**Differences between surface and bottom temperatures in the upper San Francisco Estuary: implications for Delta Smelt temperature refugia**

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1. **Introduction**
   1. Water temperature is a key variable controlling the physiology and behavior of fishes
      1. There are many examples of fish exploiting vertical differences in water temperature to optimize bioenergetics.
      2. Also many examples of fish using vertical and horizontal differences to avoid stressful or potentially lethal conditions
   2. Climate change is disrupting many of these behaviors through modification of the thermal environment
      1. Ocean species have been moving to higher latitudes as the oceans warm.
      2. Freshwater stream-dwelling species have been (or are expected to) move to higher elevations as lower elevations warm.
      3. However, some species do not have these options because of limited connectivity for dispersal (e.g., spring and lake dwelling endemics, estuarine specialized species incapable of dispersing), or migratory species that must move from one habitat to another
   3. Evidence suggests that water temperatures are already reaching stressful levels for thermally-sensitive fishes in some areas of the upper SFE and that climate change will make the situation worse (FLOAT-MAST in review, Brown et al. 2013, 2016).
      1. Although modeling studies (Vroom et al. 2017) and observational studies (Brown et al. 2016) suggest that significant vertical differences in water temperature are likely uncommon in the upper SFE, the hypothesis that vertical differences in water temperature provide significant thermal refugia for aquatic species has not been well tested.
   4. The objective of this study is to evaluate existing discrete and continuous (e.g., hourly) records of water temperature to determine the timing, frequency, duration and magnitude of differences between near-surface and near bottom water temperature.
      1. We then interpret these differences with respect to fish physiology and ecology. As test cases we consider two species of management concern in the upper SFE, Delta Smelt and Chinook Salmon.
         1. Delta Smelt is an example of an estuarine species, endemic to SFE, with limited ability to disperse to new estuaries
         2. Chinook Salmon is a migratory species that must pass through the Delta for adult migration to spawning streams and juvenile migration to the ocean.
2. **Methods**
   1. Discrete data
      1. Consolidated data base
      2. Subset of studies collecting surface and bottom temperatures
         1. Spatial distribution and sampling frequency
      3. Modeling framework
         1. Maximum difference
         2. Maximum difference in relation to surface temp
   2. Continuous data
      1. Locations of 4 sites and length of record
         1. Describe the key differences among stations (e.g., depth, salinity, etc.)
      2. Analysis or modeling framework
         1. Maximum difference per day
         2. Time of maximum difference
         3. Maximum difference in relation to surface temp
3. **Results**
   1. Discrete data
      1. Maximum difference (summary of surface and bottom temperature)
         1. Min: 5.6, 1st Q: 14.8, Median: 19.3, Mean: 18.2, 3rd Q: 21.6, Max: 29.4
         2. Min: 5.6, 1st Q: 14.7, Median: 19.1, Mean: 18, 3rd Q: 21.4, Max: 29.9
      2. Maximum difference in relation to surface temp
         1. Min: -5.76, 1st Q: -0.3, Median: -0.1, Mean: -0.18, 3rd Q: 0, Max: 6.56
      3. Is the maximum difference predictable (assessed by model performance?)
         1. See Table
   2. Continuous data
      1. Maximum difference
      2. Maximum difference in relation to surface temp
      3. Is the maximum difference predictable
4. Discussion
   1. What factors appear to favor a large difference?
   2. Are differences predictable in time/space?
   3. How do surface-bottom differences align with time periods when water temperatures are potentially stressful to temperature sensitive fishes.
      1. If differences occur when temperatures are stressful then this may be an important phenomenon that deserves more study
         1. May still be useful bioenergetically
      2. If the differences are relatively ephemeral (i.e., unpredictable/random) then they are likely not useful as far as general life history adaptation but may be useful as a strategy of last resort.
      3. It isn’t immediately obvious that management actions could be used to manipulate this phenomenon.

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| --- | --- | --- | --- | --- | --- | --- | --- |
| Model number | Model justification | Code | Adjusted R2 | AICc | 5-fold RMSE | Pearson correlation (*r*) between cross-val predicted data and observations | Proportion of correct sign (+/-) predicted in testing data (0 removed) |
| 1 | Stratification varies by space and time and mostly at a seasonal level with little interannual differences | bam(Temperature\_difference ~ te(x,y,Julian\_day\_s, d=c(2,1), bs=c("tp","cc"), k=c(40,5)),  data = temp\_dataset, method="fREML", discrete=T, nthreads=3) | 0.22 | 10801.53 | 0.4202 | 0.477 | 0.766 |
| 2 | Stratification varies by space, but not season. However, it is affected by how hot or cold the day is. | bam(Temperature\_difference ~ te(x,y,Temperature\_anomaly, d=c(2,1), bs=c("tp","tp"), k=c(40,7)),  data = temp\_dataset, method="fREML", discrete=T, nthreads=3) | 0.3 | 9807.957 | 0.3973 | 0.556 | 0.751 |
| 3 | Stratification varies by space and time, as well as how hot or cold the surface temperature is | bam(Temperature\_difference ~ te(x,y,Julian\_day\_s,Temperature\_anomaly, d=c(2,1,1), bs=c("tp","cc", "tp"), k=c(40,5,7)),  data = temp\_dataset, method="fREML", discrete=T, nthreads=3) | 0.41 | 8382.725 | 0.3606 | 0.657 | 0.775 |
| 4 | Stratification varies by space and season, as well as water year type (i.e. flow) | bam(Temperature\_difference ~ te(x,y,Julian\_day\_s, d=c(2,1), bs=c("tp","cc"), k=c(40,5), by=WaterYear)+WaterYear,  data = temp\_dataset, method="fREML", discrete=T, nthreads=3) | 0.268 | 10548.09 | 0.4201 | 0.477 | 0.766 |
| 5 | Same as model 3, but with soap-film smoother and Delta outline boundaries. Prevent bleeding from Cache Slough Complex into Suisun Marsh and vice versa | bam(Temperature\_difference ~ te(x, y,Julian\_day\_s,Temperature\_anomaly, d=c(2,1,1), bs=c("sf", "cc","tp"), k=c(40,5,7),xt = list(list(bnd = border.aut,nmax=1500),NULL,NULL))+  te(x, y, Julian\_day\_s,Temperature\_anomaly, d=c(2,1,1), bs=c("sw", "tp","cc"), k=c(40,5,7),xt = list(list(bnd = border.aut,nmax=1500),NULL,NULL)),  data = temp\_dataset, method="fREML", discrete=T, nthreads=3, knots =knots\_grid) | 0.413 | 8345.612 | 0.3601 | 0.658 | 0.774 |