aerosols and land-cover change) were included in addition to natural forcings (solar and volcanic). This suggests that anthropogenic forcings are responsible for the historical (1950–2005) monsoon weakening. They also investigate the effect of the different anthropogenic forcings by comparing the GHG-only forced climate with the combined aerosol and land-cover forcings. Without aerosol and land-cover changes, GHGs would have caused an intensification of seasonal rainfall over India. This implies that the non-GHG (aerosols and land-use) anthropogenic forcings are responsible for the observed changes in seasonal rainfall. Running the model forward, the observed weakening of monsoon rainfall continues through the late twenty-first century.

This study confirms that aerosols have substantially weakened the monsoon and masked the effect of GHG warming. However, although seasonal rainfall has weakened, extreme rainfall events (>100 mm d^{-1}) over central India have become more frequent due to the increased atmospheric moisture availability associated with GHG emissions[8]. The results of Krishnan *et al.*[3] also highlight the role of land-cover change as a substantial weakening influence on regional rainfall, but their modelling experiments do not effectively distinguish the effect of land-cover change from the effect of atmospheric aerosols — thus the relative contribution of these non-GHG anthropogenic forcings to monsoon changes in the present and future climate still needs to be quantified.

Most global coarse-resolution modelling studies project that monsoon rainfall will increase in response to future increases in GHGs, as increasing moisture will overcome the weakening of thermally driven winds. In contrast, this study shows a continued weakening of rainfall into the twenty-first century in response to increasing GHG forcing, suggesting that the wind-weakening effect dominates, consistent with another high-resolution model[9]. However, this study is not concrete evidence that the monsoon will weaken. The different responses need further investigation; they could be a consequence of the improved representation of finer-scale processes, feedbacks and orography, highlighting their potential importance in governing the response of the monsoon circulation to external forcings. Alternatively, internal variability of the monsoon could be a major confounding factor, as this alone could cause differences in the direction of future rainfall trends. A larger number of high-resolution simulations are needed to determine whether the decreasing trend is a robust response to anthropogenic forcing or a result of internal variability, whereas this study uses only a single model run.

The findings of Krishnan *et al.*[3] have substantial socio-economic implications for the region, as well as policy implications for enforcing stringent controls to reduce aerosols from fossil fuel and biomass burning. Over South Asia, biomass and agricultural burning contribute over 50% of total aerosol emissions[10]. The relatively short lifetime of aerosols (weeks) relative to GHGs (~80 years) provides scope for reducing their negative impacts relatively quickly. The results also highlight the uncertainty in the future of the monsoon to increasing anthropogenic forcings, pointing to an urgent need to reduce these uncertainties to support adaptation efforts. Improved predictions of monsoon characteristics, aided by studies such as this one, will help people to better prepare for future disasters and adapt to anthropogenic climate change. ❐

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CRYOSPHERE

Warming ocean erodes ice sheets

Antarctic ice sheets are a key player in sea-level rise in a warming climate. Now an ice-sheet modelling study clearly demonstrates that an Antarctic ice sheet/shelf system in the Atlantic Ocean will be regulated by the warming of the surrounding Southern Ocean, not by marine-ice-sheet instability.

Kazuya Kusahara

The polar regions are undergoing change as atmospheric concentrations of greenhouse gases increase[1]. The Antarctic and Greenland ice sheets are two of the most important subsystems of the Earth's climate system. These ice sheets are large reservoirs of fresh water, and more than 60% of all fresh water on the Earth's surface is pinned as ice over the Antarctic continent. If all the Antarctic ice sheets melted, global mean sea level would rise by more than 60 m. Therefore, although Antarctica is very far from human civilizations, its ice sheets could impact on our lives through sea-level change. Thus, the potential contribution to sea-level rise from Antarctic ice sheets has received much attention, both scientifically[2] and socially. Recent satellite observations have revealed accelerated ice flow from Antarctic ice sheets[3] and significant thinning of the Antarctic ice sheets/shelves[4]. At this moment, future change in the mass balance of Antarctic ice sheets represents a large uncertainty for sea-level projections[1]. Writing in *Nature Climate Change*, Matthias Mengel and colleagues[5] use a state-of-the-art ice sheet/shelf model to demonstrate that the Filchner–Ronne Ice Shelf (FRIS, one of the largest Antarctic ice shelves) and the background ice sheet respond almost linearly to the magnitude of warming in the Southern Ocean.

The Antarctic ice sheet is divided into eastern and western parts by the Transantarctic Mountains running across the continent. The West Antarctic Ice Sheet is smaller than the East Antarctic Ice Sheet, containing only about 10% of the total ice volume. Around the continent, the ice sheets extend into the ocean as ice shelves — such as FRIS, an afloat part of the West Antarctic Ice Sheet. Ice shelves have a buttressing effect on the interior ice sheet.

The fluctuation of the boundary between the ice sheet and ice shelf, the grounding line, is an important parameter in evaluating ice sheet changes and thus contribution to sea-level rise. In the present climate Antarctic ice shelves are roughly in balance, with the amount of ice transported across the grounding lines from ice sheet to ice shelf being comparable with the loss from melt and iceberg calving at the shelf edge. The melting of Antarctic ice shelves from underneath — basal melt — accounts for half of the ice loss[6].

The behaviour of ice shelves is very important for maintaining the ice sheets. Changes in the shape and size of the shelf, whether due to collapse or increased basal melt, can weaken the maintaining mechanism. Much of the West Antarctic Ice Sheet exists on bedrock that is below sea level, creating the possibility of marine-ice-sheet instability. This instability comes from the combination of the retrograde bed slope to the centre of the ice sheets and the decreasing ocean freezing point with depth. Simply, it means that once the grounding line has retreated, basal melting at the grounding line (which is moving deeper) becomes more active, thus leading to further retreat of the grounding line and ultimately massive loss of the ice sheet.

The Southern Ocean melts Antarctic ice-shelf bases. Warming of the Southern Ocean along with increasing greenhouse gas concentrations enhances basal melt of Antarctic ice shelves, resulting in retreat of the grounding lines. Cold water formation, a result of sea ice production in coastal regions, will decrease under warming climates, resulting in changes in ocean circulation and the movement of the warmer Circumpolar Deep Water further into the ice-shelf cavity. The dominant mechanisms of retreat will differ between locations, and can be oceanic thermal forcing, marine-ice-sheet instability, or a combination of the two.

Several ice shelf–ocean models[7,8] have projected that the Antarctic coastal current will bring more heat over the coming centuries, through transport of warmer water into the FRIS cavity than at present, leading to dramatic enhancement of basal melting. Mengel *et al.* investigate in detail how FRIS and the background ice sheets respond to the projected Southern Ocean warming using regional and continental-ice sheet simulations that can predict movements of the grounding line and calving front. The authors estimate the present-day mass loss of FRIS at 90 Gt yr^{-1}, which dramatically increases to 600 Gt yr^{-1} by 2100 and more than 2000 Gt yr^{-}1 at the end of the twenty-second century. Investigation of the mechanism of these changes allows them to clearly demonstrate that FRIS and the ice sheet system are controlled by the magnitude of warming in the surrounding Southern Ocean, that is, FRIS responds linearly to the magnitude of ocean heat forcing rather than to marine-ice-sheet instability. This result indicates that the dynamic response of FRIS to the surrounding ocean is largely different from that of the Amundsen Sea ice shelves, which have been in irreversible retreat due to the inherent instability[9–11].

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Looking at the bigger picture, at present it is uncertain how and to what extent each Antarctic ice sheet/shelf system responds in a warming climate, the results of Mengel *et al.* suggest anthropogenic greenhouse gas emissions may play an important role in future sea-level rise from the Antarctic ice sheets. As a next step, applications of similar simulations to all Antarctic ice sheets/shelves are required to quantify such changes. In this study, the ocean feedback to the changing ice shelf is estimated from a new parameterization of basal melting based on ice shelf-ocean model results. This is a stand-alone ice-sheet model simulation. In reality, a changing ice shelf — for example, ice front, grounding line and thickness of ice shelf — will impact on sea ice and ocean fields, and subsequently the sea ice–ocean changes will affect basal melting. To realistically represent this feedback process, the development of a dynamically coupled ice sheet/shelf–ocean model is required[12]. ❐

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