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INTEGRATED REGIONAL CHANGES IN ARCTIC CLIMATE FEEDBACKS: Implications for the Global Climate System*

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■ **Abstract** The Arctic is a key part of the global climate system because the net positive energy input to the tropics must ultimately be resolved through substantial energy losses in high-latitude regions. The Arctic influences the global climate system through both positive and negative feedbacks that involve physical, ecological, and human systems of the Arctic. The balance of evidence suggests that positive feedbacks to global warming will likely dominate in the Arctic during the next 50 to 100 years. However, the negative feedbacks associated with changing the freshwater balance of the Arctic Ocean might abruptly launch the planet into another glacial period on longer timescales. In light of uncertainties and the vulnerabilities of the climate system to responses in the Arctic, it is important that we improve our understanding of how integrated regional changes in the Arctic will likely influence the evolution of the global climate system.

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INTRODUCTION

It is well documented that global surface air temperature has warmed substantially since the middle of the nineteenth century (1) and that this warming has been particularly strong in all latitudinal regions since about 1980 (2, 3). The Intergovernmental Panel on Climate Change concluded that this warming is substantially associated with the buildup of radiatively active gases, also known as greenhouse gases, in the atmosphere as a result of fossil fuel burning (4). The substantial climatic warming that has occurred in the Arctic during the late twentieth century (Figure 1*a*,*b*) is particularly interesting because it is consistent with warming caused by the buildup of greenhouse gases in the atmosphere (the anthropogenic interpretation) and with low-frequency variability that has been observed in the Arctic since the early nineteenth century (the natural variability interpretation) (5, 6). The degree to which the warming in the Arctic is caused by anthropogenic factors versus natural variability is important. The anthropogenic interpretation predicts that the Arctic is moving toward a new state that will be characterized by a seasonally ice-free Arctic Ocean, which has the potential to further warm the planet because of absorbed solar radiation that would otherwise be reflected back to space by sea ice (6). The natural variability interpretation predicts that the Arctic should soon start cooling toward a condition that was observed in the 1960s. Thus, an important question that needs to be addressed by the scientific community is: Are the full suite of changes that are occurring in the Arctic enhancing or mitigating global warming?

Much of the focus on the issue of Arctic feedbacks to the global climate system has been on sea ice (3) because changes in the area of sea ice (Figure 1*c*) can substantially affect the ability of the region to reflect or absorb solar radiation during the Arctic summer. However, it is clear that the recent warming in the Arctic has been affecting a broad spectrum of physical, ecological, and human/cultural systems in this region (7–13). Some of these changes may be irreversible on century timescales (e.g., sea ice, soil carbon, and thermohaline circulation) and have the potential to cause rapid changes in the earth system by substantially influencing global water and energy balance (14–19). Although it is not completely understood how the full suite of responses to recent warming within the Arctic and how the exchanges of water, energy, and greenhouse gases between the Arctic and the rest of the earth system are influencing the global climate system, it is clear that the earth system is potentially vulnerable to how the Arctic responds to continued climate warming. The purpose of this review is to synthesize our understanding about the suite of pathways by which the responses within the Arctic region may have implications for the global climate system.

BACKGROUND ON THE ARCTIC CLIMATE SYSTEM

The Arctic is a key part of the global climate system because the net positive energy input to the tropics must ultimately be resolved through substantial energy losses at high latitudes. There are several avenues through which the Arctic influences the energy balance of the global climate system. These avenues include the transfer of energy and moisture between the Arctic and the other parts of the global climate system as well as the effects of the Arctic on greenhouse gas concentrations in the atmosphere. In this review, we consider five Arctic components of the climate system that may influence these exchanges with other parts of the climate system: the atmosphere, the oceans, snow and glaciers, ecosystems, and people. We first discuss alternative defintions of the Arctic. We next focus our discussion on the atmosphere of the Arctic, which is central to the climate of the Arctic and of the globe, in the context of polar amplification and recent climate changes. In the remainder of the review, we turn our attention to the role of the oceans, snow and glaciers, ecosystems, and people of the Arctic in affecting the climate system.

Definition of the Arctic

The *Arctic* is defined in many ways, each of which may be appropriate for a particular context (Figure 2). The astronomical definition of the Arctic as the region poleward of the Arctic Circle (66.5°N) ignores critical land-sea contrasts as well as the fundamental spatial variations in climate, topography, hydrology, vegetation, habitat, and ecosystems of the North. Climate classifications generally consider a climate Arctic if the mean temperature of the warmest (summer) month is below 10°C. Areas included in this definition of the Arctic include the Arctic Ocean, its peripheral seas, and most of the terrestrial areas north of the tree line. Another climatic definition of the Arctic is the location of the summertime polar front, which generally corresponds with tree line. However, the polar front undergoes such large seasonal and interannual variations that the complications of such an approach generally outweigh the advantages. An alternative approach that delimits the Arctic similarly is to define the southern limit of the Arctic as the tree line (Figure 2*a*). Hydrologically, the Arctic has been defined to include the Arctic Ocean, its marginal seas, as well as all terrestrial areas draining into the Arctic Ocean and its marginal seas (20) (Figure 2*a*). The Arctic defined in this way includes large expanses of the northern continents, including much of the boreal forest, extending as far south as about 40°N. This definition of the Arctic offers obvious advantages for studies of the Arctic's freshwater budget.

The prominence of snow and ice in the Arctic offers the possibility of cryospheric definitions. Indeed, the Arctic has been defined on the basis of the occurrence of sea ice over the oceans and permafrost over land (Figure 2*b*). Complications inherent in this approach include the large (approximately twofold) seasonal range of sea ice and the even greater range of snow cover, which varies from essentially zero (excluding Greenland and other ice caps and glaciers) in summer to more than 40 million km^2 in winter, when the climatological snow boundary reaches well into middle latitudes. Although permafrost can be a convenient delimiter of the Arctic over land, even this criterion is complicated by the fact that permafrost ranges from continuous ($>90\%$ coverage) to sporadic ($<10\%$). Nevertheless, a convenient delimiter of the Arctic in terrestrial regions is the southern limit of discontinuous or sporadic permafrost, excluding anomalies associated with elevation (e.g., the Tibetan Plateau). It is this definition of the Arctic that we will use in the remainder of our review.

The Arctic Atmosphere and the Concept of Polar Amplification

The radiative energy deficit of the Arctic atmosphere is a key driver of the hemispheric atmospheric circulation because the circulation's primary role is to transport energy to the polar regions from the tropical regions of radiative surplus. The atmospheric circulation is also a primary vehicle, together with local evapotranspiration in summer, for the supply of moisture to the Arctic atmosphere. This moisture, in turn, is supplied as precipitation to the terrestrial and ocean surfaces, thereby representing a key component of the freshwater budget of the Arctic. The atmosphere is also a critical component of the Arctic climate system through its provision of the radiative forcing and surface wind stress that affect surface and subsurface processes. Clouds and aerosols play critical roles in the spatial and temporal variations of the radiative forcing in the Arctic.

In a broad sense, *polar amplification* refers to the tendency for climatic variations, especially those of temperature, to become larger with increasing latitude. Zonally averaged changes are therefore considerably larger over the Arctic Ocean and northern terrestrial regions than in middle latitudes and the tropics. This behavior has long been noted in climate models, especially in simulations of greenhouse-driven changes (e.g., 21). There are also indications that polar amplification is a characteristic of observed temperature variations, including natural variations (5).

Polar amplification studies to date have focused primarily on atmospheric issues affecting warming in the Arctic, e.g., Serreze & Francis (6). Several atmospheric factors contribute to polar amplification. These include processes that enhance the transfer of heat into the Arctic as well as processes in the Arctic that act as positive feedback to warming initiated by the heat transferred from lower latitudes. An important mechanism of heat transfer into the Arctic is transport of water vapor through atmospheric circulation. As climate warms, the water vapor content of the lower and middle latitude atmospheres increases, and the eddy fluxes that transport sensible heat poleward also transport additional moisture into the Arctic, bringing with it substantial amounts of heat. Approximately half the warming of the Arctic can be attributed to increased fluxes from lower latitudes when there is a global warming (22). Enhanced moisture and heat transport into the Arctic can lead to further amplification of warming from changes in atmospheric water vapor and/or cloudiness. As climate warms, the air's moisture content increases, resulting in an enhancement of the natural greenhouse effect, to which water vapor is the strongest contributor in the current worldwide climate. The relatively small water vapor content of the polar atmosphere, especially during winter, makes the high latitudes especially susceptible to warming from enhanced water vapor concentrations. Moreover, the enhanced water vapor in a warmer (e.g., greenhouse) climate creates the potential for increased cloudiness. Although clouds tend to decrease the amount of short-wave radiation that reaches the surface, the greenhouse effect of water vapor in clouds results in a warming of the lower atmosphere in polar regions during most of the year, particularly during the cold season. Consequently, increased cloudiness can amplify a climatic warming in high latitudes, whether the warming is driven by increasing greenhouse gas concentrations or by other factors. These changes in cloudiness can enhance a greenhouse warming by 25% to 50% in high latitudes (23).

Strong surface-based temperature inversions, in which warm air overlays a layer of cold air at the surface, are common in the Arctic, particularly in winter under conditions of high air pressure. A reduction of snow and ice cover in high latitudes might reduce the intensity and/or frequency of surface-based inversions in the Arctic, which would result in warmer temperatures being observed at the surface. Another contribution to polar amplification is the fundamental geometric fact that the area corresponding to each increment of latitude is relatively small in the polar regions compared to lower latitudes. As a result, there is less of a tendency for compensation of positive and negative changes (trends) of temperature in polar regions. To the extent that the planetary-scale wave features shape the changes of air temperature, compensating regions of warming and cooling are characteristics of middle-latitude climate variations. The smaller ratio of area-to-latitude in the polar regions makes it more likely that a temperature change of one sign (e.g., warming) can dominate a latitude band, thereby reducing the compensation by an opposite change (e.g., cooling) and leading to a larger change in the average over an entire latitude band.

The Context of Arctic Climate Changes in Recent Decades

Although there has been a general increase in global temperatures over the second half of the previous century, the temperature increases in the Arctic (particularly northwestern North America and central Siberia) have been quite substantial (Figure 1*a*,*b*). These increases are part of a longer-term global pattern of a modest increase beginning near the start of the twentieth century with greater increase over the past 30 years (2, 3). However, the temperature increases have not been uniform in time and space. Estimates of trends strongly depend on the duration, season, and region under consideration (6, 24). Trends for 1979–1995, obtained using surface data from the central Arctic, show large changes for spring and winter; whereas changes are small for summer and autumn. Surface air temperature trends are greater for inland regions than coastal/ocean regions (25). Surface air temperatures in the 1990s were generally warmer throughout the Arctic, and the episodic warm events from the 1930s through 1950s were more variable among regions (26). Siberia had warm anomalies appear around 1980, and much of Canada has been warm since 1989. In addition to changes in mean temperatures, Alaska shows a substantial decrease in the number of extremely cold days with temperature less than −40°C.

In investigating the causes of major warm air anomalies over the twentieth century, many events are associated with weather patterns, which promote warm air advection from lower latitudes. Winter/spring warming over northern Europe and Siberia and the cooling of eastern Canada and southern Greenland during the 1980s and 1990s have been driven to some extent by enhanced westerly airflow associated with the positive phase of the Arctic Oscillation/North Atlantic Oscillation (AO/NAO), sometimes referred to as the North Atlantic seasaw (27). Many other changes in the Arctic during the 1980s and 1990s, including those of sea ice and permafrost (discussed below), have been interpreted in terms of the AO. Despite the return of the AO to more neutral conditions over the past decade, some modeling studies suggest that external forcing, including increased greenhouse gas concentrations and stratospheric ozone loss, may favor a higher frequency of its positive state (28). However, the AO/NAO record is also consistent with a red noise time series model of atmospheric variability (29).

In the North American sector, much of the warming of Alaska has resulted from a phase shift during 1976–1977 of the Pacific North American (PNA) pattern and its ocean equivalent, the Pacific Decadal Oscillation (PDO). This shift to a positive phase resulted in enhanced southerly airflow and warm advection into southern Alaska and western Canada, especially in the colder half of the year. Although it is important to stress that the associated changes or trends of temperature appear to be largely circulation driven, the past decade has seen the AO regress toward a more neutral, yet variable, state, and the Arctic has nevertheless continued to show a general warming trend.

In summary, we see a trend for warmer temperatures in the Arctic over the previous few decades with some of the warmest temperatures in the past few years. Since the mid-twentieth century, monthly temperature changes have been as large as 3°–4°C on a regional basis. There have also been trends for increasing soil temperatures in both Alaska and Siberia, with permafrost temperatures approaching 0°C in many areas. Although permafrost temperatures are increasing in much of the Arctic, the evidence for systematic increases in active layer depth or for systematic changes in the permafrost boundary is less compelling at the present time.

Variability in precipitation and snow cover is influenced both by storm tracks and orography. In general, precipitation fields show more local variability than temperature fields. Snow extent is routinely measured by satellites, but the more important snow/water equivalent amount is difficult to measure, and it is difficult to obtain reasonable areal averages. Under positive AO/NAO, there is an increased northward transport of vertically integrated moisture flux between 10°W and 100°E and a decreased transport from 150°W to 10°W, leading to a net increase of precipitation over evaporation in the Arctic (30). Although there are indications of increases of Arctic precipitation during the twentieth century (4), the sparseness of the precipitation network and the problem of gauge bias toward underestimating precipitation call such trends into question.

ARCTIC OCEAN FEEDBACKS TO THE CLIMATE SYSTEM

The oceans of the Arctic represent a critical component of the climate system because they transport heat and freshwater to and from the subpolar North Atlantic. Of primary importance are the salinity of the Arctic Ocean and sea ice formation that affect the strength of the North Atlantic Deep Water (NADW) formation (31, 32). The formation of the NADW is an important factor in maintaining the "thermohaline" circulation that transports heat from the tropics through the Atlantic Ocean to the Arctic. An important element in NADW formation is the freshwater export from the Arctic Ocean to the North Atlantic subpolar seas, where a freshwater cap can effectively stabilize the water column. Two factors that may affect the Arctic's contribution to the freshwater balance of the North Atlantic are the melting of sea ice, which we have already mentioned, and the melting of the Greenland Ice Sheet. Altimeter measurements indicate that the Greenland ice sheet is thinning around much of its periphery. However, there are indications of thickening in the interior of the ice sheet (33). The net effect of these two processes is presently a subject of debate.

The delivery of freshwater from high-latitude ecosystems is of special importance because the Arctic Ocean, which contains only about 1% of the world's ocean water and receives about 11% of the world's river runoff (20), is the most river-influenced and land-locked of all oceans. Inflow from rivers currently contributes as much as 10% of the freshwater (relative to a reference salinity of 35.0) in the upper 100 meters of the water column in the Arctic Ocean (34) and has the potential to affect freshwater export from the Arctic Ocean to the North Atlantic. Over the past 70 years there has been a 7% increase in the delivery of freshwater from the major Russian rivers to the Arctic Ocean (35). Although there has been debate about the relative contributions of changes in precipitation, the role of thawing permafrost, possible increases in fire disturbance, and human impacts (dams, diversions) to this increase, a recent analysis suggests that the only viable explanation is increased precipitation (36). Even though the discharge from the major Eurasian rivers has increased over the past several decades, there are indications that the upper layer of the central Arctic Ocean has become more saline in recent decades (37).

Peterson et al. (38) have recently synthesized Arctic hydrologic information to show that increasing river discharge, melting of glaciers, and net melting of sea ice has each contributed several thousand km^3 of freshwater to the Nordic Seas and subpolar basins over the past half century. This freshening is consistent with estimates derived from ocean hydrographic data and with the concomitant slowdown of the North Atlantic subpolar gyre (39, 40). To the extent that this slowdown involves the broader ocean thermohaline circulation, the Arctic's connection to the global climate system is manifested in ongoing changes. It is clearly a high priority for the climate research community to better understand the consequences of these changes for the climate system.

ICE AND SNOW ALBEDO FEEDBACKS TO THE CLIMATE SYSTEM

Albedo changes associated with variations in sea ice and snow cover, also known as the *albedo-temperature feedback*, influence the climate system. As ice and snow melt, the surface albedo decreases substantially, increasing by severalfold the percentage of incoming solar radiation that is absorbed by the surface. The resulting warming of the surface leads to an increase of the temperature of the lower atmosphere. The converse, an increase of the area of sea ice or snow cover, enhances the cooling of the surface by increasing the reflected fraction of the incoming solar energy. The potential magnitude of this effect was first noted in one-dimensional energy balance models (41).

Sea ice has been changing in recent decades (Figure 1*c*). On the basis of satellite data, the end-of-summer (September) area of sea ice in the Arctic has declined about 15% over the past 25 years (42). Regionally, this is seen as a retreat in the ice edge of 300–500 km in the Beaufort Sea or the East Siberian Sea depending on year. Of particular note are the extreme September ice minima of 2002–2005 (43). Part of the general downward trend in ice extent may be attributable to altered wind fields associated with the upward trend in the AO until the mid-1990s (44). A large volume of thick multi-year ice is thought to have exited the Fram Strait in the 1990s (38), leaving the Arctic with more thin first-year ice prone to melt in summer (45). The recent extreme minima may in part represent a response to this effect (46). More recent work (47) indicates that, although the impacts of altered wind fields on ice circulation are important, the overall downward trend is more clearly allied with a general warming on at least the regional scale. There appear to be feedbacks at work in the sense that increased open water and thin ice absorb more solar energy in summer, leading to less ice growth the following winter. In this sense, the albedo-temperature feedback is manifesting itself over seasonal timescales. It has been proposed that the Arctic may be near a "tipping point" between increased solar absorption in the ocean during summer and the amount of first-year sea ice that can grow during the following winter (47).

Snow cover has also been changing in recent decades. Studies based on remote sensing data from high latitudes during the past two to three decades have found decreases in snow cover duration and extent (48, 49). Snow cover area in Eurasia shows large year-to-year variability, with decreases in the early 1990s and again in 2003. Snow cover area in North America has decreased from the late 1980s onward, again with much year-to-year variability. Over the Northern Hemisphere, there appears to be a trend for reduced snow extent of approximately 4% per decade (50). Modeling studies indicate that increases in air temperature are primarily responsible for observed changes in snow cover during recent decades (13, 49).

The observational evidence from the past several decades provides some indications that temperature trends are associated with the retreat of snow and ice. Examples include the large late winter or early spring warming over northwestern North America that is enhanced by snow retreat (51). Also, the autumn warming over the Chukchi and East Siberian Seas is associated with a substantial loss of summer sea ice during the past decade.

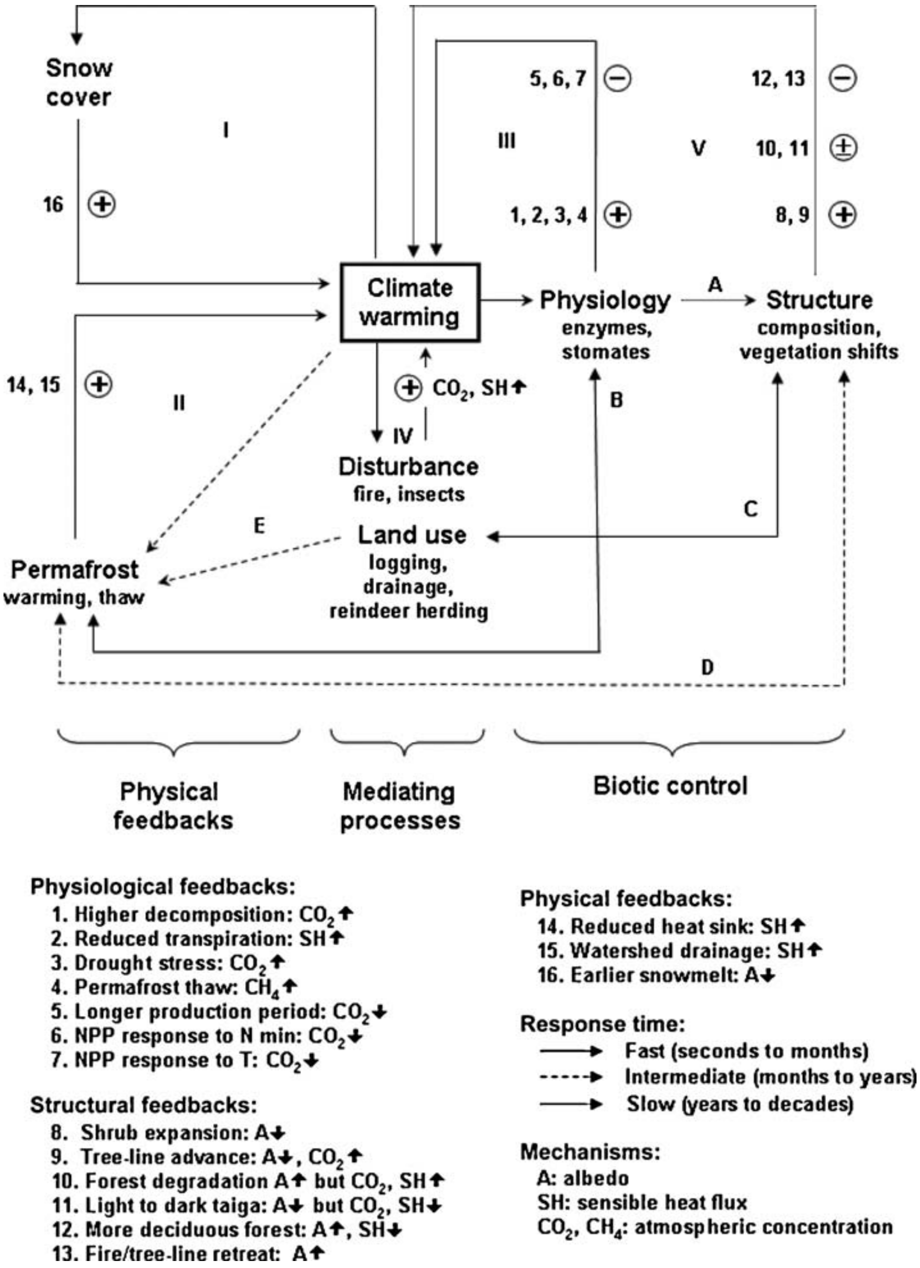
ARCTIC ECOSYSTEM FEEDBACKS TO THE CLIMATE SYSTEM

Ecosystems are characterized by interactions of organisms with the physical environment. In the following two sections, we discuss how organisms in Arctic terrestrial and ocean ecosystems may influence the climate system.

Arctic Terrestrial Ecosystems

Arctic terrestrial feedbacks to the climate system include both direct physical feedbacks of changes in snow, ice, and hydrology (as previously discussed) as well as ecosystem processes that are characterized by active biotic control (Figure 3). *Biotic control* includes functional responses of terrestrial ecosystems (e.g., changes in photosynthesis or decomposition) and changes in ecosystem structure. Functional responses are generally fast (seconds to months) and involve changes in biochemical reactions (e.g., in photosynthesis), canopy conductance to water, and timing of leaf out in spring, which may alter the exchange of greenhouse gases and the partitioning of energy. Within months to years, altered ecosystem function may translate into changes in productivity, nutrient cycling, decomposition, and life history parameters (e.g., seed production, tree longevity). At longer timescales (decades to centuries), ecosystem structure may change to include altered species composition within a vegetation type and may switch to structurally distinct vegetation types (e.g., tundra to forest). Because disturbance can alter ecosystem structure and permafrost dynamics rapidly, the response of disturbance regime to warming is critical to Arctic terrestrial feedbacks to the climate system (52).

Despite the diversity of feedback loops and processes within terrestrial ecosystems, only a few terrestrial features determine the coupling of Arctic ecosystems with the climate system (Figure 3): (*a*) albedo, (*b*) energy partitioning (i.e., the degree to which evaporative cooling or permafrost dynamics influence the partitioning between ground heat flux or transfer of heat to the atmosphere as latent or sensible heat flux), and (*c*) the emissions of the greenhouse gases CO_2 and CH_4. We first discuss the responses of ecosystem function to warming on these features and then turn our attention to the responses of ecosystem structure.


Snow cover
I
16 ⊕
III
5, 6, 7 ⊖
1, 2, 3, 4 ⊕
V
12, 13 ⊖
10, 11 ±
8, 9 ⊕
Climate warming
Physiology enzymes, stomates
A
Structure composition, vegetation shifts
14, 15 ⊕
II
⊕ CO₂, SH↑
IV
Disturbance fire, insects
B
C
E
Land use logging, drainage, reindeer herding
Permafrost warming, thaw
D
Physical feedbacks
Mediating processes
Biotic control
Physiological feedbacks:
1. Higher decomposition: CO₂↑
2. Reduced transpiration: SH↑
3. Drought stress: CO₂↑
4. Permafrost thaw: CH₄↑
5. Longer production period: CO₂↓
6. NPP response to N min: CO₂↓
7. NPP response to T: CO₂↓
Structural feedbacks:
8. Shrub expansion: A↓
9. Tree-line advance: A↓, CO₂↑
10. Forest degradation A↑ but CO₂, SH↑
11. Light to dark taiga: A↓ but CO₂, SH↓
12. More deciduous forest: A↑, SH↓
13. Fire/tree-line retreat: A↑
Physical feedbacks:
14. Reduced heat sink: SH↑
15. Watershed drainage: SH↑
16. Earlier snowmelt: A↓
Response time:
Fast (seconds to months)
Intermediate (months to years)
Slow (years to decades)
Mechanisms:
A: albedo
SH: sensible heat flux
CO₂, CH₄: atmospheric concentration

FUNCTIONAL RESPONSES Fast feedbacks of Arctic terrestrial ecosystems result from physiological responses to warming and altered hydrology. Within certain limits, the activity of enzymes increases exponentially with temperature, causing both positive and negative feedbacks. Primary production and thus carbon uptake are enhanced (negative feedback, shown as feedback 7 in Figure 3) but so are decomposition of soil organic matter and thus carbon loss (positive feedback, feedback 1 in Figure 3). Vegetation controls water loss (and therefore evaporative cooling) through stomata, which respond to air humidity fluctuations within a few seconds and to changes in soil water availability within hours (53).

Exchange of CO_2 with the Atmosphere Analyses based on satellite data suggest that carbon uptake (i.e., production) by Arctic vegetation has generally increased in recent decades (54), although production in forested regions may have declined since 1990 (55), perhaps because of warming-induced drought (56). Satellite-derived estimates of production generally increase with both warming (54) and lengthening of the growing season (57). Several studies based on remote sensing indicate that growing seasons are lengthening in the Arctic (13, 48, 49) because of the earlier onset of thaw in both northern North America and northern Eurasia. In temperate forests, each additional growing season day increases the net carbon balance by 6 g C m^{-2} (58), and a recent modeling study suggests a similar relationship for Arctic ecosystems (13) (feedback 5 in Figure 3). Some studies suggest that spring recovery of photosynthesis, which marks the start of the growing season, is related to soil thaw (59), whereas other studies identified a relationship between air temperature and the onset of photosynthesis up to six weeks before soil thaw (60). Deciduous stands begin net carbon uptake later than conifers after leaf out but compensate for the later start by higher assimilation rates during the middle of the growing season (61–63). In tundra, experimental warming has resulted in earlier growth and higher productivity (64). For forests, a similar positive response to warming is less well documented. Tree-ring studies suggest that growth responses to warming are highly site specific and depend on interactions between temperature and precipitation (65). Although positive correlations between growth and

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Figure 3 Terrestrial responses to warming in the Arctic that influence the climate system. Responses of permafrost on the left are coupled with functional (physiological) and structural biotic responses on the right either directly (*arrows* B and D) or through mediating processes of disturbance and land use (*arrows* C and E). Functional and structural biotic responses are also coupled (*arrow* A). Response pathways are identified at three timescales (seconds to months, months to years, and years to decades). Physical responses will generally result in positive feedbacks. In general, functional responses of terrestrial ecosystems act as either positive or negative feedbacks to the climate system. In contrast, most of the structural responses to warming are ambiguous because they result in both positive and negative feedbacks to the climate system. Abbreviation: NPP, net primary production.

temperature have been shown for northern Eurasian tree-line sites (66), other studies present evidence for neutral or divergent behavior (65, 67), or growth declines when water is the limiting resource (56, 68). Tree-ring studies only track changes in stem production but cannot detect parallel shifts in allocation patterns to roots or foliage. A recent analysis based on a large biometric data set from Russia indicates an overall increase in the fraction of leaves, except in regions that became drier when the fraction of wood and roots increase (69).

Most carbon in Arctic ecosystems is stored in the soil (70), and a substantial release of this carbon to the atmosphere without a compensatory response in vegetation production would constitute a significant positive feedback to the climate system (71) (feedback 1 in Figure 3). In comparison with temperate and tropical ecosystems, soil carbon in Arctic ecosystems is generally more decomposable because it has been protected from decomposition by cold and/or anaerobic (i.e., waterlogged) soil conditions rather than being residual carbon after decomposition (72, 73). The warming of aerobic soils during the growing season is generally expected to increase decomposition in Arctic ecosystems, a response that has been substantiated by numerous experimental warming studies (74). Permafrost thawing can result in large releases of CO_2 to the atmosphere (75). Almost all high-latitude warming experiments have been conducted during the growing season, but decomposition and flux measurements show that winter decomposition represents an important component of the carbon budget of Arctic and boreal ecosystems (18). Warmer winter temperatures directly affect decomposition but not productivity. The fact that Arctic warming trends are most pronounced in winter on land suggests that losses enhanced by decomposition in winter are important to consider in evaluating annual carbon balance in response to warming. One particularly interesting hypothesis involves the degree to which the heat of microbial activity might further enhance decomposition from high-latitude soils during winter (76, 77).

Although soil warming will tend to increase carbon losses from Arctic ecosystems, the net effect of warming depends on the balance between production and decomposition (feedbacks 1, 3, 5, 6, and 7 in Figure 3). Experimental warming studies indicate that an increase in production is approximately compensated by an increase in decomposition (74). However, the responses are highly site specific and difficult to predict a priori. This is especially true for the role of soil nitrogen cycling. Decomposition releases nitrogen in forms available for uptake by plants. Because production is often limited by nitrogen uptake in Arctic ecosystems (18), an increase in nitrogen availability to plants should increase production (feedback 6 in Figure 3). Several warming experiments and modeling studies provide support for this mechanism (18). Whether the capacity for increased plant growth can offset decomposition losses largely depends on the degree to which newly available nitrogen is transferred to plants versus immobilized by microbes or lost in aquatic or gaseous pathways (78, 79).

Warming can also affect the water cycle and energy feedbacks (feedback 2 in Figure 3) to influence the net carbon balance through stomatal control of CO_2 uptake (feedback 3 in Figure 3) and moisture control of decomposition. Long-term eddy covariance data in a boreal aspen stand indicate that warming associated with drought suppressed soil respiration but not production (80), resulting in a transient strong carbon sink. In contrast, drier than normal conditions reduced the sink strength of a Finnish pine forest because photosynthesis was suppressed while ecosystem respiration increased (81). In tundra and wetlands, water table levels often influence the direction of CO_2 exchange. In anaerobic boreal soils, warming could affect carbon storage by altering soil drainage patterns. Soil drainage may be especially vulnerable to the response of permafrost to climatic warming, particularly in areas of discontinuous permafrost. In recent decades, the area of lakes in regions of discontinuous permafrost has decreased in Siberia (82) and Alaska (83), but there has been an increase of lake area in regions of continuous permafrost in Siberia (82) and no change in regions of continuous permafrost of Alaska. The net effect on CO_2 exchange is not clear because drainage can either be enhanced or retarded by permafrost degradation. For example, the release of CO_2 from aerobic decomposition is likely to be enhanced if permafrost warming results in a drop of the water table (84, 85). In contrast, CO_2 emissions from soils are likely to be reduced if permafrost thaws in situations where drainage is impeded and decomposition is diminished because of anaerobic conditions (85, 86) and moss production is increased (87).

The functional responses of net CO_2 exchange of tundra ecosystems in the Arctic have been evaluated in recent syntheses involving both observations and process-based models, which suggest that tundra over the circumpolar Arctic is neither a large source nor a large sink of CO_2 (88). Observations suggest a modest source, whereas models suggest a small sink in recent decades, but the spatial variability of source/sink activity is large; McGuire et al. (89) report a sink of 17 g C m^{-2} $year^{-1}$ with a standard deviation of 40 g C m^{-2} $year^{-1}$ (see also 90). Observations and model analyses suggest that areas that have warmed and dried, such as Arctic regions of Alaska and eastern Europe, are generally a carbon source (91–93), whereas warm-wet and cold-wet tundra regions are generally a carbon sink (93). Scandinavian and Siberian peatlands, which have become warmer and wetter, are a net carbon sink of 15–25 g C m^{-2} $year^{-1}$ (94, 95). In Greenland, where there has been little warming, net carbon exchange is close to zero, with sinks in wet fens balanced by carbon losses in dry heath (96–98). Carbon fluxes in the high Arctic (generally north of 70°N) are extremely low, with a net sink of about 1 g C m^{-2} $year^{-1}$ (99). At the pan-Arctic scale, the net response of CO_2 exchange with the atmosphere is highly uncertain because of uncertainty in how hydrology has changed. The functional response of the net CO_2 exchange in the boreal forest is also highly uncertain, but it has likely also been substantially altered by warming with high regional variability that depends on both warming trends and hydrology (13, 55, 69).

Exchange of CH_4 with the Atmosphere Arctic wetlands are one of the largest natural sources of CH_4, about 70 Tg (10^{12} g) yr^{-1} (100). Fluxes of CH_4 are highly variable, both temporally and spatially. However, CH_4 emissions respond positively to soil moisture, summer soil temperature, and the presence of oxygen-transporting vascular plants such as wetland sedges (101) (feedback 4 in Figure 3). If warming and thawing of permafrost increase the area of wetlands and lakes, then efflux of CH_4 from Arctic ecosystems is likely to be further enhanced (86, 102). However, wetland drying would be expected to reduce CH_4 efflux. The net result is uncertain and probably regionally variable. The recent increase in the concentration of atmospheric CH_4 suggests that increased emissions may be predominating, contributing a positive feedback to climate warming. Especially in tundra regions, the balance of evidence suggests that tundra is currently contributing to greenhouse warming because of substantial CH_4 emissions (88, 103) that represent a radiative forcing effect, which is greater than small source/sink activity associated with the exchange of CO_2 (90, 104).

STRUCTURAL RESPONSES Of all compositional changes in the boreal forest, a shift between evergreen and deciduous tree species exerts the strongest feedback to the climate system (10, 15, 105) (feedback 12 in Figure 3). Deciduous forests have a higher albedo, have less sensible heat flux (see below), and are less flammable. A change from conifers to early successional deciduous hardwoods is mostly triggered by disturbances. The transition to late-successional conifers is more gradual but rarely takes longer than 100 years (106, 107). Higher fire occurrence, as is currently observed in most boreal regions (18), increases the proportion of deciduous forest and thus (*a*) increases the albedo, (*b*) decreases heat transfer to the atmosphere, and (*c*) decreases the flammability of boreal forests for a sustained period. The negative feedbacks to climate warming associated with these three processes are in contrast to the positive feedback associated with carbon loss from fire. Disturbance of boreal forest from insect outbreaks has a similar effect. Insect outbreaks appear to be increasing in many areas, with strong indications that this is related to warmer temperatures (18). The proportion of hardwoods in the landscape is further increased if (*a*) they become self-replacing (as opposed to an early successional stage) or if (*b*) self-replacement of conifers is prevented where it usually occurs. Both processes are triggered by an intensification of the fire regime. Self-replacement of hardwood forests via vegetative regeneration occurs if fire return intervals become shorter than the duration of the pioneer stage. On permafrost, where self-replacement of conifers is common, large, severe fires tend to reduce the strength of the local coniferous seed sources and favor hardwood species with long-distance seed dispersal (108). In Siberia, 55% of the coniferous forest on continuous permafrost soils is deciduous (*Larix* sp.) with consequently high winter albedo. Although the two evergreen conifers (*Picea obovata* and *Pinus sibirica*) also grow well on permafrost soils, *Larix* usually dominates because of its additional fire resistance. However, a recent advance of evergreen conifers into the *Larix* zone is related to increased temperature and precipitation over the past 30 years (109). Undergrowth of evergreen conifers decreases winter albedo, a positive feedback to climate warming (feedback 11 in Figure 3). In North America, where crown fires predominate (71), deciduous stands usually have a well developed second canopy layer of spruce (110).

In tundra, the most critical compositional feature is the cover of tall shrubs. In recent decades, shrub area has expanded by 1.2% decade^{-1} in Alaska (111), and remote-sensing-based analyses suggest similar trends in the circumboreal tundra (55). Warming experiments in tundra indicate that an increase in summer temperature by 1° to 2°C triggers increased shrub growth within a decade (64). Shrub tundra has a lower winter and summer albedo than sedge tundra (10) (feedback 8 in Figure 3). If the positive temperature response of shrub growth is mediated by increased nitrogen mineralization rates, a recent long-term fertilization experiment suggests that an increase in shrubs is associated with a net loss of soil carbon (112).

Changes in vegetation types include shifting biome borders along ecotones (e.g., tree line; feedback 9 in Figure 3) and switches between alternate stable states within biomes (e.g., forest to nonforest). Over the past half century, tree-line advances into northern or mountain tundra have been documented in Scandinavia, Russia, Canada, and Alaska (18). These advances were usually associated with increased growth rates of trees, increased stand density, and sometimes a more upright tree stature. However, elsewhere natural disturbances and human activities in Russia have moved tree line to the south or to lower elevations (113–115) (feedbacks 13 and 10 in Figure 3). Fires close to the tree line prevented vegetative regeneration and depleted the local seed sources so that forest regeneration failed. Once treeless, these sites lose their capacity to trap snow, and the resulting decrease in soil temperature favors tundra vegetation (116). Also, a gradual climate-driven conversion from forest to tundra has been reported from various maritime boreal regions (eastern Canada and Scandinavia) (117). Here, an increase in precipitation often associated with a decrease in fire frequency triggered a raising of the water table and a retreat of forests that generally depend on dry postfire conditions for regeneration. Replacement of forest by nonforest vegetation, mediated by disturbances, is not restricted to the forest-tundra ecotone but occurs well within the boreal biome (118). Across the boreal forest large or very frequent fires and extensive clear-cuts create conditions where succession leads to open woodlands (119, 120) or remains locked in a treeless stage (121).

Changes in vegetation structure influence all three classes of climate feedbacks: albedo, energy partitioning, and the exchange of greenhouse gases (Figure 3). The change from evergreen to deciduous forests represents a negative feedback because deciduous forests have higher albedo (summer 0.15/winter 0.21) than evergreen forests (summer 0.08/winter 0.11) (122). In closed forests, water loss is controlled by canopy transpiration, which is higher by factor 1.5 to 1.8 in deciduous than in coniferous forests, with consequently lower sensible heat flux (122).

Several vegetation changes could result in either positive or negative feedbacks depending on the relative contribution of individual processes (Figure 3). A change from light to dark taiga forests is associated with a moderate decrease of summer albedo (positive feedback) (122), a slight increase in carbon storage (negative feedback) (123), and a decrease in sensible heat flux (negative feedback) (105). Forest degradation increases summer and winter albedo (negative feedback), but leads to high losses of carbon on the order of 50% and possibly higher heat flux (positive feedback) (105). The same is true for tree-line retreat, which results in a winter albedo increase from ~0.2 to 0.6–0.8 (negative feedback) (15), but may result in substantial carbon losses from the loss of tree biomass (positive feedback).

Tree-line advance and increase in shrub tundra clearly represent positive feedbacks. Both processes decrease albedo (10) and may lead to a net loss of carbon if the increases in biomass carbon associated with more woody vegetation do not compensate for the losses in soil organic matter (112, 124). In Alaska, these positive biotic feedbacks account for only 5% of the observed heating compared to a lengthening of the snow-free season, which accounts for 95% (10). The current asymmetry between the effects of vegetation changes and the lengthening of the snow-free season is due to the vegetation changes that are just starting, and their influence will likely progressively increase and act to promote longer snow-free seasons as warming continues.

Arctic Ocean Ecosystems

As with Arctic terrestrial ecosystems, Arctic Ocean ecosystems may influence the climate system through affecting the exchange of greenhouse gases and exchange of energy between the atmosphere and the surface of the Arctic Ocean (Figure 4). Linkages between terrestrial and aquatic ecosystems have consequences for the exchange of greenhouse gases between the atmosphere and the Arctic Ocean. Arctic streams and lakes can act as conduits for CO_2 via the decomposition of dissolved and particulate carbon derived from terrestrial ecosystems (125). After spring runoff, concentrations of dissolved and particulate organic carbon in high-latitude aquatic ecosystems are highly correlated with precipitation because water is flushed through the organic layer (126). There is also a significant increase in the carbon concentrations of streams after fire. Therefore, increases in precipitation or increases in the frequency of fire disturbance in high latitudes might enhance the delivery of soil organic carbon to and subsequent decomposition in aquatic ecosystems. Arctic rivers also deliver a substantial amount of organic carbon to the Arctic Ocean (127). Key uncertainty about increases in this flux is whether this will increase the release of CO_2 from immediate decomposition in coastal ecosystems or whether the carbon will be sequestered in marine sediments (128) (feedbacks 6 and 3 in Figure 4). About half of the carbon entering the Arctic Ocean from terrestrial ecosystems is from river inputs, and about half is from the erosion of coastal soils along the Arctic Ocean (128). Although some of this carbon may become buried in ocean sediments, some of this material will likely be immediately decomposed in coastal Arctic ecosystems. Coastal erosion has increased in recent decades (129) and is associated with reduced summer cover of sea ice on the Arctic Ocean. It is expected that erosion of organic matter from soils along the coast of the Arctic Ocean will increase over the next century if sea ice continues to retreat and that this will enhance the CO_2 flux to the atmosphere from the Arctic.

Permafrost in the sediments of the ocean may also influence carbon cycling upon thaw. The coastal zones of the Arctic Ocean are underlain by a thick layer

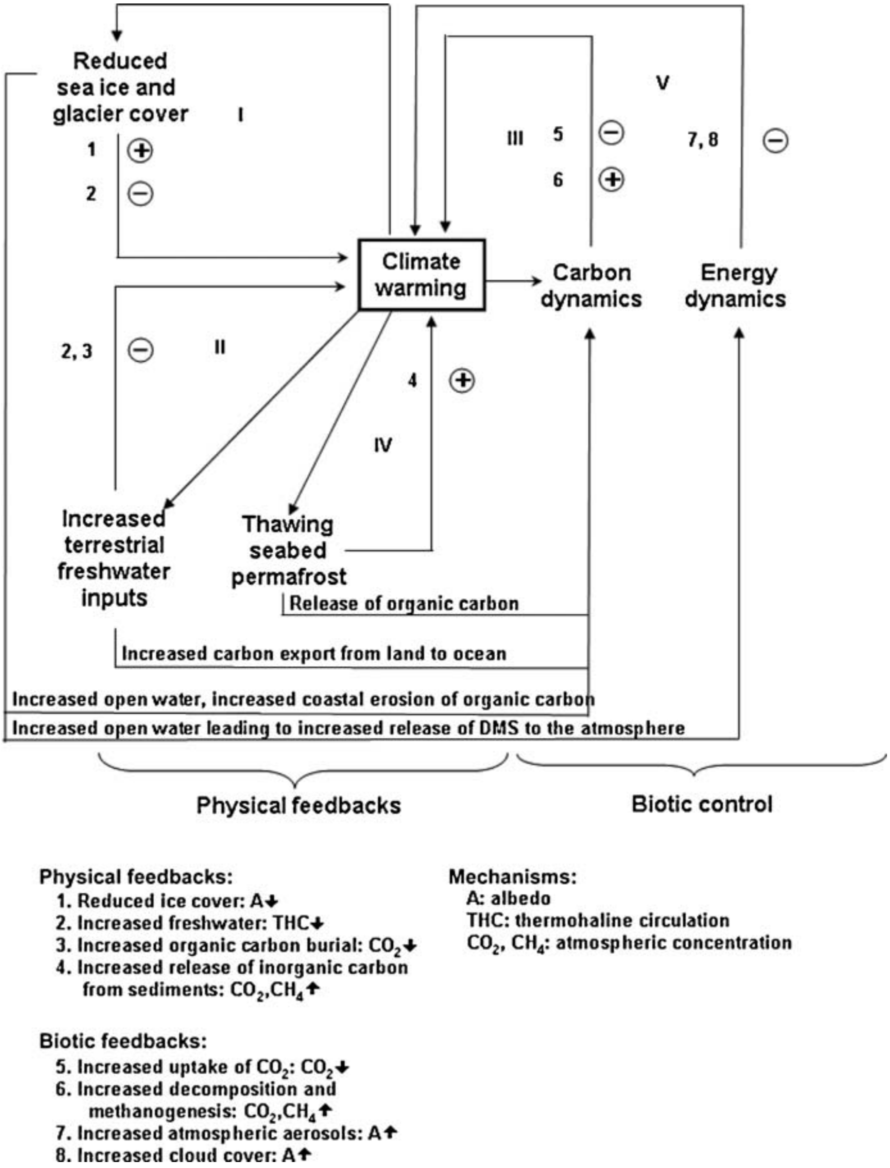

Figure 4 Arctic Ocean responses to warming that influence the climate system. Responses of sea ice, glaciers, and seabed permafrost (on the left) are coupled with biotic responses (on the right) through several mechanisms affecting carbon and energy dynamics. Physical responses to the climate system result in either positive or negative feedbacks. Although it is not clear whether the response of carbon dynamics in the Arctic Ocean will result in a positive or a negative feedback, the response of dimethylsulfide in the Arctic Ocean is likely to result in a negative feedback from increased atmospheric aerosols and increased cloud cover.

of permafrost (130), which contains an enormous amount of methane from gas hydrate deposits (131). If permafrost in the coastal areas were to degrade, there might be a substantial release of methane from these hydrates (132) (feedback 4 in Figure 4). Also, the coastal zone contains a substantial amount of carbon in frozen sediments of the seafloor, particularly in estuaries (133), which could release CO_2 through decomposition and CH_4 through methanogenesis upon thaw of the seafloor (132) (feedback 6 in Figure 4).

The carbon cycle in the central basin of the Arctic Ocean, which is poorly understood, is characterized by production in leads, polynas, and melt ponds during summer as well as by decomposition in the water column throughout both summer and winter (134). Recent studies show that primary production in the water column of the Arctic Ocean is substantially underestimated (135) and that there is likely a significant flux of CO_2 through sea ice, especially as temperatures warm in the spring (134). Although the carbon cycling of the Arctic Ocean may change as sea ice thickness decreases and sea ice extent diminishes (feedbacks 5 and 6 in Figure 4), the degree to which this will affect the overall greenhouse gas budget of the Arctic is uncertain.

The biogenic production of sulfur compounds, associated with the retreat of sea ice, in the Arctic Ocean might influence the climate system (136). Release to the atmosphere of dimethylsulfide (DMS), which originates from the precursor dimethylsulfoniopropionate produced by marine phytoplankton and sea ice algae, can lead to the production of sulfate aerosols, which are important sources of cloud condensation nuclei. If warming leads to higher production of DMS, then the increased production of sulfate aerosols can lead to a negative feedback to promote cooling either directly by reflecting incoming short-wave radiation or indirectly through the formation of clouds (137) (feedbacks 7 and 8 in Figure 4). One analysis suggests that a decrease in sea ice extent of approximately 20% over the annual cycle (about 60% during the summer-autumn season) can lead to an 80% increase in DMS production by 2080 (136). This increased production is estimated to have a cooling effect of between 5 and 13 $W\ m^{-2}$ over the Arctic Ocean during the summer months June through September, which would be a substantial negative feedback on the radiative balance of the Arctic, possibly masking the albedo-temperature feedback of decreased sea ice.

THE ROLE OF ARCTIC HUMAN SYSTEMS IN THE CLIMATE SYSTEM

Despite the relatively low human population density in the Arctic, human activities have, in general, accentuated the ecological feedbacks to the climate system that are occurring naturally in response to high-latitude warming. The nature and magnitude of these human impacts vary regionally, although the effects are not well quantified.

In the most general sense, human activities are an important contributor to all recent climate feedbacks at high latitudes because anthropogenic production of greenhouse gases contributes to high-latitude warming. In addition, soot particles from fire in the Arctic and elsewhere and from coal burning in China and Eastern Europe are transported into the Arctic as Arctic haze, increase aerosols in the Arctic atmosphere, and reduce the albedo of snow and ice. Modeling studies suggest that soot effects on net radiation and atmospheric heating are not large per unit area but contribute substantially at the pan-Arctic scale (138).

In some areas of the Arctic, people have altered land cover through reindeer grazing, changes in fire regime, agricultural land use, and forest harvest. Overgrazing by reindeer reduces albedo, caused by the loss of highly reflective lichens, the preferred winter food of reindeer. Although this albedo change has not been quantified, it is readily seen from space (139). After the economic collapse in Russia, subsidies to northern communities declined, changing the economic viability of reindeer herding and harvest. Although the effects have been regionally variable, there has been a decline in numbers of domestic reindeer, an increase in wild reindeer, and a deterioration of pastures (140). On the Yamal Peninsula, oil and gas development has constrained the range available for reindeer herding, leading to overgrazing (139). Thus, the net effect of changes in grazing pressure has been regionally variable but often leads to more intensive grazing, lower albedo, and a positive feedback to high-latitude warming of highly uncertain magnitude.

Within the boreal forest and at the latitudinal tree line, human activities have altered climate feedbacks primarily through changes in disturbance regime, leading to changes in land cover that have implications for both trace-gas and energy feedbacks, as described above. In Russia, the predominant trend has been toward an increase in fire frequency. Although this increase in area burned is clearly linked to climate warming (141), much of the area burned results from anthropogenic fires (142), making it difficult to separate climatic and anthropogenic impacts. The climate feedbacks from these anthropogenic fires are similar to those discussed above for lightning-ignited wildfire, a negative feedback to warming through increased albedo, but a positive feedback to warming as carbon is lost because of the reduced length of the fire cycle. Fire is also the main agent moving the tree line south, although warming would otherwise allow forests to advance north.

In contrast to Russia, the increase in area burned in North America clearly reflects climate-induced increases in the size of large lightning-caused fires. Although fire suppression in North America reduces area burned near population centers (143), the areal extent of these effects is relatively small and does not significantly offset the continental scale increases in area burned (144). In Scandinavia, forest management has largely eliminated wildfire as an ecologically significant process, with forest harvest becoming the prevailing agent of disturbance (71).

The conversion of forest to agriculture is characterized by positive feedbacks associated with the loss of carbon and by negative feedbacks associated with an increase in albedo. In Alaska, a recent study indicates that conversion from forest to agriculture leads to loss of nearly half (44%) of soil carbon within one to two decades (145). The conversion of forest to agriculture was extensive in Scandinavia and parts of Canada and Russia but modest in Alaska. In the prairie provinces of Canada, there was an estimated net deforestation of 12.5 million ha between 1860 and 1992 (17). Since 1950, Canadian forests have had a net gain of 3.0 million ha at the expense of agriculture. Although this is a small proportion of the total forest base (<1%), it is important to recognize that most of the aforestation has occurred in eastern Canada and that deforestation continues to occur in western Canada. In Russia, approximately 30 million ha of arable lands were abandoned between 1988 and 2001. Abandonment is most pronounced in the zone of the boreal forest because the low-productivity lands were unprofitable in the transition to a market economy. Although both aforestation and deforestation are characterized by positive and negative feedbacks, the study by Betts (146) suggests that the effects on albedo forcing are stronger than the effects on atmospheric CO_2 forcing. Thus, the substantial abandonment of agricultural land in Russia suggests a net positive feedback to climate warming.

As discussed earlier, forest harvest is also characterized by positive feedbacks associated with the loss of carbon and negative feedbacks associated with an increase in albedo. In Canada, annual forest harvest approximately doubled from ~0.5 million ha in 1970 to ~1 million ha in 1990 (147). Timber harvest in Alaska increased over six-fold from 1952 to 1992 (17). Recent trends of forest harvest rates in Canada and Alaska are substantially influenced by economics of the global forest sector, as much of the harvested wood is exported out of the region to markets in Asia and the coterminous United States. Concern over conservation issues and the collapse of Asian economies in the 1990s have had substantial impacts in decreasing forest harvest in Alaska during the 1990s. In Russia, forest harvest between 1950 and 1990 was relatively steady at about 2 million ha per year. The harvested areas were mostly concentrated in the European North (about two thirds of the total) and in the most populated regions of Siberia. With the breakup of the Soviet Union, forest harvest during the past 15 years decreased substantially to around 1 million ha per year by 2002. This estimate of recent harvest rates should probably be increased by 15% to 20% because of illegal harvest in the Russian Far East. On the basis of the Betts' study results (146), the decrease in Russian forest harvesting has likely resulted in a positive feedback to climate warming.

Human use of freshwater in the Arctic might also influence the freshwater budget of the Arctic Ocean. Although dams and impoundments of the large rivers in Siberia influence the seasonality of water discharge into the Arctic Ocean, they do not appear to have caused an increase in river discharge into the Arctic Ocean (36). Finally, concern over the impacts of climate change in the Arctic could influence international agreements on policies to control climate change. The recent release of the Arctic Climate Impact Assessment (42) has raised the awareness of the impacts being experienced by residents in the Arctic. It remains to be seen if this increased awareness will translate into decisions to more aggressively control the concentrations of greenhouse gases in the atmosphere.

CONCLUSIONS

The Arctic is a key part of the global climate system because the net positive energy input to the tropics must ultimately be resolved through substantial energy losses in the Arctic. Thus, responses of the Arctic components of the climate system to warming that influence the loss of this energy have implications for the global climate system. It is clear from this review that the many changes underway in the Arctic have substantial implications for the global climate system, and if climate model projections are correct, these changes are likely to accelerate over the next century. Our review indicates that the Arctic may influence the global climate system through many positive and negative feedbacks (Table 1). Important positive feedbacks include

- an increase in atmospheric water vapor that traps long-wave radiation near the surface;
- albedo-temperature feedbacks of reducing snow and ice cover, increasing shrub tundra cover, expansion of evergreen conifer forests, and more soot on snow and ice from more frequent fires;
- carbon release from enhanced decomposition, more frequent disturbance, and enhanced coastal erosion; and
- methane release enhanced by temperature sensitivity of methanogenic microbial processes and thawing of permafrost.

Important negative feedbacks include

- decreases in albedo associated with increasing cloudiness, more deciduous forest cover associated with more frequent disturbance, and enhanced aerosols from more frequent fire and increased DMS production in the Arctic Ocean;
- increases in carbon storage in terrestrial plants and increasing carbon uptake by marine plants;
- political pressure by Arctic residents for more aggressive efforts to control greenhouse gas concentrations; and
- increases in freshwater from (*a*) rivers into the Arctic Ocean and (*b*) thawing of sea ice and glaciers.

The balance of evidence suggests that positive feedbacks to global warming will likely dominate in the Arctic during the next 50 to 100 years. It is generally thought that the negative feedbacks associated with changing the freshwater balance of the Arctic Ocean could abruptly launch the planet into another glacial period on longer timescales.

Our understanding of the relative importance and the timescales of interactions of the feedbacks in the Arctic is far from complete. For example, we do not know how and on what timescale the oceanic changes in the North Atlantic will influence

TABLE 1 A summary of the major positive and negative feedbacks to the climate system from responses of the Arctic to ongoing and projected climate change in the region

Positive feedbacks	Effect of positive feedbacks on forcing	Negative feedbacks	Effect of negative feedbacks on forcing
Increased water vapor in the atmosphere	Water vapor as a greenhouse gas	Increased cloudiness, more deciduous forest from more frequent disturbance, and enhanced aerosols from more frequent fires as well as more production of dimethylsulfide in the Arctic Ocean	Increased albedo
Decreased snow and ice cover, increased tundra shrubs, expansion of evergreen conifer forest, and soot on snow/ice from more frequent wildfires and coal burning	Decreased albedo	Increased carbon storage by terrestrial plants from enhanced growth and increased uptake of CO_2 by marine plants	CO_2 as a greenhouse gas
CO_2 released by decomposition of soils, more frequent fire and insect disturbances, and increased coastal erosion	CO_2 as a greenhouse gas	Political pressure by Arctic residents for decision makers to more effectively control greenhouse gas concentrations	CO_2 as a greenhouse gas
Methane released by temperature sensitive methanogenic microbial processes and thawing of permafrost	Methane as a greenhouse gas	Increased freshwater inputs to the Arctic Ocean and North Atlantic from melting of sea ice and glaciers, increased precipitation, and increased river discharge	Shut down of the global thermohaline circulation

climate. We do not know with confidence how terrestrial and marine ecosystems will respond to the first-order climate changes, let alone to the changes that will ultimately result from poorly understood feedbacks. A prime example of a physical change that will almost certainly affect terrestrial ecosystems is thawing of permafrost and associated hydrologic impacts. Our understanding of climatic effects on permafrost is inadequate to permit reliable quantitative estimates of the future rates of change of permafrost, hydrology, and terrestrial ecosystems. Snow cover as well as air temperatures and radiative forcing are involved in these changes, and our ability to model the important interactions involving snow cover at resolutions less than those generally considered by climate models needs improvement. Similarly, treatments of polar clouds in climate system models, which are important in the albedo-temperature feedback, need improvement. The subsoil processes in the terrestrial Arctic are also inadequately treated in climate system models, despite the potential importance of permafrost and its relationship to releases of greenhouse gases to the atmosphere. Finally, coupled model simulations and projections of climate will need more stable simulations of the subpolar oceans, which are the ultimate drivers of the global thermohaline circulation and therefore represent a key linkage between the Arctic and other parts of the global climate system. In light of these uncertainties and the vulnerabilities of the climate system to responses in the Arctic, it is important that we improve our understanding of how integrated regional changes in the Arctic will likely influence the evolution of the global climate system.

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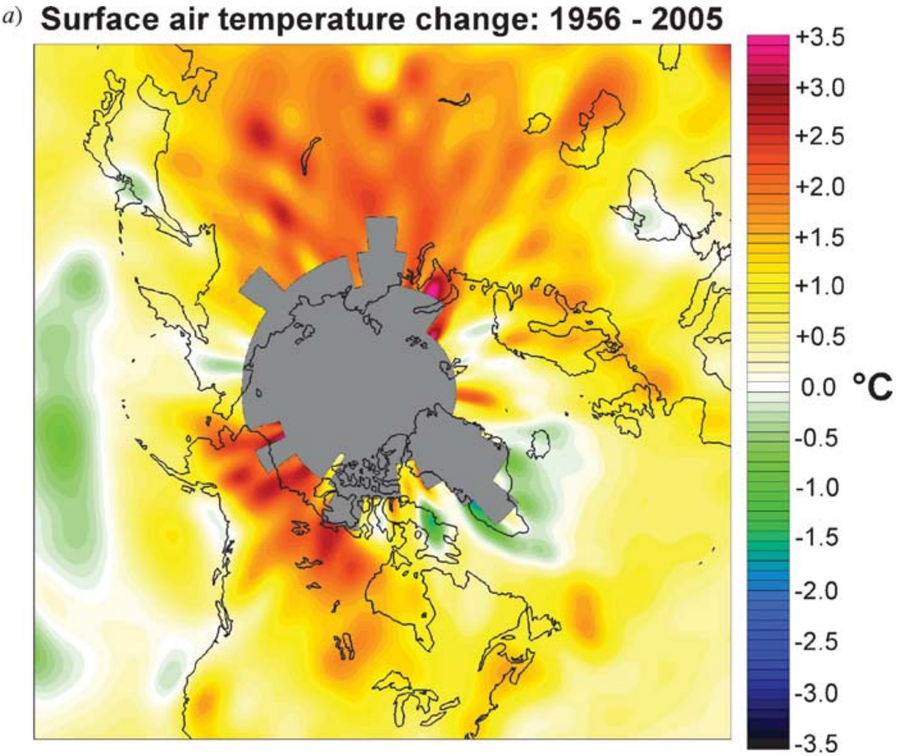
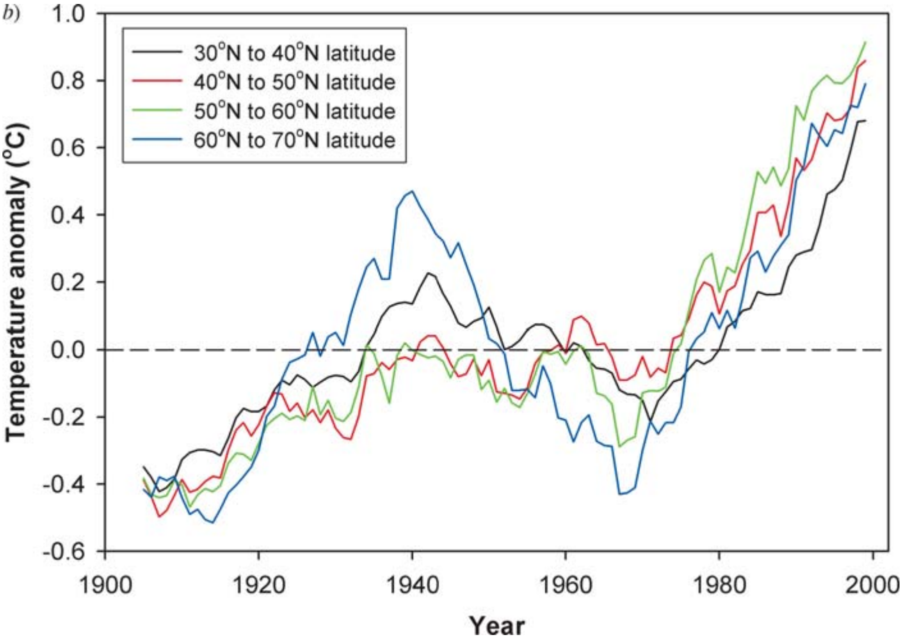


Figure 1 Surface air temperature and sea ice changes in the Arctic during the twentieth century. (*a*) Changes in surface air temperature between 1956 and 2005 (courtesy of Bill Chapman, University of Illinois). (*b*) Changes in the 10-year running mean of surface air temperature over land during the twentieth century aggregated for 10-degree latitudinal bands (courtesy of the Spatial Ecology Laboratory, University of Alaska Fairbanks). (*c*) Sea ice area anomalies during the twentieth century (courtesy of the Arctic and Antarctic Research Institute, St. Petersburg, Russia).

b)



c)

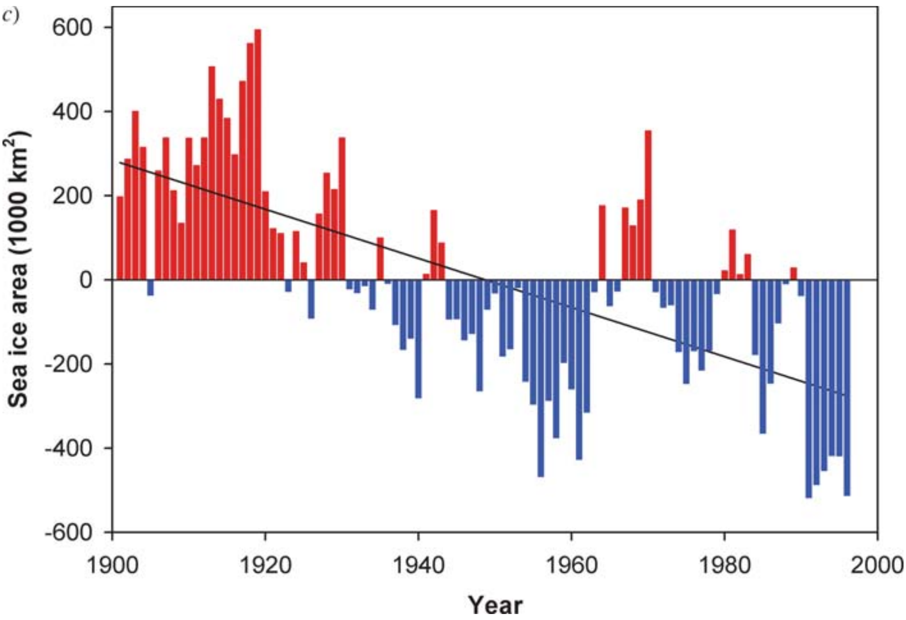


Figure 1 (*Continued*)

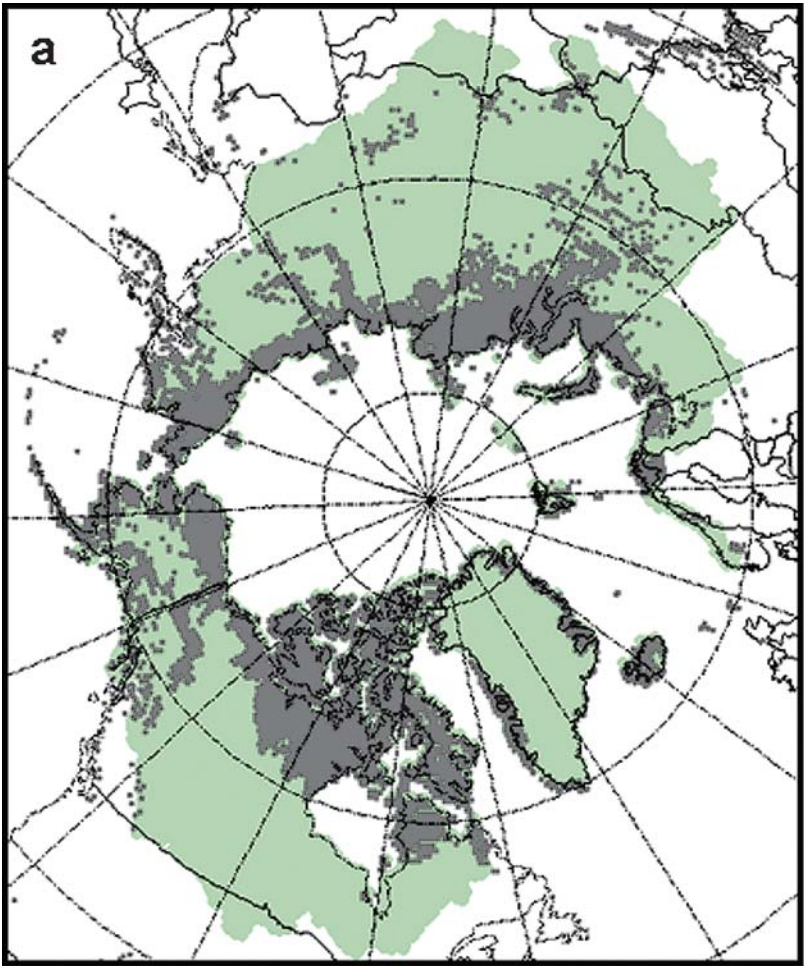


Figure 2 The Arctic, using hydrology, vegetation, and permafrost information. (*a*) The gray area depicts the distribution of both latitudinal and elevational tundra within the pan-Arctic watershed, which is depicted by the sum of the gray and green areas. The boundary between latitudinal tundra near the coast of the Arctic Ocean and the green area defines "tree line." (*b*) The green area depicts the distribution of permafrost in the Northern Hemisphere over unglaciated regions. The permafrost region in the middle left of the figure identifies the presence of permafrost on the Tibetan Plateau. These are based on permafrost maps courtesy of the International Permafrost Association (149), hydrology maps courtesy of the Complex Systems Research Center, University of New Hampshire (20), and vegetation maps courtesy of Spatial Ecology Laboratory, University of Alaska Fairbanks (71).

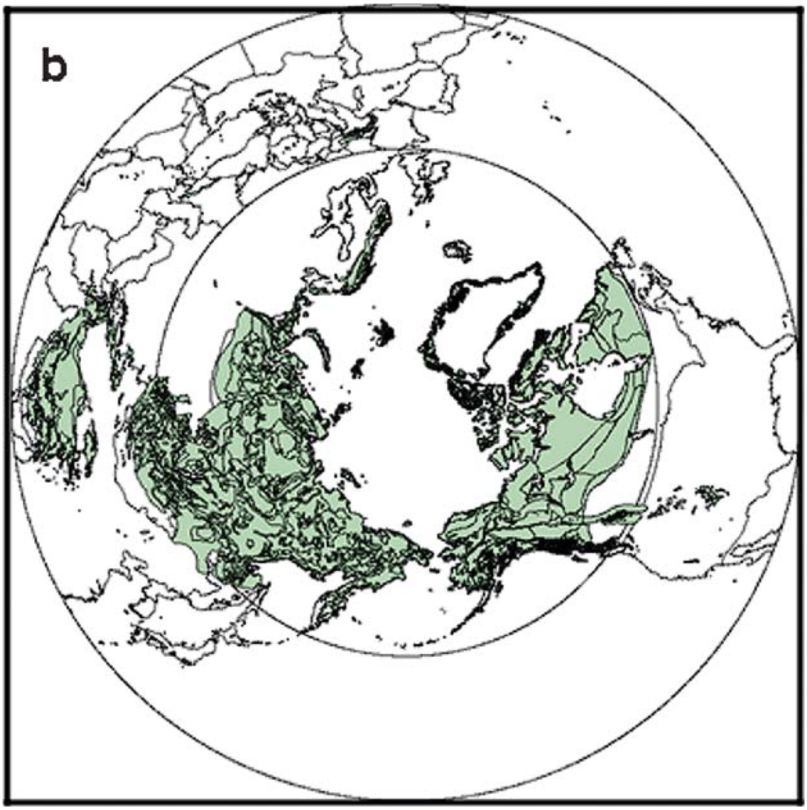


Figure 2 (*Continued*)

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ERRATA

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