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# Tipping Elements in the Arctic Marine Ecosystem

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**Abstract** The Arctic marine ecosystem contains multiple elements that present alternative states. The most obvious of which is an Arctic Ocean largely covered by an ice sheet in summer versus one largely devoid of such cover. Ecosystems under pressure typically shift between such alternative states in an abrupt, rather than smooth manner, with the level of forcing required for shifting this status termed threshold or tipping point. Loss of Arctic ice due to anthropogenic climate change is accelerating, with the extent of Arctic sea ice displaying increased variance at present, a leading indicator of the proximity of a possible tipping point. Reduced ice extent is expected, in turn, to trigger a number of additional tipping elements, physical, chemical, and biological, in motion, with potentially large impacts on the Arctic marine ecosystem.

**Keywords** Arctic · Tipping points · Ecosystem · Non-linearity · Ice · Plankton

## INTRODUCTION

Mounting human pressure on the biosphere due to increased population size and per capita resource demand is driving a need to develop the capacity to forecast how ecosystems respond to such pressures (Folke et al. 2004). For instance, the loss of Arctic summer ice cover is clearly accelerating, but predictions of when the Arctic Ocean will be devoid of ice in the summer range broadly (Perovich and Richter-Menge 2009) and the performance of existing models reveal major flaws (Wadhams 2012 [this issue]). Some authors anticipate that the Arctic Ocean will be devoid of ice in the summer within a few (Holland et al. 2006; Wang and Overland 2009; Boé et al. 2009) to several decades (Stroeve et al. 2007; Serreze et al. 2007), while others argue that a tipping point leading to summer ice loss does not necessarily exist (Eisenman and Wettlaufer 2009). These discrepancies are, to some extent, semantic because Eisenman and Wettlaufer (2009) considered a tipping point as leading to irreversible change, whereas this is not necessarily the case (e.g., Fig. 1; Lenton 2012 [this issue]). Forecasting how the Arctic marine ecosystem will respond to these changes is subject to even greater uncertainties.

Much of ecosystem science and, particularly, ecosystem management are based on the assumption that ecosystem change in response to pressures is a smooth, reversible process. However, most complex systems exhibit non-linear and complex responses to pressures that drive abrupt changes (May 1977; Scheffer et al. 2001; Scheffer and Carpenter 2003). The existence of ecological discontinuities and threshold effects driven by human perturbations of ecological systems has been recognized as a key feature of ecosystem dynamics (May 1977; Scheffer et al. 2001; Scheffer and Carpenter 2003; Groffman et al. 2006) with important managerial consequences (Groffman et al. 2006; Duarte et al. 2009).

Ecosystem thresholds and tipping points (defined in the following section) also appear in response to climate change, although our understanding of these is still limited. The Arctic Ocean is arguably one the ecosystem most stressed by climate change, as the importance of ice as a key ecosystem element renders it highly vulnerable to warming (ACIA 2004, Wassmann 2011; Wassmann et al. 2011) and because the rates of warming in the Arctic rank among the steepest on the planet (ACIA 2004; Trenberth et al. 2007). Identifying and defining the response of the Arctic marine ecosystem to the cascade of pressures derived from climate change, and the possible thresholds and tipping points involved in this response is, thus, a matter of urgency (Wassmann et al. 2011).

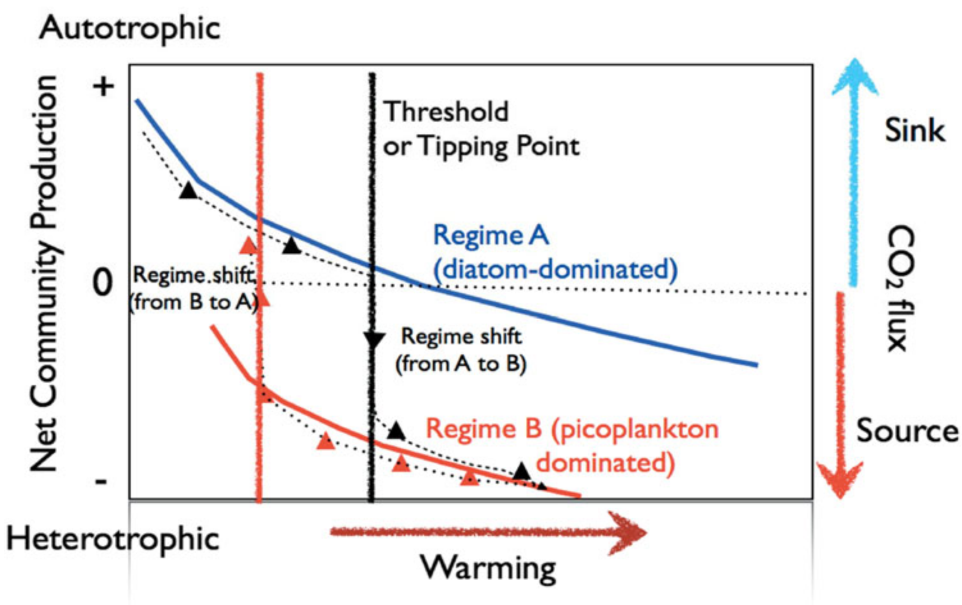


**Fig. 1** Hypothetical model illustrating the concept of threshold and tipping point in ecosystems showing alternative stable states (e.g., a diatom-dominated net autotrophic plankton community acting as a $CO_2$ sink, Regime A, versus a picoplankton-dominated net heterotrophic plankton community acting as a $CO_2$ source, Regime B; cf. Table 1) in response to pressures (e.g., seawater warming), and the hysteresis effect resulting from different tipping points to shift from one regime to the other and back often observed in these systems (e.g., Duarte et al. 2009). The *dotted line* with *black arrows* shows the trajectory of the hypothetical ecosystem when trespassing the tipping point (*black vertical line*) separating Regime A from B, and the *dotted line* with *red arrows* shows the hypothetical trajectory when warming is relaxed, implying a differential tipping point between regimes A and B during warming (*black vertical line*) and cooling (*red vertical line*) of the Arctic Ocean

Whereas evidences of changes in the Arctic environment (Overpeck et al. 1997) and realized impacts of climate change on Arctic marine ecosystems have been recently summarized (Wassmann et al. 2011), the possibility of abrupt changes in the response of these ecosystems to future climate change has not received sufficient attention as yet. A recent review of impacts of recent climate change in the Arctic ecosystem (Post et al. 2009) focused largely on the terrestrial components and discussed only possible impacts, at the population level, in key marine megafauna, but did not address the possibility of tipping points in the response of Arctic marine ecosystems to accelerating climate change. Here, we provide a first definition of ecosystem thresholds and tipping points in the context of the response of the Arctic marine ecosystem to climate change, and review the possible elements and mechanisms conducive to abrupt changes in the Arctic Ocean ecosystem.

## Thresholds and Tipping Points of Ecosystems Under Pressure

Ecosystems under pressure often display complex trajectories that derive from a combination of complex phenomena including non-linear responses, hysteresis when pressures are relaxed and shifting baselines due to global environmental changes (May 1977; Scheffer et al. 2001; Duarte et al. 2009). Growing evidence indicates that many ecosystems ranging from coral reefs, coastal ecosystems, semi-arid vegetation, and ponds can have more than one stable state (Scheffer et al. 2001). The occurrence of multiple stable states implies that the system has tipping points separating conditions conducive to different stable states (cf. Lenton et al. 2008), although systems can display tipping point behavior without experiencing bifurcations (Lenton 2012 [this issue]). Many ecosystems can undergo sudden jumps in response to changes in external pressures in the proximity of these thresholds or tipping points (May 1977; Scheffer et al. 2001; Scheffer and Carpenter 2003; Groffman et al. 2006).

Whereas the term tipping point was initially introduced in the context of the climate change debate in a metaphoric manner, it has since been formalized and introduced in the context of systems exhibiting rapid, climate-driven change, such as the Arctic (Russill and Nyssa 2009). Hence, tipping points have been defined in the context of Earth System Science as the critical point in forcing at which the future state of the system is qualitatively altered (Lenton et al. 2008). Tipping points and thresholds can be used as synonyms although the term threshold is often associated with a quantitative statement on the level of pressure required to reach the tipping point (Duarte et al. 2009). Tipping elements are defined, accordingly, as the structural components of the system directly responsible from triggering abrupt changes once a tipping point is trespassed, as they can be switched into a qualitatively different state by small perturbations (Lenton et al. 2008; Lenton 2012 [this issue]).

Accordingly, ecological tipping points can be defined as thresholds of environmental forcing beyond which key components of ecosystems exhibit abrupt changes and critical transitions. In this context, ecosystem tipping elements refer to the components of the ecosystem that exhibit critical transitions when subject to forcing. A paradigmatic example of these transitions include the shift from a clear-water, macrophyte-dominated, phase to a turbid-water phase, dominated by microalgae that contribute to light extinction in the water column, triggered by macrophytes loss in shallow aquatic ecosystems (Scheffer et al. 1993). Ecosystem tipping points can be triggered by competitive interactions, such as the competition for light between macrophytes and microalgae driving the shift between the clear-water and the turbid-water phases in shallow aquatic ecosystems. Ecosystems tipping points may also derive from cascading effects in food webs involving changes in a keystone predator. For instance, sea otters act as tipping elements in the coastal ecosystems of the Pacific coast of North America, as their decline below a particular population density due to hunting leads to a reconfiguration of the ecosystem involving the loss of kelp beds through grazing of kelp recruits by sea urchins, the preferred prey of sea otters (Dayton 1985).

Tipping points and thresholds are characteristic of ecosystems with multiple alternative stable states, and represent, more formally, a non-linear behavior where the relationship between ecosystem status and pressures differs for each of the two alternative states (Fig. 1). As environmental pressure exceeds the thresholds or tipping point, the ecosystems rearranges and shifts to the alternative regime, leading to an abrupt change in ecosystem status (Fig. 1). A characteristic feature of such non-linear systems is that the thresholds or tipping points differ for the various ecosystem states, so that the pressure driving the regime shift often must be reduced well below the level that triggered this shift for the ecosystem to revert to the original regime (Fig. 1). Hence, the tipping point for the pressure in the transition from one mode to another is not symmetric and may change with the pathway. For instance, the seawater temperature threshold conducive to a shift in Arctic plankton communities from diatom-dominated, acting as a $CO_2$ sink to a picoplankton-dominated community, acting as a $CO_2$ source with warming (i.e., shift from Mode A to Mode B in Fig. 1) is not the same, as is likely higher, as the temperature threshold for the picoplankton-dominated community to revert to a diatom-dominated community with cooling (i.e., shift from Mode B to Mode A in Fig. 1). The differential tipping points when increasing or relaxing pressures have been used to explain the apparent hysteresis where the eutrophication status of some coastal ecosystems failed to revert to their original status when nutrient inputs were reduced, as nutrient inputs must often be reduced far below those inducing eutrophication of the ecosystem to revert back to the original state (Duarte et al. 2009). This model (Fig. 1) is expected to also apply to the water temperature required to shift the Arctic marine ecosystem across different regimes with important functional implications (Table 1; Fig. 1). This behavior implies that regime shifts of ecosystems under pressure are often not directly reversible.

An extreme, but related concept is that of a point of no return. Ecosystem points of no return can be defined as a critical value of a driver beyond which the ecosystem shifts to a different regime, where the state indicator shows resistance to return to the original state as the driver is reduced below the threshold. Although pioneer studies on ecological thresholds assumed that thresholds always represented points of no return leading to irreversible change once trespassed, evidence has shown that these changes are often reversible although involving different thresholds and time scales in reverting to the original state. For instance, Mann (1977) considered that destruction of kelp beds by sea urchins was irreversible, whereas further analysis showed that kelp beds can recover (Dayton 1985). Yet, some thresholds are indeed points of no return, such as those involving species extinctions, which are, by definition, irreversible. Hence, tipping points and thresholds often, but not necessarily, delineate points of no return.

## Tipping Elements in the Arctic Environment

The main pressure on today's Arctic environment is anthropogenic climate change, responsible for recent increase in air and seawater temperatures over the Arctic (ACIA 2004; Trenberth et al. 2007; Lenton 2012 [this issue]; Wadhams 2012 [this issue]). However, anthropogenic climate change does not act in isolation, but occurs in synergy with other pressures, such as the release of pollutants to the atmosphere. An example of these synergies is the severe Arctic ozone loss during the past decades, which occurred as a result of the combined effect of anthropogenic climate change and the anthropogenic increase in stratospheric halogens (Rex et al. 2004; Tilmes et al. 2006). Spring ozone over the Arctic should itself be considered a tipping element (Lenton et al. 2008), which depletion below a tipping point potentially affects Arctic climate and, through the increased UV radiation, vulnerable Arctic species, including benthic organisms (Wiencke et al. 2000,

**Table 1** Tipping elements in the Arctic environment and marine ecosystems, indicating the likely time scale of reaction once tipping points are exceeded, whether they are already acting (i.e., the elements experience changes consistent with those expected under climate change have been already reported), and the likely consequences of these elements reaching a tipping point

| Arctic tipping element | Time scale | Consequences | References |
|---|---|---|---|
| Environmental | | | |
| Air and seawater temperature | Acting decades | Ice melting, acceleration of metabolic processes, ozone loss | ACIA (2004), Trenberth et al. (2007) |
| Sea ice | Acting decades | Changes in albedo, increased heat flux and gas exchange | Stroeve et al. (2007), Perovich et al. (2007), Serreze et al. (2007), Chang and Dickey (2004), Boé et al. (2009), Perovich and Richter-Menge (2009) |
| Greenland ice sheet and glaciers | Acting centuries | Sea level rise possibly affecting deep-water formation | Driscoll and Haug (1998), Dickson et al. (2002), Gregory et al. (2004), Zwally et al. (2002), Velicogna and Whar (2006) |
| Permafrost | Acting decades | Thermokarst processes, increased freshwater and organic carbon discharge, increased methane emissions | Peterson et al. (2002), Jorgenson et al. (2006), Lawrence et al. (2008), Guo et al. (2007), van Huissteden et al. (2011), |
| Submarine methane hydrates | Possibly acting decades to century | Increased methane emissions | Maslin et al. (2010), Shakhova et al. (2010) |
| Arctic ozone layer | Acting decades | Climate change increased UV radiation | Rex et al. (2004), Tilmes et al. (2006) |
| Human activity | Acting decades | Increased risk of pollution, ice loss and ecological impacts | Huntington et al. (2007), Wassmann (2008) |
| Boreal forest dieback | Decades | Reduced natural $CO_2$ sinks | Chapin et al. (2004), Soja et al. (2007) |
| Peat desication, decomposition and burning | Acting decades | Increased $CO_2$ emissions | Turetsky et al. (2002), Davidson and Janssens (2006), Dorrepaal et al. 2009 |
| Ocean acidification | Acting Decades | Reduced $CO_2$ sink potential, reduced calcification | Steinacher et al. (2009) |
| Biological | | | |
| Increased primary production | Acting decades | Increased organic carbon supply | Arrigo et al. (2008), Wassmann et al. (2008) |
| Shift from diatoms to picoautotrophs | Acting decades | Reduced C flow in the food web, reduced C sink capacity | Agawin et al. (2000), Morán et al. (2009), Li et al. (2009) |
| Enhanced Community Respiration relative to Production | Possibly acting decades | Reduced C flow in the food web, reduced C sink capacity | Harris et al. (2006), López-Urrutia et al. (2006) Vaquer-Sunyer et al. (2010), Regaudie-de-Gioux and Duarte (2011) |
| Decline of *Calanus glaciaris* | Uncertain decades | Impacts on the food web (fish, whales, birds) | Wassmann (2008), Wassmann et al. (2011) |
| Decline of apical consumers (e.g., walrus, polar bear) | Acting decades | Top-down effects on the food web | Wassmann et al. (2011), Renaud et al. (2008) |
| Decline in vulnerable calcifying species | Acting Decades | Ocean acidification impacts on sensitive calcifying organisms | Steinacher et al. (2009), Comeau et al. (2009) |
| Loss of sea-ice community (e.g., algae, amphipods) | Acting decades | Impacts on the food web | Wassmann et al. (2011) |

2006) and humans (Taalas et al. 1996). “Dangerous” global climate change, defined as that proceeding too fast for ecosystems to adapt naturally, threatening food production or preventing economic development to proceed in a sustainable manner (Smith et al. 2009), is believe to occur following an increase in the global mean surface temperature of 2°C above the reference year (e.g., Scholze et al. 2006; Lenton 2011). The Arctic is warming two to four times faster than the average for the planet (Screen and Simmonds 2010). Hence, the tipping point scenario for dangerous climate change in the Arctic, setting in motion most of the tipping elements that abound in the Arctic (Table 1) may be far closer than the 2°C global warming accepted for the planet.

The Arctic region is characterized by the presence of multiple environmental tipping elements (Table 1; cf. Lenton 2012 [this issue]; Wadhams 2012 [this issue]) that may, when set in motion, amplify climate change globally (cf. Lenton 2012 [this issue]) and lead to major changes in the Arctic marine ecosystems.

## Sea Ice

The characteristic element of the Arctic ecosystem is ice (Fig. 2), and the presence and importance of ice already determine the existence of a critical tipping point for the Arctic marine ecosystem. This dominant tipping point is given by the temperature at which water changes from solid to liquid phase, which is 0°C for freshwater and approximately −1.8°C for seawater, where the salt content lowers the freezing point. A transition across this tipping point leads to a phase shift from solid to liquid water. Accordingly, ice is a tipping element that responds abruptly to changes in temperature across this tipping point.

Warming and loss of ice cover drive a cascade of changes that amplify climate warming regionally and have the potential to affect climate globally (Lenton 2012 [this issue]). These changes include the reduction in albedo with declining sea-ice extent (Table 1), driving a feedback conducive to heating of the Arctic Ocean (Perovich et al. 2007), changes in the submarine irradiance field and the heat budget of the Arctic Ocean, and increased air-sea fluxes of green-house gases and other climate-active substances across the open water surface (e.g., Chang and Dickey 2004; Perovich et al. 2007; Rúiz-Halpern et al. 2010). Trespassing the tipping point for phase transition from ice to liquid water sets in motion most of the other tipping elements contained in the Arctic region (Table 1).

## Permafrost

Thawing of the permafrost on land leads to the process of thermokarst formation (Fig. 2; Table 1) by which solid soils turns into fluid soil and eventually ponds and aquatic ecosystems (Lawrence et al. 2008). Thermokarst lakes and ponds are formed in a depression by meltwater from thawing permafrost, often enhanced by the collapse of ground levels associated with permafrost thawing (Jorgenson et al. 2006; Lawrence et al. 2008; Prairie et al. 2009). Thermokarst lakes and ponds have become increasingly common in the Arctic, including Siberia and the Canadian Arctic, and can extend to 10–30% of arctic lowland landscapes with further climate change (Jorgenson et al. 2006).

Permafrost thawing, together with increased precipitation, increases freshwater discharge to the Arctic ecosystem (Table 1), which has increased by about 30% in recent years (Peterson et al. 2002), and leads to enhanced export to the Arctic Ocean of organic materials and sediments hitherto trapped in frozen soils (Guo et al. 2007; Table 1). Moreover, frozen soils and sediments contain large amounts of methane hydrates that can be released to the atmosphere (Kvenvolden 1988; van Huissteden et al. 2011).

## Methane Hydrates

Recent assessments have found bubbling of methane on the Siberian shelf (Shakhova et al. 2010) as well as in thawing Arctic permaforst, and models suggest that a global 3°C warming could release between 35 and 94 Gt C of methane, which could add up an additional 0.5°C to global warming (Maslin et al. 2010). Yet, the most likely scenario is that of gradual, long-term chronic methane release rather than an abrupt release event, so that a tipping point on the global climate due to abrupt methane release from the Arctic appears, at this point, unlikely (Lenton 2012 [this issue]; Table 1).

## Ocean Biogeochemistry

As ice cover declines, ocean water becomes exposed and solar radiation penetrates and is absorbed in the water, while the previous ice cover reflected radiation back to the atmosphere. This alters the heat budget of the Arctic Ocean, leading to warming of the waters and acceleration of the melting of ice (Perovich et al. 2007). Moreover, as more light reaches the seawater when ice is lost, primary plankton production is expected to increase (Arrigo et al. 2008; Wassmann et al. 2008; Table 1), with the associated release of dissolved organic compounds, which add to the increased delivery of organic matter from rivers. Colored organic matter dissolved in seawater absorbs light strongly and dissipates the energy as heat (Chang and Dickey 2004), thereby further increasing the warming of Arctic water once the ice cover is lost. Warming of Arctic water reduces the solubility of gases, including $CO_2$, and may lead to increased partial pressure of $CO_2$ and its release to the atmosphere (Siegenthaler and Sarmiento 1993).

Increased ice melting at sea and on land leads to a higher export of freshwater from the Arctic, which adds buoyancy and stabilizes the water column of the Arctic water exported south along the Greenland coast (Dickson et al. 2002). This added stability may affect deep-water formation in the North Atlantic and eventually slow down the thermohaline circulation (Dickson et al. 2002), which may trigger abrupt regional climate change (Driscoll and Haug 1998; Table 1). Whereas such abrupt climate changes from the collapse of the thermohaline circulation may be a distant tipping point, a slowing down is robustly predicted (Lenton 2012 [this issue]).

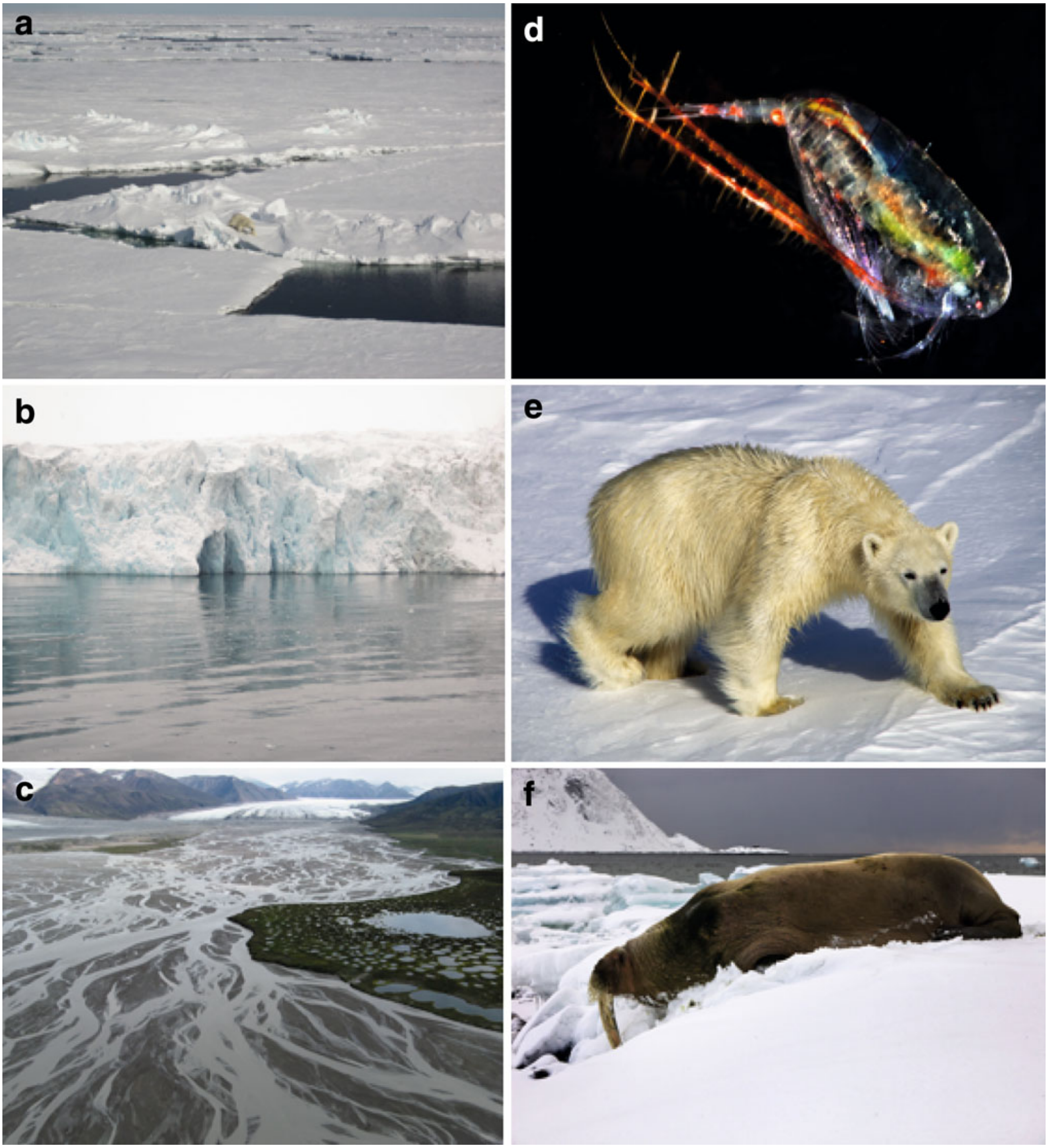


**Fig. 2** Examples of environmental (**a**–**c**) and biological (**d**–**f**) tipping elements in the Arctic ecosystem. **a** Marginal sea ice (Fram Strait, 80°40′N, 1°E); **b** glacier (Magdalena glacier, Spitzbergen, Svalbard Islands); **c** permafrost thawing and thermokarst landscape (Sirmilik National Park, Qikiqtaalkuk, Nunavut, Canada); **d** the Arctic copepod *Calanus glacialis*; **e** the polar bear, *Ursus maritimus*; and **f** the walrus, *Odobenus rosmarus*. Changes in either of these keystone species can lead to major reorganization of the Arctic marine ecosystem. *Photo courtesy* **a**, **b** Carlos M. Duarte/CSIC; **c** Isabelle Laurion; **d**–**f** Joan Costa

## Greenland Ice Sheet

The thick ice sheet in Greenland is also destabilized, as evidenced from increase ice melting and iceberg release from the Greeland ice sheet (Zwally et al. 2002; Velicogna and Whar 2006). Thinning of the Greenland ice sheet and increased glacial discharge (Fig. 2) will further increase the export of freshwater from the Arctic Ocean (Table 1), adding to the processes indicated above. Moreover, the amount of ice contained in the Greenland ice sheet is so phenomenally high that its loss can lead to a 6–7 m increase in sea level rise (Gregory et al. 2004). Whereas the time scales involved in such loss extend over centuries (Lenton et al. 2008), the process of melting of the ice sheet is self-accelerating. Destabilization of the Greenland ice sheet, which may have already been initiated (Gregory et al. 2004; Lenton et al. 2008; Lenton 2012 [this issue]), is, thus, another tipping point of global consequences as it will exacerbate problems of coastal erosion and flooding of low-laying areas already impacted by climate change.

### Terrestrial Ecosystems

In the subarctic, warmer temperatures are leading to die-back of the boreal forest (Chapin et al. 2004; Soja et al. 2007) and desiccation of extensive peat deposits (Davidson and Janssens 2006; Table 1). Peat desiccation is of particular concern because it may subsequently lead to subsurface fires, such as those experienced in Russia in the summer of 2010 (Yurganov et al. 2011), and the release of massive amounts of $CO_2$. Indeed, peat deposits may release an estimated 100 Gt C by 2100 through forest fires or aerobic decomposition of dried peat deposits (Davidson and Janssens 2006; Dorrepaal et al. 2009).

### Human Activity

Finally, reduced ice cover in the Arctic Ocean is already leading to increased human activity in the Arctic, including shipping, oil, gas and mineral exploitation, and fisheries (Wassmann 2008, 2011), which may itself affect the trajectories and impacts of climate change in the Arctic (Huntington et al. 2007).

The Arctic region contains, therefore, many of the key tipping elements of the Earth System (Table 1), which—if set in motion—can generate profound global changes (cf. Lenton 2012 [this issue], for a review). The Arctic is, thus, not at the periphery, but the core of the Earth System. Tipping points in the Arctic are of major consequence for the future of human kind as climate change progresses.

### Tipping Points in the Arctic Marine Ecosystem

The Arctic marine ecosystem is particularly vulnerable because small temperature differences can have large effects (Smetacek and Nichol 2005). Ice loss leads to the loss of critical habitat for many species which depend on ice as habitat, either for support or as substrate for hunting, resting, or reproduction, such as the polar bear, walruses (Fig. 2), seals and less charismatic species, such as ice algae (Renaud et al. 2008; Wassmann et al. 2011). Indeed, models indicate that the impacts of climate change are particularly severe when they occur in conjunction with a loss of habitat, accelerating extinction risks (Travis 2003). The loss of ice obviously entails the loss of the ice-associated biological community, including over 1000 species of sympagic algae inside the ice and at the under-ice surface (e.g., Cota and Smith 1991) and a food web of invertebrates, including several species of ice amphipods, which depend on these algae (Werner 1997, Renaud et al. 2008). Yet, these communities have been investigated in limited studies (e.g., Gradinger et al. 2010; Cota and Smith 1991) and largely restricted to the periphery of the permanent Arctic ice sheet. The characteristic communities of the permanent, multi-year ice under surface (Dunbar 1953) maybe lost before being investigated in detail (Wassmann 2011; Wassmann et al. 2011).

There is already evidence that populations of key Arctic species dependent on ice are under stress, as reflected in declining growth, condition, and reproductive output, particularly for the polar bears and some of the seal species most dependent on ice (Renaud et al. 2008; Wassmann et al. 2011; Andersen et al. 2011). As their populations decline with ice loss, they are expected to hybridize with closely related species, a process eventually leading to the loss of these species (Kelly et al. 2010).

Decline of top predator abundances can generate large changes in the Arctic marine ecosystem through cascading top-down effects (Smetacek and Nichol 2005). On the lower trophic levels, psychrophilic microbes, which depend on cold water temperatures, may be lost with even moderate Arctic warming and ice loss (Arrieta et al. 2010). Key species, such as the large Arctic copepod *Calanus glacialis* (Fig. 2) may decline in a warmer Arctic (Wassmann 2008; Wassmann et al. 2011), likely triggering major changes in the food web. An example is the little Auk (*Alle alle*) which is critically dependent on this endemic crustacean species (Węsławski et al. 1999). Experimental evidence suggests that the Pteropod *Limacina helicina*, which is an important food item for some whales and fish, maybe negatively impacted by the reduction in the saturation level of aragonite expected with ocean acidification by 2100 (Comeau et al. 2009). The decline in the saturation level of aragonite with ocean acidification is expected to be particularly severe in the Arctic Ocean (Steinacher et al. 2009; Table 1).

Changes in the Arctic are also leading to shifts in the species available to fishermen as the biogeographic ranges of subarctic species move polewards, involving shifts between cod and crustaceans, and changes in shrimp and crab species (Wassmann et al. 2011; Carstens and Weydmann 2012 [this issue]). Poleward displacement of the ranges of top predators, such as the killer whale (Higdon and Ferguson 2009), may also bring about changes in the ecosystem, possibly compensating for the effects of the loss of top Arctic predators.

Changes in community structure in Arctic marine ecosystems are expected, in turn, to trigger changes in key processes such as air–sea $CO_2$ exchange (Table 1). The phytoplankton community of a warmer Arctic is expected to shift from a dominance of diatoms to a dominance of picoplankton (Fig. 1; Agawin et al. 2000; Morán et al. 2009), as supported already by observations (Li et al. 2009; Table 1). Diatoms sink in the water column, removing $CO_2$, or are transferred up the food web to grazers. In contrast, the production of picoautotrophs is either released as dissolved organic carbon, which may be subsequently used by bacteria, or consumed by protists, most of their production being eventually respired to $CO_2$. Empirical (Regaudie-de-Gioux and Duarte 2011) and experimental (Vaquer-Sunyer et al. 2010) evidence, and theoretical expectations (Harris et al. 2006; Lopez-Urrutia et al. 2006) predict that seawater warming will lead to increased respiration rates relative to the photosynthetic rates of plankton communities (Table 1). In particular, a future 6°C warming of the Arctic Ocean surface water is expected to yield a mean increment in respiration rates of 62% (Vaquer-Sunyer et al. 2010). This increase would double the ~30% increase estimated for primary production (Wassmann et al. 2008) and possibly revert the role of Arctic planktonic communities from atmospheric $CO_2$ sinks to sources with warming (Fig. 1; Table 1), further aggravating climate change.

A warmer Arctic Ocean with reduced ice cover will also support increased human activity, including fishing, oil, gas and mineral extraction, shipping, and increased resident and tourist population, as well as increased research and military presence and operations, with the development of infrastructures (harbors, houses, roads, airports, power plants, etc.) required to support these activities (Stewart et al. 2005; Pechsiri et al. 2010, United States Arctic Research Commission 2001). Increased human activity in the Arctic also enhances risks for the Arctic biota, associated with increasing risks of accidental spills of hazardous substances, fishing pressure, and the increased encounter probability of humans and wild animals (Huntington et al. 2007; Pechsiri et al. 2010; Stewart et al. 2005).

## Facing Arctic Tipping Points: How Soon?

While environmental and biological tipping elements in the Arctic Ocean have been already identified (Fig. 2; Table 1), the corresponding tipping points with climate change are subject to considerable uncertainty (Lenton 2012 [this issue]). Whereas tools to identify ecological thresholds and tipping points are proliferating (Andersen et al. 2009; Carstens and Weydmann 2012 [this issue]), these tools requires that the threshold or tipping point be crossed (Muradian 2001). Having to cross a threshold or tipping point to realize its existence is, however, dangerous. The need to develop the capacity to anticipate the proximity of a tipping point without crossing it has prompted research to identify robust leading indicators of abrupt changes (Scheffer et al. 2009). One of the most promising indicators, tested successfully across a range of complex systems from natural to social, is increased variance in the variable measured (Scheffer et al. 2009; Carstens and Weydmann 2012 [this issue]). With regard to sea-ice cover, a remarkable feature of the time series of Arctic ice extent is the increase in the variability of Arctic ice extent in recent years (Fig. 3). This variability experienced fluctuations along the recorded period, particularly in 1996 (Carstens and Weydmann 2012 [this issue]), but returned to the baseline variability (Fig. 3). However, the variability of Arctic ice extent has increased almost fourfold since 2006 relative to the 1978–2006 period (Fig. 3), which may be interpreted to signal the proximity of a tipping point in Arctic ice extent. The existence of a tipping point in Arctic ice extent has been challenged (Eisenman and Wettlaufer 2009; Tietsche et al. 2011), mostly due to the misconception that tipping points should lead to irreversible change, which is not the case (Lenton 2012 [this issue]). Yet, our capacity to model the decline in Arctic ice extent with climate change remains poor due to insufficient understanding of the physical processes resulting in thinning of sea ice (Wadhams 2012 [this issue]). As a consequence, a tipping point for Arctic ice extent, beyond which the Arctic would remain free of ice in summer, remains possible (Wadhams 2012 [this issue]; Lenton 2012 [this issue]), and is likely to be met in the coming decades (Table 1). Some of the environmental and biological tipping elements in the Arctic region (Table 1) may not be independent of each other but may be chained in a domino of tipping elements, which may be tipped through a cascade effect once summer sea-ice cover is lost.

Evidence that other tipping elements are being perturbed is also apparent, from bubbling of methane in the Siberian shelf to increased freshwater discharge, as well as a growing contribution of picoautotrophs to Arctic marine plankton communities and decline of ice-associated top predators such as the polar bear (Table 1). However, evidence that these elements may be approaching a tipping point is not yet available, largely due to inadequate time series to evaluate leading indicators, such as changes in variance structure, and a lack of a priori knowledge on the level of climate forcing required for these elements to reach a tipping point. Unfortunately, time series on the dynamics of environmental and biological tipping elements other than sea ice are patchy at best or, in many cases, non-existent, accounting for the

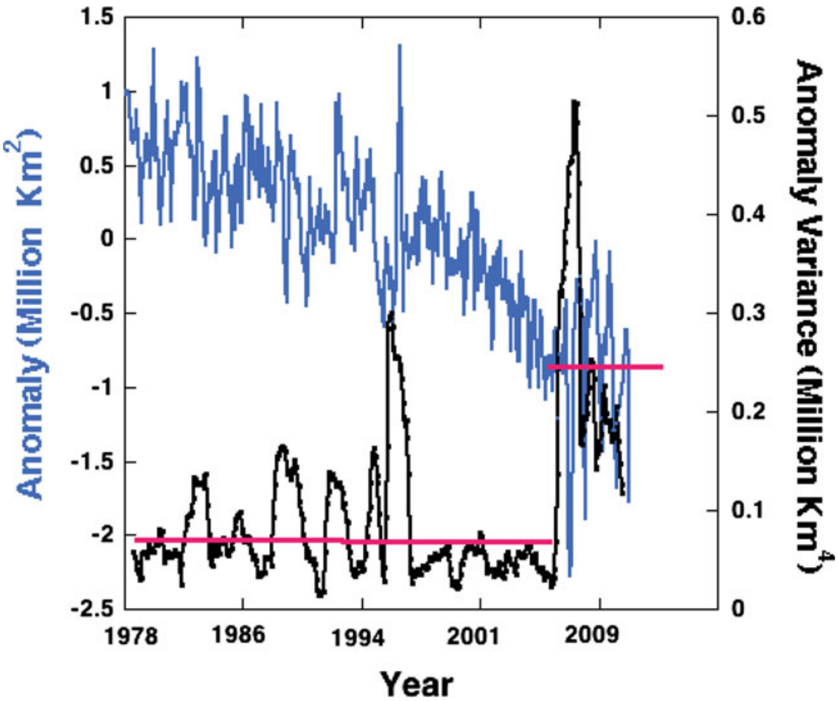


**Fig. 3** Monthly anomalies in Arctic sea-ice extent (*blue line*), relative to the monthly averages for the period November 1978–July 2011 and the average sea-ice extent anomaly variance over 16 month running windows (*black line*). The *red lines* show the mean sea-ice extent anomaly variance between Nov 1978 and December 2006 [mean (±SE) variance = 0.076 ± 0.002] and between January 2007 and July 2011 [mean (±SE) variance = 0.261 ± 0.016]. Data from Fetterer et al. (2002), accessed August 5, 2011

relative paucity of evidences of realized impacts of climate change on Arctic marine biota (Wassmann et al. 2011). A second stumbling stone is the lack of a priori quantitative knowledge on the specific thresholds of climate forcing required for Arctic tipping elements to reach a tipping point. Qualitative knowledge, i.e., identification of tipping elements in the marine ecosystem that are already show changes (Table 1), need be replaced with a priori quantitative knowledge of their corresponding tipping points with climate change. The approach toward resolving the tipping point of these elements must involve a combination of observational, experimental, and modeling approaches, and the assessment of consistency of the predictions each approach delivers.

Yet, the fact that some of the ecosystem tipping elements have been observed to be responding to climate change (Table 1) suggest that a tipping point for these elements may be relatively proximal. For instance, top predators such as the polar bear have been observed to be declining, with reduced growth, condition, and reproductive output (Table 1, Wassmann et al. 2011), and the populations are expected to show an abrupt decline once the Arctic becomes free of ice in the summer. Hence, the collapse of this key top predator, a tipping point in the Arctic ecosystem, may be occurring within decades. Similarly, a shift from a dominance of diatoms to picoplankton has already been observed in some regions of the Arctic (Table 1), suggesting that a regime shift in the plankton community may be approaching with rates of warming expected within this century. In addition, a shift from a $CO_2$ sink to a $CO_2$ source is expected to occur with 4–5°C warming of seawater temperature (cf. references in Table 1), a level of warming expected within the coming decades due to heat transfer and invasion of the Arctic basin by warm Atlantic water (Lenton 2012 [this issue]). Hence, available evidence suggests a regime shift in the Arctic marine ecosystem to be approaching, possibly within a few decades, due to changes in key environmental (i.e., physical and chemical components and processes) and biological (i.e., those involving organisms and their functions) tipping elements, within the coming decades. Shall these changes involve the extinction of key species, these changes could represent a point of no return.

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