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Optical properties in waters around the Mendeleev Ridge related to the physical features of water masses

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ABSTRACT

Irradiance profiles were measured during the Korean 2012 summer Arctic Ocean cruise and optical properties were studied. The optical attenuation coefficient in all surface waters was low, as the nutrients in the surface layers became exhausted and phytoplankton growth was only possible at the subsurface where optimal conditions of nutrients and sufficient illumination existed. This high attenuation zone was at about 40–60 m. The attenuation properties were categorized to three types. Type-1 waters had weaker maximum attenuation coefficients and were located at the Chukchi Plateau and the north margin of the study region. Type-2 water had an intense maximum of attenuation coefficient up to 0.56/m located on west flank of Mendeleev Ridge and continental slope of East Siberian Sea. Two integral parameters, attenuation depth and optical thickness, were mapped by spatial distribution. The attenuation depth was basically shallower (40 m) to the west and deeper to the east (100 m). The averaged optical thickness at the level of 30–60 m was the main zone of high attenuation. Both the optical attenuation property and the physical features of the water indicated two subsurface water masses: one is the cold shelf water well mixed with river water and transported to the east by a subsurface current along the East Siberian Slope. The other is the warmer water from the Pacific with lower nutrients and transported to the northwest along the north margin of the observed region. A cyclonically re-circulated branch of shelf water passing over the Chukchi Abyssal Plain was described in this study.

1. Introduction

The absorption capacity of seawater to solar radiation is important to oceanic thermal structure (Chang and Dickey, 2004). As solar radiation entering into the ocean is mainly in visible wavebands, optical observation is important for solar energy absorption in seawater.

In the Arctic, sea ice is a major factor influencing solar radiation penetration into the ocean. More than 80% of solar radiation is reflected back to space from the surface of snow and ice, but less than nine percent of the solar radiation energy arriving to open water is similarly reflected. Over the past few decades Arctic seasonal sea ice has decreased in extent and concentration (Tucker et al., 2001; Lindsay and Zhang, 2005). The summer extent of the Arctic sea ice cover reached a minimum in September 2007 (Stroeve et al., 2008; Perovich and Richter-Menge, 2009), followed by a new minimum record on September 19, 2012 [http://nsidc.org/arcticseaicenews/2012/09/arctic-sea-ice-extent-settles-at-record-seasonal-minimum/]. Reduced internal ice stress allows a more efficient coupling of wind forcing to the upper ocean, and increases the flux of warm Pacific Summer Water (Shimada et al., 2001; Steele et al., 2004) into the basin and caused the catastrophic changes of sea ice (Shimada et al., 2006). Sea ice retreat influences the Arctic atmosphere-ice-ocean system (Perovich et al., 2007). An increase in open water has an accelerating effect on ice–albedo feedback and sea ice retreat (Perovich et al., 2008).

The propagation of light in the ocean is influenced not only by the molecular structure of seawater, but also by colored dissolved organic matters (CDOM), suspended detritus and phytoplankton. These substances influence the propagation and attenuation of sunlight with depth. In the Canada Basin, the distribution of CDOM is relatively uniform and its influence on optical property is easy to recognize (Wozniak and Dera, 2007). The influence of the detritus is most important in the blue and red wavelengths, which can be conveniently determined from multi-spectral instrument measurements. Phytoplankton in seawater also absorbs solar radiation for photosynthesis, so the depths of the maximum chlorophyll-a and the maximum attenuation coefficient typically coincide (Manizza et al., 2005).

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The radiance, irradiance, and the derived diffuse attenuation coefficients are the apparent optical properties (AOP), which describe the more realistic radiative conditions in the water. In the polar region, light enters the ocean through leads or the partly ice free surface, and the adjacent sea ice adds it own impacts to AOP. Dickey et al. (2006) demonstrated that the diffuse attenuation coefficients are quasi-inherent optical properties since they often depend only weakly on the ambient light field. Close relationships often exist between the vertical diffuse attenuation coefficient $K_d(\lambda)$and the absorption coefficient $a(\lambda)$. $K_d(\lambda)$ can be separated into four types of contributions due to the various constituents (e.g., water, phytoplankton, detritus, and CDOM) in analogy to the absorption coefficients (see Morel, 1988; Gordon, 1991; Morel and Maritorena, 2001).

The Korean 2012 summer cruise studied a quasi-rectangular region between 170°E-150°W, 75–79°N, including the Mendeleev Ridge, the Chukchi Abyssal Plain, the Chukchi Cap, and the Northwind Ridge (Fig. 1). Woodgate et al. (2007) labeled this area as the Mendeleev Ridge and Chukchi Borderland (CBLMR) region. The cruise from August 4 to September 6 of 2012 was organized by the Korea Polar Research Institute (KOPRI) and used the Korean icebreaker ARAON. The water sources of upper ocean in the observed area are complex. This part of Canada Basin is dominated by Pacific Water, whereas in the Makarov Basin, just west of the study area, it is dominated by Atlantic source water (Jones et al., 1998). In the observed area the surface waters from Pacific and Atlantic meet together. Below the halocline, Atlantic waters are carried by a topographically-steered boundary current (Woodgate et al., 2007). Atlantic Water of the lower halocline is upwelled onto the Chukchi Sea slope/shelf to mix diapycnally with less dense Pacific Water (Woodgate et al., 2005). This enhanced shelf break upwelling can be expected to increase the availability of nutrients to the shallower shelves (ACIA, 2005).

Runoff into the East Siberian Sea discharges materials that includes suspended matter and nutrients (Gordeev et al., 1996; Wegner et al., 2003). The total suspended matter exported from the Russian territory is 102×10^6 t/year, and 25.15×10^6 t/year of total enters the East Siberian Sea (Gordeev, 2006). Freshwater affects stratification in much of the Arctic Ocean (Schlosser et al., 2002), with runoff transported in the Transpolar Drift over a time scale of about three years (Jahn et al., 2010). Advection of inflows from marginal shelves and seas (Gordeev, 2006), as well as rivers import nutrients to support phytoplankton growth (Matsuoka et al., 2009).

Ice-free continental shelves often experience intense seasonal blooms of phytoplankton owing to favorable nutrient and light conditions (Hill and Cota, 2005). Ice edge blooms are a conspicuous feature in the seasonal cycle of Arctic ecosystems with the high production in the East Siberian Sea (Perrette et al., 2011). These occur when water, rich in nutrients, is first exposed to sunlight during springtime sea-ice melt (Popova et al., 2010). Enhanced solar radiation into the ocean through leads or waters in the marginal ice zone (MIZ) enables photosynthesis in icy water. However, sea ice shades most sunlight from entering into the ocean and lowers the illumination of the underlying ocean, which limits phytoplankton growth although some seasonal conditions benefit phytoplankton growth in the summer. Since 1998, open water area in the Arctic has increased at the rate of 0.07×10^6 km^2 a^{-1}, with the greatest increases in Siberian sectors, which lead to higher rates of annual production (Pabi et al., 2008).

Annual primary production is generally controlled by nutrient availability, so the surface concentrations of nitrate, phosphate and silicic acid in Arctic waters approach detection limits after the spring bloom (Sakshaug, 2003). The nutrients supplied by Pacific Winter Water combined with light penetration without sea ice cover could produce a prominent chlorophyll *a* maximum layer (Nishino et al., 2008).

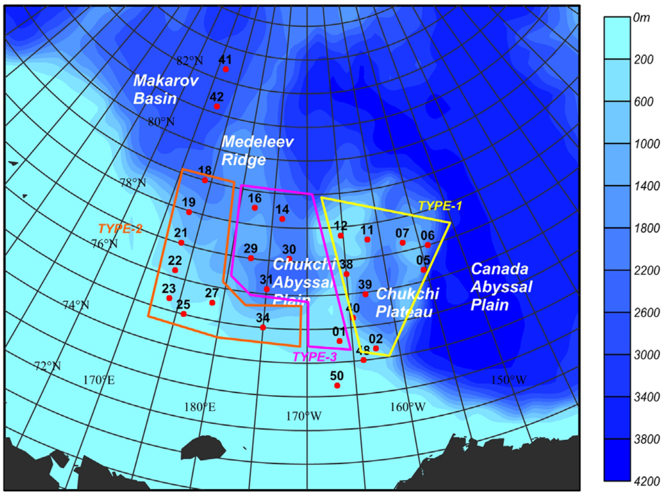

Fig. 1. Locations of stations with available irradiance data (red points). Areas with similar optical types are delineated by colored polygons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Biophysical effects are an important interaction between physical and ecological processes in the upper ocean (Dickey, 1991; Sathyendranath et al., 1991; Siegel et al., 1995). Phytoplankton absorb solar energy via pigments and thereby modify upper ocean temperature (Morel, 1988; Strutton and Chavez, 2004). The increased water temperature speeds up ice melting and changes the temperature profile of the upper ocean. It is reported that in high latitude regions, the surface temperature warms by 0.1–1.5 °C in spring/summer as a result of this absorption (Manizza et al., 2005). The presence of phytoplankton also reduces the vertical penetration of heat and cools subsurface water (Nakamoto et al., 2000). The altering of the water optical properties may change the density field of the ocean and the dynamical response of the oceanic layers to surface wind stress forcing (Shell et al., 2003). Therefore, spatial distribution of optical properties is usually taken into account in ocean numerical models (Jerlov, 1976).

In the Arctic, the optical properties of seawater are not only related to biological processes, but also to physical oceanographic water masses. Previous studies suggested that bio-optical properties in polar waters are markedly different from lower-latitude ecosystems with highly packaged cells and lower chlorophyll-specific absorption (Mitchell and Holm-Hansen, 1991; Mitchell, 1992; Sathyendranath et al., 2001). The absorption of light by phytoplankton is also species and size dependent (Yentsch and Phinney, 1989).

Measurements for optical properties in the Arctic Ocean are still rare (e.g. Mitchell, 1992; Pegau, 2002). In this study, data on irradiance, chlorophyll-a, and nutrients collected during the Korean 2012 summer cruise are used to describe the attenuation features of incident solar radiation.

2. Measurement instruments, data, and method

A high-resolution optical profiling system was used to measure irradiance and radiance in the upper water column (Model PRR-800, Biospherical Inc. San Diego, USA). The instrument includes a separate unit, Model PRR-810, measuring downwelling irradiance from the sea surface. This PRR system is configured to measure at 18 wavebands: 313, 380, 412, 443, 490, 510, 520, 532, 555, 565, 589, 625, 665, 683, 710, 765, 780 and 875 nm with 10 nm bandwidth. A compact-CTD (ALEC Inc., Kobe, Japan) was deployed together with PRR-800, and is equipped with temperature,