The Oceanic Thermohaline Circulation: An Introduction

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# The Oceanic Thermohaline Circulation: An Introduction

Hendrik M. van Aken

*Royal Netherlands Institute for Sea Research*
*The Netherlands*

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Hendrik M. van Aken
Royal Netherlands Institute for Sea Research
Department of Physical Oceanography
1790 AB Den Burg/Texel
The Netherlands
email: aken@nioz.nl

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## Dedication

In memory of my father, Reijer van Aken

## Preface

The ocean is an important part of the global climate system, as was already stated in 1798 by Benjamin Thompson, Count Rumford. The founder of modern oceanography, Matthew F. Maury, also stressed the importance of the ocean circulation for the climate by influencing the winds, the air temperature, and the hydrological cycle in his book on the physical geography of the sea published in 1855. Ongoing research over the past 150 years has confirmed these viewpoints and has identified key processes for the links between ocean circulation and climate.

With the increasing probability of climate change due to the anthropogenic emission of greenhouse gases into the atmosphere, the study of the ocean circulation has gained more than only academic interest. A good understanding of the ocean's role in the climate system is essential in order to assess the present climate status and to forecast climate changes that may result from the still-increasing emission of greenhouse gases. The globally overturning thermohaline circulation, driven by global-scale gradients in temperature and salinity, is assumed to contribute essentially to the climatic feedback mechanisms that are involved in anthropogenic climate change as well as in natural climate variability. At low latitudes the surface water is heated by interaction with the atmosphere, while at high latitudes the surface water is cooled. These cold water masses then descend into the deep abyssal basins. This deep-reaching circulation system also is involved in the storage of carbon dioxide in the ocean. While carbon dioxide is converted to organic material by primary production of phytoplankton in the near-surface photic zone, the microbial ecosystem in the deep ocean converts organic material back to dissolved inorganic carbon. When the cold deepwater from the abyssal ocean basins returns to the surface of the ocean heat and carbon dioxide again are exchanged with the atmosphere.

Nowadays numerical models of the oceanic circulation are used as part of global climate models. With these models possible future developments of the climate, which may have a profound influence on people and society all around the world, are simulated. The International Panel on Climate Change of the World Meteorological Organization and the United Nations Environmental Program also discuss the climate status of the oceans and the role of the oceans in climate in their regularly published Climate Change Scientific Assessment Reports.

In discussions with colleagues and students I often have explained the evidence for the course of the thermohaline circulation, possible changes of this circulation, and its main dynamic properties. Although nowadays the importance of the thermohaline circulation is well recognized, oceanographic textbooks generally do not present the hydrographic and dynamic aspects of the thermohaline circulation comprehensively. In many publications, especially in the fields of marine geology, chemistry, and biology, the understanding of the thermohaline circulation appears to be quite old-fashioned. Physical oceanographic papers are often rather one-sided, missing either the hydrographic, thermodynamic or hydrodynamic characteristics of this important global current system. Therefore, I decided to write this textbook, which is devoted completely to the thermohaline circulation. This book deals with a description of the thermohaline circulation, based on recent ocean observations, and with important theoretical aspects of the dynamics of the thermohaline circulations and its coupling to the atmosphere. It is intended to be used in courses for students in physical oceanography, climatology, geography and environmental sciences, paleoceanography, marine biology, and marine chemistry.

A mathematical physical approach can be very useful for the understanding of many quantitative and qualitative aspects of the thermohaline circulation. To make this book accessible for students with a variety of backgrounds, I have tried to keep the mathematics used in this book quite simple. Only some basic knowledge of differential and integral reckoning is required.

I owe thanks to several people for the support I got when preparing this book. First of all, I thank my wife Marjan, who allowed me to spend many evenings and weekends in my study. My colleagues at the Royal Netherlands Institute for Sea Research at Texel shared their expertise on several aspects of the thermohaline circulation. Leo Maas supported me in understanding the mathematical aspects of dynamic and feedback models, and was a critical reader of the manuscript. Fred Jansen introduced me to the world of paleoceanography, and Gerald Herndl and Geraldine Kramer taught me about the importance of the deep microbial ecosystem for the remineralization of organic material in the water mass of the abyssal branch of the thermohaline circulation. Wim Mook advised me with regard to the use of isotopes as tracers of the ocean circulation. Will de Ruijter of the Institute for Marine and Atmospheric Research of Utrecht University invited me to give seminars for students at his institute which form an important basis for this book. Discussions with students during the courses and seminars that I taught and during research cruises with Dutch, Indonesian, and German research vessels guided me with the choice of subjects for this textbook on the thermohaline circulation.

Finally I want to thank my late father, who in my youth stimulated my interest in science and the sea. He always encouraged and supported me in the changing choices for my studies, first engineering at the Royal Dutch Naval College, then physics and mathematics at Leiden University, and fi-

nally physical oceanography and meteorology at Utrecht University. This book is dedicated to him.

I thank Peter Wadhams, Arnold Gordon, and John Marshall, who allowed me to use figures from their publications in this book. I acknowledge all scientists who submitted their data to the public data bases that I have used to prepare the many figures, illustrating the diverse aspects of the oceanic thermohaline circulation.

Hendrik M. van Aken
Texel
October 2006

# Contents

## List of Abbreviations

| | |
|---|---|
| AABW | Antarctic Bottom Water |
| AAIW | Antarctic Intermediate Water |
| ACC | Antarctic Circumpolar Current |
| AgC | Agulhas Current |
| AgRf | Agulhas Retroflection |
| AIW | Arctic Intermediate Water |
| AMS | Accelerator mass spectrometers |
| AOU | Apparent oxygen utilization |
| BOUNCE | Boundary Current Experiment |
| BP | Years before present (present = 1950) |
| CBDW | Canadian Basin Deep Water |
| CDW | Circumpolar Deep Water |
| CFC | Chlorofluorocarbon |
| CGFZ | Charlie–Gibbs Fracture Zone |
| CIRES | Cooperative Institute for Research in Environmental Sciences |
| DNBC | Deep northern boundary current |
| DSBC | Deep southern boundary current |
| DSDP | Deep Sea Drilling Project |
| DSOW | Denmark Strait Overflow Water |
| DWBC | Deep western boundary current |
| EBDW | Eurasian Basin Deep Water |
| ECC | Equatorial Counter Current |
| ECMWF | European Centre for Medium-Range Weather Forecasting |
| EGC | East Greenland Current |
| EMC | East Madagascar Current |
| EOS | Equation of state |
| ERBE | Earth Radiation Budget Experiment |
| GCM | Global climate model |
| GEOSECS | Geochemical Ocean Section Study |
| GISP | Greenland Ice Sheet Project |
| GNAIW | Glacial North Atlantic Intermediate Water |
| GRIP | Greenland Ice Core Project |
| GSDW | Greenland Sea Deep Water |
| HOAPS | Hamburg ocean atmosphere parameters and fluxes from satellite data |
| IDW | Indian Deep Water |
| IPCC | Intergovernmental Panel on Climate Change |
| IPTS-68 | International practical temperature scale |
| ISOW | Iceland–Scotland Overflow Water |

| | |
|---|---|
| ISW | Ice Shelf Water |
| ITFW | Indonesian Trough-Flow Water |
| ITS-90 | International temperature scale 1990 |
| KNMI | Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute) |
| LC | Labrador Current |
| LCDW | Lower Circumpolar Deep Water |
| LDW | Lower Deep Water |
| LGM | Last Glacial Maximum |
| LSW | Labrador Sea Water |
| MAR | Mid-Atlantic Ridge |
| MARE | Mixing of Agulhas Rings Experiment |
| MC | Mozambique Current |
| MOC | Meridional overturning circulation |
| MSOW | Mediterranean Sea Outflow Water |
| NAC | North Atlantic Current |
| NADW | North Atlantic Deep Water |
| NCAR | National Center for Atmospheric Research |
| NCEP | National Centers for Environmental Prediction |
| NCW | Northern Component Water |
| NEADW | North East Atlantic Deep Water |
| NH | Northern Hemisphere |
| NIDW | North Indian Deep Water |
| NOAA | National Oceanographic and Atmospheric Administration |
| NSDW | Norwegian Sea Deep Water |
| ODP | Ocean Drilling Program |
| OGCM | Ocean general circulation model |
| OMPA | Optimal multiparameter analysis |
| PAIW | Pacific Arctic Intermediate Water |
| PDW | Pacific Deep Water |
| PSS-78 | Practical salinity scale 1978 |
| rAtIW | Return Atlantic Intermediate Water |
| RGR | Rio Grande Rise |
| RSOW | Red Sea Outflow Water |
| SAAMW | Sub-Antarctic Mode Water |
| SAT | Surface air temperature |
| SC | Somali Current |
| SCW | Southern Component Water |
| SEC | South Equatorial Current |
| SH | Southern Hemisphere |
| SI | Système International d'Unités (International System of Units) |
| SIOC | South Indian Ocean Current |

| | |
|---|---|
| SMOW | Standard Mean Ocean Water |
| SSS | Sea surface salinity |
| SST | Sea surface temperature |
| STMW | Subtropical Mode Water |
| SUN | Symbols, units, and nomenclature in physics |
| THC | Thermohaline circulation |
| TIC | Total inorganic carbon |
| TOA | Top of the atmosphere |
| UCDW | Upper Circumpolar Deep Water |
| WDW | Warm Deep Water |
| WGC | West Greenland Current |
| WOCE | World Ocean Circulation Experiment |
| WR | Walvis Ridge |
| WSBW | Weddell Sea Bottom Water |
| WSW | Western Shelf Water |
| WW | (Weddell Sea) Winter Water |
| YD | Younger Dryas |

# 1. Introduction

## 1.1. Climate and climate variations

The equatorial zone of the earth receives more energy per surface unit from the sun in the form of short-wave radiation than the polar regions because of the spherical form of the earth. The resulting temperature difference between the equator and the poles leads to meridional heat transport by the atmospheric and the oceanic circulation, both parts of the climate system. In its turn this heat transport mitigates the extreme cold and heat, caused by the differential heating by the sun and is responsible for a moderate global climate and a habitable earth.

It has been well established that the global climate system, of which the ocean circulation is an integral part, exhibits (natural) variability on a multitude of timescales. The ocean circulation pattern will change if the climate changes, while changes in the ocean circulation may induce climate changes. In first order the ocean will follow the changes in the atmospheric climate passively, since the ocean circulation and heat and salinity distributions are responses to the boundary conditions at the sea surface, set by the atmosphere. However, in higher order the ocean also may play an important role in amplifying or damping climate variations via several feedback mechanisms, depending on changed sea surface conditions like sea surface temperature, ice cover, etc. For climate simulation and forecasting of climate change a thorough knowledge of the ocean's role in climate is required (IPCC 2001). This is not a simple task. Despite the best efforts of thousands of people and the investments of hundreds of millions of dollars, there remain serious uncertainties about the present state of the ocean, its surface boundary conditions, and the extent to which and how it is changing (Wunsch 2003). This book deals with that part of the oceanic circulation that is assumed by many to supply the most important climatic feedbacks: the global thermohaline circulation (THC).

At present the strongest climate variation cycle is the seasonal cycle, directly driven by the variation of the solar radiation which is mainly due to the obliquity of the rotation axis of the earth relative to the plane of its orbit around the sun. Longer period climate variations have characteristic timescales ranging from a few years to at least several hundred-thousands of years. A well-known climate variation on relatively short timescales, in which the ocean plays a significant role, is the so-called El Niño phenomenon, associated with anomalous warming of the eastern tropical Pacific every 3 to 5 years. This phenomenon has worldwide consequences, e.g., the precipitation pattern over southern Africa and droughts in Indonesia and Australia. It shows that changes in the ocean circulation, combined with a feedback due to wind drift and the heat exchange with the atmosphere, can influence the global climate. Recent climate phenomena with a timescale of several hundreds of years were the Mediaeval Climate Optimum and the Little Ice Age which strongly influenced nature and society. On the long-term side of the climate spectrum, with a typical timescale of hundred-thousand years are the ice ages or glacials, connected with the formation of huge continental ice caps. During the last glacial period the climate was colder than today, but also oscillated rather irregularly between cold and relatively warm periods: the interstadials or Dansgaard–Oescher events (Dansgaard et al. 1982). After the end of the last glacial a significant cooling event occurred during the Younger Dryas, a period of 1,300 years, that abruptly terminated at ~11,640 year before present (BP).

Increased emissions of the greenhouse gases carbon dioxide, methane, and nitrous oxide, due to human activities, may lead to an anthropogenic global warming of the climate. The global mean surface temperature of the atmosphere has increased over the 20th century by about 0.6°C and is expected to lead to an anthropogenic increase in the globally averaged atmospheric surface temperature, estimated to be between 1.4 and 5.8ºC from 1990 to 2100 (IPCC 2001). A consequence of global warming may be a rise in sea level which will inundate many of the present-day population centers. But a slowing down of the deep ocean circulation also is predicted in many climate forecasts.

In the discussions of climate variability and climate change on timescales of several years to thousands of years the effects of the ocean circulation in the climate system play an important role because of the thermal inertia of the ocean's waters. The uppermost few meters of the ocean have the same heat capacity as the entire overlying atmosphere. The ocean therefore can easily drive or damp climatic temperature changes in the atmosphere. The THC, thought to be driven by meridional differences in temperature and salinity, is often considered as the main oceanic climate process. Widespread consequences are ascribed to the shutdown or acceleration of the THC, an oceanographic *deus ex machina* for climate change science (Munk and Wunsch 1998; Wunsch 2002). For the general public the possible shutdown of the THC played a dramatic role in the 2004 blockbuster motion picture “The Day after Tomorrow” by Roland Emmerich. In that movie the shutdown of the THC causes a massive snowstorm to pound New Delhi; tornadoes rip Los Angeles; hail the size of grapefruits batters Tokyo; and in New York City the temperature swings from sweltering to freezing in one day. This disaster scenario, sketched in the movie, is impossible, but the patterns described by the movie have a distant basis in real concepts, studied by climate scientists and oceanographers. In this book I want to discuss: what is the THC; what are its main characteristics and dynamics; and what is its interaction with global climate?

## 1.2. The ocean and climate

The specific heat for dry air at constant pressure, $C_p$, is of the order of 1000 $\mathrm{Jkg^{-1}{}^{o}C^{-1}}$. This value is definitely lower than the $C_p$ of seawater, approximately 4000 $\mathrm{Jkg^{-1}{}^{o}C^{-1}}$. Moreover the density of air near the sea surface amounts to 1.25 $\mathrm{kg/m^3}$, while the ocean water has a density ρ of slightly over 1000 $\mathrm{kg/m^3}$. Because of these differences the heat capacity of the atmosphere over 1 $\mathrm{m^2}$ of the ocean's surface is about equal to the heat capacity per $\mathrm{m^2}$ of the upper 3 m of the ocean. The specific heat of soil and rock is even lower than that of air, nearly 800 $\mathrm{Jkg^{-1}C^{-1}}$. With a typical soil density of 3000 $\mathrm{kg/m^3}$, the heat capacity of the uppermost meter of the earth's soil, where most of the continental seasonal heat storage is located, is about 2.4 $\mathrm{MJm^{-2}{}^{o}C^{-1}}$. Seasonal heat storage in the ocean reaches a typical depth of about 100 m. The ocean surface layer with a thickness of 100 m has a heat capacity of 400 $\mathrm{MJm^{-2}{}^{o}C^{-1}}$, two orders of magnitude larger than the typical heat capacity of the continental soil for seasonal heat storage. The large specific heat of seawater and the enormous mass of the ocean make the oceans a prime moderating factor for rapid climate variations. It certainly will prevent the ocean from cooling by over 10ºC over a matter of days to weeks, as suggested in the movie “The Day after Tomorrow.”

Because of its relatively low heat capacity the atmosphere lacks a thermal memory surpassing a few weeks. For climatic variability with timescales of seasons to hundreds of years the oceanic storage and transport of heat is a dominant factor. A standard explanation for interannual to decadal climate variability is that high-frequency stochastic variations in the atmosphere (the weather) are “integrated” by a slower-reacting ocean. The ocean responds as a stochastically driven oscillator, leading to low-frequency climate variability (Hasselmann 1976). On the timescale of the seasonal cycle (1 year) the transport of temperature anomalies by ocean currents is limited, and the heat stored in summer will be released to the atmosphere in winter in approximately the same geographic region. On this timescale the Hasselmann model may be applied, superimposed on the seasonal cycle. Climate variability caused by this mechanism does not have a preferred timescale or a preferred spatial pattern. The ocean's thermal inertia mainly converts the white noise of the weather forcing into a red spectrum response of the ocean temperature where larger timescales dominate. However, for the observed interdecadal to centennial climate variations preferential spatial and temporal patterns have been found. Therefore, the Hasselmann mechanism cannot fully explain the climate variability on these larger timescales (Te Raa 2003). For climate variations with longer timescales the oceanic circulation may alter the location where heat from a thermal anomaly in the ocean is released to the atmosphere, compared to the location where that heat was stored in the ocean, generating feedback loops in the climate system with preferential patterns and timescales.

Heat, stored in the ocean, can be transported by ocean currents which have discernable climate effects on interannual and longer timescales. Two different circulation modes are generally discriminated in oceanic circulation studies, each with their specific dynamics and timescales. The more or less regular winds over the oceans with easterly trade winds at low latitudes, prevailing westerlies at moderate latitudes and polar easterlies at arctic and antarctic latitudes drive a regular current system in the upper layers (~1000 to 1500 m) of the ocean. The main features of this system are the oceanwide anticyclonic gyres in the subtropics, cyclonic sub-arctic gyres in the North Atlantic and North Pacific oceans, and the Antarctic Circumpolar Current (ACC) in the Southern Ocean. In the equatorial zone a complicated system of surface and subsurface zonal currents is found. The northern Indian Ocean has a deviating current pattern because of the seasonally alternating monsoon winds. In the subtropical and sub-arctic gyres we find narrow and fast western boundary currents and a more diffuse recirculation further east The theory for the main dynamics of this wind-driven circulation is reasonably well understood (Pedlosky 1996). The poleward transport of warmer water and equatorward transport of colder water by the oceanic gyres maintain a meridional heat transport in the ocean. The thickness of the upper ocean layer in which this wind-driven heat transport occurs [O(1 km)] and the typical transport rates of the gyres introduce an inertia in the climate system with a characteristic timescale of the order of decades or tens of years (Nauw 2003).

Even larger timescales for climatic variability, up to hundreds of years or even a few thousand years can be reached by storage and transport of heat whereby the whole oceanic water column with a mean depth of 3700 m is involved. Here the THC is the dominating process. Zonally averaged the THC is a meridional overturning circulation (MOC). Regions of severe surface heat loss to the atmosphere at high latitudes are loosely associated with a downward mass flux of cold water which subsequently spreads at depth to lower latitudes. The downward mass flux is replenished by a poleward transport of warmer water in the upper layers of the ocean. For reasons of mass conservation the deep flow of cold water has to be connected with the upper layers by regions with upward moving deepwater (upwelling). The concept of the THC as a closed global overturning circulation with its main source of cold water in the North Atlantic Ocean and interhemispheric and interocean mass exchange has been sketched by Arnold Gordon (1986).

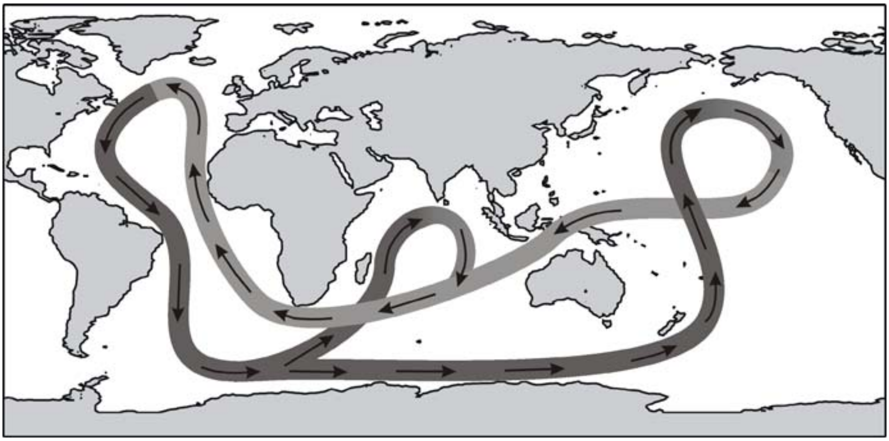

**Fig. 1.1. A schematic picture of the great oceanic conveyor belt with the main source of cold deepwater in the North Atlantic Ocean, introduced by Broecker (1987). As stressed by Broecker (1991, p. 79) "other circulation 'loops' exist in the ocean and mixing occurs among the waters traveling along these intersecting pathways." But although reality is much more complex, this simple scheme drew the attention of many for the thermohaline circulation and its possible importance for the understanding and prediction of climate change.**

This sketch was strongly simplified and popularized in the scheme of the "great oceanic conveyor belt" by Walter Broecker (1987, 1991) with emphasis on the North Atlantic Ocean as source of deepwater (Fig. 1.1). The downward mass flux at high latitudes and the subsequent lateral spreading of deepwater are assumed to be connected with thermal and evaporative forcing at the sea surface by the global atmosphere. The oceanic conveyor belt often is thought to operate like a heat engine, similar to the atmosphere, although a directly convectively driven overturning mass flux is presently thought to be impossible (Wunsch 2002). Contrary to the wind-driven circulation, a profound theoretical understanding of the THC is lacking, and no full general agreement has been reached yet even on the description of some major pathways in this circulation. Note also that in first order the direct effect of the THC is redistribution of heat; it does not change the global mean sea surface temperature. Any effects on the global mean temperature might occur by feedback mechanisms like changing sea ice and clouds which alter the albedo (reflection of short-wave sunlight), or atmospheric $CO_2$ and water vapor that change the atmosphere's opacity to long-wave radiation.

## 1.3. What is the THC?

The concept of the thermohaline circulation often is used in climatological and oceanographic publications. Wunsch (2002) has cited from literature seven different, sometimes inconsistent, and mostly incomplete definitions for the THC. Apparently the oceanographic community uses the THC concept widely, but there is no common understanding what precisely should be the THC circulation scheme or what should be considered as the main driving force for the THC.

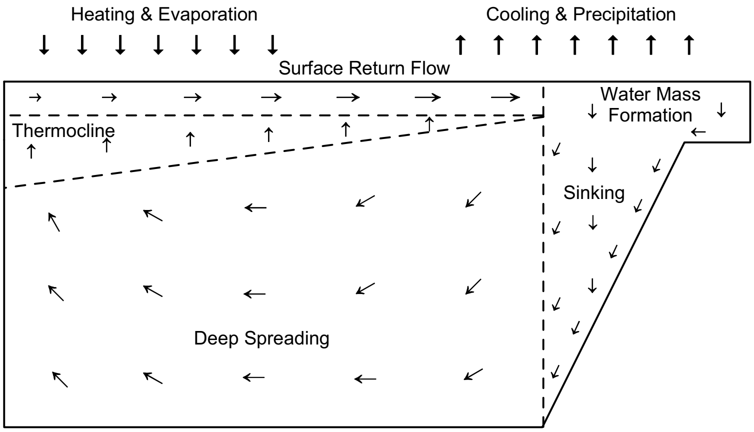


**Fig. 1.2. Sketch of the overturning thermohaline circulation, adapted from Wyrtki (1961) by the inclusion of a shallow shelf sea.**

It is not considered useful to come here with yet another definition of the concept of the global THC. Instead, extending the THC characteristics summed up by Wyrtki (1961), some aspects of the concept of the THC that will be discussed in this book will be emphasized (Fig. 1.2).

- *First*: Due to air–sea interaction in the source regions of deep ocean water, mainly cooling in winter, surface water will gain density (lose buoyancy). Air–sea interaction (cooling, evaporation, and precipitation) already modifies the warm surface currents flowing from the tropics to the source region of deepwater before they arrive there. The resulting decline and even reversal of the static stability of the density stratification in the source region will drive deep-reaching local convective mixing. In deep source regions a thick, homogeneous water mass is formed, while in source regions in shallow shelf seas the whole water column is homogenized.
- *Second*: The newly formed homogeneous high-density water mass descends or subducts into the abyssal ocean in a region with an average downward motion, where the cold water mass loses the possibility of direct contact with the atmosphere. The subduction region is not necessarily the region where the convective mixing and water mass formation takes place.
- *Third*: Hereafter the water spreads horizontally away from its subduction region. The hydrographic properties of this abyssal water mass (temperature, salinity, and natural and man-made tracers) are characteristic for its source region and formation process. The water can be followed along its path while it is (gradually) modified by mixing with surrounding water and biogeochemical aging. Adjustment of the abyssal density field will take place so that the deep flow can be described with the so-called geostrophic equilibrium. The spatial structure of this geostrophic adjustment depends on the locations where the vertical motion takes place, either subduction or upwelling.
- *Fourth*: In some regions of the ocean upwelling of the deepwater to shallower levels will take place whereby, due to turbulent mixing with shallower water, temperature, salinity, and density adapt to the overlying layers of the ocean.
- *Fifth*: The upwelled water returns to the regions where the deep convective mixing takes place. This return flow is not necessarily a simple direct link as suggested by the conveyor belt scheme shown in Figs. 1.1 and 1.2, and occurs for a large part or even completely in the wind-driven upper ocean.

In the last 100 years an increasing mass of so-called hydrographic observations has led to a progressive understanding of the main pathways and dominant processes of the global oceanic THC. The developing theoretical concepts of the ocean circulation have resulted in analytical models of several aspects of the THC. With the availability of electronic computers numerical models of the THC have been developed with different grades of complexity. Experiments with simplified THC models have strongly contributed to our understanding of the variability of climate, coupled to the THC. Advanced numerical ocean general circulation models form an essential part of the present state-of-the-art global climate models that are used for climate analysis and prediction.

The ocean circulation is a physical system, described by conservation equations for heat, salt, momentum, etc. Solutions of these equations depend on boundary equations for heat, freshwater, and momentum at the sea surface and the ocean floor. The boundary conditions at the sea surface are strongly determined by the state of the atmosphere over the ocean. Differences in seawater temperature and salinity, via the equation of state for seawater, are connected with density differences, resulting in pressure forces that determine the water motion. Since changes in the sea surface temperature in their turn will alter the exchange of heat and freshwater (evaporation) with the atmosphere, feedback mechanisms emerge, which may lead to either climate stability or variability of the climate.

To a certain degree the oceanic motion, driven by the stress, exerted by the winds over the ocean (the wind-driven circulation) can be separated from that part of the oceanic circulation that is mainly determined by the density differences, resulting from regional differences in the exchange of heat and freshwater between atmosphere and ocean (the THC). That is not a trivial distinction. Wind-driven ocean circulation may play an essential role for the formation phase of cold deepwater during the so-called preconditioning phase. The shallow surface return flow of the THC will be subject to forcing by the wind stress, thereby coupling the THC to the wind-driven circulation. Finally, the turbulent mixing in the ocean's interior, a process that appears to be essential for the maintenance of the THC, probably depends for a large part on the energy input from variable winds into the ocean.

The THC is a circulation process in the real ocean. That implies that its properties are strongly determined by the actual topography, including continents, undersea ridges, and deep passages. Also the global distribution of wind stress, surface heat, and freshwater fluxes and their seasonal and interannual variation influence the course and intensity of the THC. The THC is a global phenomenon with interhemispheric and interocean exchanges as is sketched in the conveyor belt scheme of Fig. 1.1. Because of the typical vertical stratification of temperature and salinity this mass exchange also involves a large-scale exchange of heat and freshwater between hemispheres and oceans. Better understanding of the THC will lead to a better understanding of climate and may contribute to a more accurate prediction of natural and man-made climate change.

## 1.4. Some historical notes

One of the first indications that water with low temperatures, originating from higher latitudes, can be found at depth in the subtropics, was a report by Captain Ellis of a British slave trader, the Earl of Halifax (Ellis 1751). With a bucket sea gauge, specially designed by Dr. Hales, rector of Teddington (Hales 1751), Ellis measured a temperature of 53ºF (11.7ºC) at a depth of 1190 m near the Azores. Modern measurements suggest that this reading was several degrees Celsius too warm due to warming of the water in the bucket during ascent to the surface (Warren 1981). From then onward subsurface temperature measurements were carried out during the 18th and early 19th century, which although inaccurate established that the ocean at depth generally was much colder than the near-surface waters (Krümmel 1907). This fact, trivial for modern oceanographers, has had profound implications for our understanding of the oceanic circulation. It is indicative of an overturning oceanic circulation which brings cold high-latitude water to the low latitudes. In the second half of the 19th century the minimum–maximum thermometer, devised by James Six in 1785, was fitted with an outer glass tube that protected the mercury bulb against pressure effects. This instrument, known as the Miller–Casella thermometer, became the classic instrument for subsurface temperature measurements, used during the famous worldwide oceanographic surveys by the British Challenger and the German Gazelle. At the end of the 19th century it had become an established fact that most of the ocean waters had low temperatures, derived from cooling at high latitudes. In the early 20th century accurate reversing deep-sea thermometers, since 1878, produced by Negretti en Zambra, came into general use. Already during the Challenger expedition from 1872 to 1876 prototypes of this instrument were used for testing purposes. In the 1970s they were rapidly replaced by electronic temperature sensors.

The concept of an oceanic flow, driven by density differences, was first proposed by the Italian Luigi Ferdinando, Count de Marsigli (1658–1730) with reference to the flow of water through the Bosporus between Asia and Europe. He attributed the existence of an undercurrent from the Mediterranean Sea to the Black Sea to the high density of the Mediterranean water due to an evaporation excess in the latter ocean basin. This hypothesis was substantiated with hydraulic experiments in a tank, filled with water with different densities, separated by a vertical wall. When holes in the wall were opened, the high-density water passed through the lower holes, while the lighter water passed through the upper holes in the opposite direction. Sir Benjamin Thompson, Count Rumford (1753–1814), born in Woburn, Massachusetts, but living in Europe, did careful experiments with regard to heat transfer in water and convective motion in relation with the density of water. He found that salt water, contrary to freshwater, has its highest density at the freezing point. He concluded that "cooled particles of *salt water* descend as soon as they have parted with their Heat, and in moving downwards force other warmer particles to move upwards; and in consequence this continual succession of warm particles which come to the surface of the sea, a vast deal of Heat is communicated to the air." (Thompson 1798, reprinted in 1968, p. 206). From the scarce and inaccurate subsurface temperature measurements which existed around 1800, Thompson derived that there exists a deep meridional temperature gradient, confirming that the deepwater is heated when it spreads from polar to lower latitudes. He assumed that "as its specific gravity is greater than that of water at the same depth in warmer latitudes, it will immediately spread towards the equator, and it must necessarily produce a current at the surface in an opposite direction" (Thompson 1798, reprinted in 1968, p. 209). The warming of the deepwater when spreading toward the equator was assumed to come ultimately from the sun at the warm latitudes. The low temperatures of deepwater in the subtropics were seen as a proof of the deep equatorward motion, while the Gulf Stream was identified as one of the return currents. On the resulting overturning current system Thompson noted that "The vast extent of the ocean, and its great depth, but still more numerous its currents, and the power of water to absorb a vast quantity of Heat, render it particularly well adapted as an equalizer of Heat" (p. 193). These remarkable and colorful insights into the large-scale interaction between the oceans and the atmosphere, the formation of deepwater, and the moderating effect that the oceans have on climate largely have stood unchanged for two centuries (Weaver et al. 1999).

In the 19th century the ideas of Thompson, Count Rumford, were not widely accepted, and it was generally assumed that the temperature of the deep ocean was 4°C, the temperature where freshwater attains its maximum density. Carpenter (1871) again argued that the density of seawater increased with decreasing temperature until the freezing point was reached. Similar to Thompson he advocated that the deep overturning circulation of the Atlantic Ocean was driven by the temperature difference of deepwater between the polar ocean and the equatorial regions. Polar cold, rather than equatorial heat, was assumed to be the *primum mobile* (first mover) of this circulation. He supported his arguments with a model experiment with a long narrow tank of water that was warmed with a hot metal plate at the surface at one side and a block of ice at the other side. Contrary to Thompson, however, Carpenter proposed that not the Gulf Stream but a warm current along the British Isles and Norway toward Spitsbergen formed the warm return flow for this overturning system. Carpenter also noted the consequences of the THC for the climate in western Europe. To substantiate his ideas with a sounder observational basis, he proposed "the systematic prosecution of observations of the temperature and motion of different strata of the ocean as part of the regular duty of the British navy, ..., in the interest of all nations" (Carpenter 1871, p. 87). An accurate description of the temperature distribution in the world ocean was lacking till then, and most descriptions of the THC were based on a far-reaching extrapolation of hydraulic model results and (often ill-founded) theoretical insights, as well as a few inaccurate observations. The following year, on December 21, 1872, the British naval ship HMS Challenger left the dock to survey the world ocean during a 4-year worldwide oceanographic expedition. Many deep temperature measurements were carried out that were interpreted as evidence for flushing of the deep Atlantic and Pacific oceans from antarctic rather than arctic latitudes. The return of that antarctic water from the northern portions of the Atlantic and the Pacific oceans was assumed to be carried by evaporation which was hurried down through the atmosphere to the zone of low barometric pressure in the southern hemisphere (Wyville Thomson 1877).

The Norwegian oceanographer and polar traveler Fridtjof Nansen was able to show from observations, collected in the early 20th century, that in the North Atlantic Ocean cold water also entered the Atlantic Basin over the shallow Greenland–Scotland Ridge, through the Denmark Strait between Greenland and Iceland as well as between Iceland and Scotland (Nansen 1912).

Only with the German Atlantic expedition with the steamship Meteor (Fig. 1.3) a complete and accurate description of the distribution of temperature, salinity, and dissolved oxygen in the deep water masses of the Atlantic Ocean became available. This allowed the German oceanographer Georg Wüst to develop water mass analysis methods in order to explore the spreading of deep water masses involved in the THC. He was able to discriminate different deep water types, originating from both arctic and antarctic latitudes, as well as from the Mediterranean Sea (Wüst 1933, 1935). His results still largely agree with the modern ideas about the Atlantic part of the THC.

**Fig. 1.3. A bow view of the steamship Meteor during the German Atlantic Expedition 1925–1927. Source: Spiess (1928).**

One serious problem remained, regarding the driving of the THC by density differences. This was demonstrated already nearly a century ago by the Swedish oceanographer Sandström (1908), who performed a simple laboratory experiment. In a tank filled with water he introduced a thin heating source and a cooling source. He found that when the heating was at a lower level than the cooling, a vigorous overturning circulation was excited between the two levels. If, on the other hand, they were at the same level at the water surface as in the real ocean, the ultimate stationary circulation was very weak and was confined to a thin near-surface layer. Thus, there would exist a significant flow only in a thin layer just below the surface, driven by molecular heat conduction. The rest of the ocean would be filled with stagnant cold water. Understanding of the role of turbulent mixing in the maintenance of density gradients was required to solve the apparent paradox, suggested by the experiments of Sandström.

## 1.5. The following chapters

The THC and its properties, kinematics, dynamics, and variability are presented in the following 11 chapters. In Chapter 2 the geography of the ocean basins is treated, with emphasis on the main topographic features, continents, ridges, and basins, that influence and guide the THC. Chapter 3 is devoted to the physical characteristics of seawater that are relevant to the THC, e.g., temperature, salinity, density, and specific heat. This chapter also contains a simple outline of the ocean dynamics used in following chapters. Chapter 4 has a dual purpose. The tracer methods for the hydrographic analysis of the THC in the deep ocean are introduced, while their use is illustrated with the description of the water masses in the deep Atlantic Ocean. These water masses are involved in the cold deep branch of the THC. This hydrographic description is continued in Chapter 5 for the water masses in the deep Southern, Indian and Pacific oceans. In Chapter 6 the hydrographic evidence for the return flow to the North Atlantic is presented, following the routes from the Pacific Ocean via the Bering Strait, the Indonesian through-flow, the Agulhas leakage, and via Drake Passage. The formation of high-density water masses in the arctic and antarctic seas and their descent into the abyssal ocean are discussed in Chapter 7. In Chapter 8 the dynamics that determine the horizontal structure of the (deep) flow in the abyssal basins are introduced, focused on the Stommel–Arons model for the abyssal circulation and observational evidence for this structure is discussed. The existence of deep boundary currents is an essential result of that theory, confirmed by observations. Attention also is given to the wind-driven upwelling. The role of turbulent mixing in determining the vertical hydrographic structure is explained in Chapter 9, as well as the energy requirements to maintain the turbulent mixing, following the abyssal recipes formulated by Walter Munk. Chapter 10 on energetics of the THC is devoted to the transport of heat and freshwater by the THC, including the air–sea exchange. Attention is given to the thermodynamic properties of the THC as a heat engine, leading to Sandström's theorem for the overturning circulation. This theorem states that the THC cannot function without an additional energy source that maintains the turbulent mixing in the ocean. Simple one- and two-dimensional analytical models for the THC are presented in Chapter 11, including the boundary conditions for such models that may lead to different types of feedback via the atmosphere, generating variability in the THC. The possible existence of multiple equilibria in the THC is a result of some of these simple models. Finally in Chapter 12 studies of climate variability involving changes in the THC are introduced, as well as paleoceanographic methods that are used to study the variability of the THC in the past. Changes in proxies for several hydrographic parameters show that during glacials the THC differed from the present situation, although the interpretation of such proxy data appears not to be straightforward.

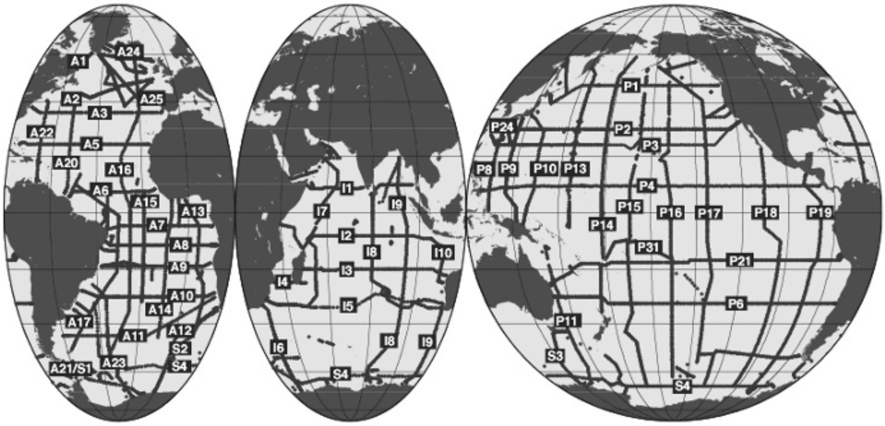


**Fig. 1.4. Hydrographic sections for the WOCE Hydrographic Program one-time survey. Additional to these sections there are repeatedly surveyed hydrographic sections, XBT sections, current meter mooring arrays, satellite observations, surface drifters, subsurface floats, and tidal stations. Source: http://woceatlas.tamu.edu/Sites/html/atlas/SOA_WOCE.html.**

In this book many examples of hydrographic observations are presented as an illustration of the characteristics of the THC. Most of these data were collected during the hydrographic program of the World Ocean Circulation Experiment (WOCE) in the 1990s (Fig. 1.4). The data from the hydrographic surveys were downloaded from the website of the former WOCE Hydrographic Program Office at the Scripps Institution of Oceanography, presently the CLIVAR and Carbon Hydrographic Data Office (http://cchdo.ucsd.edu/). The current meter data were collected from the site of the Buoy Group of the Oregon State University (http://kepler.oce.orst.edu/), while the data on the drift of subsurface floats were downloaded from the WOCE Subsurface Float Data Assembly Center at the Woods Hole Oceanographic Institution (http://wfdac.whoi.edu/). Other data sources are mentioned in the text or in the figure captions. The reader is encouraged to visit these sites and download oceanographic data for practice and further analysis.

# 2. The ocean basins

## 2.1. The bottom topography of the oceans

The oceans cover over 70% of the earth with a relatively thin layer of water. The earth is a slightly flattened sphere with an effective radius of 6371 km. On this sphere topographic relief is present which forms continents and deep basins; the latter contain the oceans. Within the oceans the currents in the upper 1000 to 1500 m are mainly driven by wind stress at the sea surface. The deep cold branch of the THC, below the wind-driven layer, is for a large part constrained and guided by the topography of the ocean basins and their interconnections.

Much information on the earth's relief can be found in global gridded relief data sets, available from the US NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/mgg/global/global.html). Examples are the ETOPO-5 earth's relief data set with a spatial resolution of 5'×5' (Anonymous 1988) or more recently the ETOPO-2 data set (Smith and Sandwell 1997; Jakobsson et al. 1999) with a horizontal resolution of 2'×2'.

The topographic range of the earth's relief, derived from the ETOPO-5 data set, is about 20 km (Fig. 2.1). The topographic range of the ocean bottom alone is of course smaller, about 11 km, or 0.17% of the earth's radius. The distribution of the relief height of the earth is bimodal, with a high cluster representing the continents including the shelf seas and a low cluster that represents the ocean basins. The mean depth of the ocean basins amounts to 3700 m, only 0.06% of the earth radius. The "aspect ratio" (ratio of the characteristic vertical and horizontal scales) of the ocean has a value of less than 0.1%. For illustration, the earth shrunken to the size of an orange with a diameter of 10 cm would have an ocean with a mean depth of only 29 μm. So the ocean is extremely flat, and therefore the motion of the ocean is often assumed to be two-dimensional in a horizontal plane. But despite the topographic flatness of the ocean, the vertically overturning circulation of the THC plays a major role on the stage of the global climate.

Whereas the ocean occupies 72% of the earth surface ($3.7\ 10^{14}\ m^2$) only 80% of the ocean is deeper than 2500 m ($2.9\ 10^{14}\ m^2$). The rest of the ocean is shelf sea or continental slope. Only this deep 80% of the ocean can participate in the deep circulation of the THC. The total volume of this deep part of the ocean amounts to $1.3\ 10^{18}\ m^3$.

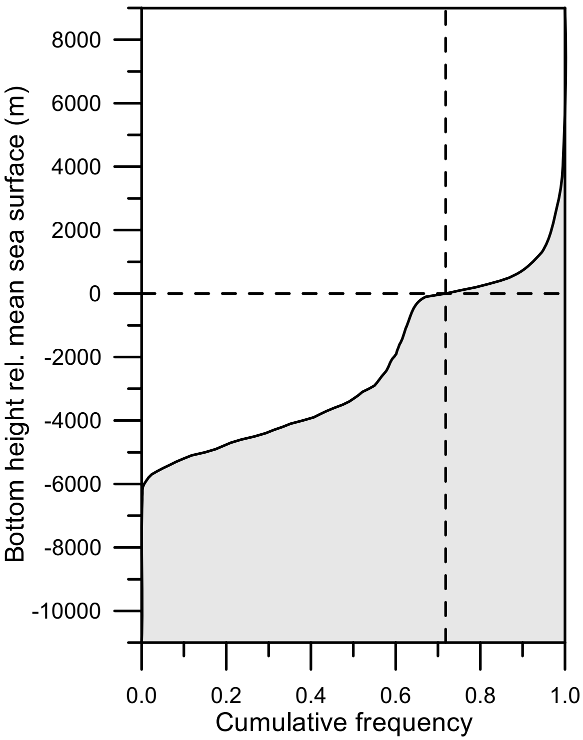


**Fig. 2.1. The cumulative frequency of the earth's relief height, relative to the mean sea surface. This frequency distribution has been derived from the ETOPO-5 global relief data set.**

## 2.2. Basins and ridges

The ocean floor displays a rich variation in topography, from isolated sea-mounts to the global system of mid-ocean ridges. The topography of the ocean basins or the bathymetry (Fig. 2.2) constrains several aspects of the ocean circulation.