

Role of Sea Ice in the Formation of Annual Carbon Dioxide Cycle in the Arctic

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Presented by Academician G.S. Golitsyn February 15, 2007

Received February 13, 2007

DOI: 10.1134/S1028334X0709022X

Exchange of carbon dioxide between the atmosphere and the ocean, which absorbs 25–50% of carbon dioxide released during fuel combustion, plays an important role in the global CO₂ cycle [1, 2]. At present, it has been established that absorption or emission of CO₂ by the World Ocean is irregular in space and variable in different seasons and years [3]. However, the role of the Arctic basin in the global and regional balance of CO₂ has not been examined by researchers, because they believed that the ice cover almost completely hampers gas exchange. The possibility of the significant influence of water areas with seasonal or constant ice cover on the regional and even global balance of CO₂ has been assumed in some recent publications [4, 5]. The present paper shows that sea ice could play a crucial role in variation of the annual cycle of CO₂ concentrations in polar latitudes.

In 2004–2005, annual monitoring of the CO₂ concentration was carried out for the first time in the polar region at drifting stations *North Pole 33* (SP-33) and *North Pole 34* (SP-34). The results showed significant seasonal variations exceeding such processes at coastal stations surrounding the Arctic Basin (Fig. 1).

Observations in the South Ocean [6] also revealed growth of the amplitude of seasonal variations south of 50° S in the sea ice field and increase in the CO₂ concentration toward this direction in winter.

The annual variation in the CO₂ concentration averaged over the latitudinal zones of both hemispheres reported in [7] is also maximal in the polar 60°–90° region. Comparison of the amplitude of annual variation in the CO₂ concentration at different latitudes based on separate stations presented in the WMO report [8] also shows its rapid attenuation from the North Pole toward the equator (Fig. 2). Further in the Southern Hemisphere, the

seasonal variation again increases toward the polar region. However, its amplitude is much smaller relative to the Northern Hemisphere.

It is evident that the polar intensification of annual variations in the CO₂ concentration with the maximum located above the ice-covered Arctic Basin can primarily be attributed to the influence of sea ice on the seasonal cycle formation. Some researchers assume that the mechanism of this influence is related to the screening of gas exchange between the ocean and the atmosphere by ice in winter. However, this assumption is invalid, because reduction of the CO₂ influx to the ocean cannot increase its content in the atmosphere in winter without a supplementary source. The atmosphere above the adjacent latitudes cannot serve as such a source, because the average CO₂ concentration does not decrease, particularly in winter, toward the pole [7] and from the coastal region toward the ice-covered sea [4].

Estimates for the Chukchi Sea [9] confirm a multiple (almost two orders of magnitude) reduction of the CO₂ influx from the atmosphere to the sea and a simi-

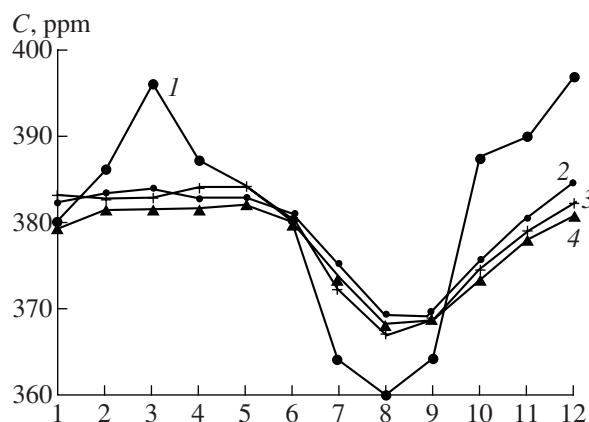


Fig. 1. Annual variation in the monthly mean CO₂ concentration in air at (1) drifting stations SP-33 (January–October 2004) and SP-34 (November 2004–December 2005) and coastal stations (2) New Alesund, (3) Barrow, and (4) Alert.

taneous decrease of its concentration in the upper marine layer due to intensification of the primary biological productivity. Despite the very low influx through the ice cover, the CO_2 concentration in the sea is restored during the winter–spring transition period. A supplementary source for the restoration of the CO_2 concentration beneath the ice cover is problematic in this scenario.

We believe that filling of the summer minimum of CO_2 concentration in air (water) above (beneath) the ice cover of the Arctic Basin can be related to the formation, growth, and alteration of the ice structure in winter. Sea ice in the Arctic Basin is formed from saline water with a salinity of $\sim 30\text{--}32\%$. Salt brine left in ice owing to the freezing of freshwater flows down to the lower surface of the ice. The brine is partly transported to upper layers of the ocean and partly conserved in closed cavities of the ice [10]. High salt concentrations in the brine provide intense reactions of the following type [11]:



This reaction promotes the emission of carbon dioxide. Together with the brine, the carbon dioxide is transported to the upper water layer beneath the ice and further to the atmosphere via microcracks. Since an inversion-related steady air layer dominates above the Arctic ice in March and April [12], CO_2 released during this period accumulates in the lower layer of the polar atmosphere, resulting in intensification of the winter gas maximum above the ice-covered ocean.

Ice melts together with the surficial snow in summer. Consequently, the ice surface is complicated by cold meltwater ponds with the poorly soluble suspended phase CaCO_3 . It is known that a zero temperature environment with the presence of CaCO_3 fosters the so-called reaction of lime water with CO_2 of the following type [11]:



This reaction is accompanied by the formation of soluble calcium hydrocarbonate and the absorption of CO_2 , which is readily soluble in cold water, from the air layer above ice. The influence of meltwater ponds on CO_2 absorption in summer has been confirmed in [4] based on direct measurements. In summer, CO_2 concentrated in the atmosphere above the Arctic Basin can also be absorbed by freshened water on the surface of ice-free waters, fractures, and channels. Ultimately, the gas is consumed for photosynthesis in the upper water layer and ice [13]. These processes promote the formation of the summer CO_2 minimum in the air above the ice and in the water layer beneath the ice.

Simultaneous monitoring of the annual CO_2 cycle above and beneath the ice cover in the Arctic Basin and seas is lacking thus far. Therefore, let us examine indirect pieces of evidence concerning the relation of the growth of winter CO_2 above the Arctic Basin with the formation and growth of ice.

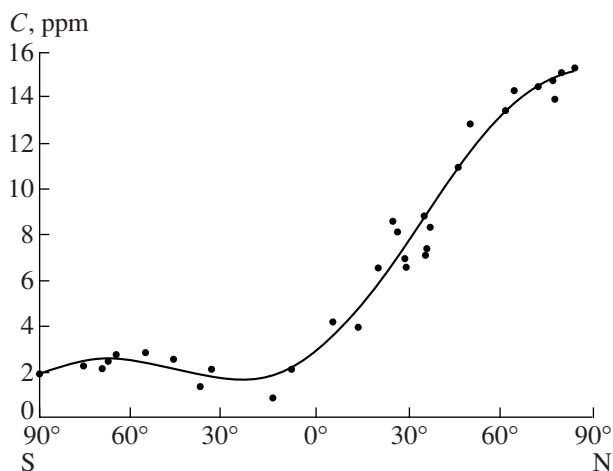


Fig. 2. Double amplitude of annual variation in the monthly mean CO_2 concentration (dots) at coastal and island stations located at different latitudes in oceanic regions of the Northern and Southern hemispheres. Monthly mean concentrations (mainly in 2004) based on the WMO data [8] were used.

One piece of evidence is provided by comparison of interannual variations in the amplitude of seasonal fluctuations of the area of sea ice in the Arctic based on [14] and the CO_2 concentration at coastal stations (Fig. 3). Positive trends of both characteristics imply that increase in the volume of ice and water involved in mutual seasonal transitions also leads to increase in the volume of CO_2 released in the course of transformation. This process is reflected in the intensification of seasonal fluctuations of the CO_2 concentration.

Data on all stations located around the Arctic basin indicate that winter maximums of the CO_2 concentration increase more rapidly than its summer minimums. At the same time, winter maximums of the sea ice cover decrease more slowly than its summer minimums (table). Such a relationship of the trends supports the following assumption: increase in seasonality of the Arctic ice cover leads to increase in the winter CO_2 flux

Coefficients of the trend of maximal and minimal values of seasonal variations in the CO_2 concentration at three Arctic stations and in an ice-covered area of the Northern Hemisphere

Parameter	Maximum in the annual variation	Minimum in the annual variation
Trend coefficient, ppm/yr		
Alert	1.5878	1.5652
Alesund	1.9305	1.7629
Barrow	1.5246	1.4591
Ice-covered area, km^2/yr	-35287.12	-54561.56

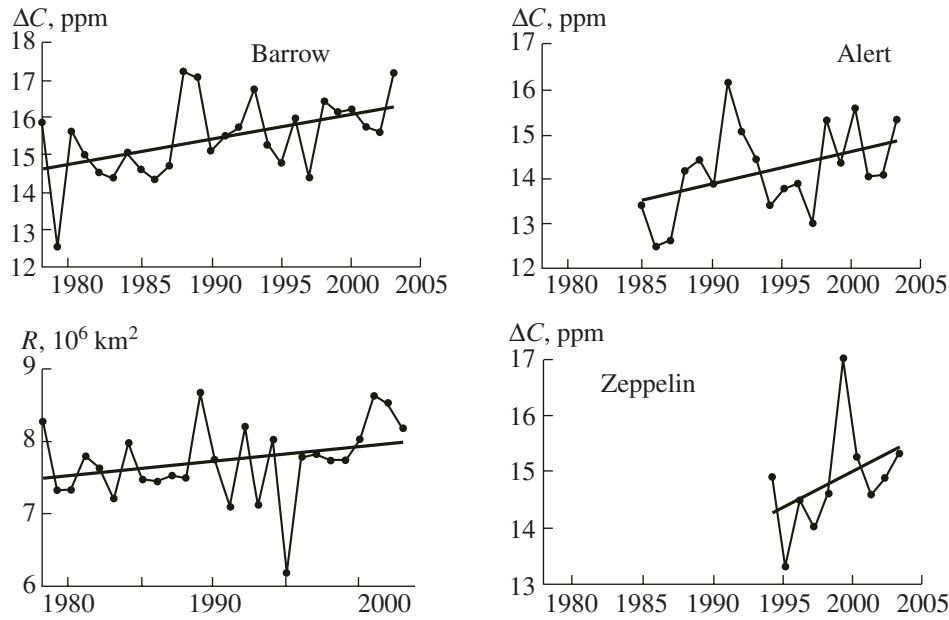


Fig. 3. Changes in the double amplitude of annual variation in the CO₂ concentration at coastal stations (ΔC) and sea ice extent areas in the Arctic (R).

from the ocean owing to increase in the volume of ice formed and accumulated in winter.

Another piece of evidence in favor of this assumption is provided by comparison of monthly variations in

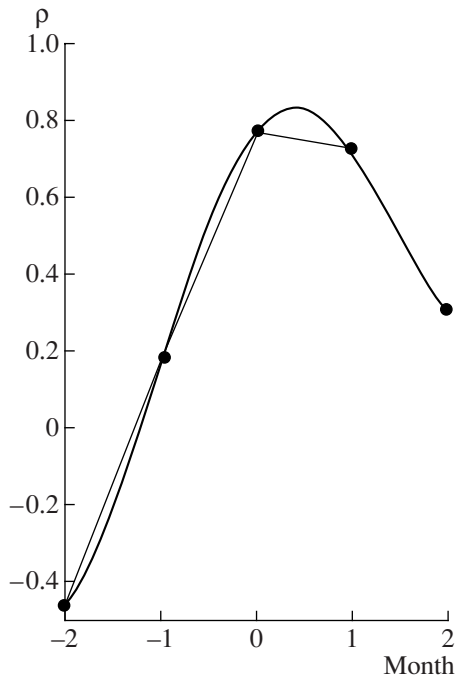


Fig. 4. Cross-correlation function between the monthly increment of ice cover thickness in the Arctic Basin and CO₂ concentration at Barrow. Dots denote correlation coefficient vs. time lag of CO₂ increment; solid curve, polynomial of the fourth degree.

the thickness of the Arctic ice cover [15] and CO₂ concentrations at Barrow in 1980–1990. Both values show high mutual correlation with the maximum recorded during an approximately 12-day-long lag of CO₂ variations (Fig. 4).

Thus, our work has revealed the active role of sea ice in the annual CO₂ cycle in the Arctic. We believe that the formation and growth of ice cover in winter can be accompanied by the emission of CO₂ to the ice-overlying atmosphere and the ice-underlying water layer, resulting in the intensification of seasonal fluctuations of CO₂ concentration at high latitudes. In contrast to the Chukchi Sea, the Arctic Basin can produce a sufficient amount of CO₂ in 1 yr, on average. [9]. In this case, accelerated reduction of the sea ice cover in summer can foster the intensification of this source owing to increase in the volume of ice formed in winter simultaneously with the growth of CO₂ supply due to the expansion of area and the prolongation of the open water season in the Arctic seas and Arctic Basin in summer.

ACKNOWLEDGMENTS

We thank meteorologists of drifting stations SP-33 and SP-34 K.F. Ievlev and V.A. Boldin for permission to use their data, V.T. Sokolov for persuance of observations at these stations, and A.P. Nedashkovskii (Pacific Institute of Oceanology, Russian Academy of Sciences) for useful discussions of the results.

This work was carried out within the framework of a contract between the Federal Agency for Science and

Innovations and the Institute of Global Climate and Ecology (subcontract no. 6-44-1/0, State contract no. 02.447.11.4007).

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