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# Winds and the orientation of a coastal plane estuary plume

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[1] Based on a calibrated coastal plane estuary plume model, ideal model hindcasts of estuary plumes are used to describe the evolution of the plume pattern in response to river discharge and local wind forcing by selecting a typical partially mixed estuary (the Cape Fear River Estuary or CFRE). With the help of an existing calibrated plume model, as described by Xia et al. (2007), simulations were conducted using different parameters to evaluate the plume behavior type and its change associated with the variation of wind forcing and river discharge. The simulations indicate that relatively moderate winds can mechanically reverse the flow direction of the plume. Downwelling favorably wind will pin the plume to the coasts while the upwelling plume could induce plume from the left side to right side in the application to CFRE. It was found that six major types of plumes may occur in the estuary and in the corresponding coastal ocean. To better understand these plumes in the CFRE and other similar river estuary systems, we also investigated how the plumes transition from one type to another. Results showed that wind direction, wind speed, and sometimes river discharge contribute to plume transitions. **Citation:** Xia, M., L. Xie, and L. J. Pietrafesa (2010), Winds and the orientation of a coastal plane estuary plume, *Geophys. Res. Lett.*, *37*, L19601, doi:10.1029/2010GL044494.

## 1. Introduction

[2] River-dominated, relatively fresh water discharging into an adjacent continental shelf forms a river or estuary plume, which is a very prominent feature in the coastal ocean and is quite evident in AVHRR satellite imagery both in the visible and infra-red bands as well as in photographs taken from aircraft and even ships.

[3] The freshwater plume is generally characterized by reduced salinity, relative to adjacent coastal waters, and modifies other water properties such as temperature, nutrients, and phytoplankton in the adjacent coastal ocean, thereby affecting the water quality and sediment structure of the local ecosystem. For example, the Cape Fear River Estuary (CFRE) plumes of fresh and low salinity water carry loads of sediment, nutrients, and pollutants into Long Bay and affect the regional water quality and ecosystem [*Mallin et al.*, 2005]. However most of the previous plume studies mainly relied on observations and satellite studies, such as was reported on by *Hickey et al.* [1998]. Though coastal plume dynamics modeling studies do exist, only a few focused on the plume alignment patterns [*Takano*, 1954, 1955; *Zhang et al.*, 1987; *Liu et al.*, 2009]. River-derived fresh water discharging into an adjacent continental shelf forms a trapped river plume that propagates to its right in a narrow region along the coast due to the effect of the Earth's rotation in the Northern Hemisphere [*Chao and Boicourt*, 1986; *Zhang et al.*, 1987]. Downwelling-favorable winds have also been found to reinforce the natural outwelling mode and further pin the plume to the coastline, while upwelling-favorable winds tend to move the plume water offshore [*Zhang et al.*, 1987; *Hickey et al.*, 1998; *Fong and Geyer*, 2002]; the influence of southeasterly to southwesterly quadrant winds contribute to the plume transport towards the northeast, while the northeasterly and northwesterly winds could drive the plume transport to the southeast as in the findings of the Patos Laggon coastal plume, Brazil [*Marques et al.*, 2009]. Furthermore, moderate to strong winds could fully reverse the plume and change its structure [*Zhang et al.*, 1987; *Kourafalou et al.*, 1996]. *Marques et al.* [2010] even concluded that local wind influence is principally transfer the momentum directly to the water column in their Patos Lagoon coastal plume dynamics study.

[4] Being that there is no detailed studies that summarize the plume transition under wind induced external forcing, including how the plume direction changes in response to different wind speeds and directions remains an interesting question. This study undertaken here is aimed to improving our understanding of the relationship between the orientation of a typical small to median size estuary and wind speed and direction by an application to CFRE.

## 2. Study Area: The Cape Fear River Estuary

[5] The CFRE is a typical small to median size estuary. The Cape Fear River, a 322 km river that flows through the heart of the North Carolina (NC) piedmont, has the largest watershed in NC. The Black River joins the Cape Fear River 24 km above Wilmington, and the Northeast Cape Fear River enters the system at Wilmington. The freshwater discharge from the Cape Fear River, the Northeast Cape Fear River, and the Black River converges in the Cape Fear Estuary and then flows into Long Bay (Figure 1). The head of the CFRE connects to the eastern end of Long Bay on the Atlantic seaboard. Because of the in-welling of coastal waters into this partially mixed estuary due to the combined effects of the astronomical tides and wind forcing [*Pietrafesa and Janowitz*, 1988], this region is an extremely

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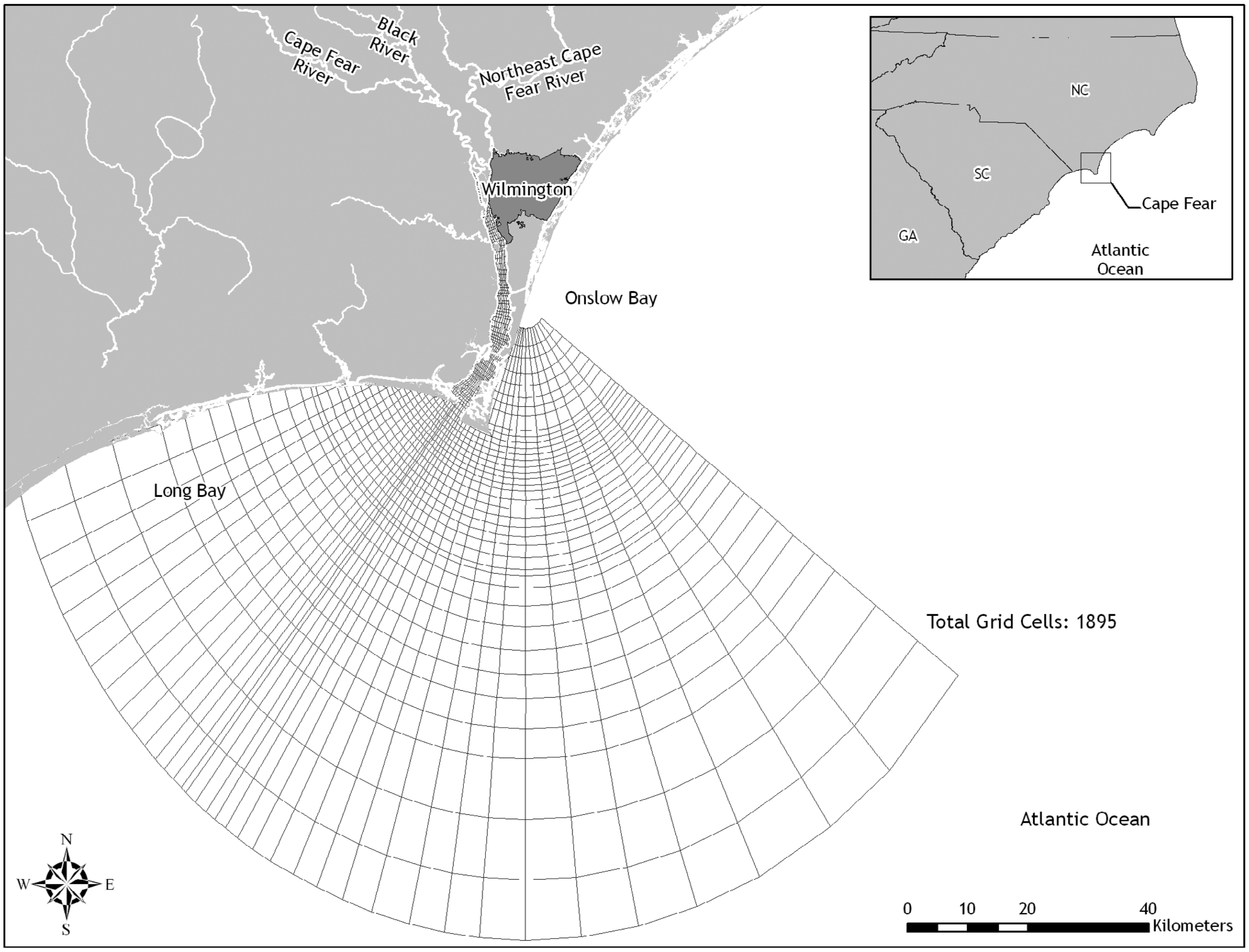

**Figure 1.** The location of the Cape Fear River Estuary and numerical model grid.

important nursery for juvenile fish, crabs, and shrimp [*Patrick and Moser*, 2001].

## 3. Methodology

### 3.1. Hydrodynamic Model and Numerical Settings

[6] The numerical model used in this study is based on a general-purpose three-dimensional hydrodynamic model, Environmental Fluid Dynamics Code or EFDC [*Hamrick*, 1992]. *Xia et al.* [2007] describe the circulation model used in this study in detail, and also presents a much more thorough validation of its water level and salinity predictions. Only key points are repeated here: in the simulations of the CFRE plume, 11 sigma layers were utilized in the vertical dimension with “finer” levels used near the free surface since sufficient vertical resolution is important for plume modeling. An orthogonal curvilinear grid was used in the model simulation with higher resolution in the river, estuary, and river mouth to adequately resolve the complex coastline. Higher resolution grids were generated near the mouth of the CFRE and over the plume region: it is 500 m at the mouth of the bay, telescoping out to 7 km at the coastal ocean. The calibrated three-dimensional hydrodynamics model was then used to examine the river plume through a series of sensitivity experiments.

### 3.2. Numerical Experiment Design

[7] In order to investigate the distribution of the CFRE plume due to external forcing, a suite of numerical experiments were conducted under various external forcing. Overall, we ran 384 experiments to test the sensitivities of the plume model that included 8 different wind directions: northerly (NN), northeasterly (NE), easterly (EE), southeasterly (SE), southerly (SS), southwesterly (SW), westerly (WW), northwesterly (NW); 6 different wind speeds: 2, 5, 10, 15, 20, and 25 in m/s; and 8 different runoffs settings including 102, average river discharge 202, 304, 1000, 1500, 2000, flood record 3238 and 4000 in $m^3/s$ (cms) (Table 1). All the simulations were run with a five-day spin up time and had the same model setup except the above-mentioned variable wind forcing and river discharge, which is consistent with that of *Xia et al.* [2007].

[8] As a follow-up study to *Xia et al.*’s [2007] and its implication to other river estuaries, this study applied the calibrated plume model to simulate the response of the

**Table 1.** A Total 384 Model Experiments for Eight Different Wind Directions[a]

| | 102 | 202 | 304 | 1000 | 1500 | 2000 | 3238 | 4000 |
|---|---|---|---|---|---|---|---|---|
| 2 | Y | Y | Y | Y | Y | Y | Y | Y |
| 5 | Y | Y | Y | Y | Y | Y | Y | Y |
| 10 | Y | Y | Y | Y | Y | Y | Y | Y |
| 15 | Y | Y | Y | Y | Y | Y | Y | Y |
| 20 | Y | Y | Y | Y | Y | Y | Y | Y |
| 25 | Y | Y | Y | Y | Y | Y | Y | Y |

[a] X-axis is the river discharge ($m^3/s$) and y-axis is the wind speed (m/s).

plume to river discharge and wind forcing. Then a summary of the plume type variation is given.

## 4. Plume Type and the Summary of the Plume Distribution

[9] As is widely known, plumes will align themselves with the coast to their right, in the absence of wind forcing [*Takano*, 1954, 1955; *Chao and Boicourt*, 1986; *Zhang et al.*, 1987; *Xia et al.*, 2007]. To determine what happens to the boundary hugging plume when wind forcing is applied, we tested 8 different wind directions and 6 different speeds for each direction with total 384 numerical experiments. The model results are presented below. It is of note that *Garvine* [2001] summarized principal plume characterizations assumed by large scale buoyant plumes; either to the left, to the right or to the right with a prominent bulge. However, our simulations show that smaller plumes can transition between Garvine's three manifestations (Figure 2).

[10] Overall, we found that six plume characterizations dominated in the Cape Fear region, defined as: Type I - with the plume turning right and being along the south coast (Figure 2a); Type II - with the plume being apart a little bit from the south coast (Figure 2b); Type III– was shown as the plume distribution of Figure 2c along the estuary orientation; Type IV- with the plume moving directly to the south of the CFRE (Figure 2d); Type V - with the plume

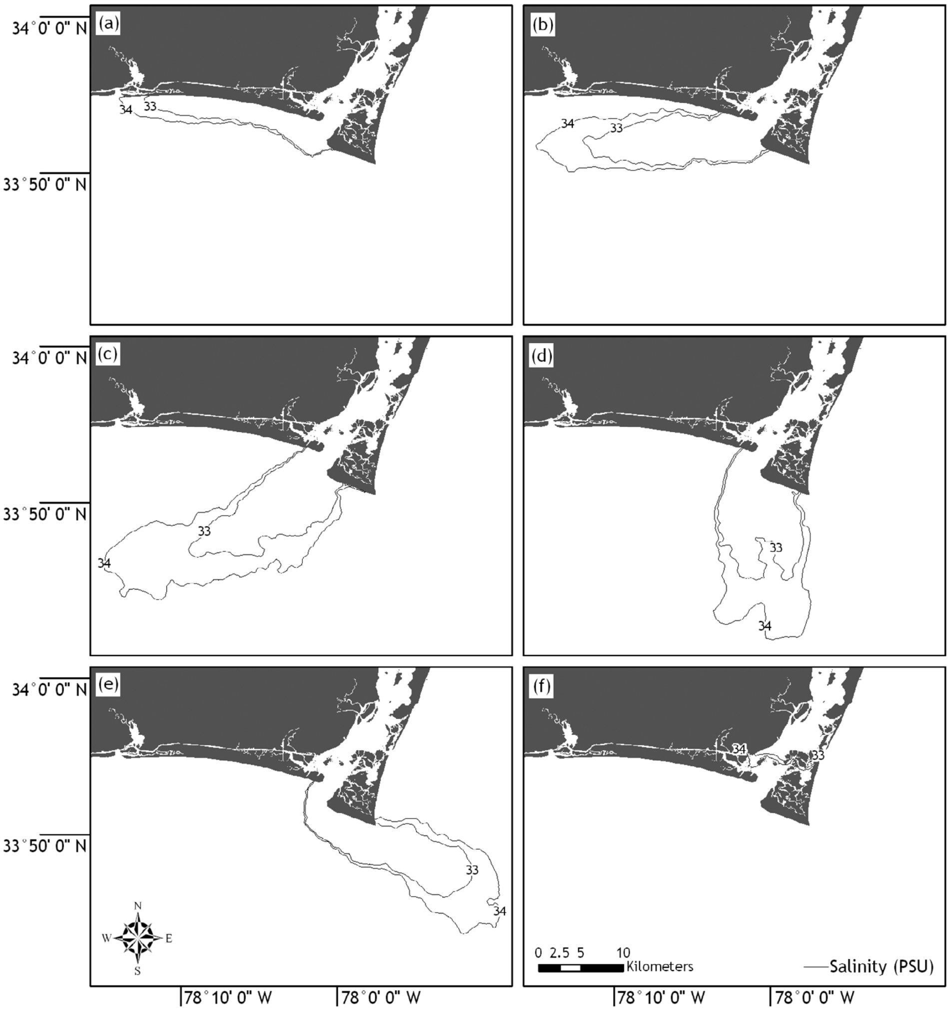

**Figure 2.** (a) Type I. The sea surface salinity fields forced by southerly wind with speed of 15m/s and river discharge of 1000 $m^3/s$. (b) Type II. Surface salinity fields forced by wind speed of 25m/s and river discharge of 1000 $m^3/s$ under the response to northeasterly winds. (c) Type III. Surface salinity fields forced by wind speed of 5m/s and normal discharge under northerly winds. (d) Type IV. Surface salinity fields forced by wind speed of 5m/s and normal discharge under northwesterly winds. (e) Type V. Surface salinity fields forced by wind speed of 10m/s and river discharge of 304 $m^3/s$ under west winds. (f) Type VI. Plume structure under southeasterly winds and normal river discharge with a wind speed of 20 m/s. All used the results after 5 day simulation.

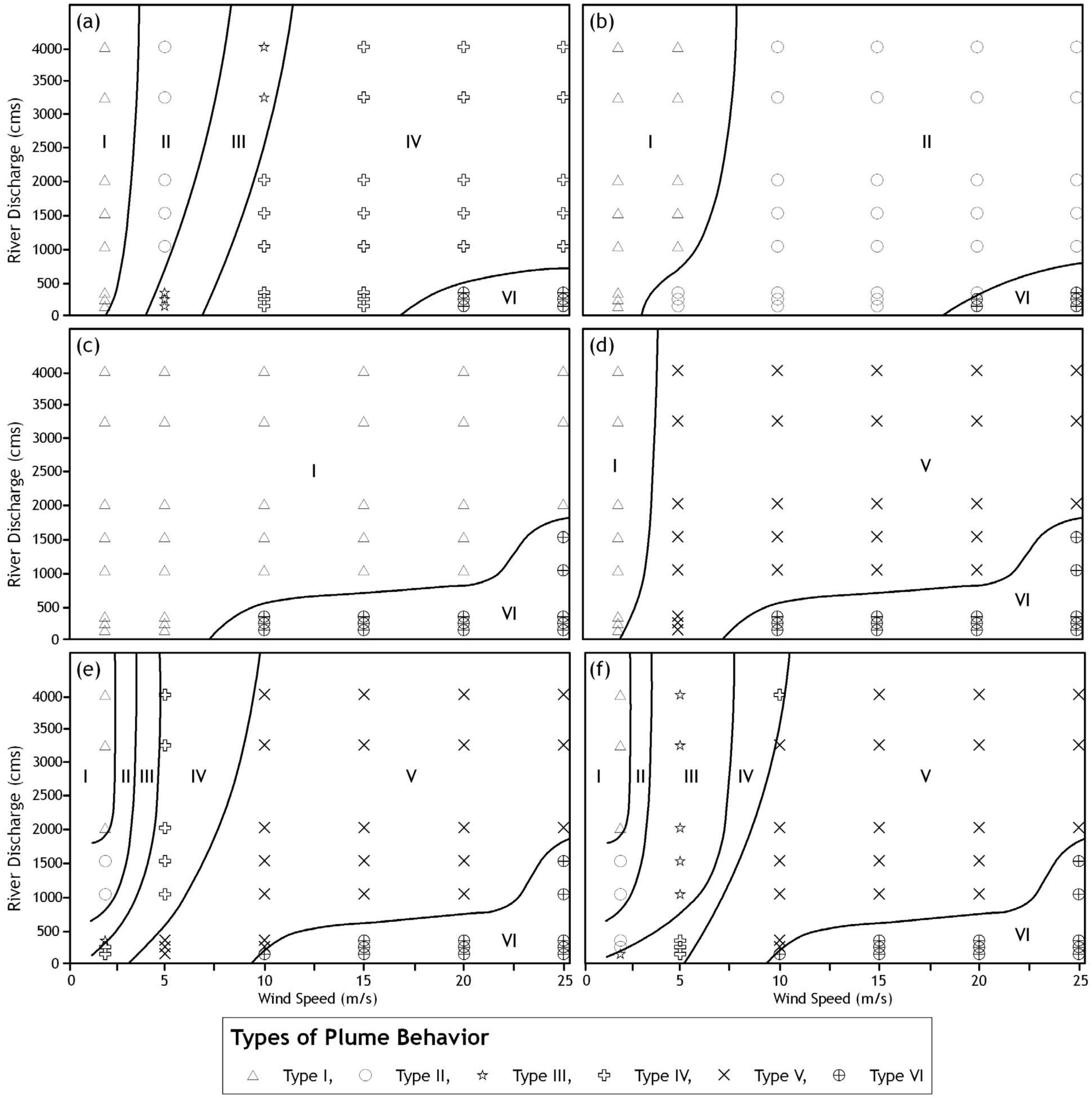

**Figure 3.** The plume behavior type under the different physical settings (a) northerly wind, (b) northeasterly wind, (c) easterly wind, southeasterly wind and southerly wind (d) southwesterly wind, (e) westerly wind, and (f) northwesterly wind.

turning left and pouring into Onslow Bay (Figure 2e); and Type VI - in which the plume can't move out of the river estuary and could even reverse the water flow, thus moving back into the estuary (Figure 2f). Based on the above, the possible plume behavior types are shown in Table 2 and Figure 3.

[11] The plume distribution under northerly wind conditions is shown in Figure 3a. We can see that northerly wind induced plumes fall within the Type I, Type II, Type III and Type IV categories. While the majority of northerly wind influenced plumes are predominately within Types III and IV, they can turn into either a type I or Type II under the combination of reduced wind magnitudes and increased runoff (Figure 3a). From Figure 3b, the northeasterly wind induced plumes are shown to be predominantly Type II but can turn to a Type I under increasing river runoff and either weak or medium wind speeds (<7m/s). Under the strong wind forcing (>20m/s) and either weak or medium river discharge (<500 $m^3/s$), plumes will be reversed and coastal water would move back to the estuary.

[12] The plume distributions under the southeasterly, easterly, and southerly downwelling-favorable wind forcing are either Type I or Type VI (Figure 3c). For example, wind-driven plumes could turn to the Type VI with high wind forcing (>10 m/s) and weak or medium river discharge. As river discharges are typically greater and wind speeds are usually less than those of Type VI, most plumes will of Type I.

**Table 2.** A Total of 384 Model Results for Eight Different Wind Directions[a]

| SP | CF | BR | NE | RD | NN | NE | EE | SE | SS | SW | WW | NW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 79 | 12 | 11 | 102 | 1 | 1 | 1 | 1 | 1 | 1 | 4 | 3 |
| 2 | 158 | 23 | 21 | 202 | 1 | 1 | 1 | 1 | 1 | 1 | 4 | 2 |
| 2 | 237 | 35 | 32 | 304 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 2 |
| 2 | 700 | 160 | 140 | 1000 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 |
| 2 | 1050 | 240 | 210 | 1500 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 |
| 2 | 1400 | 320 | 280 | 2000 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1618 | 773 | 847 | 3238 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 2000 | 1000 | 1000 | 4000 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5 | 79 | 12 | 11 | 102 | 3 | 2 | 1 | 1 | 1 | 5 | 5 | 4 |
| 5 | 158 | 23 | 21 | 202 | 3 | 2 | 1 | 1 | 1 | 5 | 5 | 4 |
| 5 | 237 | 35 | 32 | 304 | 3 | 2 | 1 | 1 | 1 | 5 | 5 | 4 |
| 5 | 700 | 160 | 140 | 1000 | 2 | 1 | 1 | 1 | 1 | 5 | 4 | 3 |
| 5 | 1050 | 240 | 210 | 1500 | 2 | 1 | 1 | 1 | 1 | 5 | 4 | 3 |
| 5 | 1400 | 320 | 280 | 2000 | 2 | 1 | 1 | 1 | 1 | 5 | 4 | 3 |
| 5 | 1618 | 773 | 847 | 3238 | 2 | 1 | 1 | 1 | 1 | 5 | 4 | 3 |
| 5 | 2000 | 1000 | 1000 | 4000 | 2 | 1 | 1 | 1 | 1 | 5 | 4 | 3 |
| 10 | 79 | 12 | 11 | 102 | 4 | 2 | 6 | 6 | 6 | 6 | 6 | 6 |
| 10 | 158 | 23 | 21 | 202 | 4 | 2 | 6 | 6 | 6 | 6 | 5 | 5 |
| 10 | 237 | 35 | 32 | 304 | 4 | 2 | 6 | 6 | 6 | 6 | 5 | 5 |
| 10 | 700 | 160 | 140 | 1000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 10 | 1050 | 240 | 210 | 1500 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 10 | 1400 | 320 | 280 | 2000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 10 | 1618 | 773 | 847 | 3238 | 3 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 10 | 2000 | 1000 | 1000 | 4000 | 3 | 2 | 1 | 1 | 1 | 5 | 5 | 4 |
| 15 | 79 | 12 | 11 | 102 | 4 | 2 | 6 | 6 | 6 | 6 | 6 | 6 |
| 15 | 158 | 23 | 21 | 202 | 4 | 2 | 6 | 6 | 6 | 6 | 6 | 6 |
| 15 | 237 | 35 | 32 | 304 | 4 | 2 | 6 | 6 | 6 | 6 | 6 | 6 |
| 15 | 700 | 160 | 140 | 1000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 15 | 1050 | 240 | 210 | 1500 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 15 | 1400 | 320 | 280 | 2000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 15 | 1618 | 773 | 847 | 3238 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 15 | 2000 | 1000 | 1000 | 4000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 20 | 79 | 12 | 11 | 102 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 20 | 158 | 23 | 21 | 202 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 20 | 237 | 35 | 32 | 304 | 6 | 2 | 6 | 6 | 6 | 6 | 6 | 6 |
| 20 | 700 | 160 | 140 | 1000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 20 | 1050 | 240 | 210 | 1500 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 20 | 1400 | 320 | 280 | 2000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 20 | 1618 | 773 | 847 | 3238 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 20 | 2000 | 1000 | 1000 | 4000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 25 | 79 | 12 | 11 | 102 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 25 | 158 | 23 | 21 | 202 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 25 | 237 | 35 | 32 | 304 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 25 | 700 | 160 | 140 | 1000 | 4 | 2 | 6 | 6 | 6 | 6 | 6 | 6 |
| 25 | 1050 | 240 | 210 | 1500 | 4 | 2 | 6 | 6 | 6 | 6 | 6 | 6 |
| 25 | 1400 | 320 | 280 | 2000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 25 | 1618 | 773 | 847 | 3238 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |
| 25 | 2000 | 1000 | 1000 | 4000 | 4 | 2 | 1 | 1 | 1 | 5 | 5 | 5 |

[a] SP is wind speed, CF is Cape Fear River discharge, BR is Black River discharge, NE is Northeast River discharge, RD is the total river discharge. The plume type behavior is listed on the column below the wind direction, which is also consistent with the river discharge and wind speed in its corresponding row. The unit of river discharge used $m^3/s$ and the wind speed used m/s.

[13] Figure 3d suggests that the southwesterly wind induced plumes fall mostly either Type V or Type VI although a very weak winds (<2m/s) have the similar pattern to a non wind forcing case and the plume hugs the south coast as a Type I. In general, the southwest-induced plume will move to south and could even turn left under the favorably conditions, however the plume won't reach this type when the wind forcing is weak (<4m/s).

[14] Westerly and northwesterly winds induced plumes orientations which have a very similar pattern to those of southwesterly wind induced plumes but can also turn into Types I, II, III, and IV under differing conditions (Figures 3e and 3f). Changing wind speed and river runoff will change plume type as shown in Figures 3e and 3f. Overall westerly, southwesterly and northwesterly upwelling favorably winds induced plume orientations having a similar pattern, and the dominance of these wind induced patterns all lie within Type V although it is possible for them to turn to Types I, II, III, and IV under reduced wind magnitude and increasing river discharge. It is very clear that upwelling winds produces most changeable wind induced plume shape results as shown in Figure 3.

## 5. Discussions

[15] Wind forcing can play a key role in the river, estuary and coastal plume formation. However, plume orientation has not been thoroughly studied. Although the effect of the ambient flow is important to large-scale plume dynamics [*Zhang et al.*, 1987; *García Berdeal et al.*, 2002], for most small and medium scale plumes, particularly those constrained in the along coastal direction by topography, local wind forcing and fresh water runoff could be two primary factors which determine plume orientation. *Marques et al.* [2009] also concluded that the wind is the dominant mechanism controlling the behavior and orientation of the medium scale Patos Lagoon coastal plume. Additionally, with a sufficiently large model domain, wind forcing and river runoff can determine the nearshore coastal current to a large degree. Because of these complex interactions between plume, wind forcing, river runoff and coastal currents, coastal currents were not included as an independent factor in this study. The conceptual plume model [*Xia et al.*, 2007] successfully simulated a series of ideal cases and summarized the plume character under the response of various types of external forcing with applications to the CFRE. In general, the wind could determine the plume orientation and every wind has a dominant plume orientation (Figure 3), although the wind speed or sometimes river runoff can slightly change its orientation. Overall: a) the westerly, southwesterly, and northwesterly upwelling favorable winds most likely could induce a Type V plume; b) easterly, southeasterly and southerly downwelling favorable wind predominantly induces a Type I plume; c) the northeasterly wind have a dominance of both Type I and Type II; and d) northerly along-estuary wind induces the Types I, II, III and IV plumes (Table 3).

[16] A river or estuary plume is an important coastal phenomenon. As a typical mid-latitude estuary, the plume

**Table 3.** Summary of Plume Types Under the Various Wind Direction[a]

| | NN | NE | EE | SE | SS | SW | WW | NW |
|---|---|---|---|---|---|---|---|---|
| Type 1 | 8 | 13 | 25 | 25 | 25 | 8 | 3 | 3 |
| Type 2 | 5 | 30 | | | | 26 | 2 | 4 |
| Type 3 | 5 | | | | | | 1 | 6 |
| Type 4 | 24 | | | | | | 7 | 4 |
| Type 5 | | | | | | | 23 | 19 |
| Type 6 | 6 | 5 | 13 | 13 | 13 | 14 | 12 | 12 |

[a] The plume type behavior summary is listed on the column below the wind direction, which is also consistent with the plume type in its corresponding row.

dynamics summarized here with an application to CFRE could also be applied to other estuary systems in kind.

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