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Coastal river plumes: Collisions and coalescence

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ABSTRACT

Plumes of buoyant river water spread in the ocean from river mouths, and these plumes influence water quality, sediment dispersal, primary productivity, and circulation along the world's coasts. Most investigations of river plumes have focused on large rivers in a coastal region, for which the physical spreading of the plume is assumed to be independent from the influence of other buoyant plumes. Here we provide new understanding of the spreading patterns of multiple plumes interacting along simplified coastal settings by investigating: (i) the relative likelihood of plume-to-plume interactions at different settings using geophysical scaling, (ii) the diversity of plume frontal collision types and the effects of these collisions on spreading patterns of plume waters using a two-dimensional hydrodynamic model, and (iii) the fundamental differences in plume spreading patterns between coasts with single and multiple rivers using a three-dimensional hydrodynamic model. Geophysical scaling suggests that coastal margins with numerous small rivers (watershed areas < 10,000 km^2), such as found along most active geologic coastal margins, were much more likely to have river plumes that collide and interact than coastal settings with large rivers (watershed areas > 100,000 km^2). When two plume fronts meet, several types of collision attributes were found, including refection, subduction and occlusion. We found that the relative differences in pre-collision plume densities and thicknesses strongly influenced the resulting collision types. The three-dimensional spreading of buoyant plumes was found to be influenced by the presence of additional rivers for all modeled scenarios, including those with and without Coriolis and wind. Combined, these results suggest that plume-to-plume interactions are common phenomena for coastal regions offshore of the world's smaller rivers and for coastal settings with multiple river mouths in close proximity, and that the spreading and fate of river waters in these settings will be strongly influenced by these interactions. We conclude that new investigations are needed to characterize how plumes interact offshore of river mouths to better understand the transport and fate of terrestrial sources of pollution, nutrients and other materials in the ocean.

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1. Introduction

As rivers flow into the sea they deliver ecologically and geochemically important loads of water, sediment, nutrients, carbon and pollutants (Beusen et al., 2005; Milliman and Farnsworth, 2011). Recent syntheses suggest that the geochemical output from the combined numerous, small watersheds of the world may surpass the output of the world's large rivers because of an efficiency of transport through these smaller landscapes (Milliman and Syvitski, 1992; Lyons et al., 2002; Wheatcroft et al., 2010; Milliman and Farnsworth, 2011). Because of these loadings, river discharge can influence coastal hydrology, morphology, ecology, biological productivity and environmental quality (Wright, 1977; Milliman and Syvitski, 1992; Jickells, 1998; Rabalais et al., 2002; Wang, 2006; Banas et al., 2009; Reifel et al., 2009; Borges and Gyphens, 2010; Hickey et al., 2010). As humans have modified the landscapes, river corridors, coastal morphology and climate of the earth, the rates and characteristics of river discharge to the sea have changed significantly (Meade, 1982; Humborg et al., 1997; Hagy et al., 2004; Syvitski et al., 2005; Ludwig et al., 2009; Bouraoui and Grizzetti, 2011; Regnier et al., 2013). It is, therefore, important to understand the rates, trends and implications of river discharge to the sea and the spatial and temporal patterns of these materials and their impacts across the seascape.

The primary pathways for many river-discharged materials in the sea are the positively buoyant river plumes that form offshore of river mouths (Fig. 1). These plumes result from fluxes of riverine freshwater and are thin layers of positively buoyant fluid dispersing over and mixing into the seawater (Wright and Coleman, 1971;

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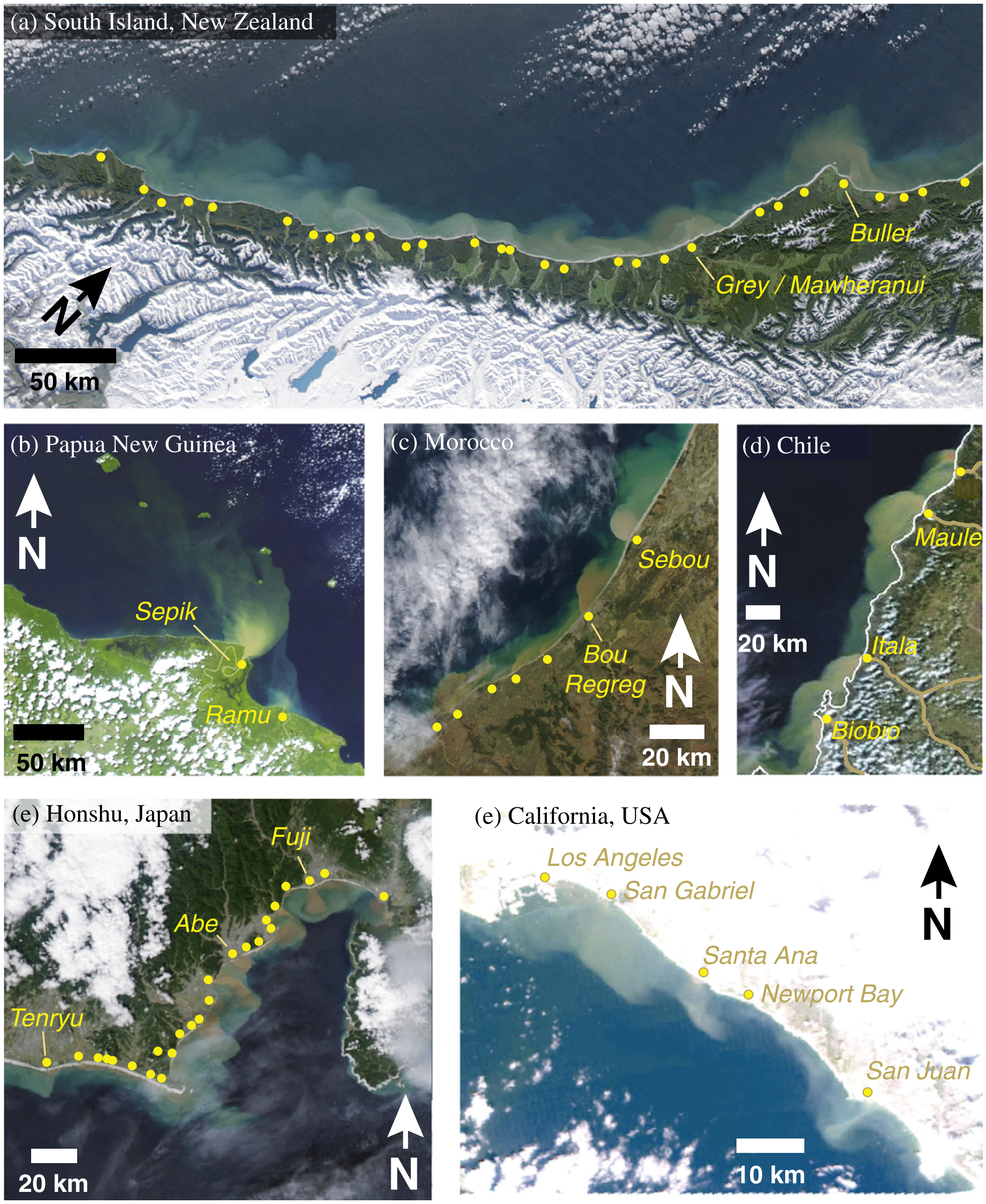

Fig. 1. Examples of coalescing river plumes from remote sensing imagery obtained by NASA's MODIS sensors, including: (a) along the west coast of New Zealand's southern island, (b) two of the largest watersheds of Papua New Guinea, the Sepik and Ramu Rivers, (c) the Moroccan west coast after Warrick and Fong (2004), (d) along Chile's central coast after Saldías et al. (2012), (e) within Suruga Bay of Japan where the Fuji River and numerous other small drainages discharge, and (f) along the urbanized coast of southern California. The locations of river mouths are shown in each image with yellow dots.

Garvine and Monk, 1974; Ingram, 1981; Lewis, 1984; Luketina and Imberger, 1987). Several conditions will influence the physical structure and spatial scales of the river plume, including: the flux and density of water discharged from a river, river mouth geometry and orientation, the strength of the Coriolis effect, and speeds and directions of coastal currents and wind stresses (Chen et al., 2009; Howarth et al., 1996; Karan and Knupp, 2009; Kingsmill, 1995; Kingsmill and Crook, 2003; Liu et al., 2009; MacCready et al., 2009; MacDonald et al., 2007; Peterson and Peterson, 2009; Piñones et al., 2005; Pullen and Allen, 2000; Simpson, 1997; Kourafalou et al., 1996; Lentz and Limeburner, 1995; Geyer et al., 2000; Fong and Geyer, 2001; Hetland, 2005; Whitney and Garvine, 2005; Lentz and Largier, 2006; Pritchard and Huntley, 2006; Valle-Levinson et al., 2007; Hetland and MacDonald, 2008; O'Donnell et al., 2008; Horner-Devine et al., 2009, 2015; Jay et al., 2010). Although considerable variability is found in the hydrodynamics of coastal plumes (Garvine, 1995), plumes generally radiate from rivers and estuaries over horizontal spatial scales that are orders-of-magnitude greater than their vertical thicknesses.

While there have been important developments in the understanding of buoyant plume hydrodynamics, most studies have focused on the plumes generated by single rivers, such as the Amazon, Columbia, Rhone, Merrimack, Connecticut, Eel, or Mississippi, that can dominate salinity and circulation patterns near their mouths (Horner-Devine et al., 2015). Fewer investigations have