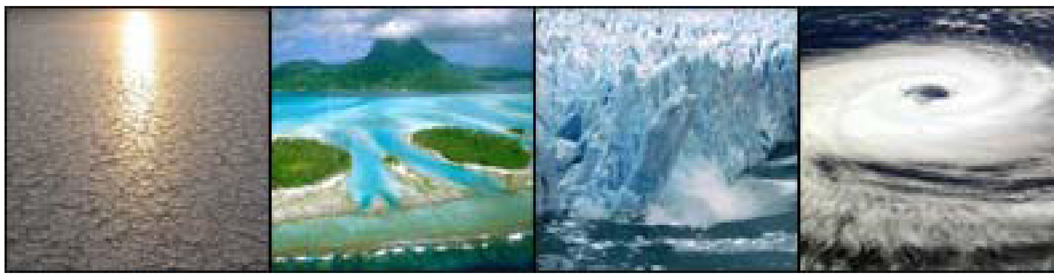
Carbon flow models

· International program
· Credits

The importance of the oceans in the carbon cycle (problematics)

Due to human activities, the atmospheric concentration of carbon dioxide (CO_2) continues to rise and will probably lead to atmospheric global warming, commonly called the greenhouse effect. Only half of the anthropogenic emissions of CO_2 remains in the atmosphere; the rest is absorbed by the oceans and terrestrial ecosystems. In the oceans, part of the carbon uptake is accomplished by the phytoplankton, a veritable submarine prairie, that fixes carbon dioxide by the process of photosynthesis and produces organic plant matter that is available for other marine organisms. Photosynthesis and the transfer of this organic matter to the deep waters comprise the oceanic biological pump.

The oceans and climate change



The biological pump is very sensitive to the physical conditions of the ocean surface that are themselves strongly influenced by atmospheric conditions. It is therefore not difficult to imagine an interaction between climate change, oceanic conditions, and this biological pump that could affect the current trend of the greenhouse effect. A climate change, by modifying the relative abundance of different planktonic species, could affect the efficiency of the biological pump for transferring organic carbon in the surface waters toward deep waters. The rules that govern the oceanic carbon cycle and its response to atmospheric warming are very complex. The Gulf of St. Lawrence itself is too small to have a significant influence on the increase of atmospheric CO_2, but the results obtained here may be generalized to other comparable coastal ecosystems.

The Greenhouse Effect

The greenhouse effect results from the selective way in which different atmospheric components act on solar radiation (from the sun) and on terrestrial radiation (solar radiation reflected by the earth). The solar radiation with very short wavelengths is absorbed by the oxygen and ozone in the upper atmosphere. Most of the solar radiation that reaches the earth's surface is within the range of the visible light; these rays pass through the carbon dioxide and water vapor of the atmosphere and heat the earth's surface. The earth reflects back most of this energy in the infrared range (radiation with longer wavelengths). Before it can escape into space, part of this radiative energy is dissipated as heat, being absorbed by water vapor, carbon dioxide, methane, and other more complex components in the upper atmosphere. The result is a warming of the lower layers of the atmosphere; this is the process known as the «greenhouse effect,» an analogy to the greenhouses used in gardening. More simply, the visible solar rays can pass through the atmosphere while the infrared rays reflected by the earth are blocked and dissipated in the form of heat.Greenhouse Effect The equilibrium between the radiative losses and gains depends largely on the concentrations of the different atmospheric components. Therefore, an increase in their concentrations has direct consequences on the overall warming of the atmosphere.

Current research on this domain

Our understanding of the phenomena involved is still too rudimentary to give accurate predictions. It is therefore essential that we set up monitoring programs in the marine environment. With time series of data spanning several years, we can separate natural variations from climate changes that can affect the biology of the oceans. To try to improve our knowledge, oceanographers from several countries, including Canada, have participated in an international program known by the acronym JGOFS, which included large-scale experiments in different oceanic regions. At the Maurice Lamontagne Institute, scientists developed different carbon flow models for the Gulf of St. Lawrence. Here we will present a simplified version of the model (annual budget) and more detailed seasonal models (winter-spring/summer-fall) that summarize the results from two years of intensive sampling.

International program on oceanic fluxes—JGOFS

The results presented here come from research conducted between 1992 and 1995 within the Canadian contingent of the International Joint Global Ocean Flux Study Program (JGOFS's Canadian coordinator: Bruce D. Johnson) with financial support from both the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canadian Department of Fisheries and Oceans (DFO; Green Plan Program). The work results from a collaboration among scientists from DFO (A. Vézina, T. Packard, C. Savenkoff, N. Silverberg, J.-C. Therriault), GIROQ (*Groupe de recherche interuniversitaire en océanographie du Québec*; L. Legendre, B. Klein), McGill University in Montréal (G. Ingram, A. Mucci), the *Institut des sciences de la mer de Rimouski* (S. Demers, G. Desrosiers, S. Roy, B. Sundby), and Memorial University in Newfoundland (R. Rivkin, D. Deibel).

Credits

The text and figures were adapted from the following articles:

Savenkoff, C., A. F.Vézina and, J.-C. Therriault. 1997. *Le cycle du carbone dans le golfe du Saint-Laurent. Nouvelles des Sciences*, the information bulletin published by the Maurice Lamontagne Institute, Fisheries and Oceans Canada-Laurentian Region. Vol. 8, no. 7, pp. 4-7.

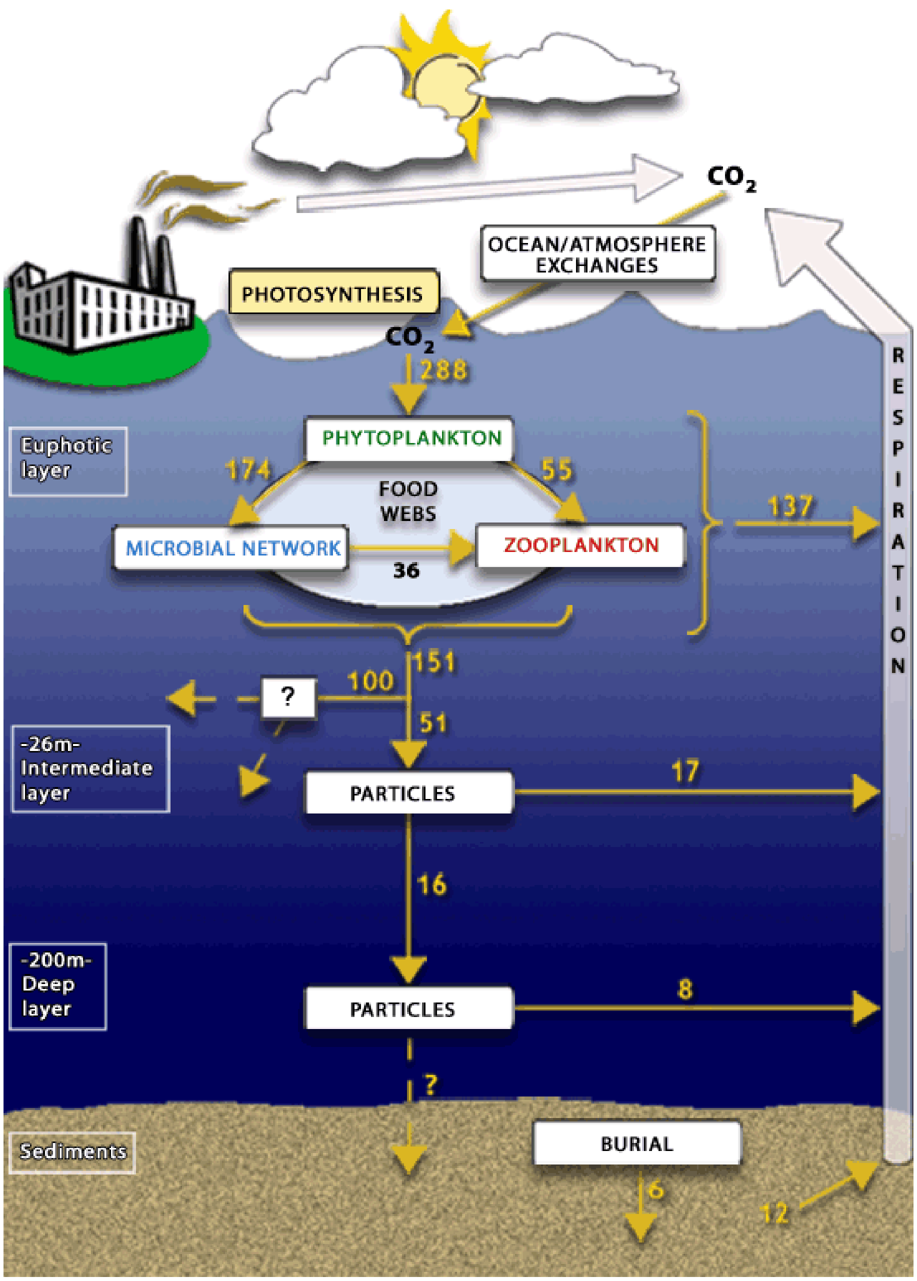
Savenkoff, C., A. F. Vézina, S. Roy, B. Klein, C. Lovejoy, J.-C. Therriault, L. Legendre, R. Rivkin, C. Bérubé, J.-E. Tremblay, and N. Silverberg. 2000. Export of biogenic carbon and structure and dynamics of the pelagic food web in the Gulf of St. Lawrence. I. Seasonal variations. Deep-Sea Research II, 47, pp. 585-607.

Vézina, A. F., C. Savenkoff, S. Roy, B. Klein, R. Rivkin, J.-C. Therriault, and L. Legendre. 2000. Export of biogenic carbon and structure and dynamics of the pelagic food web in the Gulf of St. Lawrence. II. Inverse analysis. Deep-Sea Research II, 47, pp. 609-635.

Adaptation for Internet: Robert Siron and Claude Savenkoff
Infographics: Johanne Noël
English translation: Laure Devine

Annual Budget

This figure shows that the atmosphere-ocean exchanges of carbon, in the form of carbon dioxide (CO_2), are dominated by photosynthesis in phytoplanktonic organisms, which incorporates CO_2 into the plant tissues, and respiration and decomposition, which subsequently releases and returns the CO_2 to the environment. Contrary to primary production, which only takes place in the surface waters, respiration can occur at all depths and even within the sediment.



For more information,
click on the following elements:

- Ocean/Atmosphere Exchanges
- Photosynthesis
- Euphotic Layer
- Phytoplankton
- Food Webs
- Microbial Network
- Zooplankton
- ?
- Intermediate Layer
- Particles
- Deep Layer
- Respiration
- Burial

It appears that 90% of the carbon fixed by phytoplankton is remineralized or horizontally transported within the first 100 to 150 m of the water column. Since the carbon released in this surface layer can rapidly return to the atmosphere, it has no impact on the atmospheric composition or the climate. In fact, only 10% of the carbon reaches the deep waters, where it can be trapped for decades. It is this sequestration that affects the exchange of CO_2 between the ocean and the atmosphere.

The figure also shows that a large fraction of the organic carbon produced in the surface remains unaccounted for. In fact, the amount of carbon that leaves the euphotic zone is much larger than the values measured by scientists during their oceanographic missions. We don't know what proportion of the missing carbon is remineralized in the cold intermediate layer, is exported horizontally with the surface currents, or is consumed in the upper trophic levels.

As this simplified model shows, the phytoplankton production can follow one of two paths. The first passes through the microbial network, which is composed of small phytoplankton (cell size < 5 µm in diameter), bacteria, and protozoans, and then to the zooplankton. This pathway is very efficient for recycling and keeping carbon in the surface waters. We have observed that this pathway is especially active in the summer and fall. The second pathway involves the rapid sedimentation of large phytoplankton (cell size > 5 µm in diameter; mostly diatoms) during spring blooms and/or by large-scale grazing of zooplankton on phytoplankton. This pathway is more efficient for exporting a large amount of organic matter to deep waters, by the sedimentation of fecal pellets, for example. This is seen at the beginning of the winter and in the spring. Even though there are large seasonal differences in these two trophic pathways, it seems that the transfer of the phytoplankton production through the microbial network dominates over the annual scale in the Gulf of St. Lawrence.

Seasonal budgets

- Winter-spring period
- Summer-fall period

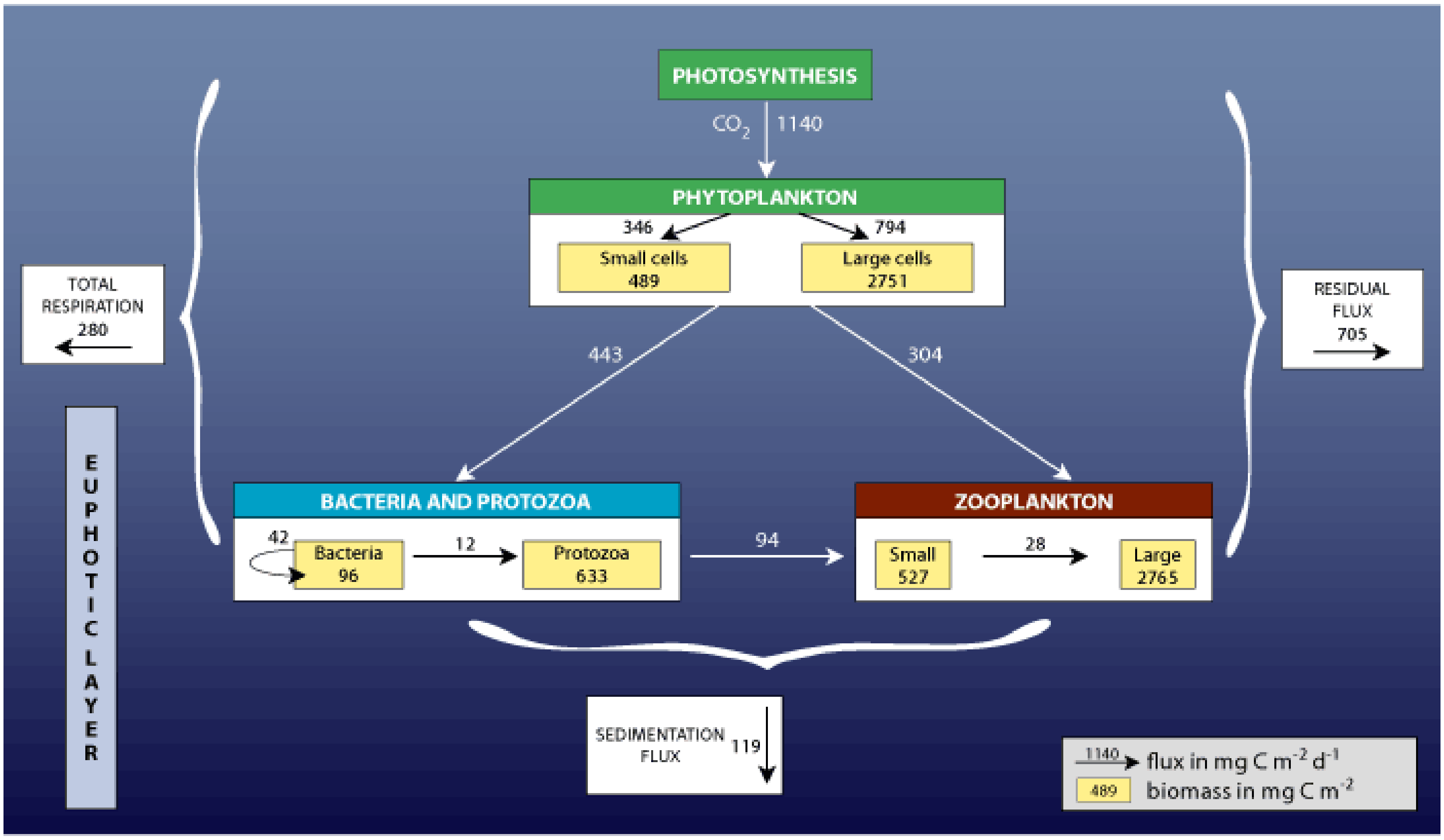
Based on different data on biomass, size structure, and metabolic processes (respiration, production, grazing, excretion, etc.) collected during the Canadian JGOFS program, we used inverse methodology to obtain seasonal mass-balance models that estimate carbon fluxes among different compartments or trophic groups in the euphotic layer. Our results show a seasonal global shift in the size structure of the trophic plankton food web, the carbon cycle, and the potential export in the Gulf of St. Lawrence between the winter-spring and summer-fall periods that is related to different oceanographic regimes.

Winter-spring period

November, December, and April here is generally characterized by a mean surface temperature near 0˚C, weak vertical stratification (surface and intermediate layers well mixed), and high nutrient concentrations (phosphate: 0.9 µM, nitrate: 6.0 µM, and silicate: 8.1 µM). The net metabolism is autotrophic (ratio of respiration to primary production < 1). The chlorophyll a concentration, primary production, and community respiration are dominated by large-celled phytoplankton. Bacterial biomass and production are relatively low (biomass: 96 mg C m^{-2}, production: 42 mg C m^{-2} d^{-1}). The zooplankton are mainly herbivorous.

This pathway is more efficient for exporting a large amount of organic matter to deep waters. Total export (residual flux and sedimentation flux) out of the euphotic layer is equivalent to 72% of the total primary production during the winter-spring period.

Trophic fluxes (organic matter consumed in milligrams of carbon per square meter per day; mg C m^{-2} d^{-1}) estimated by inverse modelling in the euphotic layer during the winter-spring period.



For more information, click on the following elements:

Photosynthesis | Phytoplankton | Bacteria and Protozoa

Zooplankton | Respiration | Euphotic Layer

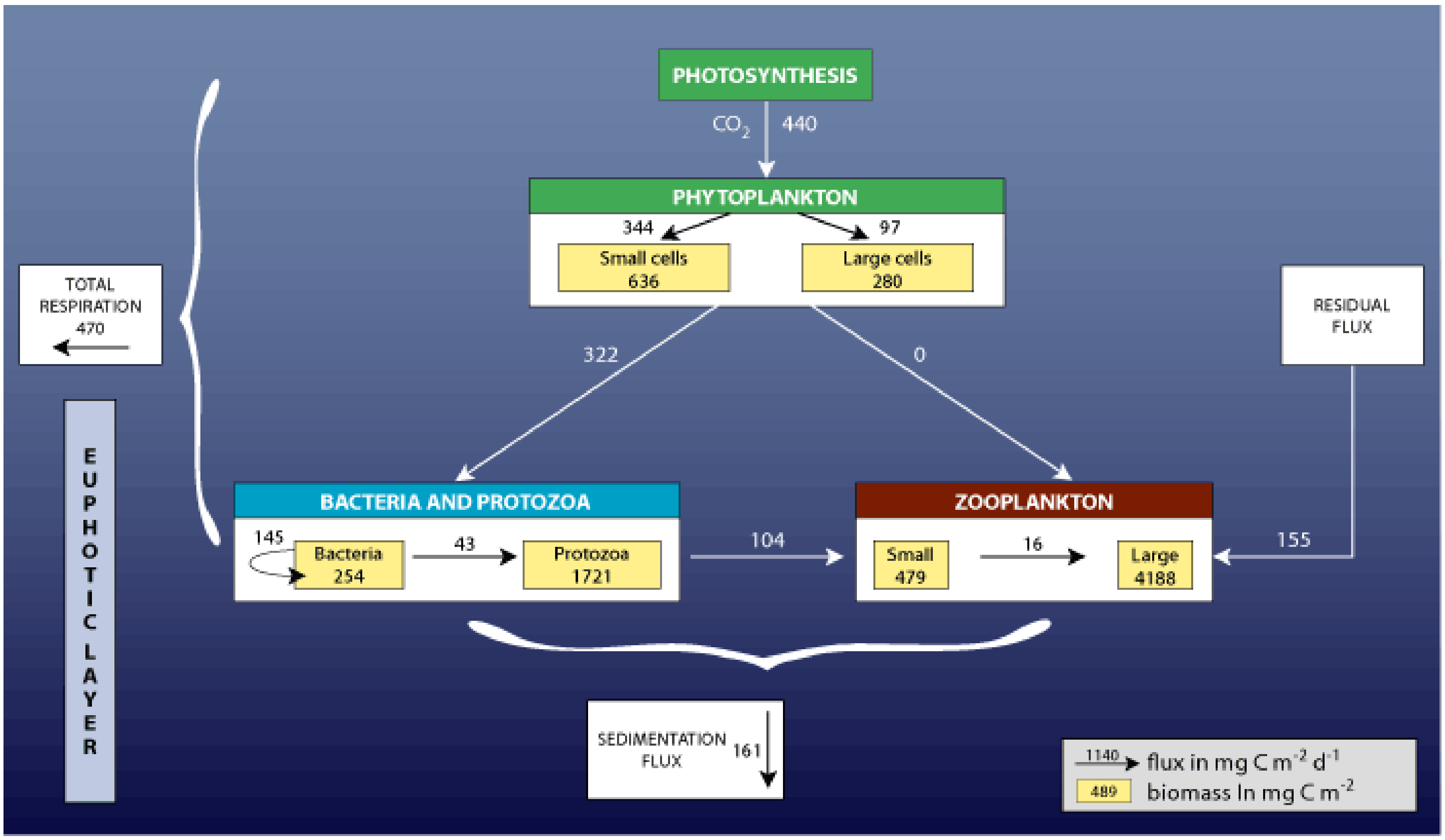
Residual Flux | Sedimentation Flux

Summer-fall period

The summer-fall period (May to October) is generally characterized by a mean surface temperature > 10°C, a well-stratified water column (surface and intermediate layers well distinguished), and low nutrient concentrations (phosphate: 0.4 μM, nitrate: 0.5 μM, and silicate: 2.1 μM). The net metabolism is heterotrophic (ratio of respiration to primary production > 1). Small-celled phytoplankton dominate the chlorophyll a concentration, primary production, and community respiration. Bacterial biomass and production are relatively high (biomass: 254 mg C m^{-2}, production: 145 mg C m^{-2} d^{-1}). The zooplankton are mainly omnivorous and graze non-chlorophyllous prey such as heterotrophic dinoflagellates and ciliates (protozoa).

This pathway is very efficient for recycling and keeping carbon in the surface waters (total export). Summing the inflowing (residual flux) and outflowing (sedimentation flux) fluxes leaves a net export of only 6 mg C m^{-2} d^{-1}, or 1% of the total primary production out of the euphotic layer during the summer-fall period.

Trophic fluxes (organic matter consumed in milligrams of carbon per square meter per day; mg C m^{-2} d^{-1}) estimated by inverse modelling in the euphotic layer during the summer-fall period.



For more information, click on the following elements:

Photosynthesis | Phytoplankton | Bacteria and Protozoa

Zooplankton | Respiration | Euphotic Layer

Residual Flux | Sedimentation Flux

Glossary

<u>Ocean-atmosphere exchanges</u> (the exchange of CO_2 across the water's surface)

Exchanges of carbon, in the form of carbon dioxide (CO_2), between the atmosphere and the oceans are dominated by photosynthesis in phytoplanktonic organisms, which incorporates CO_2 into the plant tissues, and respiration and decomposition, which subsequently releases and returns the CO_2 to the environment. A minor change in these opposite flows (photosynthesis and respiration) can modify the equilibrium and thus the proportion of anthropogenic carbon (carbon that is produced by human activities) that stays in the atmosphere.

<u>Photosynthesis</u>

The microscopic algae that make up the phytoplankton manufacture their organic tissue by combining inorganic materials like carbon dioxide (CO_2) and nutrients that are present in the water. This manufacture of living organic matter from inert matter is the result of a biochemical process known as photosynthesis, which takes place using solar energy captured by chlorophyll, a pigment present in all green plants. Because of this, photosynthesis can only take place in the ocean's euphotic zone. The primary production (or phytoplankton production) resulting from the photosynthesis is the starting point of all the food webs in the ocean.

<u>Euphotic layer</u>

Since photosynthesis requires solar energy, the phytoplankton can develop only in the surface water, where the solar rays penetrate to a certain depth. This illuminated surface layer is called the euphotic zone, and all of the ocean's primary production occurs there. The depth of the euphotic zone is variable, depending on ambient conditions and the amount of particles suspended in the seawater; its lower limit corresponds to the depth where 1% of the surface light remains. In the Gulf of St. Lawrence, the euphotic zone usually includes the top 20 to 30 meters of water.

<u>Phytoplankton</u>

Phytoplankton is a general term that includes all microscopic plants (unicellular algae usually between 1 and 100 μm) that grow in both fresh and salt water. Diatoms and dinoflagellates are among the most common phytoplankton groups in the St. Lawrence. During their development, these microscopic algae are transported with the surface water by ocean currents. A bit like a submarine prairie, the phytoplankton is the basic food source for herbivorous marine organisms like zooplankton and certain invertebrates, themselves a source of food for higher organisms (for example, fish and marine mammals). The phytoplankton is thus the base of the food webs. This primary production determines the productivity of the marine ecosystems.

In this study, phytoplankton is separated into two size classes: large phytoplankton (cell size > 5 μm in diameter; mostly diatoms) and small phytoplankton (cell size < 5 μm in diameter).

Winter-Spring	
Biomass (mg C m^{-2})	
Large phytoplankton (68%)	2751
Small phytoplankton (32%)	489
Total	3240
Primary production (mg C m^{-2} j^{-1})	
Large phytoplankton (56%)	794
Small phytoplankton (44%)	346
Total	1140

Summer-Fall	
Biomass (mg C m^{-2})	
Large phytoplankton (26%)	280
Small phytoplankton (74%)	636
Total	916
Primary production (mg C m^{-2} j^{-1})	
Large phytoplankton (23%)	97
Small phytoplankton (77%)	344
Total	414

Bacteria and protozoa

In addition to small-celled phytoplankton (< 5 µm), bacteria and protozoa compose the microbial network. While bacteria are unicellular microorganisms that are neither plants nor animals, protozoa are unicellular heterotrophs (animals) that include flagellates, dinoflagellates, and ciliates covered in this study.

Planktonic food webs

Plankton by definition includes all aquatic organisms that live suspended in the water. These organisms are plants (phytoplankton) or animals (zooplankton). As shown by this simplified carbon cycle model, the phytoplankton production can take one of two pathways (or food webs). The first passes through the microbial network and then to the zooplankton. The second pathway is dominated by the larger phytoplankton (> 5 µm in diameter, mostly diatoms) and by massive consumption of the phytoplankton by heterotrophic organisms: flagellates, dinoflagellates, ciliates, and zooplankton. Even though there are seasonal differences in the importance of these two trophic networks in the Gulf of St. Lawrence, it is the microbial network that dominates over the annual scale.

Microbial network

The microbial network is composed of very small phytoplankton cells (< 5 µm in diameter), protozoans (unicellular organisms including flagellates, dinoflagellates, and ciliates), and bacteria. The pathway through the microbial network is very efficient for recycling and holding carbon in the surface waters. In the Gulf of St. Lawrence, this pathway is mostly seen in the summer and fall; warmer and more stable water favors the development of algae like flagellates, which are able to remain in the surface waters for long periods.

Zooplankton

Zooplankton is the term used to designate all the animal organisms whose size is larger than 63 µm. The zooplankton can be separated into three size classes: small zooplankton (from 63 to 500 µm), medium zooplankton (500 µm to 5 mm), and large zooplankton (> 5 mm).

The small zooplankton group includes early larval stages of zooplankton (nauplii and copepodites).

The medium zooplankton group is made up mostly of copepods-organisms that belong to the crustacean family. Two of the most common copepod species in St. Lawrence marine waters are *Calanus finmarchicus* and *Oithona similis*.

Large zooplankton includes euphausids (krill), chaetognaths, amphipods, cnidarians and ctenophores (jellyfish), mysids, tunicates, and small fish (ichthyoplankton). In these simplified budgets, we consider only the first two size classes.

The consumption of phytoplankton by zooplankton is generally more rapid than the microbial network and results in a large quantity of organic matter. In the Gulf of St. Lawrence, this pathway for the primary production is observed from the beginning of the winter and in spring, when colder and well-mixed water favors the proliferation of diatoms.

? (the missing carbon)

The model shows that the fate of a large proportion of the organic carbon produced at the surface remains unknown. In fact, the amount of carbon that leaves the euphotic zone is much higher than the values measured by scientists during oceanographic missions using sophisticated sampling equipment like sediment traps. We do not know what proportion of this missing carbon is remineralized in the cold intermediate layer, exported horizontally with surface currents, or consumed in the upper trophic levels.

Other research efforts in the St. Lawrence Estuary will examine this issue. [PDF Format, 375KB (French only)]

Intermediate water layer

In summer, the waters of the Gulf of St. Lawrence can be divided vertically into three layers: the warm and less saline (temperature > 5.0˚C, salinity = 29.0 to 31.5) surface layer includes the euphotic zone and is located in the upper 30 meters; the intermediate layer is characterized by very cold water (thermal minimum: T = -2.0 to 2.0˚C, S = 31.5 to 33.0) and descends to about 150-200 m; the deep water layer is warmer and more saline (T > 3˚C, S = 33.0 to 34.5). There are only two layers in the winter: the surface and intermediate layers mix to make a single cold water mass while the deep water remains distinct.

Particles

Part of the primary production is exported from the euphotic zone to the underlying layers (the intermediate and deep water layers), mostly in the form of very small particles. The particle content varies as a function of the composition, the magnitude, and the size structure of the planktonic food webs. In general, however, the particle amounts decrease with depth. This decrease results from the combined effects of bacterial activity and the fragmentation, solubilization, ingestion, or decomposition (respiration) of particles during their long descent toward the deep waters.

Deep water layer

Only 10% of the carbon makes it to the deep water where it can be trapped for decades and thus affect the CO_2 exchanges between the ocean and the atmosphere. This may appear very inefficient as a method of climate regulation, but one must consider that this small flux at a local scale would become enormous when considered at a global scale.

Respiration (or decomposition)

Respiration is a metabolic process that decomposes organic matter and releases the CO_2 contained in the living organisms. Contrary to primary production, which occurs only in the surface, respiration can occur at any depth and even within the sediments. Since the recycling rate of CO_2 to the atmosphere depends on the depth at which it is liberated, the deeper the CO_2 is freed the longer its residence time in the ocean will be. Our simplified annual model indicates that 90% of the carbon fixed by the phytoplankton is remineralized or horizontally transported in the top 100-150 m of water. The carbon released in this surface layer can rapidly return to the atmosphere. Thus globally, this carbon remineralization has no effect on the composition of the atmosphere and therefore on the climate.

Burial in the sediments

A small amount of the particles that fall toward the sea floor is not decomposed and will be gradually buried in the sediments and thus removed from the carbon cycle. The marine sediment, except for the surface layer that can still be decomposed, mixed by bioturbation, or disturbed by deep waters, is considered as a trap for the carbon. The carbon, once sequestered in the deeper sediments, is incorporated into the earth's crust and constitutes stable geological layers. This «non-exchangeable» carbon is thus trapped for several hundreds of millions of years (the formation of coal or oil reserves is the best example of the fossilization process at the geological scale).

Residual flux

Winter-Spring	Summer-Fall
To balance the different mass-balance equations, the model calculates a residual flow of 705 mg C m^{-2} d^{-1} out of the euphotic layer that adds to the sedimentation flux of detrital, phytoplanktonic, and zooplanktonic matter. This residual flux takes place via passive processes (i.e., entrainment and advection), where each group is exported in proportion to its biomass.	From the Lower Estuary (nursery area for *Calanus finmarchicus*, the dominant large zooplankton species), a large number of Calanus are transported by the currents resulting from the runoff of the St. Lawrence and Great Lakes drainage systems towards the Gulf. The summer zooplankton biomass is supported directly by this advection. This transport of zooplankton production has been termed a Calanus pump (Plourde and Runge, 1993). We simulated this effect in the model by forcing an additional flux (residual flux) towards the large zooplankton compartment only. This change results in an inflowing residual of 155 mg C m^{-2} d^{-1} as estimated by the model.

Sedimentation flux

Organic matter export or particulate sedimentation flux out of the euphotic layer is made up of products resulting from the metabolism of living organisms (e.g., debris, cellular lysis, egestion, fecal pellets, dead organic matter).