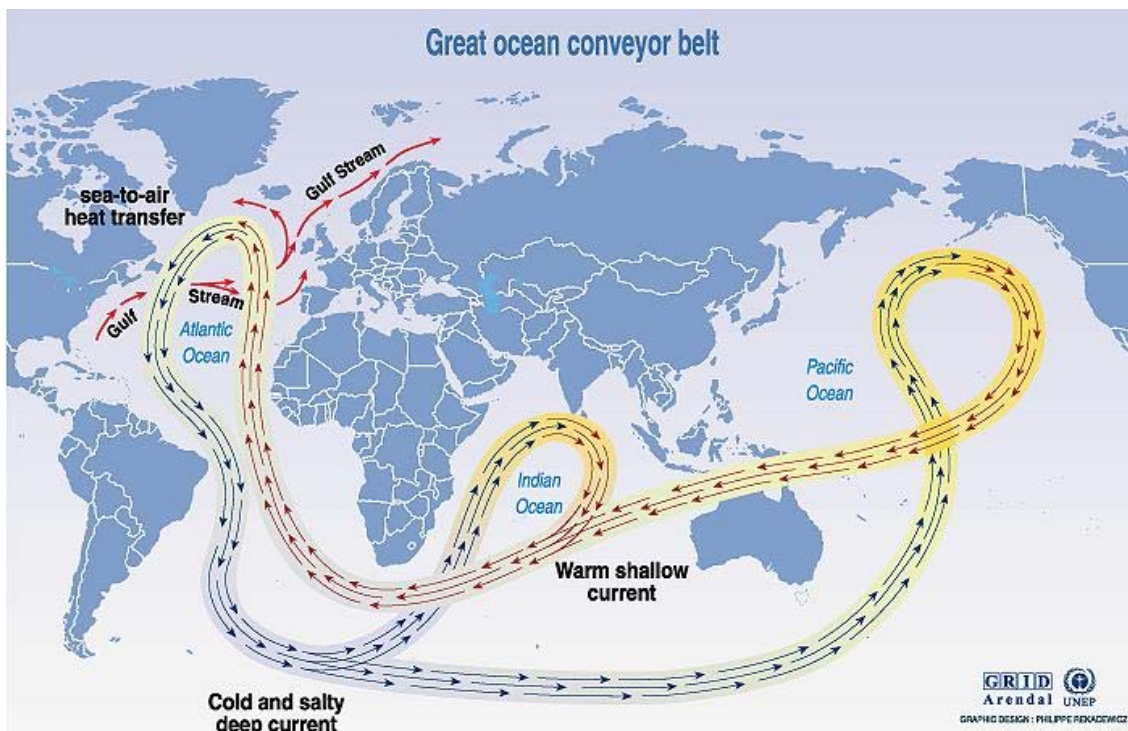


The Antarctic Circumpolar Ocean Current

A review of its influence on global ocean currents and climate within Antarctica and Europe

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Source: Broecker, 1991, in *Climate change 1995, impacts, adaptations and mitigation of climate change: scientific-technical analyses, contribution of working group 2 to the second assessment report of the intergovernmental panel on climate change*, UNEP and WMO, Cambridge press university, 1996.

Abstract

This review examines the operation of the Antarctic Circumpolar ocean current, its role in the so-called 'great ocean conveyor belt' of worldwide ocean currents and its influence on climate, particularly in northern Europe.

The development in the understanding of ocean currents and their driving forces is described using historical sources, starting from the observations of early explorers to modern scientific analysis.

The interaction of the Antarctic Circumpolar current within the ocean conveyor belt and its influence on worldwide oceanic flow is reviewed with reference to its effect on the Gulf Stream

The associated implications for climate change within Antarctica and Europe are discussed in the context of recently proposed scenarios.

Introduction

The Antarctic Circumpolar Current (ACC) encircles Antarctica, flowing from west to east, and stretches over twenty thousand kilometers forming the world's largest ocean current. The average flow rate is estimated (1) at 135 million cubic metres of water per second ($135 \times 10^6 \text{ m}^3 \text{ s}^{-1}$) or 135 Sverdrup (Sv) with 1 Sv being the estimated flow of all the world's rivers combined. Although the flow rate of the current is low, less than 20 cm s^{-1} , the current can reach a width of 2000km and depths of 2000-4000m which accounts for the huge flow rate. The absence of any continental landmass allows the ACC to circulate around the globe allowing water transfer between oceans. The ACC is driven by the strong winds of the Polar Front which extend between the latitudes of 40°S and 60°S , where the average wind speed is between 15 and 20 knots.

The Gulf Stream begins in the Caribbean and ends in the northern North Atlantic. The flow of this current varies markedly along its length from 30 Sv in the Florida Current to a peak of 150 Sv at 55°N (2). The Gulf Stream is a boundary current, these flow close to and parallel with continental margins and they dominate surface current patterns in the world's oceans. This flow is also seasonally dependant, reaching a maximum in the autumn and minimum in spring. Although the Gulf Stream undoubtedly provides a warming influence to Europe, there is considerable debate to its extent and importance for the European climate.

The ACC encircles Antarctica and thereby connects the ocean basins of the Atlantic, Indian and Pacific Oceans. The ACC smoothes out variations in water properties, for example salinity and temperature between these basins, and enables a global ocean circulation pattern. Ocean water at the high Antarctic latitudes is made cold and saline, through the formation of sea ice, causing it to sink. This cold, deep water flows to lower latitudes, equalising the temperature and salinity difference of deep ocean water, and warm, shallower water flows in the reverse direction to maintain water balance. The ACC is a key component in the so-called 'ocean conveyor belt' by allowing the free exchange of water between the ocean basins. Consequently the ACC is an important factor in worldwide ocean currents forming a linkage to the Gulf Stream.

The exchange of cold water from the Antarctic with warm water from lower latitudes regulates worldwide temperatures and is an important factor in worldwide climate. The European climate is influenced by the Gulf Stream which, in turn, is affected by the ACC. In the period between 1300 and 1800, Europe was so cold that the period has been dubbed the 'Little Ice Age'. Many researchers believe that this was due to a slowdown in the ocean current system, including the Gulf Stream, carrying heat towards Europe (3). At the same time, it has also been proposed that the southern ocean currents were stronger and that in a mirror image of the Little Ice Age, the Antarctic region warmed up by perhaps as much as 3°C. This review covers the development in understanding of the ACC and ocean conveyor belt, it then examines the implications for climate, specifically the linkage with the Gulf Stream and warming of Europe.

Early Observations

The early explorers of the southern latitudes discovered that both the air and sea became cooler as they sailed across the Southern Ocean. It was also observed that strong currents within this ocean set their ships east where the temperature change occurred. In 1775, this strong current was noted by James Cook on his second voyage with the ships Resolution and Adventure. Subsequent recordings of the current were made by Thaddeus Bellingshausen (1819-1821) and James Clark Ross (1839-43) in their journals. The southern latitudes have been known since early times for some of the strongest westerly winds on earth. This prompted sailors to term these winds the 'Roaring Forties' and 'Furious Fifties' and it is these winds which drive the ACC.

In the sixteenth century, it was observed that surface water in the Pacific Ocean off the coast of Peru and Northern Chile was unusually cold for that latitude. In 1811, Humboldt, whose name is given to the associated current, proposed that advection of cold water from southern latitudes was responsible for this lower than expected temperature.

In 1787, the scientist Richard Kirwan theorised that water in the high latitudes "is, by cold, rendered specifically heavier than that in the lower warm latitudes, hence there arises a perpetual current from the poles to the equator". In 1798, Benjamin Thomson noted that the maximum densities of pure water and salt water occurred at different

temperatures. He proposed that descending cold water, since it has higher density than water at the same depth in warmer latitudes, would spread on the sea floor and move towards the equator and that this would produce a surface current in the opposite direction. A similar theory was also proposed by Humboldt in 1814 (5). This was the start of understanding thermohaline circulation which is caused by differences in sea density caused by differences in temperature and salinity

The action of wind above a water surface results in friction at the interface causing the water to move in the direction of the wind thereby setting up a surface ocean current. During the latter part of the nineteenth century, there was scientific debate on the relative importance of wind, temperature and density differences in defining ocean circulation. In 1878, Karl Zöppritz suggested that the current was primarily set by the wind and had the same average direction. However this theory did not account for the Coriolis effect of the earth's rotation. A second theory was proposed by Vihelm Bjerknes in 1904 which gave density and temperature differences as the driver for ocean circulation.

During the Fram expedition in the Arctic (1893-6), Fridtjof Nansen found that the drift of the vessel in the sea ice did not, according to the then general opinion, follow the wind's direction but deviated between 20° and 40° to the right. This was later explained by V. Walfrid Ekman to be as a consequence of the Earth's rotation (6). He predicted that the current would spiral clockwise (for the northern hemisphere) with increasing depth and reduce in strength, the so-called Ekman spiral (7). The two apparently divergent theories were unified as Ekman showed that viscous effects were not able to transfer horizontal momentum vertically down the water column and that it was also necessary to consider downwards turbulence as well.

The Ekman spiral causes a net movement of water (to the left of the wind in the southern hemisphere) and this is known as Ekman transport. An example of this transport, called divergence, occurs when surface winds move water away from a region. In this case, subsurface waters move upwards to replace this lost water and a prominent divergence occurs, forming a gyre centre. A gyre is circular surface rotation of ocean water due to this effect which rotates to the left in the southern hemisphere and the process of moving water in or out of a gyre centre is termed Ekman pumping.

A Norwegian oceanographer Harald Sverdrup joined Roald Amundsen's North Polar expedition in 1917 and also worked under Bjerknes. During the 1930s, he developed fundamental theories on how wind surface stress transfers mechanical energy to the ocean and recognized this as the dominant factor (8). He also developed the theory of ocean circulation known as Sverdrup balance which was the first accurate description of the process. He was honoured by having the unit of volume flow for currents named after him. In 1957, Stommel suggested that the ACC is controlled by Sverdrup balance and although this is not universally accepted (9), it is still supported by some (Warren, 1996).

The Development of Oceanography and Linkages to Climate

During the 1950s, oceanography developed significantly and this was driven by two institutions, the U.S. Navy's Office of Naval Research, which actively funded many aspects of ocean research and the International Geophysical Year of 1957-8 which set up an international committee on this subject. The circulation of ocean currents became better charted using the radioactive isotope carbon 14 contained within the carbon dioxide dissolved in sea water. Nuclear tests during the late 1950s had also placed tritium and other radioactive material into the atmosphere which were also used as tracers to map the main features of ocean circulation. These methods were later supplemented by remote sensing techniques using satellites. During the 1970s, the U.S. Government funded the Geochemical Ocean Sections Study for studying ocean circulation.

In the late 1960s, the first use of computers to model ocean circulation began with an early researcher being Kirk Bryan who started modeling the Gulf Stream. In 1969, he coupled his ocean basin model to Syukoro Manabe's model of atmospheric circulation which allowed a significant simulation of climate and thermohaline ocean circulation.

Links between ocean currents and climate were suspected from early times and in 1904, Petterson suggested a relationship between outbursts of ice from Antarctica and fluctuations in the monsoon rainfall of India (10). In 1963, Jerome Namias proposed how a change in prevailing winds could change the ocean surface temperature which in turn affected the winds. It was later recognized that ocean-atmosphere feedback oscillations could occur on timescales of a few years to decades. In the late 1950s, researchers such

as Wallace Broecker and Henry Stommel began to make connections between disturbances in the ocean circulation system and changes in climate. These ideas were developed worldwide during the 1960s and 1970s, further assisted by the collected of ice cores collected from the Greenland ice cap and deep sea drilling projects such as those from the Glomar Challenger in 1968. This was also supplemented by research into deep sea geochemistry and investigation of the deep sea fossil records. In the 1980s, Broecker and others realized how much heat was actually carried by what he described as the “great conveyor belt” of sea water flowing northwards. They found that a huge amount of water was flowing slowly northward to the surface of the Atlantic and that this was as important in terms of heat flow as the well studied Gulf Stream. Although the importance of the Gulf Stream to Europe’s climate had long been recognized, it was now realized that if something shut down this conveyor belt then climate would change significantly over much of the northern hemisphere.

The Antarctic Circumpolar Current

The ACC is the world’s only global current, flowing eastwards around Antarctica in a closed current with its flow unimpeded by continents. The ACC is usually considered to be the northern border of the Southern Ocean which, because of the formation of sea ice, contains the world’s densest sea water. Since the ACC links the ocean basins of the Atlantic, Indian and Pacific Oceans, the waters carried in the ACC contain a mix of waters originating in different parts of the world. As water flows away from the ACC, it flows both to the north and to the south where it becomes a primary source for the Antarctic Bottom Water.

A difference between the ACC and other major currents is that the ACC is not a single flow but consists of two or more jets that run largely parallel to an ocean ridge system which surrounds Antarctica. Between the ACC and Antarctica there are two significant gyre systems, the Ross and Weddell Sea gyres.

An ocean front is defined as an abrupt change in the water properties, principally temperature and salinity, with lateral position. In 1939, George Deacon (13) recognised that there was more than one front in the Southern Ocean. The Polar Front (or Antarctic

Convergence) had been discovered earlier through noting changes in sea temperature and Deacon showed that it was circumpolar. Subsequently the Sub Antarctic Front was also been found to be circumpolar. These fronts separate distinctive zones of sea water, interestingly the largest water mass in the ACC is the Circumpolar Deep Water which is not Antarctic in origin but can be traced back to the outflow from the Mediterranean Sea. In the Antarctic zone, this water mass lies beneath the winter water so that between 200m to 500m, water temperature increases with depth and this was first noted on Captain Cook's second voyage.

The winds that drive the ACC are stronger than required even for a current as large as the ACC. Models of wind driven circulation which work well for other currents produce flows that are up to ten times to strong in the case of the ACC. Counter-acting forces which slow the ACC are believed to be the effect of the bottom ridges in the Southern Ocean and boundary currents associated with the ACC. Around New Zealand and South America, the ACC departs from its eastwards flow and turns to the north. At these locations, the ACC can be considered as a boundary current, like the Gulf Stream, and these are known to dissipate large amounts of energy (14) in the eddies and turbulence associated with such currents.

A phenomenon related to the ACC and its connection of the ocean basins is the Antarctic Circumpolar Wave (ACW) identified by Warren White and Ray Peterson (15) in 1996. The ACW consists of variations in sea-surface temperatures and pressures, together with sea ice extent, which propagate eastwards around the Southern Ocean with an apparent period of around four years. Although there is debate on whether this is a true ocean-atmosphere feedback oscillation (16), the ACW could have a substantial effect on rainfall in Australasia.

The Gulf Stream

In 1769, Benjamin Franklin used reports from the captains of mail ships crossing the North Atlantic to make the first map of the ocean current which we know today as the Gulf Stream. Open ocean waters are separated from coastal waters by boundary currents which flow close and parallel to continental margins and in a direction that is normally north to south. Boundary currents are named according to which side of the ocean basin they appear on and the Gulf Stream is an example of a western boundary current.

The salinity and temperature of coastal waters vary with the seasons whereas the Gulf Stream waters remain warm with relatively high salinity throughout the year. The Gulf Stream is characterised by meanders in its main stream which form eddies, rotating pockets of water which spin off the main stream. Generally, warm core eddies are found on the north side of the Gulf Stream and spin clockwise, whereas cold core eddies are found to the south and spin counterclockwise. When the Gulf Stream, or North Atlantic Current, is north of Norway, it encounters melt water from the polar ice which although cooler has considerably lower salinity. Consequently it is the North Atlantic Current which sinks beneath the melt water and ice, thereby forming North Atlantic Deep Water.

There is considerable debate to the extent of the role which the Gulf Stream plays in heating Europe. It is estimated (17) that the flow of warm water by the Gulf Stream boosts temperatures in northern Europe by between 5°C and 10°C compared with similar latitudes in Siberia. Other sources (18) suggest that the role of the Gulf Stream in the heating of Europe has been over estimated.

The Linkage between the Antarctic Circumpolar Current and European Climate

The ACC has an effect on climate in three principal ways:

- In connecting the ocean basins, the ACC redistributes heat and other ocean properties and thereby influences patterns of rainfall and temperature.

- The ACC exchanges gases, such as carbon dioxide and oxygen, with the atmosphere. The rate at which carbon dioxide is absorbed by the Southern Ocean can directly affect changes in world climate.
- The vertical movement of water caused by winter freezing and summer warming, directly controls the flow of deep water in the world's oceans.

In the early 1980s, fossil records from deep sea drilling programmes showed that there had been shifts in the North Atlantic around the time of the last ice age (approximately eleven thousand years ago) which corresponded to a climate shift on land known as 'Younger Dryas'. Studies by Hans Oeschger and others indicated that there had been very abrupt cooling around the North Atlantic and that this cooling had extended to the ocean floor. It appeared that there had been massive changes in the circulation of the North Atlantic which might have extended worldwide. Oeschger was intrigued by the rapid rise in atmospheric carbon dioxide at the end of the last ice age and that the main reservoir for this gas is the oceans.

In 1985, Broecker and his colleagues (20) suggested that there could be two modes of ocean-atmosphere operation which, in the context of North Atlantic circulation, could explain Oeschger's observations of rapid changes in carbon dioxide. Through their work on mapping global ocean currents and developing the 'great conveyor belt' theory, they realized that there was a huge mass of water moving slowly northward, near the surface of the North Atlantic which is as important for carrying heat as the much more familiar Gulf Stream. Consequently changes in this ocean conveyor belt, wherever they occurred, could have a major impact on the European climate. The circulation in the Atlantic Ocean (21) is dominated by this northward flow of upper waters (including the Gulf Stream) balanced by a return flow of deep water (the conveyor).

Broecker suggested in 1987 (22) that there was clear evidence that changes in world climate could be sudden rather than gradual. He pointed out that non-linear effects in the atmospheric system could result in a sudden shift of the climate to a new equilibrium by altering, for example, the direction of major ocean currents such as the Gulf Stream. Subsequent work showed the situation to be more complicated with individual sites of convection, which lead to the formation of deep water, being capable of switching

through global warming. In 1994, Broecker (23) described how deep water formation in the Southern Ocean can affect the stable states of Atlantic circulation.

The period of the 'Little Ice Age' has been analysed by Broecker (24) and he has suggested that a change in thermohaline circulation accompanied this period and that this could have been accompanied by an anti-phased warming in the Antarctic region. Analysis at the Taylor Dome Antarctica ice core site suggests that the air temperature could have increased by 3°C. In the appendix of this paper, evidence is provided for the anti-phasing of climate changes between the Antarctic continent and elsewhere in the world, notably European. This evidence is a correlation of the oxygen isotope records for the Antarctic Byrd and Greenland GISP2 ice cores which indicate an anti-phasing of climate oscillation between these two regions.

Consequently, the work of Broecker and others has proposed a linkage between the climates of Antarctica and Europe through worldwide thermohaline ocean circulation with the ACC as a significant driving force behind such changes.

Conclusions

The Gulf Stream is probably the most and longest studied ocean current in the world, this is likely to be due to its commercial importance and because a large proportion of the early researchers lived in the surrounding countries. Since the Gulf Stream is a warm surface current and readily observable, it is not surprising that its warming effect on Northern Europe should be appreciated at an early stage but perhaps its role has been over-estimated.

The great advances in oceanography over the last fifty years have revealed the importance of thermohaline circulation and the action of the great ocean conveyor. It is now apparent that it is not just the Gulf Stream which warms Europe. The deep water currents also have as significant, if not greater effect, and also influence the flow of surface currents such as the Gulf Stream. There are now clear linkages between changes in the Antarctic, which influence the ACC, and effects on distant currents such as the Gulf Stream. Intriguingly, we also now know of relative short duration perturbations to

these major current flows, such as the ACW, which may well have some more subtle effects on distant regions, such as in Europe.

Climatologists have argued that a halt in Gulf Stream circulation would never make Europe as cold as other parts of the northern hemisphere at similar latitudes because of the effect of the prevailing westerly winds, which also distribute the ocean's heat, and the additional effects of the great ocean conveyor. Since ocean currents and the atmosphere are inextricably linked, numerical modeling and computer simulation of a complete ocean-atmosphere model are essential and will enable more accurate forecasting of future scenarios.

Currently these models seem to provide consensus at a macro level, for example that the Gulf Stream flow is decreasing, but widely differ in their results at the micro level, such as the precise the rate of slowing. This indicates that current models are at least incomplete and, in the context of this review, further progress is required in:

- Accurate numerical modeling of fluid dynamics within oceans including the more complicated mechanisms of eddy currents and turbulent flow.
- Further investigation into historical records, such as deep ice and ocean cores, to improve the understanding of previous changes to the currents and climate.
- Increased data on the observed characteristics of major currents within the great ocean conveyor to develop and test models. In the case of the ACC, most of this work performed has been in the Drake Passage where the ACC is squeezed between the land masses of South America and Antarctica. However, it is known that the ACC path is complicated and changes direction in some locations. If this was more clearly understood, together with the action and profile of the sea floor, then more accurate modeling would be possible. This could answer some of the current discrepancies between observed flow rates and those calculated due to the influence of wind.
- Further integration of the ocean and atmosphere models. Continued advances will be required in computing resource to support such simulations, this is likely to occur. However more aspects of both the ocean and atmosphere will also need to be included. In the case of the oceans, including interactions such as the ACW,

will be necessary to understand such subtleties in the global context. These may ultimately reveal influences on the European climate.

A key enabler to recent advances in oceanography has been the interest and support shown by military organizations, such as the US department of defence, during the Cold War. In order that future progress is maintained, the continued funding of such research needs to be considered. Perhaps the future driver will be climate change, the increasing governmental awareness of this issue and the need to understand the underlying reasons.

A recurring theme is the interaction of processes which control ocean currents and climate, and the feedback mechanisms which operate to regulate change. The role of the ACC in lowering European temperature through a reduction in the flow of the Gulf Stream is an example. This could be as a result of factors, such as an increase in greenhouse gases, which provide a counteracting increase in temperature. Consequently the overall change may not be viewed as too significant although the underlying changes may be far greater. Under these circumstances, it is possible to see how a ‘tipping point’ could be reached where these effects reinforce, rather than counteract, leading to very dramatic changes. Therefore the linkage between the ACC and other currents, such as the Gulf Stream, form an integral and significant component in the overall picture of global ocean currents and world climate.

References

- (1) Antarctica – the blue continent
D. McGonigal and L. Woodworth, Francis Lincoln 2004 ISBN 0 7112 2476 5
- (2) Ocean Forces Threaten Our Climate
The Cooperative Institute for Marine and Atmospheric Studies Website
<http://oceancurrents.rsmas.miami.edu/atlantic/gulf-stream.html>
- (3) J. Gribben FirstScience.com 2006
<http://www.firstscience.com/site/articles/gribbin.asp>
- (4) Gulf Stream density structure and transport during the past millennium
D. C. Lund, J. Lynch-Stieglitz and, W. B. Curry, Nature 444, 601 - 604 (2006)
- (5) Oceanography – A View of Earth
M. G. Gross and E. Gross, Prentice Hall 1996 ISBN 0-13-231788-5 pp199-227
- (6) Some aspects of the work of V. W. Ekman
A. D. Jenkins and J. A. T. Bye, Polar Record 42 (220) 15-22 (2006)
- (7) On the Influence of the Earth's Rotation on Ocean-Currents.
V. W. Ekman Arkiv för Matematik, Astronomi och Fysik, Band2 No11 (1905)
- (8) Harald Ulrik Sverdrup, November 15, 1888 – August 21, 1957
W. A. Nierenber, <http://darwin.nap.edu/html/biomems/hsverdrup.html>
- (9) On the Dynamics of Wind-Driven Circumpolar Currents
C.E. Tansley and D. P. Marshall, Journal of Physical Oceanography, Vol 31,
p3258, 2001
- (10) The ocean-atmosphere system
A.H. Perry and J. M. Walker, Longman 1977 ISBN 0-582-48559-2 p67

- (11) The American Institute of Physics, Ocean Currents and Climate
<http://www.aip.org/history/climate/oceans.htm>
- (12) Unpleasant Surprises in the Greenhouse?
W. S. Broecker, Nature 328, pp123-6 (1987)
- (13) The Antarctic Circumpolar Current
T. Whitworth III, Oceanus Vol 31, No 2 p55 (1988)
- (14) The Work Done by the Wind on the Oceanic General Circulation
Wunsch, Journal of Physical Oceanography Vol 28 pp2232-40 (1998)
- (15) An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent
W. B. White and R. G. Peterson, Nature 380 pp699-702 (1996)
- (16) Ocean Circulation & Climate
G. Siedler, J. Church and J. Gould, Academic Press 2001 ISBN 0-12-641351-7
- (17) Failing ocean current raises fears of mini ice age
F. Pearce, NewScientist.com 30 Nov 2005 (cites Nature vol 438, p655)
- (18) The Source of Europe's Mild Climate
R. Seager, American Scientist Online – The Source of Europe's Mild Climate
July-August 2006 <http://www.americanscientist.org>
- (19) Southern Ocean and Antarctic Circumpolar Current
CSIRO Marine Research Information Sheet
<http://www.marine.csiro.au/LeafletsFolder/10ocean/10.html>
- (20) Does the Ocean-Atmosphere System Have More Than One Stable Mode of Operation?
W. S. Broecker et al, Nature 315, pp21-25 (1985)

- (21) Constraints on the Glacial Operation of the Atlantic Ocean's Conveyor Circulation
W. S. Broecker, Israel Journal of Chemistry pp1-14 Vol 42, No 1 (2002)
- (22) Unpleasant Surprises in the Greenhouse?
W. S. Broecker, Nature 328, pp123-126 (1987)
- (23) An unstable superconveyor
W. S. Broecker, Nature 367, pp414-5 (1994)
- (24) Was a change in thermohaline circulation responsible for the Little Ice Age?
W. S. Broecker, Proceedings. of the National Academy of Sciences vol 97 no4
pp1339-42

Other references used but not explicitly cited in review:

- (25) The Circulation of the World Ocean: A Numerical Study
K. Bryan and M. D. Cox, Journal of Physical Oceanography, pp320-335 vol2 (1972)
- (26) Does the Trigger for Abrupt Climate Change Reside in the Ocean or in the Atmosphere?
W. S. Broecker, Science pp1519-22 Vol 300 (2003)
- (27) North Atlantic's Transformation Pipeline Chills and Redistributes Subtropical Water
M. S. McCartney, R. G. Curry, H. F. Bezdek pp19-23 Oceanus Fall/Winter 1996
- (28) Ocean circulation and climate during the past 120,000 years
S. Rahmstorf, Nature 419, pp207-14 (2002)
- (29) South dials north
T. F. Stocker, Nature 424, pp496-9 (2003)

- (30) The Atlantic heat conveyor slows
D. Quadfasel, Nature 438, pp565-6 (2005)

Front Cover Diagrams

In clockwise direction from top left hand corner:

- a) Antarctic Circumpolar Current

Lectures 9&10 Ocean Circulation, University of East Anglia, UK

http://www.uea.ac.uk/~e930/e174/19_ocean.html

- b) Antarctic Circumpolar Wave

P. Baines, Australia's Climate Cerberus, Ecos, December 1998

- c) Great Ocean Conveyor Belt

W. S. Broecker, Climate Change 1995, Cambridge University Press 1996