their ways? Yes, the 'technocratic paradigm' has rightfully earned the Pope's rebukes given its role in our modern ecological crises. But that same paradigm also has the power — or, in moral foundation parlance, the authority — to take the lead in climate-change mitigation. Useful technologies such as carbon capture and storage and market solutions such as cap-and-trade hold promise as elements of a successful approach to climate change mitigation; a more effectively designed message might have challenged capitalists to embrace climate action as an opportunity to channel traditions of innovation, invoking the authority of economics in solving complex problems.

Such a message rooted in the moral value of authority might have appealed to conservative values, but the Pope dismissed innovation and economics as inefficient and insufficient, questioning whether climate change represents the ultimate failure of the technocratic paradigm. His plea is instead an urgent call for humanity to "overcome individualism" and replace it with "a new way of thinking about human beings, life, society and our relationship with nature". This is a noble ambition, but the Pope, of all people, should recognize that Rome was not built in a day. Not only do changes in human thinking occur at a pace too slow for the urgent crisis posed by climate change, but the "new and universal solidarity" the Pope seeks cannot emerge from the ashes of individualism. In fact, individualism (that is, "liberty") has been proposed as a sixth moral foundation valued both by conservatives and progressives, albeit in different ways[14].

Gaining traction for moral messages

Some might argue that it was not Pope Francis' goal to convince US conservatives to be concerned about climate change, but we disagree. We suspect that the Pope hoped to convince those who are least likely to be concerned about climate change and least likely to want to change their lifestyle in order to protect the planet, many of whom are conservative Americans. The Pope confirmed this suspicion by gifting *Laudato Si'* to President Trump in an apparent effort to salvage the United States' participation in the Paris Agreement.

But if Pope Francis and other climate advocates really wish to persuade conservative sceptics, a useful first step is to recognize that morality is multifaceted. Care and fairness are important when preaching to the converted. But messages of loyalty, sanctity, and authority resonate with conservatives at a moral level that may be less apparent to those with progressive ideologies. ❐

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COMMENTARY:

Impacts of the Larsen-C Ice Shelf calving event

Anna E. Hogg and G. Hilmar Gudmundsson

A giant iceberg has calved off the Larsen-C Ice Shelf, the largest remaining ice shelf on the Antarctic Peninsula, reducing its total area by ~10%. Whilst calving events are a natural phenomenon and thus not necessarily indicative of changing environmental conditions, such events can impact ice-shelf stability.

Over the past two decades floating ice shelves, which fringe 74% of Antarctica's coastline, have retreated[1,2], thinned[3] and suffered catastrophic collapse[4]. On the Antarctic Peninsula, ice-shelf retreat has been observed throughout the satellite era (18% over 50 years; ref. 2), and large sections of the Larsen-A (ref. 4), Larsen-B (ref. 5), and the Wilkins[1] ice-shelf collapsed in a matter of days in 1995, 2002, and 2008, respectively. Geological evidence suggests that ice-shelf decay of this magnitude is not unprecedented, however, prior to 2002 the Larsen-B ice shelf remained intact for the last 11,000 years (ref. 6). While Antarctic ice shelves are in direct contact with both the atmosphere and the surrounding oceans, and thus subject to changes in environmental conditions, they also go through repeated internally-driven cycles of growth and collapse. A calving event is therefore not necessarily due to changes in environmental conditions, and may simply reflect the natural growth and decay cycle of an ice shelf.

Antarctic ice shelves are important because they have retreated and thinned in key parts of the continent during a period of global climate change, because

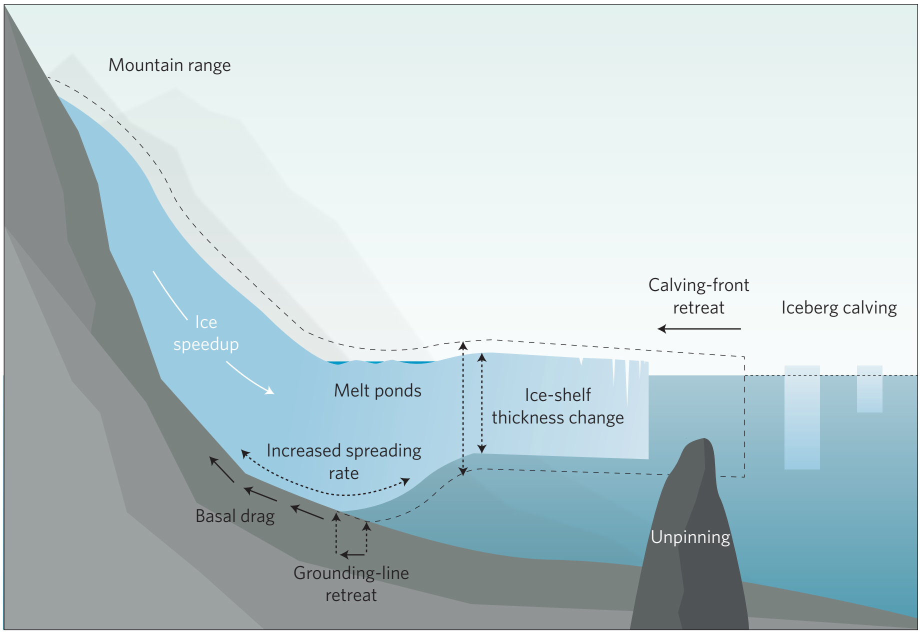

Figure 1 | Schematic showing the processes affecting ice-shelf stability. Iceberg calving, resulting in loss of contact with pinning points, causes a reduction in ice-shelf buttressing. As consequence, ice velocities and the rate of horizontal spreading around the grounding line increases. With time this can lead to ice-shelf thinning and grounding-line retreat. Melt ponds form on the ice-shelf surface in response to warm air temperatures, and warm ocean water melts the ice shelf at its base.

changes in their buttressing effect are known to modulate the grounded ice-sheet contribution to global sea-level rise, and because their melting causes ocean freshening which, in turn, influences patterns of ocean circulation. Ice-shelf collapse and thinning can be indicative of long-term changes in the regional climate. Although changes in the mass of floating ice shelves have only a modest steric impact on the rate of sea-level rise, their loss can affect the mass balance of the grounded ice-sheet by influencing the rate of ice flow inland. The presence of an ice shelf in front of a grounded glacier creates a backward pressure blocking the downward flow of ice from the interior (Fig. 1). This restrictive force decreases when ice shelves thin or collapse, and on the Antarctic Peninsula, such events have been shown to cause up to an eight-fold speed-up in the rate of ice flow inland[7]. This leads to more ice discharge into the oceans, and a consequent increase in the ice-sheet contribution to global sea-level rise. Ice rises, which are isolated high-elevation topographic features overridden by the ice-shelf, provide additional buttressing support for floating ice-shelves. If an ice shelf loses contact with an ice rise, either through sustained thinning or a large iceberg calving event, it can prompt a significant acceleration in ice speed, and possibly further destabilization of the ice front until a new equilibrium is reached (Fig. 1).

The Antarctic Peninsula experienced rapid warming through the second half of the twentieth century, but so far this trend has not been sustained during the twenty-first century[8]. Atmospheric warming, combined with strong winds that force warm dry air down from the Antarctic Peninsula's mountainous spine onto the ice shelves, causes snow densification and melt-water ponding on the ice-shelf surface during the summer months[9]. On the Larsen-C ice shelf, ice thinning has been sustained at a rate of –3.8 m per decade for the past 18 years (ref. 10), and it has been suggested that warm ocean waters are responsible for driving melting at the ice-shelf base.

On the Larsen-C ice shelf, a long >200 km crack grew, separating a plateau of ice four times the size of London (~6,000 km^2) from the Antarctic Peninsula (Fig. 2). When it calved on 12 July 2017 a giant tabular iceberg was formed, the largest on the Larsen-C since the 1980s, reducing the ice shelf to its minimum extent since satellite observations began[2]. The crack started life over a decade ago in a large crevasse field formed as the ice shelf flows towards the Gipps ice rise, a small island that anchors and provides structural support to the southern edge of the ice shelf. However, in 2014 the crack started to advance across the ice shelf, growing episodically in bursts of up to 20 km at a time at an increased rate of propagation. While the Antarctic Peninsula was engulfed by the darkness and freezing temperatures characteristic of polar winter, a secondary spur forked off the main fissure on 1 May 2017. This fracture developed into a network of cracks (Fig. 2) which provided the final pathway to the ice front, breaking through the remaining 4.5 km-wide ice bridge on 12 July 2017. The vast size of this iceberg, combined with the rapid environmental change observed on the Antarctic Peninsula, raises an important question about what impact this calving event will have on the stability of Larsen-C, the largest remaining ice shelf on the Antarctic Peninsula.

The response of the remaining Larsen-C ice, now that the large tabular iceberg has calved, is dependent on how strongly this section of the ice-shelf restrained ice flow upstream. Model calculations suggest that the effect may not be particularly strong if the iceberg removes an area termed the 'passive ice shelf', which does not provide any significant structural support[11]. However, a lot may depend on the exact nature of the calving event. The Larsen-C ice shelf is pinned to the Bawden and Gipps ice rises at the north and south limits of the ice-shelf edge, respectively. Although small icebergs break off ice shelves routinely, if iceberg calving events remove an amount of ice sufficiently large enough to unground the Larsen-C ice shelf from the Bawden ice rise, the remaining ice shelf will be in a much less stable configuration[12,13]. If only the relatively unbuttressed section east of the ice rise is lost, the effect on upstream flow may be much more limited in scope. In either case, this will provide glaciologists with the opportunity to test their ideas about how ice shelves affect ice flow.

The exact mechanical conditions that control the break-up of ice shelves are poorly known, and describing how ice shelves lose mass through iceberg calving is an outstanding unsolved issue in glacier mechanics. While iceberg calving events form part of the natural lifecycle of any ice shelf, being able to observe the developments leading up to the loss of large icebergs is of great interest, as it may lead to improved representation of calving in large-scale ice-sheet models. Several different 'calving laws' have been proposed, but difficulties in obtaining sufficient data to test our predictions have, so far, limited progress. Similarly, it is not clear what physical mechanism drives ice-shelf disintegration, meaning a direct link to global climate change cannot be established, and so model predictions of the pace and onset of future collapse events are less reliable. Crevasse propagation by melt-water ponds on the ice-shelf surface offers one possible cause for ice-shelf retreat and rapid collapse, and a widespread network of melt ponds was observed on Larsen-B ice shelf prior to its breakup[14]. A second hypothesis is that ice-shelf stability is altered as warmer ocean temperatures thin the ice due to increased sub-marine basal melt rates[3]. Other studies have shown that the geometry of the ice front is an important factor, and after retreat occurs beyond a critical limit, total ice-shelf collapse may be triggered[15].

Our ability to routinely monitor rapidly unfolding events such as this has been revolutionized in the last few years by European investment in the Copernicus Sentinel satellites. The year-round, all-weather imaging capability of Sentinel-1, combined with its frequent 6-day revisit time, has been an invaluable resource, enabling us to monitor propagation of the crack on Larsen-C using centimetre-scale displacement of the ice-shelf surface. The satellite data acquired prior to and after the Larsen-C iceberg calving event will be poured over by scientists for years to come in order to detect how Antarctica responds, and to improve our theoretical understanding of the physical mechanisms driving change. Estimates of global ice loss are now entirely reliant on data from Earth observation satellites, such as CryoSat-2, as they provide the spatial and temporal sampling and multi-measurement capability necessary to measure the processes driving imbalance. This is particularly true for the remote Antarctic continent where it is economically inefficient and logistically impossible to collect data at the spatial scale and temporal frequency required using other methods.

Irrespective of whether it forms part of the natural cycle or is caused by changing climate, this calving event presents a unique opportunity to observe the response of glaciers to changes in ice-shelf geometry. The impact of ice-shelf buttressing on upstream ice flow is a long-standing research subject and still a part of ongoing debate within the scientific community. Due to recent advances in our remote sensing capabilities, the Larsen-C calving event promises to provide us with a plethora of new data that can be used to test theoretical concepts and to validate numerical ice-flow models. The lasting legacy of this event may be a greatly improved understanding of the processes involved, and an enhanced capability to predict the global impacts of change in large ice masses in a warming world. ❐

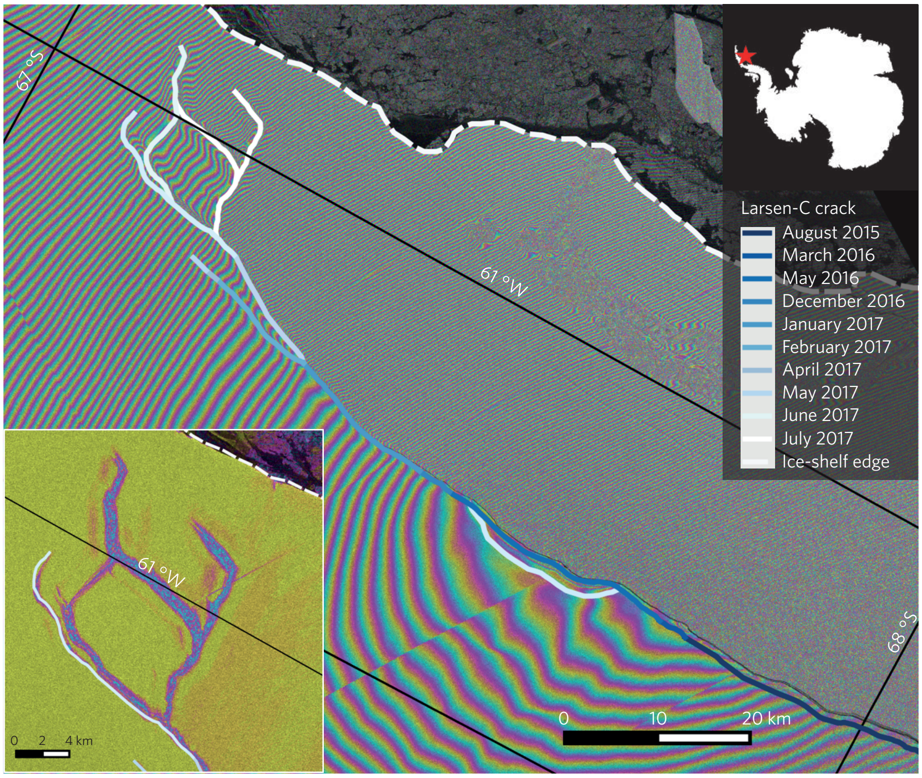

Figure 2 | The timing of crack growth on the Larsen-C ice shelf. Surface displacement of the Larsen-C ice shelf measured by interferometric processing of Sentinel-1 data (coloured fringes) was used to precisely track the location of the advancing crack (solid coloured line) between March 2016 and 6 July 2017, before reaching the coast on 12 July 2017. Also shown is the iceberg calving front (white dashed line). The detailed network of cracks which formed prior to the iceberg calving is clearly shown in the InSAR coherence image (inset).

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