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Are surface temperature and chlorophyll in a large deep lake related? An analysis based on satellite observations in synergy with hydrodynamic modelling and in-situ data

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ABSTRACT

Phytoplankton growth depends on various factors, and primarily on nutrient availability, light and water temperature, whose distributions are largely controlled by hydrodynamics. Our main objective is to analyse the link between spatial and temporal variability of surface water temperature and algal concentration in a large lake by means of remote sensing and hydrodynamic modelling. We compare ten years of satellite images showing chlorophyll concentrations and surface water temperature of Lake Geneva. Our observations suggest different correlations depending on the season. Elevated chlorophyll concentrations in spring are correlated with warmer zones. But, in summer, higher chlorophyll concentrations are observed in colder zones. We show with a three-dimensional hydrodynamic model that the spatial variability of the surface water temperature reflects the upwelling and downwelling zones resulting from wind forcing. In springtime, nearshore downwellings induce locally increased surface temperature and stratification, which are associated with high chlorophyll concentration. In summertime, colder surface temperature area, often interpreted as transient upwellings, represents the thermal surface signature of wind-induced basin-scale internal waves, bringing either nutrients or phytoplankton from deeper layers to the surface. Our study suggests the latter to be the dominant process, with the basin-scale internal wave activity and associated transient summertime upwellings and downwellings having little net effects on the algal concentration. This study finally demonstrates the necessity to connect remote sensing retrievals and three-dimensional hydrodynamic modelling to properly understand the dynamic of the lake ecosystems.

1. Introduction

Photosynthetic growth of phytoplankton in surface waters depends mainly on light, temperature, and nutrients (Reynolds, 2006). The seasonal and inter-annual variability of phytoplankton dynamics is the result of complex interactions of temporally variable abiotic and biotic parameters and mechanisms (Behrenfeld and Boss, 2014; Sommer et al., 2012) also depending on other processes, such as competition or grazing. In temperate regions, seasonal stratification governs these processes to a large extent, by limiting the upward flux of hypolimnetic nutrients to the photic surface layer of lakes (epilimnion), where light is usually abundant in oligo- to mesotrophic lakes (Sharples et al., 2001; Watanabe et al., 2016). During the stratified seasons, nutrients are consumed in the photic surface layer (Sommer et al., 2012), and only limited phytoplankton growth occurs after the first spring bloom, while phytoplankton growth progressively moves to deeper layers (Barbiero and Tuchman, 2004; Dokulil and Teubner, 2012).

In spring, the increasing lake temperature governs phytoplankton growth by two mechanisms: (i) acceleration of the physiological processes, such as nutrient uptake, growth and respiration (Berger et al., 2010; Goldman and Carpenter, 1974), and (ii) development of the thermal stratification of the water column (Diehl et al., 2002; Berger et al., 2010).

In summer, phytoplankton growth is often nutrient-limited. Long lasting coastal upwelling has been identified as an important source of nutrients, when transported from the deep water to the upper photic layer (Mackas et al., 1985). As a result, most of the primary production in the global ocean takes place in upwelling regions (Falkowski et al.,

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1998; Gruber et al., 2011). In lakes, with the exception of very large ones like Lake Baikal (Troitskaya et al., 2015), upwelling of cold and nutrient-rich deep water are mostly wind-induced and are therefore transient (Steissberg et al., 2005). MacIntyre and Jellison (2001) observed in a medium-sized lake (where Coriolis forces remain negligible) that strong wind-induced upwelling can increase nutrient upward flux and favour phytoplankton growth. Yet, the inverse effect was also observed. After a major storm event, cold hypolimnetic water in Lake Constance was correlated with significantly lower chlorophyll-*a* concentrations (CHL) than the warm, epilimnetic water (Rinke et al., 2009).

All the above-mentioned processes are associated with lateral variability in the dynamical behaviour of phytoplankton growth. Yet, lake monitoring strategies typically focus on sampling ecological parameters at the lake centre or at the deepest point, thereby neglecting spatial variability and littoral processes (Pomati et al., 2011). Traditional attempts to capture the lateral variability in phytoplankton horizontal dynamics require extensive in-situ measurements (Thackeray et al., 2004). Remote sensing applications for lake water composition (Giardino et al., 2001; Odermatt et al., 2012a) and lake surface water temperature (LSWT; (Oesch et al., 2005) have opened new perspectives for monitoring spatial and temporal water quality dynamics. However, satellite measurements remain limited in depth, i.e. to the first micrometers for LSWT and to roughly Secchi depth for the least attenuated wavelengths of reflected solar irradiation. The depth limited information and their temporal stochasticity call for an integration of both in-situ and remote sensing data into numerical models to constrain lake system studies. While this approach has often been applied in oceanography, examples of integration of in-situ, remote sensing and model data remain scarce in inland waters (Curtarelli et al., 2015; Wynne et al., 2013).This study examines the inter-seasonal relationships between satellite-observed LSWT and CHL in Lake Geneva. Data from the Advanced Very High Resolution Radiometer (AVHRR) on the US National Oceanic and Atmospheric Administration (NOAA) satellites are used for LSWT, which is a relative indicator for physical phenomena, such as stratification and upwelling. CHL is derived from the MEdium Resolution Imaging Spectrometer (MERIS) full resolution images on the European Space Agency Environmental Satellite (ENVISAT). The investigations make use of all available data pairs (e.g. AVHRR and MERIS data) acquired during the ten years of ENVISAT operations (17th May 2002 to 8th April 2012).

Based on intriguingly correlated remotely sensed CHL and LSWT image pairs (Fig. 1), we formulate two season specific hypotheses on physical and biological in Lake Geneva. First, in spring, we expect a positive relationship between phytoplankton growth and temperature; or, implicitly, dependent on the stability of the water column. We expect that phytoplankton growth is enhanced in downwelling zones, where warm surface water is converging. Second, in summer and fall, and after the build-up of the seasonal thermocline and algae growth-induced surface nutrient depletion, phytoplankton growth becomes nutrient-limited. We expect that phytoplankton growth is enhanced in upwelling zones.

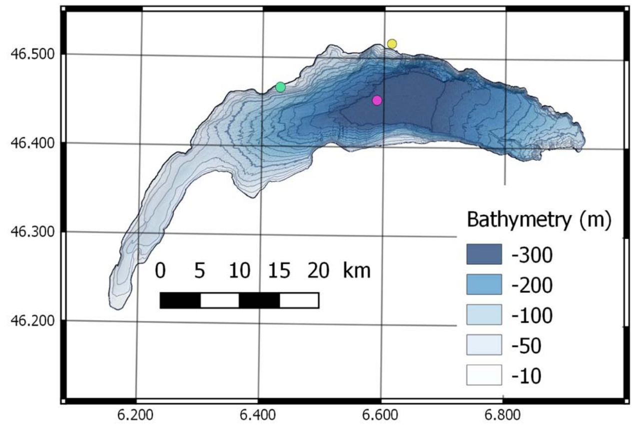

Fig. 2. Map of Lake Geneva with locations SHL2 (pink), Buchillon (green) and Pully (yellow). In-situ CHL calibration samples are regularly taken at SHL2. Temperatures measured at Buchillon and at SHL2 have been used for calibrating the three-dimensional Delft3D-Flow model. 20 m isolines are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

These hypotheses are investigated using a spatial autocorrelation indicator (Moran's *I*) for satellite data pairs. Results are analysed with respect to in-situ data such as depth-dependent annual phosphorus and CHL concentrations and the short-term spatio-temporal change in the thermal structure as inferred from a three-dimensional (3D) hydrodynamic model.

2. Study area and data

2.1. Lake Geneva study site

Lake Geneva (Fig. 2) is a perialpine lake situated at an altitude of

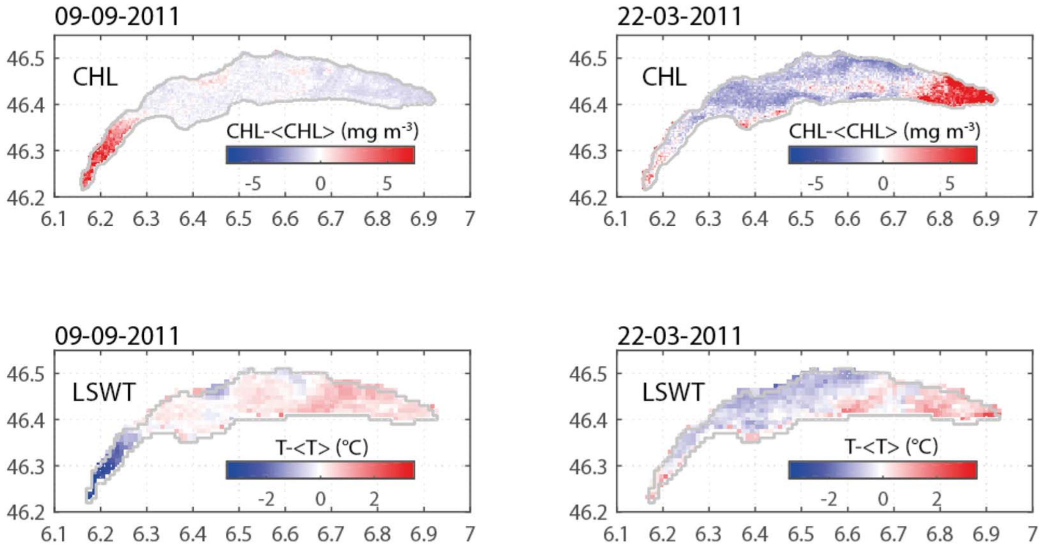

Fig. 1. Differences of chlorophyll (CHL) and lake surface water temperature (LSWT) relative to their spatial averages for two same-day scenes, one in spring (right) and one in autumn (left) 2011. Both show spatial correlation between CHL and LSWT.