ROLE OF THE OCEANS IN THE GLOBAL CLIMATE SYSTEM

Chen-Tung Arthur Chen
Institute of Marine Geology and Chemistry, National Sun Yat-sen University, Kaohsiung 804, Taiwan, R.O.C.

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Contents

Summary

Life on Earth has experienced relentless climate changes over the past 3000 million years. For example, since the demise of the dinosaurs around 65 million years ago, the average surface temperatures have at times been up to 10°C warmer, or 5°C cooler, than at present. While many factors have contributed to climate trends and fluctuations, variability in the strength of the natural greenhouse effect seems to have been of particular importance. This means that the overall range of climate extremes has apparently been set by the upper and lower limits in the abundance of CO_2 and other greenhouse gases. Furthermore, more short-term variations in atmospheric composition have at times provided positive feedback (accelerating changes) to temperature increases and decreases initially brought about by other factors. For instance, the trend towards rising temperatures in the past decade was interrupted after the 1991 Pinatubo volcano eruption in the Philippines because some 20 million tons of sulfur dioxide had been hurled into the stratosphere and circulated around the globe, cooling it for the following two years.

The analysis of air bubbles trapped in polar ice has shown the extent and rate of atmospheric CO_2 changes associated with geologically-recent climate oscillations in the Earth's Ice-Age cycle. Changes in atmospheric CO_2 over the past 160 000 years are closely correlated with carbon isotope (C-13) indicators of plankton productivity. Anomalies in the planetary orbit, which affects the amount and distribution of energy received from the sun, set the tone for glacial-interglacial temperature changes but cannot account for their magnitude. During the cooling phase of the cycle, around 200 billion (10^9) tonnes of carbon were removed from the atmosphere; a similar amount was returned during the more rapid warming periods, like the one which occurred most recently 10-15 thousand years ago.

Where did that CO_2 come from and go to? The answer must lie in the ocean with its great supply of exchangeable carbon. Marine sediment cores indicate a stronger biological CO_2 pump, but a weaker physical pump with reduced surface-to-deep ocean circulation, during the cold glacial periods. An increase in the availability of nutrients in the upper ocean is the most likely cause of enhanced marine productivity, caused either by changes in the pattern of ocean mixing, or by additional nutrient inputs from exposed continental shelves or from the atmosphere. Ice core data show that considerably more wind-blown dust from a drier, terrestrial environment reached polar regions during glacial periods. It is feasible that this dust served to fertilize the oceans: under present-day conditions, the biological productivity of much of the Southern Ocean and parts of the Pacific may be limited by the aerial supply of essential minerals, such as iron. Nutrients in the Southern Ocean are at present not fully used by phytoplankton. Wind-blown dust, however, may have promoted productivity during glacial periods.

On a shorter time scale, several processes are known to play important roles in determining sea surface temperature distribution. Large-scale wind and current motions both play a significant role in governing the observed distribution of temperature. For instance, the evolution of El Niño is thought to be influenced principally by shifts in the circulation patterns of both the atmosphere and the oceans.

1. Introduction

Oceans play a major role in controlling climate. For instance, the oceans store energy when it is in abundant supply during the day, or summer, and releases it during the night, or winter. Further, evaporation provides a continuous air conditioning treatment of tropical sea surface temperatures. Such related air-sea interactions and ocean-atmosphere transport processes, operating on a variety of time and space scales, maintain sea surface temperature. Salinity also plays a major role. It is now widely accepted that changes in surface salinity is the major driving force that can perturb the climate system. An example is the onset of the most recent cold phase, the 'Little Ice Age' from 1400 AD to 1850 AD that ended the 'Medieval Warm Period' which commenced about 900 AD. Viking settlements that flourished on Greenland in the Medieval Warm Period had to be abandoned during the early part of the Little Ice Age. This may have been caused by nothing more than changes in the enhanced freshwater supply of the Arctic Ocean, which subsequently upset the efficiency of the Nordic heat pump, hence the cooling.

Normal patterns of temperature and circulation in the Pacific involve warm surface waters and a deep thermocline in the west, but cooler surface water, a shallow thermocline and upwelling in the east. Strong trade winds maintain higher sea levels in the west. Warmer air rises and forms precipitation in the west. But the reverse is true in the east where sea level is low and the air is dry. When this system is disrupted, anomalies in the response of the oceans by the winds may deepen the thermocline in the eastern Pacific, interrupting normal upwelling and producing anomalous warm sea surface temperatures characteristic of an El Niño, with implications for a temperate zone climate such as the one in California. The effects are most notable in precipitation, winds, river outflow, circulation and, indeed, almost every other climatic variable. Moreover, the effects are seen not only in South America but around the world. The impact of El Niño on biological systems, particularly fisheries, has been the focus of many recent studies. Even marine iguanas, pelicans and other birds suffer when the upwelling of cold, nutrient-rich water ceases.

As a historical irregularity, El Niño was originally described as a purely local biological anomaly. In the decades of the 60's and 70's, the fisheries saw a major collapse in anchovy catch and a shift from an anchovies-dominated system to a mixed system of sardines and other pelagic fishes in the North Pacific. El Niño has clear demonstrable effects on the fisheries, e.g., a 50 per cent decline in yield during moderate to strong events may have an impact of some $300 M US.

Global warming, of course, affects the oceans as well. For instance, near the end of the last glacial age about 12 000 years ago, the Black Sea was a smaller, freshwater lake about 150 m lower than the Sea of Marmara off northeastern Mediterranean Sea. Warmer temperature of the Holocene melted glaciers and global sea levels rose markedly for several thousand years until a natural dam at today's Bosporus collapsed about 7500 years ago. This event sent 40 km^3 (40 billion tons) of seawater, a day, roaring into the Black Sea. The inhabitants would have been forced to flee inland about 50 km each month. Some still search for remnants of Noah's ark on the flanks of Mt. Ararat not far from the coast of the Black Sea.

The current global warming, however, may have been caused by human activities such as burning of fossils and clearing of forests. There are six major greenhouse gases: Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorcarbons (PFCs), hydrofluorcarbons (HFCs) and sulphur hexafluoride (SF_6). The last three are artificial, and have gained importance in recent years. The US Environmental Protection Administration has estimated that global warming is most likely to raise the sea level 15 cm by the year 2050 and 34 cm by the year 2100 and that there is a 1 per cent chance that global warming will go on to raise the sea level by 1 m in the next 100 years and 4 m in the next 200 years. Widespread coastal flooding and erosion, and even the near disappearance of low lying islands such as the Maldives in the Indian Ocean world occur.

2. Spatial Variations

Predictions of large-scale events in the atmosphere and oceans are often based on phenomena which occur thousands of kilometers away. For example, the timing and strength of the monsoon in India depend at least partially on the behaviour of the Somali Current off Northeast Africa, and the El Niño off Peru is governed by perturbations of the trade winds and the Equatorial current system in the western Equatorial Pacific. Similarly, variations in the seasonal extension of the polar pack ice, determined by the winds, seem to have a major effect on the global heat budget over periods of months and even years. What is true is that quantitative predictions of climate in the atmosphere or the oceans require knowledge as to the distribution and movements of water masses and their interaction with the atmosphere around the world.

Further, even phytoplankton affect the climate, not only because they affect the carbon cycle, but also because some produce dimethylsulfoniopropionate (DMSP), the precursor of dimethylsulfide (DMS). DMSP is released from the algal cells into seawater where it breaks down to DMS which escapes to the atmosphere and forms a major source of cloud condensation nuclei (CCN) in remote marine regions. The amount of CCN influences the number and size of the droplets that make up a cloud, which in turn affects its radiative properties. The more numerous and whiter the clouds, the more sunlight they reflect back to space and the more potential they have to cool the planet.

The movement of waters in the oceans with time has been depicted as the great 'conveyor belt' (An updated illustration of this is shown in Figure 1 of Chapter Role of the Oceans in Global Cycles of Carbon and Nutrients). Although it is designed as a simple representation of ocean circulation, it is quite useful in showing the linkages of ocean circulation with the Earth's climate system. The belt is driven by an increase in the salinity of surface waters from tropical regions as they move to the North Atlantic and by the net transport of water from the Atlantic to the Pacific. The poleward transport of warm surface waters in the North Atlantic results in relatively warm winters in Europe. Through the ages-and perhaps right up into the future-this conveyor belt has been known to shut down. For example, there were cold conditions in the Younger Dryas event that occurred about 10 000 years ago when the Earth had started to warm up after the last Ice-Ages. Because temperature and salinity control the movement of the conveyer belt, it is sometimes called thermohaline circulation.

At the same time the poleward flowing warm currents heat the high latitude regions, the water is cooled and sinks to form deep waters, which spread out to all major oceans and helps to make them homogenous. As a result, variations in the surface ocean water temperature anywhere are in a much smaller range (–2 to 30°C) than are the atmosphere or the land surface temperatures (~ –60 to 40°C). At any one locale, the variation is even smaller, less than 1°C between day and night, and around 10°C over the period of a year. At depths, the variations are still much smaller. The large amount of heat stored by the oceans and their slow response results in delays in the seasonal cycles compared with land.

Even so, the ocean-climate system is constantly changing, and the El Niño event in the Pacific is perhaps best known. The extreme variability in tropical weather can be anticipated from the widely different terrain found between the Tropics of Capricorn and Cancer, i.e. between 23.5°S and 23.5°N. Despite such variability, however, there exist interconnections between different regions. For instance, the atmospheric circulation over India and Indonesia is closely related to barometric pressure changes over the southern Pacific Ocean. This phenomenon is called the southern oscillation (SO). The SO is, in turn, related to El Niño and the sea temperatures off the north-western coast of South America.

During normal years, the trade winds blow from east to west, pulling warm water behind. Cold, nutrient-rich seawater of the subsurface water near the Equator wells up from below along the Equator from the coast of South America to the International Dateline, nourishing phytoplankton in the euphotic layer and supporting the Pacific food chain. A pool of warm surface water sits off Indonesia, bringing rains to the region rich in rain forests. The jet streams deliver rain to southern Mexico and the Pacific

Northwest of America.

On the other hand, during the El Niño years, which occur every three to seven years, the trade winds slacken, and stationary warm surface water east of the International Dateline prevents any upwelling of nutrient-rich deep water. As a result, productivity and fish stocks fall, and sea birds and turtles starve. The warm pool of surface water off Indonesia sloshes east, taking the storm clouds with it, thus reducing rain fall in southeast Asia. The jet streams shift north, and so do the rains. This event typically starts to develop in the summer and fall, reaching its maximum near Christmas and ending in the spring with the return of normal easterly trade winds and a resumption of Equatorial upwelling. The ocean-atmosphere system, however, often overshoots, and a cold La Niña develops. A particularly striking switch from El Niño to La Niña conditions occurred in May and June 1998, when trade winds abruptly returned to near normal strength in the eastern Pacific, and surface temperatures in the Equatorial cold tongue plummeted 8°C in only 30 days.

Under normal conditions, some of the highest levels of surface-water pCO_2 in the entire Pacific occur in the eastern Equatorial ocean (see Role of the Oceans in Global Cycles of Carbon and Nutrients). They are associated with the shoaling of the thermocline from west to east, which, along with nutrients, brings water containing high pCO_2 closer to the surface in the east. This is supplemented by the Peruvian upwelling system which brings water 100-200 per cent supersaturated in pCO_2 to the surface.

During El Niño periods, however, reduced trade winds decrease the upwelling rate. A deepening of the thermocline further reduces surface pCO_2 levels. These changes have a profound effect on the flux of CO_2 across the air-sea interface. For instance, approximately 0.9×10^{15} g C was released as CO_2 into the atmosphere in the eastern Equatorial Pacific during 1996, a normal year. In contrast, from the period from spring 1997 to spring 1998 during an El Niño event, only 0.2×10^{15} g C was released. Such a large reduction in the build-up of an important greenhouse gas in the atmosphere is expected to have reduced the greenhouse warming during that period as well.

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Bibliography

Bauch, H.A., H. Cremer and M. Kunz-Pirrung (2000). Siberian shelf sediments contain clues to paleoclimate forcing, EOS, Transactions, American Geophysical Union, 81, 21, p233 and 238. [This article describes past circulation patterns in the Arctic Ocean].

Bethoux, J.P., B. Gentili and D. Tailliez (1998). Warming and freshwater budget change in the Mediterranean since the 1940s: their possible relation to the greenhouse effect. *Geophys. Res. Lett.*, 25, 1023-1026. [The authors point out that changes in salinity of the Mediterranean Sea may have a profound impact on the circulation in the North Atlantic].

Broecker, W.S. and T.H. Peng (1982). Tracers in the Sea. *Eldigo Press*, 690pp. [This book describes various tracers, both natural and anthropogenic, in the oceans].

Changnon, S.A. (2000). El Niño 1997-1998, the Climate Event of the Century. [This book is a snapshot of events during a 14-month period starting when El Niño developed in the late spring of 1997 and ending by early summer 1998].

Chen, C.T.A., S.L. Wang and A.S. Bychkov (1995). Carbonate chemistry of the Sea of Japan. *J. Geophys. Res.*, 100, C7, 13,737-13,745. [This paper describes, in detail, the carbonate chemistry in the Sea of Japan for the first time].

Chen, C.T.A., G.C. Gong, S.L. Wang and A.S. Bychkov (1996). Redfield ratios and regeneration rates of particulate matter in the Sea of Japan as a model of closed system. *Geophys. Res. Lett.*, 23, 14, 1785-1788. [This paper proves that the decomposition of organic matter releases carbon, nitrogen and phosphorus in accordance with the Redfield Ratio].

Fashchuk, D. Ya and T.A. Ayzatullin (1986). A possible transformation of the anaerobic zone of the Black Sea. *Oceanology*, 26, 171-178. [This paper points out that changes in freshwater input may affect the thermohaline circulation in the Black Sea].

Feely, R. A., F. P. Chavez, G. Friedrich, M. J. McPhaden and R. Wanninkhof (2000). The effect of

El Niño events on variability of CO_2 fluxes in the Equatorial Pacific. *U.S. JGOFS NEWS*, 10,1-4. [This papers shows that reduced trade winds during El Niño periods decrease the upwelling rate, hence reduced CO_2 flux into the atmosphere].

Freeland, H.J. (1990). Sea surface temperatures along the coast of British Columbia: regional evidence for a warming trend. *Can. J. Fish. Aquat. Sci.*, 47, 346-350. [This paper reports a warming trend in the sea surface temperatures along the British Columbia coast].

Gore, R. (2000). A history forged by disaster. National Geographic, July, 52-71 pp. [This article describes the relentless forces that have rocked Turkey and the neighborhood for millennia. Such events may have nurtured myths of Poseidon and tales of Troy, and may explain why Noah had to build an ark].

Hill, A.E. (1998). Buoyancy effects in coastal and shelf seas. In *"The Sea"*, Vol. 10, eds. K.H. Brink and A.R. Robinson, John Wiley and Sons, N.Y., 21-62 pp. [This paper describes how freshwater input affects the flow patterns on the continental shelf].

Murray, J.W., Z. Top and E. Ozsoy (1991). Hydrographic properties and ventilation of the Black Sea, *Deep-Sea Res.*, 38, S663-689. [This article presents results from a comprehensive study of the Black Sea].

Oba, T., M. Kata, H. Kitazato, I. Koizumi, A. Omura, T. Sakai and T. Takayama (1991). Paleoenvironmental changes in the Japan Sea during the last 85 000 years. *Paleoceanography*, 6, 499-518. [This paper provides proof that the Sea of Japan was anoxic in the past].

Oguz, T. (2000). Characteristics of temporally-evolving Black Sea pelagic ecosystem and biogeochemistry, JGOFS Open Science Conference, Ocean Biogeochemistry: A new paradigm, 13-17 April, 2000, Bergen, Norway, *Conference Programme*, 136-137 pp. [This article identifies the Black Sea as a temporally evolving, non-equilibrium ecosystem].

Read, J.F. and W.J. Gould (1992). Cooling and freshening of the subpolar North Atlantic Ocean since the 1960s. *Nature*, 360, 55-57. [The authors point out that cooling and freshening of the subpolar North Atlantic Ocean has a profound impact on the ocean/climate system].

Richards, F.A. (1975). The Cariaco basin (trench). *Oceangr. Mar. Biol. Ann. Rev.*, 13, 11-67. [This paper is one of the first to describe the anoxic Cariaco trench].

Schimel, D., I. Enting, M. Heimann, T. Wigley, D. Raynaud, D. Alves and U. Siegenthaler (1995). CO_2 and the Carbon Cycle in Climate Change 1994: Radiation Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios, 35-71. [This article describes radiation forcing and feedback of the climate system].

Scranton, M.I., F.L. Sayles, M.P. Bacon and P.G. Brewer (1987). Temporal changes in the hydrography and chemistry of the Cariaco Trench. *Deep-Sea Res.*, 34, 945-963. [The authors point out that even in the deep trench there are temporal variations].

Uematsu, M., H. Minami, Y. Hijikata and Y. Kata (1996). Paleoenvironmental change estimated from the concentration of major composition in the sediments of the northern Japan Sea, *Sea Research*, 5, 143-150 (in Japanese with English abstract). [This article identifies anoxic conditions in the Sea of Japan in the past].

World Meterological Organization (1995). The Global Climate System Review, 150 pp. [This is a monograph on the world climate system monitoring between June 1991 and November 1993].

Biographical Sketch

Born in Changhwa, Taiwan, on 22 April 1949, **Prof. Chen-Tung Arthur Chen**, his wife and two daughters are currently residing in Kaohsiung, where he has been Professor at the Institute of Marine Geology and Chemistry since 1986. After receiving his B.Sc. degree in Chemical Engineering from National Taiwan University in 1970, Prof. Chen was awarded his Ph.D. degree in Chemical Oceanography from the University of Miami in 1977. In the same year, he was appointed Assistant Professor in the College of Marine Sciences of Oregon State University, where he was later promoted to Associate Professor in 1981. He served as visiting professor at National Sun Yat-Sen University (NSYSU) in Kaohsiung, Taiwan, and as Chargé de recherche (CNRS), Université Pierre et Marie Curie in Paris during 1984-1985. During this period, he founded the Institute of Marine Geology at NSYSU, and served as its director until 1989 when he was made Dean of the College of Marine Sciences, a position he held until 1992.

Prof. Chen has sat on numerous international committees, including the Scientific Committee on Oceanic Research and the World Ocean Circulation Experiment. He also served as one of the executives of the Scientific Steering Committee of the Joint Global Ocean Flux Study (JGOFS) between 1992-1995. Just prior to that, he had helped to form the Joint JGOFS / LOICZ Marginal Seas Task Team in 1991, and served as its chairman until 1995. Prof. Chen is at present one of the editors of *Oceanography Journal* and associate editor of *Marine Chemistry*. Besides having more than 150 of his own scientific papers published, Professor Chen was awarded the highly-coveted Biowako Prize for Ecology from Japan in 1997.