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Iceberg risk in the *Titanic* year of 1912: was it exceptional?

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At 2340h local time (0310 GMT) on the cold, moonless, night of 14 April 1912, near 41°47′N, 49°55′W (Marine Accident Investigation Branch, 1992), the crow's nest lookouts on board RMS *Titanic* sighted a large iceberg only 500m ahead. Despite quick action on the bridge to slow the ship, and turn to port, as well as the closing of the water-tight doors, the slow response of a large vessel meant that the iceberg still struck the ship aft of the bows. Some 100m of her hull below the waterline buckled, allowing water to flood into the ship across several compartments (Howells, 1992). In little more than two and a half hours she had sunk, with the loss of 1514 lives (Havern, 2012). A distress call requesting assistance was transmitted only 20 minutes after the collision, and RMS *Carpathia* turned and raced towards the *Titanic* at a speed of 17.5kn, 20% above her normal maximum speed. However, she did not arrive at the scene until around 0330h (15 April; 0700 GMT), by which time only 710 people remained to be rescued from the 20 lifeboats that had been able to be launched (Howells, 1992).

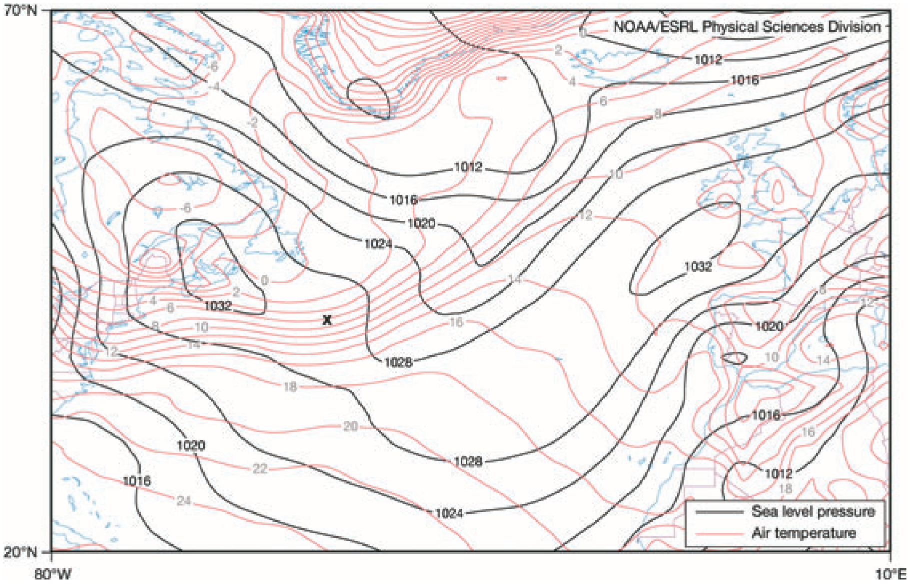

Figure 1. Sea-level pressure and air-temperature chart for 0000 GMT, 15 April 1912, taken from the ensemble mean of the twentieth century reanalysis (Compo et al., 2011). The location of the Titanic is shown by an 'X'.

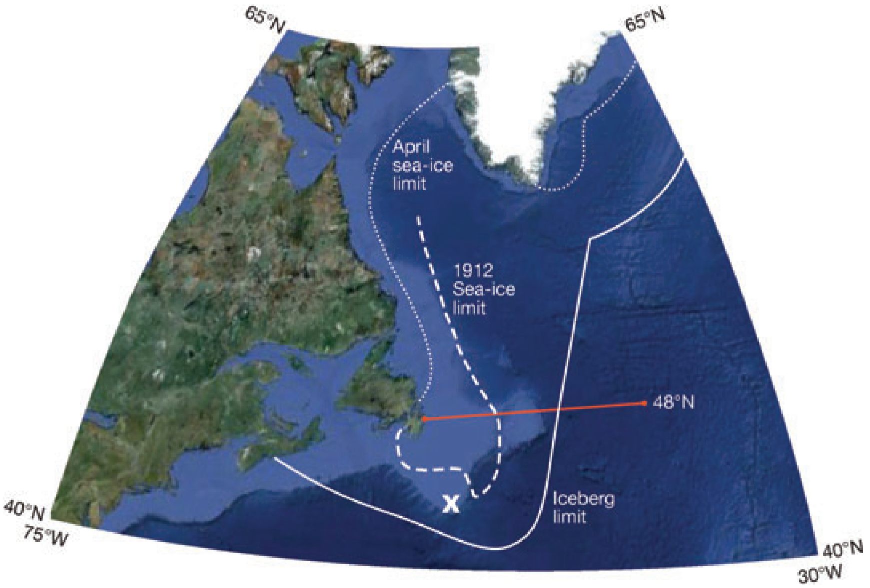

Figure 2. The average sea-ice limit for April 1979–2013 (dotted), a typical Newfoundland maximum sea-ice limit for the early twentieth century (dashed and denoted as 1912; from Hill and Jones, 1990) and the maximum iceberg limit for 1900–2000 are shown, in addition to the 48°N line. The location of the Titanic is shown by an 'X'. The blue shading shows depth, with the lightest blue denoting the continental shelf (<100m depth).

The weather, ice conditions and time of year combined to increase the iceberg hazard on that fateful day. High pressure had dominated the mid-latitude, central Atlantic for several days (Howells, 1992) and by the time of the collision a ridge linking two high-pressure centres over Nova Scotia and the south of Ireland extended across the entire Atlantic (Figure 1). This resulted in northnorthwest winds transporting near-freezing air from northeast Canada over the western Atlantic south of Newfoundland (Figure 1). These winds and temperatures, assisted by the prevailing southward flow of the ocean's Labrador Current on the Grand Banks, led to transport of icebergs and sea ice further south than is currently normal for the time of year, but not beyond the known limits to icebergs during the twentieth century (Figure 2). However, note that even in years of extreme sea-ice extent early in the twentieth century the sea-ice edge rarely extended south of 46°N (Hill and Jones, 1990). A number of reports of extensive sea-ice fields and icebergs ahead had reached the *Titanic* earlier on the day of the

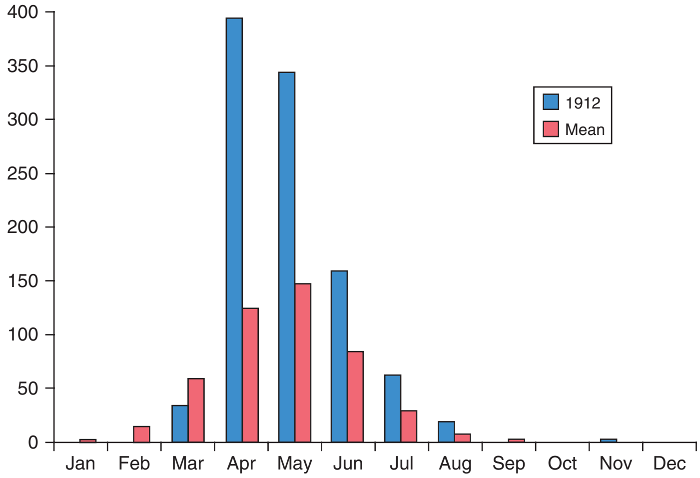

Figure 3. Mean seasonal cycle of the number of icebergs crossing 48°N, 1900–2008, and values in 1912. The 48°N line extends from Newfoundland to 40°W (as shown in Figure 2). The source of the 48°N data is given in the Acknowledgements.

collision (Howells, 1992). April and May are the peak of the iceberg hazard season in the western North Atlantic (Figure 3), partly because of the release of icebergs previously held fast within the pack ice (Marko *et al.*, 1994). In 1912, the peak number of icebergs for the year was recorded in April, whereas normally this occurs in May, and there were nearly two and a half times as many icebergs as in an average year.

Thus, 1912 had a significantly greater iceberg flux off Newfoundland than normal, and this has been taken to imply that such a flux must have an unusual cause. Olson *et al.* (2012) used the centennial anniversary to propose a new theory that more icebergs than normal were calved from Greenland that year because of the stress induced on calving glacier fronts by an enhanced tidal range around Greenland earlier in the year, due to the rare occurrence of the extreme lunar perigee on 4 January 1912. In contrast, Lawrence (2000) suggested that a different astronomical body, the Sun, was responsible for the increased number of icebergs, because of the radiative effect of a period with very low mean sunspot number. Here we will examine just how unusual 1912's iceberg record really was in the twentieth century, and suggest a rather different, glaciological explanation for the increased flux.

The iceberg record at 48°N

The International Ice Patrol (IIP) of the US Coast Guard has operated since 1913, collecting data on iceberg locations and sea-ice extents in the northwest Atlantic in order to provide ice navigation hazard warnings to shipping, and so prevent a repeat of the *Titanic* disaster (Murphy and Cass, 2012). Although there is very occasionally an iceberg incident with shipping in the region (http://www.icedata.ca/Pages/ShipCollisions/ShipCo_Index.php), the IIP claims that, since 1913, no ship that has followed ice warnings has been damaged or sunk (Christensen and Luzader, 2012). A series of comprehensive annual reports on ice conditions from the IIP is available back to the 1920s. The observational methods have changed significantly over the years, from ship reports and dedicated cruises in the early years, through aircraft patrols in the middle decades of the twentieth century, to satellite image analysis and iceberg modelling in recent times. Christensen and Luzader (2012) give a comprehensive survey of these evolving observational techniques, but whatever the technique there is confidence that the general magnitude and yearly variability is captured. Throughout this period a simple measure of the volume of icebergs encountered in a given year has been given by I48N, the monthly number of icebergs passing 48°N, from Newfoundland to ~40°W (Figure 2; Murphy and Cass, 2012). This includes any iceberg larger than 5m in above-surface length. The series extends back to 1900, incorporating ice reports pre-dating the establishment of the IIP. The series has great variability from year to year (Figure 4), reflecting strong variability in calving fluxes from western Greenland. There is an indication of episodic increase in this flux in recent decades, probably due to increases in both sea-surface temperatures in Greenland fjords and ice-sheet surface meltwater. This is investigated further by Andrews *et al.* (2013) but is not the focus of the current paper.

The year 1912 was indeed unusual, with 1038 icebergs observed to cross 48°N. However, this number does not even reach the 90th percentile of the annual number distribution – in the 112 years shown in Figure 4, 14 recorded an I48N exceeding this number. Indeed, a secondary peak in the distribution occurs just below the 1912 total

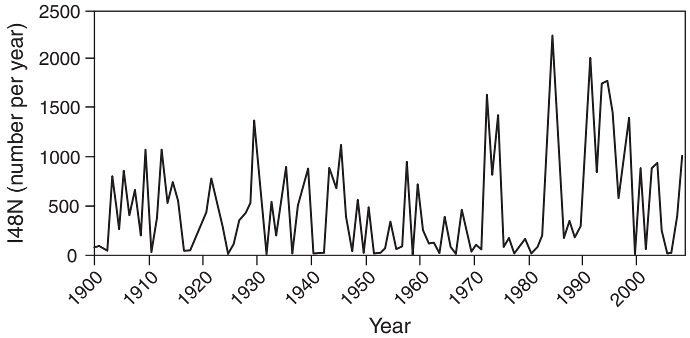

Figure 4. Total number of icebergs crossing latitude 48°N each year since 1900 (see Acknowledgements for data source). Note that the year is defined as an ice-year, beginning in October of the year before the notional record and extending to September of the ordinal year.

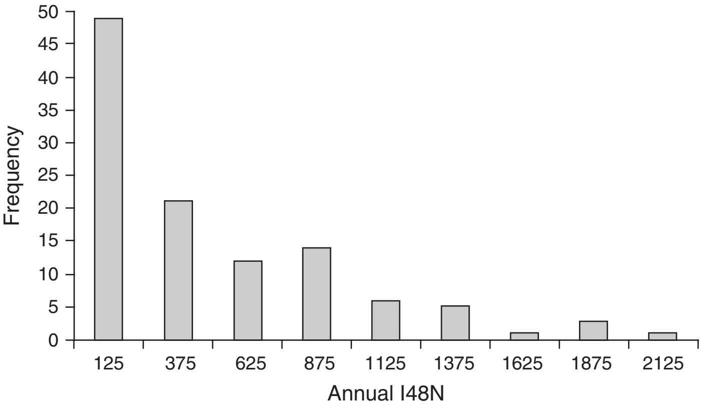

Figure 5. Distribution of annual number of icebergs crossing 48°N, 1900–2011. The labels indicate the iceberg number of the centre of each range chosen.

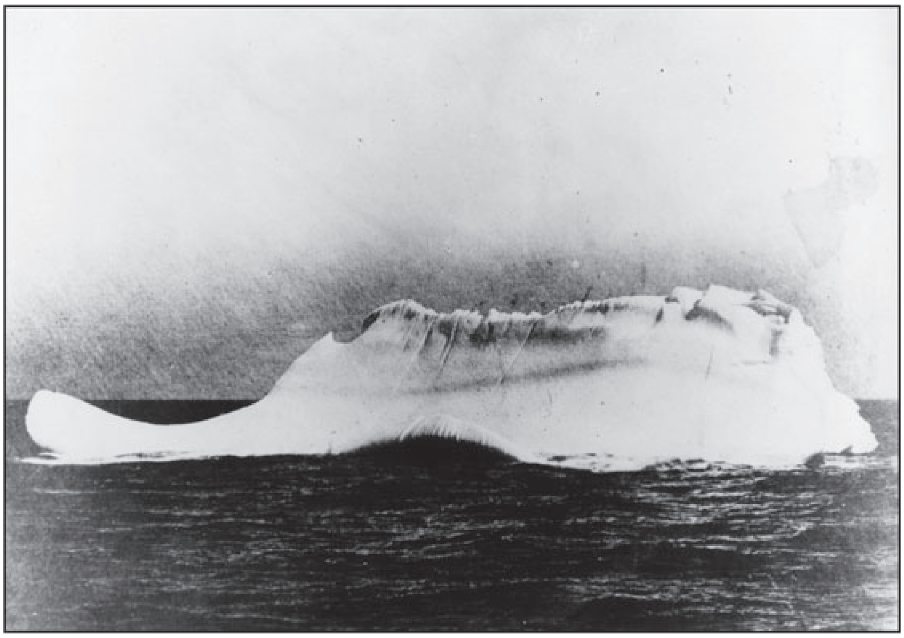

Figure 6. Iceberg believed to have been responsible for the sinking of the Titanic (reproduced with permission of The U.S. Coast Guard Historian's Office).

(Figure 5); 1912 was a significant ice-year, but not extreme.

The origin of the *Titanic* iceberg

The iceberg that sank the *Titanic* was relatively large at the time of impact at 42°N. Reports from survivors claimed the iceberg responsible was some 50–100 feet high (15–31m) and 400 feet (122m) long. The *Carpathia* reported sailing through ice up to 200 feet (61m) high on the way to the rescue and on the following day (Gardiner and Van der Vat, 1995). Although the density of ice relative to water suggests that only 13% of an iceberg should be above water, the eroded shape of most icebergs means that the ratio is more like 5:1 (16.7%; Bigg *et al.*, 1997), so the *Titanic* iceberg is likely to have been at least 90–185m deep, while being ~125m long. The Weeks–Mellor stability criterion (Weeks and Mellor, 1978) enables us to tie down the iceberg's size more tightly. As an iceberg is eroded or melted preferentially from the side, its centre of gravity eventually becomes too high for the iceberg to remain upright and it rolls over. If the reported length of 125m is assumed to be roughly correct, then this stability constraint suggests that the vertical thickness of the iceberg could not have been greater than ~100m, putting the likely above-water height around 15–17m (50–60ft), with a mass of ~2Mt. This is consistent with the dimensions of an iceberg with a red paint streak photographed by Captain de Carteret of the *Minia* (Figure 6) when at the site of the disaster searching for bodies and wreckage (http://www.titanic-nautical.com/RMS-Titanic-Iceberg-FAQ.html).

For an iceberg to still be > 100m in size at 42°N suggests that it began life as a large iceberg when calved into a Greenland fjord. We have studied the distribution of icebergs in the Atlantic during the twentieth century by using a coupled ocean–iceberg model (Andrews *et al.*, 2013; D. J. Wilton *et al.*, in prep.) that is basically an ocean circulation model with an in-built dynamical and thermodynamical iceberg-trajectory model (Bigg *et al.*, 1997), in which the icebergs are regarded as points advected within the ocean model, using the ocean circulation as forcing and supplying the ocean model with freshwater from the melting icebergs (Levine and Bigg, 2008). The iceberg model has previously been well tested in both the Arctic (Bigg *et al.*, 1997) and Antarctic (Gladstone *et al.*, 2001). This combined model is forced by the daily wind, heat and freshwater fluxes of the twentieth century atmospheric reanalysis (Compo *et al.*, 2011), with icebergs seeded into the ocean from 70 sites around the Northern Hemisphere and 29 off Antarctica (Levine and Bigg, 2008). The ocean-model resolution is dependent on position, but is ~20km near Greenland and 100km in the region of the sinking of the *Titanic* (Wadley and Bigg, 2002). The annual calving rate from the 27 sites off Greenland was set proportional to the magnitude of the I48N series (D. J. Wilton *et al.*, in prep.), as this produces an excellent correlation of the model iceberg flux at 48°N with this series (Andrews *et al.*, 2013). We are thus able to model the likely iceberg trajectories of 1912, within the limitations of the forcing and the model.

Although few icebergs have been tracked from source to Newfoundland waters (Newell, 1993), it is believed that the vast majority of icebergs in the main western Atlantic stream in the Labrador Sea originate from southern, western or northwestern Greenland. This is consistent with the limited distributional data (e.g. Valeur *et al.*, 1996), ocean circulation (Marko *et al.*, 1994) and modelled iceberg trajectories (Bigg *et al.*, 1997; D. J. Wilton *et al.*, in prep.). However, according to modelling by D. J. Wilton *et al.* (in prep.) the origin of the majority of icebergs crossing 48°N has decisively switched from southern Greenland in the early decades of the twentieth century to the more northerly, Baffin Bay, coastline of west Greenland since ~1930. It is therefore likely that the *Titanic* iceberg originated from southwest Greenland. Our model produced a range of possible trajectories for icebergs reaching the general area of the *Titanic*'s sinking within a window of ±3 months of the collision, shown in Figure 7. Only one of these is for a pathway originating from Baffin Bay (it is visible leaving Davis Strait, along the northern edge of Figure 7). The modelled iceberg passing closest to the sinking site around the correct date is highlighted in red on Figure 7. This was calved from southwest Greenland in early autumn 1911, beginning life as a model iceberg roughly 500m in length by 300m in depth and 75Mt in weight, but reducing to 2.1Mt by mid-April 1912, remarkably close to the estimated size from observations at the time.

The iceberg hazard in 1912

We have seen that 1912 was a year of raised iceberg hazard, but not exceptionally so in the long term. In the surrounding decades (1901–1920) there were 5 years with at least 700 icebergs crossing 48°N, and 1909 recorded a slightly higher flux than 1912 (Figure 4). More recently, the risk has been much greater – between 1991 and 2000 eight of the ten years recorded more than 700 icebergs and five exceeded the 1912 total. Several other periods during the twentieth century experienced iceberg risk at a similar, or greater, level to 1912 (Figure 4). Although the uncertainty in the early numbers will be higher, the continuous need to forecast this hazard for shipping suggests that the I48N series is generally reliable – ships would have been sunk regularly if it were not. For example, from reports of the time (Howells, 1992) it is very likely that the *Titanic* iceberg had been previously observed.

But why was the risk greater that year, even if not exceptional? Olson *et al.* (2012) believe that enhanced tidal stress, due to a very rare amplification of a high spring tide in January 1912 when the Moon was at its closest approach to Earth, led to greater calving and so iceberg risk. The tidal range, and hence tidal current, is indeed always enhanced along the southwest Greenland

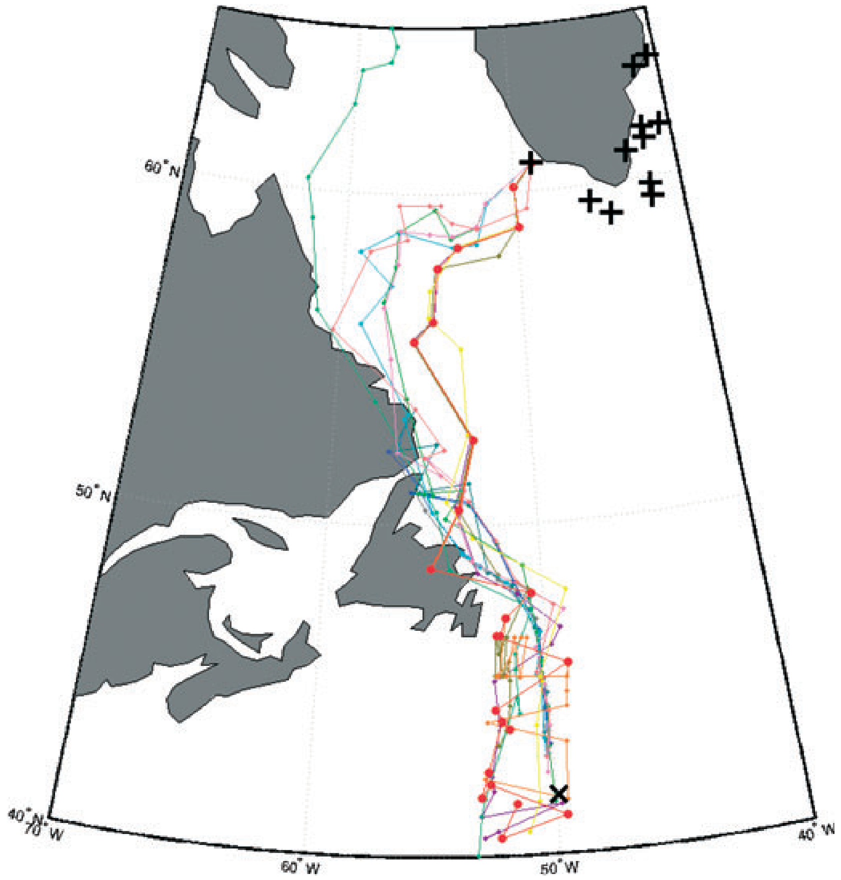

Figure 7. Trajectories of representative modelled icebergs reaching the general area (south of 44°N and west of 50°W) of the sinking of the Titanic between mid-January and mid-July 1912. The iceberg most closely matched to the time and place of the Titanic's sinking (marked by an 'X') is shown in red, with positions every 10 days marked. Other potential source points around Greenland within the area shown are given by '+' signs. The real land boundary is shown, rather than the model's representation of this; icebergs appear to cross the Labrador and Newfoundland coasts where there are differences in these boundaries (see Wadley and Bigg, 2002, for the model grid).

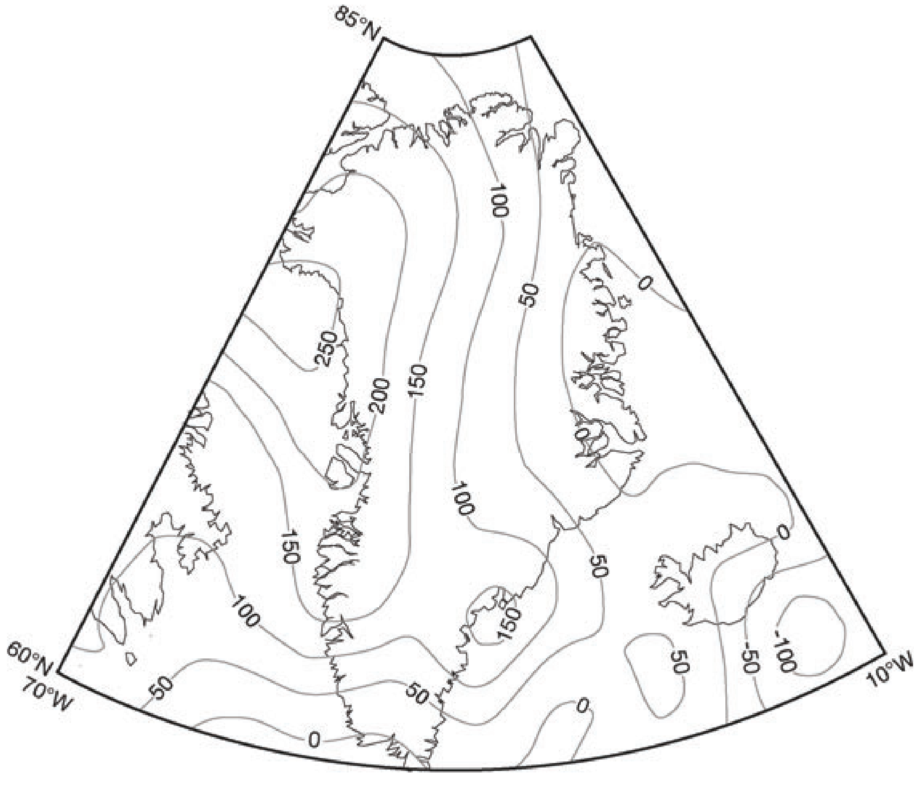

Figure 8. Anomalous precipitation rate over Greenland in 1908, relative to 1981–2010, taken from the ensemble mean of the twentieth century reanalysis (Compo et al., 2011). Units are mm year^{-1}.

coast (see figure 17.13 of Stewart, 2005). Modelled icebergs from southwest Greenland take 3–7 months to travel from the open ocean outside the fjord to 48°N (D. J. Wilton *et al.*, in prep.), which is consistent with a specific and exceptionally early January tidal signal contributing to an increased iceberg risk in the northwest Atlantic shipping routes in April 1912. An impact on the 1912 iceberg risk due to this astronomical event is therefore possible. However, an enhanced calving period concentrated over a few days in winter, when many fjords would be blocked with sea-ice, is unlikely to have been the prime cause of an increased iceberg risk, and our modelled iceberg most similar to the *Titanic* iceberg had left Greenland 3 months earlier. Note that this astronomical situation did not occur in any of the other years of significant risk, and the early iceberg peak is not unusual – a March or April peak in I48N occurs in 41% of the years from 1900 to 2011. One must conclude that the enhanced tidal forcing along the southwest Greenland coast around 4 January 1912 is unlikely to be a significant cause for the increased iceberg risk encountered by the *Titanic*. In contrast, Lawrence (2000) believed that the radiation cycle of the Sun associated with the 11 year cycle in sunspot numbers may have been responsible, with low sunspot years being associated with high iceberg risk. However, the correlation coefficient between annual sunspot number (SIDC-Team, 2013) and I48N over 1900–2011 is only −0.043, thereby not supporting such a link.

We therefore turn to consider more complex reasons for the enhanced risk of 1912. In work in preparation, Bigg *et al.* (2014) have examined the question through non-linear systems identification, assuming that iceberg calving is a non-linear function of the surface mass balance of the Greenland ice sheet (Hanna *et al.*, 2011), the large-scale atmospheric state, as given by the North Atlantic Oscillation Index (Hurrell and Deser, 2009), and the sea-surface temperature of the Labrador Sea, which is related to water temperatures in fjords where icebergs are calving. The surface mass balance is the balance between precipitation (as snowfall) and melting at the ice-sheet surface, rather than the total mass balance, which includes iceberg discharge but is poorly known.

For the early part of the twentieth century the overwhelmingly dominant term relating I48N, and hence west Greenland calving, to this combined glaciological, atmospheric and oceanic forcing is a linear expression of the Greenland ice-sheet surface mass balance, with a lag of 4 years and a correlation of ~0.6 from 1900 to 1930 (Bigg *et al.*, 2014). Other, non-linear terms including the Labrador Sea surface temperature at similar lags help to explain the variance during this period more completely, but the majority of the explained variance at this time is due to a significantly lagged surface mass balance. The physics underlying these links is not yet well understood (Bigg *et al*., 2014). However, the iceberg risk to the *Titanic* is likely to have predominantly developed around 1908, when a moderately warm and wet year over Greenland produced enhanced snow accumulation (Figure 8). We believe that this gradually soaked through cracks in the ice sheet and accumulated around its margins, which probably led to enhanced short-term outlet glacier sliding, with resulting enhanced calving.

Conclusions

The *Titanic* set sail in a year when sea-ice transport and iceberg calving rates were high, but not exceptionally so. The most likely origin for the iceberg that sank the vessel is southwest Greenland, with a calving time in the autumn of 1911, but related to an enhanced precipitation–melting balance over Greenland in 1908. Icebergs still remain a navigation hazard. The IIP has largely removed the risk of an unexpected iceberg encounter in the northwest Atlantic, but the cruise ship MV *Explorer* was holed by an iceberg in the Weddell Sea off Antarctica in 2007 and the MS *Fram* collided with a glacier in 2008, although it was not sunk. A Russian fishing boat was sunk off Antarctica in 2011. As use of the Arctic, in particular, increases in the future with the declining sea ice the ice hazard will increase in waters not previously used for shipping. As polar ice sheets are increasingly losing mass (Rignot *et al*., 2011) as well, the iceberg risk is likely to increase in the future, rather than decline.

Acknowledgements

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