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1 **Daily forecasts of Columbia River plume circulation: a tale of**
2 **spring/summer cruises**

3
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24 **Abstract**

25

26 Semi-operational daily forecasts of circulation from an observatory for the Columbia River estuary-
27 plume-shelf system routinely support oceanographic cruises, by providing 24h-ahead estimates of plume
28 location and structure for planning purposes and for near real-time interpretation of observations. This
29 paper analyzes forecast skill during spring/summer cruises in 2004-2007. Assessment addresses both
30 qualitative descriptions of major plume trends and features and quantitative representation of data from
31 (primarily) vessel-based flow-through, cast and towed systems. Forecasts emerge as robust predictors of
32 plume location and variability, with skill that has grown over time, at least in part due to improvements
33 in model algorithms. When the same version of SELFE is used as the common computational engine,
34 forecast skill is very comparable to the skill of multi-year simulation databases, which are computed
35 retrospectively. As a measure of forecast skill, 55% of the predictions of surface salinities came within 2
36 km of observations, and directional shifts in response to coastal winds were well predicted. Quantitative
37 skills for other aspects of the plume structure vary. Skill is highest for flow-through (and near-surface
38 TRIAXUS) salinities. Forecasts also capture aspects of the vertical structure of the plume as represented
39 by CTD casts (undulating TRIAXUS). Sub-tidal velocities, as compared against fixed station data, are
40 least well described among examined variables. Overall, circulation forecasts help level the playing field
41 among chief scientists with diverse disciplinary expertise. The chief scientist's expertise on plume
42 physics determines whether forecasts should be used for training and land-assisted planning, or as a
43 sophisticated *en route* planning and interpretation tool. Effective interpretation of vessel observations in
44 context of forecasts requires understanding of physical processes and modeling limitations.

45

46 **Key words:** Forecasting, cross-scale circulation modeling, river plumes, Columbia River plume

47 **1 Introduction**

48 As a major hydrographic feature in the US west coast, the Columbia River (CR) plume transports
49 freshwater as well as nutrients hundreds of miles into the Oregon (OR) and Washington (WA) shelves
50 and beyond. Often reaching northern California to the south and Vancouver Island to the north (Barnes
51 et al. 1972; Hickey et al. 1998), the plume significantly impacts an extensive and complex regional
52 marine and estuarine ecosystem (Hickey et al. 2005; Hickey and Banas 2003; Casillas 1999; Thomas
53 and Weatherbee 2006). Variability at multiple scales, including tidal, seasonal and inter-annual,

54 complicate the understanding of the plume and associated ecosystems. Other than tides, river discharge
55 and shelf winds are dominant drivers of variability.

56 Ranked second in annual discharge ($7000 \text{ m}^3/\text{s}$) in the continental United States, the CR is
57 regulated through an extensive system of dams. While dams greatly reduce flow variability relative to
58 pre-development times, the CR still experiences strong seasonal variations. Spring snow melt typically
59 leads to high-discharge freshets, which contrast with late summer minimum flows and with rain-
60 responsive winter discharges. Discharges can exceed $14000 \text{ m}^3/\text{s}$ during spring freshets or be as low as
61 $2000 \text{ m}^3/\text{s}$ in late summer. Variation across years is also notable: in recent years, maximum annual
62 discharges have oscillated from $9577 \text{ m}^3/\text{s}$ in 1997 (with peak freshet of $\sim 15000 \text{ m}^3/\text{s}$) to $3965 \text{ m}^3/\text{s}$ in
63 2001 (with no noticeable freshet). The volume and surface area of the plume expand in response to
64 increasing river discharge, in ways that also depend on shelf winds (Burla et. al., this issue)

65 The influence of shelf winds on the CR plume dynamics has long been recognized, with Barnes et
66 al. 1972 describing a bi-seasonal system where the summer plume develops under upwelling-favorable
67 wind and is oriented towards southwest off the Oregon coast, while the winter plume develops
68 northward and attached to the Washington coast in response to Coriolis and downwelling-favorable
69 winds. While this classical bi-seasonal view applies in average, a more complex picture of a "bi-
70 directional" plume has emerged in recent years, in which the summer (winter) plume water can
71 temporarily develop to the north (south) in response to day-scale changes in wind direction (Hickey et
72 al. 2005; Burla et al., this issue). Satellite images suggest that the real picture of the CR plume may be
73 even more complex with multiple patches of the residual plume scattered around Washington and
74 Oregon shelf (Hickey et al. 2005; Thomas and Weatherbee 2006), a view supported by modeling studies
75 (Garvine 1999; Garcia-Berdeal et al. 2002; Baptista et al. 2005; and, in this issue, Burla et al. and Liu et
76 al.) which also identify variability in response to tides and river discharge.

77 The multi-scale variability of the Columbia River plume poses, in particular, substantial logistical
78 challenges for chief scientists of oceanographic cruises. Numerical forecasts of 3D baroclinic circulation
79 have been used effectively to mitigate these challenges. The forecasts are conducted daily as semi-
80 operational products of the SATURN/CORIE observatory (Baptista 2006.) Other SATURN/CORIE
81 products include real-time observations from multiple stations in the estuary and plume, and near-decade
82 long hindcast simulation databases of 3D circulation.

83 The SATURN/CORIE forecasts provide both (a) 24h-ahead estimates of plume location and
84 structure for planning purposes, and (b) near real-time retrospective context for interpretation of
85 observations. While a range of chief scientists have empirically endorsed the usefulness of the forecasts,
86 this paper provides a more rigorous skill assessment for a sub-set of RISE and CMOP cruises. Selected
87 were five spring and summer cruises in the 2004-2007 period. The cruises were conducted in different
88 vessels and under chief scientists with different disciplinary backgrounds and with varying degrees of
89 expertise in CR plume dynamics.

90 After this Introduction, we describe the SATURN/CORIE forecasting system in Section 2. In
91 Section 3 we use a skilled multi-year hindcast simulation database (DB14) to summarize the seasonal
92 and inter-annual of the CR plume (see a more extensive analysis in Burla et al., this issue) and to place
93 cruises in the context of the long-term variation of the plume. Forecast skill assessment, focused on
94 plume salinity, is carried out in Section 4 by quantitative comparison against data collected during four
95 spring and summer cruises in 2005-2007 (flow-through CT, CTD casts, a profiler CTD, and buoys).
96 Because forecast strategies (and versions of the underlying model) have changed over time, we also
97 assess DB14 skill as needed for baseline reference. The Conclusions, Section 5, focus on lessons learned
98 on the usefulness of the forecasts as cruise-supporting tools.

99 **2 Forecasting system in context**

100 2.1 The SATURN/CORIE observatory

101
102

103 One of the earliest end-to-end (data-to-stakeholder) coastal margin observatories, CORIE (Baptista
104 et al. 1998; Baptista et al. 1999; Baptista 2006) was launched in June 1996 with the deployment of a
105 single telemetered conductivity-temperature-depth sensor (CTD). The first sustained forecasts were
106 launched in 1998 using a 2D barotropic model for tidal circulation. While observations and simulations
107 stayed until recently focused on the physical estuary, CORIE has progressively evolved towards the
108 vision (Baptista 2002, Baptista et al. 2008) of observatory-enabled scientific exploration as a potentially
109 transformative tool for oceanography, with implications for regional issues ranging from salmon
110 habitat/passage and hydropower management to navigation improvements and habitat restoration. In
111 2008, interdisciplinary stations with vertical mobility were deployed, signaling the beginning of the
112 transition of CORIE towards an ambitious end-to-end interdisciplinary observatory, SATURN. As did

113 the original CORIE, the fast-evolving SATURN/CORIE observatory consists of 3 integrated
114 components: a real-time observational network, a modeling system, and a cyber-infrastructure.

115 The SATURN/CORIE observation network currently consists of ~20 stations in the estuary and
116 plume, which data are regularly used to quality control forecasts and simulation databases, either in the
117 context of forward simulations (Baptista 2006; in this issue: Burla et al.) or of data assimilation (Frolov
118 2007). Data from the CORIE stations is displayed in real time, albeit with limited quality control, and is
119 then subjected to extensive off-line quality control on a monthly basis. All quality-controlled data and
120 common statistics are available through the web, for either download or visualization, providing the
121 basis for unique insights into the estuarine and plume dynamics (Fain 2001; Chawla et al. 2008; Lohan
122 and Bruland 2006; Bruland et al., this issue). Fig. 1 shows the two SATURN/CORIE stations (OGI01
123 and OGI02) that are in the plume/shelf region, together with the three RISE stations independently
124 deployed in 2004-2007 (Ed Dever, private communication).

125 The SATURN/CORIE modeling system currently consists of three sub-systems, all focused on 3D
126 circulation: *simulation databases*, *scenario simulations* and *daily forecasts*. Simulation databases extend
127 continuously from January 1, 1999 through the present (typically lagging calendar time by one year),
128 enabling the analysis of physical variability in the estuary and plume under evolving climate and water
129 regulation. Scenario simulations offer an opportunity to contrast modern Columbia River conditions
130 with reconstructed historical scenarios (e.g., pre-development circa 1880) and future scenarios of change
131 (e.g., associate with climate change or with conditions post a major Cascadia Subduction Zone event).
132 Daily forecasts offer short-term predictions of contemporary conditions, one or a few days ahead, with a
133 level of detail designed to be supportive of *en route* planning and interpretation of oceanographic
134 cruises.

135 To integrate across extensive observations and simulations, thousands of multi-purpose data and
136 simulation products, and a growing and increasingly diverse user community, the SATURN/CORIE
137 cyber-infrastructure has evolved since inception. It currently consists (Baptista et al. 2008) of a central
138 *data grid* with four external interfaces: the *observation pipeline* for acquiring data from remote sensors,
139 the *forecast factory* for managing the daily operational forecasts and generating the core data products,
140 the *long-term repository* for archiving simulation databases and scenario simulations, and an *integrative*
141 *web site* for open dissemination of the data. These interfaces, and their earlier renditions, facilitate the
142 continuous evolution of modeling capabilities in general, and forecasting capabilities in particular.

143 2.2 Circulation forecasts in support of oceanographic cruises

144 A variety of scientific cruises have been conducted in the Columbia River plume and vicinity since
145 1998, often in the context of large inter-disciplinary programs sponsored by the National Science
146 Foundation (NSF) and the National Ocean and Atmospheric Administration (NOAA). Of direct
147 relevance for this paper are NSF-supported RISE and CMOP cruises. RISE (River Influences on Shelf
148 Ecosystems) seeks to explore how the river plume modifies biological productivity along the
149 Washington and Oregon continental shelves. CMOP (Science and Technology Center for Coastal
150 Margin Observation and Prediction) explores the use of ocean observatories to advance understanding of
151 the effects of climate and human activity on coastal margins and to educate a diverse workforce.

152 SATURN/CORIE forecast products (Fig. 1) have been regularly transmitted to on-board
153 computers to aid chief scientist's planning and assess sampling strategies. Conversely, measurements
154 from the ship are transmitted to land computers for near real-time modeling skill assessment. An "ocean
155 appliance" (Howe et al. 2007) brokers the customized management of information flow from and to the
156 vessel. The primary protocol for two-way data transmission is the Ship-to-Shore Wireless Access
157 Protocol (SWAP). The signal is relayed via land-based towers with a transmission range of around 20
158 nautical miles, depending on the height of the antenna. When this range is exceeded, we also used other
159 means (e.g., satellite phones) to transmit data.

160 When CORIE daily forecasts were first launched, circa 1998, they required very intensive manual
161 intervention and monitoring and their prediction skill was modest. Today, CORIE include 6 or 7 near-
162 automatic daily forecasts, The supporting cyber-infrastructure (Baptista et al. 2008) ensures automation
163 of most processes, including in the case of forecasts the capture of external forcing from various sources,
164 the launch of simulations based on one of two models (SELFE, Zhang and Baptista 2008; ELCIRC,
165 Zhang et al. 2004), and the generation (by default or on demand) of a suite of post-simulation products
166 such as visual representations and skill assessment metrics.

167 Forecasts maintained at the time of this writing represent only a snapshot of the forecasting
168 system, as specifics of each forecast and their combination are frequently adjusted to improve skill and
169 to adjust to needs from cruises and other uses. Forecasts (Table 2) may differ in the underlying
170 numerical model, domain and grid resolution, or forcing choices. Multiplicity of forecasts is useful in
171 assessing modeling uncertainty, in differentially refining the representation of specific regions or
172 processes, and in exploring different algorithmic or forcing strategies.

173 For simplicity, we concentrate in this paper on a single forecast type ('Development forecast',
174 created in 2005). We note that the characteristics of simulations within the Development forecast have
175 changed over time, in a continuous search for increased skill. In particular, SELFE versions used in the
176 Development forecast were different for various cruises addressed in this paper: version 1.3g2 was used
177 in June 2005, version 1.3k in August 2005, and version 1.4a in 2006 and 2007 (Table 2). An essential
178 difference is that version 1.4a of SELFE uses an upwind transport algorithm for the salt balance
179 equation, in contrast to (with superior accuracy relative to) the Eulerian-Lagrangian method used in the
180 various variations of version 1.3.

181 The domain of the Development forecast includes the estuary and the plume, as well as the
182 continental shelf from central CA to Vancouver Island. Fig. 2a shows the extent of the domain and the
183 grid, with additional information on horizontal discretization provided in Fig. 2b and vertical
184 discretization characterized in Table 2. The numerical engine is SELFE (Zhang and Baptista 2008), an
185 unstructured-grid model based on the solution of the shallow-water equation with a finite element/finite
186 volume hybrid method. No data assimilation is used. Each day, two days is simulated, with the full
187 simulation including a one-day hindcast-nowcast and a one-day forecast. External forcing is retrieved
188 and processed automatically. Forcing includes river discharges (Columbia River only); atmospheric
189 conditions from the National Centers for Environmental Prediction (NCEP); and ocean conditions from
190 NCOM (Navy Coastal Ocean Model; Baron et al. 2006). Simulations are launched daily around 11am,
191 to obtain next-day conditions about 12 hours later, i.e., around 11pm of the day of the launch. Results
192 are automatically processed and displayed online together with observational data.

193

194 2.3 Simulation databases as reference baseline

195 Because the specifics (including underlying SELFE version) of the Development forecast change
196 over time, we resort in this paper to results of a SATURN/CORIE simulation database as a consistent
197 baseline against which to interpret changes in forecast skill. There are currently three major simulation
198 databases, self-redundant by design, and differing on the underlying model (SELFE or ELCIRC, Zhang
199 et al. 2004), the domain (estuary-plume-shelf or estuary), and on choices in domain discretization and
200 model parameterization. As baseline for this paper we use DB14, which is most similar to the
201 Development forecast in that it (a) utilizes SELFE, (b) covers the estuary, plume and shelf (from
202 northern California to southern British Columbia), and (c) uses the same horizontal and vertical

203 discretization. A dominant difference between DB14 and the Development forecast is that forcing for
204 DB14 is known retrospectively rather than being itself forecasted. Another important difference is that
205 DB14 consistently uses version 1.4a of SELFE, while the Development forecast uses a range of versions
206 over time (see Table 2).

207 **3 Characteristics of the virtual CR plume**

208 3.1 Contextual variability

209
210 To place the spring and summer cruise periods analyzed in this paper in a longer-term context of
211 variability, we summarize here characteristics of the CR plume for a two-year period (2005-2006) as
212 represented by DB14 simulations. A more extensive treatment of the topic of CR plume variability using
213 multiple CORIE simulation databases is provided by Burla et al. (this issue). Other recent studies of
214 seasonal and inter-annual variability of the plume include Thomas and Weatherbee (2006), who
215 analyzed the six years of satellite data 1998-2003 and concluded that inter-annual differences in winter
216 plume are mainly due to wind forcing but summer inter-annual differences are dominated by differences
217 in discharge volume.

218 Due to its large river discharge, the CR plume is "supercritical" (Fong and Geyer 2002) in the sense
219 that the Coriolis-induced coastal jet cannot carry away the entire river discharge without help from
220 coastal wind and ambient currents. Characteristic of super-critical behavior, the plume tends to develop
221 a circular bulge (Horner-Devine et al. 2006) with discharge-dependent diameter that is then altered by
222 the coastal wind and large-scale ocean currents. An Empirical Orthogonal Function (EOF) analysis of
223 model results (Burla et al 2008) suggests that the first EOF represents the natural tendency of the CR
224 plume to veer right under Coriolis, while the 2nd EOF corresponds to the bi-directional plume; the two
225 EOFs account for approximately 44% and 21% of the total variance respectively.

226 To characterize the plume variability relative to external forcing, we will use here the plume
227 thickness, area, and centroid location as well as volume (not shown, but used to compute thickness).
228 Plume volume and area are calculated as:

229 { 1 }
$$P_a = \int \hat{S}_0 dA,$$

230 where the volume and area integrations are done in a region that encompasses the entire plume², and \hat{S}
231 (and the surface value \hat{S}_0) is a measurement of local "freshness":

$$232 \quad \{2\} \quad \hat{S} = \max(0, 1 - S / S_{ref}),$$

233 in which S is the salinity, S_{ref} is a cut-off ocean salinity. The plume thickness is then:

$$234 \quad \{3\} \quad P_t = P_v / P_a.$$

235 The location of the plume centroid is computed as:

$$236 \quad \{4\} \quad \mathbf{x}_p = \frac{\int \mathbf{x} \hat{S}_0 dA}{\int \hat{S}_0 dA}.$$

237 Similar but slightly different definitions of these plume metrics are used in Burla et al. (this issue).

238 Fig. 3 re-enforces the notion that freshwater discharge and coastal wind (especially alongshore wind)
239 are major drivers of the variability of plume characteristics³. Discharge varies seasonally in relatively
240 predictable ways. Maximum discharges (often > 10,000m³/s) occur during spring freshets, typically in
241 late May and early June. During winter months, the discharge tends to peak in correspondence to heavy
242 rainfall. Moderate to low discharges occur between winter and the spring freshet, and minimum
243 discharges occur between summer and fall (~3000m³/s). Inter-annual variability is also significant, as
244 illustrated by comparing 2005 and 2006, with 2006 having a larger and longer spring freshet, as well as
245 larger discharges in winter.

246 Except for some periods in summer and early fall, coastal winds are strong (>10m/s) and storms (up
247 to 20m/s) are particularly frequent during winter and spring months. Studies conducted during the
248 summer "quiet" months have found wind reversal to be frequent which leads to the formation of bi-
249 modal plumes (e.g., Hickey et al. 2005). Fig. 3 shows that significant reversals also occur during winter

² The bounding box we used is 43°N to the south (Newport, OR), 48°N to the north (Juan de Fuca Strait), and 150 km offshore from the mouth of the estuary). Due to the relatively low $S_{ref}=28$ psu used in Figs. 3-5, extending the bounding box have no effects on the results.

³ The influence from large-scale coastal currents, and in particular the California Current, is also noteworthy. While we have not analyzed this influence in detail, sensitivity tests suggest that this influence is secondary relative to the influence of river discharge and coastal winds, at least in the near-plume region.

250 months, when a combination of large discharge and strong and highly variable wind makes the plume
251 dynamics more variable than is often recognized.

252 The plume area and thickness are in general inversely correlated (Fig. 3; cf. Eq. (3)). The plume
253 area is largest under upwelling favorable wind and high discharge (e.g., spring freshet in May 2005 and
254 May 2006), and smallest during low discharge periods (e.g., August 2005). Notably, the very high
255 discharge during Nov-Dec. 2006 did not result in a large plume because strong downwelling wind
256 pushed the plume tightly against the coast, and the plume was almost non-existent on several days
257 within this period (also similarly in early January 2006). The plume thickened considerably during this
258 period ($>30\text{m}$), and the large variation in thickness around the days when the plume vanishes resulted
259 from the near singularity in Eq. (3). Thickness ranges from $<2\text{m}$ during summer months to over 40m
260 during winter storms, and can change by as much as 20m in a 2-5 day period. Peaks in plume thickness
261 generally align with those in downwelling wind, with larger peaks during higher discharges, although
262 there appears to be a phase lag of ~ 0.2 days, likely due to nonlinear effects (e.g., inertia and turbulent
263 mixing).

264 Variation of the plume centroid shows complex patterns (Fig. 3). While the plume is always
265 constrained to the west of the river mouth, the north-south excursion of the plume can be very large
266 (e.g., ~ 110 km from May 20 to June 3 2005, with more common excursions of ~ 40 km within ~ 5 days.)
267 The north-south movement is much faster than the east-west movement, most likely due to geographic
268 constraint and the generally stronger along-shore wind component. In general, the plume centroid moves
269 with the coastal wind largely as expected. It moves southwestward during upwelling, and north to
270 northeastward during relaxation and downwelling, with some phase lag. The on- and offshore movement
271 of the centroid is mainly determined by the east-west component of the wind. Thus, depending on the
272 combination of the two components of the wind, northwest or southeast movement of the plume is also
273 common (e.g., around Feb. 15 2006). The movement is also controlled, to a lesser extent, by the
274 discharge; in both 2005 and 2006 we observe quickest movements during the spring freshets.

275 In addition to the primary driving forces of wind and discharges, the plume also responds to tidal
276 modulation and mixing. This is apparent during summer months, when the other two forces are
277 relatively weak. The spring-neap variation can be clearly seen in the plume thickness, and to a lesser

278 extent, in the centroid location (Fig. 5). Tidal mixing plays an important role in the near-plume
279 processes.

280 3.2 Cruise conditions

281 The five cruises discussed in this paper were conducted from May through August, in 2004-2007,
282 and offer a perspective into the very significant variability that occurs within the ‘summer plume’
283 regime of Barnes et al. (1972). Fig. 6 allows for a quick overview of the differences in forcing (river
284 discharge and shelf winds) and plume surface signature across cruises, while Fig. 4a-e provides details
285 into the variation in forcing and aggregate plume metrics (area, thickness and location) within each
286 cruise. All plume characteristics are computed from DB14, except for Aug. 2007 where development
287 forecast is used (because DB14 is not yet available for 2007.)

288 The three cruises in 2005 and 2006 offer a contrast in river discharge regimes. The June 1-18, 2005
289 cruise took place shortly after the freshet and the discharge was moderate ($\sim 7000 \text{ m}^3/\text{s}$) and declining
290 (Fig. 4b). By the time the next cruise (Aug. 4-25, 2005) started, the discharge had reached its yearly
291 minimum ($\sim 3000 \text{ m}^3/\text{s}$; Fig. 4c). The wind was highly variable, especially in June, but was generally
292 weak during the August cruise. The decline of the plume size during this period can be seen clearly in
293 Fig. 4c. The mean surface plume and the standard deviation during the two cruises are shown in Fig. 6,
294 which demonstrates the strong variability of the plume. Due to several strong downwelling events
295 during the first cruise, the residual plume shows a circular bulge outside the mouth and a northward
296 propagating jet that hugs the coastline, although there is a considerable plume south of the mouth as
297 well, reminiscent of the upwelling periods. Note that downwelling favorable wind re-enforces the
298 natural mode of the plume while upwelling favorable wind counters it. The mean plume in the August
299 cruise, however, is a typical southwestward tending plume located offshore. Large anomalies exist in the
300 near-field plume, with larger values in June (Fig. 6). The large anomalies to the north of the mouth even
301 during the primarily upwelling period of August 2005 are a testament to the bi-directional nature of the
302 plume (Hickey et al. 2005; Fig. 6).

303 The May 10-June 6 cruise in 2006 took place during the freshet and thus exhibited distinctive
304 characteristics from the two 2005 cruises. The wind was again variable with six strong downwelling
305 events alternated by relaxation and upwelling periods. The large river discharge is the most dominating
306 feature of this period. For example, plume thicknesses are considerably different during two

307 downwelling events of comparable magnitude (the line and the left boundary of the box in Fig. 4d), with
308 the large freshwater discharge during the second downwelling event (the box in Fig. 4d) more than
309 doubling the plume thickness. Although the forcing conditions and the plume centroid location at the
310 beginning and end of the cruise were very close to each other, the plume area first dwindled to less than
311 half due to the downwelling events and then increased to more than twice the initial value towards the
312 end of the period. The mean plume resembles that of June 2005, albeit with larger extent, and the
313 standard deviation is all much higher than in June 2005 (Fig. 6). The maximum anomaly reaches as high
314 as 17 psu.

315 The first half of the Aug. 13-30 2007 CMOP cruise took place under primarily downwelling wind
316 which relaxes to upwelling-favorable wind during the second half of the cruise. Such a wind condition
317 plus the persistent downwelling wind that occurred one week prior to the cruise leads to a maximum
318 thickness around August 21 (Fig. 4e). As compared to the August 2005 cruise, the plume extent during
319 the '07 cruise is larger and with a visible northward component (Fig. 6). The size difference is due to the
320 larger discharge (~ 4000 versus ~ 6000 m^3/s). The northward extent is a reflection of 'old plume' water,
321 associated with a strong downwelling event that occurred the week prior to the cruise, and is thus a
322 witness to the temporal memory of the system.

323 Conditions for the July 2004 RISE cruise were similar to those for August 2005, although with a
324 significant event of wind relaxation around July 20-21 (Fig. 4a), increasing the footprint of the
325 northward extent of the plume relative to August 2005. The plume is also more attached to the coast,
326 likely because of the smaller period of sustained upwelling.

327 **4 Forecast skill assessment**

328 As discussed in Section 2.2, of the several CORIE forecasts available we will concentrate on the
329 skill assessment on the full-domain, SELFE-based *development* forecast, which has run continuously
330 since 2005⁴. Note again that different versions of SELFE were in use at the time of various 2005-2007
331 cruises (Table 2). Most data presented in this section were collected by vessel-based instruments, and
332 there is some uncertainty regarding the exact depth associated with the data collection. The
333 corresponding model results were extracted at the estimated instrument depth. Each daily forecast

⁴ In 2004, only ELCIRC-based forecasts were being run. Results shown in this paper for 2004 are, unless otherwise noted, from DB14.

334 consists of one-day hindcast simulation and one-day forecast simulation; for consistency, the results
335 shown here were concatenated for the full cruise period from the one-day forecast simulations.

336 **4.1 Tracking exercise**

337 One of the most stringent tests we have conducted for the forecast skill was the use of near real-
338 time model outputs to help find plume fronts in Aug. 21-23 2007, a period of establishing upwelling
339 conditions after a downwelling period with lingering plume memory (Figs. 4e&7). Each day, a pre-
340 defined cruise path, based on the development forecast results, was made available to the chief scientist
341 on the R/V Wecoma. The paths consisted of hourly "waypoints" that were intended to sample across
342 plume fronts multiple times (Fig. 7). A similar exercise was conducted in Aug 29-30.

343 We measure the model errors as the distance between the ship location and corresponding surface
344 salinity isoline predicted by the forecast (Fig. 7). The average error is 3.6 km. The error is within 2 km
345 more than 55% of the time, and within 5 km more than 70% of the time (Fig. 8b); only less than 10% of
346 the time is the error over 8 km. This level of skill was considered useful by the chief scientist, who
347 reported that the ship was often very near the plume front judging by the different colors of the two
348 types of water. Remaining errors in locating the plume are attributed in part to grid resolution (the grid is
349 typically coarser than 0.5 km in the plume region) and in part due to errors in wind forcing (partially
350 illustrated, at a single offshore station, in Fig. 8a) and in over-estimated thermocline depth in the NCOM
351 ocean forcing (not shown). While SATURN/CORIE simulation databases are not yet available for 2007,
352 our experience with other years indicates that hindcast simulations, which are forced with improved
353 winds and discharges, tend to lead to overall improvement over the forecasts. All uncertainties
354 considered, the forecasts capture plume location in a useful manner, despite the plume's large variability
355 during the period.

356 **4.2 Flow-through salinity data**

357 The comparison of flow-through data from any of the 2004-2007 cruises against simulations
358 (forecasts or DB14) is illustrative of both the complexity of the CR plume dynamics and the challenges
359 of assessing modeling skill. For instance, for the cruise in July 2004, DB14 results shows overall
360 impressive skill in tracking regime changes, but grossly over-predict (at the vessel location) the plume
361 extent July 17-18 in response to a fast transition from upwelling to downwelling conditions. Note also
362 that errors appear to be substantially different in different regions of the plume. For example, if we
363 divide the plume region into three sub-regions: bulge (defined, for this purpose, as the region within 10

364 km of the mouth of the CR), north plume (north of the mouth but outside the bulge) and south plume,
365 visual inspection (Fig. 9b; note band identifying the location of the vessel in the bulge or in the
366 south/north plume) suggests that errors are often largest during this particular cruise in the highly
367 varying bulge.

368 Fig. 14 suggests that forecasts and DB14 skills are comparable “in bulk”. However, using flow-
369 through data from the three cruises in 2005-2006 to assess forecast skill and to compare it against DB14
370 skill, we will show that absolute and relative performances are highly nuanced. The contextual
371 information for the plume during these cruises has been summarized in Section 3. Due to the range of
372 discharge regimes during these periods (from low flow in Aug. 2005, to moderate flow in June 2005 to
373 high flow freshet in June 2006), the comparisons shown below are representative of many other cruises.
374 In all three cruises, forecast results were sent near real-time to the R/V Wecoma and used in support of
375 *en route* cruise planning by the same chief scientist (Hickey).

376 Figs. 10a, 11a and 12a show the tracks of the vessel relative to the plume position at the start of
377 each cruise. The modeled plume was very responsive to the wind. Significant variability of plume size
378 within and across cruises was mainly controlled by a combination of the magnitudes of river discharge
379 and wind regime. Plume orientation exhibited different "modes", sometimes even with multiple patches
380 (e.g., June 16, 2005; Fig. 10a). With a more discriminating scale than that used in Figs. 10a, 11a and
381 12a, we are able to see more patches along the WA and OR coast that were likely remnants of old CR
382 plume (not shown). The bi-directional mode described by Hickey et al. (2005) can be observed on June
383 7 and 14, 2005 (Fig. 10a), for example.

384 A broad range of salinities were covered in the flow-through data (Figs. 10b, 11b and 12b). Spatial
385 and temporal variation of salinity was reasonably represented in the forecast. In certain periods, forecast
386 errors appear more responsive to errors in external forcing than in others; for instance, RMS errors for
387 both salinities and wind were largest during the June 2005 cruise, and visual inspection suggests the
388 period June 05-09, 2005 as illustrative of the strong influence in forcing error. However, we caution that
389 it would be over-simplistic to attribute errors only to forcing in general and to wind forcing in particular;
390 for example, the memory of the system significantly complicates the interpretation.

391 The comparison of forecast skill during the 2005-2006 cruises against DB14 skill is particularly
392 interesting (Figs. 10b, 11b, and 12b; Tables 3, 4; and particularly Table 5). Overall, DB14 far
393 outperforms forecasts during June 2005, but slightly underperforms (especially based on correlation
394 coefficients) forecasts in May 2006. In August 2005, determination of whether DB14 or the forecast has

395 better skill is complex: forecasts slightly outperform DB14 based on RMS errors, yet DB14 is far
396 superior (in all regions of the plume but the south plume) based on correlation factors. Note that
397 correlation factors can be interpreted as indicative of model skill in representing plume variability/trends
398 around the mean state, while RMS errors capture direct mismatches including those between the mean
399 states. In general, RMS forecast errors are substantially smaller in the low-discharge August 2005 cruise
400 than in the large discharge June 2005 and May 2006 cruises – but this is not true for correlations factors,
401 which improve regardless of river discharge with each new cruise. For DB14, RMS errors are lower for
402 lower river discharges, but correlation factors stay at similar levels across all three cruises.

403 The explanation for the above behavior is not straightforward, and it is confounded by the fact that
404 all metrics are being computed from a relatively scarce dataset with each of the three regions. The case
405 can however be made that a large part of the explanation lies on the evolving versions of SELFE used in
406 the forecasts over time. Indeed, the SELFE versions used in 2005 differ within Development forecasts,
407 and between forecasts and DB14 (Table 2.) Both forecasts and DB14 use SELFE version 1.4a in 2006
408 (Table 2). Version 1.4a has been independently verified to be the most accurate among the SELFE
409 versions used in this paper (Zhang and Baptista 2008). We thus interpret the results as suggesting, as the
410 first order message, that version 1.4a brought substantially enhanced skill to the forecasts. We also
411 interpret the results as suggesting that although salinity values are better estimated in low discharge
412 conditions, plume variability and trends are captured throughout all discharge regimes at an
413 approximately consistent level. The marginally better performance of the forecast versus DB14 in May
414 2006 is difficult to interpret, given the confounding uncertainties in the forecasted river discharge, ocean
415 conditions (in particular, thermocline depths from NCOM forecasts) and actual instrument depth (due to
416 ship motion.)

417 Across all 2004-2007 cruises, forecasts have different skills in different regions (Table 3). Using
418 the previously introduced three sub-regions, RMS errors show least skill for the bulge than for the north
419 and south plume (due to the larger variation of the mean state therein), although correlations show a
420 more consistent cross-region skill. Different factors may affect differentially the skill in each region.
421 For instance, introducing the freshwater discharges from the Grays Harbor and Willapa Bay watersheds
422 in the forecasts for August 2007 (“Experimental forecast”) substantially improves correlation
423 coefficients for the North plume (from 0.82 to 0.91) while leaving correlations for all other regions
424 unaffected (Table 3; Fig. 13b).

425 **4.3 Salinity data from casts**

426 The vertical structure of the plume is determined by a combination of winds, river discharge and
427 tides, as well as by processes that hydrostatic models (like SELFE and ELCIRC) and current grid
428 resolutions are not designed to address (e.g., salt fingering and internal waves, Nash and Moum 2005).
429 CTD casts taken from the R/V Forerunner and the R/V Wecoma provide insights both into the response
430 of plume structure to forcing and into the ability of models to represent observed structure. The R/V
431 Forerunner casts were obtained in day-long cruises, which partially overlap with Wecoma and/or Pt. Sur
432 cruises in 2005-2007.

433 The casts will be analyzed in three groupings. The first grouping consists of six R/V Forerunner
434 cruises with observations along similar pathways (Figs. 15 & 16). Five of these cruises were in June,
435 with river discharges ranging from 6,100 to 6500 m³/s in 2005 and 9000 to 10000 m³/s in 2006; the
436 August cruise has substantially smaller river discharge ~4,500 m³/s. Taken as an aggregate, and non-
437 withstanding different tide and wind regimes, salinity patterns for these six cruises suggest that
438 increased freshwater discharge leads to increased plume thickness near the mouth of the estuary (e.g.,
439 compare Fig. 15a with Figs. 15b-c and Figs. 16a-c), as anticipated from the theory of buoyant jets. In
440 general, the forecasts captured the observed response near surface to river discharge meaningfully,
441 although (likely because the different SELFE versions used in the forecasts for different cruises) not as
442 clearly as DB14 does. In the deeper depths, however, the change of SELFE version from forecast to
443 DB14 seems to have often led to under-prediction of the salinity.

444 The second grouping (Fig. 17) consists of two 2005 R/V Forerunner cruises, geographically
445 concentrated at the entrance of the estuary or in the near-field coastal jet to the North. Results suggest
446 that DB14 has better skill than the Development forecast, that both types of simulation capture usefully
447 (but not in detail) elements of the variability of the plume. The third grouping (Fig. 18) consists of 4
448 days of casts from the R/V Wecoma: Aug. 21-23 and 25, 2007. In this case, only forecasts are available.
449 We observe a general degradation of skill with increasing distance from the coast or increasing depth,
450 possibly a reflection of uncertainties in forcing ocean conditions.

451 **4.4 Salinity data from a TRIAXUS fish**

452 Salinity data was also collected by a TRIAXUS, towed from the Pt. Sur during the 2004-2006
453 cruises (Figs. 19-21). The data were gathered near the surface in 2005 but at 10-40 m below surface in
454 2004 and 2006.

455 For the surface data (June 1-4, 2005), both the Development forecast and DB14 have a very strong
456 skill to describe the TRIAXUS data (visually, Fig. 19b; and based on RMS errors and correlation
457 coefficients, see Table 3). While that skill appears at first sight disproportionately high by contrast with
458 the skill reported for the flow-through data (Section 4.2; Table 3), the explanation lies in the much
459 shorter time span of the available TRIAXUS data (after gaps are removed for hourly averaging), which
460 avoids the periods of much larger model errors during the transition from upwelling to downwelling,
461 starting on June 5 (see Fig. 10b for context). Between the Development forecast and DB14, the latter
462 has a higher degree of skill.

463 Comparisons against undulating data are less satisfactory, consistent with the lesser ability of the
464 model to describe vertical structure versus surface “fingerprint” of the plume. However, performance is
465 better for July 11-27, 2004 (where the observed variability is smaller and is better captured by the
466 model) than it is for June 5-12, 2006 (Fig. 20). Note that TRIAXUS data set has many gaps in July
467 2004, and, in particular, misses the July 17 event where flow-through data for the surface plume was
468 poorly represented (Section 4.2; Fig. 9b). We do not have significant overlapping flow-through data for
469 June 2006 (Fig. 21). DB14 is more skilled than Development forecast for June 2006, but mostly because
470 of background salinity values (forecast does well in variability); we do not have development forecast
471 for July 2004.

472 **4.5 Sub-tidal velocities from buoys**

473 The previous types of data were collected from vessels, and offer useful insights into plume
474 gradients and geometry. Complementary to these data are in-situ measurements from moorings and
475 buoys, which have the advantage of decoupling space from time, and thus serve as witness to specific
476 events. Long-term time series were gathered at 3 RISE and 2 CORIE offshore buoys (Fig. 1), and are
477 being used in separate papers for a systematic analysis of the modeling skill of SATURN/CORIE
478 simulations (e.g., Burla et al, this issue.) Here we use the velocity information at OGI01 to illustrate the
479 challenges of forecasting sub-tidal velocities.

480 Velocity variation is particularly difficult to model in this region because the transient plume can
481 significantly alter ambient currents. While tides are an important part of the process, the mean transport
482 is primarily governed by the sub-tidal velocity. Fig. 22a shows comparisons of low-passed velocity, at
483 multiple depths, at OGI01, for June 2006. The forecasts capture near surface velocity reasonably well,
484 but miss important events in the deeper layers. The improvement from the development forecast to

485 DB14 is marginal at best (Fig. 22b), which suggests that if forcing errors are responsible, these errors are
486 shared between the two types of simulation. A possibility is that errors result from the initial and
487 boundary conditions obtained from NCOM for temperature and salinity.

488 In all cases, the errors are much larger for the east-west component than the north-south
489 component, especially at deeper depths (Figs. 22b), where the influence of large-scale currents (e.g.,
490 California Current system) may be more important. Note that we have not imposed any velocity
491 boundary conditions from NCOM at the ocean boundary and therefore large-scale currents may not be
492 accurately represented in the models. Comparison of velocity variances indicates that the model tends to
493 under-estimate the velocity variability, especially for the east-west component (Fig. 22a), possibly due
494 to low signal-to-noise ratio for this component. The under-estimation of variability may be related to
495 numerical dissipation inherent in the models (Zhang and Baptista 2008) as well as errors in representing
496 turbulent mixing. We have since obtained improved results with newer versions of SELFE.

497

498 **5. Conclusions and implications**

499 With the foundation of an efficient and robust numerical model (SELFE, Zhang and Baptista 2008),
500 we have been able to forecast the circulation in the CR estuary and plume on a routine basis, with
501 meaningful predictive skill, as a part of the SATURN/CORIE observatory. Given the regional
502 importance of the CR, these forecasts have the potential to be an important supporting tool towards the
503 scientific understanding of the Pacific Northwest coastal margin ecosystem. The forecasts are an open
504 resource, available to the scientific community as outreach of the Science and Technology Center for
505 Coastal Margin Observation and Prediction. By placing those forecasts aboard vessels, we have
506 provided chief scientists in oceanographic cruises anticipatory (24h-ahead) insights into plume location,
507 size, and gradients. The forecasts have already been beneficially applied in a variety of NSF- and
508 NOAA-funded cruises, with chief scientists of very different disciplinary backgrounds, supporting
509 scientific objectives as diverse as characterizing microbial communities, nutrient fluxes, salmon habitats,
510 bird distributions, and harmful algal blooms.

511 Using a small sub-set of those cruises (specifically, one CMOP and four RISE cruises in 2004-
512 2007) as example, we documented in this paper the level of predictive skill that can be currently
513 achieved for the CR plume. This level of skill has increased over time, as first ELCIRC (not discussed
514 here) and then SELFE matured as cross-scale baroclinic circulation models. For further progress,
515 improvements in external forcing (both ocean and atmospheric circulation at sub-basin scale) are

516 considered essential. Not addressed in this paper are the predictive capabilities for the estuary, which
517 (benefiting from the more constrained and more tidally dominated nature of the estuary) tend to be
518 superior to those for the plume.

519 Characterizing the level of skill of a forecast in general terms is challenging. Of the skill
520 assessments presented here, the metric (a distance) used to document the plume tracking capabilities for
521 August 2007 is perhaps the most useful and intuitive, albeit least conventional. Getting a vessel located
522 next to the “feature” of interest is clearly a first-level concern for any chief scientist aboard an
523 oceanographic cruise. SATURN/CORIE forecasts have often been able to minimize “guessing”, an
524 accomplishment of practical significance in as broad and complex environment as the CR plume. This is
525 particularly useful during periods of fast transition between wind regimes. High-gradients in the plume
526 are particularly well forecasted: over 55% of the time plume concentrations near gradients were
527 predicted within 2 km during the tracking exercise of August 2007. This effectively opens the door to a
528 wide range of scientific applications, in particular in relation to adaptive sampling schemes using vessels
529 and other mobile platforms such as gliders and autonomous underwater vehicles. Novel fast and model-
530 independent data assimilation schemes (Frolov 2007) will be invaluable in exploring such opportunities.

531 Integrative metrics (such as RMS error and correlation factors) are also important, although
532 mostly retrospectively. While it might be difficult to relate in near real-time an integrative metric to a
533 small scale feature of interest, these metrics offer the trained investigator fundamental insights into
534 relative skills of different forecasts. They also offer the ability to place forecast skill in perspective
535 relative to algorithmic changes in models, to changes in model parameters, and to the nature and
536 predictive skill of external forcing. This is best done retrospectively, and with the benefit of a reference
537 long-term simulation database. For instance, Table 5 strongly suggests (but does not demonstrate) that
538 SELFE version 1.4a has superior skill relative to version 1.3g2, and (arguably only based on correlation
539 factors, with RMS errors offering a confounding factor) to version 1.3k. Consolidating and translating
540 those insights into practical near real-time guidance to a chief scientist, regardless of disciplinary
541 background, is a worthy future challenge.

542 The intuition of a chief scientist remains an invaluable tool. For instance, Hickey pointed to
543 limitations in the forecast skill of the plume north of the CR, suggesting that the absence of freshwater
544 from WA rivers could be a factor, before correlation factors (e.g., in Table 3, compare correlation
545 factors for Dev-N and Exp-N) backed numerically that intuition. One of the most important
546 contributions of the forecasts is thus arguably to develop and assist the intuition of the chief scientists.

547 Graphical representations of the plume available aboard in near real time, in formats comfortable to the
548 particular chief scientist, are a major benefit. As an example of customization, a window into the
549 multiple self-redundant forecasts (differences among which offer insights into uncertainty) can either be
550 useful or distracting/overwhelming to different chief scientists.

551 Unsurprisingly, graphical representations offer qualitative insights that are highly complementary
552 to what metrics provide. For instance, Fig. 15 offers compelling evidence of the superior ability of DB14
553 (versus Dev forecasts) to represent near-surface plume structure, and in particular, the effect of river
554 discharge on plume thickness. In this particular case, this visual representation may outweigh
555 quantitative ways to characterize model skill, given general data scarcity and the inability of metrics
556 such as RMS to discriminate errors in the representation of a specific target feature versus errors
557 elsewhere in the water column.

558 While forecasts are strictly hydrodynamic at this point, there is an opportunity to use empirical
559 relationships to bring forecast products closer to ecological variables of interest. For instance, as
560 suggested by Bruland et al. (this issue), nitrate concentration in the CR plume has a strong empirical
561 relationship with salinity. While plume salinity and nitrate observations are relatively scarce, forecasts
562 and hindcasts of salinities may (within the constraints of model uncertainty) be able to fill in gaps by
563 helping predict or re-construct nitrate fields through empirically derived correlations, for periods and/or
564 regions when/where data is not available. Also pointed out by Bruland et al. (this issue), temperatures
565 and/or salinities in the CR estuary may offer an effective index for shelf upwelling. Research to develop
566 such an index is underway based on CORIE observational data (Charles Seaton, personal
567 communication). Once the index is robustly tested based on observational data, its computation will
568 become an integral by-product of SATURN/CORIE forecasts and hindcasts, again eyeing the potential
569 to fill past gaps and/or to anticipate prevailing conditions.

570 While this aspect was purposefully de-emphasized in this paper, we note in closing that careful
571 treatment of many aspects influencing numerical accuracy, efficiency and robustness (taken in
572 combination) matters a great deal in representing the cross-scale complexity of the CR plume. The use
573 of unstructured grids enables great flexibility in spatial resolution, but it alone will not guarantee the
574 necessary efficiency, robustness or accuracy. For example, the slow convergence rate of ELCIRC (not
575 shown) means that aggressive refinement is not always possible, and therefore the higher-order schemes
576 used in SELFE are instrumental in modeling important aspects of plume circulation efficiently.

577 The choice of numerical algorithm must be guided by a judicious balance of considerations,
578 because formal numerical accuracy does not always translate in optimal practical skill for complex
579 systems like the CR. For instance (comparisons not shown), while the performance of ELCIRC in
580 conserving volume and mass is superior to SELFE for the CR system, the overall accuracy and the
581 ability to represent plume (and estuary) features is far superior in SELFE. Similarly, while high-order
582 conservative schemes exist (e.g., discontinuous Galerkin method), efficiency considerations limit their
583 value to forecasting systems such as SATURN/CORIE at the moment. Our experiences with evolving
584 from ELCIRC to SELFE as the default model in the SATURN/CORIE system suggest that forecasting
585 systems should be designed from inception to allow for interchanging computational engines, as new
586 models evolve and computational barriers are removed.

587 The use of multiple forecasts to study the same feature is an effective way to get insights into
588 errors and uncertainties in complex systems. Inter-comparisons between multiple self-redundant
589 forecasts (and also the use of simulation databases as baseline reference) shed light on different
590 manifestation of errors across different models and modeling options. For example, although SELFE
591 results are generally better than ELCIRC's, the improvement is not uniform (e.g., Burla et al. this issue);
592 one of the confounding factors is error compensation, which is common in modeling this type of
593 systems. Our long-term plan for improving forecast skill calls for categorizing errors and uncertainties
594 from various sources (code, parameterizations, external forcing) with the help of the data assimilation
595 techniques emerging from the work of Frolov (2007).

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683 **TABLE CAPTIONS**

684 Table 1: Cruise periods
685 Table 2: Configurations of select forecast and hindcast simulations
686 Table 3: RMS errors and correlation coefficients for near-surface salinities
687 Table 4. Aggregate error statistics
688 Table 5: RMS errors and correlation coefficients for 2005-2006 forecasts, normalized by DB14

689

690 **FIGURE CAPTIONS**

691

692 Fig. 1: SATURN/CORIE forecasts are delivered to on board web servers to assist *en route* cruise
693 planning and data interpretation. Data from cruises (here, RISE and CMOP) and fixed observation
694 networks (here, RISE and a sub-set of SATURN/CORIE) are used for near real-time and *a posteriori*
695 forecast skill assessment. Information flow, from sensor data to realistic forcing and simulation
696 products, is enabled by the SATURN/CORIE cyber-infrastructure.

697

698 Fig. 2. (a) Model grid used for development forecasts, and (b) grid resolution shown as equivalent radius
699 in km.

700

701 Figure 3. Plume characteristics for years (a) 2005 and (b) 2006. The bars indicate the cruise periods.
702 Unless indicated otherwise, all variables are from a SELFE hindcast database (DB14) and 30-hour low-
703 pass filtered using a 4th order Butterworth filter. Tidal range is calculated at the NOAA Astoria tide
704 gauge location. The wind time series is the measured values at NDBC's Columbia River buoy.
705 Discharge is measured at Beaver Army station. The cut-off ocean salinity is $S_{ref}=28$ psu. Box 1 in (a)
706 corresponds to upwelling periods, during which the plume generally became thinner, and centroid
707 moved offshore and southward. Box 2 indicates that the combination of downwelling wind and freshet
708 lead to dramatic movement of plume in the north-south direction and thickening of the plume. Box 3
709 shows that downwelling in a low-discharge period only led to a small increase in the thickness. For year
710 2006 as shown in (b), in contrast to 2005, the river discharge in winter of 2006 was comparable to that
711 during the annual spring freshet. The plume thickness exhibited large oscillation near the beginning and
712 end of the year.

713

714 Figure 4. Plume characteristics during (a) July 2004, (b) June 2005, (c) Aug. 2005, (d) May 2006, and
715 (e) Aug. 2007 cruises. See Fig. 3 for explanation of variables used; the only exception is in 2007, where
716 the plume characteristics is calculated using the development forecast (DB14 results not available for
717 this year).

718

719 Figure 5. During a relatively constant (low) discharge and weak wind period in the Aug. 2005 cruise
720 (indicated as the bar), the spring-neap cycle can be clearly seen in the plume thickness, and to a lesser
721 extent, the centroid locations (which were also influenced by the shifting wind). See Fig. 3 for
722 explanation of variables used; note that no variables are filtered.

723

724 Figure 6. Statistics of plume during five cruises. The wind time series is the measured values at NDBC's
725 Columbia River buoy, and discharges are measured at Beaver Army station (extracted from DB14).

726

727 Fig. 7. "Feature tracking" exercise conducted in Aug. 2007. The red dots are the positions of Wecoma,
728 and the black dotted lines are the corresponding salinity isolines for the measured salinity values at the
729 instrument depth (4 m) from the forecast. See Fig. 8 for the error statistics. The forecast skill is generally
730 good; most times the chief scientist was able to locate the plume front (judging by the different water
731 colors) with help from the forecast.

732

733 Fig. 8. (a) The salinity values, the model errors in terms of the minimum distance between the Wecoma
734 position and the corresponding salinity isoline, and the wind errors at the 39 way points shown in the
735 previous figure. The correlation coefficient between wind errors and distance errors is only 0.01, again
736 indicating that the plume responds to the time history of the wind. (b) Cumulative percentages as a
737 function of model error distances. Over 55% of the time the error distance is within 2km, and >70% of
738 the time it is within 5km. The model performance is satisfactory, given the errors in wind forcing, and
739 the fact that the model resolution in the region is coarser than 0.5km.

740

741 Figure 9. Flow-thru comparisons during July 2004 RISE cruise. (a) Wecoma cruise paths (red lines) and
742 the corresponding surface plume (at 28 and 30 psu; black dotted lines) at the start of each cruise as
743 predicted by the development forecast. (b) Comparison of salinities at instrument depth (approximately
744 4 m from the surface). Since the dev forecast was not yet deployed for this cruise, DB14 results are used.
745 The salinities have been hourly averaged. The wind is measured at the Columbia River buoy.

746

747 Figure 10. Flow-thru comparisons during June 2005 RISE cruise. (a) Wecoma cruise paths (red lines)
748 and the corresponding surface plume (at 28 and 30 psu; black dotted lines) at the start of each cruise as
749 predicted by the development forecast. Partially guided by the forecast, the cruise paths cross the plume
750 many times to study the gradients. (b) Comparison of salinities at instrument depth (approximately 4 m
751 from the surface). The salinities have been hourly averaged. The wind is measured at the Columbia
752 River buoy.

753

754 Figure 11. Flow-thru comparisons during Aug. 2005 RISE cruise. (a) Wecoma cruise paths (red lines)
755 and the corresponding surface plume (at 28 and 30 psu; black dotted lines) at the start of each cruise as
756 predicted by the development forecast. (b) Comparison of salinities at instrument depth (approximately
757 4 m from the surface). The salinities have been hourly averaged. The wind is measured at the Columbia
758 River buoy.

759

760 Fig. 12. (a) May 2006 Wecoma cruise paths (red lines) and the corresponding surface plume (at 28 and
761 30 psu; black dotted lines) at the start of each cruise as predicted by the dev forecast. The wind regime
762 during this period is very variable, resulting in different plume orientations. (b) Comparison of near-
763 surface salinities. The discharges are high in this spring freshet period.

764

765 Figure 13. Flow-thru comparisons during Aug. 2007 CMOP cruise. This cruise was concurrent with the
766 feature tracking exercise shown in Fig. 7. (a) Wecoma cruise paths (red lines) and the corresponding
767 surface plume (at 28 and 30 psu; black dotted lines) at the start of each cruise as predicted by the

768 development forecast. (b) Comparison of salinities at instrument depth (approximately 4 m from the
769 surface). The DB14 results are not available for this cruise; results from two forecasts are shown here.
770 The salinities have been hourly averaged. The wind is measured at the Columbia River buoy.

771

772 Fig. 14 Scatter plot of data and model (development forecast and DB14) for near-surface flow-through
773 measurements collected by Wecoma and Pt Sur. Both model and data have been hourly averaged. The
774 comparison for DB14 is done from 2004 to 2006, whereas the comparison for the development forecast
775 is done from 2006 and 2007; same version of SELFE (v1.4a) was used for the comparisons. The RMSE
776 and correlation coefficients can be found in Table 4.

777

778 Fig. 15 CTD cast comparison in 2005 cruises by Forerunner, near the CR mouth. The cast locations are
779 shown on top of each column; the first casts are indicated as squares, the last as circles, and the rest as
780 pluses. During these cruises, the M/V Forerunner followed similar patterns. Therefore the influence of
781 increasing discharge on the plume thickness is visible from the casts.

782

783 Fig. 16 CTD cast comparison in the 2006 cruise by Forerunner, near the CR mouth. The cast locations
784 are shown on top of each column; the first casts are indicated as squares, the last as circles, and the rest
785 as pluses. During these cruises, the M/V Forerunner followed similar patterns. Therefore the influence
786 of increasing discharge on the plume thickness is visible from the casts.

787

788 Fig. 17 Other CTD casts in 2005 by Forerunner. Cast locations are shown on top of each column. The
789 first casts are indicated as squares, the last as circles, and the rest as pluses.

790

791 Fig. 18 Other CTD casts in 2007 cruise by Wecoma. Cast locations are shown on top of each column.
792 The first casts are indicated as squares, the last as circles, and the rest as pluses.

793

794 Fig. 19 Surface CTD data from Pt Sur in June 2005. (a) Cruise path. (b) Salinity comparison along the
795 path.

796

797 Fig. 20 CTD data collected from Pt Sur at *deeper* depths in July 2004. (a) Cruise path. (b) Salinity
798 comparison along the path at the specified depths. The RMS error is 0.84 psu and the correlation
799 coefficient is 0.75.

800

801 Fig. 21 CTD data collected from Pt Sur at *deeper* depths in June 2006. (a) Cruise path. (b) Salinity
802 comparison along the path at the specified depths. The RMS error is 1.26 psu (dev) and 0.82 (DB14),
803 and the correlation coefficient is 0.68 (dev) and 0.66 (DB14).

804

805 Figure 22. (a) Comparison of residual velocity at ogi01 (Fig. 1), during June 2006 cruise. The depths are
806 relative to free surface. Ellipses for the total velocity (including the tides) are shown next to each depth.
807 (b) Correlation coefficients for u (dashed lines) and v (solid lines).

808