Lecture Notes in Earth Sciences 66

Helmut Wilhelm Walter Zürn
Hans-Georg Wenzel (Eds.)

Tidal Phenomena

With 111 Figures and 30 Tables

Springer

Editors

Prof. Dr. Helmut Wilhelm
Universität Karlsruhe, Geophysikalisches Institut
Hertzstraße 16, D-76187 Karlsruhe, Germany

Dr. Walter Zürn
Observatorium Schiltach
Heubach 206, D-77709 Wolfach, Germany

Prof. Dr. Hans-Georg Wenzel
Universität Karlsruhe, Geodätisches Institut
Englerstraße 7, D-76128 Karlsruhe, Germany

"For all Lecture Notes in Earth Sciences published till now please see final pages of the book"

Cataloging-in-Publication data applied for

Die Deutsche Bibliothek - CIP-Einheitsaufnahme

Tidal phenomena / ed.: Helmut Wilhelm ... - Berlin ; Heidelberg ; New York ; Barcelona ; Budapest ; Honkong ; London ; Mailand ; Paris ; Santa Clara ; Singapur ; Tokio : Springer, 1997
(Lecture notes in earth sciences ; Vol. 66)
ISBN 3-540-62833-9

ISSN 0930-0317
ISBN 3-540-62833-9 Springer-Verlag Berlin Heidelberg New York

Typesetting: Camera ready by editors
SPIN: 10552261 32/3142-543210 - Printed on acid-free paper

Preface

The idea for this book came up during a seminar on 'Tidal Phenomena' held at Oberwolfach (Black Forest) from October 17 - 21, 1994, sponsored by the German Geophysical Society (Deutsche Geophysikalische Gesellschaft, DGG). The contributions here represent essentials of the lectures given at this seminar in the form of either upgraded manuscripts or extended abstracts. The aim of this seminar was to give tidal reseachers, who are working as experienced experts on special problems, an opportunity to extend their views and to get a wider impression of the broad spectrum of tidal effects occurring in different regions of the earth, and moreover in the planetary system and the universe. It was also intended to introduce the results of modern tidal research to open-minded scientists who like to cast a glance beyond their personal fields of work.

The programme of the seminar has been published in the DGG-Mitteilungen, Special Volume II/1995. Some authors, who have not been able to contribute the full text of their lecture, were persuaded by the editors, to deliver at least an abstract and a list of references in order to give the interested reader a chance to obtain original information about the subject of the corresponding lecture. The scientific content of each article lies in the responsability of the authors alone.

After an expansive phase during the seventies, tidal research has an internationally appreciated position in Germany. A great part of this work is performed within the frame of a geodetic-geophysical working group which meets once per year. Interest in tidal phenomena on a larger scale, as decribed in this volume, however surpasses the subjects of this working group at least partially.

The fascination of tides arises from the regularity of their appearence and their conspicuous influence on very precise measurements of many natural physical phenomena. We hope that this book will mediate at least a faint image of the enthusiasm which tides can arise in people who have gotten in close contact with them.

Karlsruhe, April 1997

Helmut Wilhelm, Walter Zürn, Hans-Georg Wenzel

TABLE OF CONTENTS

Introduction

The goal of this book is to provide insight into the very different aspects of modern tidal research which are normally treated in separated scientific disciplines. Earth tides, ocean tides, atmospheric tides are pertaining to geophysics and geodesy, oceanography and meteorology, respectively. Tidally induced phenomena are investigated in geomagnetism, hydrology, climatology, and geology. Tides on planets are discussed in planetology, and tides of stars and galaxies are part of astronomy and astrophysics. Finally, a fundamental understanding of tides is provided by general relativity, i. e. by the theoretical foundations of physics.

The first section concentrates on the tidal potential and the tides of the solid earth. In the first contribution the earth-bound tide-generating potential and its spectrum is derived. This spectrum contains periods up to 20942 years, i. e. the period of the mean ecliptic longitude of the sun's perigee. The tidal spectrum also contains the gravitational influences of the planets Mercury, Venus, Mars, Jupiter, and Saturn. The tidal potential for the earth is, of course, relevant for all but the last three articles and the one about the Chandler wobble.

In the strict sense, tides on earth are caused by the gravitational forces related to this potential. In a wider sense, all measured temporal variations caused by the celestial motion of the earth and other heavenly bodies can be called tidal variations. To be more distinctive, this term is however restricted to the effects which are related to the gravitational variations derived from the tide-generating potential, whereas the other variations which are not related to *gravitational* effects of the earth's celestial motion are sometimes called tide-related or tidal-like variations. In this book both kinds of variations are subsummed in the term 'tidal phenomena' which also comprises tides in larger spatial expanses like the solar or the galactic system.

The second contribution gives a state-of-the-art introduction to the theory of the deformation of a rotating, elliptical, elastic, gravitating earth by tidal forces. Special attention is paid to different descriptions (Langrangian, Eulerian and a mixed combination of both) of the incrementals. Perturbations to the results of this theory which are caused by lateral heterogeneities and by anelasticity in the earth's mantle are also discussed.

The analysis of tidal observations has long been necessary for the prediction of tides in harbours. A substantial increase in accuracy of the tidal models became necessary when the precision of earth tide measurements was enhanced by orders of magnitude, especially due to the advent of superconducting gravimeters. The analysis of earth tides must be able to extract tiny effects from the data, and the third article describes a widely used modern analysis method based on least squares.

The fourth contribution discusses earth tide observations and the difficulties of their geophysical interpretation. Only a few characteristic examples could be

selected from a multitude of experimental results and with those an attempt is made to give insight into the controversial views of different research groups towards the meaning of (apparent) spatial variations of the earth's response to tidal forcing. Systematic disturbances arise from ocean attraction and loading in all measurements and from local heterogeneities in tilt and strain records.

Earth tides are the response of the earth to gravitational forcing by the moon, the sun and the planets, and the tidal deformation of the earth is physically a forced oscillation. If the period of the forcing lies in the vicinity of the period of a free mode of the earth, a resonance effect is to be expected in the response. The nearly-diurnal free-wobble (NDFW), associated with the free core nutation (FCN), has its eigenperiod in the diurnal frequency band. This resonance arises due to the ellipticity of the core-mantle boundary. The effect from this mode in the spectrum of measured earth tides and the conclusions, which can be drawn, are the subject of the fifth article.

To the public tides are generally associated with ocean tides, because the regularity of the appearance of tidal currents and sea level changes is inevitably noticed by everyone who ever lived for some time at the sea-side. The practical aspects of navigation of vessels near the coasts implied early continuous observation of the tides in ports and necessitated the prediction of tidal heights and current velocities. Ocean tides are even used to generate electrical power. In order to understand why the marine tides show a specific appearance at different locations they need to be modelled. The first article in the second section gives an overview about specific ocean tide phenomena and current methods of ocean tide modelling. It is interesting to note that ocean tides and earth tides are intimately interacting.

The influence of ocean tides on earth tide measurements is described in the next article. While the effect on tilt and strain is declining rapidly with increasing distance from the coast, gravity is considerably affected to very large distances. This systematic, so-called indirect effect, has to be precisely modelled in order to be reliably separable from the data. On the other hand this effect can be used to improve local ocean tide or earth tide models, if it can be determined with sufficient accuracy.

The moon's orbit around the earth has changed during the 4.5 billion years of the earth's existence. But the angular momentum of the two-body system must approximately be conserved. The earth's spin is decelerated by tidal friction, so that the number of days during a month or a year decreases with time. The orbital angular momentum of the moon correspondingly increases, so that the moon is moving away from the earth and, consequently, the number of days during a month should increase. Hence, there are two counteracting effects regarding the development of the number of days during a lunar month. Actually, the second effect is smaller than the first one and the increase in the length of the day is accompanied by a decrease in the number of days per month since the Proterozoic. There is no discussion about the fact that the main part of tidal dissipation occurs in the oceans but it is still not completely resolved how large the effect of viscous dissipation in the earth's mantle is. The friction of ocean

tides at the sea bottom is the main cause for the increase in the length of the day and in the moon's distance with time. The third contribution in this section explains these effects in detail and describes the results of modern observation techniques like VLBI.

The last article of this section is devoted to the so-called pole tide associated with the Chandler wobble. The major questions here concern the excitation mechanism of this free mode and the problem whether the pole tide is an equilibrium tide or not; both are addressed in the article. Note that the differential forces for the pole tide are centrifugal, not gravitational.

The third part of the book describes effects which mainly arise from non-gravitational variations related to the celestial motions of the earth which are also responsible for the tide-generating gravitational forces. Atmospheric tides, i. e. tidal variations in pressure, temperature or wind direction and velocity, are predominantly excited by thermal input from the sun into the atmosphere, i. e. by the solar radiational flux. However, the gravitational signal, although very small, is also detectable by refined time series analysis. The first article gives a review of the excitation mechanisms, the observations and the theoretical interpretation of the measured atmospheric signals.

The second contribution touches palaeoclimatic varitations like the ice ages which may have been caused by variations of the solar radiation incident on the earth's atmosphere, resulting from the precession of the earth's celestial orbit and from variations of its obliquity and eccentricity. The last two parameters are held constant in tidal theory although they show long period changes which are taken into account in climate research. Actually there is observational evidence for corresponding periods in climatic indicators, but certain discrepancies imply that other mechanisms related to earth-sea-atmosphere interactions or astrophysical phenomena must be investigated also as possible candidates for a source of climate variations.

The third article in this section describes geomagnetic variations which, to a great part, are also caused by varations of solar irradiance, but also by regularly varying particle fluxes in the ionosphere and magnetosphere. In addition, they contain a small fraction of gravitationally induced lunar tides, whereas the solar gravitational tidal influence is overwhelmed by the thermal driving mechanisms of the ionospheric dynamo.

The fourth section of the book is devoted to special tidal phenomena which largely depend on local conditions. Boreholes in sediments or crystalline rocks often exhibit tidal variations in water level which are investigated with respect to hydrogeological parameters. The first contribution in this part introduces the relations between hydrology and tides and exemplifies the corresponding effects for some aquifer models. An increasing number of corresponding investigations of tidal water level variations shows a rising interest of hydrologists in this research branch.

In the second article, the controversial discussion about tidal triggering of earthquakes and volcanic events is critically reviewed. It is generally well known that a positive outcome of a statistical analysis does not necessarily prove a

physical relation between the corresponding events, but as it is shown in this paper, this rule is often neglected in superficial investigations.

The third contribution is a report about the influence of the so-called geological effect on earth tides, especially on tidal tilt measurements. A temporal variation of the tidal tilt response in the vicinity of an earthquake fault is considered to be indicative for regional stress build-up before an earthquake happens, and corresponding investigations using a tilt station array at the North-Anatolian Fault Zone are described.

In the last section of the book tidal effects in physical systems located at increasing distance from the earth are considered. The first contribution gives a short summary and literature of tidal perturbations of satellite orbits. The second article contains an account of tidal phenomena on Jupiter's satellite Io, which displays strong volcanism and obviously extracts the necessary energy for this internal activity from tidal friction. The third contribution is a summary introducing the reader to the important tidal interaction between binary stars, and the last article extends the view to tidal interactions between galaxies.

The main purpose of this book is to give a glimpse on the fascinating variety of tidal phenomena happening in nature. The human experience is naturally concentrated on the earth, and so earth-bound phenomena are the predominating effects compiled in this lecture script. However, the last chapter which looks far out beyond the earth's neighbourhood, demonstrates that tides are existing everywhere in the universe and are of outmost importance for ist past and future.

Helmut Wilhelm
Walter Zürn
Hans-Georg Wenzel