Marine Geology 385 (2017) 304–327

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Invited review article

Benthic storms, nepheloid layers, and linkage with upper ocean dynamics in the western North Atlantic

Wilford D. Gardner [a,*], Brian E. Tucholke [b], Mary Jo Richardson [a], Pierre E. Biscaye [c]

[a] Texas A&M University, College Station, TX 77845, USA
[b] Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[c] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA

ARTICLE INFO

Article history:
Received 20 July 2016
Received in revised form 20 December 2016
Accepted 30 December 2016
Available online 10 January 2017

Keywords:
Benthic storms
Benthic nepheloid layer
Abyssal currents
Seafloor erosion
Eddy kinetic energy
Cyclogenesis

ABSTRACT

Benthic storms are episodic periods of strong abyssal currents and intense, benthic nepheloid (turbid) layer development. In order to interpret the driving forces that create and sustain these storms, we synthesize measurements of deep ocean currents, nephelometer-based particulate matter (PM) concentrations, and seafloor time-series photographs collected during several science programs that spanned two decades in the western North Atlantic. Benthic storms occurred in areas with high sea-surface eddy kinetic energy, and they most frequently occurred beneath the meandering Gulf Stream or its associated rings, which generate deep cyclones, anticyclones, and/or topographic waves; these create currents with sufficient bed-shear stress to erode and resuspend sediment, thus initiating or enhancing benthic storms. Occasionally, strong currents do not correspond with large increases in PM concentrations, suggesting that easily erodible sediment was previously swept away. Periods of moderate to low currents associated with high PM concentrations are also observed; these are interpreted as advection of PM delivered as storm tails from distal storm events. Outside of areas with high surface and deep eddy kinetic energy, benthic nepheloid layers are weak to non-existent, indicating that benthic storms are necessary to create and maintain strong nepheloid layers. Origins and intensities of benthic storms are best identified using a combination of time-series measurements of bottom currents, PM concentration, and bottom photographs, and these should be coupled with water-column and surface-circulation data to better interpret the specific relations between shallow and deep circulation patterns. Understanding the generation of benthic nepheloid layers is necessary in order to properly interpret PM distribution and its influence on global biogeochemistry.

Contents

* Corresponding author.
E-mail addresses: wgardner@ocean.tamu.edu (W.D. Gardner), btucholke@whoi.edu (B.E. Tucholke), mrichardson@ocean.tamu.edu (M.J. Richardson), biscaye@ldeo.columbia.edu (P.E. Biscaye).

http://dx.doi.org/10.1016/j.margeo.2016.12.012

1. Introduction

Jerlov (1953) reported the discovery of cloudy (turbid) layers near the seafloor using optical measurements, and he summarized views that these layers might be generated by earthquakes (later shown to generate submarine slides and turbidity currents), volcanic eruptions, or seafloor erosion by strong bottom currents. Ewing and Thorndike (1965) called these turbid bottom waters "nepheloid layers" (from the Greek word "nephos", meaning cloud) and stated that "the nepheloid layer is a permanent and widespread feature, not a transitory response to a storm or earthquake nor restricted to the vicinity of a submarine canyon."

The spatial variability of the benthic nepheloid layer (hereafter 'nepheloid layer') in the Atlantic Ocean was mapped by Eittreim et al. (1976) based on an optical index using Lamont-Doherty nephelometer data (Thorndike, 1975). Biscaye and Eittreim (1977) converted this optical index to particulate matter (PM) concentrations using the measured mass of particles filtered from water samples collected from hydrographic casts at the depths where the optical measurements were made. From samples taken over a 12-year period they found that near-bottom PM concentrations varied spatially by a factor of 70 across the western North Atlantic Basin, with the highest concentrations near the western margin of the basin (Fig. 1). They suggested that the strong nepheloid layer at the margin was caused by seafloor erosion beneath the Deep Western Boundary Current (DWBC), the cold, deep southward flow of bottom water formed at high latitudes in the North Atlantic. Tucholke and Eittreim (1974) examined the nepheloid layer in the southern part of the basin over the Greater Antilles Outer Ridge and the Puerto Rico Trench. The layer there is in Antarctic Bottom Water (AABW) that underlies and generally follows the path of the DWBC, and it is much weaker than the nepheloid layer to the northwest.

Heezen and Hollister (1972, pp. 358–359) suggested that, in addition to mean currents near the sea floor, perturbations from deep eddy-type flows could affect seafloor erosion, suspension, and advection of sediment. Laine (1977) and Laine and Hollister (1981) noted that the strongest nepheloid layers corresponded closely with the mean circulation of a deep gyre system in the basin as proposed by Worthington (1976) and further explained by Hogg (1983) and Hogg et al. (1986). These ideas about patterns of deep circulation have been supported by subsequent models and current measurements (Arbic et al., 2009, 2010; Wright et al., 2013) and are reviewed in detail by Turnewitsch et al. (2013).

Much of what has been inferred about patterns of bottom currents and their effects in eroding and transporting sediment is taken from extensive compilations of bottom photographs that exhibit bedforms and show relative intensity and direction of currents (e.g., Heezen and Hollister, 1972; Hollister and Heezen, 1972; Tucholke et al., 1973, 1985; Hollister and McCave, 1984; McCave and Tucholke, 1986; Hollister and Nowell, 1991). Unfortunately, individual photographs provide little or no information about timing of current events and they have rarely been coupled with direct measurements of currents or bottom-water turbidity.

It wasn't until the late 1970's and early 1980's that time-series measurements of bottom currents were made simultaneously with moored nephelometers for periods longer than a week (Johnson et al., 1976). Large, episodic increases in bottom-water turbidity in the deep ocean were first documented in long time-series measurements (2.5-month duration) using a long-term nephelometer (LTN) moored 20 m above the seafloor on the northwestern Bermuda Rise in the Western North Atlantic (Gardner and Sullivan, 1981). They coined the term "benthic storms" to describe these events. Similar events were later intensely studied on the lower continental rise south of Nova Scotia during the High Energy Benthic Boundary Layer Experiment (HEBBLE) (Hollister and McCave, 1984; Gardner et al., 1985a; Hollister and Nowell, 1991; Pak, 1983; Pak and Zaneveld, 1983; Grant et al., 1985); they have also been studied on the lowermost continental rise and Hatteras Abyssal Plain off the eastern United States (Isley et al., 1990), in the northeast Atlantic (Klein and Mittelstaedt, 1992), and in the Argentine Basin (Richardson et al., 1993). Benthic storms are analogous to dust storms in that the fluid (air/water) moves fast enough to erode and resuspend the underlying sediment, mixing it with the overlying fluid to create clouds of dust/PM that are redistributed downwind/downstream.

McCave (1986) summarized the state of research on nepheloid layers 30 years ago, and since then numerous studies have contributed to understanding their origin and development. Nonetheless, major questions remain: How ubiquitous, variable or persistent are nepheloid layers? What primary driving forces create and maintain the layers? How do surface-water circulation (e.g., the Gulf Stream) and deep-water currents (e.g., the DWBC) affect nepheloid layers? How frequent and intense are benthic storms? Are sustained high current speeds required to both initiate and maintain nepheloid layers or are they generated and maintained primarily by intermittent benthic storms?

In this paper, we first review known characteristics and proposed origins of the permanent nepheloid layer, and we then investigate how