LETTERS
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Mapping the future expansion of Arctic open water

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Sea ice impacts most of the Arctic environment, from ocean circulation and marine ecosystems to animal migration and marine transportation. Sea ice has thinned and decreased in age over the observational record[1,2]. Ice extent has decreased[3]. Reduced ice cover has warmed the surface ocean[4], accelerated coastal erosion[5,6] and impacted biological productivity[7]. Declines in Arctic sea-ice extent cannot be explained by internal climate variability alone and can be attributed to anthropogenic effects[8,9]. However, extent is a poor measure of ice decline at specific locations as it integrates over the entire Arctic basin and thus contains no spatial information. The open water season, in contrast, is a metric that represents the duration of open water over a year at an individual location[10,11]. Here we present maps of the open water season over the period 1920–2100 using daily output from a 30-member initial-condition ensemble of business-as-usual climate simulations[12] that characterize the expansion of Arctic open water, determine when the open water season will move away from pre-industrial conditions ('shift' time) and identify when human forcing will take the Arctic sea-ice system outside its normal bounds ('emergence' time). The majority of the Arctic nearshore regions began shifting in 1990 and will begin leaving the range of internal variability in 2040. Models suggest that ice will cover coastal regions for only half of the year by 2070.

The Community Earth System Model Large Ensemble (CESM-LE) is a publicly available climate model ensemble designed to study variability of the climate system in the presence and absence of human-induced climate change[12]. The CESM-LE uses a 1-degree version of the CESM-CAM5 model[13], historical forcing for the period 1850–2005 and Representative Concentration Pathway (RCP) 8.5 forcing from 2005–2100, which assumes that greenhouse gas emissions will continue to rise throughout the entire twenty-first century. The 30 ensemble members all use the same Earth system model and the same external forcing, but vary by round-off differences in the initial atmospheric state. A 1799-year-long model run with constant pre-industrial (1850) forcing characterizes variability in the absence of climate change. Thus the design of the CESM-LE allows characterization of both the internal variability, or variability in a climate state derived from the inherently chaotic nature of the climate system alone, and natural variability, which refers to both internal variability and the impact of external forcing.

We employ the CESM-LE to quantify uncertainty in projections due to internal variability, but neglect uncertainty attributable to model physics or climate forcing differences[14–16]. The CESM-LE nonetheless adds value to our understanding of the future Arctic for three reasons: the CESM-LE successfully captures observed declines in average sea-ice extent in all months (Supplementary Fig. 1); sea-ice trends over the observational period for the Coupled Model Intercomparison Project 5 (CMIP5), which includes uncertainty due to both differing model physics and natural variability, and the CESM-LE are nearly identical[17], implying that natural variability dominates uncertainty in CMIP5 projections; and the RCP 8.5 forcing at present slightly underestimates the observed emissions[18], and thus provides a reasonable or even conservative scenario.

The observed sea-ice decline can be attributed to anthropogenic forcing without a large ensemble[9]. However, a large ensemble (30+ members) is required for our analysis. All ensemble members are necessary to get statistically representative estimates of the mean and variance of the open water season (Supplementary Fig. 2). We note that the number of ensemble members needed to achieve a statistically representative sample or detect a significant trend will depend on the application and climate parameter[19]. In addition, the CESM-LE is the first publicly available single model large ensemble to retain daily output of sea-ice concentration, without which an analysis of changes to the open water season would be impossible.

In pre-industrial times, the open water season in the ice-affected Arctic varied spatially as a function of radiative, oceanic and atmospheric forcing (Fig. 1). The inner Arctic Ocean was continuously ice-covered and the length of the open water season in the zone between the minimum and maximum ice extent correlates positively with latitude (Fig. 1a and Supplementary Fig. 3). In 2000, the mean length of the open water season over the Beaufort, Chukchi, Eastern Siberian, and Laptev seas is 1.5–2 times the duration in the pre-industrial control (Supplementary Figs 4 and 5). The change in the open water season is even greater in the Nordic seas. By 2050, the entire Arctic coastline, and most of the Arctic Ocean will experience an additional 60 days of open water each year, with many sites having more than 100 additional days of open water (Fig. 2 and Supplementary Fig. 6). By 2100, much of the Arctic has greater than 150 additional days of open water as compared with the pre-industrial control.

The expansion of open water comes from both earlier onset of break-up and later dates of freeze-up (Fig. 1 and Supplementary Figs 7 and 8). The pre-industrial dates of first and last open water track the patterns of sea-ice growth and retreat, whereas the patterns of subsequent change are more complicated. The Barents, Nordic, Chukchi, and East Siberian seas experience the biggest changes in the length and timing of the open water season, which is likely to be due to changes in the influx of warm ocean water from the Pacific and Atlantic, as observations of ocean heat fluxes have been

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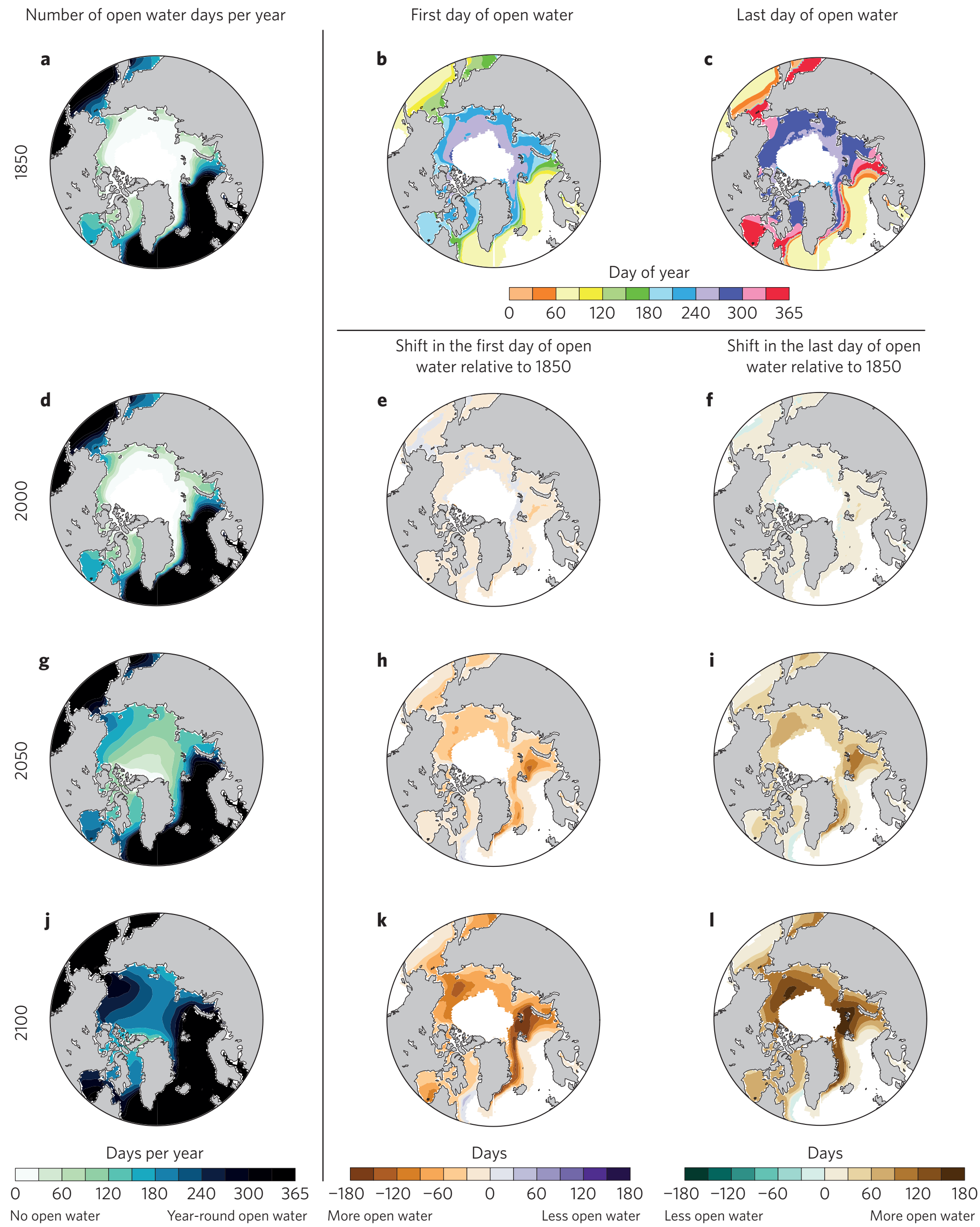

Figure 1 | Changes in the open water season in the CESM-LE. a,d,g,j, The ensemble mean of the number of open water days shows the expansion of the open water season over the period 1850–2100. **b,c**, The mean pre-industrial day of year of the first and last day of open water in 1850 are generally functions of latitude with variations due to patterns of sea-ice motion. **e,f,h,i,k,l**, Both the first day of open water (middle column) and last day of open water (right column) shift relative to 1850 values, resulting in an expanded open water season.

linked to sea-ice loss in the past[20,21]. The shift in the projected date of freeze-up is larger than the shift in the first day of open water, similar to trends in observational data sets[5,22] and attributed to the increased heat stored in the surface ocean after longer-lasting open water conditions.

As the open water season lengthens, the variability typically decreases (Supplementary Fig. 9). In 1850, the sea-ice edge and coastal zones represented areas of high interannual variability in the length of the open water season. However, once consistent open water is present along the coast, the variability declines considerably (Fig. 3). This suggests that predicting sea-ice conditions in coastal and shelf regions will become easier as the open water season lengthens.

At individual model grid cells along the coast, measurements and the CESM-LE are in close agreement regarding the number of open water days (Fig. 3). To illustrate the diverse patterns in predicted sea-ice change along the Arctic coastline, we highlight four locations.

Along the Alaskan North Slope, at Drew Point (Fig. 3a), a site of rapid and accelerating coastal retreat[5,6], the open water regime is highly variable before around 2000. Variability declines as the open water season expands. This area is prone to highly variable open water seasons because it lies near the pre-industrial minimum ice edge and is influenced by sea-ice transport and break-up patterns from both the east and the west. In the late spring, sea ice that includes thick multi-year ice from the Canadian Arctic Archipelago

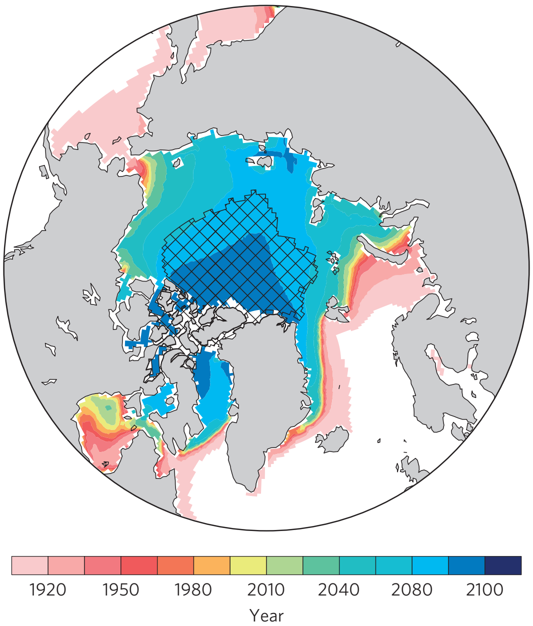

Figure 2 | Last year with ice coverage for 182 days. The timing of the transition to ice coverage for half a year is a function of latitude and the patterns of sea-ice motion. The hatched region shows where open water never occurred in the pre-industrial control run and white represents the area where open water persists for the entire year. Regions near the maximum sea-ice edge never saw 182 days of ice coverage even in the pre-industrial period (light pink colours), and regions in north Greenland and the northern Canadian Arctic are projected to maintain at least half a year of ice coverage at the end of the CESM-LE model integrations.

is transported from east to west along the northern coast of Alaska by the Beaufort Gyre, whereas open water approaches Drew Point both from the Cape Bathurst Polynya to the east and the Chukchi Polynya to the west[23,24].

North of Russia's Siberian coastline in the Laptev Sea (Fig. 3b), the pre-industrial open water season is shorter but is more variable than at Drew Point, and once the open water season begins to expand it does so more slowly. The shallow Siberian shelf lies along the path of the Northern Sea Route. Shelf water is kept relatively fresh by water supplied by Eurasian rivers and new sea ice forms both during freeze-up and within wintertime polynyas[25]. The dilation of the open water season results in large expanses of open water adjacent to the coast in which larger waves can form[26], resulting in rapid (up to 20 m yr^{-1}) rates of coastal erosion[27].

Within the northwest region of the Canadian Arctic Archipelago, sea ice is at present landfast for much of the year and ice is exchanged with the Arctic Ocean; ice typically flows into the Canadian Arctic Archipelago north of the Parry Channel and out through the Amundsen Gulf and M'Clure Strait[28]. At a site within the Western Parry Channel of the Canadian Arctic Archipelago, the most direct route through the Northwest Passage (Fig. 3c), the open water season is very short but starts to expand around 2000. This time marks the onset of younging of the sea ice within the Parry Channel, which makes it more susceptible to summertime melt (Supplementary Movie 1).

Svalbard is located just north of the pre-industrial minimum extent ice edge in the Barents Sea. This region has seen some of the greatest decreases in sea-ice coverage owing to increased warmth and intensity of northward flowing Atlantic water[21]. In pre-industrial times, this region experienced a short, yet highly variable open water season (Fig. 3d), similar to the sites on the Beaufort and Laptev seas (Fig. 3a,b). However, after the site shifts into a regime of expanding open water, the interannual variability remains high owing to Svalbard's position within the main zone of ice export from the Arctic Ocean to the North Atlantic.

We determine the timing of shift and emergence of the open water season at every grid cell across the ice-affected Arctic (Fig. 4a,b, inset shows distribution of timing). The zone between the minimum and maximum sea-ice extent is the first area to shift, finishing in 1990. By 2000, all but the inner Arctic Ocean and regions of seasonal sea ice such as the Sea of Okhotsk have shifted.

The inner Arctic Ocean and the southern portions of the Canadian Arctic Archipelago, which saw no open water in the pre-industrial period, shift starting in 2000 and quickly emerge. The background state for these regions had full ice coverage, and thus the onset of any consistent open water marks emergence. This contrasts with the Alaskan and Siberian shelves, which all shift before 2000, but emerge after 2050. As the shelf regions lie along the minimum sea-ice edge, they experience higher pre-industrial variability and thus require a larger change to fully emerge from the range of internal variability. The coastal areas at the mouths of the Mackenzie, Kolyma, Lena and Yenisei rivers emerge after 2090 or not at all within the simulation time period. These areas have particularly high internal variability owing to the interaction between the motion of the sea-ice edge and the creation of new sea ice in wintertime polynyas. Heat influx from river discharge is not adequately captured in the CESM-LE, so predictions in these areas possibly suffer from insufficient physical process complexity.

This location-specific analysis contrasts with an identical shift and emergence analysis of whole-Arctic sea-ice extent (Supplementary Fig. 1). The late summer months of August, September and October shift in the early 1980s and emerge around 2015, whereas the winter months shift up until 2005 and emerge between 2025 and 2035. Thus the shift and emergence of whole-Arctic sea-ice extent in most months leads the timing of location-specific dates. This makes sense considering that the whole-Arctic sea-ice extent integrates all locations and is more directly tied to the long term and seasonal heat balance than any individual location.

We calculate the rate of increase of open water conditions by fitting a linear trend to the projected open water history after emergence and before reliable year-round open water conditions (Fig. 4c, inset shows distribution of rate). Across the Arctic, this rate of expansion of open water days generally increases northwards, consistent with the effect of the ice-albedo feedback. The significant satellite-based rates of increase are in most places higher than the model ensemble mean[11,29], suggesting that over the period 1979–2013 internal variability served to enhance the anthropogenic effect[17] (Fig. 4d). These patterns are in agreement with the impact of the positive mode of the Arctic Oscillation (AO) in the 1990s[30] and the increased advection of warm Atlantic water into the Barents Sea[21]. A positive phase of the AO results in enhanced generation of first-year ice along the Siberian Coast, decreased convergence and multi-year ice formation in the Canadian Arctic, and subsequent negative summertime minimum extent anomalies[30]. Whereas individual model ensemble members capture AO-like variability, and some even have AO-histories similar to Earth's history, the CESM-LE averages across ensemble members experiencing positive and negative AO modes in a given year (Supplementary Figs 10–12).

The shift of sea-ice extent and open water regime out of pre-industrial conditions marks a transition of the Arctic climate system that impacts all aspects of the Arctic environment. Sea ice forms one of the Earth's major biomes, supporting the polar ecosystem, from ice algae to polar bears, and indigenous peoples' livelihoods. Sea ice also prohibits commercial shipping access and makes natural resource extraction in already harsh and unpredictable polar regions even more challenging. The long pre-industrial control run and the 30-member ensemble of the CESM-LE successfully captures observed Arctic sea-ice change and identifies the time of regime

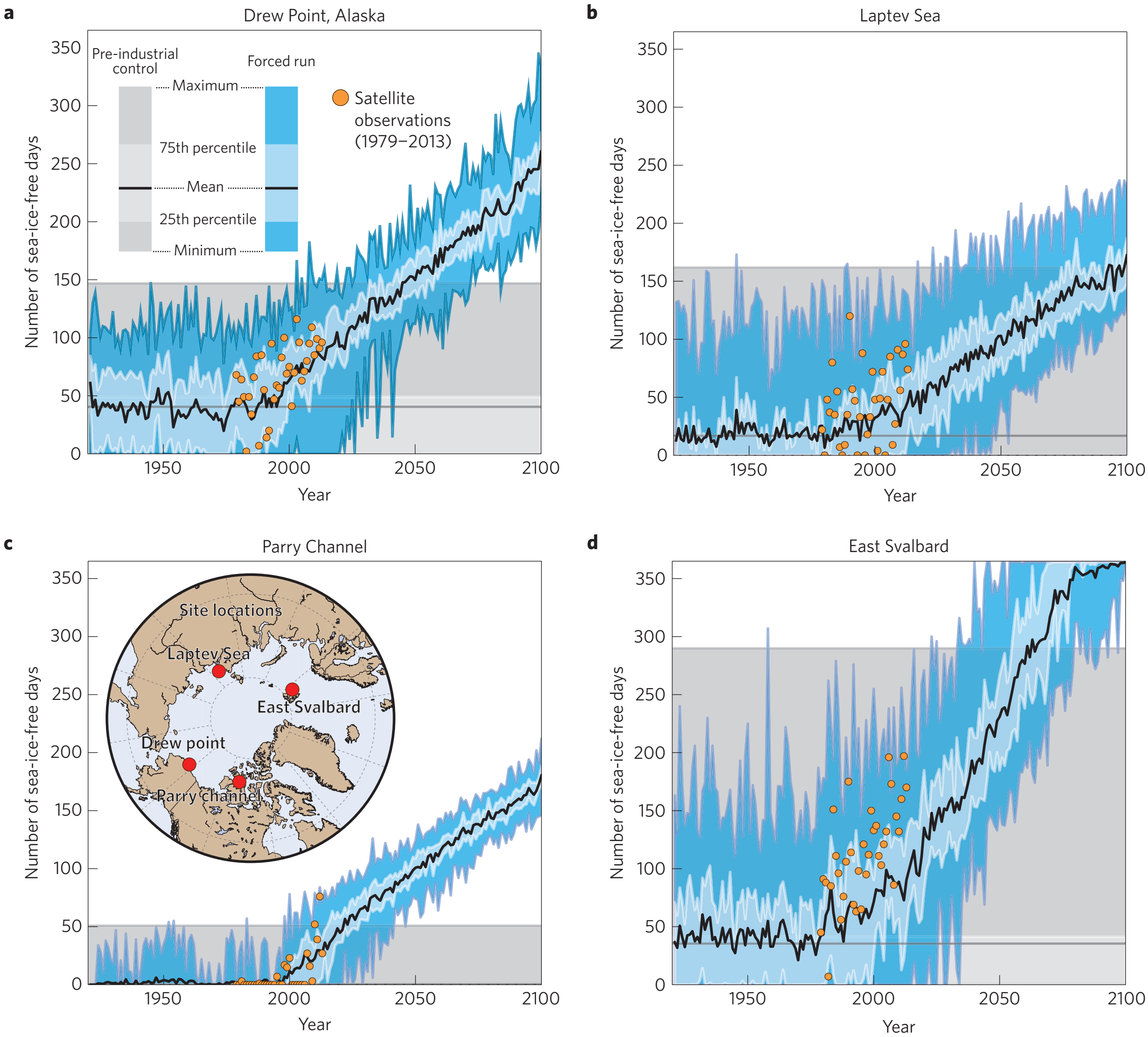

Figure 3 | Change in the open water season at four locations. a–d, Ensemble distribution of the number of open water days and satellite observations at four coastal locations: Drew Point (**a**), Laptev Sea (**b**), Parry Channel (**c**) and East Svalbard (**d**), as shown in the inset map in **c**. At each location, satellite observations fall within the range of model spread, indicating that the model ensemble is consistent with the observations. The patterns of background variability and anthropogenically forced change in the open water season vary seasonally across the Arctic but make sense in the context of local thermodynamic, atmospheric and oceanic forcing.

shift and full emergence in both the extent of sea ice and duration of ice-free conditions. Across the Arctic, the sea-ice system is already on its march out of the range of internal variability and towards the point in time when human forcing will take the system outside its normal bounds.

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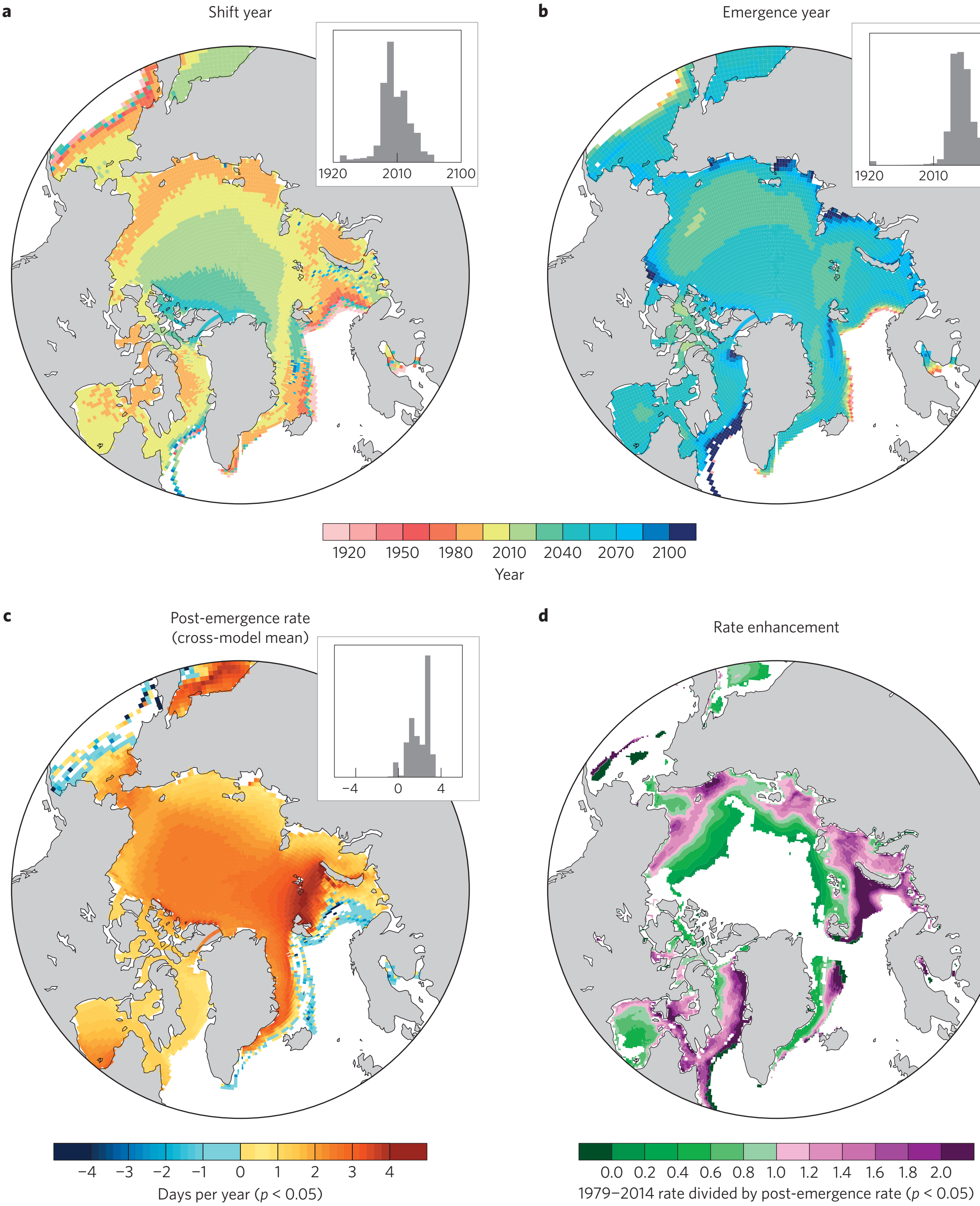

Figure 4 | Shift, emergence and post-emergence expansion of the open water season. a,**b**, Date of shift out of the pre-industrial regime (**a**) and full emergence from the noise of internal variability (**b**) for the number of open water days per year. Insets show the distribution of timing. **c**,**d**, After emergence, the open water season expands (**c**) at a rate that is in many places slower than the rate observed from satellite observations (**d**). This indicates that natural variability has served to enhance the rate of open water season expansion in many areas of the sea-ice-impacted Arctic. Inset in **c** shows the distribution of rate.

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Author contributions
K.R.B., J.E.K. and I.O. designed the study, K.R.B. performed the analysis, K.R.B. and C.R.M. designed the statistical methods, and K.R.B. wrote the manuscript with input from all co-authors.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to K.R.B.

Competing financial interests
The authors declare no competing financial interests.

Corrigendum: Mapping the future expansion of Arctic open water

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In the version of this Letter originally published online, the sentence beginning 'In the late spring, sea ice that includes...' should have ended '...Cape Bathurst Polynya to the east and the Chukchi Polynya to the west[23,24]'. In addition, in Fig. 3c,d and the caption, 'East Svalbard' and 'Parry Channel' were swapped; Fig. 3c should have been 'Parry Channel' and Fig. 3d 'East Svalbard'. Finally, the journal name in ref. 28 was incorrect and should have read '*J. Geophys. Res.*' This has been corrected in all versions of the Letter.