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Vignette 13: The Salish Sea Model

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13 THE SALISH SEA MODEL – FOR DIAGNOSTIC BIOPHYSICAL ASSESSMENTS SUPPORTING ECOSYSTEM RESTORATION AND WATER QUALITY MANAGEMENT

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"Why is there persistent annual occurrence of hypoxia in Hood Canal but not in Saratoga Passage? Why does Padilla Bay support a healthy eelgrass meadow while Skagit Bay and Port Susan appear to be losing vegetation? Why do we continue to detect PCBs in fish tissue and the food web despite many years of source control and sediment remediation efforts? Will nutrient reduction strategies be effective in managing dissolved oxygen near algal blooms? And will they also provide ocean acidification relief? What do we know about the operation of net-pens and potential spreading of released particulate matter and disease, and how does Salish Sea circulation and transport affect accumulation of microplastics and marine debris?"

These are examples of some of the leading questions currently being addressed by our water quality management and regulatory agencies. Given numerous concerns related to the health of the ecosystem and the possibility of anthropogenic impacts—from population growth to climate impacts, such as sea level rise—scientists, engineers, and planners seek an improved basic understanding of the biophysical behavior of the Salish Sea. The Salish Sea Model (SSM) development was motivated by this urgent need for a comprehensive predictive model that could diagnose water quality issues and concerns and serve as a planning tool in support of Puget Sound restoration efforts. The model framework and formulation were selected specifically to allow assessments of concerns, such as recurring hypoxia in Puget Sound, loss of eelgrass meadows, loss of nearshore habitat, and persistence of toxic contaminants in sediments and tissue. The SSM was developed by the Pacific Northwest National Laboratory in collaboration with the Washington State Department of Ecology (Ecology) and with support from the United States Environmental Protection Agency (USEPA) (Khangaonkar et al. 2018).

The SSM was designed to function at an academic/scientific research level of quality, but with practical applications and use by the broad Salish Sea community in mind. It uses an unstructured approach in which the model domain is represented by a grid/mesh made up of triangular cells over which Navier-Stokes equations of continuity and momentum are solved. This provides flexibility, encompassing regions with complex shorelines and the presence of multiple islands. The approach also allows the model resolution to be refined locally for site-specific applications. Right from early-developmental stages, SSM sub-domains with the finite volume community ocean model (FVCOM) framework have been deployed in support of feasibility analyses for nearshore restoration projects. Despite best intentions, efforts to restore nearshore habitats can result in poor outcomes if water circulation and transport are not properly addressed. Land use constraints can lead to selection of suboptimal restoration alternatives that may result in undesirable consequences, such as flooding, deterioration of water quality, and erosion, that require immediate remedies and costly repairs. Quantitative models designed for application to the nearshore

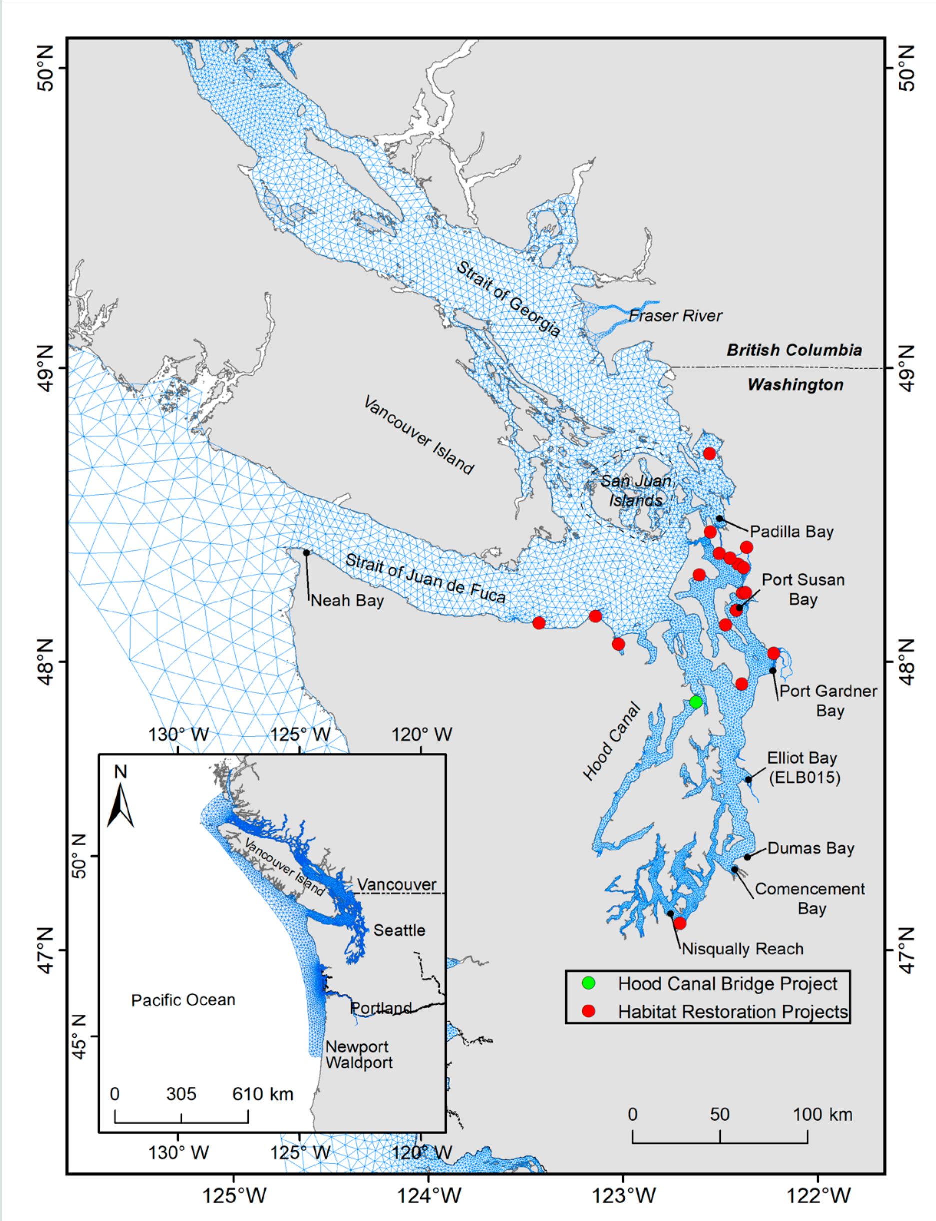

Figure 1: Project sites in the Salish Sea where site-specific applications of FVCOM based hydrodynamic models were developed as part of restoration feasibility or environmental assessment and design efforts. These applications included stand-alone as well high-resolution sub-basin applications embedded within SSM. Source: Tarang Khangaonkar

environment can minimize uncertainty about restoration goals, such as recovery of tidal exchange, supply of sediment and nutrients, and establishment of fish migration pathways. Starting with one of the earliest and largest restoration efforts in Puget Sound (Nisqually National Wildlife Refuge) to recent projects in the Whidbey Basin, the model has provided hydrodynamic simulations in the intertidal nearshore environment, predicting cumulative effects of multiple dike-removal, dike breach, and dike-setback scenarios on tidal currents, inundation frequency, connectivity, and sedimentation and erosion processes. Figure 1 shows locations of various sites in the Salish Sea where SSM was used with high resolution (≈10-25 m) in sub-basins of interest, either in stand-alone (cut-out) mode or embedded within SSM as part of restoration feasibility or impact assessments prior to project implementation.

The familiarity with the Salish Sea environment and years of on-water experience sometimes convinces us of potential remedial actions based on intuition, personal convictions, and desired expectations. However, this inland fjord is complex, and the nearshore intertidal reaches where most development activity and anthropogenic impacts first occur—with tidal ranges greater than 3 meters over most of the domain—are too complex and challenging to rely on scaling inferences and past project experiences alone. For example, having recognized that the anthropogenic nutrient loads to the Hood Canal basins were relatively small, many of us were convinced that hypoxia in Hood Canal was somehow tied to the Hood Canal floating bridge. The hypothesis was that bridge presence directly obstructed surface currents and therefore likely impacted large-scale circulation and flushing (Khangaonkar & Wang 2013). Application of the SSM as part of the Hood Canal Bridge Impact Assessment showed that the floating bridge indeed creates a zone of influence which affects currents, salinity, and temperature patterns in the near field (3-6 km; Khangaonkar et al. 2019). However, it also demonstrated that the original intuitive conviction that the bridge contributes to hypoxia in the Lynch Cove region of Hood Canal approximately

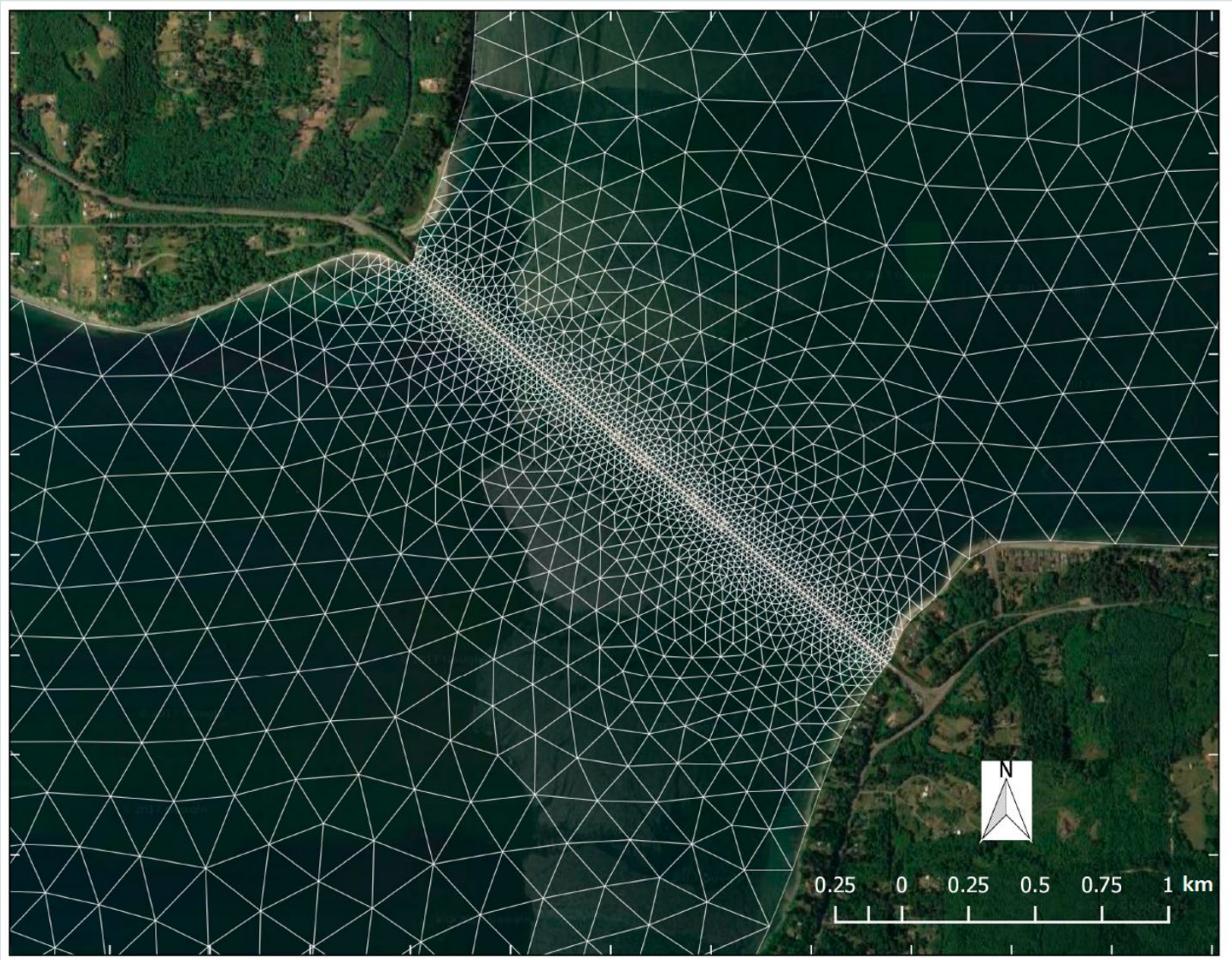

Figure 2. Salish Sea Model grid with refinement near the Hood Canal Bridge region to facilitate incorporation of the bridge block effects on circulation and water quality (biogeochemistry).

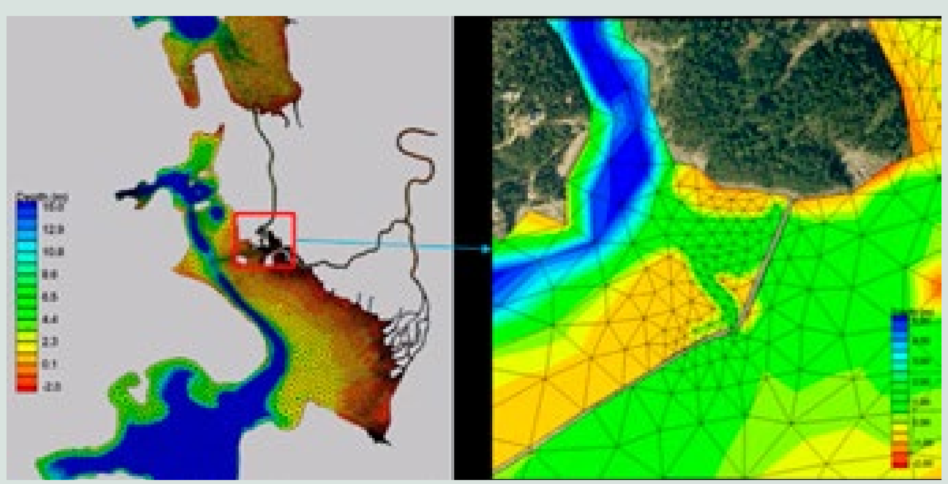

Figure 3. A closeup of model grid near McGlinn Island jetty near the mouth of North Fork Skagit River.

80 kilometers away was likely incorrect. The magnitude of hypoxia and overall basin flushing time appeared to be unaffected by the presence of the bridge based on numerous model tests. However, the SSM-based modeling effort did show that the hypoxia magnitude (exposure in area-days) was instead directly affected by overall nutrient pollution entering the Salish Sea and the resulting increase in algal growth. In other words, improvement to Hood Canal hypoxia will require overall improvement in Salish Sea water quality and cannot be addressed by Hood Canal sub-basin focused actions alone. Figure 2 shows a SSM grid with site-specific refinement down to 18-meter scale for embedded simulation of the Hood Canal Bridge block along with the rest of the domain.

This ability of SSM to conduct high resolution applications with shoreline structures has proven particularly useful in providing information to decision makers in situations where ecosystem goals may conflict with regional infrastructure needs. For example, the 16-kilometer Swinomish Federal Navigation Channel, which provides navigation access to Northern Puget Sound by connecting Skagit and Padilla Bays requires periodic maintenance dredging and dikes to train Skagit River flow and sediments away from the channel.

The Swinomish Channel is in need of repairs to dikes/jetties, as sedimentation has increased, but the wear and tear and resulting breaches are seen as beneficial to migrating fish. The proposed repairs and dike constriction actions for channel maintenance appear to be in conflict with salmon habitat restoration goals aimed at improving access, connectivity, and brackish water habitat. The model was applied to assess the feasibility of achieving the desired dual outcome of (a) reducing sedimentation and shoaling in the Swinomish Channel and (b) providing a direct migration pathway and improved conveyance of freshwater. Figure 3 shows a closeup of model grid refinement and application to evaluate impacts on sediment deposition and salinity patterns. The results showed that connectivity and the desired brackish environment could be restored effectively through one of the scenarios considered but would come at increased dredging and maintenance costs (Khangaonkar et al. 2017).

For the scientific and the regulatory community in the Salish Sea, a key performance measure for acceptance of biogeochemical models has always been their ability to reproduce nutrient-algae annual cycles and dissolved oxygen (DO) levels. DO is often regarded as an indicator of water quality, and the ability of the model to reproduce recurring hypoxia in sub-basins, such as Lynch Cove, Penn Cove, and East Sound, and responsiveness to anthropogenic nutrient loads from watershed runoff and wastewater loads is desired. This elusive goal had stymied ecosystem modeling research and nutrient management efforts in the region for decades. The SSM has successfully reproduced estuarine circulation, inter-basin exchanges, and annual biogeochemical cycles in the inner waters of Puget Sound, Georgia Basin, the San Juan Islands, and the Northwest Straits. SSM-based results have shown that nutrient loads from land-based sources are responsible for approximately 62% of exposure to hypoxic waters in the Salish Sea (Khangaonkar et al. 2018). The model has since been selected as the tool of choice by the USEPA and Ecology for developing the Marine Water Quality Implementation Strategy (MWQ IS) and is currently supporting the Puget Sound Nutrient Source Reduction Project (Ahmed et al. 2019).

In recent years, several new capabilities have been added to SSM in preparation for its use in sea level rise and climate change impact projections. The model now includes explicit simulation of turbidity, zooplankton, and eelgrass, and performs at a higher skill level for dissolved oxygen (DO) and ocean acidification (OA) or pH predictions. The SSM had previously demonstrated that the effects of the altered ocean chemistry in the upwelled shelf waters as a result of climate change would propagate into the inner Salish Sea and impact biogeochemistry, resulting in higher predicted algal biomass, a potential species shift from diatoms towards dinoflagellates, and increased regions of hypoxia and acidification (Khangaonkar et al. 2019). Since then, to improve ecological response predictions, micro- and meso-zooplankton kinetics have been incorporated, along with eelgrass, which may compete with phytoplankton for available nutrients in the photic zone along the shorelines. Figure 4 provides updated projections for ocean acidification impacts in the Salish Sea for Y2095. Results point to the possibility that the bottom layer of the Salish Sea water column (lower 15% of water depth) will be exposed to low pH waters with $\Omega A < 1$, 100% of the time. For the bottom layer, which already experiences exposure to corrosive water in present condition, this represents an increase of approximately 20%. However, for the surface waters including the photic zone, the projection for the future Y2095 scenario represents a near doubling, over a 114% increase in exposure to waters with ΩA < 1 (Khangaonkar et al. 2021; Note: these results are limited in that they are based on projections from a single ensemble member run of the National Center for Atmospheric research (NCAR) Community Earth System Model (CESM) and must be interpreted with appropriate caution. However, we believe that the results still provide a useful peek into the type of response one may expect over the Salish Sea in the future.)

In collaboration with University of Washington (UW) and Washington State Department of Fish and Wildlife, and with USEPA support, a toxics fate and transport module for SSM is currently under development. The SSM-toxics module development effort targets tracking of PCBs and metals from sources such as outfalls through the water column, to produced organic particles, and through the food chain to fish tissue data that has been collected by the Washington Department of Fish and Wildlife over many years. The model was also used by the same team in connection with tracking of toxics in Puget Sound, which includes pharmaceuticals such as opioids and the chemotherapy drug melphalan, along with a suite of 62 other contaminants (James et al. 2020). The SSM was used to compute a Salish Sea-wide map of effluent concentration from 99 wastewater outfalls over a one-year period to examine cumulative effects. An outfall effluent plume module FVCOM-Plume has been developed to provide dynamic plume dilution and transport analysis in tidal environments (Premathilake & Khangaonkar 2019). We expect that dynamic application of SSM with FVCOM-Plume will help regulatory agencies with accurate aquatic and human health exposure assessments in the Salish Sea.

In collaboration with NOAA Center for Operational Oceanographic Products and Services (COOPS), Ecology, UW-NANOOS, the PNNL SSM team is developing a high-resolution version of SSM towards SSM-OFS, an Operational Forecast System for the Salish Sea, for navigation and maritime emergency response support. Community access to SSM is available through the Salish Sea Modeling Center that was recently established through a memorandum of understanding between University of Washington, Tacoma and PNNL with support from USEPA, Puget Sound Partnership, City of Tacoma, and the University of Washington.

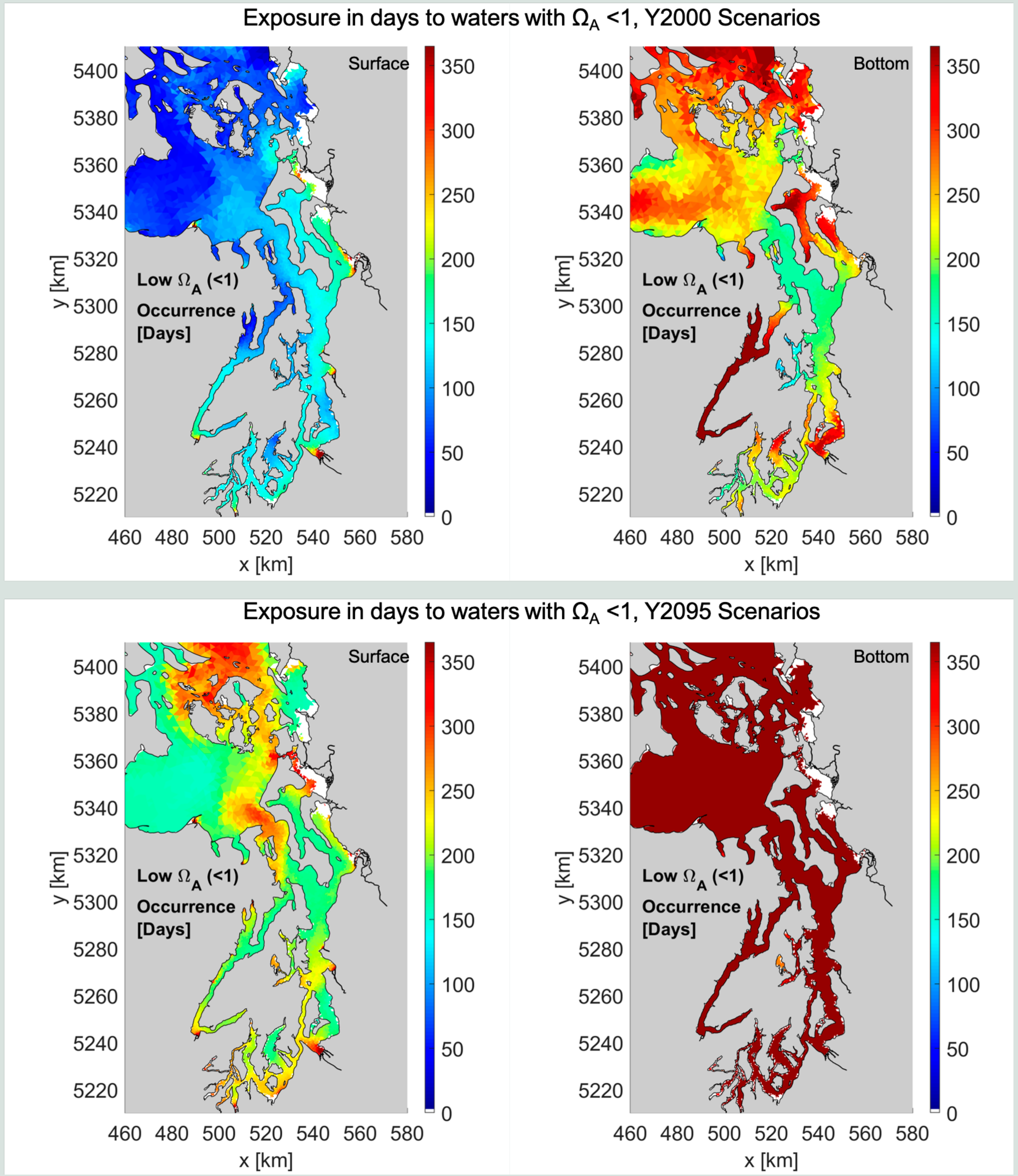

Figure 4. Projected exposure in days to waters corrosive to shell forming organisms with aragonite saturation ΩA < 1 for surface and bottom layers of Salish Sea. Top panel: Historical Y2000 scenario simulation, surface and bottom layer. Bottom panel: Future Y2095 simulation, surface and bottom layer. Surface layer corresponds to upper 3% of the water column and bottom layer corresponds to lower 15% of the water column.