The Importance of Environmental Exposure History in Forecasting Dungeness Crab Megalopae Occurrence Using J-SCOPE, a High-Resolution Model for the US Pacific Northwest

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Abstract

The Dungeness crab (Metacarcinus magister) fishery is one of the highest value fisheries in the US Pacific Northwest, but its catch size fluctuates widely across years. Although the underlying causes of this variability are not well understood, the abundance of M. magister megalopae has been linked to recruitment into the adult fishery four years later. These pelagic megalopae are exposed to a range of ocean conditions during their dispersal period, which may drive their occurrence patterns. Environmental exposure history has been found to be important for some pelagic organisms, so we hypothesized that inclusion of environmental exposure history would improve our ability to predict M. magister megalopae occurrence patterns compared to using 'in situ' conditions alone. We combined local observations of M. magister megalopae and regional simulations of ocean conditions to model megalopae occurrence using a generalized linear model (GLM) framework. The modeled ocean conditions were extracted from J-SCOPE, a high-resolution coupled physical-biogeochemical model. The analysis included variables from J-SCOPE identified in the literature as important for larval crab occurrence: temperature, salinity, dissolved oxygen concentration, nitrate concentration, phytoplankton concentration, aragonite and calcite saturation state, and pH. GLMs were developed with either in situ ocean conditions or environmental exposure histories generated using particle tracking experiments. We found that inclusion of exposure history improved the ability of the GLMs to predict megalopae occurrence. Of the five swimming behaviors used to simulate megalopae dispersal, several behaviors generated GLMs with superior fits to the observations, so a biological ensemble of these models was constructed. Our results highlight the importance of including exposure history in larval occurrence modeling and help provide a method for predicting pelagic megalopae occurrence. This work is a step towards developing a forecast product to support management of the fishery.

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Dungeness crab populations fluctuate and correlate to megalopae abundance

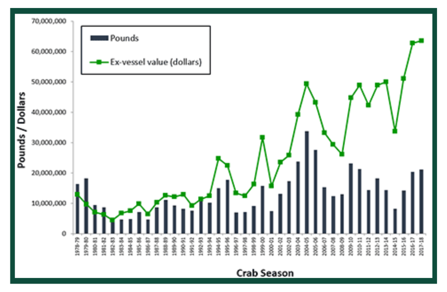


Figure 1. Oregon commercial Dungeness crab catch.[1]

The Dungeness crab fishery is one of the highest value fisheries in the US Pacific Northwest, but catch rates fluctuate interannually[1] (Fig. 1). Variable environmental conditions are hypothesized to be drivers, though precise mechanisms are not well understood. However, the abundance of the last larval stage, the megalopal stage, is correlated to the abundance of fishery catch in Oregon four years later[2] (Fig. 2).

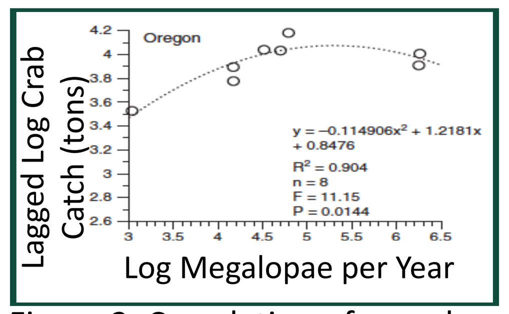


Figure 2. Correlation of megalopae abundance and adult catch.[2]

Hypothesis: Environmental exposure history of Dungeness megalopae is important for predicting their distribution. A statistical model for predicting megalopae occurrence that includes exposure history will out-perform a model that uses only *'in situ'* ocean conditions coincident with megalopae sampling.

Extracting megalopae habitat: '*in situ*' conditions versus simulated exposure history

J-SCOPE (JISAO's Seasonal Coastal Ocean Prediction of the Ecosystem[3,4]) produces historical ocean simulations ('hindcasts'):

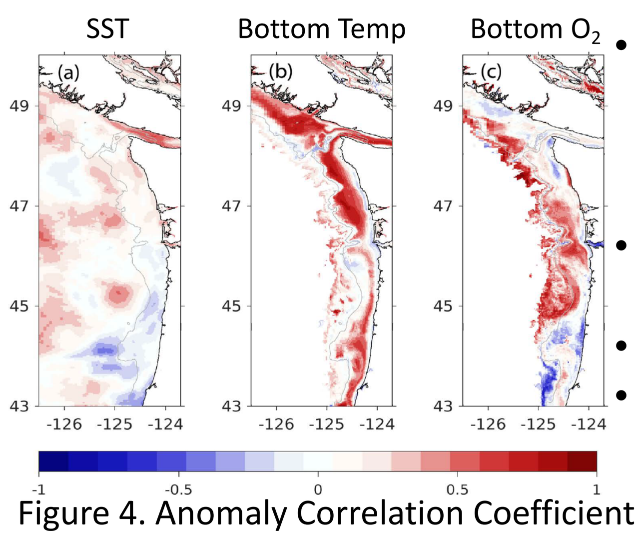
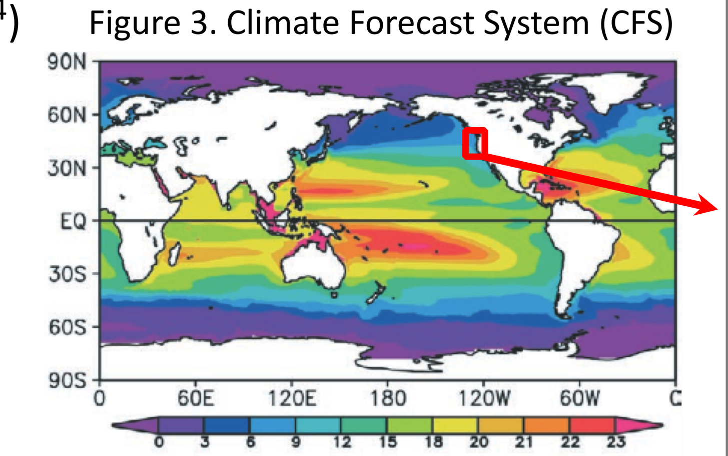
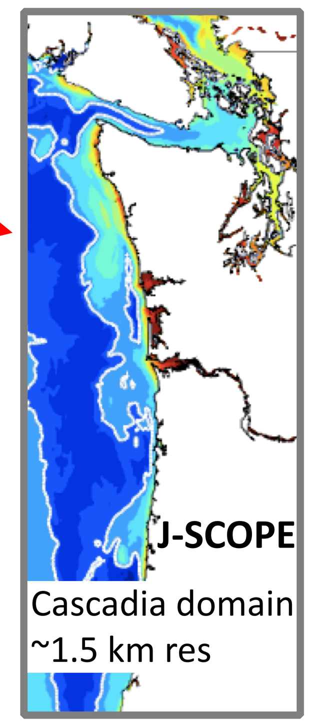


Figure 4. Anomaly Correlation Coefficient for seasonal forecast vs hindcast.[3,4]

- NOAA's CFS (coupled air/sea/land model; Fig. 3) provides boundary & atm forcing of ROMS-based regional model with biogeochemistry
- Modeled fields: T, S, O, NO_3, Chl a; derived variables: pH, Ω
- Model skill evaluated[3,4] (Fig. 4)
- Fields applied to habitat modeling: sardine[5], crab, pteropods[6], and hake[7]

Figure 3. Climate Forecast System (CFS)

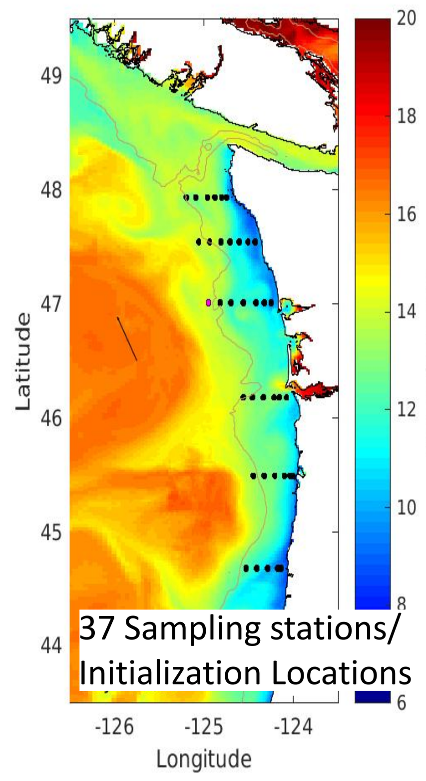




Check out our website: www.nanoos.org/products/j-scope

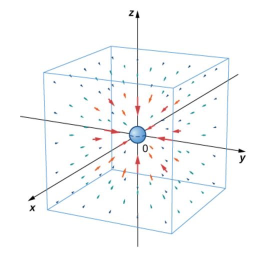
Figure 5. Megalopae sampling locations (37 stations, years 2009-2017) used for environmental conditions extraction (*in situ* model) and particle simulation initialization (exposure history models).

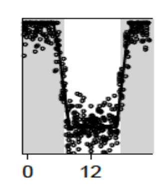
A. ***'in situ'* conditions extracted** from J-SCOPE hindcasts at times and locations where megalopae were sampled, averaged between 0-30m depth.



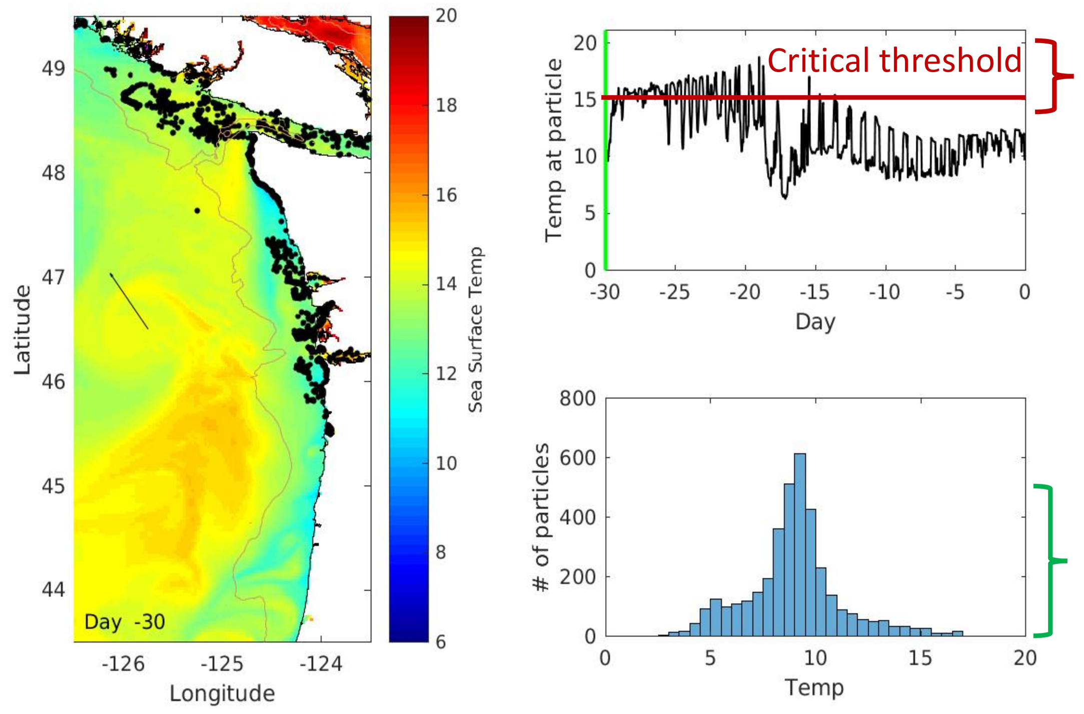
B. **Exposure history simulations**: particles initialized and tracked backward for 30 days (LTRANSv2[8])

- **Advection, random displacement,** and **environmental conditions** from JSCOPE hindcasts[3,4]
- **Larval Behavior**
  - Diel vertical migration (DVM)[9]
  - Surface-following
  - Passive
  - Combination





More information in Norton et al., 2020, *Front. Mar. Sci.* **7**:102.



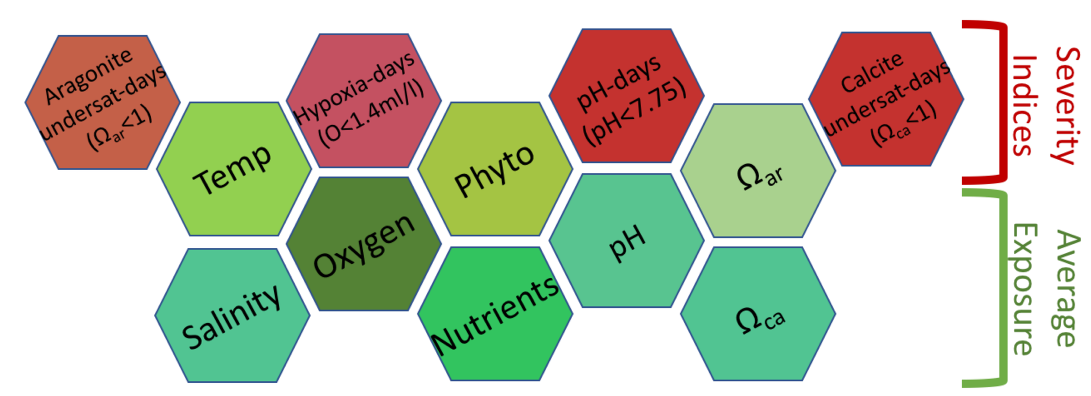


Figure 6. Two measures of environmental **exposure history calculated** along particle trajectories.[6,10]

Developing statistical models of megalopae occurrence

- Generalized linear models developed in Matlab ('stepwiseglm') using a logit link:

$$f(\mu) = log\left(\frac{\mu}{1-\mu}\right) \quad \text{with} \quad \mu = \frac{e^{X_b}}{1+e^{X_b}}$$

and X_b is a linear combination of predictor variables

- Model fit: Akaike Information Criterion corrected for small sample sizes (AICc)
- Model performance: Area Under the (ROC) Curve (AUC)

References: [1]https://www.dfw.state.or.us/MRP/shellfish/commercial/crab/landings.asp. [2]Shanks, A.L., 2013, *Fish. Oceanogr*. **22**:263-272 [3]Siedlecki et al., 2016, *Sci. Rep*. **6**: 27203. [4]http://www.nanoos.org /products/j-scope/home.php. [5]Kaplan et al., 2016, *Fish. Oceanogr*. **25**:15-27. [6]Bednarsek et al., 2017, *Prog. Oceanogr*. **145**:1-24. [7]Malick et al., (in prep). [8]Schlag, Z.R., North, E.W. 2012, LTRANSv2 User Gu ide, UMCES. [9]Hobbs, R.C., Botsford, L.W, 1992, *Mar. Biol*. **112**:417-428. 10Hauri et al., 2013, *Geophys. Res. Lett*. **40**:3424-3428.

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Behavior affects environmental exposure history

Behavior characterized larval depth habitat (Fig. 5), which determined environmental exposure history (Fig. 6). Particles with similar depth habitats experienced similar environmental conditions (e.g., EH-DVM30/EH-P1/EH-D15P; EH-DVM60/EH-P30), while particles with unique depth habitats experienced unique environmental conditions (e.g., EH-S1).

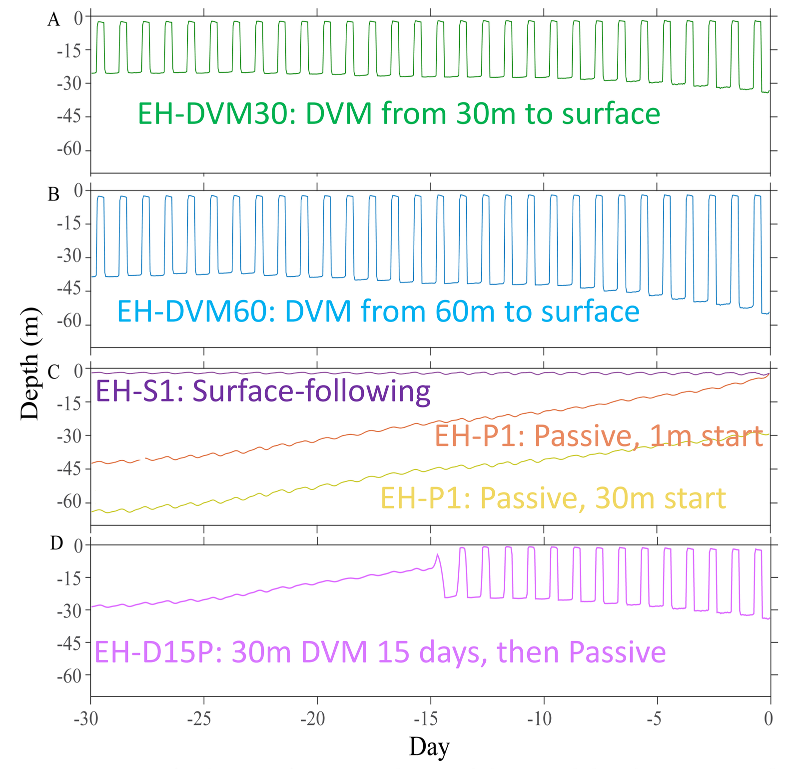
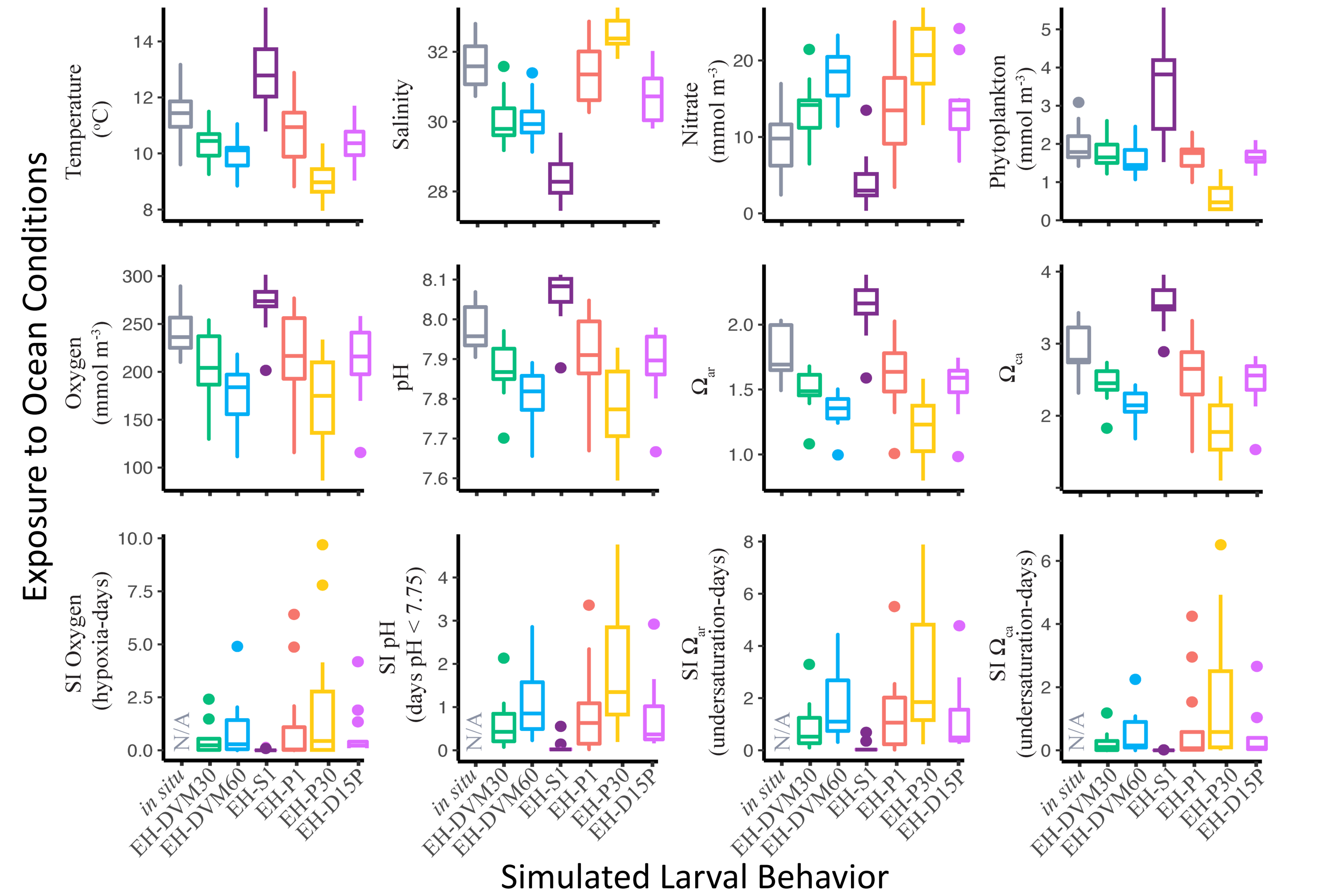


Figure 7. (Above) Simulated larval behaviors for exposure history experiments.

Figure 8. (Right) Exposure history differed among dispersal behaviors.



Exposure history improves model fit and performance compared to *in situ* model

Table 1. Generalized linear models (GLMs) for *in situ* and exposure history (EH) behaviors. All exposure history GLMs had better fit (i.e., lower AICc) and performance (i.e., higher AUC) than the *in situ* model, regardless of which behavior was simulated. Predictor variables varied among models; significant predictors in **bold**, direction of correlation indicated (i.e., positive (+) or negative (-)).

Experiment	Predictors (bold p<0.05)	ΔAICc	in-sample AUC
in situ	**-N**	11.8	0.602
EH-DVM30	**+O**	4.7	0.644
EH-DVM60	**+S, +O**	5.3	0.650
EH-S1	-T, **-N, -**SI Ωca	7.9	0.645
EH-P1	**+S**, **+O**	0.0	0.658
EH-P30	+P, **-SI Ωar**	1.9	0.625
EH-D15P	**+pH**	1.7	0.657

Model fit metric: lower is better

Model performance metric: higher is better

in situ model had worst fit and performance of all models

Good model fit and performance from **several exposure history models**

Biological ensemble skillfully predicts megalopae occurrence

Table 2. The best models (see Table 1) were selected to compose a **biological ensemble**. Model performance (AUC) is shown for an out-of-sample year (2017) for each model individually and for the biological ensemble as a whole. An AUC of 0.94 indicates that probably of megalopae occurrence was correctly ranked at 94% of the stations.

Experiment	Equation (bold p<0.05)	2017 AUC
EH-DVM30	-3.01 + 0.109***O**	0.814
EH-DVM60	-6.42 + 0.132***S** + 0.00988***O**	0.936
EH-S1	1.77 - 0.157*T - 0.0994***N** - 79.5*(SI Ωca)	0.757
EH-P1	-11.0 + 0.248***S** + 0.0111***O**	0.914
EH-D15P	-34.9 + 4.32***pH**	0.779
Biological Ensemble:		**0.943**

AUC > 0.5 is skillful

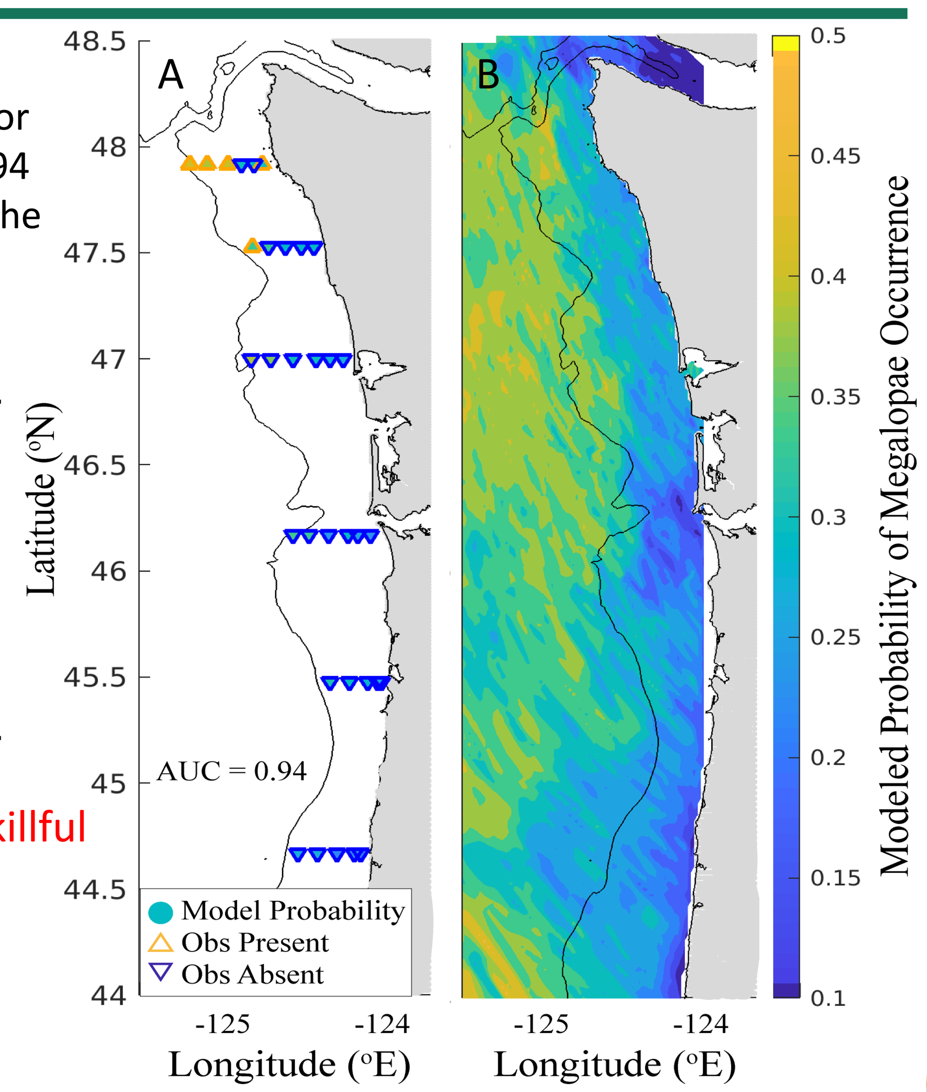


Figure 9. (Right) The biological ensemble predicting (A) megalopae occurrence compared to observed occurrence, and (B) habitat probabilities throughout the J-SCOPE domain, both for the out-of-sample test year 2017.

Summary and Next Steps

- **Prediction of megalopae habitat is possible** using a combination of tools: ocean condition modeling, particle tracking, and statistical modeling
- **Exposure history improves our ability to model occurrence** of Dungeness megalopae
- **Simulated behavior affects environmental exposure** likely by driving differences in depth habitat
- **A biological ensemble of models provided the most skillful prediction** of megalopae habitat
- Next steps: Build on this occurrence model to predict megalopae *abundance*