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Shutdown of convection triggers increase of surface chlorophyll

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ABSTRACT

The long-standing explanation of the triggering cause of the surface increase of phytoplankton visible in spring satellite images argues that phytoplankton biomass accumulation begins once the mixed layer depths become shallower than a 'critical depth'. However, a series of recent studies have found evidence for phytoplankton increase in deep mixed layers, and several hypotheses have been proposed to explain this early increase. In this manuscript it is suggested that the surface concentration of phytoplankton increases rapidly in a 'surface bloom' when atmospheric cooling of the ocean turns into an atmospheric heating at the end of winter. The hypothesis is supported by analysis of satellite observations of chlorophyll and of heat fluxes from atmospheric reanalysis from the North Atlantic.

1. Introduction

Satellite images show that the subpolar North Atlantic turns green every spring in response to an explosive surface increase of freely drifting microscopic algae, called phytoplankton. The primary production during this 'spring bloom' is of considerable interest to oceanographers, because it is the first link of the area's food chain and contributes significantly to global photosynthesis and ocean carbon uptake (Takahashi et al., 2009). It is generally believed that the increase in surface chlorophyll coincides with the onset of the spring bloom, when growth from photosynthesis first outweighs losses, driving primary production (e.g. Siegel et al., 2002). However Behrenfeld (2010) cautioned that net biomass increase may start earlier in the season without a signature in the surface phytoplankton concentration, if ocean turbulence rapidly mixes the new phytoplankton down into the deep ocean. We will therefore refer to changes in ocean color as the *surface spring bloom* to distinguish them from the proper spring bloom which represents the net increase of phytoplankton biomass throughout the entire water column. In this paper we test the hypothesis that surface spring blooms are associated with a change in air–sea heat fluxes and begin when winter cooling of the ocean switches to spring warming, thereby reducing vertical mixing of phytoplankton.

The prevailing view is that the surface greening coincides with the spring bloom (e.g. Follows and Dutkiewicz, 2002; Siegel et al., 2002) and its onset can be explained with the "critical depth" hypothesis (Gran and Braarud, 1935; Riley, 1946; Sverdrup, 1953). Like terrestrial plants, phytoplankton need sunlight and nutrients (carbon, phosphorous, nitrogen, silica, iron, etc.) to grow. This constrains phytoplankton production, because the euphotic layer, the surface layer of the ocean with sufficient light for photosynthesis, is often stripped of nutrients by previous phytoplankton growth. According to the critical depth hypothesis, winter cooling and winds churn the upper ocean and bring nutrient-rich waters to the surface, but this benefit is outweighed by the downward mixing of phytoplankton below the euphotic layer. As spring approaches, cooling and winds wane, resulting in a shallowing of the mixing layer. Meanwhile, the day length and solar insolation levels increase. The active mixing layer reaches a "critical depth" when phytoplankton experience sufficient light levels that their growth balances the losses due to consumption by zooplankton, respiration, sinking, etc. When the mixing layer shoals above this critical depth, the phytoplankton population starts growing, creating a bloom. If the phytoplankton concentration increases uniformly in a shallowing mixing layer, the surface concentration will necessarily increase. Therefore, the spring bloom and surface spring bloom coincide under this hypothesis. A deficiency of the hypothesis is that it cannot be rigorously tested against observations because of the difficulty of measuring the depth of the mixing layer and the biological parameters required to compute the critical depth (Siegel et al., 2002).

Since the early 1950s (Sverdrup, 1953), the depth of the mixed layer, where density is nearly homogeneous, has been used as a proxy for the active mixing layer–measurements of the mixing layer require sophisticated turbulence probes, while the mixed layer can be more easily estimated by taking routine vertical profiles of temperature and salinity to compute density. However, the mixed layer proxy is imperfect. It

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does indeed track a layer that has been mixed, but the mixing may not be active anymore. The mixed layer takes days to weeks to develop a near-surface vertical density gradient (restratification) once vertical mixing subsides as a result of a drop in air–sea surface fluxes or through instabilities of surface currents that cause warm water to slide over cold water (Boccaletti et al., 2007; Taylor and Ferrari, 2011a). On the other hand, the surface phytoplankton concentration can increase as soon as vertical mixing subsides. Several authors have reported the occurrence of phytoplankton blooms in mixed layers deeper than the critical depth from shipboard measurements of temperature, salinity, and phytoplankton concentration (Boss and Behrenfeld, 2010; Dale and Heimdal, 1999; Townsend et al., 1992).

Alternatively we argue that phytoplankton increase at the ocean surface, as seen from satellites, starts when vertical mixing subsides. In the suboplar North Atlantic, wintertime vertical mixing is primarily driven by surface cooling through convection, particularly away from coastal regions where winds are also important. Hence, we put forward the hypothesis that the surface bloom begins when ocean cooling subsides at the end of winter and turns into surface heating, resulting in a shutdown of vertical convection and a reduction in mixing. We refer to this scenario as the convection shutdown hypothesis. Waniek (2003) and Taylor and Ferrari (2011b) have confirmed that the timing of the shift from cooling to heating in air–sea heat fluxes is a very robust indicator of surface blooms in numerical and mathematical models of the North Atlantic bloom. There have also been observational reports of blooms starting when the heat flux changed sign (Koeve et al., 2002). The goal of this paper is to test the convection shutdown hypothesis using 8 years of satellite measurements over the whole subpolar North Atlantic.

The paper is organized as follows. We introduce the data sets used in the analysis in Section 2. The data are used to test the convection shutdown hypothesis in Section 3. Section 4 confirms that freshwater fluxes and winds are of secondary importance in driving deep mixing in the subpolar North Atlantic and can therefore be ignored, at leading order, in the analysis. Section 5 compares and contrasts the convective shutdown hypothesis with the critical depth hypothesis. Finally we discuss the implications of our results for understanding ocean productivity.

2. Data and methods

To test the convection shutdown hypothesis, we analyzed timeseries of the net air–sea heat flux and chlorophyll concentration from the North Atlantic for the years 2003–2010. The heat flux and chlorophyll concentration are readily available on a global scale from remote-sensing products, unlike the mixed layer depth and the biological parameters–phytoplankton cellular growth, respiration and consumption rates–which are needed to directly test the critical depth hypothesis and can only be obtained from fragmentary and difficult shipboard measurements.

Chlorophyll concentrations were inferred from measurements of ocean color from the NASA MODIS-Aqua satellite using the algorithm OC3M described in Feldman et al. (1989) and O'Reilly et al. (2000)–the algorithm returns chlorophyll-a, a specific form of chlorophyll used in oxygenic photosynthesis. Although chlorophyll concentration depends on other factors in addition to phytoplankton abundance, it has been used successfully to study phytoplankton biomass especially at the end of winter when concentrations are low (Henson et al., 2009). The data, downloaded from http://oceandata.sci.gsfc.nasa.gov/MODISA/Binned, was already averaged over 8-day intervals and was further processed by averaging in 1°x1° degree latitude, longitude bins. The analysis was carried out using data for the period from 2003 to 2010. The rate of chlorophyll increase in each bin was computed as the 8-day rate of change in surface chlorophyll divided by the 8-day average chlorophyll concentration, i.e. $Chl^{-1} \times dChl/dt$ where Chl is the averaged chlorophyll concentration. Years with less than 50% data coverage between January and June, due to cloud coverage in a particular bin, were not included in the analysis to guarantee that there were sufficient data points to identify the onset of the surface bloom.

The net air–sea heat flux was obtained from the daily ECMWF ERA-interim reanalysis. The air–sea heat flux from this product was estimated based on a bulk algorithm with atmospheric conditions from a 4D-var data assimilation model with sea-surface temperatures from the OSTIA analysis (Dee et al., 2011; Donlon et al., 2007). In order to facilitate comparison with the chlorophyll concentration, and to reduce scatter in the data, the heat flux timeseries were averaged over 8 days in the same 1°x1° bins as the MODIS-Aqua data. The 8-day average is further supported by the analysis of Taylor and Ferrari (2011b), who find that the growth rate of phytoplankton populations responds only to heat flux changes on timescales longer than a few days; transient reversals from cooling to heating associated with the daily cycle and high frequency storms are too short to result in an appreciable population growth.

The ERA-Interim surface fluxes were used, because they capture the seasonal and interannual variability, as well as the spatial structure, of the net heat flux over the North Atlantic (Balmaseda et al., 2010). Balmaseda et al. (2008) reported that the ERA-Interim surface fluxes, when used to initialize the ocean component of the ECMWF seasonal forecasting system, had a consistent positive impact on the skill of the seasonal forecast. However no uncertainty estimates were provided for the ERA-Interim surface fluxes. Therefore we repeated the key calculation leading to Fig. 3, but using the surface heat flux from a different reanalysis by the National Centers for Environmental Prediction Global Ocean Data Assimilation System (Kanamitsu et al., 2002) downloaded from http://iridl.ldeo.columbia.edu. The results were essentially identical to the ones presented in the next section building confidence in the surface flux products.

3. The convection shutdown hypothesis

A map of the whole 45–61°N and 10–50°W analysis region in the North Atlantic is indicated by a black box in Fig. 1. Coastal areas, where cooling is not the main driver of vertical mixing, were omitted from the analysis by excluding regions where the water depth is less than 1000 m. The sudden increases in phytoplankton biomass associated with the surface spring bloom in the subpolar waters are highlighted by the large seasonal variations in chlorophyll concentrations in this region (Fig. 1). As an illustration, the timeseries of chlorophyll concentration (black lines and circles in Fig. 2) and the 8-day averaged heat flux (red curve in Fig. 2) are shown for three arbitrary 1°x1° areas centered at 25.5°W, 57.5°N, at 37.5°W, 53.5°N and at 31.5°W, 51.5°N respectively (indicated by black stars in Fig. 1). The timeseries are shown for an arbitrary subset of 3 years 2004–2006. The seasonal cycle in heat flux is visible in the large negative values (cooling) in winter, favoring convective mixing, and positive values (heating) in summer. The surface spring bloom is visible as an abrupt increase in chlorophyll concentration each spring and it coincides closely with the timing of the first shift from cooling to heating in most years when there is chlorophyll data.

To test the convection shutdown hypothesis quantitatively, it is useful to define a "convection shutdown time", $t_{Q=0}$, corresponding to the end of wintertime convection. Although high frequency variability was removed from the heat flux timeseries, there were still short intervals of less than 8 days when the heat flux became positive. Based on the modeling study of Taylor and Ferrari (2011b), we expected the phytoplankton concentration to increase very quickly (a few days) after the end of convective forcing. However, we did not expect to detect responses faster than 8 days, since the chlorophyll concentration is averaged over 8-day intervals. We therefore defined the convection shutdown time as the first time in each calendar year when the heat flux remained positive for more than 8 days. Comparing the convection shutdown time (dashed gray vertical lines in Fig. 2) with the chlorophyll

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