Streamlined Pacific Cod Analyses & Figures

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Contents

Pacific Cod (Pac cod):

Loading Data:

Pacific cod: larval data only are included for this species. Pac cod spawn in March and April under the sea ice, live roughly 13 years, and transform to juveniles at standard lengths between 25 and 35 mm.

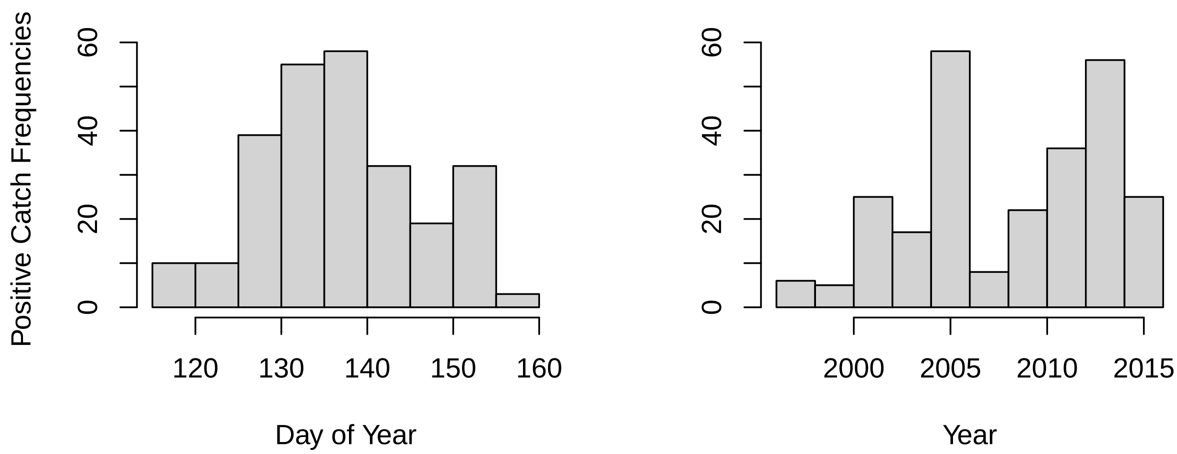
These data have been trimmed. The larval data are constrained to depths between 40 and 250 meters and to latitudes south of 62 degrees north. Larvae are linked to CTD-derived, *in situ* temperature and salinity measurements and constrained to days of year between 99 and 160.

Descriptive Information:

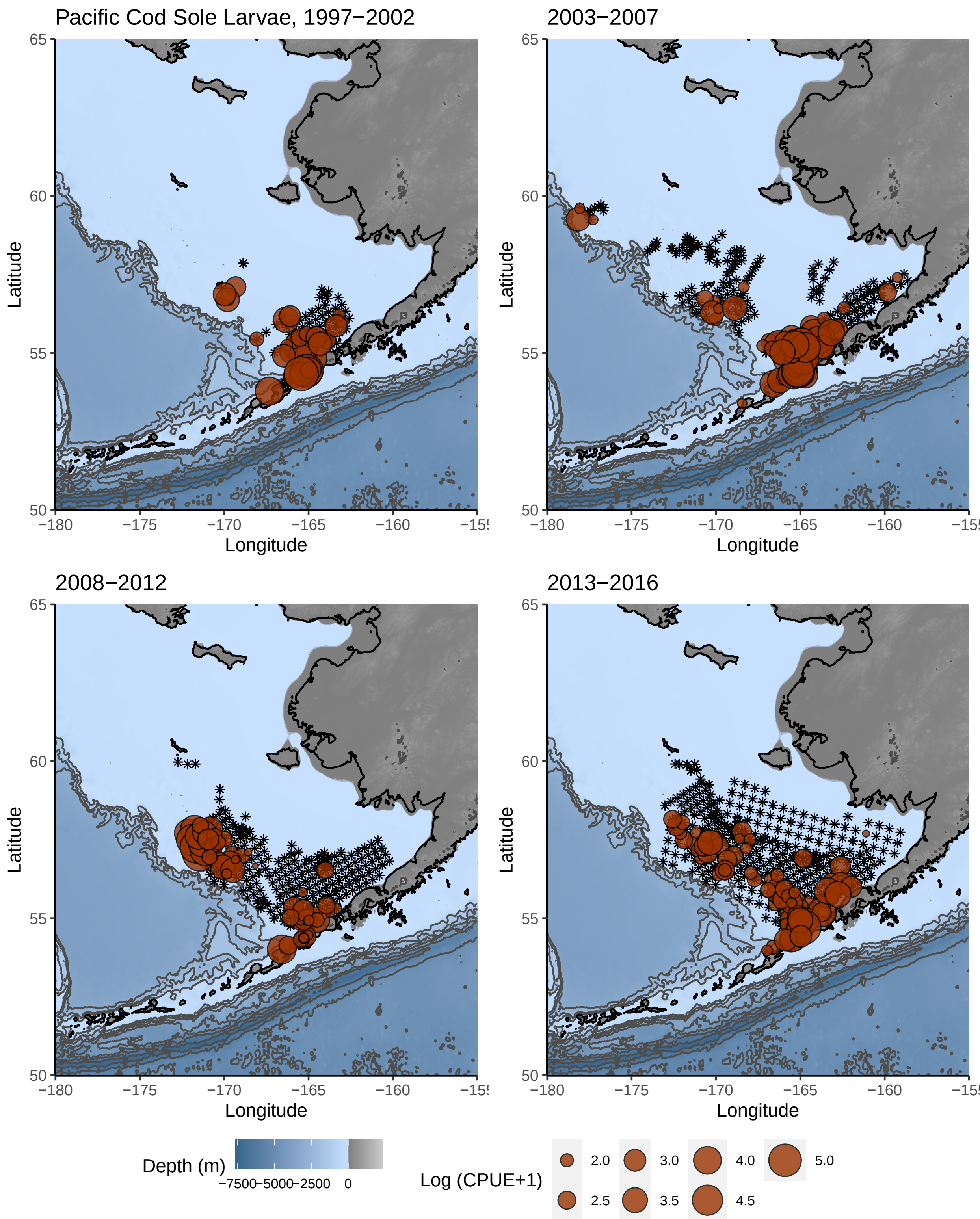
Table 1: Descriptive Metrics for Pac Cod Larval Data

Lat Range	Lon Range	Day of Year Range	Bottom Depth Range
53.4-60	-178.2 to -158.6	100-159	41-232

The following two plots show *the day of year distribution for positive Pac cod larval catch* (left) and *the year distribution for positive Pac cod larval catch* (right).


Positive Catch Frequencies
0
20
40
60
120
130
140
150
160
Day of Year
2000
2005
2010
2015
Year

The following plots show Pacific cod larval catch distributions (Catch per unit effort, or per 10m^2) across five year increments from 1997 to 2016



Larval Generalized Additive Models:

Now we'll move into the GAMs. The following code *is only necessary if the data were re-trimmed and new GAMs need to be run.* In this case, modify markdown document such that "{eval = TRUE}". The other model figures are marked as "eval = FALSE" if they, as of the last model run, do not produce the best model results. **Make sure to save the new models as RDS objects.**

Pac cod larvae were best explained by the bivariate salinity-temperature model, in which the spatial and temporal distribution of larvae were modelled in association with a smooth containing *in situ* salinity-temperature data.

We begin with the base larval model:

```
lv.base<-readRDS("./GAM Models/pc_larvae_base.rds")
summary(lv.base)
```

```
##
## Family: Tweedie(p=1.99)
## Link function: log
##
## Formula:
## (Cper10m2 + 1) ~ factor(year) + s(doy, k = 7) + s(lon, lat) +
##     s(bottom_depth, k = 5)
##
## Parametric coefficients:
##                  Estimate Std. Error t value Pr(>|t|)
## (Intercept)       2.04070    0.24120   8.461  < 2e-16 ***
## factor(year)1998 -2.74255    0.79055  -3.469 0.000539 ***
## factor(year)1999 -1.60274    0.44936  -3.567 0.000375 ***
## factor(year)2000 -0.34340    0.36565  -0.939 0.347825
## factor(year)2002 -0.45637    0.28200  -1.618 0.105832
## factor(year)2003  0.05707    0.29787   0.192 0.848092
## factor(year)2005  0.76069    0.27020   2.815 0.004948 **
## factor(year)2006 -0.89549    0.26542  -3.374 0.000763 ***
## factor(year)2007 -0.95460    0.29112  -3.279 0.001069 **
## factor(year)2008 -1.48808    0.37718  -3.945 8.40e-05 ***
## factor(year)2009 -1.26863    0.26901  -4.716 2.67e-06 ***
## factor(year)2010 -1.79217    0.26173  -6.847 1.16e-11 ***
## factor(year)2011 -1.10303    0.36171  -3.050 0.002339 **
## factor(year)2012 -1.04801    0.25663  -4.084 4.70e-05 ***
## factor(year)2013 -1.34211    0.31357  -4.280 2.01e-05 ***
## factor(year)2014 -1.13162    0.25758  -4.393 1.21e-05 ***
## factor(year)2015 -0.59351    0.32136  -1.847 0.064997 .
## factor(year)2016 -1.06127    0.25806  -4.113 4.16e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                    edf Ref.df      F  p-value
## s(doy)           5.446  5.842  7.598  < 2e-16 ***
## s(lon,lat)      25.516 28.228 36.425  < 2e-16 ***
## s(bottom_depth)  3.376  3.766 10.599 1.74e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
```

```
## R-sq.(adj) =  0.409   Deviance explained = 66.8%
## -REML = 2904.5  Scale est. = 0.97973   n = 1341
```

```
AIC(lv.base)
```

```
## [1] 5757.555
```

Then additive temperature and salinity, in individual additive terms. This is the second-best performing model.

```
lv.temp.sal<-readRDS("./GAM Models/pc_larvae_addtempsal.rds")
summary(lv.temp.sal)
```

```
##
## Family: Tweedie(p=1.99)
## Link function: log
##
## Formula:
## (Cper10m2 + 1) ~ factor(year) + s(doy, k = 7) + s(lon, lat) +
##     s(bottom_depth, k = 5) + s(temperature) + s(salinity)
##
## Parametric coefficients:
##                   Estimate Std. Error t value Pr(>|t|)
## (Intercept)         2.0903     0.2452   8.525  < 2e-16 ***
## factor(year)1998  -2.8428     0.7818  -3.636 0.000288 ***
## factor(year)1999  -1.6629     0.4533  -3.669 0.000254 ***
## factor(year)2000  -0.3168     0.3683  -0.860 0.389891
## factor(year)2002  -0.1301     0.3026  -0.430 0.667216
## factor(year)2003   0.1741     0.3119   0.558 0.576830
## factor(year)2005   0.8696     0.2979   2.919 0.003571 **
## factor(year)2006  -1.0685     0.2717  -3.933 8.84e-05 ***
## factor(year)2007  -1.2128     0.2980  -4.070 4.99e-05 ***
## factor(year)2008  -1.6331     0.3966  -4.118 4.07e-05 ***
## factor(year)2009  -1.5123     0.2745  -5.509 4.36e-08 ***
## factor(year)2010  -2.0776     0.2665  -7.795 1.33e-14 ***
## factor(year)2011  -1.0191     0.3702  -2.753 0.005988 **
## factor(year)2012  -1.2640     0.2829  -4.468 8.59e-06 ***
## factor(year)2013  -1.5218     0.3286  -4.632 4.00e-06 ***
## factor(year)2014  -1.0425     0.2753  -3.787 0.000160 ***
## factor(year)2015  -0.8572     0.3263  -2.627 0.008709 **
## factor(year)2016  -1.1057     0.3149  -3.511 0.000462 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                    edf Ref.df      F  p-value
## s(doy)           5.326  5.776  6.120 1.36e-05 ***
## s(lon,lat)      25.208 28.085 31.661  < 2e-16 ***
## s(bottom_depth)  2.892  3.392  8.500 1.36e-05 ***
## s(temperature)   7.039  8.144  3.253  0.00105 **
## s(salinity)      4.247  5.359  5.696 3.23e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
##
## R-sq.(adj) =  0.409   Deviance explained =   68%
## -REML =   2894  Scale est. = 0.95462   n = 1341
```

```
AIC(lv.temp.sal)
```

```
## [1] 5728.172
```

And finally, the best performing model: the bivariate salinity-temperature additive term:

```
lv.2d<-readRDS("./GAM Models/pc_larvae_2d.rds")
summary(lv.2d)
```

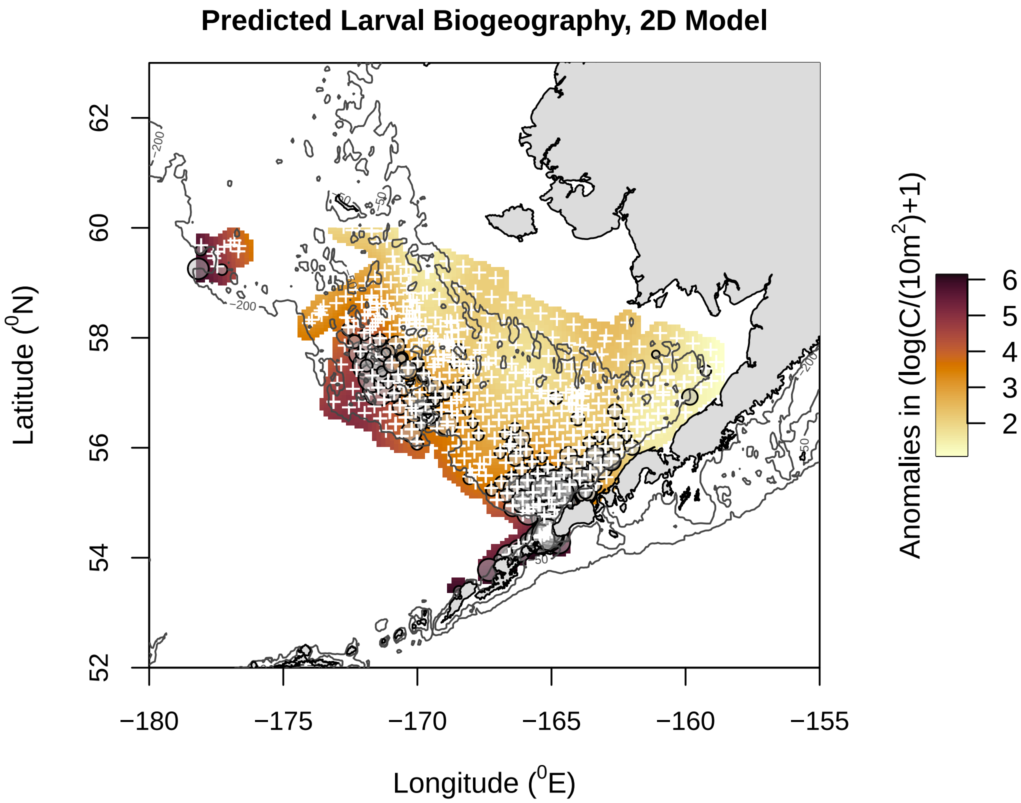
```
##
## Family: Tweedie(p=1.99)
## Link function: log
##
## Formula:
## (Cper10m2 + 1) ~ factor(year) + s(lon, lat) + s(doy, k = 7) +
##     s(bottom_depth) + te(salinity, temperature)
##
## Parametric coefficients:
##                   Estimate Std. Error t value Pr(>|t|)
## (Intercept)         2.0879     0.2436   8.570  < 2e-16 ***
## factor(year)1998  -2.3098     0.7784  -2.967 0.003061 **
## factor(year)1999  -1.4926     0.4467  -3.341 0.000858 ***
## factor(year)2000  -0.1195     0.3629  -0.329 0.742046
## factor(year)2002  -0.2172     0.2881  -0.754 0.450934
## factor(year)2003   0.1298     0.3109   0.418 0.676293
## factor(year)2005   0.8371     0.2899   2.887 0.003951 **
## factor(year)2006  -0.8527     0.2723  -3.132 0.001777 **
## factor(year)2007  -1.1480     0.2989  -3.840 0.000129 ***
## factor(year)2008  -1.5688     0.3966  -3.955 8.07e-05 ***
## factor(year)2009  -1.2820     0.2722  -4.709 2.76e-06 ***
## factor(year)2010  -1.7863     0.2622  -6.814 1.46e-11 ***
## factor(year)2011  -1.0594     0.3696  -2.866 0.004223 **
## factor(year)2012  -1.0463     0.2795  -3.744 0.000189 ***
## factor(year)2013  -1.4455     0.3362  -4.299 1.85e-05 ***
## factor(year)2014  -1.3757     0.2737  -5.026 5.72e-07 ***
## factor(year)2015  -0.9187     0.3307  -2.778 0.005554 **
## factor(year)2016  -1.4635     0.3100  -4.720 2.61e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                              edf Ref.df      F  p-value
## s(lon,lat)                24.591 27.832 29.922  < 2e-16 ***
## s(doy)                     5.362  5.797  6.445 1.12e-05 ***
## s(bottom_depth)            1.002  1.003 30.235  < 2e-16 ***
## te(salinity,temperature) 16.809 18.822  7.831  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

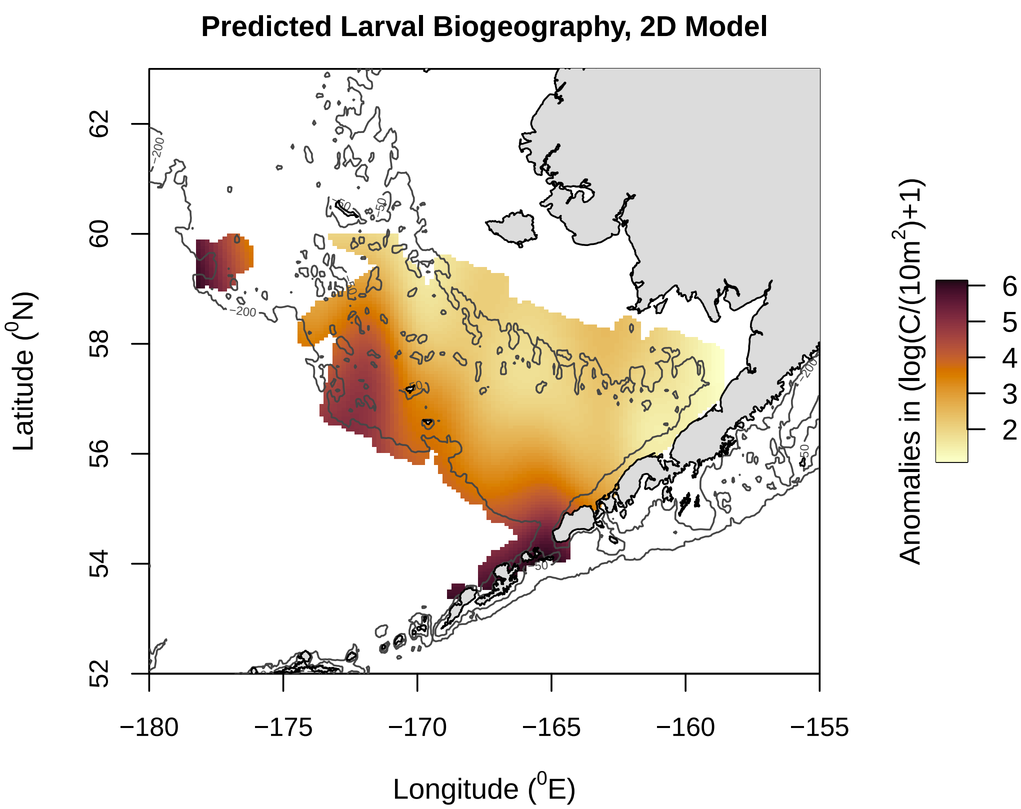
```
##
## R-sq.(adj) =  0.444   Deviance explained = 69.8%
## -REML =   2852  Scale est. = 0.90782   n = 1341
```

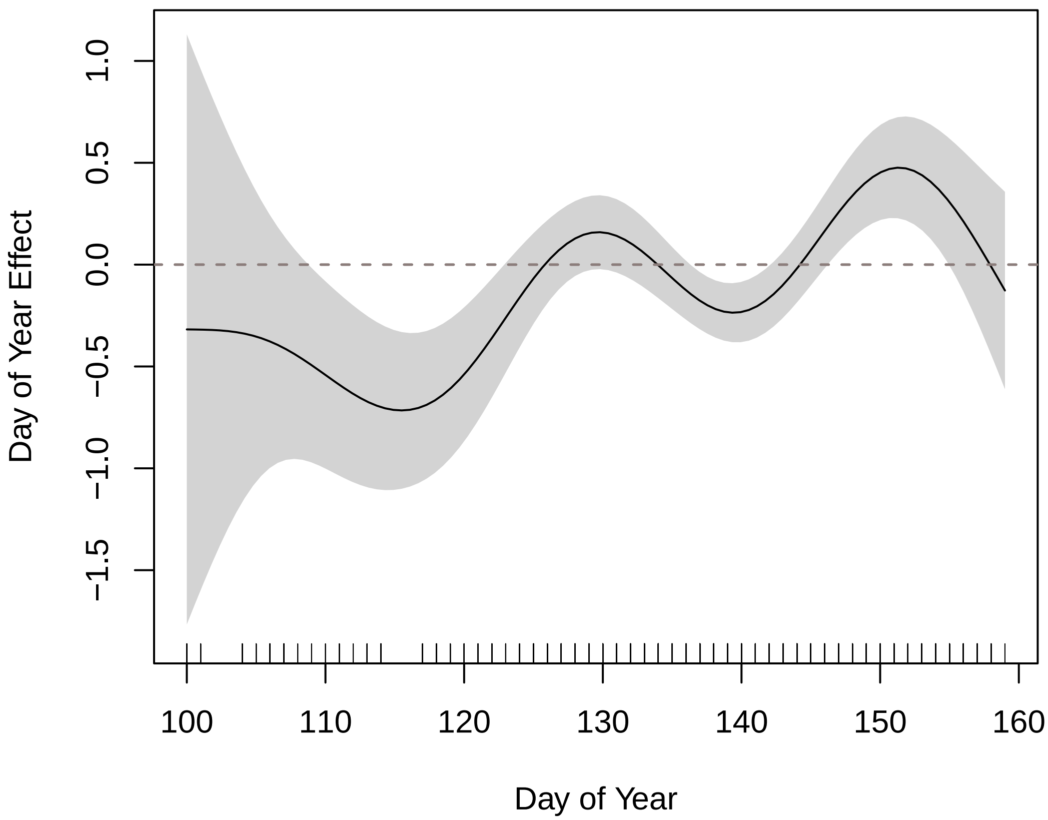
```
AIC(lv.2d)
```

```
## [1] 5638.339
```

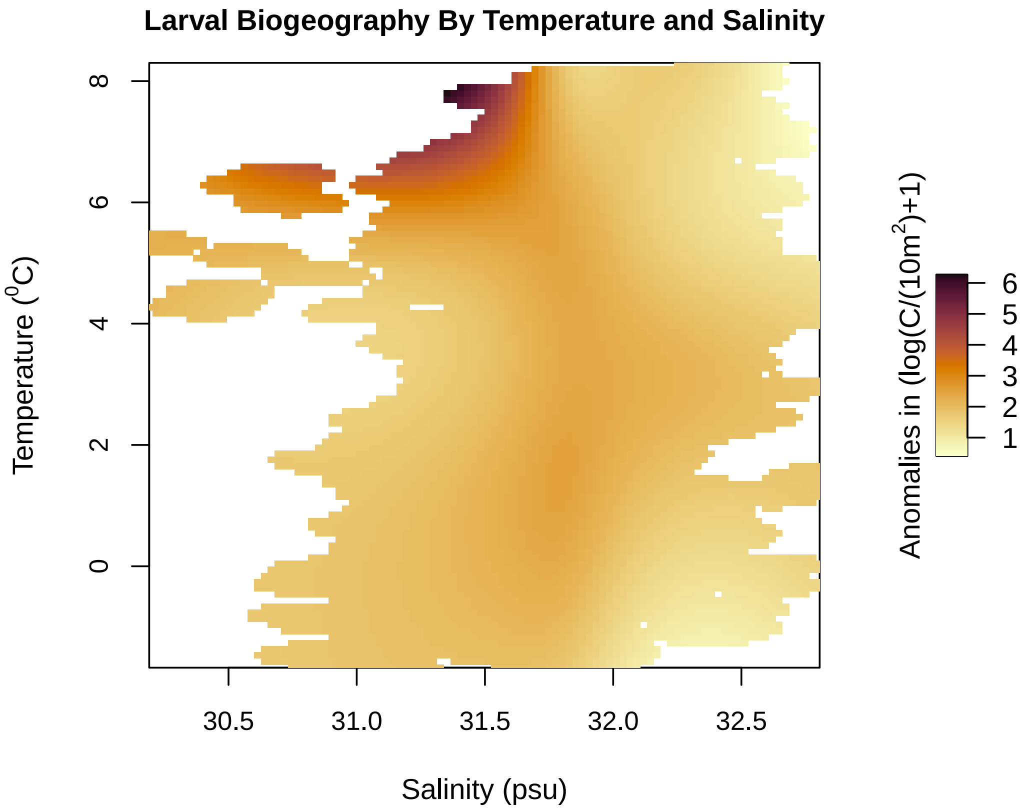
The following plot is the predicted Pac cod larval biogeography based on the best performing model, the bivariate salinity-temperature GAM. Observations (log transformed, n+1) are shown as well.

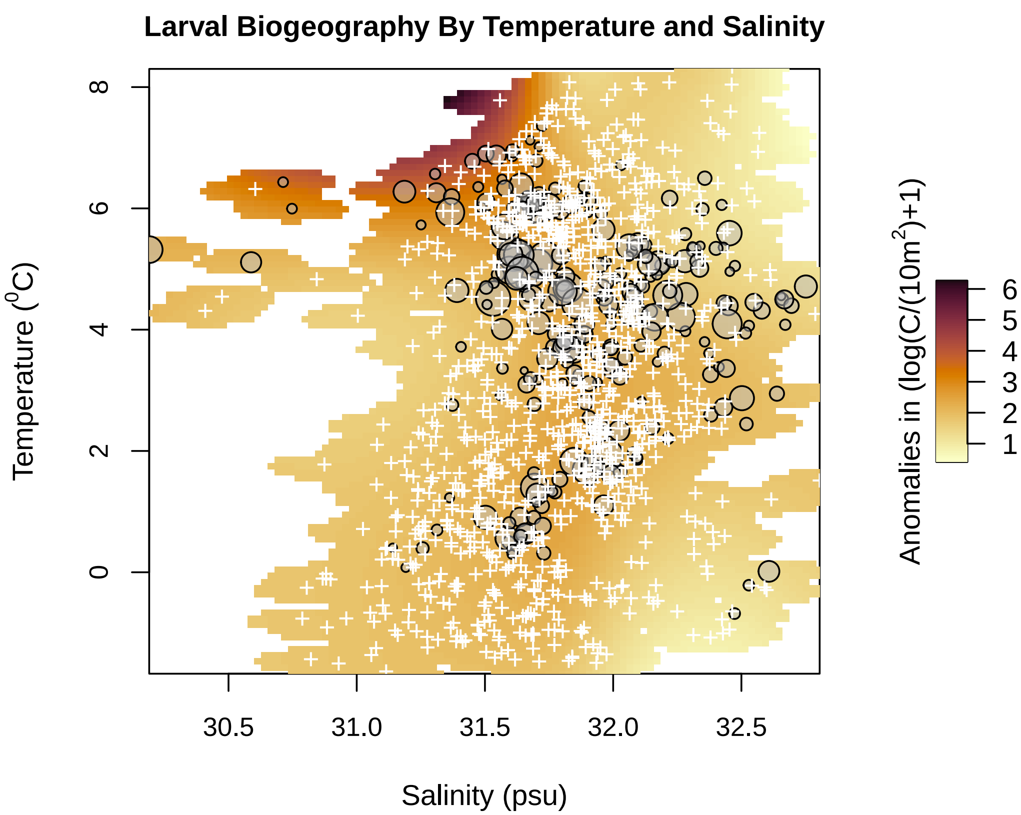

Predicted Larval Biogeography, 2D Model
Latitude (0N)
Longitude (0E)
Anomalies in (log(C/(10m2)+1)
-180
-175
-170
-165
-160
-155
52
54
56
58
60
62
2
3
4
5
6
-200
-50


Predicted Larval Biogeography, 2D Model
Latitude (0N)
Longitude (0E)
Anomalies in (log(C/(10m2)+1)
-180
-175
-170
-165
-160
-155
52
54
56
58
60
62
2
3
4
5
6
-200
-50



With this bivariate model, we can also calculate the predicted anomalous larval catch (more or less than expected) on a salinity-temperature plot. This figure shows that prediction, with observed larval catch (log(n=1)) overlaid.


Larval Biogeography By Temperature and Salinity
Temperature (^{0}C)
Salinity (psu)
30.5
31.0
31.5
32.0
32.5
0
2
4
6
8
Anomalies in (log(C/(10m^2)+1)
1
2
3
4
5
6


Larval Biogeography By Temperature and Salinity
Temperature (^{0}C)
Salinity (psu)
30.5
31.0
31.5
32.0
32.5
0
2
4
6
8
Anomalies in (log(C/(10m^2)+1)
1
2
3
4
5
6

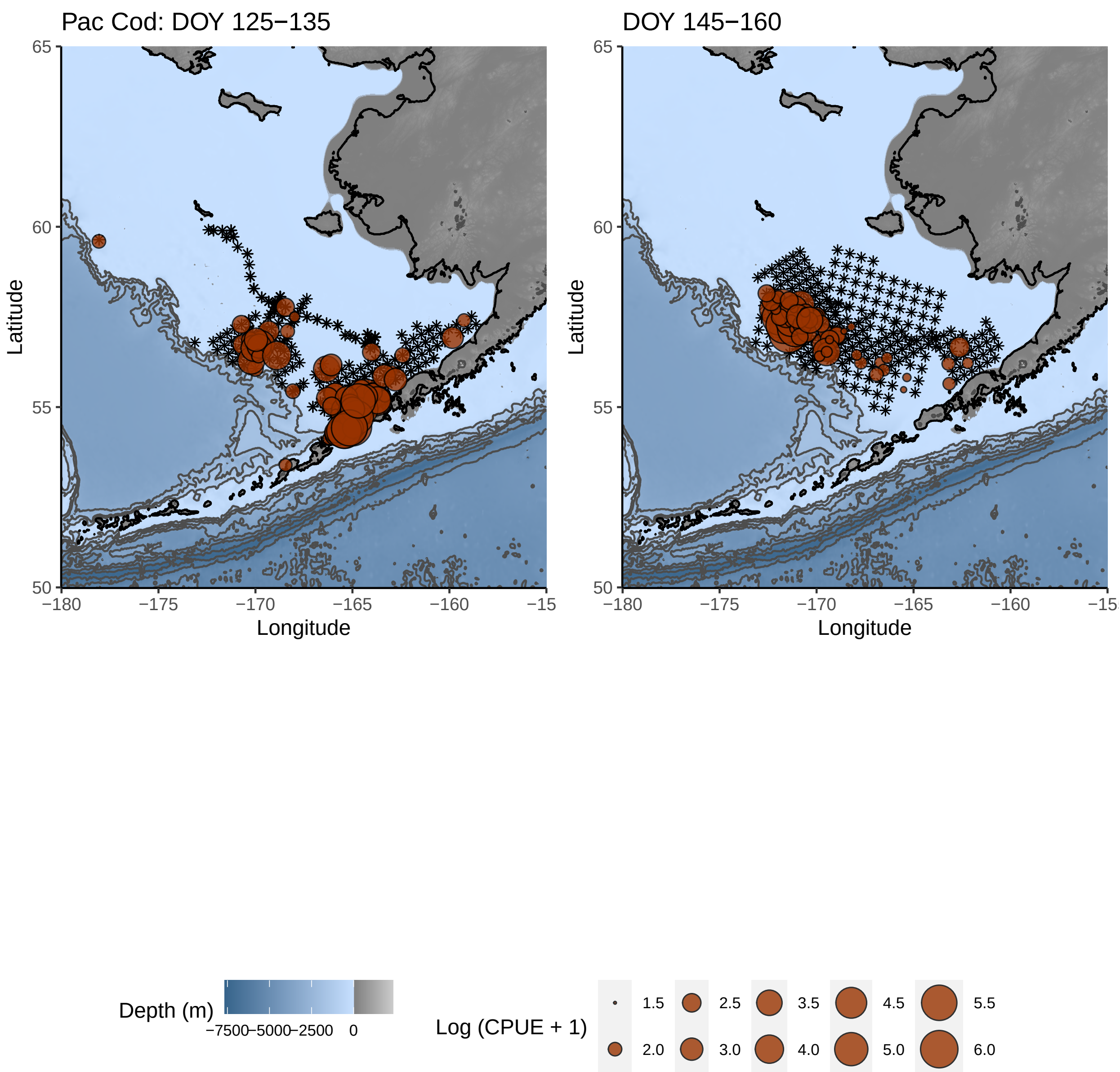
To again share the improvements of the best performing models from the base models, we can look at the AIC division produces.

Table 2: Model Power through AIC Comparisons, Pacific Cod

	Best Divided By Base	Best Divided By Second Best
Larvae	0.979294	0.9843173

Appendix

The following plots investigate the diverging phenological peaks in larval density in order to evaluate whether different peaks correlate to different spatial areas in the BS.



Pac Cod: DOY 125−135
DOY 145−160
Latitude
Longitude
65
60
55
50
−180
−175
−170
−165
−160
Depth (m)
−7500
−5000
−2500
0
Log (CPUE + 1)
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0