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Spatial and temporal variations in high turbidity surface water off the Thule region, northwestern Greenland

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ABSTRACT

Glacial meltwater discharge from the Greenland ice sheet and ice caps forms high turbidity water in the proglacial ocean off the Greenland coast. Although the timing and magnitude of high turbidity water export affect the coastal marine environment, for example, through impacts on biological productivity, little is known about the characteristics of this high turbidity water. In this paper, we therefore report on the spatial and temporal variations in high turbidity water off the Thule region in northwestern Greenland, based on remote sensing reflectance data at a wavelength of 555 nm (Rrs555). The high turbidity area, identified on the basis of high reflectivity (Rrs555 $\geq$ 0.0070 sr^{-1}), was generally distributed near the coast, where many outlet glaciers terminate in the ocean and on land. The extent of the high turbidity area exhibited substantial seasonal and interannual variability, and its annual maximum extent was significantly correlated with summer air temperature. Assuming a linear relationship between the high turbidity area and summer temperature, annual maximum extent increases under the influence of increasing glacial meltwater discharge, as can be inferred from present and predicted future warming trends.

1. Introduction

The Greenland ice sheet has experienced significant net mass loss in recent years. The average rate of ice mass loss from Greenland has been 229 $\pm$ 60 Gt a^{-1} (sea level equivalent of 0.633 mm a^{-1}) over the period 2005 to 2010 (IPCC, 2013). Ice sheet mass loss occurs mainly due to meltwater runoff associated with surface melt and ice discharge at the terminus of a calving glacier. Meltwater runoff from the Greenland ice sheet has increased in response to warming air temperatures in recent years (Hanna et al., 2008) and possibly accounts for more than a half of total ice sheet mass loss (van den Broeke et al., 2009). Outlet glaciers have been thinning rapidly (Ewert et al., 2012; Pritchard et al., 2009; Sørensen et al., 2011), and higher losses at the ice sheet margin where many outlet glaciers are located (Khan et al., 2015) imply significant increases in ice discharge into oceans.

Meltwater from the base of outlet glaciers transports sediments from land to the ocean and spreads as high turbidity water adjacent to the ice sheet (Chu, 2014, Fig. 1). During the summer melt season, a high turbidity plume is frequently observed near the calving front of marine-terminating outlet glaciers in Greenland (e.g., Chauché et al., 2014). The magnitude and timing of turbid meltwater discharge impact on the coastal marine environment. Sediment in glacial meltwater delivers macro and micro nutrients to coastal oceans (Bhatia et al., 2013a, 2013b; Statham et al., 2008) and could potentially impact on marine biological productivity. This effect could explain a strong correlation between modeled Greenland ice sheet runoff and annual maximum chlorophyll concentrations; the latter are used as an indicator of the amount of phytoplankton off the coast of Greenland, based on ocean color satellite data analyses ($R^2 = 0.81$) (Bhatia et al., 2013b; Frajka-Williams and Rhines, 2010). On the other hand, high concentrations of suspended sediment may limit light availability (Retamal et al., 2008). An understanding of the processes generating high turbidity water off the ice sheet and of related variability are thus essential to assess the impact of ice sheet melting on the marine environment. Previous studies have used MODIS visible satellite images to measure spatial variations in sediment concentrations and the extent of high turbidity

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Fig. 1. Turbid glacial meltwater discharge from a glacier to the ocean. The photo was taken from a helicopter off western Greenland (71.3°N, 53.0°W) on 11 July 2012.

water, in particular in Kangerlussuaq Fjord off southwestern Greenland (Chu et al., 2009; Hudson et al., 2014; McGrath et al., 2010). However, Kangerlussuaq Fjord is located at the margin of a narrow, confined proglacial river and its environment is therefore significantly different from that of the coastal ocean. To better understand the impact of glacial meltwater input on the ocean environment, we need to focus on high turbidity water in the open oceans. However, there is little quantitative information regarding the extent and variability of high turbidity water in open coastal ocean off the Greenland ice sheet.

In mid-latitude open coastal regions, where oceans are affected by river runoff, normalized water-leaving radiance at a wavelength of 555 nm (nLw555: mW cm^{-2} μm^{-1} sr^{-1}) is commonly used to analyze the distribution of turbid water (e.g., Caballero et al., 2011, 2014; Saldías et al., 2012). Caballero et al. (2014) showed that the development of turbid plumes off southwestern Spain was influenced by discharges from the Guadalquivir river and by precipitation. Saldías et al. (2012) revealed that turbid plumes with an extent > 1000 km^2 occur off central Chile following large-scale river runoff events associated with strong southward winds. However, this method has not been applied to the proglacial ocean off Greenland thus far.

In this study, we focus on the behavior of high turbidity water to identify the impact of glacial meltwater on marine coastal environments off Greenland. The aim of the present study is to analyze variations in the spatial extent of high turbidity water in the open ocean off the Greenland ice sheet and to investigate temporal variation mechanisms. Targeting at the Thule region in northwestern Greenland, we use Aqua/MODIS satellite data from 2002 to 2014.

2. Study area

This study focuses on an area consisting of relatively open fjords/ocean off the Thule region in northwestern Greenland (76–78°N, 65–75°W) (Fig. 2a). Several studies of glacier dynamics around Inglefield Bredning, in the northern area of Steensby Land, have recently been conducted (Dawes and van As, 2010; Porter et al., 2014; Sugiyama et al., 2015). Inglefield Bredning is a 10–15 km wide and 100 km long fjord with maximum depth >900 m (Fig. 2b). Seven outlet glaciers (about 1–7 km wide) terminate in this fjord from the northern flank of Inglefield Bredning. Heilprin and Tracy Glaciers are the largest marine-terminating glaciers in the region (about 5–7 km wide), discharging into the eastern margin of the fjord at rates > 1000 m a^{-1} (Porter et al., 2014). Bowdoin Glacier flows into Bowdoin Fjord, a part of the Inglefield Bredning fjord system, at a rate of ~500 m a^{-1} (Sugiyama et al., 2015). Four outlet glaciers (about 2–7 km wide) discharge into Wolstenholme Fjord, in the southern area of Steensby Land, but relatively little is known about the dynamics of these glaciers. Moreover, a number of land-terminating glaciers and ice caps are located near the coastline of fjord systems. Meltwater and sediment discharge from these glaciers and ice caps is affecting fjords/ocean in the study area. Because ice mass loss is increasing in the northwestern part of Greenland (Khan et al., 2010), studying this region is important to investigate and monitor the influence of glacial meltwater on the ocean environment. Furthermore, between autumn and spring, sea ice covers nearly the entire ocean surface in this region; however, in summer, a large portion of sea ice melts and open ocean appears (see Section 3.3). The ocean environment in this area is thus significantly affected by glacial meltwater discharge in summer, when both continental ice and sea ice melt.

3. Data and methods

3.1. High turbidity water satellite data

Satellite remote sensing of seawater optical properties is the most efficient technique to detect high turbidity water over a broad area. As described below, turbidity of near-surface water is well represented by remote sensing reflectance at a wavelength of 555 nm (Rrs555: sr^{-1}). Rrs555 data used for this study were obtained from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua multispectral platform. We used the level three data with a spatial resolution of about 0.0417° and temporal resolution of eight days. The period of analysis was from July to August (the period corresponding to open water in summer; see Section 3.3) during 2002–2014. These data products were downloaded from NASA's Ocean Color Web (http://oceancolor.gsfc.nasa.gov).

3.2. Detection of high turbidity water

Coastal ocean waters with high sediment concentrations have a spectral peak in remote sensing reflectance at wavelengths of 550–600 nm (IOCCG, 2000). Caballero et al. (2011, 2014) measured the extent of high turbidity water in a marine region that was influenced by the Guadalquivir estuary using the following relationship;

$$\mathrm{nLw555} = F_0 \times \mathrm{Rrs555} \quad \left(\mathrm{mW\ cm^{-2}\ \mu m^{-1}\ sr^{-1}}\right), \tag{1}$$

where F_0 is annual spectral mean extraterrestrial solar irradiance. In the 545–565 nm band on Aqua, the F_0 value corresponds to 186.09 mW cm^{-2} μm^{-1} (Neckel and Labs, 1984). The value of nLw555 defined by Equation (1) correlates better with the concentration of suspended sediments in near-surface waters than other wavelengths and has been frequently used as tracer to detect high turbidity river plume (Lahet and Stramski, 2010; Nezlin and DiGiacomo, 2005; Nezlin et al., 2005, 2008; Otero and Siegel, 2004; Thomas and Weatherbee, 2006; Valente and da Silva, 2009). Previous studies adopted $\mathrm{nLw555} = 1.3$ mW cm^{-2} μm^{-1} sr^{-1} as a threshold to detect a high turbidity plume boundary (Caballero et al., 2011, 2014; Nezlin and DiGiacomo, 2005; Nezlin et al., 2005; Otero and Siegel, 2004; Valente and da Silva, 2009). We thus identified the ocean area covered with high turbidity water (high turbidity area) based on the condition that $\mathrm{Rrs555} \geq 0.0070$ sr^{-1}, as per the previously-used