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Advanced information on the Crafoord Prize in Geosciences 2006

## Earth's operation as a chemical, physical, and biological system

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Royal Swedish Academy of Sciences, Box 50005, SE-104 05 Stockholm, Sweden

Tel: +46 8 673 95 00, Fax: +46 8 15 56 70, E-mail: [info@kva.se](mailto:info@kva.se), Websites: [www.kva.se](http://www.kva.se), [www.crafoordprize.se](http://www.crafoordprize.se)

## Planet Earth – an Integrated Chemical, Physical and Biological System

A hypothetical extraterrestrial observer somewhere in outer Space, would probably consider the different spheres of the Earth, atmosphere-biosphere-hydrosphere-cryosphere-geosphere, and their interlinked processes as an entity, or a living body in Space, that could be termed the Earth System. Our gradually increasing scientific insights and empirically gained knowledge have taught us that these spheres themselves compose different systems that are closely coupled through a complex of dynamic processes, acting on different spatial and temporal scales. Knowledge about the mechanisms behind the interlinked processes --- how together they constitute the dynamic Earth System, and how its different parts have varied over longer time scales --- is of profound importance if we humans are to be able to understand our ambient world and our own role within the Earth System.

This year's Crafoord Prize winner in Geosciences, **W. S. Broecker**, is a true pioneer and giant in Earth System Science. His contributions have been profound, far-reaching and partly revolutionary in ocean biogeochemistry, ocean circulation (Fig. 1), air-sea gas exchange, the role of the ocean in the carbon cycle, the role of the ocean in abrupt climate change, isotope geochemistry, and the dynamics of the ice ages. Through this breadth and depth of knowledge and interests and with his uncanny ability to integrate and synthesize diverse sets of information, he has greatly advanced our understanding of the Earth System, as it is now and in the past. With these insights he has also promoted a scientific approach to solving the problems that global society may face in the future.

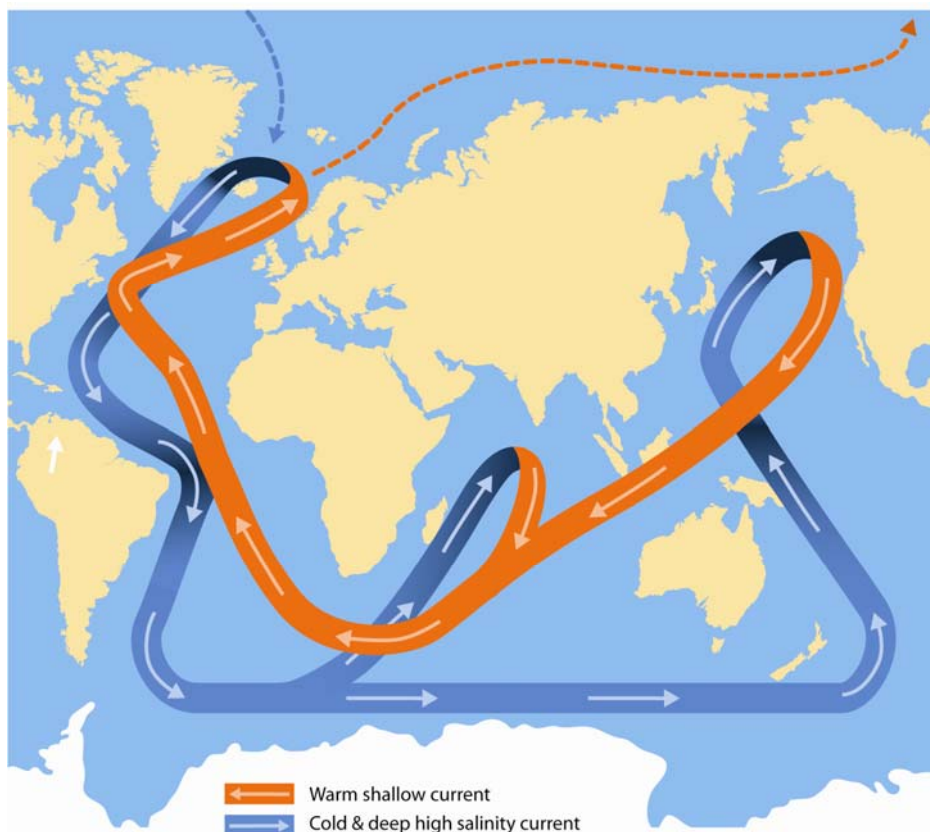


Figure 1. The oceanic conveyor belt circulation. The sinking of surface water in the North Atlantic forms the North Atlantic Deep Water, which spreads as bottom and intermediate water masses to the other ocean basins.

## Early work

In a career spanning more than 50 years, Broecker has published about 450 papers, over 50 of them in *Science* and *Nature*, and authored or co-authored nine textbooks.

Broecker's early publications, beginning in 1953, mostly relate to the development and use of radioisotopes for a wide variety of studies. He was, with his colleagues, an early pioneer of techniques that exploit uranium series decays in particular for both short-term and long-term dating purposes (e.g. Kulp et al. 1954). His own early work was mainly devoted to developing more accurate  $^{14}\text{C}$  techniques for measuring the radiocarbon content of ocean water (Broecker et al. 1956), for archaeological studies to track the effects of atom bomb tests on atmospheric  $^{14}\text{C}$  (Broecker and Walton 1959; Broecker et al. 1959) and for fundamental geochemistry (Broecker 1962).

By the late 1960s Broecker was using a wide variety of isotope techniques to explore the fundamentals of oceanography and geochemistry, both bomb-derived radioisotopes such as  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$ , and uranium series techniques such as  $^{226}\text{Ra}/^{222}\text{Rn}$  and  $^{230}\text{Th}/^{234}\text{U}$  (Broecker 1966a; Broecker et al. 1967; Broecker et al. 1968a,b). He also developed the use of sediment isotopes for climate change studies, and was an early supporter of the astronomical theory of Quaternary climate change (Broecker 1966b; Broecker et al. 1968c).

It is also notable that Broecker wrote a paper describing abrupt climate change as early as 1960 (Broecker et al. 1960), and was in the mid-sixties already invoking rapid transitions between stable atmosphere-ocean climate regimes to explain sudden changes in past climate (Broecker 1966). Thus he explored ideas far ahead of their time: it was to take another 20-30 years before these research topics became scientifically "hot".

## Ocean biogeochemistry

Over the past 40 years Broecker has revolutionized chemical oceanography. One way he did so was through his intellectual leadership of the Geochemical Oceans Sections (GEOSECS) program, which assembled for the first time a global-scale picture of the chemical state of the world ocean. This comprehensive survey, which began in the early 1970s, provided the basis for a new understanding of global ocean processes; it paved the way for numerous novel studies of global biogeochemical cycles.

In his classic text *Chemical Oceanography*, Broecker (1974) gave an exposition of the factors controlling concentrations of biologically active elements in sea water in terms of inputs to the ocean "sink" via rivers and the atmosphere, and sedimentation of the biological flux from the surface to the deep (as illustrated in Fig. 2). This was different to that of the earlier ideas; in Broecker's scheme, seawater composition was determined not mainly by chemical equilibrium, but by a geochemical steady state.

Broecker's kinetic model of ocean chemistry, which 35 years ago persuaded everyone to think of the ocean as a dynamic system defined by inputs and outputs rather than one at equilibrium, established a theme that endures throughout the rest of his work. For example, when combined with his exposition of "Conveyor Belt" circulation (Fig. 1), this shed light on the variations in depth and location of many of the elements.

These ideas did not originate exclusively with Broecker, but he was the major contributor and he expressed them in a readily comprehensible synthesis.

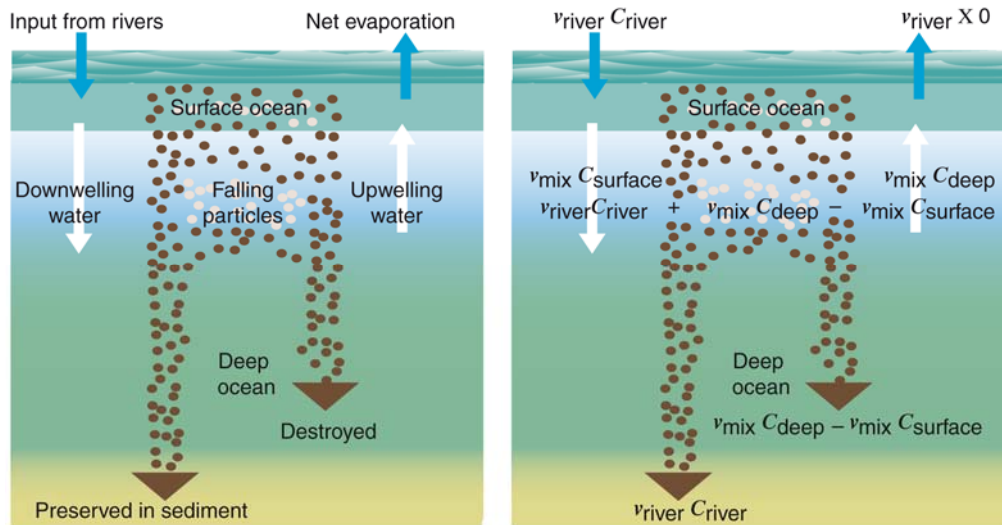


Figure 2. Box model illustrating the steady state conditions of biolimiting elements. After Broecker (1974).

## The role of the ocean in the carbon cycle and in controlling atmospheric CO<sub>2</sub>

One notable outcome of Broecker's biogeochemical understanding of the ocean was that it became possible to identify the physical and biogeochemical processes that control the ocean carbon cycle and, therefore, the ocean's role in regulating carbon dioxide concentrations in the atmosphere. Broecker made a seminal contribution to our understanding of the relationship between atmospheric CO<sub>2</sub> concentrations and ocean chemistry, both in the way it affects modern anthropogenic CO<sub>2</sub> and in explaining natural variations of atmospheric composition in the past.

Broecker was an early exponent of the use of tracers to measure the rates of vertical mixing in the oceans, which he recognized as an important unknown in calculating the rate of uptake of CO<sub>2</sub> from the atmosphere to the oceans and vice versa (Broecker 1962). He subsequently used the radiocarbon inventory of the ocean to derive what remains the most important single constraint on the global air-sea gas exchange of CO<sub>2</sub> (Broecker et al. 1985a) clearly showing the advantages and pitfalls of using bomb-derived <sup>14</sup>C as a tracer for the uptake of anthropogenic CO<sub>2</sub> (Broecker et al. 1980).

Through his own research and its impact on the research of others, Broecker has played a key role for our understanding of the ocean carbon cycle (Fig. 2). His research serves as the basis for our understanding of the ocean processes that regulate carbon dioxide concentrations in the atmosphere, with profound implications.

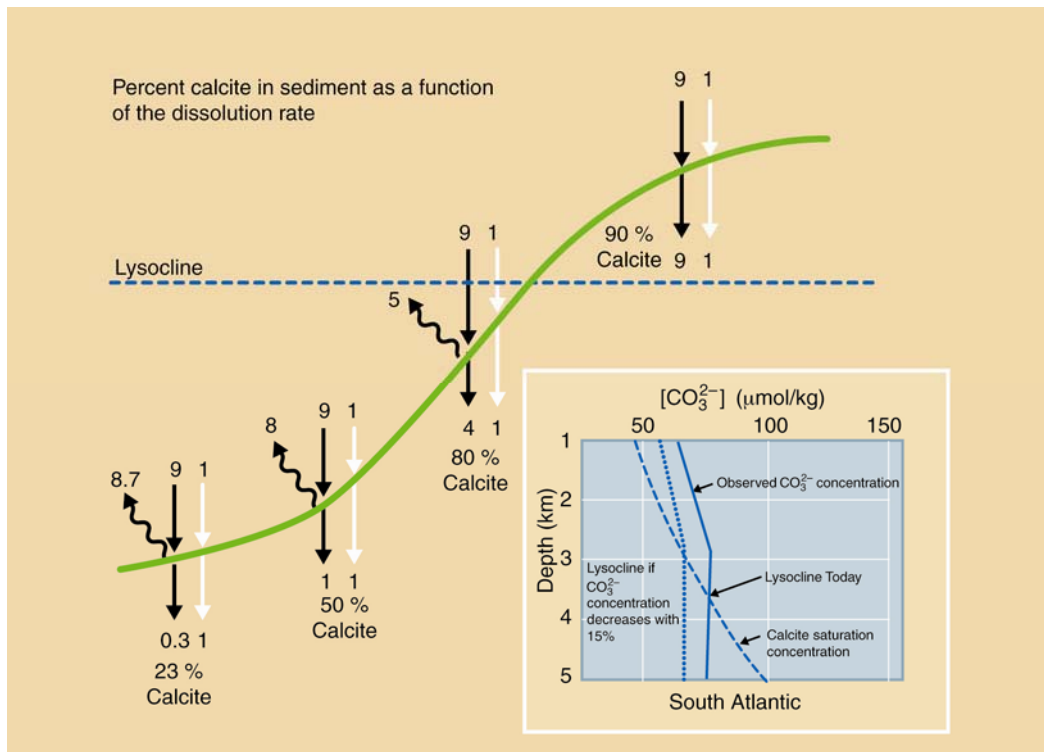


Figure 3. Calcium carbonate in the sediment impacts the capacity of the ocean to sequester  $\text{CO}_2$ , and may act as an important regulator of atmospheric  $\text{CO}_2$  on glacial – interglacial time scales. The driving force for calcite dissolution and thus the percentage of calcite in the sediment, as a function of water depth, depends on the rain rate and the accumulation rate of non  $\text{CaCO}_3$  debris (right arrow) and the rain rate and accumulation rate of calcite (left arrow), with the wavy arrows representing the solution rate of calcite. The right insert shows how the calcite saturation concentration (expressed as carbonate ion) increases with depth mainly because of the pressure effect (calcium and carbonate ions occupy less volume when dissolved in seawater than when locked up in  $\text{CaCO}_3$ ). The carbonate ion concentration profile at a decrease of 15%, expected with about a 70 ppm  $\text{pCO}_2$  increase, is shown and the corresponding decrease of the so-called lysocline depth is indicated. After Broecker (1992b).

When the first results from the corings of the Antarctic ice cap were published in the early 1980s, showing remarkable variation of  $\text{CO}_2$  concentration with the glacial cycles, Broecker was soon writing articles evaluating hypotheses to explain these changes (Broecker 1982a,b). Among the most important ideas to pinpoint the cause of the large  $\text{CO}_2$  variations was the explanation of the role of carbonate compensation in amplifying  $\text{CO}_2$  change (Fig. 3) (Broecker and Peng 1987), evidence for pH changes using boron isotopes (Fig.3) (Sanyal et al. 1995), size distribution of  $\text{CaCO}_3$  fragments (Broecker and Clark 1999), and the search for dissolution and preservation events in sediments (Broecker and Sanyal 1997; Broecker et al. 1993). Although there is still much to learn about the carbon cycle, what is striking about all these papers is that they so clearly lay out the alternatives for each mechanism considered, make clear predictions about what should be observed for consistency, and are prepared to reject hypotheses that do not work. Thus Broecker's approach exemplifies the scientific method, free of dogma and preconception, as applied to this very complex problem.



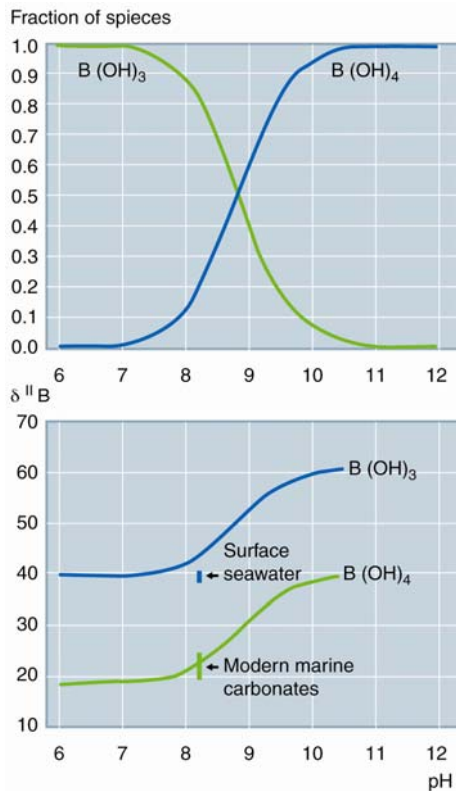


Figure 4. The speciation of borate dissolved in seawater changes with pH, with the charged species dominating at high pH and the neutral at low pH. The isotopes of boron are not distributed uniformly between these two chemical forms. Rather, the heavy isotope,  $^{11}B$ , is depleted by about 22‰ in the charged species relative to the neutral species. As it is the charged species that is incorporated into marine calcite, its isotopic composition is preserved in the sediment record. The isotopic composition of this species depends on pH. The higher the pH, the closer this value will be to the isotopic composition of the bulk borate in seawater. It is for this reason that the isotopic record in foraminifera offers a means to test the idea that it was a higher rain rate of organic matter to the sea floor during glacial time which caused the atmosphere's  $CO_2$  content to drop. The higher  $CO_3^{2-}$  ion content of deep seawater required by this scenario would be accompanied by a higher pH and hence a higher  $^{11}B$  to  $^{10}B$  ratio in the shells of benthic foraminifera. After Broecker (1992b)

## Ocean circulation and abrupt climate change

As mentioned above, ideas about sudden changes in climate (mode-switching) in the ocean-atmosphere system were already being voiced in Broecker's work from the 1960s. However, it seems to have been after the publication of the DYE3 ice core record from Greenland (Dansgaard et al. 1982), showing a replication of the earlier Camp Century ice core record, that Broecker realized that re-organization of North Atlantic deep water formation might explain the oscillating and rapid climate shifts seen in Greenland during the last glacial period; these were later named by him Bond cycles, separated by warm Dansgaard-Oeschger events. They included the Younger Dryas cold event (the 1100-year long return to near-glacial conditions) the abrupt end of which at about 11,600 years BP initiated the current mild interglacial climate. In making this leap, Broecker would have been aware of a box-model (Stommel 1961) indicating the possibility of two modes of operation for the global thermohaline circulation forced by temperature and atmospheric fresh water fluxes.

Broecker was also aware of the evidence for sudden regime change observed in North Atlantic sediment cores (Ruddiman and McIntyre 1981). He synthesised this with his own idea of the oceanic conveyor belt circulation (Fig. 4), realizing that switching off that circulation could potentially explain the rapid changes. In particular, Broecker realized that oceanic and atmospheric circulations have multiple stable modes of operation, and that changes from one mode to another may explain the abrupt climate changes that have occurred in the past. Like many really good ideas, this one seems obvious in hindsight, but it was resisted by many at the time it was put forward.

Some physical oceanographers have criticized Broecker's conveyor-belt analogy, complaining that it is too simplistic a description of the overturning circulation. Likewise, others considered Stommel's box model as a too highly over-simplified

description, intended as only a theoretical exercise rather than an actual portrayal of the real thermohaline circulation. Nevertheless, acceptance of the basic conveyor belt concept is now nearly universal; the evidence strongly supports a largely North Atlantic source for abrupt global changes, and Broecker's concept is the only one that provides a causal mechanism.

There has been a great deal of elaboration of the basic idea, with Broecker himself as one of the main players, by investigations of the triggering role for these coolings played by sudden discharges of fresh water from pro-glacial lakes (Broecker et al. 1989), large flotillas of icebergs calved from the large Northern hemisphere ice sheets and sea ice expansion (Broecker 2006). Broecker has also played a key role in formulating and understanding the hemispheric anti-phase behaviour of the glacial climate, recorded in Greenland and Antarctic ice cores, which he coined "the bipolar seesaw" (Broecker 1998), and for which the conveyor belt circulation with its variable meridional transport of warm water masses may be the key mechanism.

The principles and hypotheses on ocean circulation, rapid climate change and the bipolar seesaw mechanism formulated by Broecker have subsequently inspired countless studies of the physical mechanisms of climate change, not only to explain past changes, but also in terms of how climate might change in the future.

## **Outlook**

W. S. Broecker has applied his considerable energies and intellect to making significant and long lasting contributions to the geosciences and society through service and outreach. He has an unparalleled international reputation not just as a researcher but also as a spokesman for his field. He was one of the first scientists to raise concerns over rising greenhouse gas concentrations, and he has since taken on a personal mission to educate decision makers and the general public about the role of greenhouse gases in global warming and the potential attendant consequences on the climate system.

The message that the climate system, even left to itself, can change suddenly and substantially rather than gradually as a predictable response to forcing is very important at the present time. Broecker has consistently been very outspoken in warning of the possibility that the climate might change abruptly due to the present greenhouse forcing, writing and speaking about this so-called "unplanned experiment" from the mid 80s onwards (Broecker et al. 1985b; Broecker 1987). Within this field, others have played their parts in recognizing the importance of abrupt climate change, but Broecker stands out as the innovative, eloquent and inspirational scientist of our time.

His advocacy has been characterised by his consistently open mind; and he has been ready to criticize those on both sides of the debate who have become detached from the science itself. Because of this, it is notable that he enjoys wide respect across the spectrum of opinions. Even scientists who do not think that the on-going climate warming is a cause for alarm are supportive of Broecker, who comes across as someone prepared to be driven by evidence rather than fettered by dogma. With his extraordinary commitment Broecker has made important contributions to the global dialogue on policy change and through his international leadership in climate change science he has played a leading role in global environmental policy debate.

In a wider context, Broecker has been a strong and active teacher of his subject and an educator, producing accessible and engaging books and articles that can capture the attention of the general public and students, while avoiding the trap of “dumbing down” the subject to make it palatable to non-specialists. Annoyed by the high prices charged by publishers of both journals and books he has, since 1982, been publishing his own works at cost price, via the "eldigio" press, to make them available to the widest possible readership. Several of his books and articles have served to present the basic science with great clarity to a non-specialized audience (Broecker 1974; Broecker 1985; Broecker 1992a, b), while another (Broecker and Peng 1982) has been the classic chemical oceanography textbook for almost 25 years

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