Preface

The term "algal bloom" is used to describe the temporal and spatial accumulation of phytoplankton—in general or a single species—in an aquatic environment. The phenomenon of water discoloration produced by harmful algal blooms is an intrinsic phenomenon of the Earth's aquatic environments and is well known from history, however its incidence and proliferation throughout the world's oceans remained relatively undiscovered and not understood until the last century.

However, during the last 40–50 years, this natural marine biological phenomenon has become increasingly frequent and widespread causing serious concern not solely in the scientific community but also to the authorities, fisheries, industry, and the public in general. The occurrence of such events, termed *harmful algal blooms* (HABs), began being reported by mass media as front-page news, due to their impact causing severe economic losses and damage, direct human health problems, and the image of a degrading marine and coastal environment. Technological development and in particular new monitoring techniques including satellite Earth observation (EO) have facilitated research advances.

The main motivation of this book resides in the role that the Nansen Environmental and Remote Sensing Center (NERSC) in Bergen played in the early initiation and further development of integrated satellite EO, *in situ* monitoring, and ocean ecosystem modeling methodologies not only to study scientifically, but also to reveal, monitor, and forecast algal blooms (HABs, in particular) as well as to develop tools for dissemination of the information to the relevant stakeholders, including applications related to fisheries and aquaculture (Pettersson, 1990; Stiansen *et al.*, 2002).

Back in the 1980s, a team of scientists at the Nansen Center led by Prof. Ola M. Johannessen started to tackle the highly challenging scientific task of developing physical oceanography into operational oceanography, or "weather forecasting" for the oceans, through combined development of satellite remote sensing, field

The harmful *Chrysochromulina polylepis* bloom in 1988 in Norwegian coastal waters got huge media attention that prompted headlines like "*The algae disaster*", "*When the ocean dies*", and "*The algae is thrown away*". *Courtesy*: Bergens Tidende.

observations, and numerical ocean modeling (e.g., Johannessen and Pettersson, 1988).

Unexpectedly, in May–June 1988 the algae *Chrysochromulina polylepis* created a massive harmful bloom in a large part of southern coastal Norwegian waters, generating a range of environmental problems and causing severe losses of fish to the Norwegian aquaculture industry amounting to some €4 million (Johannessen and Pettersson, 1988; Dundas *et al*., 1989; Johannessen *et al*., 1989a, b). *Ad hoc* monitoring and forecasting activities were initiated by mobilizing public authorities, scientists, and other stakeholders. The Institute of Marine Research and the University of Bergen initiated dedicated ship surveillance cruises to the bloom area. Two aircraft from the Norwegian Pollution Authority (SFT) and the Swedish Coastguard equipped with side-looking airborne radar (SLAR) as well as infrared (IR) and ultraviolet (UV) airborne sensors—instrumentation intended for oil spill reconnaissance and not designed for HAB detection were used in daily reconnaissance. The *ad hoc* established team of scientists along with other experts were nevertheless successful in delineating the HAB areas of *C. polylepis* and providing valuable forecasts of bloom development in other areas, which could be used to take action to mitigate economic losses. Several aquaculture cages were towed away into less saline fjord areas to escape the bloom area (see photo on the book cover) and reduce the losses of caged fish. The event received extensive TV and newspaper media attention and details on how the bloom developed were for the first time ever in Norway broadcast daily.

Early during the bloom it was determined that thermal fronts in marine waters were intimately related to off-coastal extension of the bloom, a finding that triggered the processing and use of AVHRR to delineate ocean temperature fronts. These IR satellite images (see Figure 4.1) provided daily information on the sea surface temperature (and, hence, advection of the *C. polylepis* area) in the meanders and small-scale eddies driven by the Norwegian Coastal Current (NCC). Even at this stage of HAB research, Johannessen and Pettersson (1988), Dundas *et al.* (1989), and Johannessen *et al.* (1989a, b) combined their spaceborne data with a two-layer quasi-geostrophic ocean model implemented at the Nansen Center (e.g., Haugan *et al.*, 1991) (see Figure 4.3) and demonstrated the use of this model to predict advection of the *C. polylepis* bloom.

In the wake of this event, discussions in Norway accelerated the establishment of a national pilot project for ocean monitoring and forecasting (HOV or Hav overvåkning og varsling; see, e.g., Johannessen and Pettersson, 1988). Thus, Norway at that time was an international forerunner in initiating and developing operational oceanography services by setting up and using a state-of-the-art observational ocean *in situ* network, satellite and airborne remote-sensing technologies, and comprehensive coupling of marine hydrodynamic and ecosystem modeling in near real-time monitoring and forecasting. During the last three decades the Nansen Center has taken great strides in this direction through research development of methodologies, synergistic applications of multi-sensor satellite data, and data assimilation in numerical ocean circulation and ecosystem models.

Accordingly, this book is focused on the relevant research activities at the Nansen Center; however, the authors have also pursued the goal of portraying the state of the art in HAB-related activities across the world.

Furthermore, studies have revealed that the detrimental effects of HAB events are multifaceted. They not only involve algal toxin action, but also the impact of factors like the high abundance of phytoplankton biomass, exudation of mucilage, alteration of biogeochemical status of the aquatic environment (e.g., depletion of dissolved oxygen), significant changes in the indigenous trophic/food web interactions, etc.

Numerous investigations have shown that the aftermath of HAB events is not only confined to the welfare status of the aquatic ecosystem, but propagates further affecting humans through toxic contamination of food, deteriorating sanitary conditions, and very significant economic losses.

Despite the extensive scientific knowledge that has already been built up, the reasons for such extensive proliferation and increased incidence of HABs throughout the world during recent decades remain unclear and, generally, are attributed to the combined action of natural ecosystem variability, anthropogenic impact, and climate change. Understandably, ranking the actual role of each of these mechanisms in generating HABs is difficult because they steadily enhance with time and, furthermore, are intimately interrelated in many ways.

In some coastal and off-shore regions of the world's oceans, HABs emerge on a regular basis, but the exact timing of their onset, location, actual extent, and duration may vary significantly from year to year. Bloom-triggering factors are often associated with physical, chemical, and biological conditions and their seasonal variation. At the same time, there are many areas in the oceans and seas where HABs originate unexpectedly or very irregularly. Such events may be brought about through invasive alien algae species being transported to a new geographical region by ballast water, for example.

Moreover, the nature of HABs proves to be complicated and again not well understood. For example, traditionally harmful algae do not always remain harmful and, *vice versa*, some blooms of phytoplankton species known as non-harmful turn out to be harmful under specific local conditions. The exact qualification of a HAB as a harmful/non-harmful bloom requires identification and monitoring using shipborne surveys, sampling, and sophisticated laboratory analyses.

The extent, frequency, spatial, and temporal dynamics of the HAB life cycle—as well as the nature of this phenomenon in conjunction with the associated challenges to aquatic environments and eventually to human society—are all factors that in concert warrant the necessity of developing an efficient integrated system of early detection and warning, monitoring, and prediction of HAB events, in order to take mitigatory actions.

In light of the above, remote-sensing surveillance (especially spaceborne and airborne) are instrumental in the early detection and further monitoring of HABs. This is prompted by such valuable attributes of satellite remote sensing as unrivaled high spatial coverage of oceanic/marine areas and high revisiting frequency (e.g., daily), which is of paramount importance when tackling the problem of HAB monitoring. But are these capabilities really sufficient for satellite remote sensing to be a reliable and complementary monitoring tool? If they are not, what are the limitations? Are such limitations of a current technical, methodological, or fundamental nature? What is required then to perform this challenging task? What complementary means need to be involved or need to be developed? What should an "ideal" monitoring system look like? What components should it encompass? What is already being done in this respect and what is to be done in the future?

This book has been conceived as an endeavor to explore the above suite of issues and is organized in five thematic chapters. To accommodate the above thrust, we begin by discussing in *Chapter 1* both the main criteria that attribute phytoplankton species and associated blooms to the category of harmful ones. Then we refer to HAB-driven detrimental effects. This is followed by characterization of the spatial distribution of occurrence of HAB events and associated specific toxic contamination throughout the world's oceans. Finally, we analyze the variety of consequences of HAB events from the perspectives of (i) aquatic system ecology, (ii) human ecology (health/food safety/sanitary conditions), and (iii) social economy (direct and indirect losses).

Chapter 2 addresses the biology and ecology of harmful algal species. We examine the role of major factors favoring the occurrence of HABs, including ocean physics, biogeochemistry, weather conditions, climate change, and anthropogenic impact (e.g., eutrophication). This is followed by extensive illustrative material produced by a number of case studies conducted in the North and Baltic Seas as well as in the Galician Rias mostly as part of large-scale international research projects coordinated by the Nansen Center.

Based on the first two chapters reflecting the fundamentals of HABs as a hydrobiological phenomenon, *Chapter 3* opens the discussion of issues that are at the base of remote sensing of HABs. As an indirect method, remote sensing always deals with proxy variables. Therefore, in order to meet the challenge of efficient use of remote-sensing means for detection and monitoring of HABs, it is mandatory to identify the appropriate proxies. The latter should be related to in-water color-producing agents (CPAs) inherent in harmful (and also in non-harmful) algae and producing the effect of water discoloration. This choice is motivated by the present availability of satellite sensors operating in the visible range of the electromagnetic spectrum, which is fundamentally important since it is only visible radiation that appreciably penetrates the water column. In pursuit of this goal, we begin Chapter 3 by examining such proxies, which reside in the pigment composition inherent in the cells of various harmful algae species, cell absorption, and backscattering as well as light emission/fluorescence properties. The optical properties of other CPAs generally coexisting with algae in natural waters and also affecting the light signal are discussed as well. These sections are followed by an overview of the variety of methodological approaches suggested so far for remote detection, density assessment, and monitoring of HABs.

Because the presence of a HAB in the water column may also have some surface expressions such as anomalies in water surface temperature and roughness, we conclude Chapter 3 with a discussion of the prerequisites for synergistic use of satellite remote-sensing Earth observation (EO) means. Satellite sensors operating in the visible, infrared, and microwave spectral regions constitute such means, the latter two being the most appropriate tools to investigate the surface micro-layer structure of the ocean surface.

Chapter 4 expands on the practical integrated monitoring of HABs using satellite EO information sources. First, we present the methodological approaches employed and the results of studies of identify HAB events. Although the literature on this issue is extremely extensive, the scope of this section does not allow us to review the entire range of such publications; instead, we only address the most recent ones to give ample examples from as wide a variety of marine/aquatic environments *throughout the world* as possible in order to better illustrate our discussions in Chapters 1 and 2.

Moreover, an important aim of this overview is to reveal the extent to which methodological approaches aimed at the identification of harmful algal species, as discussed in Chapter 3, have actually been realized in current integrated remote-sensing studies or services of HAB identification and monitoring.

Section 4.2 is devoted to the discussion of practical implementation of a synergistic approach to identification and monitoring of algal blooms, in general, and HABs, in particular. This is done to highlight the conditions under which this approach presents its virtues in full measure.

Chapter 4 concludes with an extensive section exemplifying a couple of integrated HAB monitoring systems using satellite EO data, which are presently operational and constitute a part of national services of HAB detection, surveillance, and early warning. The discussion in this section is predominantly based on the experience gained by Norway, as part of the European Commission and European Space Agency Global Monitoring for Environment and Security (GMES) system, as well as by the U.S.A., where there are already several services for this purpose.

Chapter 5 provides a review of the presently available coupled ocean and marine ecosystem models developed for forecasting the development of the marine ecosystem, including (harmful) algal blooms. Again, the emphasis is on the ecological models used by the Norwegian HAB monitoring research community. This is done partly to make Chapter 4 comprehensive and partly to complete the description of the Norwegian HAB monitoring and prediction service.

Finally, the *Afterword* presents our vision of the present state of the art in integrated HAB monitoring and forecasting systems as well as the prospects of more sophisticated methodologies becoming available in the future and further improvements of logistic practices supporting such services due to the new satellite sensors scheduled for launch.

During the final editing of the manuscript one of our prime satellites supplying optical Earth observation data—the European Envisat satellite—has stopped sending data to Earth, after near 10 years of successful operation. Fortunately, for our purposes, optical ocean color data are available from other satellites and space agencies. These data are now being used more extensively by us while waiting for the European Sentinel satellites due for launch in the coming years. This event emphasizes the need for international cooperation, continuity, and backup solutions for sensors in order to support both research and operations using satellite Earth observation data.

This book is essentially a sharing of our experiences in the basic and practical research development of the methodologies, their validation, and implementation of HAB monitoring from space and model-based prediction of how such events are likely to unfold. Welcome to *Monitoring of Harmful Algal Blooms*.

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May 2012
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http://www.springer.com/978-3-540-22892-9

Monitoring of Harmful Algal Blooms
Pettersson, L.H.; Pozdnyakov, D.
2013, XXXI, 309 p., Hardcover
ISBN: 978-3-540-22892-9