Final Report

Collaborative Project: Improving the Representation of Coastal and Estuarine Processes in Earth System Models

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Introduction

This project aimed to improve long term global climate simulations by resolving and enhancing the representation of the processes involved in the cycling of freshwater through estuaries and coastal regions. This was a collaborative multi-institution project consisting of physical oceanographers, climate model developers, and computational scientists. It specifically targeted the DOE objectives of advancing simulation and predictive capability of climate models through improvements in resolution and physical process representation. The main computational objectives were:

1. To develop computationally efficient, but physically based, parameterizations of estuary and continental shelf mixing processes for use in an Earth System Model (CESM).
2. To develop a two-way nested regional modeling framework in order to dynamically downscale the climate response of particular coastal ocean regions and to upscale the impact of the regional coastal processes to the global climate in an Earth System Model (CESM).
3. To develop computational infrastructure to enhance the efficiency of data transfer between specific sources and destinations, i.e., a point-to-point communication capability, (used in *objective 1*) within POP, the ocean component of CESM.

Sensitivity of CESM to Aspects of the Virtual Salt Flux River Forcing

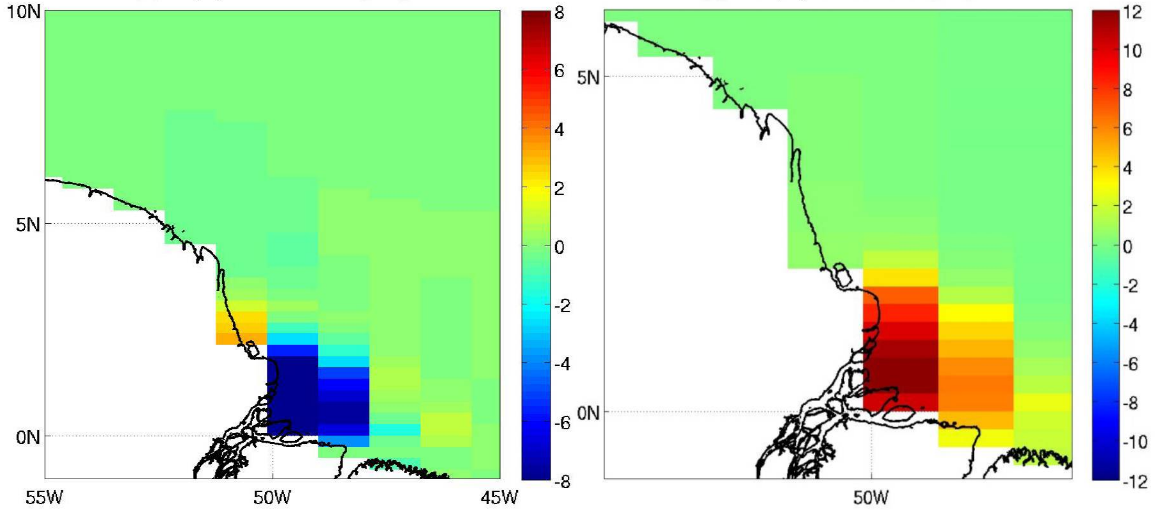
In the Community Earth System Model (CESM), and many other ESMs, the river volume flux is imposed as additional precipitation (i.e., the augmented precipitation approach) over a certain surface area in the vicinity of the actual river mouth. This equivalent river volume flux is then applied to the salinity transport equation as an unphysical virtual salt flux (VSF), representing the dilution effect of the added freshwater on salinity, but not on ocean mass or sea level. This approach provides a closure to the global hydrologic cycle, but does not represent the important transport and mixing dynamics in estuaries, river plumes, and continental shelves. To provide a basis for physically interpreting the results of including the estuary and shelf box parameterizations, we first evaluated the sensitivity of the CESM simulations to a number of poorly constrained, or arbitrary assumptions in the standard formulation of the model:

- *The area of spreading of riverine freshwater.* The standard formulation uses a completely arbitrary distance-weighted spreading function with a maximum radius of 300km. Spreading the freshwater over a broad area tends to reduce the impact of river discharge on salinity. We tested this dependence in cases with no spreading (discharge input to single grid point closest to the river mouth) and a spreading radius of 150 km. The impacts of the horizontal spreading are illustrated by comparing the default standard POP configuration (V300CS, e-folding length of 1000km with a maximum spreading radius of 300km) and the POP simulation with a reduced spreading scale (V150CS, e-folding length of 300km with a maximum spreading radius of 150km) to mimic the localization of river input that is closer to reality. Figure 1a shows the local salinity differences near the mouth of the Amazon. The surface salinity in the V150CS can be more than a 10 psu fresher than that in the V300CS near the river mouth, with a weak increase in salinity offshore and further along the coast where the river spreading was eliminated. A similar pattern of response, though weaker is found for all rivers. Further analysis of the differences is provided by vertical profiles of the upper ocean stratification near the surface in Figure 2. While the direct forcing change is at the sea surface, the response is seen to extend through the mixed layer. The total response is a result of direct changes in forcing in addition to feedbacks through changes in static stability and eddy diffusivity.
- *Contribution of river freshwater input to the surface buoyancy flux within KPP.* The formulation of the KPP vertical mixing scheme used in CESM has an implicit dependence on the river freshwater input through the calculation of the Monin-Obukhov length scale. This had an unexpectedly large impact on the solution. Disabling the river freshwater contribution to the surface buoyancy flux within KPP (but not within the salinity conservation equation, denoted by V150CSK) resulted in changes of more than 5 psu near larger rivers. Figure 1b show the 30-year averaged surface salinity differences between V150CSK and V150CS near the mouth of the Amazon. The salinity can be more than 12 psu lower in the V150CS than the V150CSK in a single point close to the Amazon River mouth. The impact on the top level salinity is roughly proportional to the mean river runoff (Tseng et al., 2015). Our analysis indicates that the impact of runoff becomes significant when the runoff dominates the total surface buoyancy flux in the KPP. Including the river runoff in the surface buoyancy fluxes of KPP acts to shallow and stabilize the surface boundary layer, thereby trapping the impact of the surface forcing in a thinner layer and amplifying the local surface dilution effect.
- *The use of a constant reference salinity in the VSF.* In order to conserve salt globally when using a VSF formulation of the freshwater forcing (as CESM does) requires that constant reference salinity, rather than the actual local

salinity be used in converting freshwater flux to salt flux. The error in doing so is typically small (~10 %) in the open ocean, but can be very large near river mouths where the local salinity significantly departs from the global average value. The use of a constant reference salinity, typically about 35 psu, exaggerates the dilution effect of the freshwater input in low salinity coastal waters. Figure 1c shows the difference between a case using the local salinity (V150LS) and the constant reference salinity (V150CS) in the vicinity of Amazon River. A large difference of more than 6 psu is observed but we note that this is partially due to the additional amplification of the runoff contribution on the surface buoyancy flux in KPP discussed above. However, a major concern of using the local salinity is the lack of global salinity conservation. This problem can be remedied by adding a small globally uniform correction to the open ocean precipitation. Additional tests using this correction (not shown) indicate that it has little impact on the circulation, but accomplishes the desired global salt conservation.

The responses of the model to the changes described above were non-linear and in several cases partially offsetting, so it was important to evaluate the sensitivity for each in turn.

(a) V150CS-V300CS (b) V150CSK-V150CS



(c) V150LS-V150CS (d) S10MLS-S10MCS

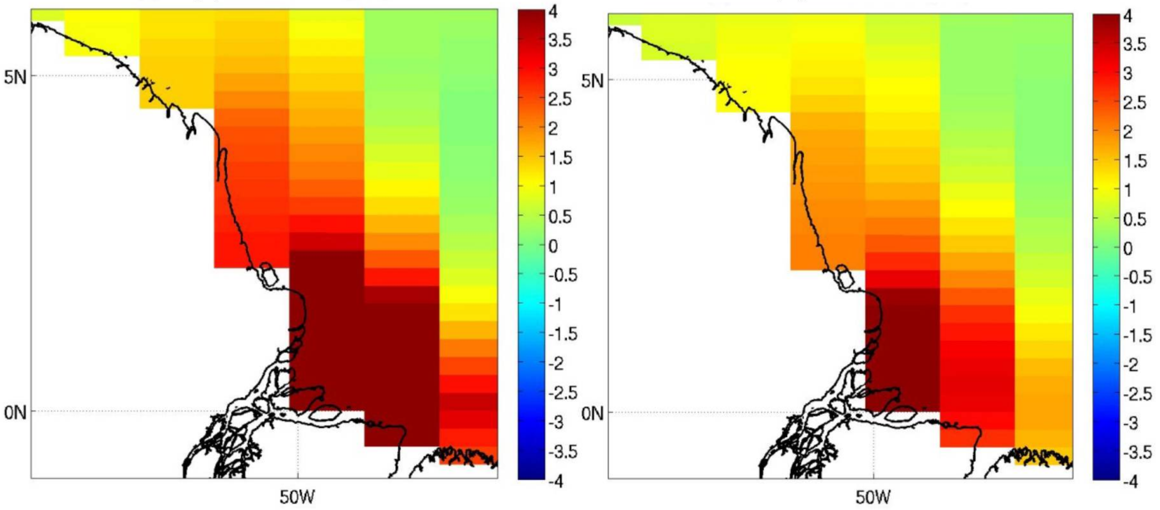


Figure 1: 30-year averaged surface salinity differences near the mouth of the Amazon River. (a) The difference between V150CS and V300CS; (b) The difference between V150CSK and V150CS; (c) The difference between V150LS and V150CS; (d) The difference between S10MLS and S10MCS.

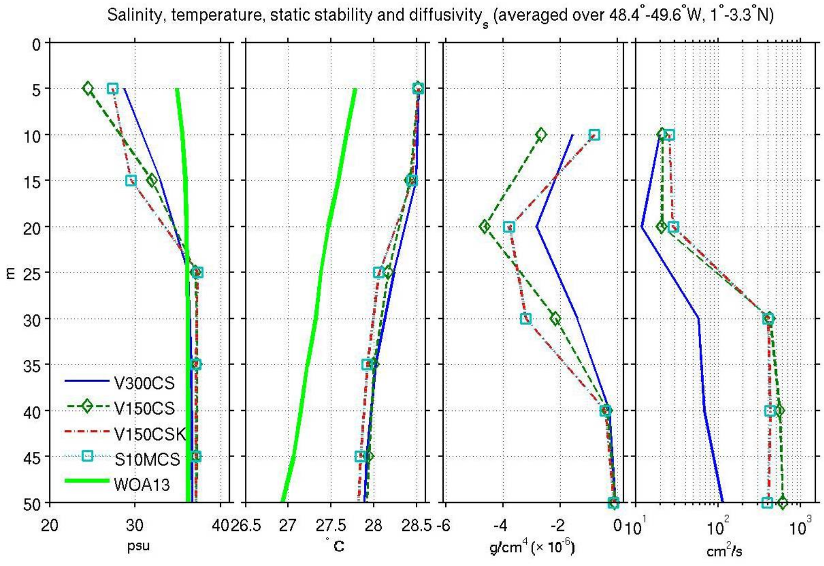


Figure 2: 30-year averaged vertical profiles of salinity, temperature, static stability and vertical eddy diffusivity in the Amazon River mouths as simulated by the V300CS, V150CS, V150CSK and S10MCS. The thin solid line is the WOA13.

Estuary-shelf freshwater exchange parameterizations for the CESM

The first proposed improvement to the representation of riverine freshwater input was to distribute the input vertically over multiple grid cells to represent the mixing processes in estuaries and shelf plumes, while retaining the familiar virtual salt flux form. A scheme to do so was developed and implemented that allowed the distribution of the salinity dilution effect of river water over a prescribed depth, which need not correspond to an integer number of grid cells. The impact of this additional vertical mixing was found to be most dramatic when the depth of estuary mixing was comparable to, or greater than, the local surface boundary layer depth. For cases where the depth of freshwater mixing was less than the boundary layer depth the response was a linear decrease in the dilution effect. Overall, the impacts of the choices in the basic formulation of the virtual salt flux as described above were found to a have a greater impact on the solution than the vertical mixing of river water.

Estuary Box Model (EBM): Global models such as CESM do not resolve estuaries and do not include estuarine physical processes. In nature, riverine freshwater entering estuaries is mixed with saltier waters entering from the mouth; reducing stratification and increasing the salinity of water flowing out of the estuary through the mouth. This vertical exchange of salt driven by estuary processes has been added to CESM by developing, testing, and coupling the EBM.

The steady-state governing equations of the EBM are conservation of water volume, salinity, and gravitational potential energy (derived from the density advection-diffusion equation). Two inputs come from CESM fields: time-varying river discharge and lower-layer open ocean salinity at the mouth. Other input parameters are set with a new input table: dimensions of the mouth, tidal amplitude (only needed for horizontal diffusion), and two dimensionless mixing parameters that set the strength of vertical and horizontal tidal diffusion within the estuary. To date, customized parameter values have been specified for the 20 largest estuaries (accounting for approximately 60% of the global river discharge) based on comparisons with available observations. All other estuaries are represented by a standard parameter set. The EBM outputs are the estuary outflow salinity and volume flux; the product of these outputs is the estuary exchange salinity flux. Currently, the exchange flux is introduced to the adjacent CESM ocean cell as a vertical salt flux that redistributes salt from the lower to upper grid levels. Instead of adding volume due to river discharge, salt is removed from the sea surface via a VSF (as described above).

Offline tests and comparison to observations from a range of estuaries indicates the EBM can represent stratification for well-mixed, partially mixed, and highly stratified estuaries (Figure 3). An offline case study for the Columbia River (Figure 4) shows the EBM compares well to observed salinities and volume fluxes from a high-resolution regional ocean model (described below). The EBM has been included in the source code for CESM2 and has been applied globally to 787 rivers. Two CESM test cases have been run for 60 simulation years (for one cycle of the "CORE-IA" forcing) to illustrate the effects of estuarine mixing. The control case has all river inputs concentrated at one ocean grid cell (no spreading radius) and no EBM. The second case is identical for the first 30 years and then the EBM (and vertical estuary exchange flux) is turned on for the remainder of the run. At river discharge points, the EBM run has higher surface salinities as expected due to the exchange fluxes (Figure 5). Regionally, in the vicinity of many input points, the EBM results in higher surface salinities and reduced near-surface stratification. Remote effects of applying the EBM to the Amazon and some other large rivers included unanticipated lower salinity regions (~0.2 lower than the control). The lower salinities are a consequence of feedbacks in the VSF implementation (that uses the local surface salinity) and changes due to the estuary exchange flow. These results indicate significant sensitivity to how riverine freshwater is introduced into CESM.

Shelf Plume Box Model (SPBM): With limited horizontal and vertical resolution, global models such as CESM do not fully resolve processes influencing the evolution of river plumes on the shelf. For each river input, the SPBM creates a series of evolving plume boxes each initially filled with the volume and salinity output each day from the corresponding EBM. A given plume box then evolves under light-wind conditions by propagating down-shelf as a buoyancy-driven plume and thickening and increasing salinity via shear-driven entrainment. When upwelling-favorable winds occur, the plume box is transported offshore via Ekman transport and rapidly thickens and increases salinity via wind-driven mixing. The water in the plume box is delivered to the CESM ocean model when it crosses the shelf break or reaches a maximum age (currently set to 30 days). At this delivery time and position, the exchange flow necessary to balance the salt flux delivered by the plume box is imposed. The river input associated with the box also is imposed at this time and location (either as a VSF or net volume flux). In this way, the SPBM changes the timing, location, and salinity of freshwater delivery to the open ocean.

The SPBM has been run (offline of CESM) for the Columbia River plume and compared to high-resolution regional model results (Figure 6). The SPBM is able to represent the general characteristics of down-shelf propagation, mixing, and wind-driven offshore transport of the plume. A test run of CESM with the SPBM activated for the Columbia River (Figure 7) illustrates the increased surface salinities and decreased near-surface stratification as compared to a run without the SPBM. Applying the SPBM globally in CESM is still under development.

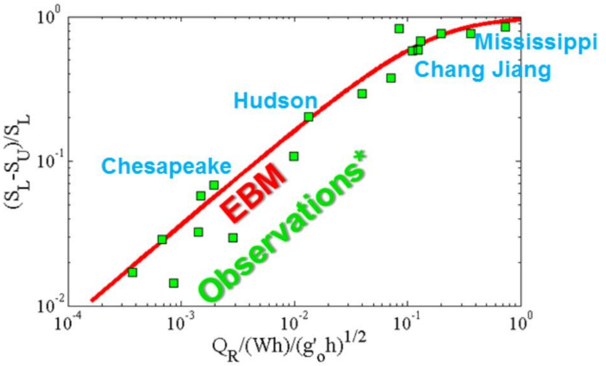


Figure 3 The points are observations in 13 estuaries regenerated from Geyer (2010), the solid line is the EBM solution.

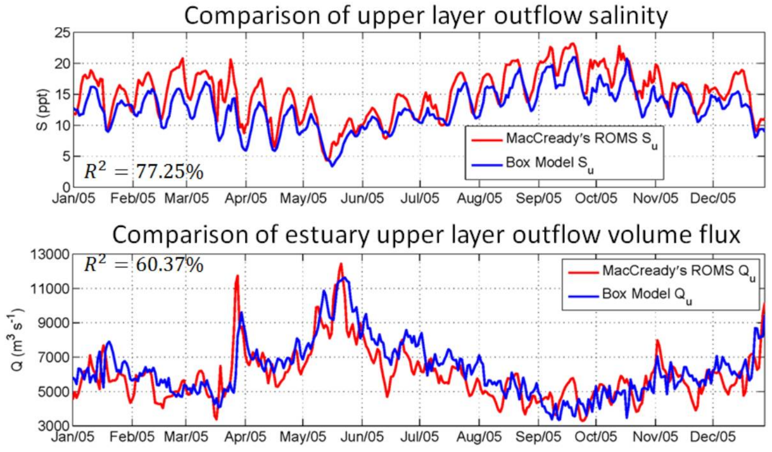


Figure 4 Time series of upper-layer salinity (upper panel) and volume flux (lower panel) at the Columbia River mouth. The red curve is from the high-resolution regional model and the blue curve is from the EBM solution.

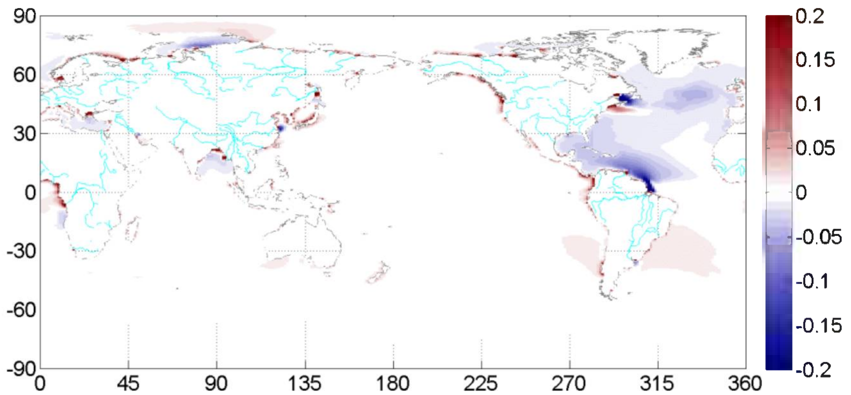


Figure 5 Sea surface salinity difference between the EBM run and control run for CESM. Results are averaged over the last 30 simulation years and positive values indicate the EBM run has higher salinities.

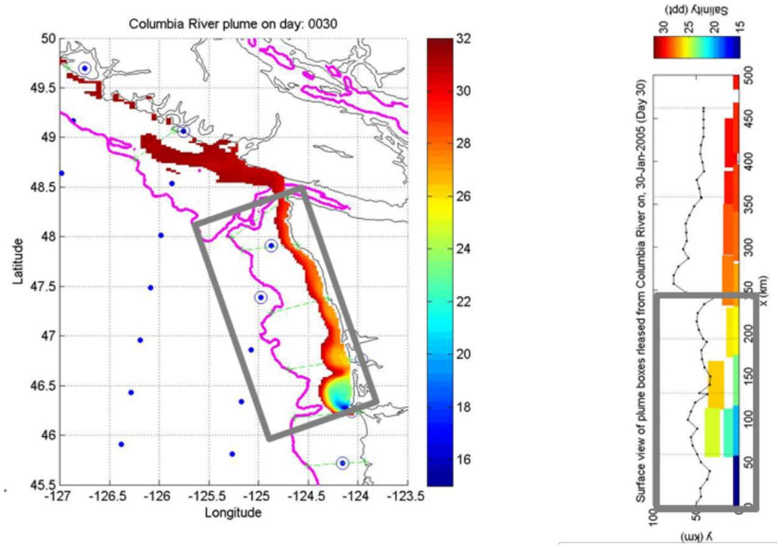


Figure 6 Sea surface salinity associated with the Columbia River plume in the high-resolution regional model (left panel) and the SPBM (right panel). The gray box is included for reference; it bounds the same area in both graphs. The shelf break is indicated by magenta and black curves in the left and right panels, respectively. Blue points in the left panel show CESM grid-points.

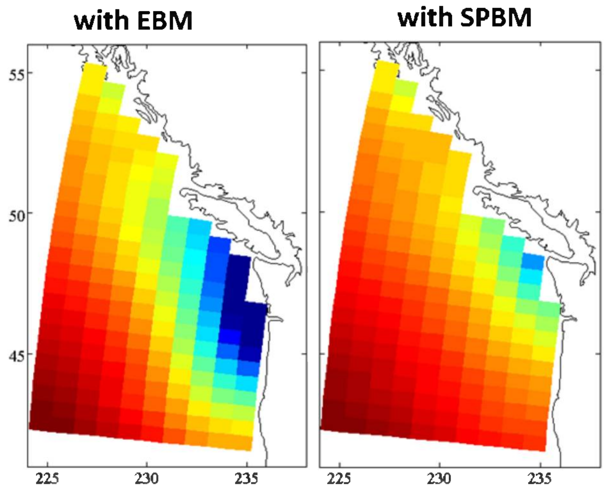


Figure 7 Sea surface salinity in the Northeast Pacific for CESM test runs with the EBM (left panel) and the SPBM for the Columbia River plume (right panel). The field is from July of the second simulation year.

Nested Regional Modeling

Globally about half of commercial fish catch is from the continental shelf, but this region is poorly resolved in ESM's, including CESM. As a result, the physical environment, such as river plumes and wind-driven upwelling, are not well represented, along with the resulting biological productivity. One strategy for providing decade-to-century estimates of the effect of climate change in specific coastal regions is downscaling, using a high-resolution model nested inside the ESM. As part of our project we conducted several dozen downscaling experiments using a ROMS ocean model of the NE Pacific nested in CESM (Fig. 8). The original ROMS model was forced with the best available external fields (atmosphere, ocean, 16 rivers, tides) and had excellent skill when compared with observations. In addition to testing downscaling of CESM, the regional model was used as a reference solution for testing the Estuary and Shelf Box Models described above.

Our new model experiments systematically replaced the ocean and atmosphere forcing fields with those available as part of CESM (POP ocean and CAM atmosphere). The regional high-resolution model was then run multiple times for 2005 and 2099 to assess (i) how skill was affected by nesting in CESM, and (ii) how shelf conditions might change into the future. Model tides and rivers were held to 2005 conditions.

Results:

- The nesting was successful in that stable year-long simulations were not disrupted by the coarse resolution of the CESM fields.
- The CAM atmospheric fields appeared similar to that from our standard WRF model (for 2005), and only differed substantially in 2099 by having warmer surface air temperature. RCP's 4.5 and 8.5 were both used.

- The POP ocean appeared to have a larger effect on shelf properties, biased somewhat warm (2 °C) and fresh (1psu) in surface waters, in 2005 (Figures 8 and 9).
- The nested model and fields from CESM-POP were compared to mooring records in 2005, and it was found that biases were roughly cut in half using the nested ROMS model, and details of the river plume were much better represented (Figure 9).
- All years using CESM forcing (2005 and 2099, RCP 4.5 and 8.5) exhibited much smaller Available Potential Energy signal from wind-driven upwelling, compared to the original model (Figure 10). The reason for this is not yet clear, and is the subject of ongoing analysis. If the nesting truly decreases upwelling by this much then it is a significant problem for downscaling inside CESM in this region.
- The volume flux from river sources in this region in CESM is at least a factor of two too large. This may contribute to the fresh bias in surface waters. Note that in our experiments we used actual, observed river flows, and so should not have been affected by this bias. However the POP fields used as open boundary conditions may have been influenced by this problem.
- Results have been presented at several meetings and a manuscript is in preparation.

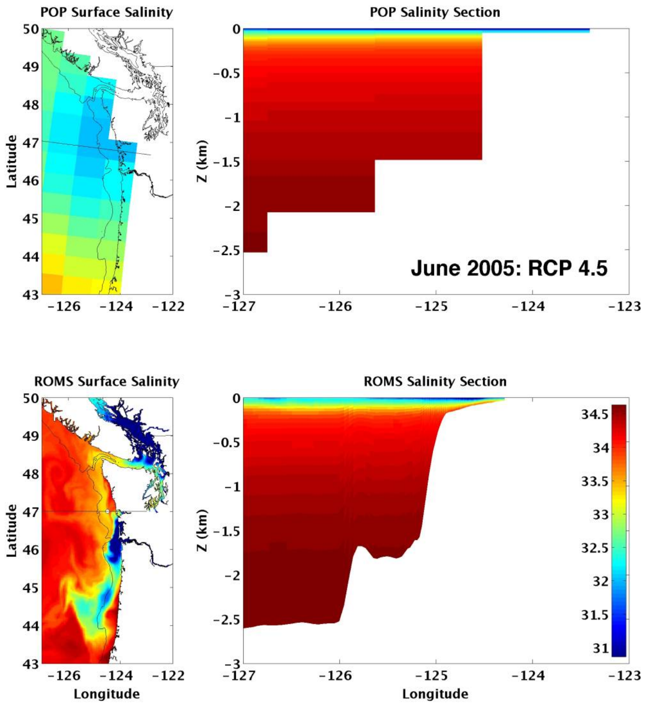


Figure 8: CESM-POP ocean salinity fields (upper panels), and regional ROMS model (lower panels) for the NE Pacific. The coarse POP grid does not resolve the continental shelf or the effect of large freshwater sources such as the Columbia River.

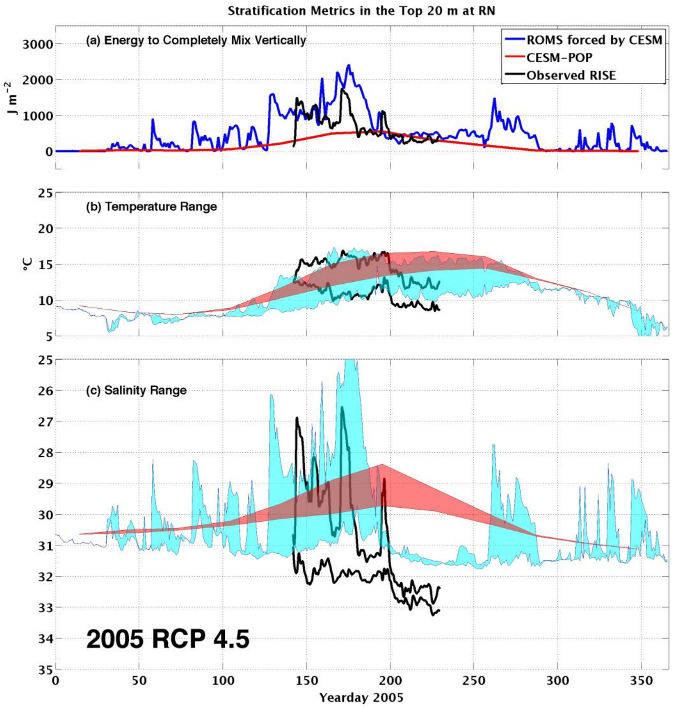


Figure 9: Tests of nested model skill in surface stratification against mooring records on the shelf at 47N, 70 m water depth. (a) Energy required to fully mix the top 20 m of water column. (b) temperature and (c) salinity range from 1-20 m. For all panels observations are black, original CESM-POP fields are red, and ROMS fields (nested inside CESM) are blue. The ROMS model decreases the errors in POP by about half.

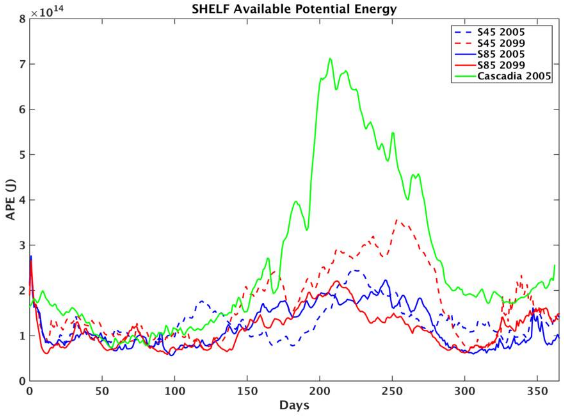


Figure 10: Available Potential Energy integrated over the continental shelf in 5 ROMS simulations, versus year day. The strong signal of spring-summer upwelling is apparent in the original "Cascadia 2005" line (green). The other four lines are the same model nested inside CESM, for different years (2005 and 2099) and different

RCP's. There is no significant difference among the CESM-nested runs, but all show a much smaller upwelling signal than the original run.

CESM Infrastructure

We developed and implemented a general point-to point (P2P) communication capability within POP. This capability allows unnecessary global communications (broadcasts, gathers, reductions, etc.) to be replaced by more efficient data transfers between relevant subsets of processes. This capability was developed to implement the Shelf Box Model described above, however it can be used for a number of other aspects of the POP code besides our new parameterizations. For example, the original implementation of the POP deep-water overflow parameterization uses global reductions. Like the estuary-shelf box model, the overflow parameterization consists of regional calculations that require communication within the small groups of processors that contain the relevant data for each overflow. The inefficiency of using global communication for regional calculations is demonstrated by the improvement of the overflow parameterization with the new P2P capability. The Table 1 below details the speedup of the overflow parameterization code in POP for a 5 day run on a one degree ocean model with 64, 128, 256, and 480 cores.

Number of cores	ORIG overflow	P2P overflow	Speedup
64	3.88s	1.11s	3.5
128	3.15s	.34s	9.3
256	2.37s	.20s	11.9
480	3.00s	.21s	14.2

Table 1: the speedup of the overflow parameterization code in one degree POP for a 5 day run

Project Personnel

In addition to the project co-investigators the following personnel contributed to the efforts:

- Yu-heng Tseng (NCAR) Implementation of parameterizations in CESM, assistance in preparing boundary data for regional model, integration of control and sensitivity experiments, analysis of simulation results, preparation of manuscripts, coordination of team meetings.
- Alison Baker (NCAR) Development and implementation of point-to-point communication module.
- Qiang Sun (Univ. Connecticut, graduate student) Development and testing of estuary and shelf box models, analysis of simulation results, preparation of manuscripts

Presentations

Bryan, F., J. Dennis, P. MacCready, M. Whitney (2011) Improving the Representation of Coastal and Estuarine Processes in Earth System Models. *Poster*, DOE Climate Modeling PI Meeting, Washington DC.

MacCready, P. (2012) An overview of the physics of estuarine circulation, with biogeochemical implications. *Invited seminar*, NCAR, Boulder, CO.

MacCready, P., Y.-H. Tseng, F. Bryan, M. Whitney (2014) Coastal Downscaling: Can CESM fields successfully force regional coastal ocean simulations with strong freshwater forcing? (YES). *Poster*, DOE Integrated Climate Modeling Principal Investigator Meeting 2014, Bolger Center, Maryland.

MacCready, P., Y.-H. Tseng, F. Bryan, M. Whitney (2014) Coastal Downscaling: Can CESM fields successfully force regional coastal ocean simulations with strong freshwater forcing? (MAYBE). *Poster*, Fall AGU Meeting, San Francisco.

Sun, Q. and Whitney, M. M. (2013) A Box Model Approach for Improving the Representation of Riverine Freshwater Inputs in Climate Models, Mid-Atlantic Bight Physical Oceanography and Meteorology Conference, Oct. 17, 2013, in Narragansett, RI.

Sun, Q.; Whitney, M. M.; Bryan, F. O.; MacCready, P. and Tseng, Y-H (2014) Box Models Approach for Improving the Representation of Riverine Freshwater Inputs in Climate Models, Ocean Sciences Meeting, Feb. 28, 2014, in Honolulu, HI.

Tseng, Y-H, F. Bryan, J. Dennis, A. Baker, P. MacCready, M. Whitney (2012) Estuary-shelf freshwater exchange parameterizations in CESM. 17th Annual CCSM Workshop, June, 19, 2012 in Breckenridge, CO.

Tseng, Y-H, F. Bryan, J. Dennis, A. Baker, P. MacCready, M. Whitney (2012) Estuary-shelf freshwater exchange parameterizations in CESM. 2013 CESM Ocean Model Working Group Meeting, January 22, 2013, in Boulder, CO.

Tseng, Y. H.; Bryan, F. O. (2014) The effects of river and estuary runoff parameterization in the Community Earth System Model, Ocean Sciences Meeting, Feb. 24, 2014, in Honolulu, HI.

Tseng, Y-H, Q. Sun, M. Whitney, P. MacCready, and F. Bryan (2014) Implementation of Estuary-Shelf Freshwater Exchange Parameterizations in the Community Earth System Model. 2014 DOE PI MEETING, May 12, 2014, in Potomoc, MD.

Tseng, Y-H, F. Bryan, J. Dennis, A. Baker, P. MacCready, M. Whitney (2014) Implementation of estuary-shelf freshwater exchange parameterizations in CESM 2014 19th Annual CESM Workshop, June 17, 2014, in Breckenridge, CO.

Whitney, M. M.; Sun, Q.; Bryan, F. O.; MacCready, P. and Tseng, Y (2015) Physically-Based Parameterization of Terrestrial Fluxes in POP, CESM Ocean Model Working Group Meeting, Jan. 15, 2015, in Boulder, CO.

Whitney, M. M.; Sun, Q.; Bryan, F. O.; MacCready, P. and Tseng, Y. (2015) Improving the Representation of Riverine Freshwater Inputs in Climate Models, Open Science Conference on Salinity and Freshwater Changes in the Ocean, Oct 14, 2015, in Hamburg, Germany.

Publications

MacCready, P., Y.-H. Tseng, F. Bryan, M. Whitney (*in preparation*) Coastal ocean downscaling experiments using CESM in a region of freshwater influence.

Sun, Q.; Whitney, M. M.; Bryan, F. O.; MacCready, P. and Tseng, Y. (*in preparation*) A Box Model for Representing Estuarine Processes in Earth System Models, *Ocean Modeling*, to be submitted January 2016.

Tseng, Y-H, F.O. Bryan, and M. Whitney (*in preparation*) Impacts of the representation of riverine freshwater input in the Community Earth System Model. *Ocean Modeling*, to be submitted November 2015.