Remote Sensing of Environment 114 (2010) 332–344

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

MODIS imagery of turbid plumes in San Diego coastal waters during rainstorm events

Florence Lahet, Dariusz Stramski *

Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0238, USA

ARTICLE INFO

Article history:
Received 6 November 2008
Received in revised form 13 August 2009
Accepted 20 September 2009

Keywords:
Ocean color
MODIS
Coastal ocean
Turbid plumes
Rainstorm events
Southern California

ABSTRACT

Data of normalized water-leaving radiance, *nLw*, obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite at spatial resolution of 250 m (band 1 centered at 645 nm) and 500 m (band 4 at 555 nm) are used to study turbid plumes in coastal waters of southern California during rainstorm events in winter of 2004–2005. Our study area includes San Diego coastal waters, which extend approximately 25 km offshore between Point Loma and 10 km south of the US–Mexican border. These waters are influenced by terrigenous input of particulate and dissolved materials from San Diego and Tijuana watersheds and non-point sources along the shore. Optimum threshold values of satellite-derived normalized water-leaving radiances at both wavebands were established for distinguishing the plume from ambient ocean waters. These threshold values were determined by searching for a maximum correlation between the estimates of satellite-derived plume area calculated using a broad range of *nLw* values and the environmental variables characterizing rainfall, river discharge, wind, and tides. A correlation analysis involving the amount of precipitated water accumulated during a storm event over the San Diego and Tijuana watersheds was selected as the basis for final determinations of the optimum threshold nLw_{thr} and subsequent calculations of the plume area. By applying this method to a sequence of MODIS imagery, we demonstrate the spatial extent and evolution of the plume during rainstorm events under various conditions of precipitation, river discharge, wind forcing, and coastal currents.

1. Introduction

Ocean color remote sensing offers an attractive approach to distinguish turbid plumes produced by stormwater discharge in the coastal ocean from ambient marine waters. Optical sensors deployed on aircrafts or satellites provide a means to detect plumes over extended spatial and temporal scales that cannot be adequately addressed with traditional analysis of discrete water samples. Plumes are influenced by various factors such as the nature and magnitude of runoff discharged from rivers and other sources, wind, currents, tides, and the buoyancy of water (Stumpf et al., 1993; Garvine, 1995; Chao, 1998; Warrick et al., 2004b; Ahn et al., 2005). Several studies of stormwater plumes in the Southern California Bight showed the potential usefulness of ocean color satellite data for water quality assessment and coastal management (e.g., Ahn et al., 2005; Warrick et al., 2007; Nezlin et al., 2008).

Using satellite observations from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Nezlin and DiGiacomo (2005) analyzed the relationship between the amount of precipitated rainwater and plume characteristics over the San Pedro Shelf, which is adjacent to the coastal watershed within the Los Angeles metropolitan area. By assessing maximum correlation between the plume size and precipitated rainwater, they found that satellite-derived normalized water-leaving radiances, *nLw*, above the threshold value of 1.3 mW $cm^{-2}\mu m^{-1} sr^{-1}$ at 555 nm allowed discrimination of the runoff plume from ambient ocean waters. Nezlin et al. (2005) compared the relationships between plume size derived from SeaWiFS and rainstorm data in different coastal areas of southern California. They showed that the primary factors controlling the relationships include watershed land-use characteristics, watershed size, and land topography.

The objective of this study is to analyze the satellite-derived plume area in relation to environmental parameters during rainstorm events in the San Diego region of southern California. We use ocean color imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) flown aboard the Aqua spacecraft. Two high spatial resolution bands, 1 and 4, within the visible spectral region are used. The MODIS band 1 with a spatial resolution of 250 m has a spectral range of 620–670 nm with a center wavelength of 645 nm. The band 4 with a resolution of 500 m has a spectral range of 545–565 nm centered at 555 nm. Recent studies demonstrated the potential of these bands to monitor water quality in estuarine and coastal waters (Hu et al., 2004; Chen et al., 2007; Shutler et al., 2007).

We examine the time period from December 28, 2004 through March 7, 2005, which represents the third heaviest rainfall season in southern California since records began in 1850 (NOAA National Weather Service, 2007). During that period, repeated and at times long periods of intense rain and runoff had a significant effect on coastal water quality in the San Diego region. We defined several storm events using rainfall data and analyzed eighteen MODIS images. We discuss the determinations of threshold values for satellite-derived water-leaving

* Corresponding author. Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego, La Jolla, 9500 Gilman Dr, CA 92093-0238, USA.
E-mail address: dstramski@ucsd.edu (D. Stramski).

0034-4257/$ – see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2009.09.017

radiances, $nLw(645)$ at 645 nm and $nLw(555)$ at 555 nm, which are used to define a plume. These threshold determinations are based on examining the correlation between the plume area and environmental parameters (rainfall, Tijuana River discharge, wind, tides). Using a sequence of MODIS images, we illustrate the spatial extent and evolution of the plume during selected rainstorm events.

2. Characterization of the study area

The study area extends along the San Diego coastline from approximately Point Loma in the north to 10 km south of the US–Mexican border, and is defined by latitudes of about 32°26′N and 32°41′N and longitudes 117°04′W and 117°22′W (Fig. 1). This area includes the coastal ocean waters extending about 25 km offshore. The enclosed waters of San Diego Bay are not considered for plume determinations, as our interest is focused just on coastal ocean waters adjacent directly to the open ocean. The San Diego Bay is connected with the ocean near Point Loma.

The environmental problems in the study area occur due to the large population of the San Diego-Tijuana metropolitan area and the concentrated commercial, naval, and recreational activities (Schiff et al., 2000). There are multiple sources of particles, organic substances, nutrients, and contaminants that discharge into the coastal ocean in this region (Tran et al., 1997; Zeng & Vista, 1997; Zeng et al., 1997). Significant degradation of coastal water quality is caused by stormwater runoff during episodic rainstorm events, mainly in the winter season (e.g., Characklis & Wiesner, 1997; Davis et al., 2001). In particular, the Tijuana River discharges into the ocean just north of the US–Mexican border. After heavy rains, the Tijuana River carries runoff from the city of Tijuana and from sewage that overflows from the International Wastewater Treatment Plant in Tijuana. Plumes from the river can travel north along the San Diego coast at least as far as Point Loma, or south along the Mexican coast of northern Baja California. The storm drain system also contributes to pollution of coastal waters. Consequently, turbid plumes in coastal waters, especially during storms, represent an environmental hazard due to associated pollutants. The beaches of Imperial Beach north of the Tijuana River mouth were closed during 83 days in 2005.

Our study region is characterized by an arid warm Mediterranean climate with 85% of precipitation occurring during a rainy season from November through March. The average annual precipitation is less than 300 mm. Rainfall is highly variable from year to year and from month to month. Droughts are typical. Floods occur at times, although they are generally short lasting. Climate in the region can vary considerably over short geographical distances. For example, the western slope of the Peninsular Range (the prominent topographic feature of the region) receives about 1 m and the foothills west of the Peninsular Range about 400–500 mm of annual rainfall (Isla & Lee, 2006).

There are eleven hydrologic units in the San Diego region, which are associated with river/stream systems that discharge into the Pacific Ocean (Fig. 2). We have considered the following hydrologic units (from south to north): Tijuana (TIJ), Otay (OT), Sweetwater (SW), Pueblo San Diego (PUE), San Diego (SD), Penasquitos (PEN), and San Dieguito (SDo) (see also Nezlin & Stein, 2005). Whereas the southernmost units (TIJ and OT) are adjacent to the coastal waters of direct interest to our study, the remaining units may also affect the area through the outflow from San Diego Bay or predominant southward transport of coastal waters from the north. The rivers of the region are small but have generally high sediment yields. For example, Tijuana, Sweetwater, and San Diego rivers are characterized by a mean annual flow of 28.9×10^6, 7.42×10^6, and $13.7 \times 10^6 m^3 yr^{-1}$ and a mean annual suspended sediment flux of 0.206×10^6, 0.0043×10^6, and 0.010×10^6 ton yr^{-1}, respectively (Inman & Jenkins, 1999).

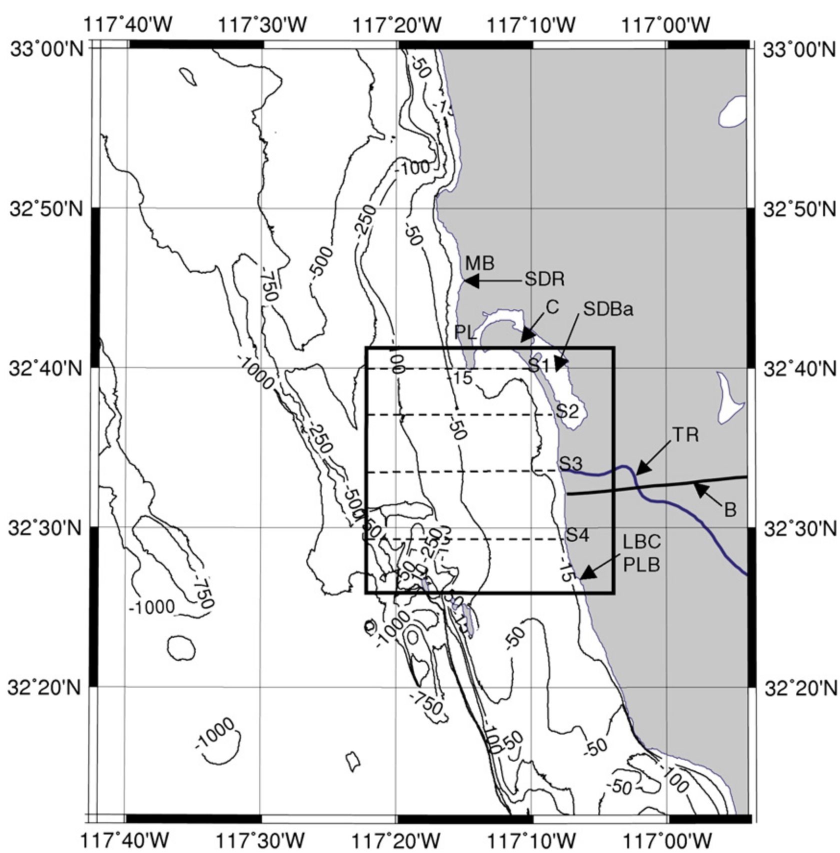

Fig. 1. Map of southern California coastal waters showing the study area (black box). The map specifies the location of Mission Bay (MB), San Diego River mouth (SDR), Point Loma (PL), Coronado (C), San Diego Bay (SDBa), Tijuana River (TR), the US–Mexican border (B), Los Buenos Creek mouth and Punta Los Buenos (LBC and PLB). The bathymetry is shown. The four sections, S1, S2, S3, and S4, for which the offshore extent of plume was calculated (Table 3 and relevant text in Section 4.3) are also shown as dashed lines.