CORIE: the first decade of a coastal-margin collaborative observatory

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***Abstract*- CORIE, a pioneering observatory for the Columbia River, has over the last decade advanced the state-of-the-art in coastal-margin observation and prediction. Lessons learned are being used to scale upwards the concepts and capabilities of CORIE, at a time when U.S.-wide ocean observing initiatives are being implemented.**

I. Introduction

Designed as a multi-purpose, cross-scale *coastal-margin observatory* for the Columbia River estuary and plume, CORIE [1-3] was initiated in June 1996, with the deployment of a single telemetered CTD. Since then, CORIE has progressively fulfilled the vision of an end-to-end system with observation, modeling and information delivery components (Fig. 1).

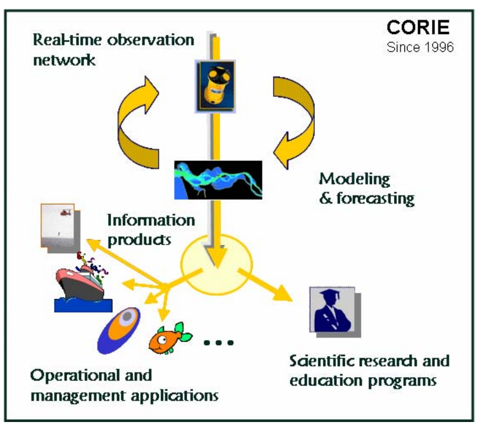

Figure 1. CORIE is demonstrative of the power of integration of observations and simulations, towards science and management-driven understanding and prediction of coastal margin systems.

Although there has been to date a deliberate focus on observing and modeling physical properties, CORIE products and analyses have had broader impact, enabling innovative thinking in both coastal oceanography and ecosystem science, and contributing to address management and operational issues such as salmon survival, navigation improvements, and flow regulation.

The CORIE infrastructure and tools are currently being extended in diverse ways, including: (a) a geographically-flexible rapid-deployment forecasting system for estuarine and coastal circulation; (b) an observation network for Pacific Northwest estuaries; and (c) a next-generation river-to-ocean observation and prediction system. Each extension addresses a perceived need towards the vision of an integrated US ocean observing system.

II. The Columbia River At-A-Glance

Second in annual discharge in the USA, the Columbia River provides 70% of freshwater inflow to the Eastern North Pacific Ocean, between S. Francisco Bay and the Strait of Juan de Fuca. Highly coupled, the Columbia River estuary and plume respond dramatically to changes in tide, discharge, ocean conditions, and shelf winds (Fig. 2). The plume [4] extends north to British Columbia and south to California, and is a major feature in the upwelling-prone Oregon-Washington shelf. Tides are strong; wetting and drying is extensive; and channel circulation is highly stratified leading to formation of estuarine turbidity maxima [5, 6].

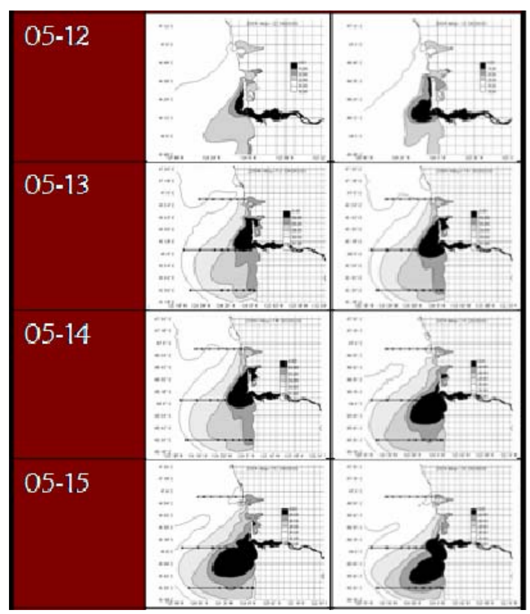

Figure 2. Columbia River plume at 4AM (left panels) and midnight (right panels) for May 12-15 2004. Images (forecasted salinity contours) illustrate plume variability

III. CORIE Observations and Simulations

Our objectives in developing CORIE were: (a) to create a multi-purpose regional infrastructure for science and management in the Columbia River estuary and plume; and (b)

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to develop portable technologies to advance observation and prediction of coastal margins. To meet these objectives, CORIE includes both an observation network and a modeling system, integrated by an information management infrastructure, and focused on 3D baroclinic circulation processes and features. Only the observation network and the modeling system are explicitly described in this paper.

A. Observation Network

The observation network has 18 fixed stations in the estuary and 2 in the plume/shelf. Sensors vary from station to station, with temperature taken at all stations, and water level, salinity, and velocity profiles measured selectively. All but the most off-shore station have real-time telemetry; all are deployed continuously, except the near-plume station (deployed only from late-Spring to early-Fall). A vessel operated by a local community college has been equipped with automated oceanographic instrumentation (salinity, temperature, turbidity, DO and velocity profiles) and telemetry, thus constituting a frequently-deployed mobile station. The telemetry network is occasionally used in support of other vessels, including vessels from the UNOLS fleet.

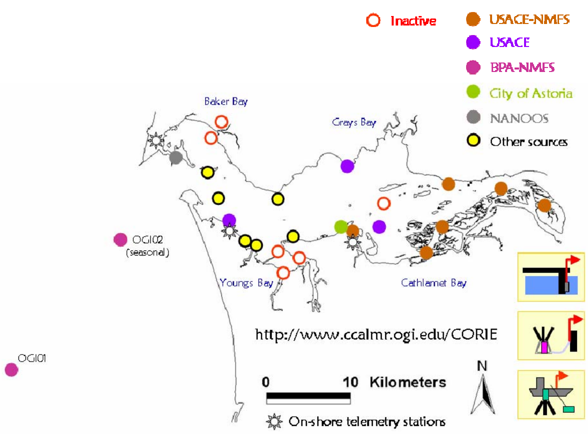

Figure 3. Location of the fixed CORIE stations. Colors represent sources of funding, illustrating the multiplicity of uses of the CORIE data.

Data from the CORIE stations is displayed in real time on the web, albeit with limited quality control, and is then subjected to extensive off-line quality control on a monthly basis. All quality-controlled data is available through the web, for either download or visualization, as are common data statistics.

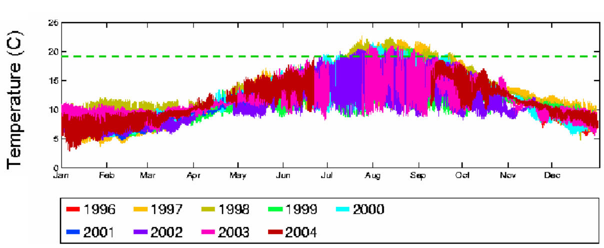

Figure 4. A multi-year time series of temperatures at the Tansy Point station, in the lower estuary, overlaid against a criterion for maximum temperature for favorable salmon habitat.

The length of the CORIE data records are allowing interesting insights into the estuarine dynamics, both physically and ecologically. For instance, Fig. 4 shows that the estuary does not meet the criterion for extensive periods of July, August and September. It also illustrates the cooling (warming) effect of the tidally induced penetration of ocean waters during Summer (Winter).

B. Modeling System

The modeling system is designed for systematic generation of quality-controlled simulations of cross-scale 3D baroclinic circulation, in the form of: daily forecasts; multi-year databases; and process/scenario simulations. "Cross-scale" means estuary, plume, and shelf/slope between northern California and southern British Columbia. Numerical grids are unstructured in the horizontal, with highest resolution in the estuary (~100 m) and near-plume (~250 m). Time steps are 60-90 s. Integral to design is automated access to all external forcings (tides, ocean conditions, atmospheric conditions, river inputs) and to a core set of observations from CORIE and other regional in-situ networks.

Two unstructured-grid numerical models (ELCIRC [7] and SELFE [8]) are used interchangeably as computational engines. Both use semi-implicit Eulerian-Lagrangian numerical methods to solve shallow water equations. Their differences lay in specific underlying methods (e.g. finite volumes with finite difference approximation of derivatives [7] or finite elements with finite volumes for the vertical momentum equation [8]); and in vertical representation of the domain (*Z*-coordinates [7]; or *Z*-coordinates over grids designed locally with *S*- or hybrid *SZ* hybrid constructs [8]).

Three 3D circulation forecasts are produced daily, inter-compared, and compared against data. Each represents a different choice in model, domain (full domain vs. estuary only), and model parameterization (variable, currently turbulence closure). Since 1999, several multi-year simulation databases have been constructed, with the most recent: DB11 (ELCIRC, full-domain [9]), DB12 (SELFE, estuary only), and DB14 (SELFE, full-domain). All forecasts and databases are generated without data assimilation.

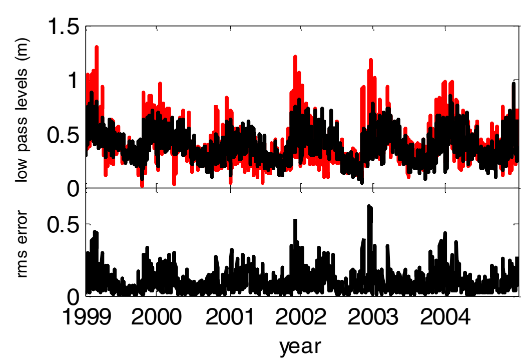

Figure 5: CORIE DB12 captures important long-term trends of low-pass water levels in the estuary (top; model is black; data red). However, variable model errors (bottom) confound inter-annual analyses.

Results show useful predictive skill, even under such challenging conditions as high-river discharge and fast-changing winds. Simulation databases (e.g. DB12-DB14) predict well the spatial, tidal, seasonal, and inter-annual variations of water level (Fig. 5), currents and salinity (Fig. 6); locations of estuary and plume fronts; and responses of the plume to wind shifts. Limitations persist, including variability of errors in time (Fig. 5) and tendency of ELCIRC-based simulations for under-predicting salinity in the near-plume. Although some are associated with numerical algorithms, remaining limitations often relate to errors in external forcings.

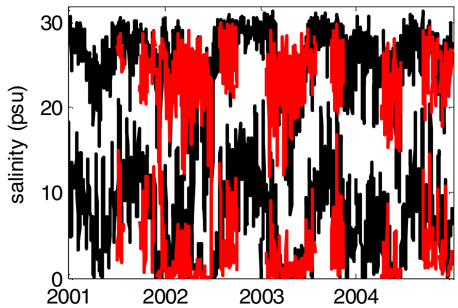

Figure 6: Trends in maximum/minimum daily salinities (model is black; data red) at this complex channel station were first captured using SELFE (CORIE DB12).

IV. SELECTED CORIE APPLICATIONS

The observational and modeling products of CORIE have been extensively used for science and management of the Columbia River. Selected applications are described below.

A. Near-real time support of scientific cruises

CORIE daily forecasts routinely provide near real-time support for oceanographic and fisheries cruises, in particular

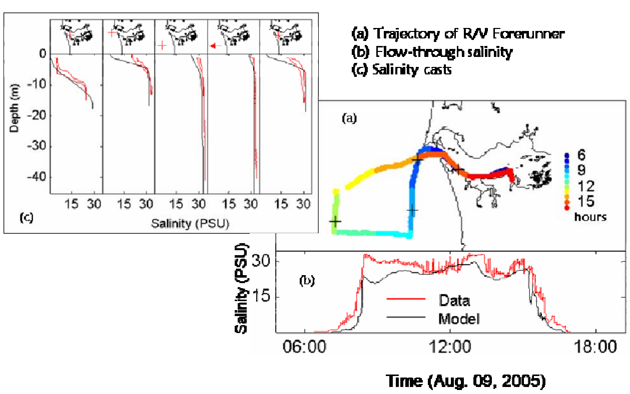

Figure 7. Vessels contribute through on-board sensors to the near real-time quality control of the CORIE forecasts that they receive at an on-board web server.

by enabling vessels to have direct access to products that identify, 24 hours ahead, the location and/or frontal characteristics of the plume. These forecasts are used to guide cruise planning and daily adjustments of sampling strategies.

Fig. 2 shows composites of forecasts customized for a NOAA Fisheries cruise in 2004, while Fig. 7 is representative of routine graphical displays. Model forecasts are quality-controlled in near real-time with data collected at the vessel, at other collaborating vessels, and at fixed CORIE stations. Enabling technologies include CORIE forecasts, observations, and information technology; a real-time telemetry network; on-vessel instrumentation, typically in the form of flow-through and/or hull-mounted sensors such as CTDs and ADCPs; and an on-board web server.

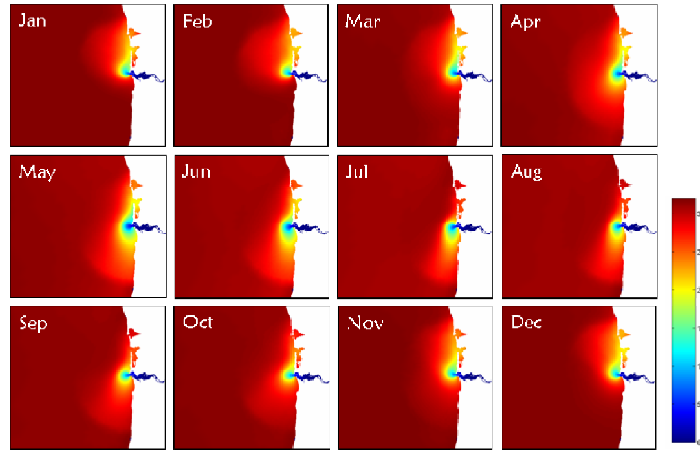

Figure 8: Climatology of sea surface plume salinity, based on DB11

B. Role of the plume on ocean salmon survival

CORIE databases provide a uniquely refined description of the context of physical variability in the Columbia River plume. Fig. 8 shows the 1999-2004 monthly climatology for plume surface salinities, as described by DB11; general seasonal trends identified in the early 70's by [10] are recognizable, with the winter plume oriented northward and closely attached to the coast, and the summer plume oriented southward and much more detached from the coast. However, the Columbia River plume is remarkable in its variability at multiple scales. We have shown earlier that the summer plume may change direction radically in the course of a few days (Fig. 2), in response to changes in shelf winds, a behavior independently described by a recent observationally-based publication [11].

Although CORIE databases are purely physical, their analysis in contrast with biological data creates a powerful instrument for development and/or testing of hypotheses relating salmon behavior with plume characteristics and management strategies (Burla, *personal communication*). As an example, strong correlations were found between smolt-to-adult ratios (SARs) for steelhead and plume size generated from CORIE simulation databases; however, spring Chinook smolt-to-adult ratios were much less sensitive to plume conditions. The implication is that controlling time-of-ocean entry might be an effective management strategy for some salmon species, although not for all.

C. Changes in estuarine habitat opportunity for salmon

Strategies to characterize physical habitat opportunity from multi-year simulation databases of circulation were introduced by [12], who defined favorable habitat for juvenile Columbia River salmon, based on water depth (D) and depth–averaged velocity ($\vec{U}$), as habitat where:

$$\begin{cases} 0.1m \le \eta \le 2m \\ \left|\vec{U}\right| \le 0.3m/s \end{cases} \quad (1)$$

These metrics where extended to local (rather than depth-averaged) velocity and to salinity by [13]; metrics were also more recently extended to temperature. Favorable habitat is defined as:

$$\begin{cases} \left|\vec{u}\right| \le 0.3m/s \\ 0 \le S \le 5psu \\ 0 \le T \le 19°C \end{cases} \quad (2)$$

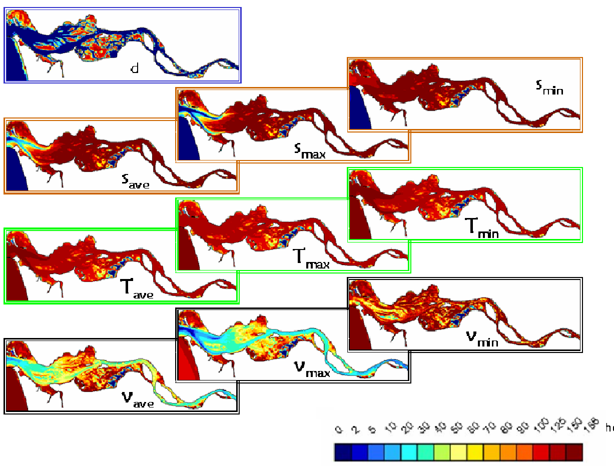

Figure 9. Climatologies of habitat opportunity (in hours per week), generated from the CORIE database DB11 using metrics based on water depth (d), salinity (S), temperature (T) and velocity (v). Where variations exist over depth (S, T and v), metrics using maximum, minimum and average values of the physical quantity are shown.

Filtering the CORIE circulation databases with the above criteria enables the development of annual climatologies of habitat opportunity (Fig. 9) and even the exploration of the seasonal and inter-annual variability (Fig. 10) of this potentially important ecological metric.

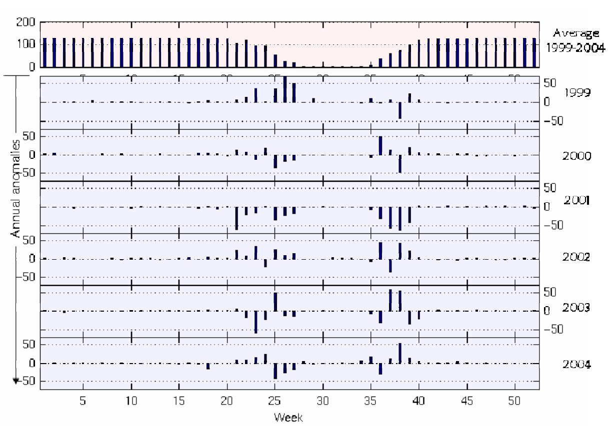

Figure 10. The top panel shows average (1999-2004) habitat opportunity, in hours per week, based on depth-averaged temperature. The bottom panels show annual anomalies. Temperature-based habitat opportunity drops dramatically during the summer. Inter-annual variability is primarily due to changes in the timing of transition to and from summer temperatures (see Fig. 4).

This methodology is useful to evaluate, prior to implementation, the impact of anthropogenic actions – whether those actions have the potential for negative impact or are intended for estuarine restoration. A high-profile example was the application of the methodology to build consensus among participating agencies (U.S. Army Corps of Engineers, Port of Portland, U.S. Fish and Wildlife Service, and NOAA Fisheries) on specific issues within the process of Re-consultation for the Columbia River Channel Deepening [13].

V. SCALING UP CORIE

Integrated ocean observation and prediction evolved over the last decade from remote abstraction into feasible concept, in part because of identifiable implementation opportunities including the Ocean Observation Initiative (OOI) and the Integrated Ocean Observing System (IOOS). In this context, pilot systems like CORIE offer "lessons learned", as well as capabilities and tools that are potentially upward scalable. Examples of scalability are presented below.

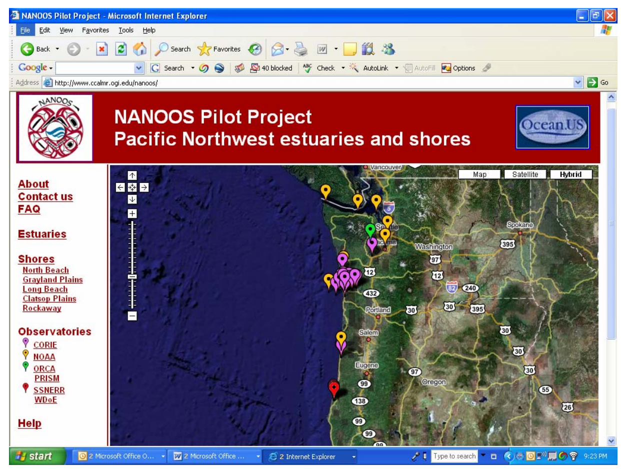

Figure 11. Markers with colors other than orange show NANOOS stations supported by the CORIE data management infrastructure. Orange markers denote NOAA stations.

A. Scaling up observation networks

In the spirit of the U.S. Integrated Ocean Observing Systems and under the umbrella of the Northwest Association of Ocean Observing Systems, the CORIE data management infrastructure was extended to support near real-time data acquisition in various Pacific Northwest estuaries (Fig. 11). In most cases, collaborations were established with a local entity (typically a state agency or a university) that assumed responsibility for the deployment and maintenance of the field and telemetry instrumentation. When these collaborators had data acquisition and distribution capabilities in place, appropriate interfaces with CORIE protocols were established; otherwise, CORIE tools, protocols and training were provided, to minimize the learning curve of local technicians. Off-line quality control is typically a local responsibility, while standardize display (with customized identifiers such as institutional logos) are provided centrally.

B. Scaling up modeling systems

The CORIE modeling system has been developed and systematically improved and validated over a decade. This has been possible because of the nature of the Columbia River – a system that both raises a variety of fundable scientific questions, and that is an economic regional driver. For most other US estuaries, the opportunities for funding sophisticated modeling systems are much more limited.

To address the reality of those many other estuaries and coastal margins, we developed a geographically flexible rapid-deployment forecasting system that directly leverages the CORIE modeling and information management capabilities. This system was designed and is currently used to create daily circulation forecasts for multiple – and drastically different in size, freshwater inputs, economic importance and development stage – estuaries and coastal margins (Fig. 12). At the core of each forecast are (a) numerical models of 3D baroclinic circulation – such as [7] or [8], (b) an information system that provides access to multiple global and regional ocean and atmospheric forecasts and (where available) to discharge and oceanographic data from national, regional and local networks, (c) visual and automated quality controls, and (d) an interactive, geo-referenced web-based display interface.

The system allows for a 24h cycle between the availability of an appropriate numerical grid and the routine production of daily 3D circulation forecasts, with quality automatically controlled against existing field observations (where those are available). The intent is to minimize the effort of initial deployment. Model expertise is required to improve the forecasts over time.

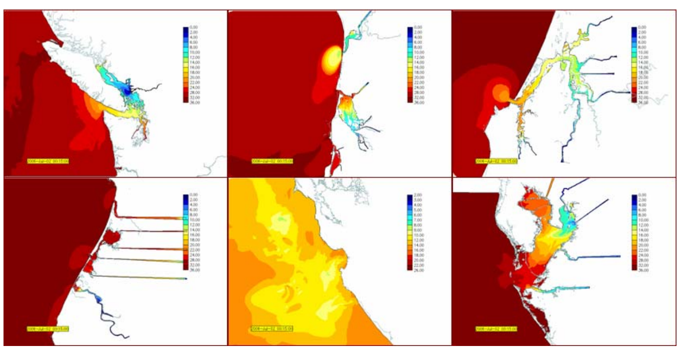

Figure 12. Daily forecasts of 3D baroclinic circulation are currently produced for15 coastal-margin systems, including: Fraser River/Strait of Georgia/Juan de Fuca Strait (top left); Nehalem River/Tillamook Bay/Netarts Bay (top center); Coos Bay (top right); Humboldt Bay (bottom left); Monterey Bay (bottom center); and Tampa Bay (bottom right). Forecast quality is variable, and iteratively improved. All images shown are for surface salinities (temperatures, in the case of Monterey Bay) on July 2, 2006 at 0:15AM.

C. Scaling up the impact of ocean science and technology

As a multi-purpose regional infrastructure, CORIE has influenced science, management and education in the Columbia River basin and the Pacific Northwest. Yet, it lacks the critical mass for truly transformative impact.

A recently funded NSF Science and Technology Center for Coastal Margin Observation & Prediction (CMOP, www.stccmop.org) is undertaking the challenge of scaling up such impact. Loosely motivated by the CORIE experience, CMOP is a multi-institutional center with complementary responsibilities in research, education, knowledge transfer and diversity.

CMOP will address major science questions on the impact of climate on coastal margins, the role of coastal margins on global elemental cycles, and the seaward propagation of anthropogenic impacts. Integral to CMOP activities is a new river-to-ocean testbed observatory for the Pacific Northwest, which will leverage extensive resources from partner institutions [1] into *configurable integrations* of modeling systems, heterogeneous observation networks, and information systems–all aimed at fundamental advancements in science and at the delivery of more reliable information to scientists, educators, resource managers, and interested citizens.

ACKNOWLEDGMENT

CORIE has had contributions from innumerable individuals, over many years. The core OHSU team (Charles Seaton, Paul Turner, Ethan vanMartre, Michael Wilkin, and Dr. Joseph Zhang) has provided an outstanding blend of dedication and multi-faceted skill, augmented at times by the talent of others (such as Dr. Arun Chawla, Dr. Mike Zulauf, Phil Barrett and Cole McCandlish). OHSU students and alumni (among others, Ed Myers, Cynthia Archer, Michela Burla, Sergey Frolov, Nick Hagerty, Bill Howe, Nate Hyde, Aaron Racicot, among others) have kept the CORIE vision fresh and evolutionary. Colleagues from different disciplines and affiliations (Drs. Ed Casillas, Todd Leen, Jan Newton, George Priest, David Maier, Barbara Hickey, Claudio Silva, Curtis Roegner, David Martin, Jack Barth, among others) generously provided the incentive and expertise to explore new ideas and concepts. Funding for CORIE and extensions thereof, as well as for CORIE-based science, has been provided in part by various programs within the National Science Foundation, National Oceanic and Atmospheric Administration, U.S. Army Corps of Engineers, Bonneville Power Administration, U.S. Fish and Wildlife Service, Office of Naval Research, Oregon Department of Geology and Mineral Industries, and City of Astoria.

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