of gross primary productivity to Arctic temperature anomalies also appears to be reproduced to some extent in future climate simulations from the fifth Coupled Model Intercomparison Project (CMIP5), and Kim *et al.* suggest that Arctic-related gross primary productivity anomalies may be amplified in the future.

Whether the relationship found implies a decreasing carbon sink capacity of North American ecosystems in the coming decades is unclear. In particular, the differentiated responses of phenology, photosynthesis and respiration to spring cooling, superimposed on the long-term warming trend, need to be more thoroughly examined. For example, an earlier onset of the growing season due to the warming trend, combined with more frequent cold spells linked to Arctic warming could imply more frequent early spring plant damage. Since the increasing trend in the global CO$_2$ sink is mainly dominated by northern ecosystems[2], it is also worth evaluating whether mid-latitude ecosystems in Eurasia respond similarly to Arctic warming, possibly creating a hemisphere-scale decrease in CO$_2$ uptake capacity in response to Arctic warming.

Interestingly, Kim *et al.* also find significant variations in certain crop yields in the United States in response to winter Arctic warming, as a result of changes in precipitation in some regions and colder winters and springs in others. Irrigation could be used in water-limited regions to counter the drying effects, but spring frost may be harder to manage after sowing, and may impose heavy losses. Given that these events appear to be linked to variations in Arctic sea-ice extent during the previous autumn, the results by Kim *et al.* may allow farmers to anticipate spring weather and manage their crops accordingly.

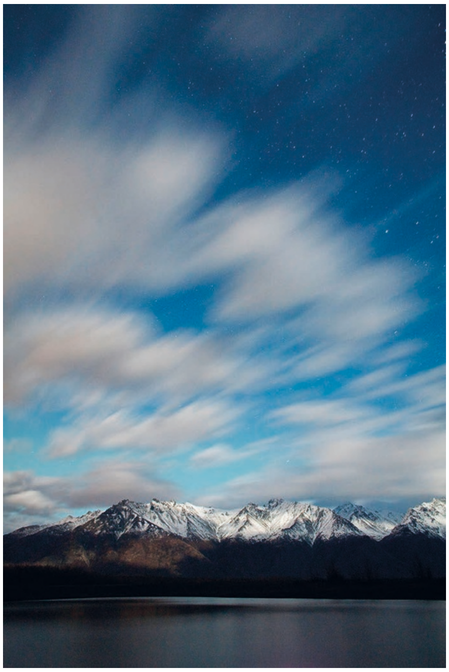
DESIGN PICS INC / ALAMY STOCK PHOTO

Figure 1 | Arctic weather. Kim *et al.*[5] use an Arctic climate index along with simulations and observations to show that warmer sea surface temperatures in winter over the Bering Strait impose harsher spring conditions over North America. They further demonstrate that these colder temperatures result in a decrease in the CO$_2$ uptake capacity of ecosystems.

The link found between Arctic warming and continental cooling is probably not a simple cause–effect mechanism[8]. It is likely to vary between seasons, regions and the warming versus cooling states, and nonlinear effects or additional factors must be taken into account. A deeper look at the differences between the different land-surface and Earth system models may help better constrain the response of mid-latitude ecosystems to climate variability.

Long-term warming trends in the Arctic have increased carbon uptake in the Northern Hemisphere. Kim *et al.*[5] have now demonstrated that interannual variability in Arctic temperatures can also affect productivity in far-removed regions of North America, possibly countering the long-term trend. ❒

Ana Bastos is at the Laboratoire des Science du Climat et de l'Environnement, Orme des Merisiers, Bat 701, Pt3b, 91191 Gif-sur-Yvette Cedex, France.
e-mail: ana.bastos@lsce.ipsl.fr

References

1. Le Queré, C. *et al. Earth Syst. Sci. Data* **8,** 605–649 (2016).
2. Peylin, P. *et al. Biogeosciences* **10,** 6699–6720 (2013).
3. Keeling, C. D., Whorf, T. P., Wahlen, M. & van der Plichtt, J. *Nature* **375,** 666–670 (1995).
4. Overland, J. E., Wood, K. R. & Wang, M. *Polar Res.* **30,** 15787 (2011).
5. Kim, J.-S., Kug, J.-S. & Jeong, S.-J. *Nat. Geosci.* **10,** 572–576 (2017).
6. Piao, S. *et al. Global Biogeochem. Cycles* **23,** GB4026 (2009).
7. Kug, J.-S. *et al. Nat. Geosci.* **8,** 759–762 (2015).
8. Overland, J. E. *et al. Nat. Clim. Change* **6,** 992–999 (2016).

PLANETARY SCIENCE

Bypassing the habitable zone

In our own solar system, Venus is too hot, Mars is too cold and Earth is just right. Simulations show that making an icy planet habitable is not as simple as melting its ice: many icy bodies swing from too cold to too hot, bypassing just right.

Andrew P. Ingersoll

Every time a planet is discovered orbiting another star, people ask if it is habitable. The habitable zone, where terrestrial water-based life could exist, is defined as the region of a stellar system where liquid water can persist. The limits of the habitable zone depend on the composition of gases in the planet's atmosphere, surface gravity and the abundance of water. They also depend on the star's power output, the wavelength of light that it emits and the history of the star-planet system. Sun-like stars brighten over time, so if a planet starts out in a snowball state with its surface nearly covered by ice, the ice will eventually melt as the star's power increases — the habitable zone comes out to meet the planet. Indeed, previous climate models have suggested that the icy worlds common in our Solar System and extra-solar systems could enter a habitable stage with sufficient solar radiation. However, writing in *Nature Geoscience*, Yang *et al.*[1] find that some planets transition from Mars-like snowballs to Venus-like hothouses as their host stars brighten without ever experiencing Earth-like habitable conditions.

The climate of water-rich worlds depends on two positive feedbacks (Fig. 1). First, there is the ice-albedo feedback[2,3]. Ice has a high albedo: ice on a planet's surface reflects most of the sunlight (or starlight) back to space. This acts to cool the planet, which leads to more ice and makes the planet even colder. Second, there is the water vapour feedback. Water vapour in a planet's atmosphere acts as a greenhouse gas and traps infrared light emitted by the planet. This acts to warm the planet, which evaporates more surface water and makes the planet even warmer. Both ice-albedo and water vapour feedbacks operate on present-day Earth and result in a climate that is sensitive to imposed changes in both solar output and greenhouse gases.

On cold icy planets, the ice-albedo feedback dominates. This was probably the state of early Earth when the young Sun's power output was only 70% of its present value. The most recent snowball episode occurred 600–800 million years ago[4]. Earth was probably able to escape its snowball state due to volcanic outgassing of greenhouse gases into the atmosphere and increased solar radiation from the Sun[5]. However, many small icy bodies like Jupiter's moon Europa and Saturn's moon Enceladus lack substantial volcanic outgassing of greenhouse gases. So, there is only sunlight to warm the planet.

Yang *et al.*[1] apply a comprehensive 3D global climate model to the climatic evolution of an icy planet lacking the emission of greenhouse gases other than water vapour. Compared to previous simulations, the 3D model is able to accurately simulate transport of water vapour to the upper atmosphere — a key process in a planet's transition to a Venus-like hothouse state.

In the simulations, the ice-albedo feedback initially keeps the planet cold and retards melting as stellar power increases. Without atmospheric greenhouse gases, the stellar flux at which melting occurs is high — about 10% to 40% more than that received by the Earth's atmosphere. When the ice finally does melt, the resulting drop in albedo makes the planet much warmer very quickly. If the planet is sufficiently warm for the water vapour feedback to kick in, the planet transitions into a moist greenhouse or a runaway greenhouse state[6]. In a runaway greenhouse the oceans vaporize completely. In a moist greenhouse some oceans remain. But in both cases the atmosphere contains so much water that substantial water vapour reaches the upper atmosphere where it is destroyed by sunlight and lost to space[7]. The planet never passes through a long-lived period of habitability.

To explain why an abrupt climate transition did not occur on Earth, Yang *et al.* call on the stabilizing feedback that CO_2 has on Earth's long-term climate[5]. Higher global temperatures increase weathering rates of silicate rocks. Increased weathering delivers more calcium and magnesium to the oceans, which remove dissolved CO_2 from the atmosphere and precipitate carbonate rocks. Enhanced removal of atmospheric CO_2 reduces its greenhouse effect and results in cooling. Lower global temperatures, by contrast, result in slower silicate weathering and slower drawdown of CO_2, allowing atmospheric CO_2 outgassed by volcanism to build up and warm the planet. The Earth's active carbonate–silicate cycle acts to stabilize the climate. This negative feedback has long been regarded as the mechanism that nudged Earth out of its most recent snowball state and into the present stable temperate climate between 600–800 million years ago[5].

CO_2 as a stabilizer of long-term climate seemingly contrasts with CO_2 as the instigator of global warming, but these effects operate on different timescales. The natural response of atmospheric CO_2 to temperature changes driven by the carbonate–silicate cycle acts over millions of years. By contrast, the CO_2 build-up over the past century is forced by human activities. The long-term negative feedback driven by increased weathering rates has not kicked in yet. Other feedbacks involving sudden turnover of the oceans and surges of the ice sheets[8] act on intermediate timescales, and how they would operate on a small icy planet as its stellar power increases remains unknown.

Compared with earlier planetary climate models, the Yang *et al.* model is sophisticated. It is 3D and covers the globe with multiple vertical levels. It calculates the winds and their effects on temperatures, clouds, water vapour, snow and ice. It contains a realistic radiative

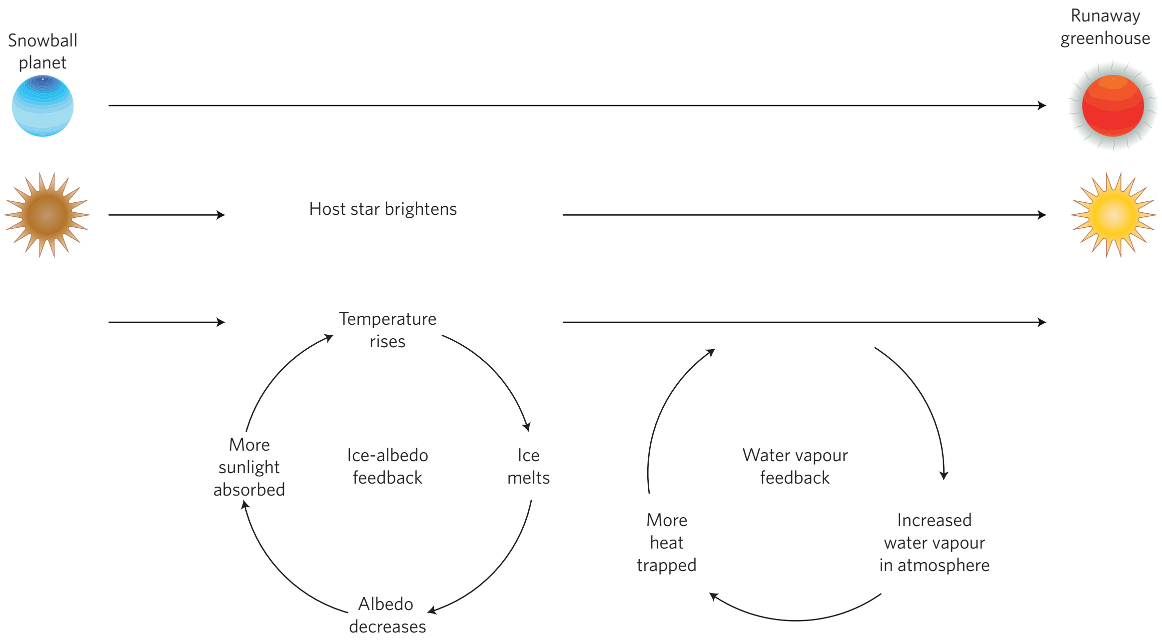

Figure 1 | Climate feedbacks in series. The positive ice-albedo and water vapour feedbacks act to amplify changes in a planet's temperature. The ice-albedo feedback can cause a planet to transition to or from an icy snowball state, and the water vapour feedback can lead to a runaway greenhouse state. Yang *et al.*[1] show that some icy bodies abruptly transition between these two states as they warm without passing through a habitable state.

transfer scheme — the part that calculates the absorption of sunlight and the emission of infrared radiation. What is remarkable is that climate models developed for Earth can now be transferred to other planets with relative ease.

Yang *et al.*[1] show that a small, uninhabitable icy world can bypass a habitable climate and go straight to an equally uninhabitable greenhouse as its host star brightens. Still, our own Solar System hints that the answer may be more complicated. Geological evidence shows that early Earth had both warm episodes and snowball episodes. And early Mars once had liquid water flowing on its surface, even though Mars today is dry and frozen. The warm episodes are not consistent with the steady increase of solar power — an enigma known as the faint young Sun paradox[9]. The near absence of water on Venus today suggests that a runaway greenhouse caused it to lose a large amount of water[7]. But whether there was an earlier snowball phase or a habitable phase is unknown. The lesson for the search for habitable worlds beyond our Solar System is that our models, based on Earth experience, still have large uncertainties. ☐

Andrew P. Ingersoll is at the Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA.
e-mail: api@gps.caltech.edu

References

1. Yang, J. *et al. Nat. Geosci.* **10,** 556–560 (2017).
2. Budyko, M. I. *Tellus* **21,** 611–619 (1969).
3. Sellers, W. D. *J. Appl. Meteorol.* **8,** 392–400 (1969).
4. Hoffman, P. F., Kaufman, A. J., Halverson, G. P. & Schrag, D. P. *Science* **281,** 1342–1346 (1998).
5. Pierrehumbert, R. T. *Nature* **429,** 646–649 (2004).
6. Ingersoll, A. P. *J. Atmos. Sci.* **26,** 1191–1198 (1969).
7. Kasting, J. F., Chen, H. & Kopparapu, R. K. *Astrophys. J. Lett.* **813,** L3 (2015).
8. Bond, G. *et al. Nature* **365,** 143–147 (1993).
9. Wordsworth, R. D., Kerber, L. Pierrehumbert, R. T., Forget, F. & Head, J. W. *J. Geophys. Res. Planets* **120,** 1201–1219 (2015).