# Integrated Assessment of Ocean Acidification Risks to Pteropods in the Northern High Latitudes: Regional Comparison of Exposure, Sensitivity and Adaptive Capacity

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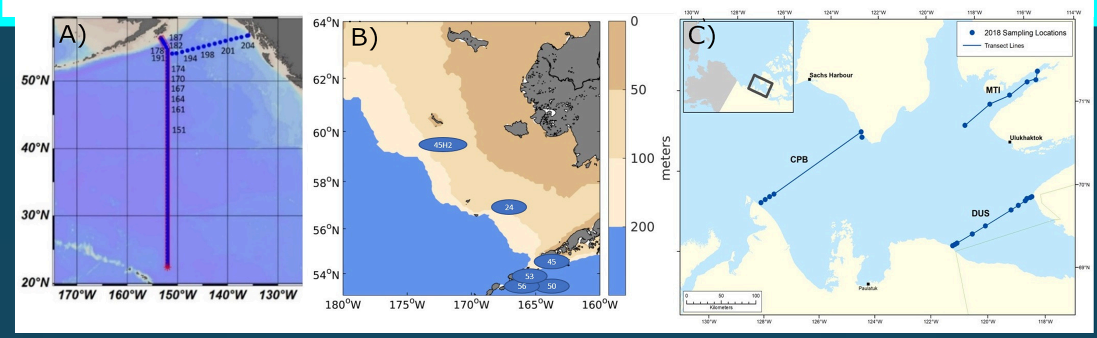
## Abstract

Exposure to the impact of ocean acidification (OA) is increasing in high-latitudinal productive habitats. Pelagic calcifying snails (pteropods), a significant component of the diet of economically important fish, are found in high abundance in these regions. Pteropods have thin shells that readily dissolve at low aragonite saturation state (Ωar), making them susceptible to OA. Here, we conducted a first integrated risk assessment for pteropods in the Eastern Pacific subpolar gyre, the Gulf of Alaska (GoA), Bering Sea, and Amundsen Gulf. We determined the risk for pteropod populations by integrating measures of OA exposure, biological sensitivity, and resilience. Exposure was based on physical-chemical hydrographic observations and regional biogeochemical model outputs, delineating seasonal and decadal changes in carbonate chemistry conditions. Biological sensitivity was based on pteropod morphometrics and shell-building processes, including shell dissolution, density and thickness. Resilience and adaptive capacity were based on species diversity and spatial connectivity, derived from the particle tracking modelling. Extensive shell dissolution was found in the central and western part of the subpolar gyre, parts of the Bering Sea, and Amundsen Gulf. Despite the presence of different morphotypes, genetic analyses based on mitochondrial haplotypes identified a single species, without differentiation between the morphological forms, coinciding with evidence of widespread spatial connectivity. We found that shell morphometric characteristics depends on omega saturation state (Ωar); under Ωar decline, pteropods build flatter and thinner shells, which is indicative of a certain level of phenotypic plasticity.

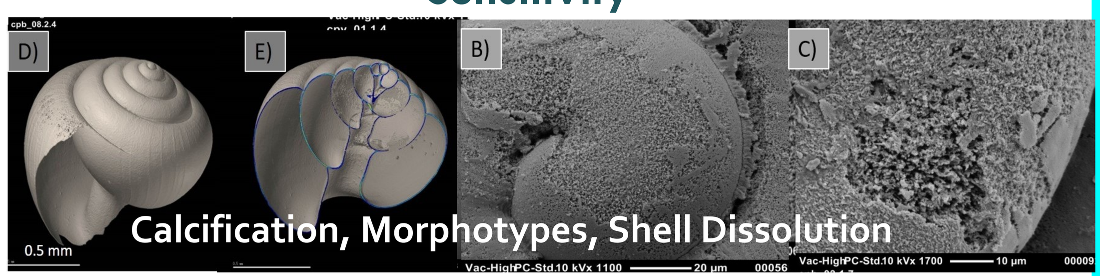
An integrated risk evaluation based on multiple approaches assumes a high risk for pteropod population persistence with intensification of OA in the high latitude eastern North Pacific because of their known vulnerability, along with limited evidence of species diversity despite their connectivity and our current lack of sufficient knowledge of their adaptive capacity. Such a comprehensive understanding would permit improved prediction of ecosystem change relevant to effective fisheries resource management, as well as a more robust foundation for monitoring ecosystem health and investigating OA impacts in high-latitudinal habitats.

## Figure 1: Area of Investigations

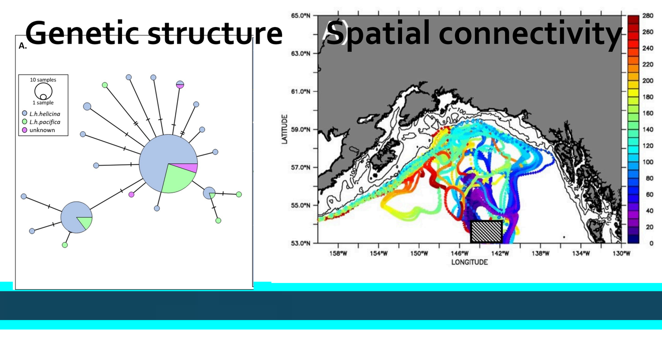
Biological samples taken in the Eastern pacific subpolar gyre and the GoA (A; samples analyzed from stations 164 to 204), and the Bering Sea (B; blue ellipses) and Amundsen Gulf (C) with three indicated transects related to the pteropod origin (Cape Bathurst (CPB), Dolphin and Union Strait (DUS), and Minto Inlet (MTI)



## Figure 2: Parameters of Pteropod Biological Sensitivity

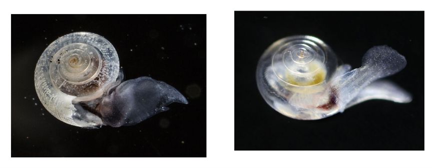



## Figure 3: Parameters of Adaptive Capacity

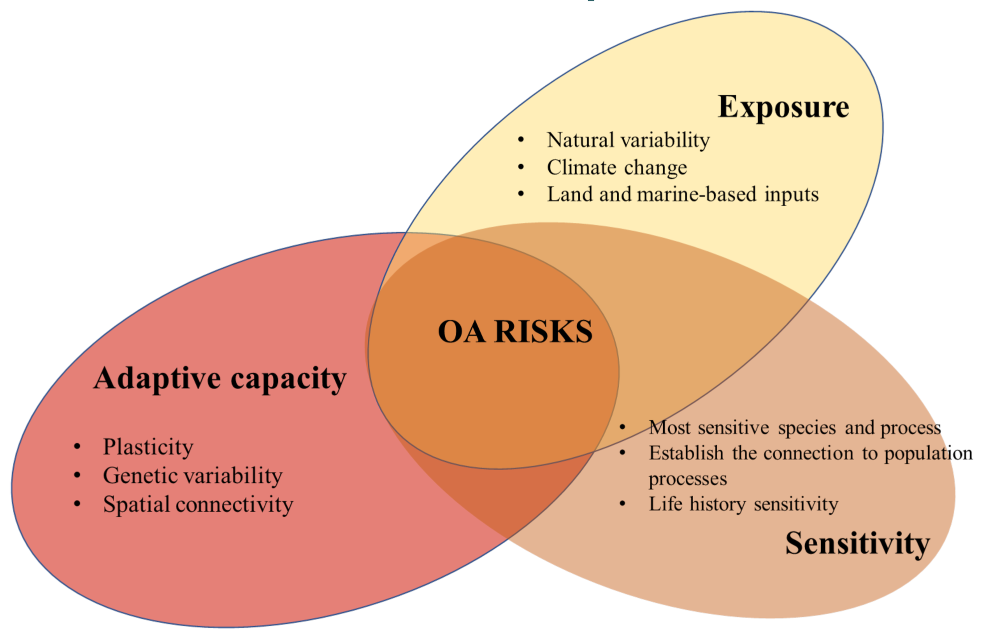



## Figure 4: High Latitudinal Pteropods as OA indicators – RATIONALE:

- Pteropods are shelled pelagic snails and belong to zooplankton group.
- One of the highest abundances on the global scale in the Northern high latitudes
- Essential food sources for salmon, Arctic cod, char.
- Ideal sentinel species because of their extreme sensitivity to OA.
- Limited understanding of OA impact on pteropods and their adaptation strategies in the high latitudinal regions.



## Figure 5: Biological OA Risk Assessment – Framework for this study




## OA Exposure in the Subpolar Gyre and the Gulf of Alaska

- **Significant reduction of suitable habitat for marine calcifiers**

Figure 6: Plot of observational data from the P16N cruise (Eastern Pacific subpolar gyre related to the aragonite saturation state, Ωar (E, F). Indicated are the two solid black contour lines showing Ωar of 1 and 1.3.

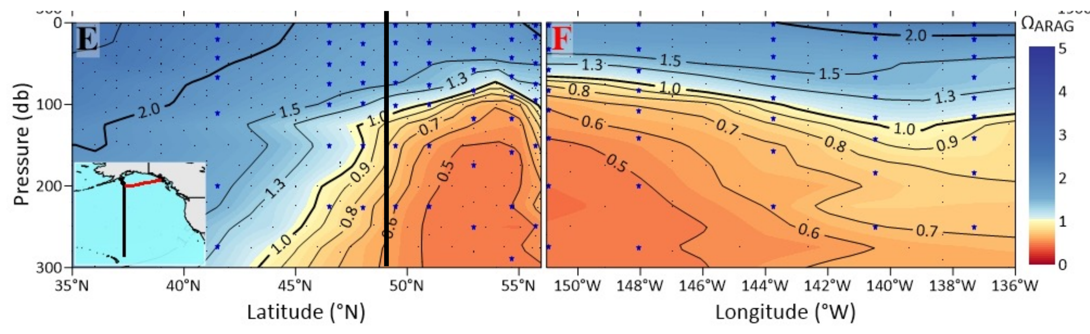
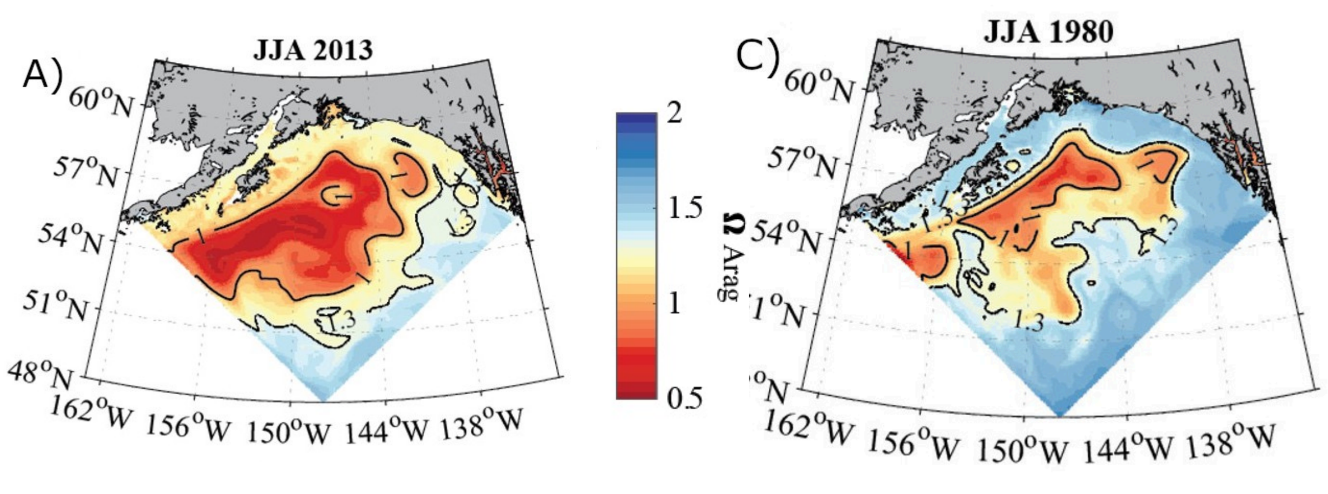
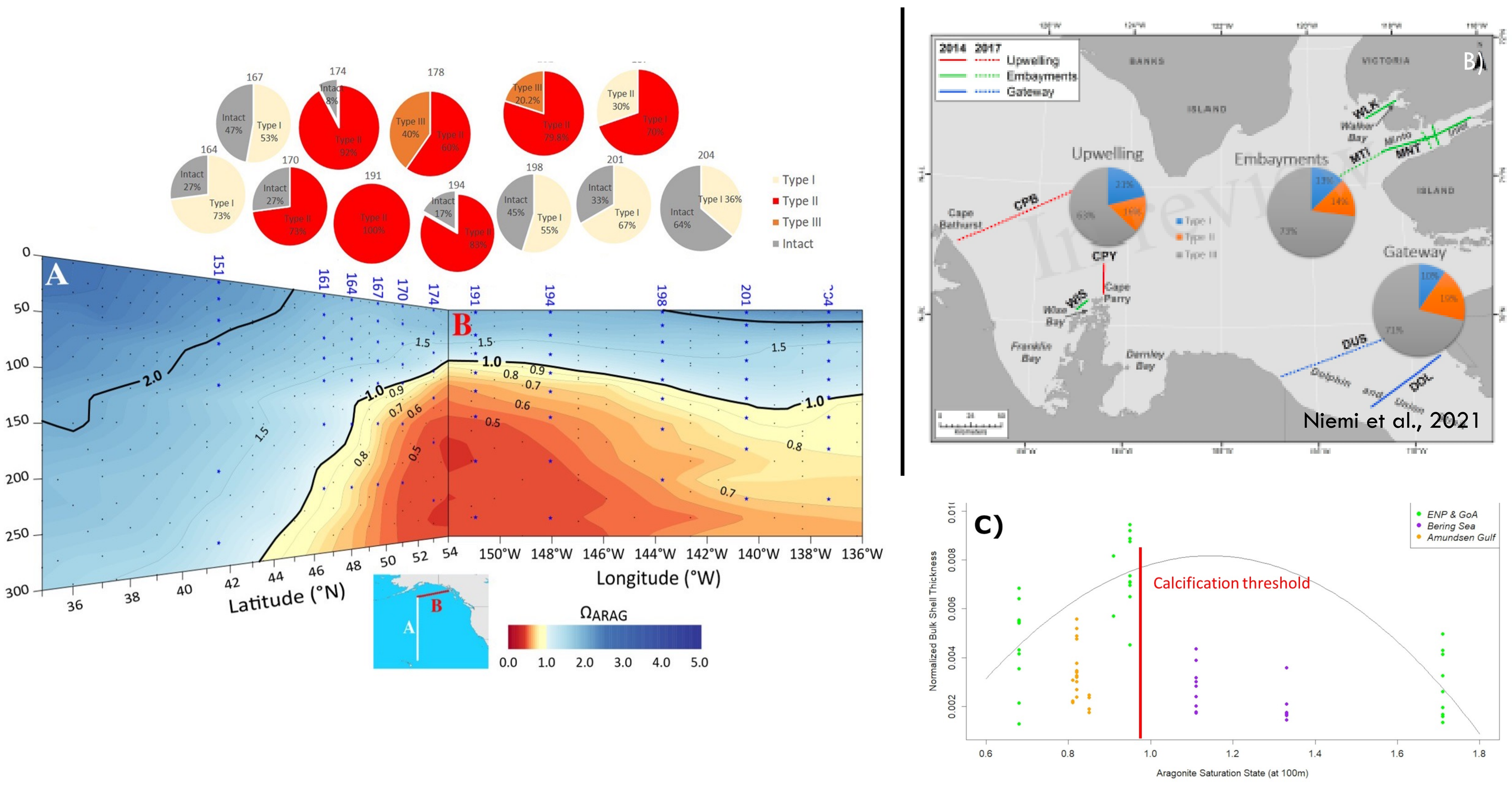


Figure 7. Average seasonal aragonite saturation state ($\Omega_{ar}$) across the upper 50 to 100 m in the GoA for June to August for 2013 (A) and 1980 (C), showing significant decrease in $\Omega_{ar}$ under current conditions. Solid black contour lines depict aragonite saturation state equal to 1 and 1.3. Model output is from the GOA-COBALT hindcast simulation described by Hauri et al. (2020).




## Pteropod Biomineralization across the Northern High Latitudes: Dissolution and Calcification

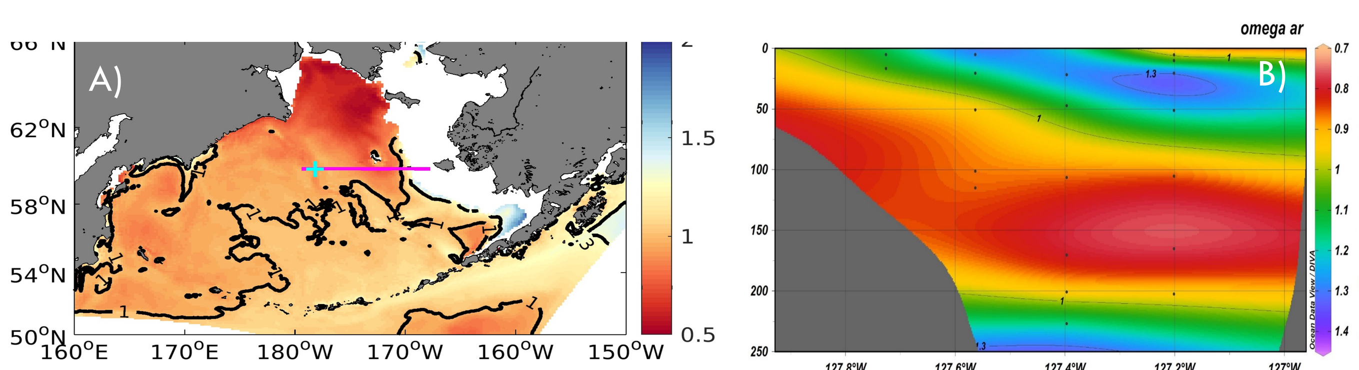
Figure 9: A) The depth of aragonite saturation state (Ωar; based on observational data) along two sections conducted on P16N cruise in the Eastern Pacific subpolar gyre and GoA with corresponding proportions of different types of pteropod shell dissolution. The severity of the dissolution increases with the shallowing of the Ωar. B) Extent of different types of shell dissolution across the Amundsen Sea, showing severe pteropod shell dissolution over the OA-exposed habitats (see Niemi et al., 2021). C) Normalized bulk shell thickness along the omega saturation state (ar) in three basins in *Limacina helicina pacifica*, showing decline in calcification related to reduced Ωar.




## OA Exposure in the Bering Asea and Amundsen Gulf

- **The exposure close or below the thresholds critical for the calcifiers**

Figure 8: Ωar across the upper 50 to 100 m in the Bering Sea for June to August (A) averaged over 2003-2012 (modeled data). Solid black contour lines depict aragonite saturation state equals 1. Model output is from the Bering10K hindcast simulation described by Pilcher et al. (2019). B) Transect plots of (Ωar) in the Amundsen Gulf in the Canadian Arctic sampled in August 2018. Transect extend across the mouth of the Gulf from Cape Bathurst (C), showing severe Ωar conditions.



## Pteropod adaptive capacity across the Northern High Latitudes: genetic structure and spatial connectivity

Figure 10: Minimum spanning network between 20 CO1 Haplotypes sequenced across 176 L. helicina morphotypes, sampled from the Eastern Pacific, GoA, Bering Sea and Amundsen Gulf. Haplotypes are joined by number of mutations (horizontal lines), circle sizes represent number of individuals representing each haplotype. The two morphotypes are represented in blue (*L. helicina helicina*) and green (*L. helicina pacifica*). (B) Distribution of the three most common COI haplotypes across sampling stations in the Eastern Pacific subpolar gyre, GoA, Bering Sea and the Amundsen Gulf. It is clear that there are no genetically distinct haplotypes. This lack of genetic structure across large scales indicates reduced potential for adaptive capacity through subspecies diversity. However, adaptive variation within species requires further investigation.

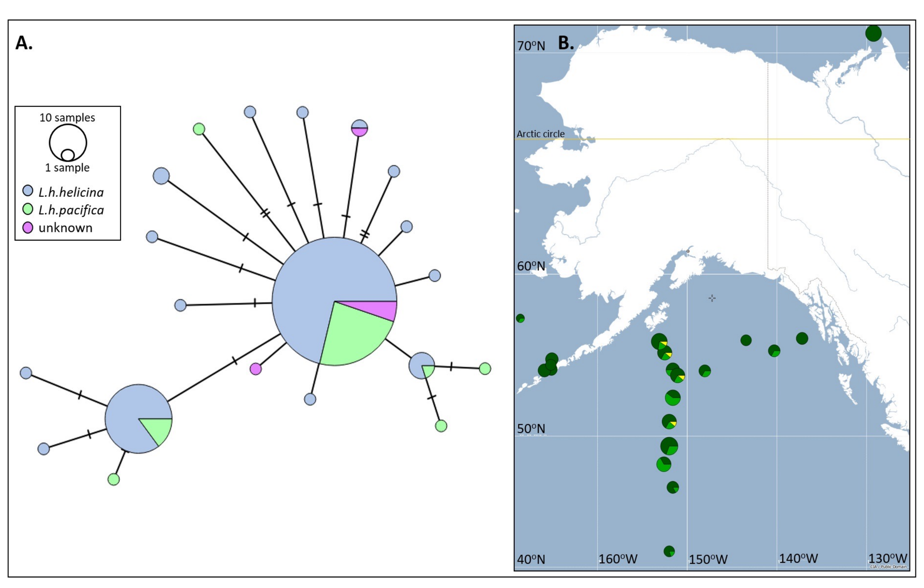
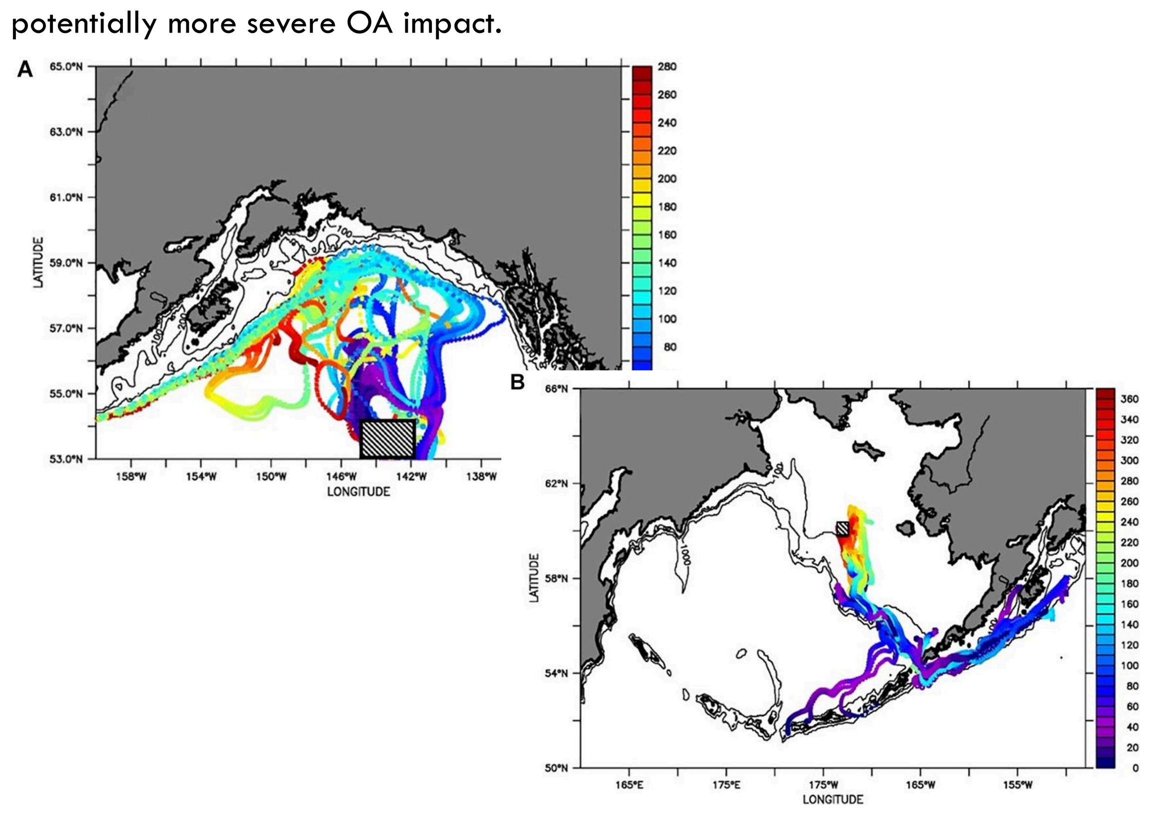


Figure 10: Particle tracking at (A) 200 m depth in the Eastern Pacific subpolar gyre for a time period of 8 months (280 days), and (B) at 50 m depth in the Bering Sea for the time period of 12 months (365 days). Vertical scale bar indicates (A) number of days in the forward tracked particles since their release near 53°N, 143°W on April 15, 2012; and for (B) days of the backward tracked particles using 60°N, 173°W as ending location on April 15, 2017 (with initial release in April 15, 2016). Blue colors indicate shorter, and red color indicate longer time intervals since release. There is a high level of spatial connectivity throughout their life history in the subpolar gyre, which can be a potential mitigation population strategy. However, the supply of early stage pteropods originates in the OA hotspot, counteracting this capacity. The connectivity in the Bergin Sea is much lower, indicating potentially more severe OA impact.



## Conclusions and Next Steps: Monitoring and Biological Pump

Comprehensive risk integration permits improved prediction of ecosystem change relevant to effective fisheries resource management. Pteropods are an excellent indicator supporting the integration of pteropods in future OA monitoring of ecosystem health with uses for various stakeholders and field programs.

Given the changes in pteropod shell building processes, reduced calcification and shell thickness, along with increased dissolution, and the fact that these regions are the habitats with one of the highest pteropod abundances on a global scale might imply potentially significant biogeochemical effects related to the biological pump. This might result in lower carbonate export fluxes over time, suggesting that an important component of the alkalinity change in the North Pacific may be the result of changes in pteropod production and dissolution. Moving forward into the future, the ecological and biogeochemical implications of these long-term changes will depend on multiple interacting processes, including the morphotype distribution, net shell calcification and dissolution, changes in the morphometrics, their abundance and phenology, which should be consistently monitored