Marine Climate and Climate Change

Storms, Wind Waves and Storm Surges

Ralf Weisse and Hans von Storch

Marine Climate and Climate Change

Storms, Wind Waves and Storm Surges

Springer

Published in association with
Praxis Publishing
Chichester, UK

Dr Ralf Weisse and Professor Dr Hans von Storch
GKSS Institute for Coastal Research
Geesthacht
Germany

SPRINGER–PRAXIS BOOKS IN ENVIRONMENTAL SCIENCES
SUBJECT *ADVISORY EDITOR*: John Mason, M.B.E., B.Sc., M.Sc., Ph.D.

ISBN 978-3-540-25316-7 Springer-Verlag Berlin Heidelberg New York

Springer is part of Springer-Science + Business Media (springer.com)

Library of Congress Control Number: 2009933600

Cover design: Jim Wilkie
Project management: OPS Ltd, Gt Yarmouth, Norfolk, UK

Printed in Germany on acid-free paper

Contents

Preface

Having been involved for more than 15 years in wind, wave, and storm surge research, we have been in contact with many people having different interests in these topics. Most of them were seeking long time series of data over the often poorly sampled coastal, offshore, and ocean regions. We have collaborated with a shipyard developing RoRo and RoPax ferries operating on fixed routes. Environmental conditions such as sea states or currents to be expected on these routes during the lifetime of a vessel to them was a critical issue. Companies involved in the design and operation of offshore wind farms were interested in extreme sea states and loads to be expected at their sites, but also in the frequency and duration of fair-weather windows that can be used to mount or to maintain their equipment. Oil and gas producers were concerned about possible future changes in the wind, wave, and storm surge climate because they wish to guarantee present safety levels for their platforms and equipment in the future as well. And, of course, coastal engineers were asking for statistics of sea level extremes to be used for coastal protection planning.

Despite the different interests, long time series of wind, waves, or water levels were of primary importance to all of them. Over the oceans, such data are seldom available and often data from computer models are used instead. We have been involved in the development of such computer-generated data for many years and we know that there are numerous pitfalls in the use of these data. We feel that a thorough understanding of the basics and principles behind such data can help in successfully applying them and in improving their benefits. This book therefore provides an introduction to the climate system and to climate variability. It describes and discusses high-impact marine weather phenomena such as tropical and extra-tropical cyclones, wind waves, tides, storm surges, and mean sea level. The book further provides an overview about computer models used for simulating these phenomena, discusses their use for generating computer data that are, in many cases, used as a replacement for the often limited or missing measurements, and illustrates the numerous pitfalls one may encounter in applying such data. Eventually, we review what presently (as of early 2009) is known about past and future marine climate change and variability.

In more detail, Chapter 1 provides an introduction to climate and climate variability. It explains the concepts that are fundamental for our understanding of the functioning of the system and its fluctuations. Emphasis is put on the concept of different scales and their interplay, as well as on externally and internally driven climate variability.

Chapter 2 introduces in detail the high-impact marine weather phenomena this book is about. We begin with an introduction to mid-latitude storms and storm tracks, followed by a discussion of tropical cyclones. Subsequently, we also consider the impacts caused by these phenomena; namely, wind-generated waves at the sea surface (the sea state) and storm surges. Tides and mean sea level are also included as they may contribute to extreme sea levels.

Chapter 3 provides an overview of models used for simulating the marine environment. We focus on quasi-realistic models; that is, complex computer models that describe reality as much as possible and that are used as a reality substitute. The latter means that these models are employed to derive data; namely, data that have not been measured. This is done by blending models and the few existing data. The better the existing data and the more advanced the blending techniques and the models, the better the model data. However, there is usually a number of problems involved in all models, blending techniques, and existing data.

Chapter 4 deals with problems associated with such data and present techniques to assess long-term changes in marine climate. It first describes to some extent problems related to data quality and the risk for making wrong inferences when problems are ignored. Subsequently, approaches are introduced to reduce data quality problems. These comprise the use of proxy data and reanalyses. Of course, both approaches pose new problems that are discussed in some detail. Chapter 4 is also about the techniques required to assess long-term changes in marine climate. Regionalization techniques are discussed that are used to obtain information at regional and local scales from global or large-scale data. Such techniques are needed, for instance, when local data are limited but coarse-grid or large-scale data are available. Again, different approaches exist, each with its advantages and disadvantages. Scenario and projection techniques are used when potential future changes are considered. They are used widely in marine and climate science and usually address problems of the type "What ... if ...?". For example, what will happen to storm surges in the North Sea when the statistics on North Atlantic extra-tropical cyclones change? Or, what will happen to the height of storm surges in Hamburg, Germany, if dredging in the River Elbe is continued? Chapter 4 concludes with an introduction to detection and attribution techniques. Detection refers to techniques that identify ongoing changes, while attribution is used to associate causes with the changes.

Chapter 5 provides an overview of the state of knowledge of past and future marine climate change and variability. The view presented is a snapshot as of early 2009, when this chapter was completed. Apart from specifically discussing changes in tropical and extra-tropical cyclone statistics, wind waves, and water levels, there is a brief discussion on the role of consensus in science and on uncertainty assessment in climate change projections.

The book is aimed at professionals in many fields, including coastal and offshore engineers, atmospheric and oceanic researchers, and perhaps coastal and offshore planners. It will also inform and be of interest to authorities and administrations involved in marine issues. Further, the book is suitable for graduate courses on climate for atmospheric, oceanic, and environmental sciences.

ACKNOWLEDGMENTS

Starting the book was easy, arriving at the final product was not. It actually took us significantly more time than originally scheduled. We are grateful to Praxis Publishing and to Clive Horwood for their patience with us. Neil Shuttlewood applied his professional editorial skills to the project; Beate Gardeike's computer and artistic skills greatly enhanced the figures in this book. Their efforts greatly improved the quality of the final product. We are particularly grateful to Heinz Günther for his helpful comments on various drafts of the wave and wave-modeling sections. Thanks also to Nikolaus Groll for his comments on the manuscript.

Many people provided graphics and/or permission to reproduce their figures. We are particularly grateful to, in alphabetical order, Lars Bärring (Lund University), Denis Bray (GKSS Research Center), John Church (CSIRO, Australia), Ulrich Cubasch (Freie Universität Berlin), Krzysztof Fortuniak (University of Lodz), Sverre Haver (Statoil), Peter Höppe (Munich Re), Hans-Jörg Isemer (GKSS Research Center), Slava Kharin (University of Victoria), Wolfgang Koch (GKSS Research Center), Christopher Landsea (NOAA), Susanne Lehner (German Aerospace Agency), Kam-biu Liu (Louisiana State University), Uwe Mikolajewicz (Max-Planck-Institute for Meteorology), Andreas Plüß (Federal Waterways Research and Engineering Institute), Ricard Ray (NASA), Konstanze Reichert (OceanWaves GmbH), Burkhardt Rockel (GKSS Research Center), Elke Roßkamp (German Weather Service), Michaela Sickmöller, Matthias Tomczak (Flinders University), Xiaolan Wang (Environment Canada), Jörg Winterfeldt (GKSS Research Center), and Friedwart Ziemer (GKSS Research Center).

Permission to reproduce copyrighted material is greatly acknowledged and has been obtained from the American Geophysical Union, the American Meteorological Society, the European Center for Medium-range Weather Forecast, the German National Weather Service, the Intergovernmental Panel on Climate Change (IPCC)/Cambridge University Press, the National Oceanic and Atmospheric Administration (NOAA), the United Nations Environment Program (UNEP)/GRID Arendal, the World Meteorological Organization (WMO), *Nature*, Springer-Verlag, Elsevier, and Wiley–Blackwell Publishing.

Figures

Tables

Abbreviations and acronyms

3DVAR	Three-Dimensional Variational Data Assimilation
4DVAR	Four-Dimensional Variational Data Assimilation
ACC	Antarctic Circumpolar Current
ACE	Accumulated Cyclone Energy (index)
AMO	Atlantic Multidecadal Oscillation
AMS	American Meteorological Society
BALTIMOS	BALTIc MOdel System
CaRD10	California Reanalysis Downscaling at 10 km
CDAS	Climate Data Assimilation System
CERFACS	Centre de Recherche et de Formation Avancée en Calcul Scientifique
CRIEPI	Central Research Institute of Electric Power Industry
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DNMI	Norwegian Meteorological Office
DOE	Department Of Energy
ECHAM5	Global climate model developed by the Max-Planck-Institut für Meteorologie, Hamburg, Germany
ECMWF	European Center for Medium-range Weather Forecast
EOF	Empirical Orthogonal Function
ERA	ECMWF Reanalyses
ERS	European Remote Sensing Satellite
FNOC	Fleet Numerical Operational Center
GCM	General Circulation Model
GECCO	German part of Estimating the Circulation and Climate of the Ocean effort
GFDL	Geophysical Fluid Dynamics Laboratory
GIA	Glacial Isostatic Adjustment

GKSS	GKSS Research Center
GODAS	NCEP Global Ocean Data Assimilation System
GP	Genesis Potential (tropical cyclone)
HadAM3	Hadley Centre Atmosphere Model
HAMSOM	Hamburg Shelf Ocean Model
INGV	Instituto Nazionale di Geofisica e Vulcanologia
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
JCDAS	JMA Climate Data Assimilation System
JMA	Japan Meteorological Agency
LAM	Limited Area Model
MOC	Meridional Overturning Circulation
MPI	Maximum Potential Intensity
NARR	North American Regional Reanalysis
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
OI	Optimal Interpolation
PDI	Power Dissipation Index
POL	Proudman Oceanographic Laboratory
RCAO	Regional Coupled Atmosphere Ocean (model)
RCM	Regional Climate Model; Regional GCM
SAR	Synthetic Aperture Radar
SLP	Sea Level Pressure
SODA	Simple Ocean Data Assimilation
SRES	Special Report on Emissions Scenarios
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
SWAN	Simulating Waves Nearshore
TELEMAC2D	A two-dimensional hydrodynamic model
THC	Thermohaline Circulation
TRIM3D	Tidal, Residual, and Intertidal Mudflat Model
UKFOAM	U.K. Forecasting Ocean Assimilation Model
VOS	Voluntary Observing Ship
WAM	Third-generation wave model developed by a group of European wave modelers
WAMOS	Wave Monitoring System based on nautical radar
WASA	Waves and Storms in the northeast Atlantic (EU project)
WAVEWATCH	Third-generation wave model developed at NOAA/NCEP
WMO	World Meteorological Organization
XBT	eXpendable Bathy-Thermograph

1

Climate and climate variability

1.1 INTRODUCTION

In the following we describe some basic concepts that are fundamental for understanding (marine) climate and climate variability. We begin with a brief historical review on earlier and more modern concepts of climate and subsequently define *marine weather* and *marine climate* as used throughout the remainder of this book (Section 1.2). In Section 1.3 an overview of the present understanding of the global climate system is provided. In particular, the components of the climate system and the general circulations of the atmosphere and the oceans are addressed. We further show that the planetary-scale features of atmospheric circulation may be determined without any knowledge on regional details. In Section 1.4 concepts for understanding observed climate variability are discussed. Here emphasis is put on internally driven climate variability, in particular on the concept of stochastic climate models. This concept is considered to be fundamental for understanding observed climate variability ranging from several months to hundreds of years. We conclude with a discussion of the interplay between large-scale[1] climate and regional-scale climate. It is shown that there are some large-scale constraints that may be used to describe regional climate variations in terms of large-scale changes. Also, feedbacks of the regional on the large scale are discussed. It is demonstrated that in general the *details* of regional climate are unimportant, while its *statistics* indeed do matter for realistically modeling the observed climate.

1.2 DEFINITION OF CLIMATE

The word *climate* is originally deduced from the Greek *climatos* meaning *tilt* or *declination*. It refers to the fact that the average weather conditions at a specific place

[1] For the concept of scales see Appendix A.1.

depend largely on the angle of incidence of incoming solar radiation. It was originally used to distinguish between the *regional* aspects of the average weather conditions; for instance, between tropical and polar climates (von Storch *et al.*, 1999). In earlier times the term *climate* was mainly associated with the near-surface atmospheric parameters that had a noticeable influence on human well-being such as near-surface temperature, humidity, or surface pressure (Humboldt, 1845). Köppen (1923) defined climate as "the average weather conditions and their evolution in time[2] at a specific place" and developed a classification scheme primarily based on latitude, surface temperature, and precipitation.

In the last few decades the concept of climate has considerably broadened. It was recognized that oceans, ice sheets, and the land surface strongly interact with the overlying atmosphere and have a profound influence on average weather conditions. Nowadays they are considered therefore as components of the *climate system* (see Section 1.3). Also the fact that the climate of a specific place is not constant but itself can vary over time became more and more acknowledged. By the year 2000, the American Meteorological Society (AMS) defined climate as "the slowly varying aspects of the atmosphere–hydrosphere–land surface system" (Glickman, 2000). The definition of the Intergovernmental Panel on Climate Change (IPCC) reads: "Climate in a narrow sense is usually defined as the 'average weather', or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system" (Solomon *et al.*, 2007).

Within this book we are engaged with the *marine* aspects of weather and climate. While weather is often defined as "the state of *atmosphere*[3]" (Glickman, 2000), the state of the *oceans* associated with atmospheric conditions is usually not considered. Within this book we therefore use the term *marine weather* to refer to the state of the atmosphere and the corresponding state of the oceans. The term *marine climate* is defined as the statistical description of marine weather in terms of mean and variability, following the IPCC's concept for the definition of climate.

In its broader sense marine climate covers many aspects such as the statistics of ocean temperature and salinity, ocean circulation, or atmospheric conditions. This book is about some components of marine climate, namely the statistics of phenomena such as tropical and extra-tropical marine storms,[4] wind-generated waves at the sea surface (the sea state), or storm surges. In other words, this book is about *high-*

---

[2] Here only the annual course of long-term averages is referred to, in contrast to the variability of long-term averages themselves (climate variability).

[3] Here the term state refers to past, present, or future conditions of temperature, humidity, precipitation, cloudiness, wind, etc.

[4] That is, that part of the life cycle that is occurring over the oceans; in other words, before landfall.

impact aspects of marine climate. In the following we use the terms *marine weather* and *marine climate* to refer to these high-impact aspects only.

1.3 THE CLIMATE SYSTEM

1.3.1 Components of the climate system

While for many years climate was usually associated with the state of the atmosphere, the concept has considerably changed in the recent past. Nowadays the term climate generally refers to the state of the *climate system* consisting of the atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere (Glickman, 2000). Here the hydrosphere consists of all water in the liquid phase distributed over the Earth, including the oceans, lakes, rivers, and subterranean water; the cryosphere comprises ice and snow on the Earth's surface including the major ice sheets of Greenland and Antarctica, other glaciers, permafrost, and sea ice; the lithosphere refers to the solid Earth—that is, the continents and the ocean floor; while the biosphere is made of the terrestrial and the marine flora and fauna (Figure 1.1, see color section).

While in many climate studies there is still a predominant interest in the state of the atmosphere, the climate system concept now explicitly acknowledges the fact that processes within and interactions among the different climate system components may have a profound impact on the climate and hence the state of the atmosphere. For instance, incoming solar radiation is larger in the tropics than in polar regions. This differential heating needs to be balanced by a poleward meridional heat transport in order to maintain quasi-stationary climate conditions. Figure 1.2 shows that this transport is accomplished not solely by the atmosphere, but that a substantial fraction is provided also by the oceans. While the atmosphere in principle dominates in mid- and high latitudes, most of the transport in low latitudes is accomplished by the oceans.

The state of the climate system is not constant but varies as a result of externally forced and internally driven variations. The distinction between the two sources is not always very clear. Usually the phrase *externally forced* refers to all variations in the climate system that are caused by external factors which are not affected by the climatic variables themselves. This comprises changes in Earth's orbital parameters or solar variations. Climate variations caused by changes in terrestial forcings—for instance, radiative relevant variations in atmospheric composition such as those caused by major volcanic eruptions or by human activity—are usually also considered as externally forced variations. Internally driven variability may be caused by internal instabilities, interactions, and feedbacks within the climate system. We will return to these issues in more detail in Section 1.4.

The components of the climate system are characterized by different *time scales*;[5] that is, the time different components need to adopt to a perturbation differs. As a

---

[5] See Appendix A.1 for a discussion of the concept of scales.

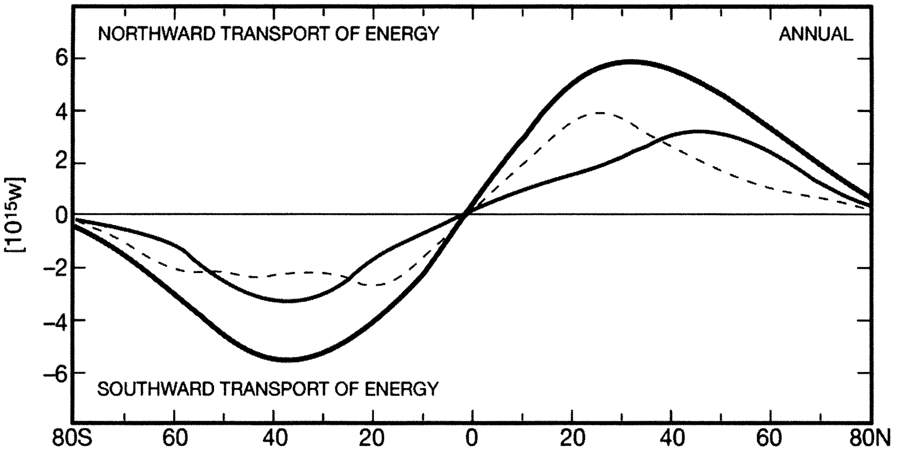


Figure 1.2. Mean zonally averaged meridional heat transport. Ocean (dashed); atmosphere (solid); ocean and atmosphere combined (heavy solid line). Redrawn after data from Peixoto and Oort (1992).

consequence the time it takes for different components to exert a noticeable influence on the climate system also varies. For instance, the lithosphere possesses the longest time scale and the slowest response within the climate system. For the phenomena and processes considered in this book such processes may therefore be treated as constant. Similarly, variations in the biosphere can be neglected. Processes in the hydrosphere, the atmosphere, and the cryosphere and their interaction are, however, essential. From these sub-systems, atmosphere and ocean are most relevant. They will be discussed in more detail next.

1.3.2 General circulation of the atmosphere

In its broadest sense the term *general circulation* refers to the *statistics* of atmospheric motions at the *planetary scale*[6] (Glickman, 2000). A simplified sketch and an intuitive approach are provided by two numerical experiments.[7] In the first experiment Fischer *et al.* (1991) used a general atmospheric circulation model[8] in which the Earth was entirely covered with water (aqua planet). Sea surface temperatures (SSTs) were prescribed such that warmer temperatures prevail near the equator and colder temperatures occurred near the poles. The initialized SSTs were zonally symmetric; in other words, there were no temperature variations along each latitude belt. At the top of the atmosphere, incoming solar radiation was prescribed. The atmosphere was

---

[6] These are large-scale motions with typical dimensions in the order of 1,000 km (see Appendix A.1).

[7] These are experiments with quasi-realistic models of the atmosphere by means of which otherwise impossible experiments can be conducted (see Chapter 3).

[8] A global atmosphere model with a typical horizontal grid spacing of about 250 km–500 km. For details see Chapter 3.

motionless (at rest) at the beginning of the experiment. When the experiment was started, the atmosphere remained mainly motionless for about the first ten days apart from some small motions near the equator (Figure 1.3). Starting at Day 10 a rapid development can be inferred during which typical features of global mean atmospheric circulation emerge from the initially motionless background: First, tropical cells and the trade wind system are visible. Another ten days later indirect Ferrel cells with westerly and northerly near-surface winds appear. Vaguely, also a polar cell can be inferred. Kinetic energy distribution (Figure 1.3c) shows that turbulent motions first show up near the equator from where they move to their observed locations at mid-latitudes within about ten days. The circulation obtained after about one or two months corresponds rather closely to the observed global mean circulation.

In an earlier experiment Washington (1968) used a similar atmosphere model but prescribed a realistic land–sea distribution and topography. Again the experiment started from an initially motionless atmosphere and was driven by incoming solar radiation at the top of the atmosphere. As in the experiment of Fischer *et al.* (1991) a realistic planetary-scale circulation emerged within a couple of days, but in addition an imprint of the land–sea distribution and the topography on the circulation can be inferred (Figure 1.4). After about 40 days or so a characteristic macro-turbulent structure in the mid-latitudes of both hemispheres has developed, while low pressure gradients prevail in the tropics.

Three lessons can be learned from these experiments:

1. *Incoming solar radiation and differential heating*[9] *are the main drivers of planetary-scale atmospheric circulation.* The atmosphere represents a thermodynamic system that constantly receives and re-emits energy and transforms incoming thermal energy into mechanical energy in the form of winds in the atmosphere and currents in the ocean. Eventually, the mechanical energy provided is dissipated to thermal energy by turbulent processes and re-radiated into space.
2. *Globally averaged features of atmospheric circulation defined as the arithmetic mean of many local features may be determined directly without knowledge on local details.* The basic features of planetary-scale atmospheric circulation emerge from a state at rest within a couple of days. Regional details such as topography, land–sea distribution, or land use are unimportant for these features to evolve. Also, major features of the general circulation of the atmosphere such as tropical meridional cells or mid-latitude jet streams associated with baroclinic instabilities and the formation of storms can be simulated well for a planet entirely covered with water.
3. *Land–sea distribution as well as the largest mountain ranges such as the Himalayas, the Rocky Mountains and the Andes modify the global-scale features of atmospheric circulation.* When these features are taken into account a more realistic picture of planetary-scale circulation emerges (Figure 1.4). Their impact can already be described by low-resolution general circulation models.

[9] Difference in incoming solar radiation between the poles and the equator.

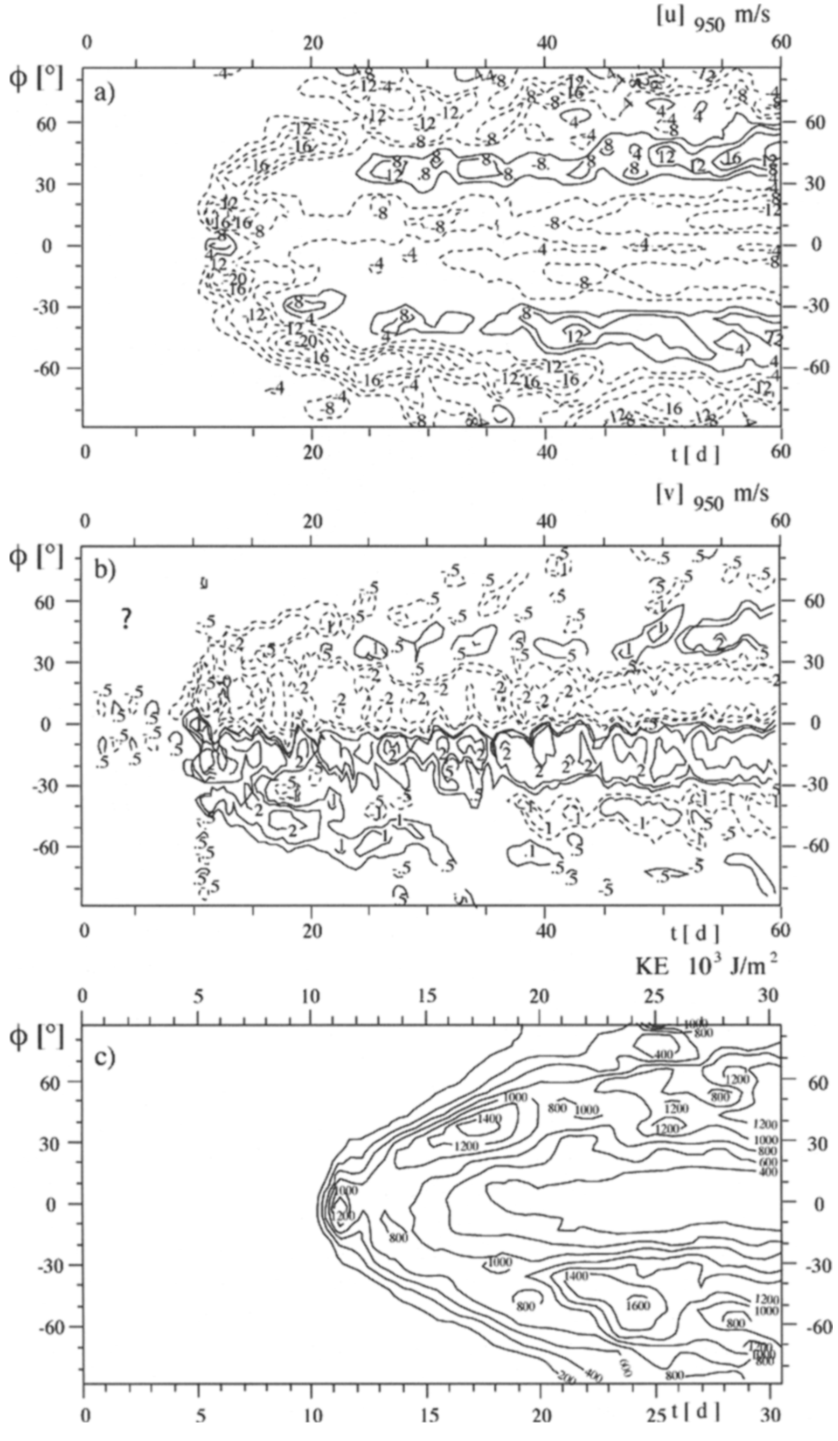
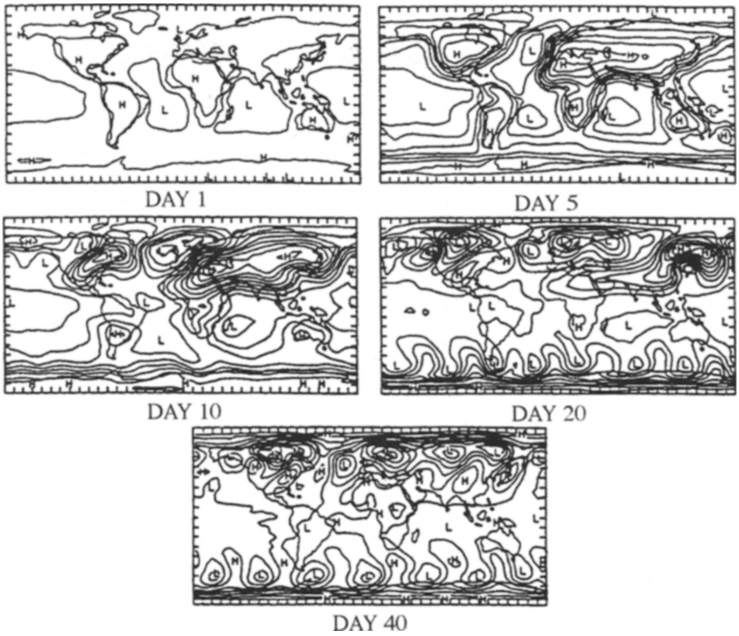


Figure 1.3. General circulation of the atmosphere emerging from an isothermal state at rest on an aqua planet. Zonal (a) and meridional (b) wind speed at 950 hPa in $\mathrm{m\,s^{-1}}$ and kinetic energy of the disturbances (c) in $10^3\,\mathrm{J\,m^{-2}}$. All variables are shown as zonal averages. Note the different scales on the time axis. Redrawn after Fischer *et al.* (1991).



DAY 1 DAY 5 DAY 10 DAY 20 DAY 40

Figure 1.4. General circulation of the atmosphere emerging from an isothermal state at rest on a planet with realistic topography and land–sea distribution. Shown are sea surface pressure fields after 1, 5, 10, 20, and 40 days after initialization of the experiment. Redrawn after Washington (1968).

Global mean circulation as obtained from the two experiments is schematically sketched in Figure 1.5. Air warming over equatorial regions initially rises and subsequently moves poleward at higher altitudes. During its poleward propagation the air is cooling and parts of it are descending to the surface. In both hemispheres the latter occurs near 30° latitude where near-surface high-pressure systems are formed. When the descending air reaches the surface, parts of it are re-circulating equatorwards forming the so-called *trade wind* systems. The remaining part propagates poleward. Similarly, cold air is descending over the poles and propagating equatorwards. At about 60° latitude the surface branches of both air flows meet and the converging air is forced to rise.

As a result of this interplay, three meridional overturning cells can be inferred: the tropical cell is usually referred to as the *Hadley cell* while the mid-latitude cell is known as the *Ferrel cell*. The Hadley and the polar cells are both directly (thermally) driven cells, while the Ferrel cell represents a dynamical consequence of the existence of Hadley and polar cells. The surface branches of Hadley cells form the trade wind patterns. Their convergence zone is located in the tropics and is generally referred to as the *intertropical convergence zone*. Similar to the subtropics horizontal near-surface wind speeds are on average not very strong because the predominant air motion is vertical and horizontal temperature differences are small. Without horizontal temperature differences, however, there is little horizontal pressure gradient resulting in low wind conditions. The situation is different for the region where the cold surface branch of the polar cell meets the moderate temperate air provided by Ferrel cells. Here strong meridional temperature and pressure gradients occur and result in strong

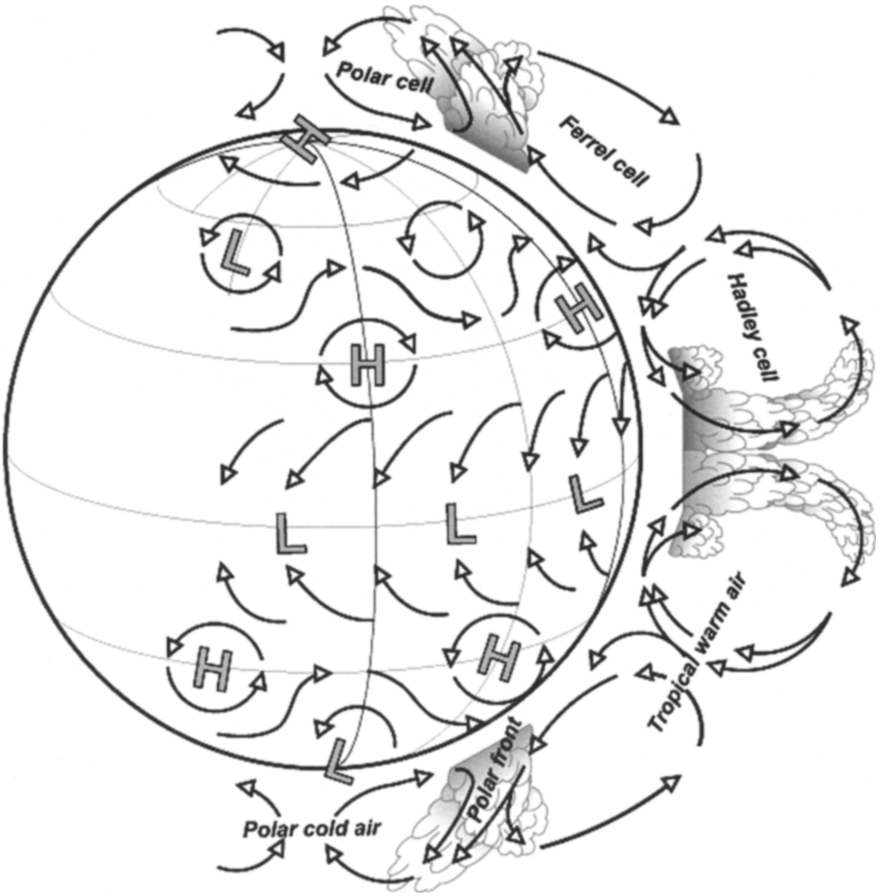


Figure 1.5. Schematic diagram of the general circulation of the atmosphere. Surface high- and low-pressure systems are indicated by the letters H and L; arrows over the globe indicate surface winds; arrows on the right-hand side indicate circulation in meridional overturning cells.

westerly winds. These regions are characterized by unsteady but statistically quasi-stationary states with short-term baroclinic disturbances; that is, synoptic weather systems such as extra-tropical low-pressure systems.

1.3.3 General circulation of the oceans

Traditionally, in oceanography circulation is divided into a wind-driven and a density-driven part. The latter was frequently referred to as thermohaline circulation (THC). Nowadays the phrase meridional overturning circulation (MOC) is used more often. The observed circulation is, however, not simply the sum of these two parts. Instead, more or less complex interactions may occur. For instance, wind-driven circulation may modify density patterns which in turn influence density-driven circulation. In general it can be stated, however, that wind-driven circulation is strongest at the surface while the density-driven part dominates at depth. In the following we briefly review mean wind and mean density-driven circulation. Also meridional heat transport provided by the ocean circulation is briefly discussed.

Wind-driven circulation. Wind-driven circulation is forced by the transfer of momentum from the atmosphere to the ocean surface. As a result, it dominates at the surface and in the upper layers of the oceans. The processes at the air–sea interface are described to some extent in Section 2.5.1. More details can be found in textbooks such as Apel (1987).

Figure 1.6 shows a schematic sketch of mean wind-driven circulation at the ocean surface. The most noticeable features are large clockwise circulation patterns in the North Atlantic and the North Pacific, as well as anticlockwise circulation patterns in the Southern Hemisphere. In all cases the circulation patterns are anticyclonic and coincide with the position and structure of atmospheric subtropical high-pressure systems, although some displacement and asymmetry can be inferred. In particular, strong poleward currents occur on the western boundaries of the gyres while a weaker and broader return flow occurs on the eastern boundaries. The gyres are generally more pronounced in the Northern than in the Southern Hemisphere. In the Southern Hemisphere a strong circumpolar current system is noticeable. It is referred to as the Antarctic circumpolar current and owes its existence to the absence of continental barriers in the extra-tropical west-wind zone of the Southern Hemisphere.

The strong poleward currents on the western boundaries are called *western boundary currents.* In the Northern Hemisphere they comprise the Gulf Stream in the North Atlantic and the Kuroshio in the North Pacific. The Brazil current and the Agulhas stream represent their less pronounced counterparts in the Southern Hemisphere. Eastern boundary currents are the California and the Peru current in the Pacific, the Canary and the Benguela current in the Atlantic, and the Leeuwin current on the western side of Australia (Figure 1.6).

Western boundary currents transport warm water from the tropics to the mid-latitudes while eastern boundary currents are associated with the equatorward transport of cold water. As a consequence the currents have an effect on the regional distribution of sea surface temperatures (SSTs). They cause a zonal asymmetry with above-average SSTs[10] at the mid- to high latitudes on the eastern side of the ocean basins which are under the influence of western boundary currents, and below average SSTs in areas where eastern boundary currents prevail (Figure 1.7).

Another, but similarly important source for observed zonal temperature anomalies is atmospheric advection. In the mid-latitudes the prevailing wind direction is from the west to the east which, in winter, brings relatively mild air masses that have been in contact with a relatively warm ocean to, for instance, Europe. On the other side of the Atlantic, the U.S. East Coast is, however, mainly under the influence of relatively cold continental air masses. This leads, on average, to colder winters when compared with average conditions at the same latitudes in Europe.

---

[10] Relative to the zonally averaged SST for each latitude.