

**CORIE modeling system: status of hindcast simulations as  
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**An internal report**

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## **Abstract**

This is the second of a two-part paper on ELCIRC, an Eulerian-Lagrangian finite difference/finite volume model designed for the simulation of 3D baroclinic circulation across river-to-ocean scales. In part one (Zhang et al. [2004]), we described the formulation of ELCIRC and assessed its baseline numerical skill. Here, we describe the application of ELCIRC in the context of CORIE, an ocean observing system for the Columbia River estuary and plume. We first introduce the CORIE modeling system, and describe its multiple modes of simulation, external forcings, observational controls and automated products. We then focus on the evaluation of highly-resolved year-long ELCIRC simulations, using two specific variables (water level and salinity) to characterize simulation quality and sensitivity to modeling choices. We show that, process-wise, simulations capture important aspects of the response of estuarine and plume circulation to ocean, river and atmospheric forcings. Quantitatively, water levels are robustly represented, while salinity intrusion and plume dynamics remain challenging. Our analysis highlights the benefits of conducting model evaluations over large time windows (months to years), to avoid significant localized biases. The robustness and efficiency of ELCIRC have proved invaluable in identifying and reducing non-algorithmic sources of errors, including parameterization (e.g., turbulence closure and stresses at the air-water interface) and external forcings (e.g., ocean conditions, and atmospheric forcings).

**Key words:** Mathematical Modeling. Ocean, coastal and estuarine circulation. Eulerian Lagrangian methods. Finite volumes. Finite differences. Semi-implicit methods.

**Regional index terms:** USA. Pacific Northwest. Columbia River.

## 1 Introduction

Integrated ocean observing systems (Clark and Isern [2003]; Martin [2003]; USCOP [2004]) are expected to dramatically improve understanding of the ocean across scales and processes, and to provide unprecedented, objective information to address societal priorities regarding ocean preservation and utilization. Meeting these lofty expectations will require improvements in underlying technologies (models, sensors and information technologies) as well as adjustments in their use.

A preview of challenges to come has been provided by selected prototype ocean observing systems (Parker [1997]; Glenn et al. [2000]; Steere et al. [2000]; Rhodes [2001]; Baptista [2002]). Developed and maintained since 1996 for the Columbia River estuary and plume, CORIE (CCALMR [1996-2004b]; Baptista et al. [1998]; Baptista et al. [1999]) is one such prototype system. CORIE was designed from the onset as a multi-purpose regional infrastructure for research, education and management. The design includes a real-time observation network, a modeling system, and a web-based information system. The development of these three components has been tightly integrated, under the responsibility of a single research team but leveraged by extensive collaborations (see Acknowledgements).

Perhaps surprisingly, of the three CORIE components, the modeling system has posed the most fundamental challenges, calling for new modeling technologies and paradigms. In particular, we found the need to develop a new cross-scale 3D baroclinic circulation code (ELCIRC; Zhang et al. [2004]) in order to meet operational requirements

of efficiency and quality. Also, automated integrative procedures - including the generation of model forcings, quality controls and modeling products - have become essential to create, improve and interpret simulations. Moreover, multiple simulation modes - including daily forecasts, multi-year hindcasts and scenario simulations – forced the development of multi-scale, long-term calibration and validation strategies and procedures.

Here, we describe the CORIE modeling system (Section 2) and present selected results (Section 3), with emphasis on water levels and salinities. The description of the modeling system is intended as a reference for derivative papers, which will complement the present work by exploring in further depth specific modeling aspects or scientific and management applications of CORIE. The results shown in Section 3 illustrate the extent to which the modeling system is already able to describe complex multi-scale circulation processes in the Columbia River, and help identify directions for further improvement. We also (Section 4) discuss implications for derivative research on Columbia River circulation, for further algorithmic development of cross-scale numerical models, and for coastal estuarine and plume modeling within the requirements of ocean observing systems.

## **2 The CORIE modeling system**

One of the world's classic river-dominated estuaries, the Columbia River is a highly dynamic system that responds dramatically to changes in ocean tides and water properties, regulated river discharges, and coastal winds. A dominant hydrographic feature in the U.S. West Coast, the Columbia River plume exports dissolved and

particulate matter hundreds of kilometers along and across the continental shelf (Barnes et al. [1972]; Grimes and Kingsford [1996]). In response to seasonal changes of the large-scale coastal circulation patterns, the plume typically develops northward along the coastal shelf in fall/winter, and southwestward offshore of the shelf in spring/summer; however, the direction, thickness and width of the plume – and, in particular, the near-field plume – can change in hours to days in response to local wind (CCALMR [1996-2004a]; Hickey et al. [1998]; Garcia-Berdeal et al. [2002]).

Compressed and often stratified, the estuary is subject to extreme variations in extent of salinity intrusion and in stratification regime (Hamilton [1990]; Jay and Smith [1990]; Chawla et al. [in prep.]). Two main channels (one dredged for navigation) cut the otherwise shallow estuary (Fig. 1); a shallow coastal region north of the Columbia River mouth combine with Coriolis to establish an underlying tendency for the near-plume to move North, which is countered by the exit angle of the navigation channel and either countered or reinforced by local winds.

To address the challenges of Columbia River circulation, we have implemented a modeling system that integrates *models*, *forcings*, *controls* and *products* (Fig. 2; Sections 2.1, 2.3, 2.4 and 2.6); the system is designed to operate on a sustained manner across multiple scales of space and time. Our design allows for diverse modes of simulation (Section 2.2), each with different timing requirements for forcings, controls and products. Data assimilation is used only sparingly (Section 2.5). Computational and archival requirements are met with a dedicated, evolving computer infrastructure (Section 2.7).

The domain of simulation spans from the Bonneville Dam and the Willamette Falls, approximately 240 km upstream of the entrance to the Columbia River estuary, to and beyond the continental shelf of California, Oregon, Washington and British Columbia. Computational grids (Fig. 3; latter, see also Fig. 11a and Fig. 20c for local details) are typically 3D, unstructured in the horizontal and with z-coordinates in the vertical.

## 2.1 Models

Modeling circulation in the Columbia River estuary and plume is unusually challenging, with elements of complexity that include: (a) highly variable and nonlinear forcings (wind, tides, river discharge); (b) dynamic density fronts and strong buoyancy-driven flow; and (c) tight connectivity across drastically different spatial scales (from under 100m to well above 10km) and temporal scales (minutes to decades).

Because of these complexities, circulation has been the quasi-exclusive focus of the CORIE modeling system to date. After initial trails with off-the-shelf circulation codes, we found the development of a new 3D baroclinic circulation model to be a necessary and effective mechanism to address physical complexity within the multiple CORIE modes of simulation (Section 2.2).

The motivation, formulation and basic skill assessment of the new model, ELCIRC, were presented in Zhang et al. [2004]. In summary, ELCIRC is a finite-difference/finite-volume model, based on unstructured grids; the numerical scheme is robust, volume conservative, and numerically efficient. Within the constraints of the hydrostatic approximation, the ELCIRC physical formulation offers a unified river-to-ocean

approach, allying to features of state-of-the-art ocean models the ability to treat high-advection regions and extensive wetting and drying.

## 2.2 Modes of simulation

The multiple uses of CORIE require that the modeling system support different modes of simulation. Scientific cruises, within ecological and fisheries projects, provided the original motivation for the development of *daily forecasts*, which routinely produce next-day predictions. This capability is maintained at OHSU on a 24-7 semi-operational basis, and is in consideration for transition to the National Oceanic and Atmospheric Administration (NOAA), for full operational use.

By contrast, *hindcast databases* provide a sustained, long-term foundation for detailed process studies and for guidance on management issues. An ultimate goal is to enable multi-scale understanding of long-term variability in the Columbia River, including the impact of global climate and anthropogenic activity. Simulations for hindcast databases are conducted retrospectively, with realistic bathymetry and external forcings. Although exceptions apply, hindcast databases are typically built in year-long segments, through the appropriate juxtaposition of series of week-long simulations; weeks start at 00:00PST and are numbered sequentially (week 01 is from 00:00PST 01/01 to 24:00PST 01/07; week 02 is from 00:00PST 01/08 to 24:00PST 01/14; and so forth)

Similar to hindcast databases except for a predominantly exploratory perspective, *calibration runs* are used to evaluate alternative modeling choices, towards improved capabilities of the CORIE modeling system. Calibration runs are retrospective, and

typically use realistic bathymetry and external forcings; the basic simulation unit is one week, with simulations over multiple weeks being conducted when necessary.

Finally, *scenario simulations* are used to explore scientific or management questions (Bottom et al. [2001]; USACE [2001]). Scenario simulations are customized to the specific question they are meant to address; they often involve artificial choices of bathymetry or external forcings, and can be conducted for past, present, or future conditions.

### 2.3 External forcings

Ocean, atmospheric and river influences control much of the dynamics of the Columbia River estuary and plume. All these influences are highly variable in space and time, as partially illustrated in Figs. 4-8. Accounting for this variability is challenging, yet essential to a successful simulation of circulation. We describe below strategies and information sources to characterize external forcings in the CORIE modeling system. Where they diverge, we briefly note the differences between strategies to address forcings for daily forecasts and for retrospective simulations (hindcast databases and calibration runs).

#### 2.3.1 *River inputs*

The Columbia River system is currently the only source of freshwater accounted for within the CORIE modeling system. While the Columbia River is indeed a dominant freshwater source in the Pacific Northwest (see Fig. 4a for geographic reference), notably absent is the input from the Strait of Juan de Fuca (Fig. 4b). Within the Columbia River, freshwater inputs are considered from Bonneville Dam (for the main stem of the



Columbia River) and Newberg (for Willamette River) - Fig. 4c. Neglected are smaller freshwater inputs, including those from the Cowlitz, Lewis and Sandy rivers (Fig. 4d). As illustrated in Fig. 4e, Bonneville discharges retain - despite heavy hydropower regulation - substantial seasonal (e.g., spring freshets) and inter-annual variability (e.g., in response to El Niño – Southern Oscillation and to Pacific Decadal Oscillation).

For retrospective simulations, information on freshwater discharges is obtained from two USGS gauges (USGS-ID 14128870, downstream of the Bonneville dam; and USGS-ID 14197900, at Newberg). Temperature data for Columbia River is obtained from the same site that records the river discharge. Temperature data for Willamette River is obtained from a USGS gauge in Portland (USGS-ID 14211720) located approximately 60 km downstream of the Newberg gauge. Data from the same gauges is used for the daily forecasts, through short-term extrapolation.

The importance of correctly characterizing the temperature of the river end member is illustrated in Fig. 5; this figure shows that river temperature tightly bounds estuarine temperature from above in summer, and from below in winter.

### 2.3.2 *Ocean conditions*

We have used four semi-diurnal ( $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_2$ ) and four diurnal ( $K_1$ ,  $O_1$ ,  $P_1$ ,  $Q_1$ ) constituents to characterize ocean tides at the boundaries of the CORIE computational domain. Spatially variable tidal amplitudes and phases are available for the Eastern North Pacific from at least two different sources (Egbert [1994] and Myers and Baptista [2001]); we have typically used Myers and Baptista [2001] (e.g., Table 1), after early tests showed limited sensitivity of the results to this choice. Nodal factors and

astronomical arguments are calculated from the tidal package of Foreman [1977]. The earth tidal potential (from Reid [1990]) can be included, but has typically been neglected.

Seasonal climatology for ocean salinity and temperature is available from Levitus [1982]. By default, this climatology has been used in the CORIE modeling system. However, Levitus climatology is notably coarse (Fig. 6), in particular for coastal applications, and inherently unable to capture the inter-annual variability of salinity and temperature. Work is in progress (Foreman, private communication) to complement the Levitus climatology with a range of Pacific Northwest coastal data sets.

As an alternative to climatology, we are exploring the use of output from operational Navy products to define ocean salinity and temperature conditions, using 2002 hindcast database simulations as the benchmark. Developed by the Naval Research Laboratory for application to coastal and global prediction of ocean dynamic and thermodynamic fields (Martin [2000]), the Navy Coastal Ocean Model (NCOM) is a variant of the Princeton Ocean Model (POM; Blumberg and Mellor [1987]). A global ocean model based on NCOM (Global NCOM) is presently in the final stages evaluation for operational use. This model runs using  $1/8^{\text{th}}$  degree horizontal resolution and 40 vertical levels that are a combination of sigma levels in the upper 150m of the ocean and z-levels from 150m to the ocean bottom (Rhodes [2001]; sample output in Fig. 7). The model has been tested using both climatological forcing and real time atmospheric forcing from the Navy's Operational Global Atmospheric Prediction System (NOGAPS; Rosmond [2002]). Global NCOM has been spun up from a climatological state to the present, using a combination of NOGAPS forcing and the assimilation of satellite altimeter data and 3D

temperature and salinity observations derived from the Modular Ocean Data Assimilation System (MODAS; Fox [2002]).

To date, CORIE simulations have relied on the internal physics of the model and on external (winds and atmospheric pressure) and internal (density gradients) forcings to generate ocean set-up and circulation within the modeling domain. We anticipate soon to be compelled to explore the extent to which Global NCOM might provide beneficial external forcings for set-up and/or currents.

### 2.3.3 *Atmospheric forcings*

Several different atmospheric forcings are utilized by the CORIE modeling system. They are divided into two main groups: near-surface atmospheric properties, and the downwelling radiative fluxes at the surface. The atmospheric properties include the x- and y-components of the wind at a height of 10m, the surface atmospheric pressure (reduced to mean sea level), the air temperature at a height of 2m, and the specific humidity at a height of 2m. The radiative fluxes include the downwelling shortwave (solar) and the downwelling longwave (infrared) radiations at the water surface.

This forcing data has been compiled from a number of different sources, but the data falls into two broad divisions: locally archived forecast data (e.g., Fig. 8a,b), and reanalysis data (essentially hindcast data which incorporates large amounts of data assimilation.) The forecast datasets include data from (a) the NOAA National Centers for Environmental Prediction (NCEP)'s Global Forecast System (GFS, also referred to as the MRF and/or AVN forecasts); (b) NCEP's Eta Model; and (c) the Advanced Regional Prediction System developed at the University of Oklahoma, as modified and run at

Oregon State University (OSU/ARPS). The reanalysis dataset is comprised of data from a joint project of NCEP with the National Center for Atmospheric Research (NCAR), the NCAR/NCEP Global Reanalysis Project.

The CORIE archive of GFS data covers the time period from 04/2001–present. The OSU/ARPS data has been retained from 05/2001–02/2004. The Eta forecasts are locally stored between from 07/2003 through the present. Our subset of the Global Reanalysis data covers the years 1988–2001. The different datasets are stored on their original grids, and at the output frequency chosen by their authors. Interpolation to the CORIE grids and times occurs at runtime; this interpolation might involve the weighted average of more than one dataset (e.g., see Section 3.1.1)

Prior to 07/2003, the GFS atmospheric properties were obtained at 1 degree resolution, with "snapshot" values every 12 hours. The radiative fluxes were stored as 3-hour averages, on a 0.7 degree resolution (prior to 11/2002) or 0.5 degree resolution (after 11/2002). The area retained for both datasets covered approximately 129W–120W & 35N–51N. After 7/2003, the GFS atmospheric properties were stored as 3-hour snapshots, and all variables were retained for the Pacific basin east of 180W.

The Eta model forecasts are at a 12 km resolution, with 3-hour snapshots for all variables. The area retained is the portion of the Eta grid 218 west of 100° W (NCEP [2004]), which encloses the North Pacific along the western coast of North America from southern Mexico northwards into the Alaskan panhandle. The OSU/ARPS forecasts are also at a 12 km resolution, though with 1-hour snapshots. The output covers the approximate area of 128W–119W & 41N–47N, and includes only the atmospheric

properties; radiative fluxes were not output. The NCAR/NCEP global reanalysis data was output at a 1.875 degree resolution, as 6-hour snapshots (atmospheric properties) or 6-hour averages (radiative fluxes); the full global dataset was retained.

## 2.4 Observational controls

Inherent to the concept of the CORIE modeling system are systematic quality controls, based on comparisons against data from various long-term observational networks (Fig. 9 and Fig. 10). Most of these networks have real-time or quasi real-time telemetry, thus supporting both hindcast simulations (databases and calibration runs) and daily forecasts. Key observation networks include:

CORIE: The CORIE real-time observation network covers the estuary extensively and the near-ocean sparingly (Fig. 9; CCALMR [1996-2004c]). At each station, in-situ sensors measure various combinations of water temperature, salinity, pressure, velocity, and atmospheric parameters. Observations are available in both real-time and as long-term archives, some nearly 8 year long. We have also equipped the M/V Forerunner, a 50ft vessel operated by the Clatsop Community College for seamanship training, with a pump-through conductivity-temperature sensor and a hull-mounted acoustic Doppler profiler. The vessel's instruments are designed to operate automatically anytime the vessel is en route, thus serendipitously accumulating an extensive data record in the estuary and plume; the vessel is also used for targeted CORIE cruises (e.g., Fig. 39).

NOAA Center for Operational Oceanographic Products and Services (CO-OPS): CO-OPS maintains a nation wide network of coastal and estuarine tidal stations that are referenced to standard benchmarks and provide both historical verified and real time

unverified observations of water levels. CO-OPS stations in the CORIE modeling domain are shown in Fig. 10, panels 1-3.

NOAA National Data Buoy Center (NDBC): NDBC maintains a national network of buoys that measure atmospheric winds, barometric pressure and wind gusts. Some of the buoys also provide information on sea surface temperature and wind driven ocean surface waves. NDBC stations in the CORIE modeling domain are shown in Fig. 10, panels 2-3; data from one of the CORIE stations (ogi01) will also soon be available through the NDBC data repository.

U.S. Army Corps of Engineers (USACE) and U.S. Geological Survey (USGS): The Northwest Division of USACE maintains, in cooperation with the USGS, an exhaustive database of real-time observations for the major streams and rivers for the Northwest Pacific region. The USGS also monitors water quality and stream flow conditions of all the major streams and rivers across the country. Both agencies maintain several gauges that provide real-time river discharge, temperature and water level information in the CORIE domain (Fig. 10, panel 1).

Besides systematic quality control of CORIE simulations against information from long-term fixed observation networks, we conduct more “random” quality controls against episodic data from a range of sources. Particularly useful are Synthetic Aperture Radar satellite images (e.g., Fig. 20a) and diverse oceanographic studies, including: (a) an extensive 1990-91 plume study with moorings and vessels (Hickey et al. [1998]); (b) extensive estuarine cruises in the estuary conducted as a part of the Columbia River component (CRETM [1990-2000]) of a national land-margin ecosystem research

program (LMER Coordinating Committee (W. Boynton [1992])); CORIE cruises conducted episodically in the estuary and plume since 1996; and cruises conducted by NOAA Fisheries since 1998 along coastal transects in California, Oregon and Washington and at or near the mouth of the Columbia River.

## 2.5 Data assimilation and nudging

It is the CORIE philosophy that the numerical circulation model is ultimately responsible to represent the physics inside the domain, once appropriate choices have been made for parameters and external forcings. We thus have used data assimilation sparingly: primarily, to improve the definition of external forcings and for off-line optimization of empirical parameters

Specifically, data assimilation was used to define ocean tidal forcings (Myers and Baptista [2001]) and is being used to optimize bottom friction (Frolov et al. [2004]). In addition, under certain circumstances, we locally nudge ocean conditions (salinity and temperature) to information from either a global circulation model or climatology - which in turn have either been data assimilated or objectively analyzed from data; with this nudging, we seek to impose non-reflective ocean boundary conditions and to moderate errors in heat balance calculations resulting from the specification of imprecise atmospheric forcings.

CORIE nudging has been based on the simple algorithm:

$$\hat{\beta}^n(x, y, z) = (1 - \alpha)\beta_{ELCIRC}^n(x, y, z) + \alpha\beta_{base}^n(x, y, z)$$

{1} *with*

$$\alpha(x, y, z) = \gamma(x, y)\psi(z)$$

where  $\hat{\beta}^n$  is the nudged value at time  $n$ ,  $\beta_{ELCIRC}^n$  is the value computed directly by solving the governing equations, and  $\beta_{base}^n$  is the reference value from a global circulation model or from climatology. The nudging factor  $\gamma$  is typically zero in the estuary and near-plume, increasing towards the ocean in patterns dictated by the objectives of the particular simulation. The vertical nudging profile  $\psi$  is linear or step-wise linear.

## 2.6 Products

The large number of simulations conducted daily within CORIE requires systematic, standardized processing. Automated procedures have been established for separate but similar processing of daily forecasts and of hindcast simulations (both hindcast databases and calibration runs). Each procedure results in an ensemble of web-based products designed to describe patterns of circulation, at various scales and under multiple perspectives; these products also provide detailed comparisons against field observations. Several figures shown in this paper are minor modifications or groupings of automated products (e.g., Figs. 17-19, 25, 31-33 and 39). A separate publication will describe the scope and underlying infrastructure of the CORIE modeling products; for hindcasts, public access to those products is available (CCALMR [2003-2004]).

## 2.7 Computational infrastructure

The dedicated CORIE computational infrastructure has evolved substantially since 1996, in an attempt to support progressively more ambitious simulation goals. At the time of this writing, the infrastructure includes 20 dual CPU Intel compute nodes (2.4 GHz, 4 Gb) organized as a Beowulf cluster, and 28 TB of online disk array. For a baroclinic simulation on a typical computational grid (33634 horizontal nodes; 50389 horizontal



hybrid elements; 62 z-levels) and with a typical time step (1.5 minute), ELCIRC runs 2.5-3 times faster than real time, in a single CPU. The upper bound in this range applies to simulations with a zero-equation turbulence closure, and the lower to simulations with a 2.5-equation turbulence closure. Purely barotropic simulations can be run with a 15 minute time step, and are about 60 times faster than real-time; however, rarely is it justified to run a barotropic simulation in the Columbia River, due to the strong influence of buoyancy. About 0.8 TB of online storage are required to store a typical year-long baroclinic simulation.

### **3 Selected results**

Simulations of Columbia River circulation are sensitive – often in complex, non-linear manners - to a wide range of modeling choices, including initialization strategies and representation of internal parameters, bathymetry and external forcings. To understand and address this sensitivity, we have developed a sustained, iterative process that involves simulations at multiple time windows.

Anchoring this process are hindcast databases, which typically extend for at least a full year, and often reflect best-available knowledge at some point in time. It is, however, the exploratory nature of complementary calibration runs that contributes most to advancing the state of modeling within CORIE. Calibration runs can be as short as one week, or as long as several months. At any given day, as many as twelve calibration runs might be in progress, each exploring different modeling strategies. Occasionally, one of these calibration runs evolves into a hindcast database.

As an illustration of the process, we will describe in Section 3.1 a baseline simulation (hindcast database 06, year 2002), and will then show how alternative modeling options affect the representation of selected physical processes and variables (Section 3.2). Changes in the CORIE treatment of turbulence closure and ocean conditions will be introduced as a consequence of this particular iteration loop. Because of space restrictions, we will focus our analysis of the CORIE results on just two variables; water levels and salinity. Velocities and temperatures will be addressed in separate publications; however, because salt propagation is essentially a transport problem, the analysis provides a stringent, albeit indirect, assessment of the circulation capabilities of the numerical model.

### 3.1 Baseline simulation

We choose hindcast database 06 (henceforth, DB06) as baseline because it represents the most recent full-year simulation, and it marks an important turning point within the CORIE modeling system. Indeed, DB06 was the first database built using hybrid-element grids (i.e., grids with both triangles and quadrangles), and inspired substantial changes in the treatment of turbulence closure and ocean conditions (see Section 3.2).

#### 3.1.1 *Simulation set-up*

DB06 was conducted without data assimilation, and extends over the entire year of 2002. Simulations are organized in 12 ensembles. Each ensemble is composed of several weeks run sequentially and spun up from Levitus conditions. To reduce discontinuities across ensembles, contiguous ensembles overlap by one week: the first week of each ensemble is considered warm-up, and eventually discarded in favor of the last week of the previous ensemble. The warm up for the first ensemble is longer, starting 11/26/2001.

Transitions between ensembles occur on 02/05; 03/05; 04/02; 04/30; 06/04; 07/02; 08/06; 09/03; 10/08; 11/05; and 12/03 (all in 2002).

As typical within CORIE, the horizontal grid extends from the Bonneville Dam and the Willamette Falls to and beyond the continental shelf of California, Oregon, Washington and British Columbia. A combination of quadrangles and triangles are used, with highest spatial resolution concentrated in the Columbia River estuary and near plume; over 35% of the elements in the grid have an equivalent diameter between 100 and 200m (Fig. 11c). Upstream of the estuary, the main river channel is carefully delineated, but flood plains are often under-detailed: thus, that part of the grid functions primarily as a conduit for freshwater discharge into the estuary, and expectations of local accuracy are low.

The ELCIRC formulation assumes grid orthogonality (Zhang et al. [2004]). While strict orthogonality is difficult to ensure, deviations from orthogonality can be evaluated using “orthogonality indices”, which we define separately for triangles and for quadrangles (Appendix). For triangles, a positive index value corresponds to an orthogonal element; for quadrangles, the closer the index value is to unity the closer the element is to orthogonality. As applied to the grid used in DB06, orthogonality indices show that most but not all elements achieve or approach orthogonality (Fig. 12b,d). Further improvements towards orthogonality are desirable but very costly, and have not been considered a priority over other sources of modeling uncertainty within CORIE. The lack of tools for automated enforcement of grid orthogonality will need to be addressed in the near future, in response to the increasing popularity of models such as UnTRIM (Casulli and Zanolli [1998], Casulli and Walters [2000]) and ELCIRC.

The vertical grid consists of 62 z-levels, with finer resolution concentrated on the top 30 meters of the water column (Fig. 13). As typical in z-coordinate models, near-bottom representation is challenging for ELCIRC. With our choice of vertical and horizontal grids, we minimize the difficulties in the estuary and near plume, at the expense of the continental shelf, continental slope and deep ocean (Fig. 14).

The ability to handle Courant numbers well above unity is one of the strengths of the Eulerian-Lagrangian algorithm of ELCIRC. We capitalize on this strength to use a time step of 1.5 minutes, for which Courant numbers as large as 4 (in the estuary; Fig. 15) and even 10 (upriver; figure not shown) are common. A time step of as much as 15 minutes would still have been appropriate for purely barotropic simulations; however, time steps larger than 1.5 minutes lead to parasitic oscillations in the vicinity of strong baroclinic forcings.

To understand these oscillations, we note that a Courant-Friedrich-Lévy condition associated with the baroclinic term can be estimated via the maximum internal wave speed as:

$$\{2\} \quad Cu' = \frac{\Delta t \sqrt{g'h}}{\Delta x} \leq 1$$

where  $g' = g \frac{\Delta \rho}{\rho_0}$  is the reduced gravity. Therefore, a theoretical maximum time step for stability can be estimated as:

$$\{3\} \quad \Delta t_{\max} \sim \frac{175}{\sqrt{9.8 * 25 / 1025 * 20}} \cong 79 \text{ sec},$$

assuming a typical channel depth of  $h=20\text{m}$ , an horizontal resolution of 175m (e.g., see Fig. 11), and an extreme case of freshwater ( $\rho=1000\text{kg/m}^3$ ) at the surface and saltwater

( $\rho=1025\text{kg/m}^3$ ) at the bottom. This order-of-magnitude estimate lends credence to the trial and error analysis that led to the choice of an operational time step of 1.5min.

ELCIRC allows only limited algorithmic flexibility. Of particular importance are the implicitness factor  $\theta$  (see Eq. 37 in Zhang et al. [2004]) and the strategy for selecting the sub-time step used to track the characteristic lines. Based on the formal analysis of Casulli and Cattani [1994], we set  $\theta$  to 0.6, thus weighing the present time step slightly more than the previous time step in the treatment of terms of the continuity and momentum equations that are handled implicitly; empirical trial-and-error supported this choice.

By default, the tracking of characteristic lines in ELCIRC performed with simple Euler integration.  $N$  integration steps (referred to as sub-time steps) are allowed for tracking between times  $n+1$  and  $n$ . In DB06, we let the sub-time step be chosen automatically, to account for local gradients of velocity. Specifically:

$$\{4\} \quad N = \max \left\{ N_{\min}, \min \left[ N_{\max}, \max(N_x, N_y, N_z) \right] \right\}$$

where  $N_{\min}$  and  $N_{\max}$  are user-specified limits (2 and 9, for DB06) and

$$\begin{aligned} N_x &= 10 \left| \frac{\partial u}{\partial l} \right| \Delta t, \\ \{5\} \quad N_y &= 10 \left| \frac{\partial v}{\partial l} \right| \Delta t, \\ N_z &= \frac{|w| \Delta t}{\Delta z}, \end{aligned}$$

where  $u, v$ , and  $w$  are velocities in the  $x, y$  and  $z$  directions, horizontal gradients  $\left| \frac{\partial u}{\partial l} \right|$

and  $\left| \frac{\partial v}{\partial l} \right|$  are computed along sides of elements, and  $\Delta z$  is the local vertical grid size.

We note that experiments where we enforced smaller sub-time steps or tracked the characteristic lines with higher-order methods (e.g., Runge-Kutta 5<sup>th</sup> order) revealed no substantial gains in accuracy (results not shown).

Three types of physical parameterization play potentially important roles in the model outputs: bottom friction, surface stress, and vertical mixing. Choices for DB06 were as follows:

Bottom friction: The existence of different bed forms in the Columbia River, upstream and downstream of the Astoria-Tongue Point region, has long been recognized (Hamilton [1990]). We coarsely represent this difference by imposing a spatially varying bottom drag coefficient ( $C_{Db}$ ; see Eq. 14 in Zhang et al. [2004]). Specifically, we allow for a frictionless bottom ( $C_{Db}=0$ ) in the continental shelf and in the Columbia River up to 20km upstream of the estuary entrance; we impose substantial friction ( $C_{Db}=0.0045$ ) above 30 km upstream of the estuary entrance; and we let  $C_{Db}$  transition linearly in between these two regions. While characterization of bottom friction is not a closed issue for the Columbia River (e.g., Frolov et al. [2004]), improvements of model results based on optimizing values of  $C_{Db}$  have been modest. Internal calculation of  $C_{Db}$  based on matching model velocities with bottom boundary layer profiles (Eq. 15 in Zhang et al. [2004]) has not proved clearly superior, either, possibly because of the difficulty of z-coordinate models such as ELCIRC in representing the bottom boundary layer.

Surface stress: Through sensitivity analysis, partially reported in Section 3.2.1, we found the bulk aerodynamic algorithm of Zeng et al. [1998] to be superior to more traditional, simpler, but less process-driven surface stress formulations (e.g., see review

in Pond and Pickard [1998]). As described in Zhang et al. [2004], the algorithm of Zeng et al. [1998] accounts for surface layer stability, free convection and variable roughness length at the ocean-atmosphere interface. This algorithm is now standard within the CORIE modeling system, whenever simulations use the output of atmospheric models to drive wind fields and heat balance budgets (as in DB06).

Vertical mixing: ELCIRC offers various alternatives for characterizing vertical mixing. While more advanced schemes are used in simulations reported in Section 3.2, in DB06 we use a zero-equation closure scheme based on Pacanowski and Philander [1981]. Specifically, we assume that the local eddy viscosity and diffusivity,  $K_{mv}$  and  $K_{hv}$ , only depend on the gradient Richardson number,  $Ri$ :

$$\{6\} \quad K_{mv} = \frac{\nu_0}{(1+5Ri)^2} + \nu_b,$$

$$\{7\} \quad K_{hv} = \frac{K_{mv}}{1+5Ri} + K_b$$

The values of the three mixing limits originally suggested by Pacanowski and Philander [1981] are:  $\nu_0 = 5 \times 10^{-3}$ ,  $\nu_b = 10^{-4}$  and  $K_b = 10^{-5} \text{ m}^2 \text{ s}^{-1}$ . We retain the values for  $\nu_b$  and  $K_b$ , but use a spatially variable  $\nu_0$ , to partially recognize the different mixing regimes inside and outside of the estuary, and, more specifically, to prevent over-mixing inside the estuary. We set:

$$\{8\} \quad \nu_0 = \begin{cases} 0.002 & \text{if } h < 40 \\ 0.01 & \text{if } h \geq 40 \end{cases}$$

where  $h$  is the depth (relative to MSL).

We note that while horizontal diffusion is not represented in ELCIRC as a physical process, the ELCIRC algorithm is numerically diffusive. In particular, the form of the leading-order truncation error term in the 1D case (Zhang et al. [2004]) is:

$$\{9\} \quad \varepsilon = \frac{1}{8} \Delta x^2 \text{frac}(Cu)(1 - \text{frac}(Cu)) \frac{\partial^2 c}{\partial x^2} \equiv D_{\text{num}} \Delta t \frac{\partial^2 c}{\partial x^2}$$

where  $\text{frac}(Cu)$  stands for the fractional part of the Courant number. We recognize that  $\text{frac}(Cu)(1 - \text{frac}(Cu)) \leq 0.25$ , and scale local spatial resolution through the equivalent diameter of an element, to estimate the local maximum value for  $D_{\text{num}}$  as:

$$\{10\} \quad \max(D_{\text{num}}) \sim \frac{1}{32} \frac{\Delta x^2}{\Delta t}$$

While clearly simplistic (e.g., note the assumption of locally 1D flows), these estimates provide useful insight and guidelines, as they are essentially a metric of the local resolution: for instance, Fig. 15 suggests that additional refinement in the continental shelf, perhaps including the plume near-field, might greatly enhance the ability to represent coastal eddies and other sharp spatial features.

Arguably, external forcings are currently the single most significant source of uncertainty for CORIE simulations. In DB06, external forcings were imposed as follows (see Section 2.3 for reference):

- Discharges and temperatures were imposed at freshwater boundaries at Bonneville Dam and Willamette Falls, based on local hourly observations (Section 2.3.1); zero salinity was imposed at these boundaries.



- Water levels were imposed at the ocean boundary from harmonic synthesis of eight tidal constituents, as provided by Myers and Baptista [2001] (see Table 1); astronomic arguments were computed from Foreman [1977]. No low-frequency set-up was imposed at the boundaries, and the tidal potential was neglected
- Coastal winds from archived GFS and OSU/ARPS forecasts (Section 2.3.3) were transformed into surface stresses via the algorithm of Zeng et al. [1998]. GFS was used where no OSU/ARPS data are available; where the two sources overlap, the higher resolution OSU/ARPS was weighted more heavily (2/3) than GFS (1/3). The same weighted approach was used for atmospheric pressure, humidity, and air temperature. Radiative fluxes were taken exclusively from GFS.
- Ocean salinities and temperature fields were imposed as initial conditions, from climatology (Levitus [1982]). Leveraging the Eulerian-Lagrangian formulation of ELCIRC, scalar fields were allowed to leave the domain through the ocean boundary in outgoing flows; scalar values at the previous time step were imposed during incoming flows. The inflow boundary condition is over-simplistic, and a better alternative will be discussed in Section 3.2.

### 3.1.2 *Representation of water levels*

We first consider water levels at a single station, Tongue Point (*tpoin*, in CORIE's 5-digit terminology for field stations). A station of the NOAA CO-OPS tidal network (Fig. 10), Tongue Point is located inside the estuary approximately 30 km upstream from the entrance (Fig. 9). Long-term water levels observations, with accurate vertical datums, are available; the record for 2002, in particular, is uninterrupted (Fig. 17e).

DB06 provides a robust description of Tongue Point water levels. The average error<sup>1</sup> for a full year simulation is  $-0.02$  m, with a standard deviation of  $0.17$  m and a root mean square error of  $0.17$  m. Water levels are overestimated at most by  $0.47$ m, and underestimated at most by  $0.82$ m. Histograms of errors are shown in Fig. 18, both for the full signal and for specific frequency bands, defined as *low pass* ( $T > 30$  h), *band pass* ( $9.6 \text{ h} \leq T \leq 30 \text{ h}$ ; i.e., astronomic tidal range) and *high pass* ( $T < 9.6$  h; thus inclusive of shallow water tides).

Time series of errors at Tongue Point (Fig. 17b,d) suggest that band pass and high pass errors respond directly to tidal forcing, and tend to be largest during spring tides; band pass errors are substantially larger than high pass errors, reflecting the relative difference of the signals being represented (astronomic tides are much larger than shallow water tides). While tides are non-stationary in the Columbia River due to interactions with river discharge, harmonic analysis for the full year of 2002 (Tables 1 and 2) provide useful, if simplified, context. We note, in particular that in most constituents the tidal amplitudes are over-estimated and the model simulations lead the data (smaller phase lag); the exception is the M6 component, where the amplitudes are underpredicted by the model, thus suggesting that bottom friction should be stronger.

Low pass errors (Fig. 17c) show a seasonal trend, with the model tending to overestimate observations in summer, and underestimating them in winter; strong winter storms in January and December introduce the largest errors (see also Section 3.2.1). We note that the model is able to generate internally a significant part of the low pass signal,

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<sup>1</sup> Throughout this paper, model error is defined as “simulations minus observations”. Although simplistic, as it ignores observation errors, this definition is appropriate for the purposes of our discussion.

even if that signal is not forced at the domain boundaries; coastal winds and atmospheric pressure gradients are responsible for that internal generation.

A comparison of error patterns across selected stations of the NOAA CO-OPS tidal network is shown in Fig. 19 (see Fig. 10 for station locations); there is remarkable spatial coherence at all frequencies, with some informative exceptions. In particular:

- Low pass errors (Fig. 19a) tend to show near-synchronous spikes (underestimations) during strong winter storms, consistent with the regional development of a frontal system; in this regard, the southernmost station (*cmoc1*) is the least correlated of all stations. A detailed analysis of the correlation between frontal systems and water level response will be presented elsewhere.
- The average error at *cnbw1*, a station at the entrance of the Strait of Juan de Fuca, is substantially larger than that of any other station (Table 3). This is consistent with the fact that we are truncating the strait, neglecting tidal propagation into the Puget Sound and the Strait of Georgia and creating ideal conditions for standing wave patterns. The effect of this oversimplification of the domain is seen clearly in the low pass and band pass errors (Fig. 19a,c) and in the amplitudes of specific tidal constituents (in particular for M2 and M4; Table 4).
- High pass errors (Fig. 19b) are typically small, and smaller than band pass errors. The two cases (*cwbw1* and *skaw1*) where substantial high pass errors occur are stations located in shallow areas with very poor grid and bathymetric resolution (Willapa Bay and in a freshwater affluent of the Columbia River, respectively); high pass errors at these stations are dominated by shallow water tidal

frequencies, an indication that local resolution is insufficient to account for strong tidal nonlinearities occurring in these areas.

- Errors at Tongue Point are generally coherent with dominant errors at coastal stations. However, the spring-neap asymmetry of band pass errors is, at Tongue Point, larger than those at coastal stations (except for coastal stations, such as *cnbw1* and *cwbw1*, which are affected by special circumstances).
- C74a+C73a generally provides a better description of amplitudes and phases of tidal constituents than DB06 does.

### 3.1.3 *Representation of wetting and drying*

The Columbia River is subject to extensive wetting and drying. Representation of this process is challenging, but necessary and within the type of capabilities expected of ELCIRC. In Fig. 20, we provide (a) a snapshot comparison, during low water conditions, of a SAR image identifying (with some subjectivity) wet and dry areas and (b) a DB06 simulation displaying equivalent information; for reference, we also include a representation of the DB06 numerical grid, which permits identification of the areas that are kept permanently dry in the modeling domain. The three images (Fig. 20a-c) are consistently georeferenced, and the SAR and DB06 images are synoptic within 5 minutes.

The qualitative agreement between the simulations and the SAR image is remarkably good in the mainstem estuary, and in the western part of Cathlamet Bay. By contrast, the agreement is quite poor in the eastern part of Cathlamet Bay. Closer analysis reveals, however, that this disagreement is not related to the simulation of wetting and drying.

Rather, topography in this part of the bay is in error by as much as 3 meters, placing several islands (Marsh, Brush, Horseshoe, Tronson, Grassy and Queens) below MSL when they are indeed 1m<sup>+</sup> above MSL.

We find the results very encouraging relative to the ability of ELCIRC to represent wetting and drying processes, but reserve a finer-scale and more quantitative analysis for when a grid reflective of the recently available bathymetry (Fig. 30) and of corrections to the topography of the Cathlamet Bay islands, is available; such grid is currently under construction.

#### 3.1.4 *Representation of salinity fields*

Columbia River salinity fields vary dramatically in space and time (Jay and Smith [1990]), with major oceanographic and ecological implications. Multi-scale representation of this variability is extremely challenging, and a major goal of the CORIE modeling system. This paper provides only an introduction to challenges and successes towards this goal. We begin by examining year-long time series of salinities at three stations, where CORIE sensors are available: *ogi01*, *red26* and *am169*.

Station *ogi01* is located in the continental shelf, at about 100m depth, and approximately 25 km southwest of the mouth of the Columbia River estuary (Fig. 9); the station is in the path of the near plume during periods of northerly wind, which are dominant during the spring and summer; during the winter, southerly winds dominate, and *ogi01* is off the plume path for extended periods (e.g., see pattern of observed daily maximum and minimum salinities in January and February, Fig. 21a). DB06 simulations (Fig. 19b) show a plume that is responsive to changes in wind direction, but is in general

substantially fresher than observed; in particular, plume freshness in response to high river discharges appears excessive.

Station *red26* (Fig. 9) is approximately 13 km upstream of the mouth of the estuary, near the navigation channel. Bottom daily maximum salinities from DB06 track well those observed at the bottom CORIE sensor (Fig. 22). In particular, we note the good correlation between observed and simulated sudden dips in salinity (e.g., at the end of January and beginning of July); the conditions for generation of these dips are under investigation, one hypothesis being that they coincide with the simultaneous occurrence of downwelling-favorable winds and neap tides. Like those observed, daily minimum salinities from DB06 decrease substantially during Spring freshets. In general, however, the comparison of observed and simulated salinities and daily minimum salinities suggest that the simulated estuary is fresher during ebb than it should be, particularly during the latter half of the year.

Station *amb169* (Fig. 9 and Fig. 23) is located further upstream in the estuary, approximately 20 km from the mouth, and also near the navigation channel. Often fresh during ebb, and occasionally fresh throughout the entire tidal cycle during spans of the Spring freshet, *amb169* is a challenging station to represent numerically. In particular, DB06 shows consistently lower levels of salt than those observed, including a tendency, for most of the year, to predict freshwater conditions during ebb, even at the bottom.

The results presented above (and additional results available at CCALMR [1996-2004a]) suggest as a whole that DB06 salinities are responsive to river forcings, coastal winds, and spring-neap cycles, but that salt penetration in the estuary tends to be under

predicted and the size of the freshwater plume tends to be exaggerated. As a baseline for further analysis in Section 3.2.3, year-long salt volumes in the estuary (in the form of 15 day running averages) and plume volumes (defined by the 30 psu contour) are plotted in Fig. 24. The salt volume in the estuary behaves qualitatively as expected, responding to both the seasonal variation of river discharges and to spring-neap cycles. However, plume volumes show strong discontinuities at the transitions between simulation ensembles; the resulting picture is that of a simulation that does not reach equilibrium within each ensemble, and is drastically affected by the initialization strategy adopted in constructing DB06.

### 3.2 Sensitivity to modeling choices

To explore the sensitivity of the results to modeling choices, we present in this section selected results from various databases and calibration runs. While others will also be described in specific contexts, the following simulations will be used extensively:

DB07: This database is built exactly as DB06, except that we simulated all weeks sequentially, rather than in separate ensembles. Our intention was to eliminate discontinuities such as those shown in Fig. 24b. While continuity was indeed achieved, the database was terminated after 36 weeks, because the size of the plume was growing unrealistically large.

Calibration run 73a (C73a): Designed initially as a short-term simulation, but eventually run sequentially for several months, C73a was cold started on 04/23/2002. The set-up of C73a differs from DB07 in that: (a) a 2.5-equation turbulence closure scheme was used ( $k-kl$ , Umlauf and Burchard [2003]); (b) ocean salinities and temperatures were

initialized from Global NCOM outputs (See Section 2.3.2); and (c) ocean salinities and temperatures outside a radius of 100km from the mouth of the estuary were nudged to Global NCOM outputs. The nudging factor ( $\gamma(x,y)$ ; Eq. 1) was varied linearly from 0 at 100km radius to 5% at 300km radius, and was fixed at 5% outside the latter radius. The vertical nudging profile was uniform, with  $\psi=1$  (Eq. 1).

C74a and C74b: These calibration runs differ from 73a only by the starting dates, which are 11/26/2001 (C74a) and 01/29/2002 (C74b). By design, C74b extends only to 03/12/2002. At the time of this writing, C74a has progressed to 03/25/2002; when this simulation starts overlapping with C73a (i.e., after 04/23/2002), differences in overlapping weeks will be analyzed, and a decision made whether to create a new hindcast database by merging C73a and C74a simulations, or, alternatively, by continuing C74a until the end of the year. For now the two calibration runs will be analyzed together (C74a+C73a).

### 3.2.1 *Parameterization of surface stresses*

Fig. 25 motivates our preference for a particular parameterization of surface stresses (Zeng et al. [1998]). This figure shows the week-averaged root mean square errors of low-pass water levels at Tongue Point, contrasted against the x-component (i.e., approximately, the E-W component) of the Ekman transport in the vicinity of the Columbia River. In addition to simulations that we have described earlier (DB06, DB07, C73a and C74a), results are included for DB04 and DB05. The x-component of the Ekman transport is computed from external forcings and ELCIRC results as (following Cushman-Roisin [1994]):



$$\begin{aligned}
 E_k^x &= \int_0^T dt \int_L U(x, y) ds \quad (\text{in m}^3) \\
 U(x, y) &= \int_{-\infty}^0 u(x, y, z) dz = \frac{\tau_y(x, y)}{\rho_0 f} \quad (\text{in m}^2 / \text{s})
 \end{aligned}
 \tag{11}$$

where  $L$  bounds a rectangle centered at the mouth of the estuary,  $T=7$  days,  $u$  is the  $x$ -component of the water velocity,  $\tau_y$  is the  $y$ -component of the wind stress, and  $\rho_0$  and  $f$  are respectively a reference density and the Coriolis factor.

DB04 and DB05 were built with an early version of ELCIRC (version 4.01, rather than 5.01 used in most recent runs). Like DB06 and DB07, they are initialized from Levitus and use a zero-equation parameterization of vertical mixing (Pacanowski and Philander [1981]), although other set-up details differ from DB06 and DB07. Most importantly, DB05 is the first hindcast database to use the approach of Zeng et al. [1998] to parameterize surface stresses, while DB04 uses one of the empirical relationships of Pond and Pickard [1998]. Zeng et al. [1998] is also used in DB06, DB07, C73a and C74a.

DB04 responds to downwelling events early and late in the year with the type of large root mean square errors that were characteristic of early databases and calibration runs, all of which used Pond and Pickard [1998]. In DB05- DB07, C73a and C74a, this type of error is greatly attenuated relative to DB04. None of the substantial modifications introduced after DB05 (in code formulation, external forcings or simulation set-up) significantly affects the response of errors to downwelling conditions, thus confirming surface stress parameterization as the transformative element in improving in-estuary response to coastal winds during downwelling.

Remaining errors in water levels during downwelling regimes are currently being investigated; the prevailing hypothesis is that errors derive predominantly from the difficulty of external forecasts to represent the intensity and phase of strong winter frontal systems. In support of this hypothesis, we note that ELCIRC is very sensitive to changes in wind forcing, and tends to capture well the occurrence of downwelling events.

We use Fig. 26 to illustrate this point: the bottom panel shows the N-S component of coastal winds off the mouth of the Columbia River, and the top panel shows the average plume thickness (based on the 30psu contour), from 04/23 through 08/21. With a more advanced turbulence closure than DB06 and DB07, C73a is most responsive to changes in wind direction. In particular, C73a reveals three major downwelling events between the end of May and the middle of July. In spite of discontinuities during transitions between simulation ensembles, DB06 also clearly captures the three events; by contrast, DB07 only captures two of the events. Close examination reveals that the reason why the late June events goes undetected in DB07 is that a mistake was made in the set-up of the atmospheric forcing in that week, for that simulation; the mistake (which did not occur in either DB06 or C73a) involved using the atmospheric forcing from the previous week, rather than the correct forcing (Fig. 26b). This mistake unintentionally illustrates the ability of ELCIRC to respond quickly to change in wind fields.

### *3.2.2 Considerations on reaching equilibrium*

Fig. 24 and Fig. 26 clearly show discontinuities in plume characteristics, as simulated in DB06. These discontinuities result from building DB06 through a combination of

ensembles of multiple weeks, with each ensemble built separately, typically with a single week of warm-up (see Section 3.1.1).

While the detected discontinuities are unacceptable, the strategy of building a database through multiple ensembles, rather than unbroken sequential simulations, is computationally attractive: taking advantage of the availability of multiple dedicated processors, it effectively amounts to coarse-grain parallelization, without the need for a parallel ELCIRC. Indeed, some variation of this strategy is likely to be adopted, for practical reasons, when building multi-year simulation databases, even when a parallel ELCIRC is available.

The issue of how long does it takes for a simulation to reach dynamic equilibrium is, therefore, pertinent. Fig. 27 suggests that the answer varies substantially with the modeling strategy. The contrast between DB06 and DB07 shows that, for the choices made in setting up those databases, several months are required to reach equilibrium in terms of plume volume. However, plume volumes are much smaller in C73a, where both (a) a different turbulent closure is used; and (b) ocean salinities and temperatures are nudged to Global NCOM outputs (which are, themselves, assimilated to observations); this raises the possibility that, under the conditions of C73a, equilibrium could be reached much faster.

This possibility is strongly reinforced by Fig. 28. The figure compares plume volumes and average plume thicknesses for C74a and C74b; as described earlier, the two series overlap from 01/ 29 to 03/12, and are identical (and identical to C73a) except that they are cold started at different times: Nov. 26, 2001 and Jan. 29, 2002 respectively. We

observe a quick convergence of C74b towards C74a, both in terms of plume volume and plume thickness – suggesting that reaching equilibrium might be a matter of a few weeks, rather than several months. A comparison of instantaneous water levels, salinities and temperatures in the estuary (*am169*) and in the near-plume region (*ogi01*) further confirms the rapid convergence, across a range of parameters (Fig. 40 and Fig. 41).

The important consequence is that segmentation of multi-year simulations in periods substantially smaller than one year might be both computationally effective and physically justified, when *k-kl* and nudging are utilized. A more comprehensive analysis will be conducted when on-going C74a simulations start overlapping with C73a simulations.

### 3.2.3 *Salt penetration in the estuary*

The analysis of DB06 results showed insufficient salt penetration in the estuary (Section 3.1.4). For contrast, we show in Fig. 29 salt volumes in the estuary for DB07, C73a and C74a, as well as for C76a. All volumes are scaled by the volume of the water in the relevant region of the estuary, relative to MSL; they are thus expressed in units of salinity, and represent a physically intuitive measure of the average salinity in the region of the estuary chosen for the analysis.

C76a is a calibration run, identical to 73a except for the fact that we loaded to the computational grid new bathymetry data recently acquired by the US Army Corps of Engineers<sup>2</sup>. Differences between the reference and new bathymetry (Fig. 30) are primarily in the North channel, and in some of the lateral bays; the South channel is

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<sup>2</sup> We note that to more fully address the implications of the new bathymetric data, the local refinement of the computational grid needs to be adjusted to the new features, an on-going process.

routinely surveyed for navigation maintenance, and its bathymetry representation is current in the reference bathymetry.

All simulations respond to changes in river discharge and to spring-neap modulations, but there are noticeable differences in the amounts of salt present in each case. In particular, we note that:

- DB06 and DB07 (which are strictly identical until 02/05), diverge after DB06 is first reinitialized to Levitus conditions. DB07 shows the least amount of salt in the estuary. The explanation is straightforward: without periodic re-initialization to Levitus, and with a simplistic turbulence closure, the DB07 plume grows steadily, and, as a consequence, the coastal water entrained into the estuary during flood is fresher than in DB06.
- C74a+C73a show larger salt volumes than DB06. We note that C74a+C73a and DB06 have different treatment of ocean conditions (nudging to Global NCOM and re-initialization to Levitus, respectively). However, we attribute the additional salt volume in C74a+C73a primarily to differences in parameterization of vertical mixing. Indeed, vertical mixing plays a key role in determining both salt penetration during floods, and resistance to salt flushing during ebbs; the more realistic turbulence closure of C74a+C73a appears to prevent or reduce the exaggerated ebb flushing that characterizes DB06 and DB07. A comparison between Fig. 6 and Fig. 7 suggests that Levitus climatology is saltier than Global NCOM near the Columbia River; hence, the differences in salt volumes induced by the two alternative turbulence closures might be even more substantial for the

same ocean conditions than shown by comparing DB06 with C74a+C73a; this is a testable hypothesis, which will be separately investigated.

- C76a shows only marginally larger salt volumes than C73a.

To expand upon these results, we show in Fig. 31a (Fig. 31b) the weekly maxima (minima) of the maximum instantaneous salinities over the water column; for the target week, the maxima of maxima and minima of maxima reflect, respectively, limits of salt penetration and of salt flushing (at the bottom) for that week. Results are shown for DB06 and C73a+C74a, and for three weeks, in January, June and September, respectively.

We concentrate first on results for C73a+C74a. We note that maximum penetration follows expected seasonal behavior. In January, coastal downwelling (or the fact that the plume has moved north, or both) and moderate discharges combine for deep salt penetration; in June, high river discharges minimize penetration; in September, low river discharges again enable deeper penetration. A similar analysis applies to flushing, which is most extensive in June.

While the above qualitative behavior also applies to DB06, differences between C73a+C74a and DB06 are quite pronounced, suggesting that  $k-kl$  is more effective than a zero-order closure model in forcing salt deeper in the estuary during floods, and in protecting it from flushing during ebbs.

An abbreviated comparison between C76a and C73a (Fig. 32) shows much less clear patterns, confirming (see also Fig. 29) that neither bathymetry substantially favors salt penetration over the other. Local differences can however, be substantial, as illustrated

both by Fig. 32 and by maximum salt penetration at three estuarine cross-sections (Fig. 33). Also, we note that in this analysis we mapped the two bathymetries onto the same grid, which was built with the old bathymetry as reference; any conclusions are therefore preliminary, and need to be re-evaluated when a grid specifically designed for the new bathymetry is available.

#### 3.2.4 Vertical mixing

We showed earlier that there are tangible differences between C74a+C73a and DB06 (and DB07), relative to salt penetration. Here, we examine more carefully differences in vertical mixing, and their implications for salt dynamics.

Fig. 34 through Fig. 36 show for *ogi01*, *red26* and *aml69*, respectively, the vertical structure of vertical mixing, as described by a zero-equation (in DB06; based on Pacanowski and Philander [1981]) and a 2.5-equation (in C73a; *k-kl*, based on Umlauf and Burchard [2003]). The figures extend over two spring-neap cycles in a high river discharge period (04/28 through 05/28), and also show the vertical structure of salinity that results at the station for each choice of turbulence closure, and their difference. Differences in vertical mixing are striking, both in magnitude (with mixing for C73a mostly in the  $10^{-4}$  m<sup>2</sup>/s range, and mixing for DB06 often an order of magnitude higher in the estuary) and structure (with regions of maximum and minimum mixing often reversed between DB06 and C73a).

These differences in vertical mixing lead<sup>3</sup> to moderate-to-large differences in salinity distribution at the estuary stations (*red26* and *am169*), as shown in Fig. 35 and Fig. 36. Year-long examination of daily maximum and minimum salinities at the estuary bottom (Fig. 37) reveals that C74a+C73a has substantially better ability than DB06 (and DB07) to retain salt during ebb. At *red26*, levels of C74a+C73a salt retained during ebb are consistent with those observed. At *am169*, C74a+C73a still underpredicts observations, both during ebb and flood – but the pattern during ebbs is substantially improved relative to DB06 and DB07.

It is however at the offshore station, *ogi01*, that the impact of the difference in vertical mixing is most dramatic: major differences can be seen in upper layer thickness and in the pattern of apparent absence/presence of the plume, both during high flow periods (Fig. 34) and year long (Fig. 38). Comparison against cruise data (Fig. 39) suggests that the impact of turbulence closure is visible in the plume substantially closer to shore than *ogi01*.

Overall, the use of a 2.5-equation turbulence closure (rather than a zero-equation one) appears strongly desirable for the modeling of Columbia River dynamics, and, in particular, of the plume dynamics and extent of salinity intrusion in the estuary. Further work will be necessary to choose an “optimized” 2.5-equation closure. Separate analyses (e.g., Zhang and Baptista [2004]) suggest that the various schemes within the framework

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<sup>3</sup> We note that the differences between salinity distributions in DB06 (or DB07) and in C73a (or C74a) are the result of both different turbulence closures and different treatment of ocean conditions. However, Levitus climatology (used in DB06 and DB07) tends to provide more saline conditions than Global NCOM (used in C73a and C74a) near the Columbia River – thus giving at least partial credence to the hypothesis that increases in salinity within the estuary for C73a and C74a are the result of their more physically-based turbulence closure.



of Umlauf and Burchard [2003] offer advantages over the more traditional scheme of Mellor and Yamada [1982].

#### **4 Final considerations**

CORIE offers an early example of the inclusion of sustained multi-scale modeling in ocean observing systems. Through educated trial and error, we have since 1996 made substantial progress towards a physically-based description of the baroclinic circulation of the Columbia River estuary and plume.

ELCIRC has been an integral part of that progress: indeed, the introduction of ELCIRC in the CORIE modeling system, some three years ago, has been transformative of our ability to conduct a very large number of meaningful, long-term 3D baroclinic simulations. Together with extensive long-term observations, these simulations are providing new insights into the Columbia River circulation.

While we will further develop the theme elsewhere, the modeling work reported in this paper already shows how responsive the Columbia River is to continental shelf processes – thus opening the doors, for instance, to understanding the impact on the estuary and plume of climatic cycles such as El Niño-Southern Oscillation and Pacific Decadal Oscillation.

From our perspective, two challenges stand in the critical path of CORIE as an effective modeling infrastructure for the Columbia River system. One relates to computational performance; in spite of the efficiency of the serial version of ELCIRC, our lofty ultimate goal of building multiple-decade simulation databases will require the parallelization of ELCIRC, an on-going process (Walpole, private communication).

Availability of a parallel ELCIRC, coupled with the 40 CPUs available in the CORIE computer cluster, is expected to be transformative in the short-term ability to generate multi-year hindcast databases.

The other challenge – which we have partially addressed in this paper - relates to an improved description of salt dynamics in the estuary and plume. We have already shown that substantial improvements result from the use of a 2.5-equation turbulence closure and of ocean conditions derived from the global NCOM model. Those efforts will continue. Concurrently, we are developing strategies to improve the treatment of the bottom boundary layer, through a model (Zhang and Baptista, private communication) that retains the computational advantages of ELCIRC while allowing for hybrid coordinates in the vertical. We are also modifying the default computational grid with a three-fold objective: (a) to improve the description of the bathymetry in the Columbia River estuary; (b) to refine the resolution in the continental shelf, to improve representation of critical upwelling and downwelling processes; and (c) to improve representation of tides and freshwater inputs in the northern part of the CORIE computational domain, by including in the domain (even if coarsely) the full extent of the Strait of Juan de Fuca, as well as the Puget Sound, the Strait of Georgia, and the discharge of the Fraser river.

We have maintained an extensive array of observations in the estuary, and other agencies have substantial observational assets deployed in the Columbia River, along the coast, and in the continental shelf. However, with few exceptions (Hickey et al. [1998]), detailed observations of plume dynamics have been scarce. Extensive Columbia River plume surveys will be conducted in May and July of 2004, by two different but

overlapping multi-investigator teams, using diverse and sophisticated observation techniques from land, airborne and in-water (moored and mobile) platforms. High expectations exist for the generation of outstanding data sets that can be used for detailed benchmarking of models within and outside the CORIE modeling system.

## 5 Appendix – Definition of metrics for grid orthogonality

Following Casulli and Zanolli 1998, a grid is defined as orthogonal if within each element a point (“center”, although not necessarily the geometric center) can be identified such that the segment joining the centers of two adjacent elements, and the side shared by the two elements, have a non empty intersection and are perpendicular to each other.

The indices of orthogonality defined in this section are an attempt to provide a practical quantitative metric with which to evaluate the extent to which hybrid grids meet this requirement. For triangles, we define the index of orthogonality as:

$$\{12\} \quad \mathcal{G}_3 = \frac{2L_{\min}}{R}, \quad (-2 \leq \mathcal{G}_3 \leq 1)$$

where  $R$  is the circum-radius of the triangle, and  $L_{\min}$  is the minimum signed distance from the circum-center to the three sides (Fig. 12a). The element is orthogonal if  $\mathcal{G}_3 > 0$  (otherwise non-orthogonal), and is equilateral if  $\mathcal{G}_3 = 1$ .

For quadrangles, we define the index of orthogonality as (Fig. 12c):

$$\mathcal{G}_4 = \frac{R_4}{R}, \quad (0 \leq \mathcal{G}_4 < \infty)$$

where  $R$  is the circum-radius of the triangle formed by nodes 1 to 3<sup>4</sup>,  $R_4$  is the distance from node 4 to the circum-center of nodes 1 to 3. The element is orthogonal if  $\mathcal{G}_4 = 1$ ;

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<sup>4</sup> In a more strict sense than used in this paper, indices should arguably be computed using all combinations of three consecutive nodes within the quadrangle.

otherwise it is non-orthogonal. Note that this index for quadrangles assumes that the circumcenter is inside the element, a requirement that needs to be checked first.

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(a) C74a water elevations; (b) C74b-C74a water elevations; (c) C74a salinity time-series; (d) C74b-C74a salinity time-series; (e) C74a temperature time-series; (f) C74b-C74a temperature time-series.

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