instance, with sea ice loss, increasing exposure of open water to solar radiation has resulted in an August sea surface temperature as much as 3°C higher, upper-ocean heat content as much as 25% higher, and freshwater accumulation as much as 25% higher, over much of the Arctic Ocean compared to the 1970s (Jeffries et al., 2013). However, freshwater accumulation increases ocean stratification, preventing the free cycling of nutrients from shallow to deep and limiting biological productivity, which might otherwise be favoured by warmer temperatures: “A warming Arctic... will simply be an ice-free version of the desert it already is” (Economist, 2013). A further concern is the acidification of the Arctic ocean, a process to which it is particularly susceptible because of the greater solubility of CO₂ in cold water. Changes in ocean chemistry may already be impacting the ability of some animals to build shells (Carmack et al., 2012). Likewise, the greening of the Arctic is not uniform: some boreal forests are actually exhibiting less vegetation growth now than they did in the 1980s (Figure 5), with droughts, forest fires, animal and insect behavior and pollution among the possible explanations (Xu et al., 2013).

Third, Arctic amplification ensures that the actual atmospheric temperature increase in high northern latitudes will be much greater than the global average value. Under the business-as-usual scenario, a 2.6–4.8 (mean 3.7)°C global average temperature increase is likely by the 2090s. This implies a warming, even without considering worst-case scenarios, of 9°C over large parts the Arctic (Figure 6). This rate of warming exceeds anything encountered during human occupation of Arctic latitudes.

Conclusion: fast change, further change

Recent changes to the atmosphere, cryosphere, land and oceans of the Arctic are exceptional on a timescale of thousands of years. Processes of Arctic Amplification, particularly but not only the positive feedback resulting from declining albedo, have caused accelerated change compared to the global average. While the feedbacks that have caused this acceleration are natural, physical processes, the changes that

initiate them are beyond significant doubt anthropogenic: humankind is changing the Arctic, principally through GHG emissions at lower latitudes. By the end of the 21st century, without significant, early reductions in such emissions, it is highly improbable that the Arctic will be anything other than significantly warmer than it is now. While this warming will be ecologically-beneficial in some respects, it will also be detrimental in others, with the net outcome still unclear. An enhanced commitment to research and monitoring is imperative to understand and manage exceptional change in what is still a sparsely-documented part of the world. 21st-century climate and environmental change in the Arctic will exceed that previously encountered there by people, and will require correspondingly unprecedented responses.

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Figure captions

Figure 1 Recent Arctic air-temperature change is exceptional on a timescale of many centuries. Reconstructed temperature anomaly record (blue, with uncertainty limits in grey) and observed values (red, for late 19th–20th centuries) from North of 60°N

Source: adapted from Kaufman et al. (2009).

Figure 2 Recent Arctic sea-ice change is exceptional in the long-term. Reconstructed late-summer sea-ice extent (red, with uncertainty limits in lighter red) and observed values (blue, for late 19th–20th centuries)

Source: Kinnard et al. (2011)

Figure 3 Northern Hemisphere spring snow extent is in decline. Snow cover anomalies (annual departures from the long-term mean) in the Northern Hemisphere show increasingly negative values since the mid-1990s

Source: <http://nsidc.org/arcticseaicenews/2012/07/>

Figure 4 The Arctic is warming more than twice as fast as the rest of the Earth. Global temperature anomalies for 2000–2009, i.e. how much warmer or cooler a region was compared to its 1951–1980 mean. Global temperatures were about 0.6°C higher in 2000–2009 compared to 1951–1980, but for the Arctic, this figure was about 2°C

Source: <http://climate.nasa.gov/news/927>

Figure 5 The Arctic is greening – mostly. Changes in vegetation growth in the Arctic 1982–2011, assessed by the satellite-measured Normalized Difference Vegetation Index (NDVI). Green indicates increased growth and brown indicates decreased growth

Source: <http://earthobservatory.nasa.gov/IOTD/view.php?id=80637>

Figure 6 The Arctic will continue to warm at a faster rate than the rest of the Earth. Modeled surface air temperature change by 2081–2100 for future GHG emissions scenarios RCP2.6 and RCP8.5, respectively reflecting atmospheric CO₂ concentrations of 421 and 936 ppm by 2100 (IPCC, 2013). Hatching indicates regions where the predicted mean is small compared to natural variability. Stippling indicates regions where the predicted mean is large compared to natural variability

Source: http://www.climate2013.org/images/uploads/WGIAR5-SPM_Aproved27Sep2013.pdf

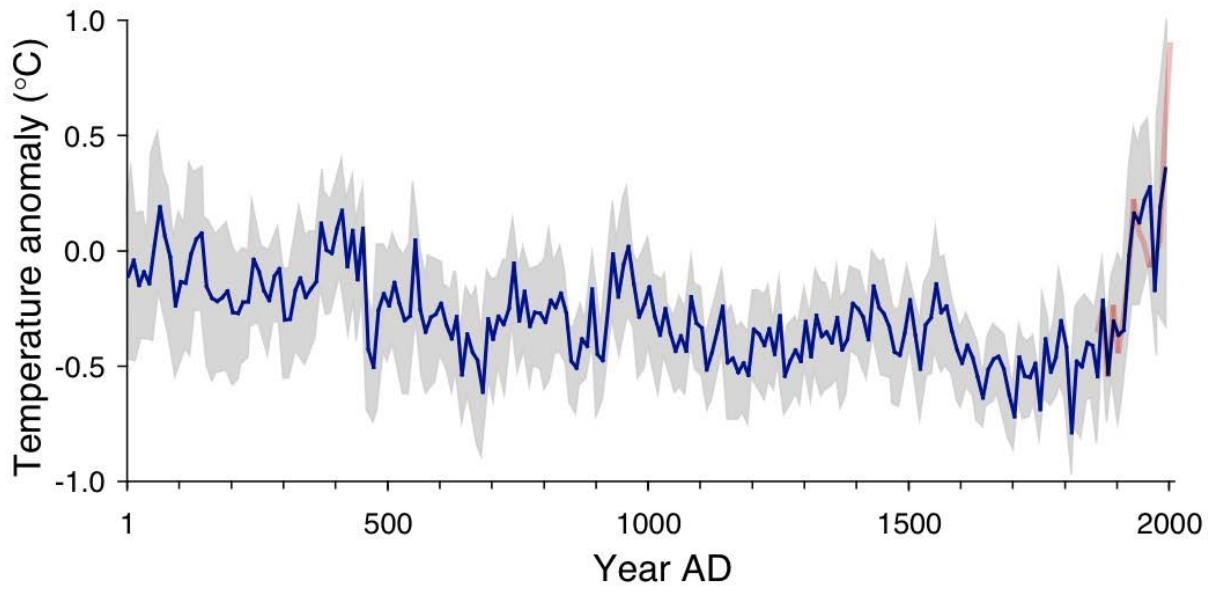


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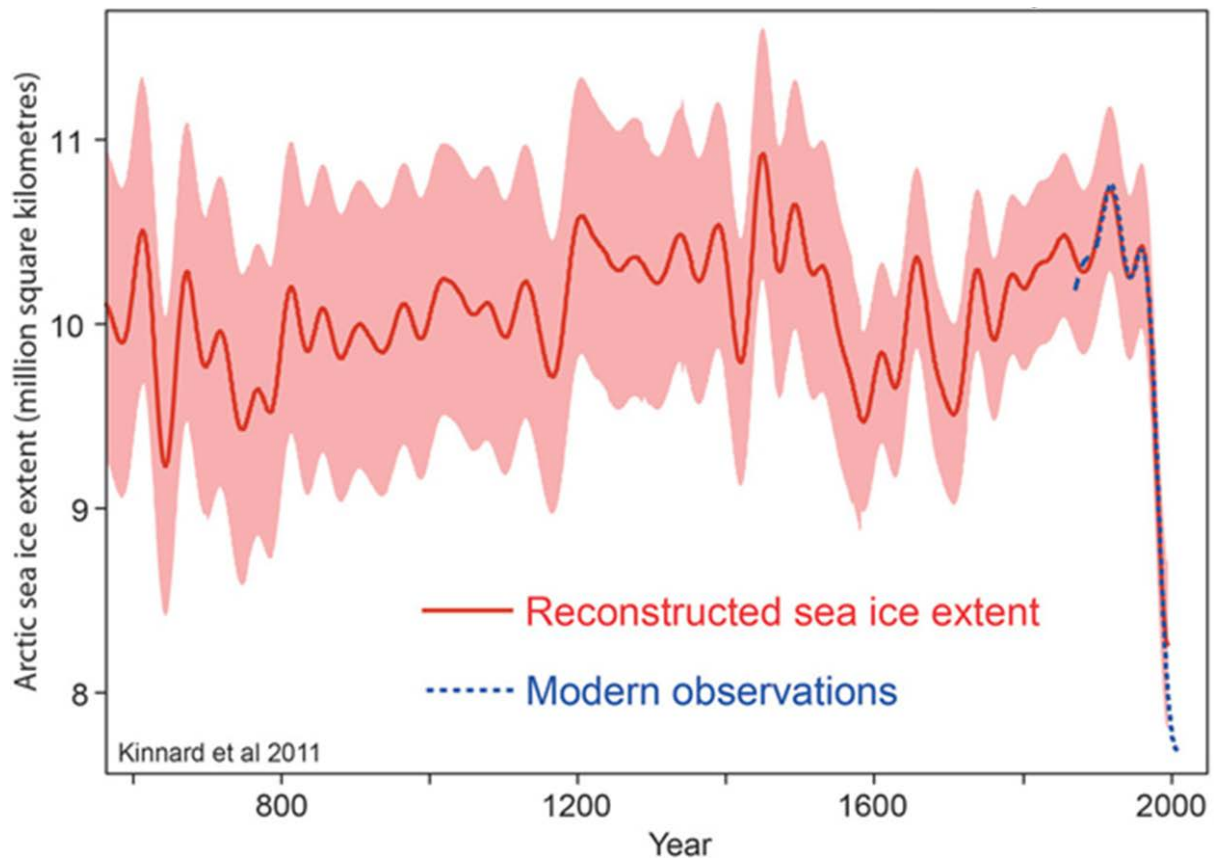


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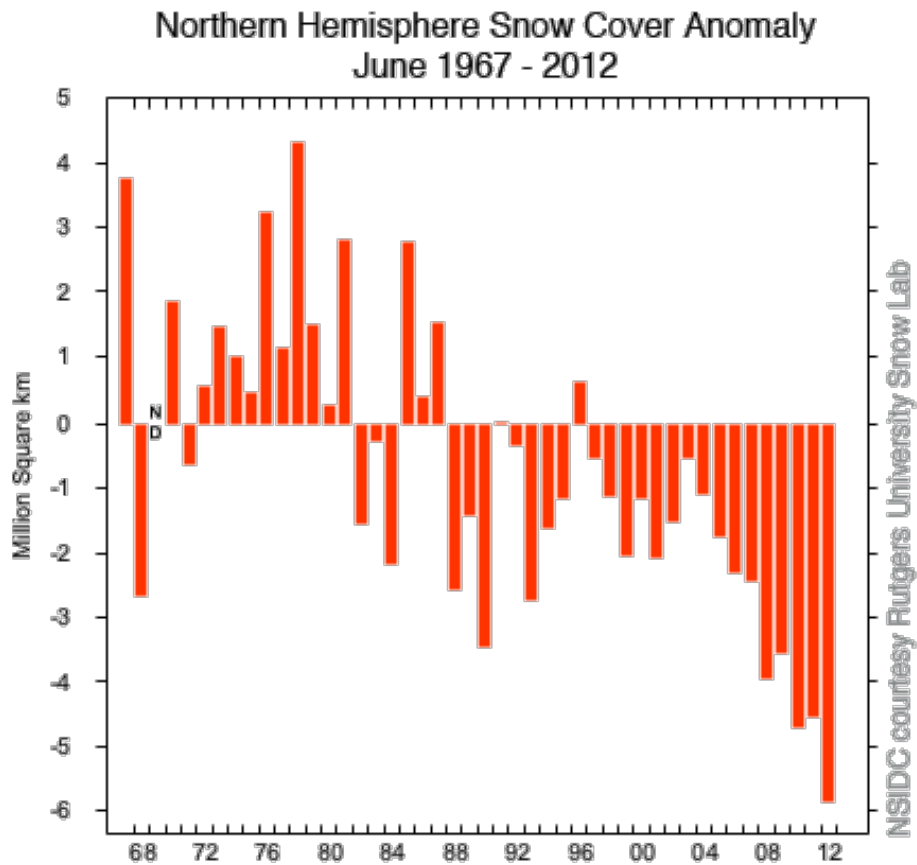


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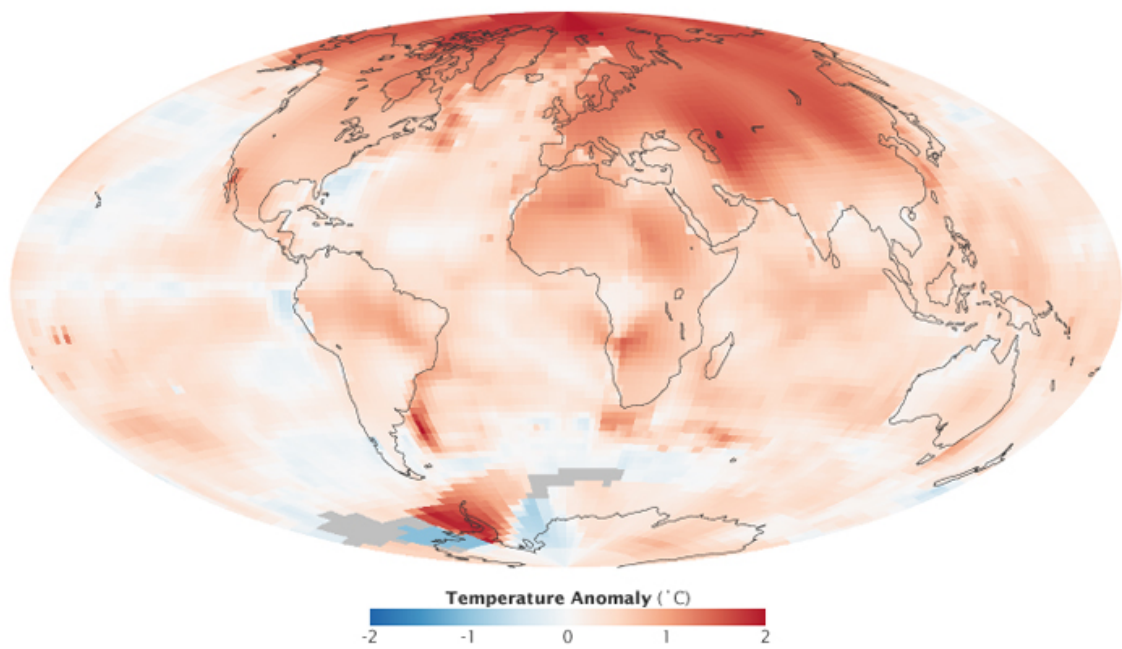


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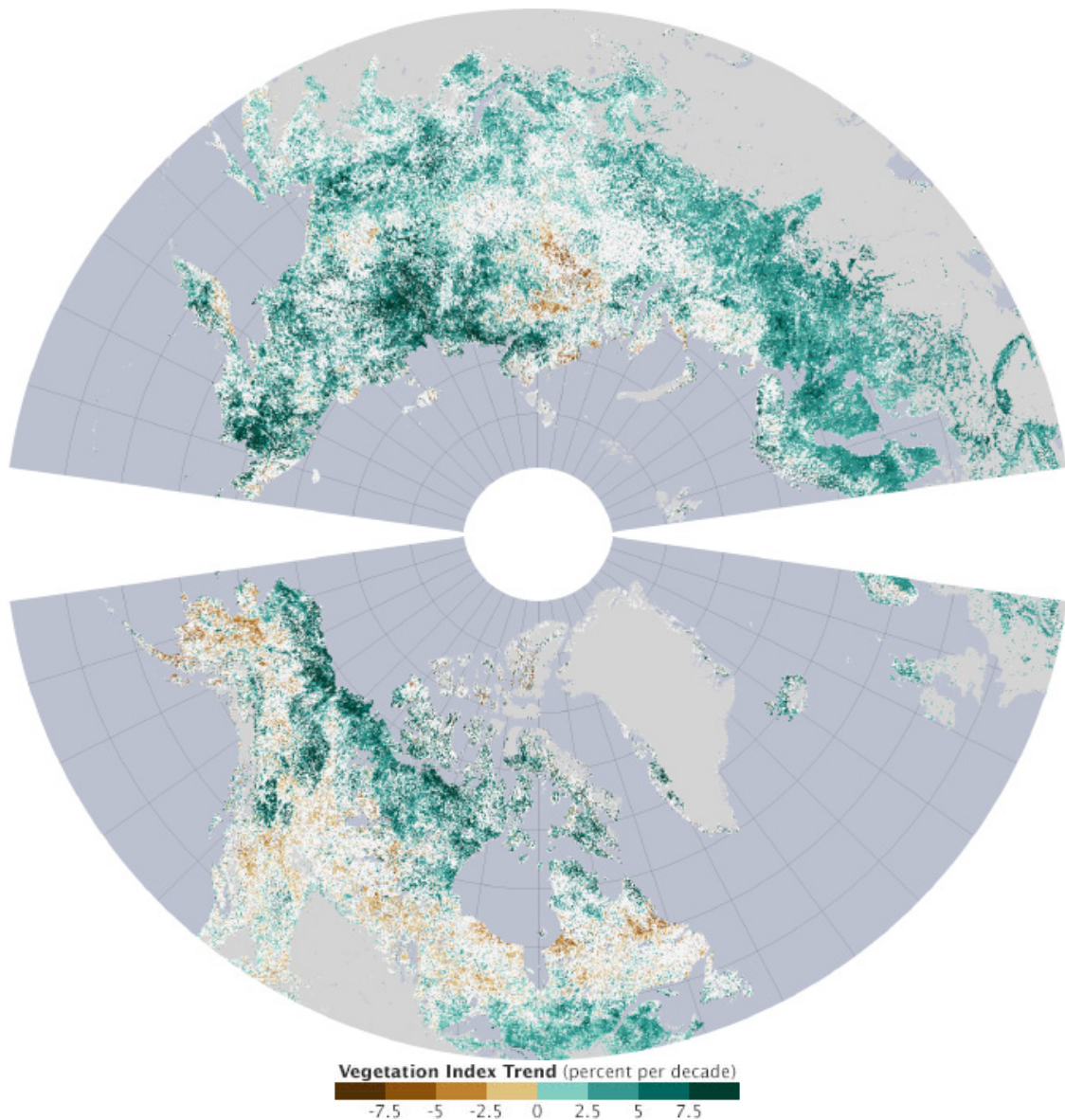


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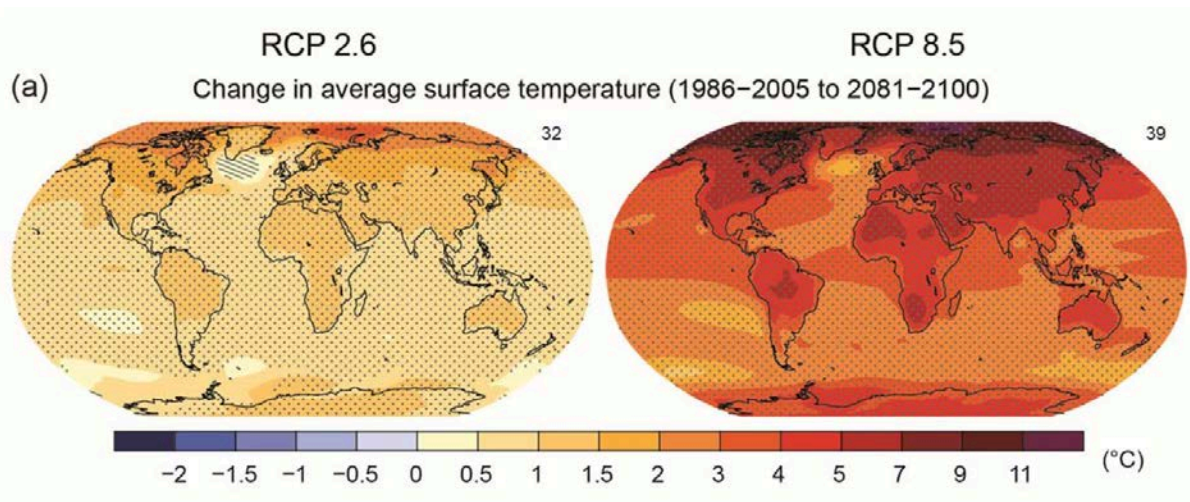


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