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Global assessment of benthic nepheloid layers and linkage with upper ocean dynamics

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ABSTRACT

Global maps of the maximum bottom concentration, thickness, and integrated particle mass in benthic nepheloid layers are published here to support collaborations to understand deep ocean sediment dynamics, linkage with upper ocean dynamics, and assessing the potential for scavenging of adsorption-prone elements near the deep ocean seafloor. Mapping the intensity of benthic particle concentrations from natural oceanic processes also provides a baseline that will aid in quantifying the industrial impact of current and future deep-sea mining. Benthic nepheloid layers have been mapped using 6,392 full-depth profiles made during 64 cruises using our transmissometers mounted on CTDs in multiple national/international programs including WOCE, SAVE, JGOFS, CLIVAR-Repeat Hydrography, and GO-SHIP during the last four decades. Intense benthic nepheloid layers are found in areas where eddy kinetic energy in overlying waters, mean kinetic energy 50 m above bottom (mab), and energy dissipation in the bottom boundary layer are near the highest values in the ocean. Areas of intense benthic nepheloid layers include the Western North Atlantic, Argentine Basin in the South Atlantic, parts of the Southern Ocean and areas around South Africa. Benthic nepheloid layers are weak or absent in most of the Pacific, Indian, and Atlantic basins away from continental margins. High surface eddy kinetic energy is associated with the Kuroshio Current east of Japan. Data south of the Kuroshio show weak nepheloid layers, but no transmissometer data exist beneath the Kuroshio, a deficiency that should be remedied to increase understanding of eddy dynamics in un-sampled and under-sampled oceanic areas.

1. Introduction

Optical instruments have been used for many decades to measure turbidity in bodies of water to estimate particle abundance and distribution (Biscaye and Eittreim, 1977; Gardner et al., 2017; Jerlov, 1953). It has long been known that particle concentrations are elevated in the euphotic zone resulting mostly from primary production of phytoplankton (up to 100's to 1000's $\mu g\,l^{-1}$), or river discharge into lakes or oceans (μg's to g's/l). Particles are not long-term conservative components in water because they can sink or rise depending on their density, thus moving across isopycnals, as well as being advected or subducted with the surrounding water. Consequently, particles can transport mass downward even through a stratified water column. Some dissolved or colloidal elements/compounds can adsorb onto particles and be transported downward more rapidly than through settling, diffusional or turbulent mixing, or subduction. Optical measurements have also shown that although particle concentrations in the open ocean decrease to very low values in the water column deeper than about 100–200 m (5–12 $\mu g\,l^{-1}$; Brewer et al., 1976; Gardner et al., 1985), particle concentration can increase near the seafloor, sometimes very significantly (100's–1000's $\mu g\,l^{-1}$: Gardner et al., 1985; Hill et al., 2011). Satellite ocean color data can be used to map particle concentrations globally in surface waters (Gardner et al., 2006; Henson et al., 2010; Stramski et al., 2008). High-resolution vertical measurements throughout the water column primarily depend on CTD hydrocasts, which provide lower horizontal and temporal resolution than satellite data. Profiling floats or gliders with attached optical instruments increase temporal and spatial resolution (Johnson et al., 2009), however most of them presently profile to 2000 m or less. Gliders that will profile to 6000 m are being built. All of these instruments can yield important high-resolution data from multiple sensors simultaneously.

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The geographic variability of particle concentrations near the seafloor is orders of magnitude greater than in the mid-water column (Biscaye and Eittreim, 1977). Their synthesis of data in the North and South Atlantic show areas of high concentrations in the Western North Atlantic and in the Argentine Basin. Their initial hypothesis was that the high concentrations were caused by sediment eroded and resuspended by deep boundary currents generated by polar waters sinking and moving equatorward. Also noted was a spatial association between elevated nepheloid layer particulate matter concentrations (PM) and eddy kinetic energy (EKE) (Hollister and McCave, 1984) or bottom trapped topographic Rossby waves (Grant et al., 1985), however, no global map of bottom concentrations existed. Weatherly and Kelley (1985) suggested that cold filaments of Antarctic Bottom Water were passing through a region south of Nova Scotia in the Western North Atlantic where the dynamics of sediment resuspension was investigated for several years during the High Energy Benthic Boundary Layer Experiment (HEBBLE). The state of general understanding about nepheloid layers 30 yr ago was reviewed by McCave (1986), and many of the concepts have not changed. However, most of the data in this paper were collected since that review, giving us a much clearer picture of global geographic distribution, intensity, and variability. New physical measurements and models have also improved our understanding of dynamics in the ocean. In this paper we present the first global maps of bottom particle concentrations, thickness of the nepheloid layer, and integrated particle mass within bottom nepheloid layers compiled from transmissometer data we have collected during the last four decades. We compare these data with global maps of EKE, benthic energy dissipation, mean near-bottom kinetic energy, and refer to newly published time-series measurements in benthic nepheloid layers to better understand the causes, likely location, and variability of strong and weak nepheloid layers.

2. Methods and data

Transmissometers were integrated with CTDs and lowered to the seafloor on 64 cruises occupying 6,392 stations. Transmissometers used in WOCE, JGOFS, SAVE and other open ocean projects up until about year 2000 were 25 cm pathlength, SeaTech instruments with a 660 nm LED light source. One cruise during the HEBBLE program (R/V Knorr cruise 74, 1974) used a 1-m folded pathlength SeaTech instrument, as did one cruise in the Western North Atlantic (R/V Oceanus cruise 134, 1983).

The methods for using the 25-cm path length SeaTech transmissometers are given in papers published for those projects (Gardner et al., 1985, 1993) and in more detail on the Ocean Data View (ODV) web site: https://odv.awi.de/fileadmin/user_upload/odv/data/Transmissometer/info). Explained briefly, a transmissometer measures in volts (0–5 volts (V)) the transmission (T) of light across a path of known length (r). Voltage is then converted to beam attenuation of light (c) by the equation:

$$V/5 = T = e^{-cr},$$

which can be rewritten as

$$c = -(1/r) * \ln(T)$$

Data from transmissometers with different path lengths can thus be compared using the same equation.

Light from a red LED is scattered and/or absorbed by water (c_w), particles in the water column (c_p), and colored dissolved organic matter (c_{CDOM}), the sum of which is defined as beam attenuation (c). Thus, $c = c_w + c_{CDOM} + c_p$. In the red spectrum used for our measurements, scattering and absorption by CDOM is considered negligible in most open ocean waters, so attenuation by particles (c_p) equals the total attenuation measured (c) minus the attenuation by water (c_w). SeaTech transmissometers were factory calibrated in particle-free water and the electronics were adjusted so that $c_w = 0.364$. An initial dry air reading was made at the factory and any drift of the instrument could be detected and corrected by comparison with the air reading in the field during an expedition.

Processing of the data included data averaging (1 or 2 db binning), examination and removal of transient spikes, determination of water column minimum value, adjustments for light source drift based on air readings, and final calibration by regressions of particulate mass (PM) or particulate organic carbon (POC) concentrations versus c_p, when PM or POC data were collected.

We transitioned to WetLabs C-STAR transmissometers in ~2000, as SeaTech ceased production and the CLIVAR Repeat Hydrography program started. The WetLabs C-STARs used a 660 nm LED, and the instruments were converted to improved 650 nm LEDs around 2013. Each instrument was factory calibrated in particle-free water and internal firmware was used to subtract attenuation due to water (c_w) from the output data stream. Later WetLabs added an algorithm to correct for instrument internal temperature hysteresis as the external temperature varied quickly in the upper water column. We had developed our own temperature correction with the SeaTech transmissometers (Gardner et al., 1993). The voltage was corrected for drift in the instrument by using factory and field air and blocked beam readings:

$$\mathrm{Tr} = \left((V_{\mathrm{Sig}} - V_{\mathrm{Block}})/(V_{\mathrm{Fac}} - V_{\mathrm{Block}})\right) * (V_{\mathrm{FacAir}}/V_{\mathrm{FieldAir}}),$$

where

- V_{Sig} is the measured output voltage,
- V_{Block} is the output voltage with the beam blocked during calibration,
- V_{Fac} is the factory clean-water value,
- V_{FacAir} is the factory measured voltage output in air,
- V_{FieldAir} is the field measured voltage output in air.

WetLabs C-STAR instruments were used on the CLIVAR Repeat Hydrography/GO-SHIP cruises, but we rarely had the opportunity to collect and filter calibration samples on these cruises, which for us were "ships of opportunity" for data collection. Shipboard technicians were instructed to clean the transmissometer windows prior to each cast and to do a pre-cast air calibration through the CTD every 20 casts and at the beginning and end of the cruise. When FieldBlock and FieldAir are taken several times during the cruise, the calibration values can be linearly interpolated for every day in the cruise between the dates when calibrations occurred and applied to the data. So, if the sensor shift is not linear over the duration of the expedition, it can be accounted for by interpolation.

Without in situ samples we could not establish a known concentration for the minimum values in the water column nor was there particle-free water available on the ship for calibration. Thus we resorted to using the common method proposed by SeaTech of using the cruise minimum voltage or a cruise-average minimum on each cast. We later set this value to zero. This means we can't compare particle minima between oceans, however, the uncertainty in measurements at the low minimum values from many different instruments with many different operators over 4 decades convinced us this was the best solution. Filtration sampling by Brewer et al. (1976) and our own measurements in many oceans shows minimum concentrations of about 5–12 $\mu g\, l^{-1}$. The purpose of this paper is to quantify properties of nepheloid layers such as the thickness and "excess mass" of particles, which requires subtracting the "clear water" concentrations. One could add