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Dispersal forcing of southern California river plumes, based on field and remote sensing observations

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Abstract River plumes are important pathways of terrestrial materials entering the sea. In southern California, rivers are known to be the dominant source of littoral, shelf and basin sediment and coastal pollution, although a basic understanding of the dynamics of these river inputs does not exist. Here we evaluate forcing parameters of a southern California river plume using ship-based hydrographic surveys and satellite remote sensing measurements to provide the first insights of river dispersal dynamics in southern California. Our results suggest that plumes of the Santa Clara River are strongly influenced by river inertia, producing jet-like structures ~10 km offshore during annual recurrence (~two-year) flood events and ~30 km during exceptional (~10-year recurrence) floods. Upwelling-favorable winds may be strong following stormwater events and can alter dispersal pathways of these plumes. Due to similar runoff relationships and other reported satellite observations, we hypothesize that interia-dominated dispersal may be an important characteristic of the small, mountainous rivers throughout southern California.

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Introduction

Rivers plumes are active sites of terrestrial material input into the sea and respond to forcing from discharge inertia, buoyancy, Coriolis, turbulence, and particle settling (Wright 1977; Garvine 1995). This river flux can directly influence coastal sediment budgets, ocean biogeochemistry, pollution patterns, and circulation in coastal waters (e.g., Wheatcroft et al. 1997; Bay et al. 1999; Kudela and Cochlan 2000; Pullen and Allen 2000; Carey et al. 2002). Recent investigations of river–sea margins have focused on small, mountainous watersheds, since they have high yields of sediment discharge, which are largely event-driven (Milliman and Syvitski 1992; Nittrouer 1999; Wheatcroft 2000; Mertes and Warrick 2001; Fuller et al. 2003). Transport and fate of materials discharged by these rivers will be related to river plume spatial and temporal scaling during these discharge events.

Almost 20 million people live in the southern California region, and urban development related to this population has resulted in dramatic changes in terrestrial inputs of water, sediment and pollution (Anderson et al. 1993). The small, mountainous rivers of southern California are the dominant sources of littoral, shelf, and basin sediment (Schwalbach and Gorsline 1985; Inman and Jenkins 1999; Willis and Griggs 2003), although they also provide the largest loads of pollution to the Southern California Bight (surpassing the numerous wastewater treatment plants discharging directly to the continental shelf; Bay et al. 1999). Although dispersal of this river discharge into coastal waters is understood to be important, limited knowledge of the dispersal dynamics exists. For example, it is know that plume waters near river mouths can contain elevated concentrations of nutrients and are excessively turbid (Mertes et al. 1998), even though sediment appears to rapidly settle from these plumes (Mertes and Warrick 2001). It is unknown, however, what forcing parameters are important to the dispersal dynamics of these materials.

In this study we present field and remote sensing observations of plumes from the Santa Clara River, which is a major southern California watershed and the largest sediment source of the Southern California Bight (Schwalbach and Gorsline 1985; Inman and Jenkins 1999). Warrick and Milliman (2003) suggest that the Santa Clara River may undergo hyperpycnal discharge (negative buoyancy flows of sediment along the seabed due to exceptional river suspended sediment concentrations) during large (~five year recurrence interval) flooding events, although these types of plumes have never been observed. Here we focus on discharge forcing of the easily observed hypopycnal (positively buoyant) plume, which can be observed during all flood events and is the dominant pathway for river water, dissolved materials, and at least a portion of the sediment load. Our observations are used to calculate forcing parameters, which are used in turn to provide insights of the forcing dynamics of these plumes.

Study area

The Santa Clara River (Fig. 1) is a large drainage of the Transverse Ranges of southern California and, like all rivers of this region, has ephemeral discharge due to episodic winter rainfall and dry summers (Inman and Jenkins 1999). The exceptionally high sediment production rates of the Santa Clara River are primarily a function of steep landscape underlain by weak sedimentary rocks and intense seasonal precipitation (Scott and Williams 1978; Warrick 2002). High annual variability in flood discharge and sediment loads exists due to precipitation inputs related largely to El Niño-Southern Oscillation (ENSO) phenomena (Inman and Jenkins 1999). Wet, ENSO years (such as 1969 and 1998) can have order of magnitude greater rates of runoff than average annual runoff (40 versus 4 cm/year, respectively; Warrick 2002).

Methods

The Santa Clara River plume was evaluated with river gauging, shipboard hydrography, and satellite remote sensing observations. These observations were used to compute forcing parameters following work of Armi (1986), Garvine (1995) and Geyer et al. (2000). River discharge data were obtained from the US Geological Survey (USGS) stream gauging site 11114000 (Santa Clara River at Montalvo), which is ~6 km from the river mouth and incorporates 99.2% of the 4,220-km^2 watershed. The river channel geometry and slope changes little between the USGS gauge and the mouth, in part due to levees (the channel width at both sites is approximately 0.3 km).

Shipboard observations were conducted during a large flood event in January 1997. The cruise dates captured the entire flood event: rising, peak, and falling discharge conditions (Fig. 2). Peak river discharge was gauged to be 460 m^3 s^{-1} (which suggests a ~2.5-year recurrence interval; Warrick 2002), and total water discharge during the event was ~25×10^6 m^3. At a series of stations (Fig. 1b), CTD (conductivity, temperature and depth) and beam transmission at 660-nm (25-cm path length) profiles and water samples at depth were obtained (complete summaries of instrumentation, techniques and results are provided in Toole and Siegel 2001, and Warrick 2002). Water depth at each station was determined from the shipboard depth sounder, and the CTD carousel was lowered to within ~1 m of this depth to detail as much of the water column as possible.

Remote sensing observations are provided by a multispectral Landsat Thematic Mapper (TM) image

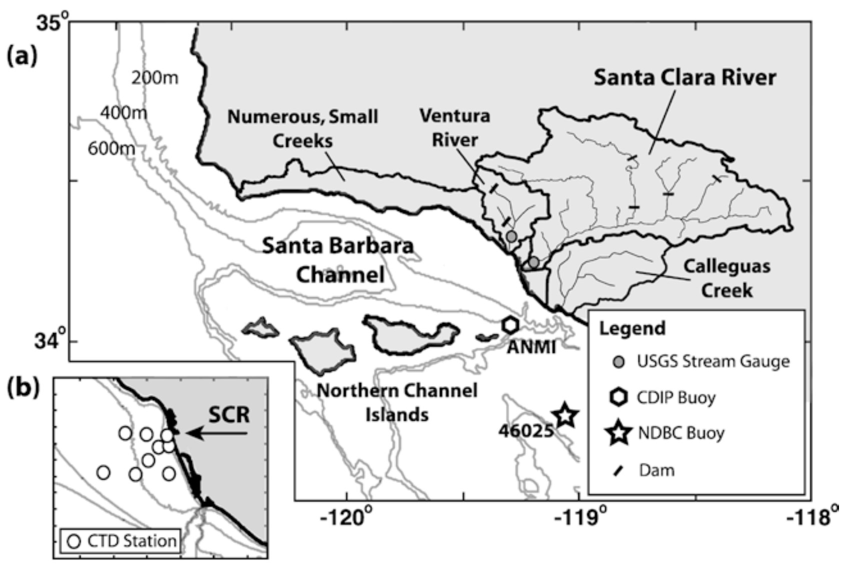

Fig. 1a, b The Santa Clara River drainage and Santa Barbara Channel study area. **a** Location of the drainages, stream gauges and offshore buoys used in this study. **b** Location of the CTD stations offshore of the Santa Clara River (*SCR*) mouth

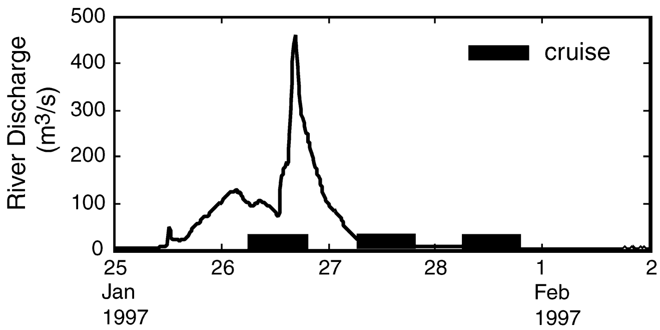

Fig. 2 Discharge in the Santa Clara River at USGS gauging station 11114000 during the January 1997 cruise dates

previously published by Mertes et al. (1998) and new results from the Sea-Viewing Wide-Field-of-View (SeaWiFS) satellite sensor. The Landsat TM image from Mertes et al. (1998) is presented in relative turbidity levels (high to low); the SeaWiFS data were used to calculate suspended sediment concentrations of the surface water using the spectral mixture analysis methods of Warrick et al. (2003). These results have a maximum expected error of ±20 mg/l. SeaWiFS results were compared to surface currents (measured at 5-m depth) at the Coastal Data Information Program (CDIP, http://cdip.ucsd.edu) ANMI site and wind at the NOAA National Data Buoy Center (NDBC, http://www.ndbc.noaa.gov) buoy 46025 (Fig. 1a).

Results and interpretations

Shipboard observations

During 1997, 26 CTD casts were obtained during 26–28 January, which correspond with peak river discharge conditions on 26 January (example water column CTD profiles are shown in Fig. 3). For each station a well-mixed, freshened surface layer was observed in the upper 2–6 m of the water column, which corresponded with extremely turbid waters. Salinity of these surface water layers ranged from 30 to 33 psu, which were measurably lower than the ambient coastal water salinity below the surface plume (33.4±0.1 psu). Further, salinity was freshest and surface plumes were thickest closest to the river mouth (data shown in Warrick 2002).

Four non-dimensional parameters of the January 1997 Santa Clara River plume observations are computed and compared here (Table 1) to evaluate river plume forcing.

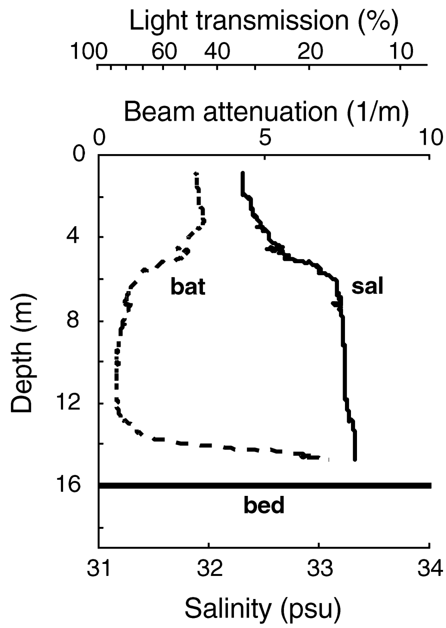

Fig. 3 Example shipboard hydrographic data collected off the Santa Clara River mouth during the January 1997 river plume cruises. Salinity (*sal*, *thick line*) and beam attenuation (*bat*, *dashed line*) profiles from CTD casts within the river plume on 28 January 1997. A scale for percent light attenuation is also given for beam attenuation

The "plume initiation" internal Froude number (F_i) is the ratio of river discharge velocity to buoyancy velocity (Geyer et al. 2000) and is used to compare inertia forcing to buoyancy forcing at the river mouth. A peak river discharge velocity of 0.5 m/s was computed from USGS gauging data (discharge, depth and width) for the 1997 event. Buoyancy velocity can be assessed with the baroclinic pressure anomaly (P_f), which is defined as:

$$P_f = g\int_{-h}^{0}[\rho_0 - \rho(z)]dz \tag{1}$$

where ρ_0 is the ambient seawater density, $\rho(z)$ is the density at depth z, and h is the total water depth (Geyer et al. 2000). Values of P_f ranged from 25 to 107 Pa (average = 50 Pa) within the plume (the maximum value was measured directly offshore of the river mouth on 26 January 1997). Using the hydrostatic assumption, the maximum measured sea-level displacement is then 1.1 cm, which is equivalent to a velocity anomaly of 0.46 m/s using Bernoulli's equation. This suggests that F_i was >1 during the 1997 plume observations

Table 1 Plume parameters from observations of the Santa Clara River discharge for the January 1997 event

Parameter	Name	Santa Clara River values	Significance
F_i	"Plume initiation" Froude	>1	Inertia dominant (*at plume initiation*)
F_p	"Within plume" Froude	1.1–1.6	Inertia important (*within plume*)
K_m	"Mouth" Kelvin	~0.1	Inertia > rotation (*at river mouth*)
K_p	"Plume" Kelvin	~1	Inertia~rotation (*within plume*)
L_i	Inertia radius	10 km	River inertia length scale

(Table 1), and under these conditions, Garvine (1995) assumes that the plume dynamics near the river mouth will be dominated by momentum flux from the river.

The "within plume" Froude number (F_p) is defined to be the plume velocity divided by the lowest mode internal wave speed (Armi 1986) and is used to evaluate inertia forcing within the plume. Although direct measurements of the plume velocity were not made, buoyancy velocities (calculated above) suggest that they ranged between 0.2 and 0.5 m/s. The lowest mode internal wave speed (C_i) was approximated for coastal river plumes from the CTD casts using the following equation:

$$C_i = (g' h_p)^{0.5} \quad (2)$$

where g' is the reduced gravitational constant (i.e., buoyancy anomaly; $g' = g\ \Delta\rho/\rho_p$, where $\Delta\rho$ is the density difference between plume water, ρ_p, and the ambient ocean water, ρ_0), and h_p is the thickness of the plume (Pond and Pickard 1983, p. 238). Internal wave speeds were computed for each cruise station and ranged between 0.15 and 0.30 m/s within the plume (plume average = 0.22 m/s). These velocities were used to compute F_p at each station, which ranged from 1.1 to 1.6 (average = 1.4; Table 1). These Froude numbers are high compared to other river and estuarine plumes, which further suggests strong inertia forcing from the river (Geyer et al. 2000).

The "mouth" Kelvin number (K_m) can be used to compare inertia and rotational forcing at the river mouth and has been defined as the ratio of the width of the plume at the mouth (L_m) to the deformation radius (L_D), which is defined to be:

$$L_D = \frac{(g' h_p)^{1/2}}{f} \quad (3)$$

where g' is the maximum measured buoyancy anomaly of the plume (~0.02 m/s^2), h_p is the thickness of the plume (~5 m), and f is the Coriolis parameter (~8.2×10^{-5}/s). Thus, for the Santa Clara River L_D is approximately 4 km, which produces a K_m of ~0.1 (Table 1). This suggests that inertial forces at the mouth are more important than rotation effects (Garvine 1995).

Finally, the "plume" Kelvin number (K_P) is defined as the ratio of plume width (L_P) to L_D (Garvine 1995). The L_P of the Santa Clara River plume was estimated to be on the order of 5–10 km from the field data collected on 26 and 27 January (see Warrick 2002). Thus, K_P is on the order of unity (Table 1), which suggests that the Santa Clara River plume is influenced by both inertia and rotation once significantly offshore.

The four plume parameters above suggest that inertial forces are important to the initial advection of the Santa Clara River plume. Under these conditions, Garvine (1995) has suggested that the discharge momentum flux will influence a spatial scale approximately equal to the inertial radius (L_i), which is defined to be:

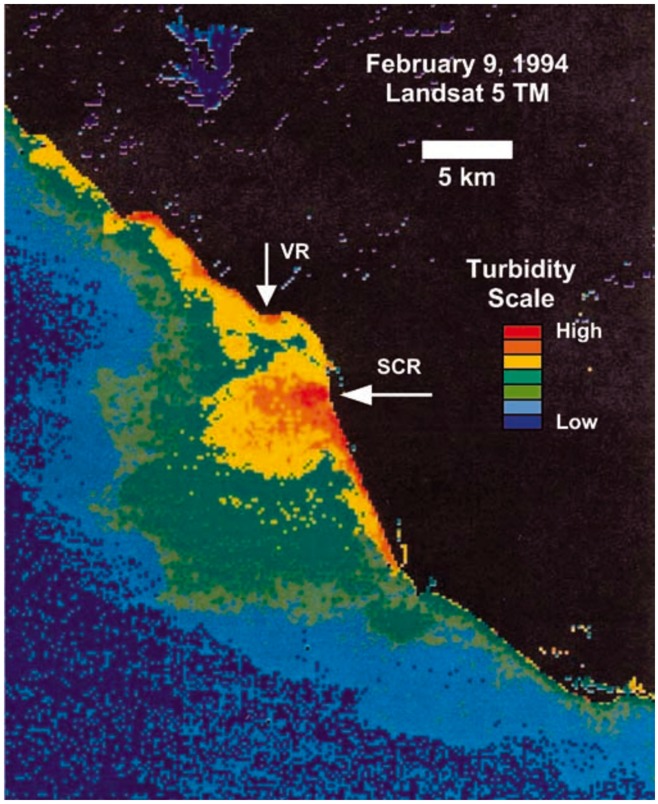

Fig. 4 Landsat TM image of turbidity levels in the Santa Clara River (*SCR*) and Ventura River (*VR*) plumes following a small storm (after Mertes et al. 1998)

$$L_i = \frac{u_f}{f} \quad (4)$$

where u_f is a representative velocity within the plume. Direct measurements of plume velocity were not made, although calculated river discharge and plume buoyancy velocities suggest u_f may be on the order of 0.5 m/s for the 1997 event. Thus, during the 1997 event the inertial forces of the Santa Clara River should have dominated plume advection within ~10 km of the river mouth.

Remote sensing observations

The spatial distribution of river discharge can be evaluated with a Landsat TM image of the Santa Barbara Channel, published by Mertes et al. (1998) and shown in Fig. 4. This image was obtained on 9 February 1994, immediately following a 2-day, 6-cm rainfall event (as recorded in gauges within the City of Santa Barbara), and it is the only Landsat image of the river mouth region obtained during high flow. Unfortunately, the Santa Clara River gauge was not operational during this winter period, although a maximum discharge of 15 m^3/s was measured at the nearby Ventura River gauge (USGS Station 11118500; Fig. 1a) on 8 February 1994. This peak discharge has an annual recurrence probability (p) of 85% (recurrence interval = 1.18 years), and is 8 times

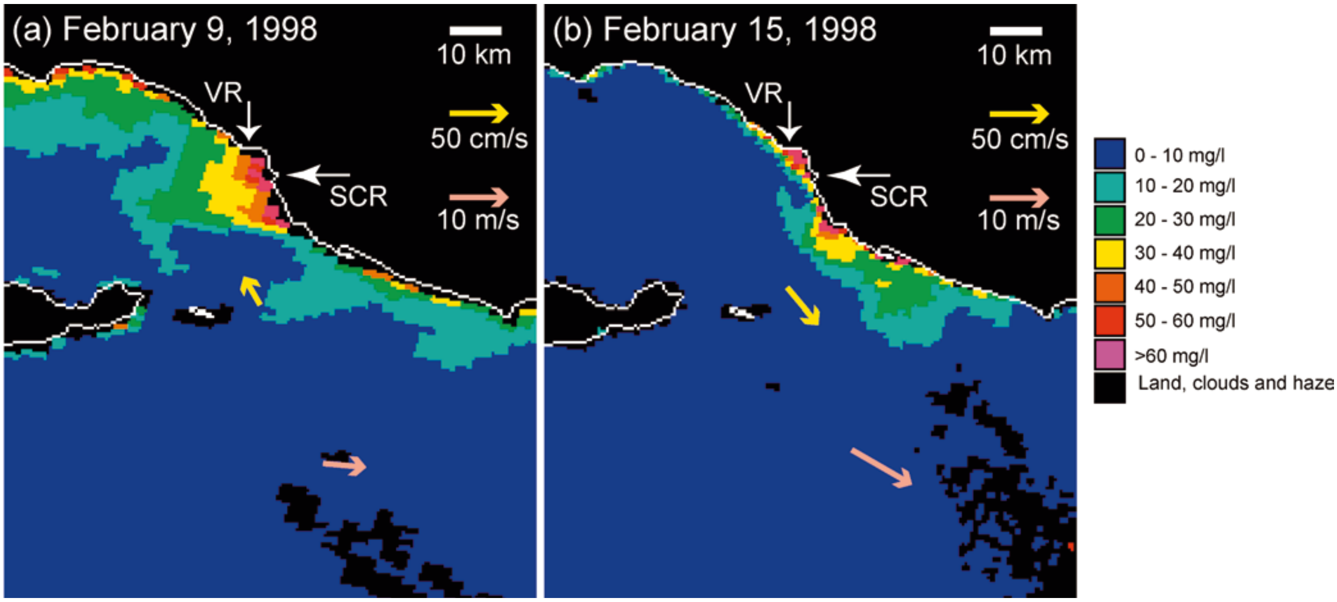

Fig. 5a, b SeaWiFS imagery of the suspended sediment concentrations in the Santa Clara River (*SCR*) and Ventura River (*VR*) plumes following large storms of 1998. **a** 9 February 1998, and **b** 15 February 1998. Mean surface currents at ANMI (*yellow arrows*) and mean wind vectors at NDBC 46025 (*pink arrows*) are shown for the 12 h prior to the imagery

smaller than the expected annual peak discharge (recurrence interval = 2.3 years) for the Ventura River of 120 m^3/s (Warrick 2002). Thus, the discharge that produced the plume in Fig. 4 was not an unusually large event. The plume is, however, jet-like for 5–10 km (as shown through the yellow color; Fig. 4). This jet-like structure is highly indicative of an inertia-dominated plume (Fischer et al. 1979), and it appears to last over an inertial radius scale (L_i) calculated above (~10 km) for a significantly larger event. Farther than ~10 km from the river mouth, the Santa Clara River plume becomes radially dispersed, as shown by the green and light blue colors.

Inertial forces will dissipate due to friction along the plume boundaries, after which the plume will be more subject to other forces. Buoyancy and rotational effects would tend to force the Santa Clara River plume poleward due to a geostrophic balance (e.g., see Kourafalou et al. 1996a). This post-inertial forcing can be observed in two SeaWiFS images obtained after peak discharges from the Santa Clara River, when current and wind conditions differed significantly (Fig. 5).

During the 9 February 1998 image, regional winds were ~7 m/s from the west and mean surface currents were poleward (0.25 m/s) into the Santa Barbara Channel (Fig. 5a). The resulting plume is observed to advect ~30 km westward into the Santa Barbara Channel, which compares well to the L_i scale of 30 km suggested for the large event (peak discharge~3,000 m^3/s; peak velocity~1.5 m/s; flood recurrence interval~10 years).

The 15 February 1998 image (Fig. 5b) shows the plume rotated sharply to the southeast of the river mouth, which is coincident to strong northwest winds (12 m/s) and equatorward surface currents of ~0.4 m/s. Further, no jet-like plume structure can be identified immediately in front of the Santa Clara River mouth (i.e., $L_i < 5$ km), presumably because flow in the Santa Clara River had almost ceased. Thus, the plume inertia, which had likely dropped due to falling discharge rates, was overcome by strong forcing by winds and currents. Hence, although the Santa Clara plume may have been initially dominated by inertia forcing, local winds and currents have dramatically altered plume advection.

Discussion and conclusions

Rivers of southern California deliver large amounts of freshwater, sediment and pollution to the Southern California Bight during energetic discharge events. Our compilation of shipboard and satellite observations provides the first insights into the dispersal forcing and dynamics of this river dispersal into the coastal ocean. These results suggest that river inertia and coastal wind and current forcing are important to dispersal transport.

Our Santa Clara River results show that much of the river discharge is advected in a jet-like hypopycnal plume due to high initial discharge inertia (Table 1 and Fig. 4). This jet-like plume structure was observed to extend ~10 km offshore during annual recurrence runoff events and ~30 km offshore during exceptional runoff events. As inertia is dissipated (largely due to turbulent mixing), the plume will be much more subject to bouyancy and rotational forcing (Fischer et al. 1979). However, as observed by many researchers (Kourafalou et al. 1996b; Pullen and Allen 2000; Geyer et al. 2000) and remote sensing here (Fig. 5b), the surface plume is dramatically altered by local wind stresses and coastal currents. In southern California these storm-event wind stresses are commonly poleward (downwelling favorable) prior to and during peak river discharge, then equatorward (upwelling-favorable) following discharge (Dorman and Winant 2000). Complicating this pattern, however, are regional current patterns through the Santa Barbara Channel, which respond to strong regional pressure gradients and may override the wind-generated currents (Harms and Winant 1998).

The dispersal mechanisms reported here are similar to those found in the Eel River plume of Northern California. Using similar methods, Geyer et al. (2000) found the Eel River plume to be forced by inertial effects within ~10 km of the river mouth, although the strong wind stresses in this region are also important to plume advection within and outside of this distance (Pullen and Allen 2000). Not unexpectedly, the Santa Clara and Eel River plumes experience somewhat similar wind patterns during and after storms, although wind stresses are generally lower within the Southern California Bight (Winant and Dorman 1997).

These two inertial-dominated rivers (Santa Clara and Eel) classify into the "case 1", or fast-flowing, river plume types of Garvine (1995), for which strong boundary fronts and significant across-shore fluxes are expected (such as shown for thermal outfalls by Scarpace and Green 1973). These river plume types are significantly different from most estuarine and large river systems (or, "case 2"), which advect largely in the alongshore direction due to geostrophic momentum balances (Garvine 1995).

It is important to note that the Santa Clara River is not especially unique to southern California with respect to these forcing parameters. Discharge velocities and channel slopes of other southern California rivers are very similar to the Santa Clara River (Browlie and Taylor 1981). Further, remote sensing results of Mertes and Warrick (2001) show a number of jet-like plume shapes from the largest southern California rivers (most notably from the Santa Ana River). We suggest, therefore, that our results can serve as a model for river dispersal from other southern California rivers.

In this context, future work on the dispersal of river sediment, pollutants, nutrients, and other materials in southern California should consider the rapid across-shore transport that will be produced by strong inertial forcing from the rivers. This across-shore transport will likely have important biogeochemical and ecosystem impacts, since river water and constituents are delivered rapidly to coastal waters kilometers away from the river mouths.

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