TOWARDS A MULTI-PURPOSE FORECAST SYSTEM FOR THE COLUMBIA RIVER ESTUARY

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I. Introduction

We envision that nowcast-forecast systems (NFS) will, over the next decade, become essential supporting tools for multi-purpose management, engineering and research in coastal and estuarine systems. However, coastal and estuarine NFS must first address a wide range of scientific, logistical and socio-economic challenges.

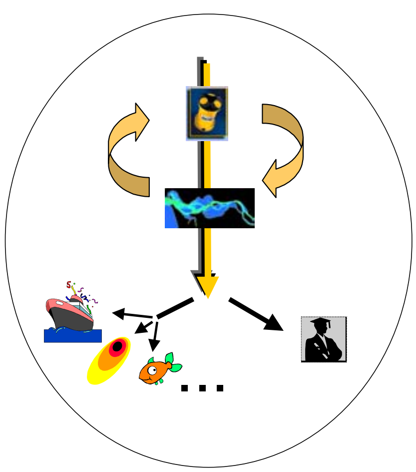

Fig. 1: CORIE (http://www.ccalmr.ogi.edu/CORIE) tightly integrates real-time monitoring of hydrologic and meteorological conditions with state-of-the-art computer models, to characterize and predict complex circulation and mixing processes in support of multiple research, education and management goals.

This paper provides an overview of the pilot nowcast-forecast system CORIE, its emerging applications and lessons learned. The development of CORIE was initiated in June 1996. While its region of application is the Columbia River estuary and vicinity, many of the CORIE challenges are emblematic of those of NFS for other large, active coastal waterways.

II. About the Columbia River

The Columbia River is the second largest river in the United States in river discharge (annual average of 211 kcfs), after the Mississippi. It is 1,950 km long and, with its tributaries, drains an area over 660,500 km^2, including portions of seven western USA states and a Canadian province. The Columbia River provides 60% (winter) to 90% (summer) of the freshwater input to the Northeast Pacific Ocean between S. Francisco and the Strait of Juan de Fuca.

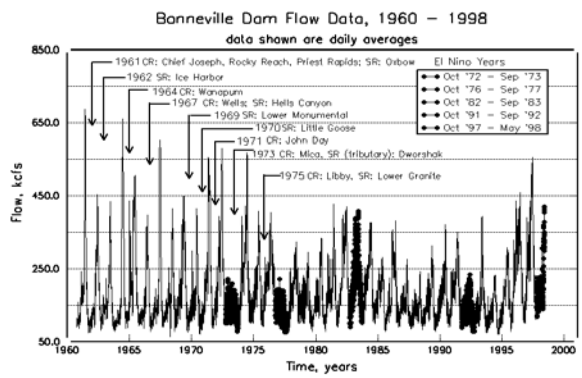

Fig. 2: 1960-98 discharge for the Columbia River at Bonneville Dam (courtesy of the U.S. Army Corps of Engineers). Also shown are construction years for major dams in the Columbia (CR) and Snake (SR) rivers. The large peaks coincide with spring freshets. There is a trend of decreased peaks after hydrosystem regulation (Sherwood et al. 1990), but exceptions have occurred in recent years. The circles indicate El Niño years. While El Niño may lead to depressed freshets due to decreased winter snowpack, neither 82-83 nor 97-98 conforms to the pattern. (From Sommerfield and Baptista, in prep.)

While intense hydrosystem regulation has reduced natural variations (Fig. 2), monthly-average river discharge, $Q_{M,}$ still ranges from 100 to 500 kcfs. Seasonal changes reflect a watershed divided by the Cascade Mountains into a moist coastal basin (8% in area, 24% in annual river discharge) and a semi-arid interior basin whose major freshwater contribution is in the form of a snowmelt "freshet" between April and July. From late fall to early spring Q_M fluctuates mostly in response to precipitation in the coastal basin. In late spring, in response to snowmelt, Q_M becomes consistently higher, averaging about 450 kcfs. Summer Q_M is the lowest, averaging 100kcfs.

The Columbia River estuary is a classic river estuary. Tidal currents are generally very strong and ebb-dominated, salinity intrusion is compressed and vertical stratification is highly variable, ranging from homogeneous to salt wedge conditions. The biological communities differ from those found in many other estuaries, in part because these communities need to tolerate unusually low and variable salinity. Strong estuarine turbidity maxima (ETM, defined as zones of high near-bed concentration of hydrodynamically trapped particles) develop in both channels of the estuary (Navigation and North Channels) and are the locus of intense geochemical and biological activity.

The Columbia River plume is a major oceanographic feature in the North Eastern Pacific Ocean. In response to prevailing coastal winds and currents, the plume generally extends south and offshore to northern California in summer and north and alongshore to southern British Columbia in winter.

The Columbia River basin is the focus of natural resource and environmental management issues that profoundly affect the economic viability of communities in the region. Typical of many developed waterways, users of the Columbia River grapple with issues related to navigational safety, dredging and dredged materials management, water quality management, environmental monitoring, oil spill response, search and rescue and natural hazards planning. However, the major natural resource controversy facing the region is the recovery of threatened and endangered salmon and steelhead stocks that once supported a large population of native peoples in the Columbia River basin. Anadromous fish use all segments of the Columbia River system - tributaries, mainstem channel, estuary and plume - at different stages of their life histories, but a century of intensive human development throughout the basin has impacted the ecosystem function of each segment. Hydrosystem operations and structural modifications for navigation and reclamation are among the most visible causes of impact.

III. CORIE motivation and design considerations

CORIE is designed with a multi-purpose perspective, under two umbrella concepts: (1) a Columbia River-specific multi-purpose scientific and management tool, and (2) a testbed for evolving, site-independent technologies for observation and predictive understanding of coasts and estuaries.

A. CORIE as a Columbia River tool

CORIE has the potential to become a much needed, widely used infrastructure to support and integrate long-term inter-disciplinary research in the Columbia River, and to help bridge traditional gaps among science, policy and management decisions. This potential, and the inherent variability of the Columbia River, requires CORIE:

- to address multiple scales of variability in space and time;
- to blend real-time and archival functions with regard to both observational and modeling data; and
- to accommodate multiple levels of processing and information distribution.

Setting priorities on scales of variability was critical to enable a productive effort. Early priorities have been on the estuary (with recent expansion to the plume) and on tidal, seasonal and inter-annual variability. These space and time scales (with the addition of wind waves and swell) will likely remain the top CORIE priorities over the next 3-5 years. In addition, elements of CORIE (modeling, in particular) have addressed both the river below Bonneville dam and the Northeast Pacific Ocean. Efforts in these two domains are, however, primarily to set boundary conditions for the estuary and plume; a systematic expansion towards either of these two space scales will depend upon new long-term opportunities or partnerships. As time evolves, CORIE will also have an active role in understanding variability at decadal and inter-decadal scales. An element of these scales of variability that may arguably already be detectable in the CORIE records is the effect of the 1997-98 El Niño (Fig. 3).

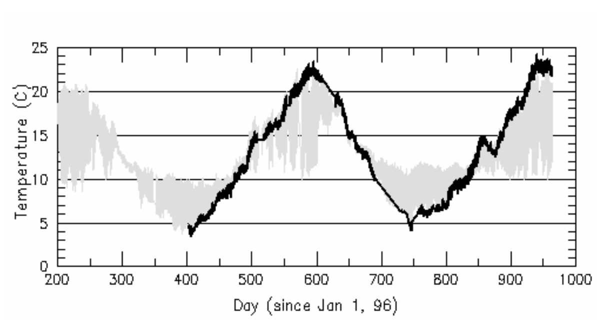

Fig. 3: Temperature at an estuarine station (Tansy Pt., gray) and a riverine station (Woody Is., black). Locations are shown in Fig. 4 and Table 1. Data illustrate the archival value of NFS. The difference in tidal variability between stations is clear and reflects their location in the estuary. Seasonal fluctuations are strong (~20^0C). Temperature at Woody Is. envelopes that at Tansy Pt. from below in winter and from above in summer, illustrating the moderating role of the ocean (and providing an element of confidence on the sensors). Temperatures in winter 97 and summer 98 exceed those of prior hydrologic year, which may be tied to the 1997-98 El Niño. This type of cause-effect will become easier to identify as the record becomes longer.

While we are interested in a wide range of coastal and environmental processes and parameters, early emphasis has been on physical characteristics, in particular circulation, temperature, salinity and, to a lesser extent, suspended sediments. We envision a future step addressing selected water quality and ecosystem processes. These processes are, however, often beyond the reach of continuous time-series observation and predictive modeling in the Columbia River and other complex natural systems.

To improve the understanding, real-time monitoring and prediction of biogeochemical processes and interactions relevant to estuaries, we have, in parallel with CORIE, developed a laboratory-scale rotating annular flume, RALF (Darland et al, in prep; Yang et al., in prep.). Approximate dimensions are $41x42cm^2$ of cross section, 91cm of internal diameter, and 175cm of external diameter. RALF is supported by evolving numerical models ("virtual RALF") and by (in addition to grab samples) real-time instrumentation for physical and geochemical parameters. Early focus has been on investigation and modeling of metal bioavailability at sediment-water interfaces.

B. CORIE as a technology testbed

Because of their long-term perspective, real-time access, logistical infrastructure and research synergism, NFS are natural testbeds for evolving coastal and estuarine technology. During the early development of CORIE, we concentrated on commercial off-the-shelf technology, limiting the use of experimental instruments. Thus, CORIE's role as an instrumentation testbed to date primarily has been to confirm that most instruments perform to specification. The most notable exception was signal corruption, over time, in CTDs of a particular brand, because of the development of ground loops in stations with shore power.

As CORIE reaches a stable state of operation, we are more actively pursuing the use of experimental instrumentation, both through in-house fabrication and by making CORIE available for beta-installation of new commercial technology. In-house fabrication has emphasized low-cost instrumentation (e.g., thermistor chains with high spatial resolution). As a pilot for experimentation with new commercial instrumentation, we will soon install beta optical backscatter sensors designed to prevent fouling in long-term deployments. Over time, we expect to add beta-deployments of real-time geochemical and ecological sensors (including, but not restricted to, the outgrowth of technologies tested in RALF).

In addition to enabling experimentation with individual instrumentation, NFS are themselves new technology, the evolution of which will in part be dictated by pilot systems like CORIE. Aspects of NFS technology of particular interest for further exploration include monitoring network optimization, coordinated unmanned deployment of mobile observational platforms, novel benchmarking strategies for numerical models and integrated multi-scale NFS. Each of these aspects will strongly influence the viability of fixed and rapid-deployment NFS in support of coastal and estuarine research, management and operations.

IV. CORIE infrastructure

At the heart of CORIE are a real-time monitoring network, a data acquisition and management system and a numerical modeling system. The next three sections briefly describe each of these components, and a fourth section addresses some of the operational logistics.

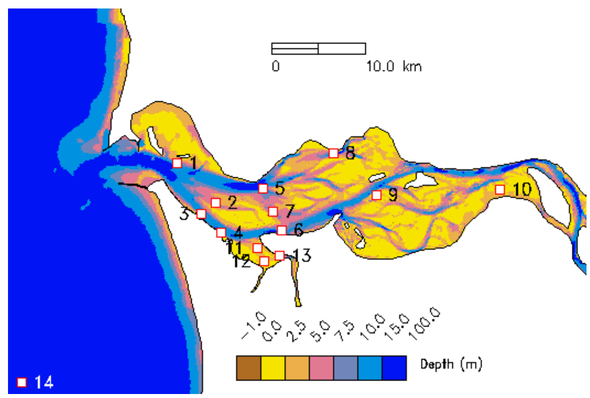

Fig. 4: Most CORIE stations are distributed strategically: along the deep channels, in shallow areas in the mainstem and in one lateral bay. We have recently deployed an offshore station (at ~100m depth), reflecting an increased interest in plume dynamics.

A. Real-time monitoring network

The CORIE monitoring system (Wilkin et al., in preparation) includes an array of 14 permanent stations (Fig. 4), a variable number of temporary stations, and one mobile station. We currently monitor in various combinations at each station (Table 1): temperature T, salinity S (via conductivity), water depth D, water velocity V, acoustic backscatter AS, wind speed and direction W, and air temperature T_A. All instruments report data in real-time through a telemetry network based on spread-spectrum radio technology. "Real-time" is defined by latencies of typically a few seconds. The sampling interval ranges from 1 to 15 minutes, with choices determined mostly by the type of power available. Most stations in the network have shore power, and are equipped with a computer for local data stream handling and backup storage. A few stations are powered by batteries or by battery/solar panel combinations.

Several stations are internet nodes, enabling two-way communication with the instruments. We routinely use two-way communication for the operation of the fixed network (e.g., monitoring of instrumentation status, initiating or modifying sampling protocols, etc). We also have demonstrated, as a proof of concept, the feasibility of providing internet-based navigation information products, both real-time and predicted, to a vessel operating in the lower Columbia River. In support of the scientific surveys we conduct in the estuary, we configured the research vessel we use - Clatsop Community College (CCC)'s M/V Forerunner - to maintain a continuous internet connection, by pointing to different CORIE receiving stations depending on the vessel location.

Table 1: Observed variables at CORIE stations

Station	V	C	T	D	AS	W,T_A
1. Sand I.		*SP*	*SP,PR*	*SP*		
2. Desd. S.		*SP*	*SP*	*SP*		
3. Red26	*PR*	*SP*	*SP,PR*	*SP*	*PR*	
4. Tansy P.	*PR*	*SP*	*SP,PR*	*SP*	*PR*	*SP*
5. AM012	*PR*	*SP*	*SP*	*SP*	*PR*	
6. AM169	*PR*	*SP*	*SP*	*SP*	*PR*	
7. AM084		*SP*	*SP*	*SP*		
8. Grays P.		*SP*	*SP*	*SP*		
9. Rice I.						*SP*
10. Woody			*SP*	*SP*		
11. YB101		*SP*	*SP*	*SP*		
12. Lw&Cl		*SP*	*SP*	*SP*		
13. Yacht		*SP*	*SP*	*SP*		
14. OGI01	*PR*	*MP*	*MP*		*PR*	

Note: Observed variables are defined in the text. *SP, MP* and *PR* denote respectively single-point, multi-point and profile observations. Station composition may change over time

B. Real-time data acquisition and management system

Data acquired from the CORIE instruments are pulled across the internet to the Oregon Graduate Institute (OGI) in real-time, using a data acquisition system that, while conceptually inspired by REINAS (Long et al. 1996), relies on different software and archival choices (McCandlish et al., in prep.). Typically, data backups are generated at various intermediate steps between the instrument and OGI. The data are parsed and then archived in a NetCDF-based flat file system. In parallel, automatic scripts access the data following a pre-defined schedule, process the data at a basic level, and display them in near real-time on the Web (e.g., Fig. 5). Naturally, more detailed processing can be performed *a posteriori*. While such processing has been done mostly on an *as-needed* basis, we are now developing standard procedures for non-real time processing. The concept is that users will be able to select their access point to the entire database, by choosing among various pre-defined levels of data processing.

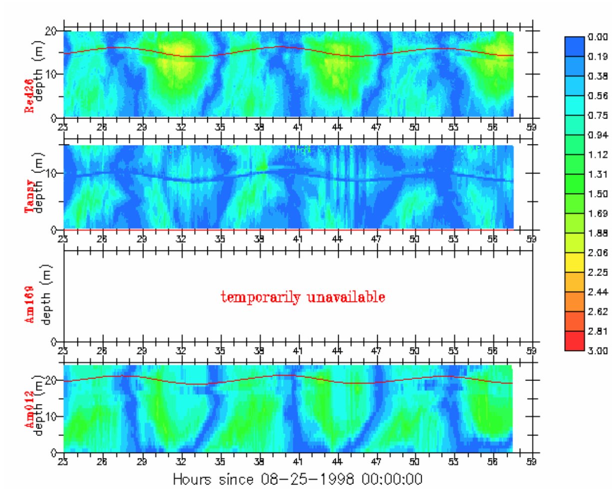

Fig. 5: The above contrast among 36 h time-series of profiles of velocity magnitude at four stations is one of various displays automatically posted in the web at pre-defined intervals. CORIE scripts are able to recognize and report temporary data gaps.

C. Numerical modeling system

The CORIE modeling system includes a suite of circulation and transport codes, applied to multiple domains:

- The Columbia River estuary and near-shore coastal zone, cut upstream either at Longview (forecast domain) or at Bonneville dam, Oregon City and Kelso (Fig. 6).
- The Columbia River zone of influence, including part of the estuary and portions of the adjacent coast (from southern British Columbia to northern California) traversed by the plume; and
- The North Eastern Pacific Ocean, north of latitude 30°N and east of longitude 165°W, a domain used primarily to define ocean boundary conditions for CORIE. Most of the effort has been on tidal circulation (Myers and Baptista, in prep.) but the emphasis is shifting towards wind-driven and density-driven circulation.

We use four circulation codes: ADCIRC2D (Luettich and Westerink 1995), QUODDY (Lynch, et al. 1996), POM (Blumberg and Mellor 1987) and WET2D (Beck and Baptista 1997), all of which solve for the shallow water equations. All codes except POM are based on finite elements and use unstructured triangular grids. Codes differ on the dimensionality (2D or 3D) and on whether they include wetting and drying and baroclinic effects.

Early modeling (Salil et al., in prep.) focused on tidal propagation and circulation over the complex topography of the estuary. This modeling has resulted in regular daily forecasts of barotropic circulation (section V) and an evolving long-term (since July 1996) database of uninterrupted barotropic simulations. Modeling emphasis is now on the vertical structure of circulation and density in the estuary and the plume, and on residual transport.

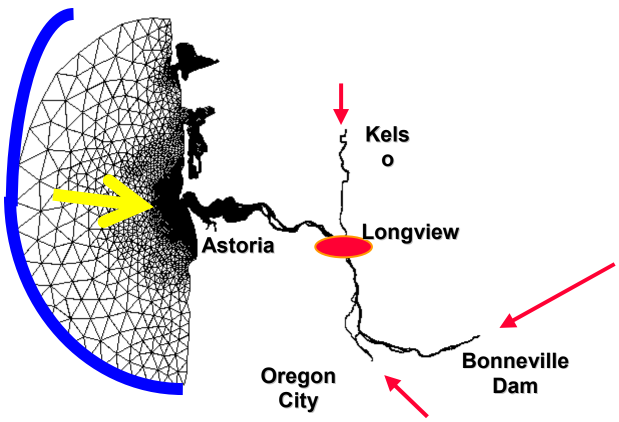

Fig. 6: A primary domain for estuarine modeling benchmarks extends upstream to Bonneville dam, at the Columbia River mile 146. Primary forcings include river discharges (dominated by the Columbia River, but including the Cowlitz at Kelso and the Willamette at Oregon City) and ocean conditions. Wind, critical in the plume, is secondary in the estuary. The domain for forecasts is shorter, with Longview levels used for upstream forcing.

Overall, results suggest that we are able to describe the depth averaged circulation (levels and 2D velocities) quite effectively (e.g., Fig. 8), but that we still systematically under-estimate saltwater intrusion in 3D baroclinic runs. This appears to result from combined limitations in the description of vertical mixing in the estuary and of (S,T) boundary conditions in the ocean.

D. Operational logistics

A small group of researchers (composed of the first five authors) provides the vision and ensures the continued daily operation of CORIE. A broader group (including the remaining authors) has provided additional expertise, either hands-on or conceptual, on an as-needed basis. Field operations are conducted out of the Marine Environmental Research and Training Station (MERTS), in Astoria, OR. Vessels (the 50-ft M/V Forerunner and the 21-ft R/V Tansy Point) and operators are provided by the Marine Safety Program of CCC, a MERTS partner with OGI.

Most CORIE cruises have been coordinated with cruises of the NSF Land-Margin Ecosystem Research (LMER) project on the Columbia River Estuarine Turbidity Maximum (CRETM).

V. Circulation forecasts

Circulation forecasting is an early goal of CORIE, and a natural integrator of the various components of the system. Exploratory forecasts (Figs. 7 and 8) for the estuary are performed daily using ADCIRC2D. Forecasts will be extended to 3D circulation when the quality of the baroclinic simulations so warrants.

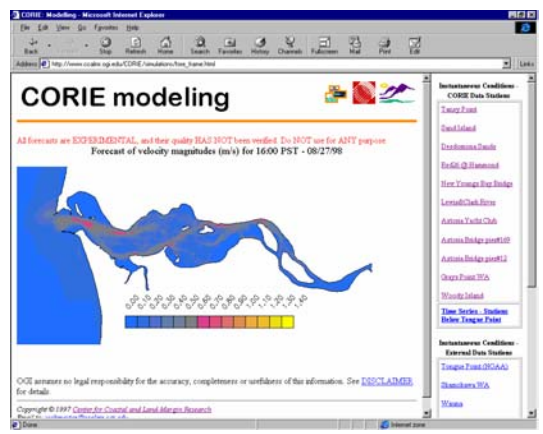

Fig. 7: Forecasts of depth-averaged barotropic circulation have been produced routinely since March 1998, with hourly results posted daily in the Web (Pearson and Baptista, in prep.).

Our forecasts are being produced without data assimilation. The "nowcast" function is provided only by the independent specification of external boundary conditions in the river, ocean, and atmosphere. The rationale is that the estuary is a constrained enough system that a sound model should require no data assimilation if forced properly at the boundaries (i.e., there is little memory for initial conditions). This rationale appears vindicated by the consistent quality of the results obtained (e.g., Fig. 8).

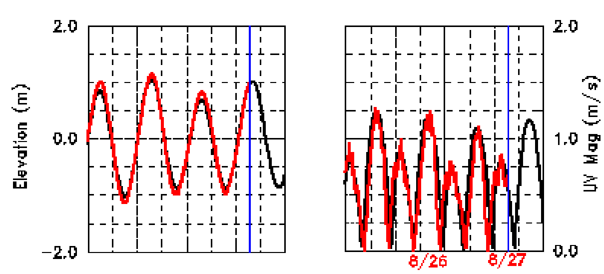

Fig. 8: Model forecasts are automatically compared against available data, on a real-time basis. Here, we show comparisons of computed (black) versus oberved (dark gray) elevations and depth-averaged velocities at station Red26. The image was extracted from an automatically generated Web display.

The forecasts are conducted with a minimum of human intervention: short of system failutre, import of the upstream boundary conditions (from the LOADMAX system, courtesy of the Port of Potland) is the only operation that is not fully automated. The UNIX CRON utility is used as the central broker of processing tools, initiating and killing relevant processes in proper timing and order via a simple pre-defined configuration file. In addition to the actual simulations, the forecasting operations can be broken into three broad categories: acquisition of external forcings data and input file generation, process monitoring (including disk space management) and Web visualization. These individual operations rely on sets of processing codes written in C and PERL that manipulate data files and images, with overall control provided by a central configuration file.

VI. Final considerations

CORIE demonstrates that highly resolved NFS can be developed quickly and effectively even for a complex system like the Columbia River. While many technical and scientific challenges still remain, the most threatening challenges for NFS are logistical and often related to maintenance rather than development. Timely adoption by consortia of users, preferably in direct and quantifiable support of their core mission, is essential for the long-term viability of any coastal and estuarine NFS.

Consistently, CORIE modeling and data products have become more broadly available as the system reaches stable operation. Various applications are now relying to various degrees on CORIE products. Most of these applications are science-driven, but some meaningfully blend science and management and a few are community driven. The latter group includes use of CORIE data by bar pilots to enhance their understanding of circulation and by fishermen to guide the choice of fishing grounds. The former two groups include interdisciplinary, often inter-institutional, research on:

- dynamics and ecology of estuarine turbidity maxima;
- ocean survival of salmonids relative to migrational timing, fish health and oceanographic conditions;
- transport and speciation of metals at disrupted sediment-water interfaces;
- coordinated control of autonomous objects;
- amplification of El Niño-Southern Oscillation (ENSO) climate effects in estuaries; and
- adaptive unstructured grid generation.

VII. Acknowledgments

Early development of CORIE (Jun 96-Sep 98) was funded by the Office of Naval Research (Grant N00014-96-1-0893). Applications of CORIE have or will be funded by the National Science Foundation (LMER Grant OCE-9412038, EGB Program and SGER Program), Bonneville Power Administration, National Marine Fisheries Service, Defense Advanced Research Projects Agency (Software Enabled Control Program) and Office of Naval Research (Modeling and Prediction Program). The development and maintenance of a system like CORIE requires strong community support. Thanks are due the Clatsop Community College (in particular J. Wubben, P. Killion, M. Drage, B. Antilla and A. Jaques), U.S. Coast Guard, Northwest River Forecast Center, U.S. Geological Survey, Oregon Department of Transportation, Coastal Studies and Technology Center, U.S. Army Corps of Engineers, Port of Portland, City of Astoria, Columbia Pacific Community Information Center, M. Covell, and Capt. R. Johnson (Columbia River Bar Pilots).

VIII. References

Note: references *in preparation* are excluded from this list. Check http://www.ccalmr.ogi.edu/publications for their status.

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