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Sensitivity of Arctic carbon in a changing climate

The Arctic has been warming rapidly in the past few decades. A key question is how that warming will affect the cycling of carbon (C) in the Arctic system. At present, the Arctic is a global sink for C. If that changes and the Arctic becomes a carbon source, global climate warming may speed up.

Here we define the Arctic as the Arctic Ocean plus the lands that drain into the Arctic or that have permafrost, excluding high-elevation areas farther south such as the Tibetan Plateau or Antarctica (Fig. 1). The Arctic contains vast amounts of carbon (Table 1).

Contemporary Arctic carbon stocks and fluxes

Atmospheric measurements indicate that the Arctic is a modest C sink with about 400 Tg (megatons) taken from the atmosphere in an average year (Fig. 2). This amount can vary greatly from year to year. Studies of carbon dioxide (CO_2) flows at specific sites also indicate great variation from year to year.

Combining various studies and estimates for the terrestrial Arctic, it appears that land areas are a sink for approximately 300–600 Tg (C) yr^{-1}. This amount is 30–60% of the

Arctic Carbon Stocks

Location	Amount, billions of tonnes
Land	
Soil	1400-1850
Living plants	60-70
Ocean	
Water column	
Dissolved inorganic carbon	310
Dissolved organic carbon	9
Sediments	9,4
Methane Hydrates	
Ocean	30-170
Land	2-65
Total	~1820-2485

Table 1. Estimates of current Arctic carbon stocks.

global estimate for the net C sink on land [1]. Lakes and rivers are a source of C to the atmosphere with 40–84 Tg (C) released each year.

Seawater in the Arctic appears to be a sink for 24–100 Tg (C) yr^{-1}. This accounts for 1–5% of the global estimate for the ocean C sink [1]. Carbon is also carried from land to rivers, from rivers to ocean, and from ocean to ocean. There is considerable uncertainty involved in most estimates of C transport, but river transport, ocean currents, and coastal erosion appear responsible for the largest amounts [1].

Recent atmospheric studies indicate that the Arctic is a source for 15–50 Tg of methane (CH_4) each year, or 3–9% of the global total net emissions from land and sea [1]. Site studies show a higher emission rate of 31–100 Tg (CH_4) yr^{-1} from land and freshwater sources combined.

The role of small lakes in permafrost areas is greater than previously thought. These lakes are surrounded by carbon-rich soils laid down in the last ice age, now being released as the water thaws the frozen soil. Methane hydrates, which are ice-like solids in permafrost and below the floor of the ocean that contain a single molecule of CH_4 in a cage-like structure, do not appear to contribute much to Arctic emissions at present.

The response of Arctic carbon to climate change

In the next decade or two, the boreal forest may continue to grow, absorbing more carbon as trees become larger and the treeline expands northward. On the other hand, forest fires may increase in frequency and extent and insect outbreaks may kill more trees. Both of these processes would release carbon to the atmosphere. Which trend dominates the other depends in part on precipitation: dry conditions may reduce plant growth and lead to more fires.

It is also unclear whether increased CO_2 concentration in the atmosphere will stimulate plant growth in the Arctic because plant growth may be more limited by nitrogen availability in the soil than by atmospheric

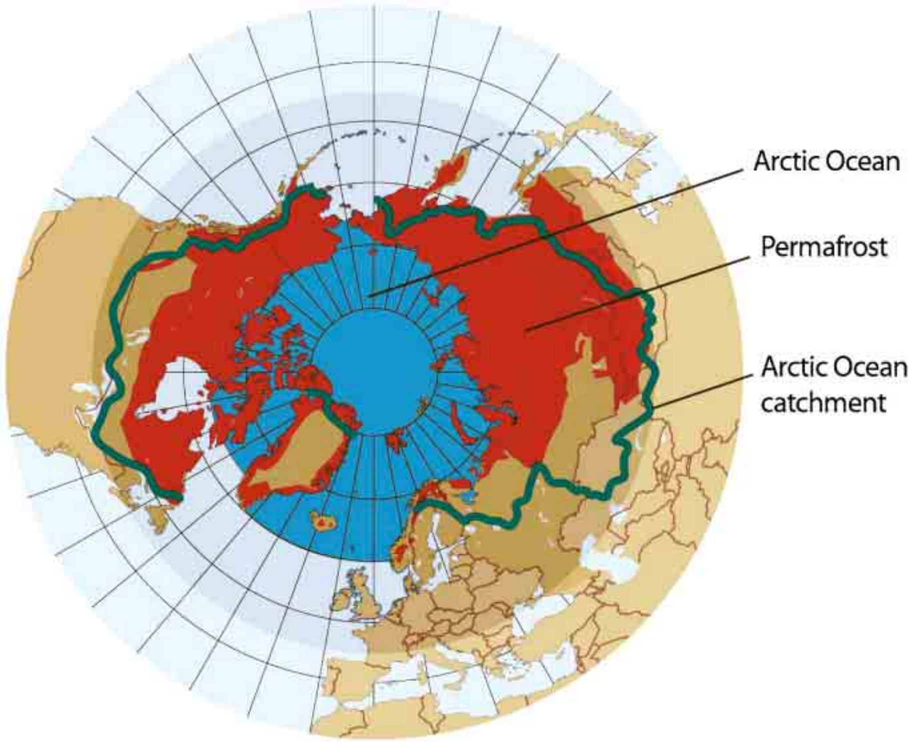

Figure 1. The region that we consider the Arctic. Source: [7].

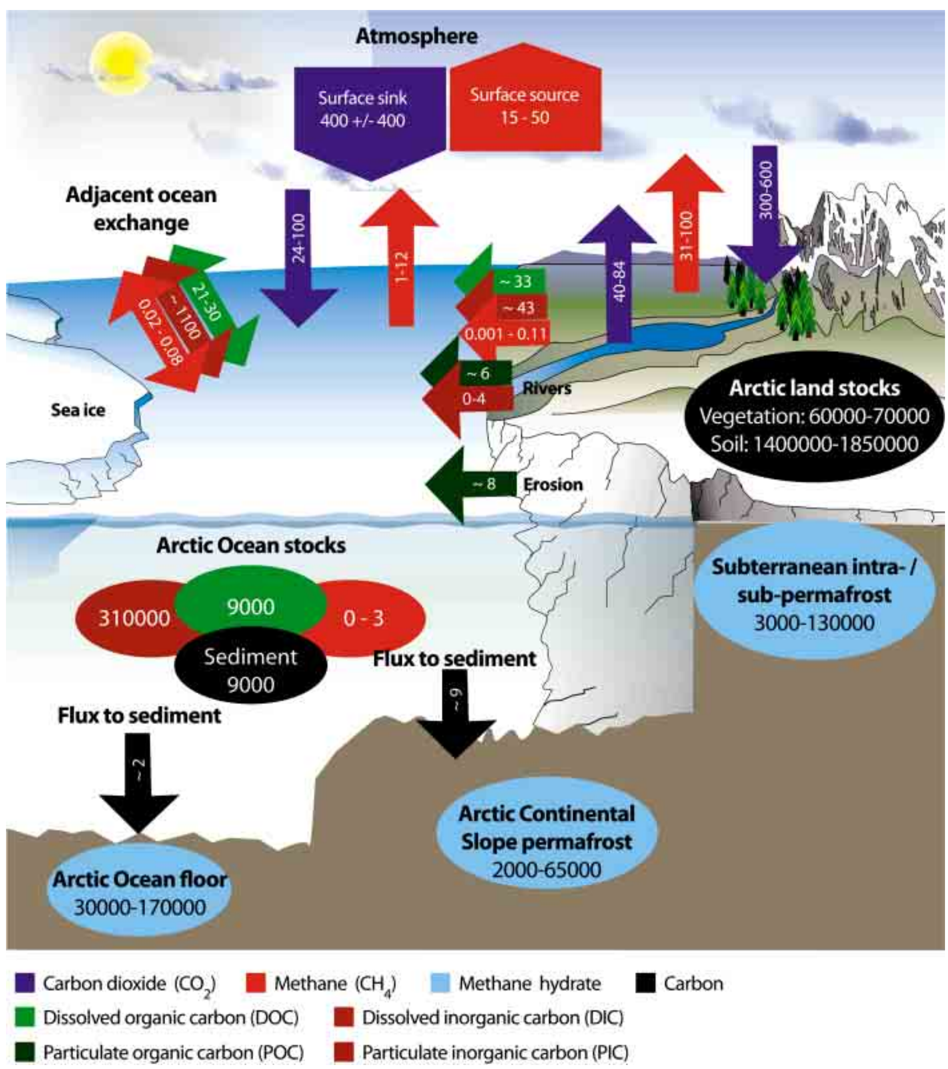

Figure 2. Current state of the Arctic carbon cycle showing amounts of carbon stored in various environmental reservoirs (units: millions of tonnes C, or millions of tonnes CH_4 for methane and methane hydrate) and the net flux of compounds (units: millions of tonnes C per year, or millions of tonnes CH_4 per year for methane) that determine the movement of carbon between environmental compartments. Source: [7].

CO_2 [2]. Although shrubs are moving into tundra areas, the movement of the actual treeline is very slow and will likely only have an effect on the C cycle of the Arctic over the course of several centuries.

Thawing of near-surface permafrost will mobilise C stored in the soil. Different studies show different patterns over time, but most agree that much carbon will become available by the end of this century [1]. Furthermore, fire in permafrost landscapes may accelerate thawing, a factor that has not been considered in studies to date.

Once permafrost has thawed, the release of C depends primarily on the wetness of the soil. Wetter soils will release more CH_4 but relatively less CO_2 than dry soils. Recent trends in the Arctic indicate that landscapes are typically drying as a result of climate change [3–5].

However, the changes in the Arctic carbon cycle appear to have only a modest influence on global climate. One study [6] projected a potential maximum release of 50 Pg (gigatons) of carbon from the Arctic terrestrial environment through this century, far lower than the 1500 Pg that are expected to be released even by low-end estimates of fossil fuel burning over the same period [6].

In the marine environment, too, feedbacks between climate and the C cycle can be both positive and negative. Reduced sea ice will allow more exchange of carbon from sea water to the atmosphere. It will also allow more light to reach the water, stimulating more plankton growth and thus uptake of carbon.

On the other hand, melting of ice will result in more freshwater in upper ocean layers, which can reduce biological activity and lead to less carbon being taken up by biota. These effects will act very differently in each season, making projections of the net change even more difficult. As the ocean warms, it can hold less dissolved CO_2. Furthermore, warmer water may lead to increased production of CO_2 and CH_4 through decomposition and other biological activity.

The discharge of water from land to sea increased in the Arctic throughout the 20th century, and is projected to continue to rise and perhaps accelerate during the 21st century. Increased water flow will likely be connected with increased C transport though the partitioning of carbon is difficult to predict: one possibility is that carbon carried by rivers ends up stored in coastal sediments. Another possibility is that this carbon decomposes in the water column and is released as CO_2 and CH_4.

The release of CH_4 from gas hydrates currently locked in permafrost is likely to be a very slow process. Most hydrates are at considerable depth and so would not be affected in the short-term by near-surface thawing. Nonetheless, the fate of these gas hydrates remains largely uncertain in both the short- and long-term.

Further research should focus on sensitive elements of the carbon cycle

Current understanding of the Arctic C cycle is limited by considerable uncertainties, and integrated studies of regional carbon dynamics are necessary. Such studies should focus on understanding the mechanisms responsible for changes in C dynamics at the regional scale.

The resulting information should be incorporated into modelling efforts that connect carbon dynamics and climate. The studies should focus on sensitive parts of the system, for example areas experiencing major changes or thresholds such as permafrost loss or increased fire disturbance.

A major challenge for carbon modelling is upscaling: connecting fine-scale observational studies with the larger scales at which models describe the environment. Observational networks should be designed to capture regional variations and also to reveal the underlying processes that govern C dynamics at various scales. That information can be used to model the interactions among various parts of the C cycle. Observational studies should also focus on small- and large-scale processes so that both can be incorporated in models.

The improved understanding of C dynamics can be incorporated first in simpler models where the basic ideas can be tested. Then, more complex models that couple air, land, and sea can be developed or revised based on new and better understanding of the fundamental factors involved. This, in turn, will allow a more confident exploration of the relationships between climate change and carbon cycling in the Arctic. ■

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