Phytoplankton, i.e. algae and cyanobacteria, form the bottom of the marine food web and thus their fate has repercussions on marine but also terrestrial ecosystems. Climate change and other anthropological processes alter the marine habitat on a global scale and affect phytoplankton abundance and composition in various, often unprecedented ways. A comprehensive understanding of these complex biogeochemical interactions is prerequisite to sustainable stewardship of oceans and lakes, and thus for maintaining life on this planet, including that of a growing human population. The main objective of this thesis was therefore to quantify the impact of environmental forcing on phytoplankton abundance and distribution.

Satellites offer a synoptic view of water from space, complementary to localized observations recorded from just above or below the water surface (in situ), i.e. from research vessels, ferries (so-called ships-of-opportunity), and coastal observatories. These distinct perspectives on the ecosystem offer information at complementary temporal and spatial scales that are required to derive long-term trends and to link these trends to i.e. changing environmental conditions. However, each perspective comes with its own conceptual and technological challenges. I utilized these distinct perspectives on water to pursue my research objective. This was attempted in three stages, which also define the structure of this book.

First, I assessed and revised methodologies for in situ measurements of water colour. Second, I developed innovative approaches to analyse and corroborate observations that were acquired from space, above-, and below-water. Third, I derived long-term phytoplankton trends and attributed these to changing environmental conditions. In the following, I will give a brief summary of the insights gained at each stage.

**Revised Methodologies for Above-surface Water Colour Observations**

Water surface reflections need to be corrected for to quantify the colour of water from above the surface. Most existing correction approaches are based on the assumption that the water surface acts as a mirror and reflects a well-defined patch of the sky. This assumption holds for perfectly flat water surfaces, which are rarely found in natural en-
environments. Wind-roughened water surfaces reflect light from anywhere in the sky. This is problematic because light intensity and colour vary throughout the sky, which is not accounted for by existing approaches. Furthermore, reflections of the sun disc on the water surface – sun glint – can contribute significantly to the observed water signal. Sun glint is also not covered by existing approaches and thus measurement geometries need to be constrained such that sun glint contributions are minimized. These constraints, however, can often not be met when recording from e.g. fixed-position moorings or ships-of-opportunity. As a result, the majority of observations from such platforms are not available for further analysis, or need to be assigned large error margins. In chapter 3, a new correction approach (3C) is proposed to mitigate these limitations. Fundamental to 3C is a mathematical model to approximate sun and sky light. 3C was validated with a data set of matching above- and below-water measurements collected in the Baltic Sea. The improvement over conventional corrections was most pronounced under inhomogeneous sky conditions. It was further demonstrated that accounting for sun glint relaxes constraints on measurement geometry. 3C will help to utilize significantly more observations from fixed-position or ship-borne instruments that previously had to be discarded.

Adjacency effects are contaminations of the sky light that stem from surrounding land cover, which typically reflects orders of magnitude stronger than water. Adjacency effects in coastal regions and lakes may not be assumed constant throughout the sky, and can thus contaminate measurements of water colour similar to sun and sky glint. The magnitude of this artefact was studied in chapter 4. We analysed a data set of sky light measurements that was recorded in two viewing directions and over a complete vegetation period of the terrestrial land cover background. It was concluded that adjacency effects contributed considerably, dependent on viewing direction and season. In situ water colour measurements often serve as ground truth in validation efforts of remote sensing products. Quantifying the impact of adjacency effects on these observations is therefore an important contribution to earth observation frameworks, and will enhance data quality of inland water and coastal area water quality products.

In summary, sky and sun glint, as well as adjacency effects were identified as the most important sources of non-water related variability in above-surface water colour measurements. Open source software libraries were developed to correct water colour measurements for sky and sun glint, and to quantify the potential impact of adjacency effects on these measurements.
CORROBORATING INDEPENDENT PERSPECTIVES ON PHYTOPLANKTON BLOOM

Highly variable vertical mixing makes the Baltic Sea a great challenge for optical monitoring approaches. Bright cyanobacterial surface blooms are in stark contrast to otherwise predominantly dark Baltic Sea waters, which facilitates reporting on surface bloom occurrences based on remotely sensed observations. Several in the Baltic Sea commonly encountered cyanobacterial species can adjust their buoyancy to actively migrate in the water column, which can cause their vertical distributions to be highly variable on small spatial scales. Neither cell abundance at depth nor at the surface can be considered representative of bloom biomass when most cells are concentrated in the surface layers. Remotely sensed surface bloom occurrence is therefore a weak proxy for cell abundance or bloom biomass, which are key parameters for ecosystem models and assessments of eutrophication status. Several passenger and cargo ferries in the Baltic Sea are equipped with instruments that autonomously sample various parameters at several meters depth in a flow-through set up (ferryboxes). Vertical stratification introduces opposing biases to satellite and ferrybox-derived bloom estimates. This was demonstrated in chapter 5, where thirteen years of cyanobacterial summer bloom timing were derived from remote sensing and ferryboxes in the Baltic Sea and found to differ markedly for most years. Occasional periods of calm and warm weather were shown to promote these discrepancies in bloom timing by supporting vertical stratification.

In cyanobacterial blooms, coherent dynamics between distinct ferrybox measurement channels can be interpreted as driven by the same source – cyanobacterial cells. Combinations of cyanobacterial pigment fluorescence and turbidity varied coherently in the 2005 central Baltic Sea cyanobacterial bloom. In chapter 6 wavelet coherence analysis was applied to spatially resolve this coherence, which was found to be significant at all encountered levels of stratification. It was concluded that in highly stratified conditions, e.g. at low wind speed and elevated sea surface temperature, coherent observations indicate where surface accumulations will greatly affect remote sensing measurements while ferrybox-derived pigment concentrations can be rather low. In well-mixed cyanobacteria dominated blooms, concentrations derived from space and in situ are directly comparable. Both conditions can automatically be identified with the developed approach, which is a precursor to near-real time processing efforts and further data assimilation.

In summary, discrepancies in cyanobacterial bloom observations from space and at depth due to vertical stratification were predicted from environmental forcing factors, i.e. the short-term history of wind-forced mixing, radiation, and sea surface temper-
Interpretation of in situ sampled spatial variability by means of wavelet coherence analysis adds a stratification-independent perspective to distinguish high- from low-biomass surface bloom. These results are going to improve bloom biomass estimations and ecosystem status assessments at arbitrary levels of bloom stratification.

**Effects of Environmental Change on Phytoplankton Bloom**

Spring bloom observations in the Baltic Sea are scarce. High average cloud cover in the region limits use of satellite remote sensing, and high costs of dedicated research cruises and coastal laboratories limit their spatio-temporal coverage. For this reason, fluorescence measurements from ships-of-opportunity are the primary source of observations to study spring bloom dynamics in this region. Deriving phytoplankton spring bloom phenology from such unattended and automated pigment fluorescence measurements presents a number of challenges that were met in chapter 7.

Existing procedures for automated quality control and processing had to be revised to ensure consistently high quality of data collected by generations of instrumentation. This groundwork yielded a 15-year phytoplankton spring bloom phenology, which was tested for decadal trends. Negative trends in spring bloom peak- and average-concentration were found and an increase in bloom duration was derived corroboratively from a set of conceptually differing bloom metrics. Significant decadal trends were then analysed against inter-annual variability in bloom timing and intensity, and environmental drivers (nutrient concentration, temperature, radiation level, wind speed). Bloom intensity was mainly determined by winter nutrient concentration, while bloom timing and duration co-varied with meteorological conditions. Longer blooms corresponded to higher water temperature, more intense solar radiation, and lower wind speed. These findings help to better disentangle ecosystem response to changing nutrient availability and climatic conditions. The suggested improvements in automated processing and quality control promote increased use of ferrybox observations for scientific research and monitoring purposes.

In summary, it was concluded that over the period 2000 to 2014, nutrient reduction efforts led to a decreasing bloom intensity trend of $-0.31 \pm 10 \text{ mg m}^{-3} \text{ yr}^{-1}$, while changes in Baltic Sea environmental conditions associated with global change correspond to a lengthening spring bloom duration of $1.04 \pm 20 \text{ day yr}^{-1}$. 