to 5,000 GtC in the four comprehensive CMIP5-ESMs (red line in Fig. 1). Thus, there is no evidence of the pronounced decrease in the ratio under high CO_2 emission levels as simulated by the seven EMICs analysed (blue line in Fig. 1) and shown with simpler models[2]. This lower predicted warming in EMICs than in CMIP5-ESMs is in agreement with an earlier study[6] and is of particular concern because EMICs are the tool of choice for long-term climate response simulations as simulations with CMIP5-ESMs are still computationally too expensive to run for more than a couple of centuries.

One element that was not investigated in detail in this study is why the global warming response to cumulative carbon emissions in the four CMIP5-ESMs differs from the EMICs. It is well known that radiative forcing increases non-linearly as the concentration of CO_2 in the atmosphere increases; at higher CO_2 concentrations the increase in radiative forcing becomes smaller. Therefore further addition of CO_2 to the atmosphere has a progressively smaller warming effect. At the same time, the ability of the ocean and land to take up heat and CO_2 is also diminished under higher CO_2 concentrations, counteracting the dampening in radiative forcing and resulting in a linear relationship between warming and cumulative CO_2 emissions up to 2,000 GtC (ref. 7). In EMICs, it is believed[2] that the diminished radiative forcing dominates over the decreasing ability of the ocean and land to take up heat and CO_2 at high emissions. This results in a decrease in the ratio of warming to emissions at high cumulative carbon emissions in EMICs. The fact that CMIP5-ESMs instead show a constant ratio of warming with carbon emissions even at high cumulative CO_2 emissions is likely to be related to some physical processes that are included in the CMIP5-ESMs — but not in the EMICs — that result in different warming responses. Three possible factors are: first, CMIP5-ESMs tend to initially warm at a slower rate after being forced by CO_2 than EMICs[6]. As a result, the CMIP5-ESMs simulate a stronger weakening of the heat fluxes into the deep ocean under continued CO_2 emissions, and a stronger global warming. Second, the climate sensitivity — the change in temperature for a given change in CO_2 concentration — may also increase as cloud cover[8] and ocean heat uptake patterns[9] change under global warming. Third, the radiative forcing of CO_2 might rise slightly (~5%) more linearly with high CO_2 concentrations[10] in CMIP5-ESMs. Ocean physics, clouds feedbacks and radiative forcing are all features that are simulated only in a simplified manner and at a coarse resolution in EMICs. But how can we verify these processes and validate the models? Observations might help constrain ocean circulation changes, which have been identified as contributing factors for changes in ocean heat uptake efficiency and efficacy[11], whereas the changes in climate sensitivity over time may be less approachable with observational constraints. In any case, additional analysis and sensitivity studies are urgently needed to better understand not only the causes of the differences between CMIP5-ESMs and EMICs, but also among the individual models.

Ultimately, the work by Tokarska and colleagues[1] highlights that the regulatory framework based on cumulative CO_2 emissions is probably robust over a much wider range of plausible CO_2 emissions than previously thought. This implies that the unregulated exploitation of fossil fuel resources could result in significant, more profound climate change. ❐

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ATMOSPHERIC DYNAMICS

Arctic winds of change

The Earth's climate evolves in response to both externally forced changes and internal variability. Now research suggests that both drivers combine to set the pace of Arctic warming caused by large-scale sea-ice loss.

Dirk Notz

Never before, since the beginning of reliable observations, has the maximum extent of Arctic winter sea ice been as low as this year[1]. Such large-scale loss of sea ice is one of the most visible manifestations of climate change, and also a key driver of the rapid warming that the Arctic currently experiences[2]. However, the quantitative contribution of sea-ice loss to Arctic warming has remained unclear. Now writing in *Nature Climate Change*, James Screen and Jennifer Francis[3] suggest that the warming contribution of sea ice is not constant, but modified by atmospheric circulation patterns that are related to the surface temperature distribution in the Pacific.

Despite its geographical remoteness, the Arctic is probably one of the regions most intensely studied by climate researchers. Their interest is, among others, driven by the rapidity of climate change in the high northern latitudes, with a warming rate that is two to three times as fast as for rest of the planet (Fig. 1). This Arctic amplification, which is both a robust outcome of climate model simulations[4] and of observational records, increases the melt rates of sea ice, land ice and permafrost soils alike. The various melting processes, in turn, further amplify the initial warming, as less sea ice reflects less warming sunlight, a lower ice sheet has a higher temperature because atmospheric temperature increases towards sea level, and melting permafrost soils emit methane, a very effective greenhouse gas.

The high rates of warming in the Arctic are related to a number of factors. The most important ones are those related to surface processes[4]. First, for a given surface warming, less longwave radiation is emitted back into space at high latitudes compared with lower latitudes, so an increase in incoming radiation causes a larger net warming. Second, as the high latitudes warm, the ice cover decreases, and so does the reflectivity of the surface. Hence, sunlight is more effectively absorbed by the surface, contributing further to high rates of warming. In the Arctic, this second process is, to a substantial degree, related to the shrinking sea-ice cover in the Arctic Ocean.

In their study[3], Screen and Francis explore this contribution of sea-ice loss to Arctic amplification in more detail. To do so, they first analysed data sets based on observational records and found that sea-ice loss seems to contribute more to Arctic warming when the Pacific Ocean in the northeastern mid-latitudes is comparatively cold, and vice versa. These temperature patterns of the Pacific Ocean are often consistent for a number of years, which is why their large-scale fluctuation is referred to as the Pacific Decadal Oscillation, a natural climate cycle. To understand these linkages in more detail, Screen and Francis used a numerical atmospheric model in which they prescribed either low or high sea-ice coverage, and either a cool or warm Pacific Ocean, consistent with observed patterns of the Pacific Decadal Oscillation.

Examining the warming in the central Arctic for the various model configurations, they found a similar relationship as in the observations. They then used their simulations to suggest a possible mechanism for these linkages. The explanation is related to the fact that air over open water is much warmer than air over sea ice, which is why the loss of sea ice goes along with a local warming of the air. If that warm air can be transported into the central Arctic, from areas of sea-ice loss at the ice edge, then the contribution of sea-ice loss to Arctic warming is increased. Screen and Francis find, in their simulations, that the efficiency of this transport is related to changes in the wind pattern driven by the temperature structure of the Pacific Ocean. That is, when the prescribed oceanic temperature in the northeastern Pacific was colder, northward winds were enhanced, as was the contribution of sea-ice loss to Arctic warming.

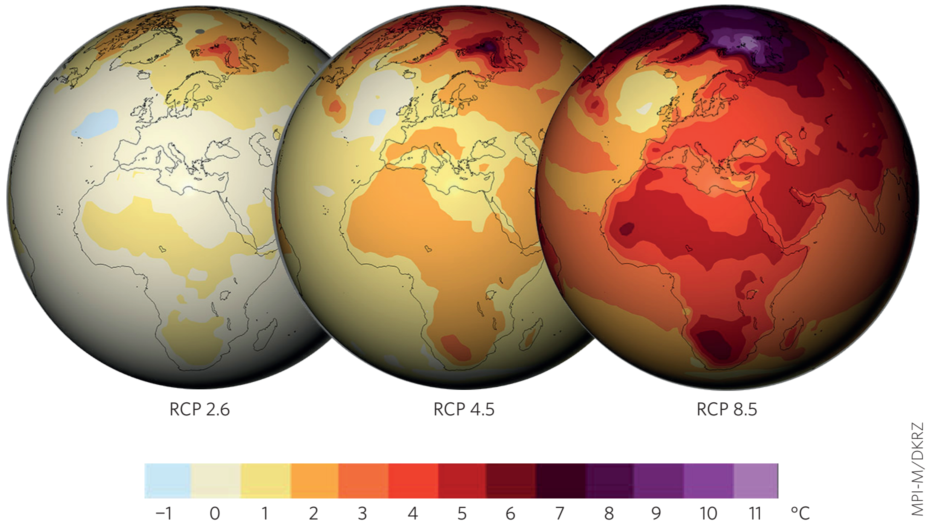

Figure 1 | Enhanced Arctic warming. Model simulations of possible warming throughout the twenty-first century for three different representative concentration pathways (RCPs) clearly show the enhanced Arctic warming.

The study implies that the effect of externally forced changes of the climate system, such as the ongoing Arctic sea-ice loss, can vary in response to internal variations of the climate system. This finding, if robust, would have important implications not only for our understanding of climate change, but also for helping us to better predict the short-term evolution of climate on seasonal to decadal time scales. For example, if recent comparatively warm surface temperatures of the northeastern Pacific are maintained, this study[3] suggests that Arctic wintertime warming might be slowed down for some time.

However, as with all studies that suggest new ideas, it remains to be seen if follow-up work confirms the findings. The mechanistic description and the agreement between observation and simulation that Screen and Francis[3] present certainly invite such work. In reality, the past winter has certainly not followed the study's overall findings — according to the proposed mechanism, North Pacific temperatures would have been suggestive of rather low Arctic warming temperatures, but observations show that the central Arctic has been consistently well above average. The rapid changes in the Arctic will certainly keep these remote latitudes in the spotlight of our research attention for some time to come. ❒

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