Assessing phenological shifts in zooplankton and forage fishes with dynamic linear models

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SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
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RESEARCH

Climate Change Effects on San Francisco Estuary Aquatic Ecosystems: A Review

Bruce Herbold[1], Eva Bush[2], Gonzalo Castillo[3], Denise Colombano[4], Rosemary Hartman[5], Peggy Lehman[6], Brian Mahardja[7], Ted Sommer[8]

ABSTRACT

Climate change is intensifying the effects of multiple interacting stressors on aquatic ecosystems worldwide. In the San Francisco Estuary, signals of climate change are apparent in the long-term monitoring record. Here we synthesize current and potential future climate change effects on three main ecosystems (floodplain, tidal marsh, and open water) in the upper estuary and two representative native fishes that commonly occur in these ecosystems (anadromous Chinook Salmon, *Oncorhynchus tshawytscha* and estuarine resident Sacramento Splittail, *Pogonichthys macrolepidotus*). Based on our review, we found that the estuary is experiencing shifting baseline environmental conditions, amplification of extremes, and restructuring of physical habitats and biological communities. We present priority topics for research and monitoring, and a conceptual model of how the estuary currently functions in relation to climate variables. In addition, we discuss four tools for management of climate change effects: regulatory, water infrastructure, habitat development, and biological measures. We conclude that adapting to climate change requires fundamental changes in management.

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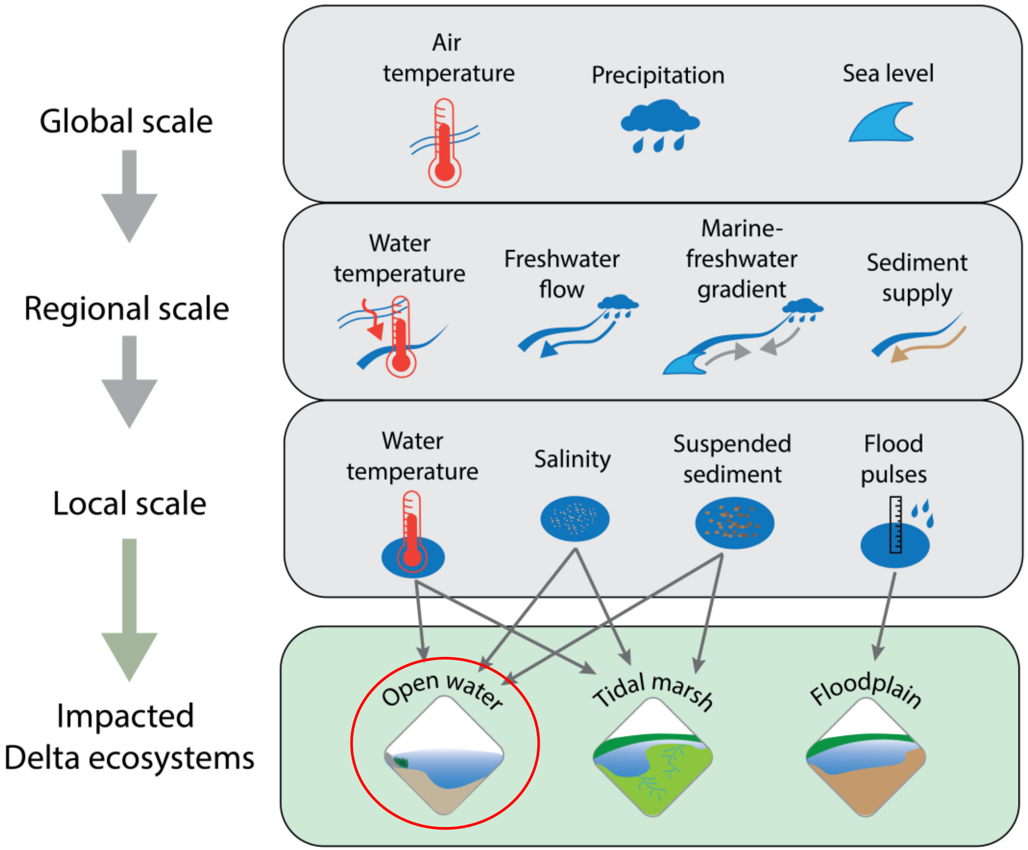
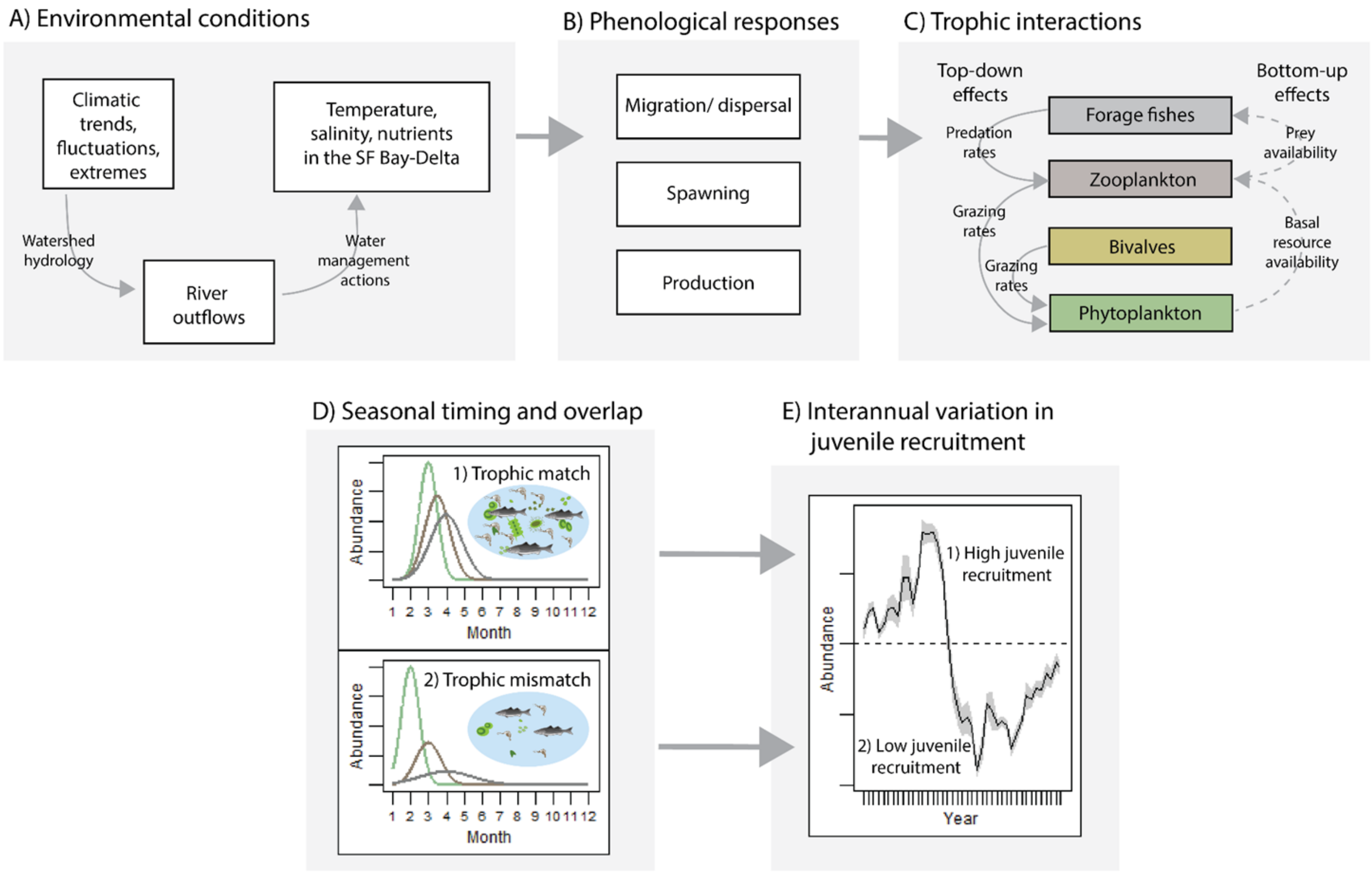
KEY WORDS

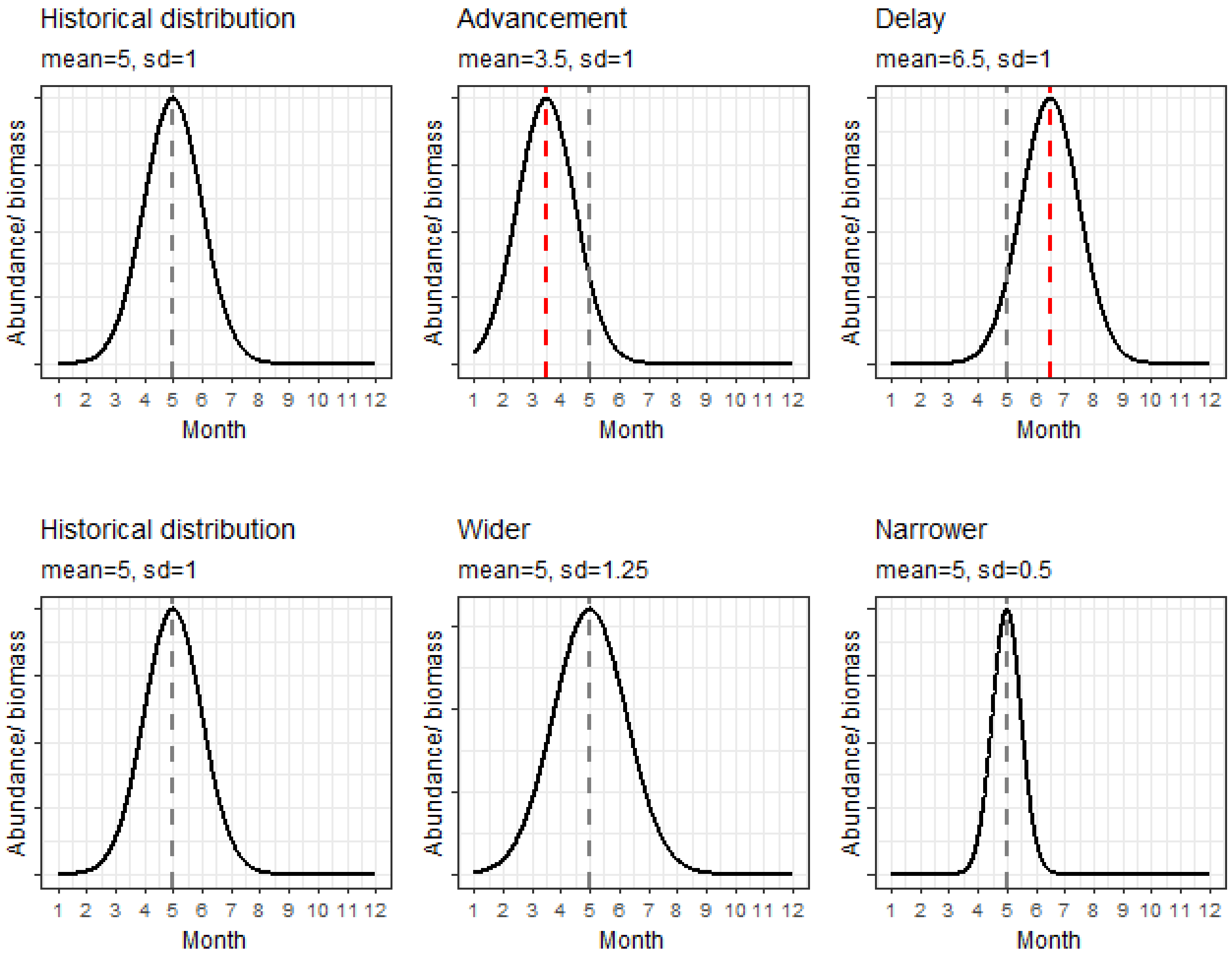
Chinook Salmon, Sacramento Splittail, tidal marsh, floodplain, open water, drought, flood

Climate change alterations to the timing, frequency, magnitude, and spatial extent of environmental drivers, and impacted ecosystems





A) Environmental conditions
Climatic trends, fluctuations, extremes
Temperature, salinity, nutrients in the SF Bay-Delta
Watershed hydrology
River outflows
Water management actions
B) Phenological responses
Migration/ dispersal
Spawning
Production
C) Trophic interactions
Top-down effects
Bottom-up effects
Forage fishes
Zooplankton
Bivalves
Phytoplankton
Predation rates
Grazing rates
Grazing rates
Prey availability
Basal resource availability
D) Seasonal timing and overlap
1) Trophic match
2) Trophic mismatch
Abundance
Month
1 2 3 4 5 6 7 8 9 10 11 12
E) Interannual variation in juvenile recruitment
1) High juvenile recruitment
2) Low juvenile recruitment
Abundance
Year

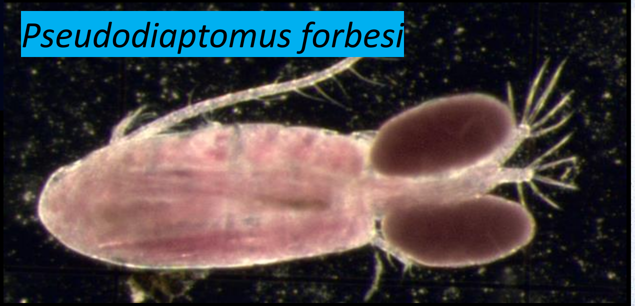


Historical distribution
mean=5, sd=1
Advancement
mean=3.5, sd=1
Delay
mean=6.5, sd=1
Historical distribution
mean=5, sd=1
Wider
mean=5, sd=1.25
Narrower
mean=5, sd=0.5
Abundance/ biomass
Month
1 2 3 4 5 6 7 8 9 10 11 12

Overarching study question

Do zooplankton and forage fishes shift their phenology in response to changing environmental conditions?

Mesozooplankton



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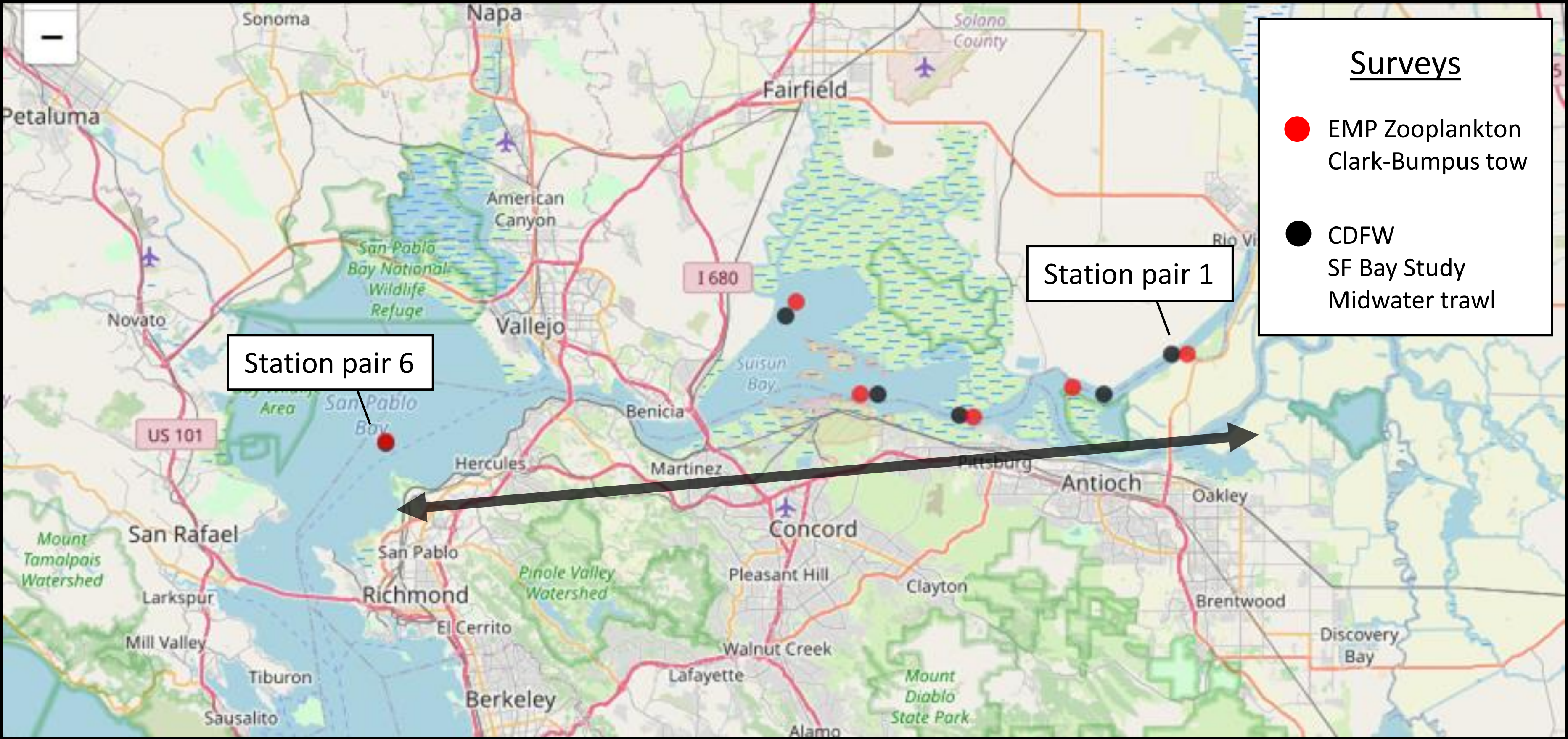
Forage fishes

©James Ervin

Paired station design: Monthly sampling 1995-present



Why Dynamic Linear Models?

A DLM captures relationships between a predictor and a response variable in a time-varying fashion by fitting a random walk for each parameter of the regression (i.e., one for the slope and another one for the intercept), updating parameters at each timestep.

Leathers, Ruhi et al. 2022 L&O https://doi.org/10.1002/lno.12264

DLM model with spatial covariance

1) The state process

$$X_t = X_{t-1} + W_t, \; W_t = MVN(0, Q)$$

Time-varying regression parameters for each site (intercept and slope 'states')

Conditioned on previous time step

Process error (random deviations due to environmental/demographic stochasticity, allowed to covary across sites)

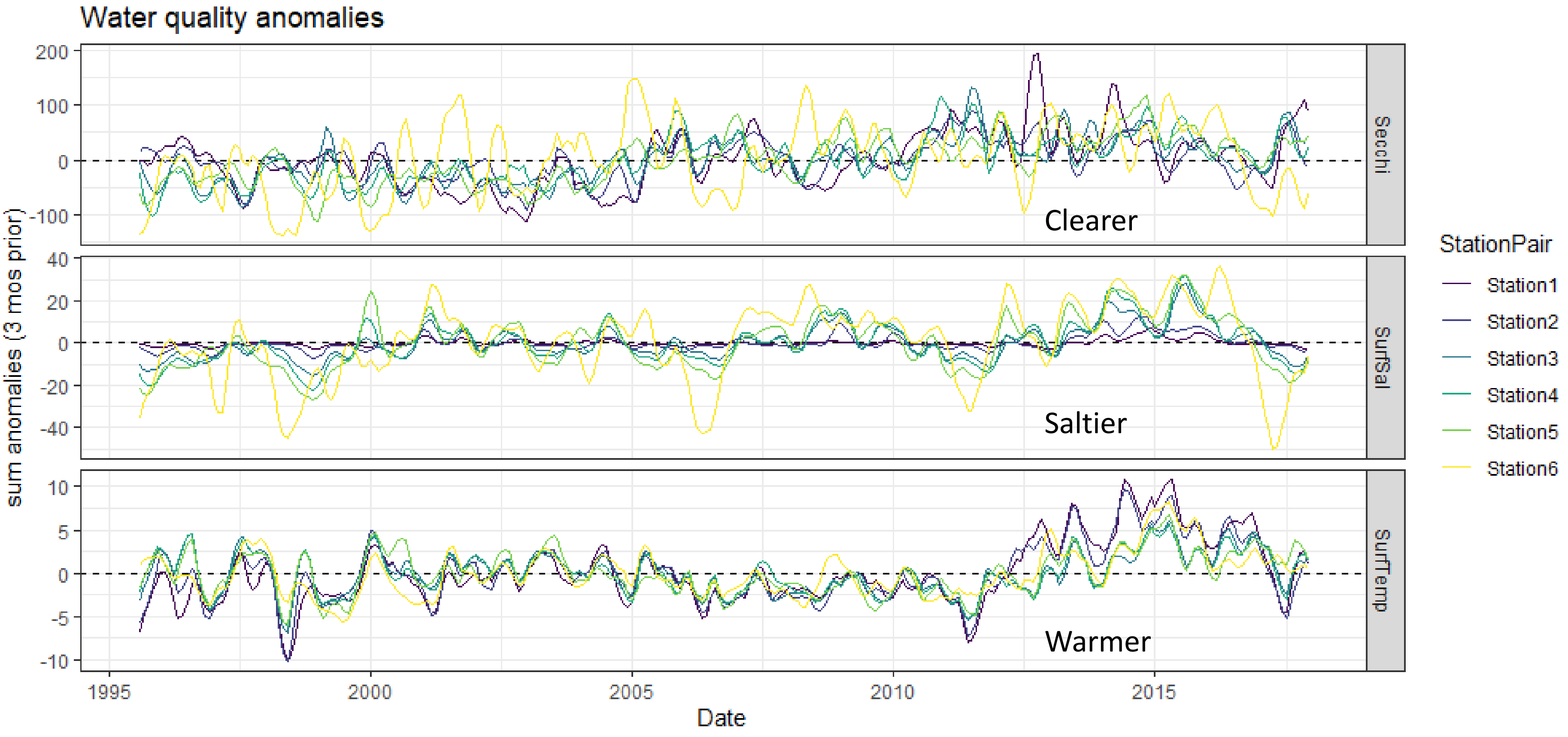
2) The observation process

$$Y_t = ZX_t + V_t, \; V_t = MVN(0, R)$$

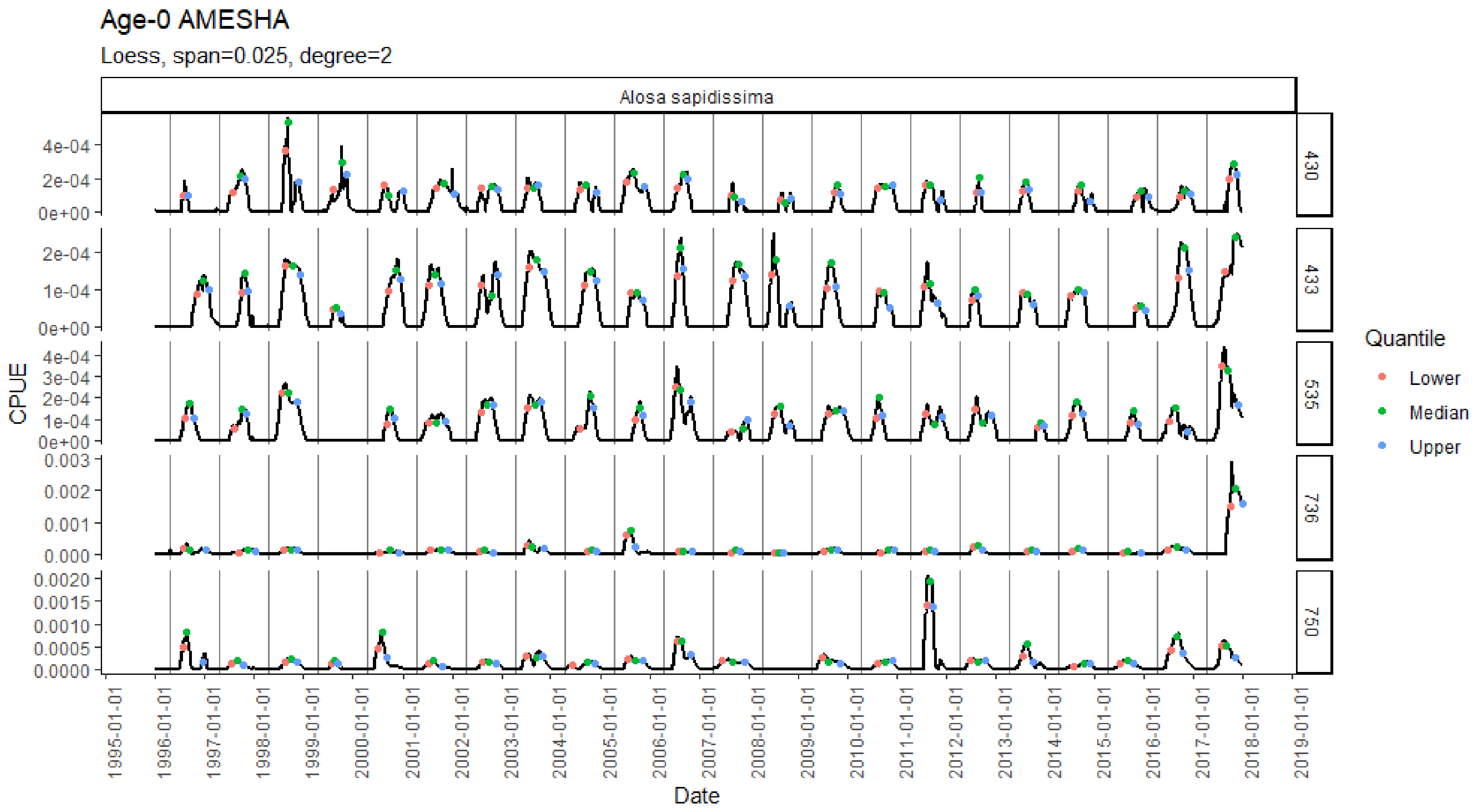
Noisy observations (e.g., timing of peak catch) for each site

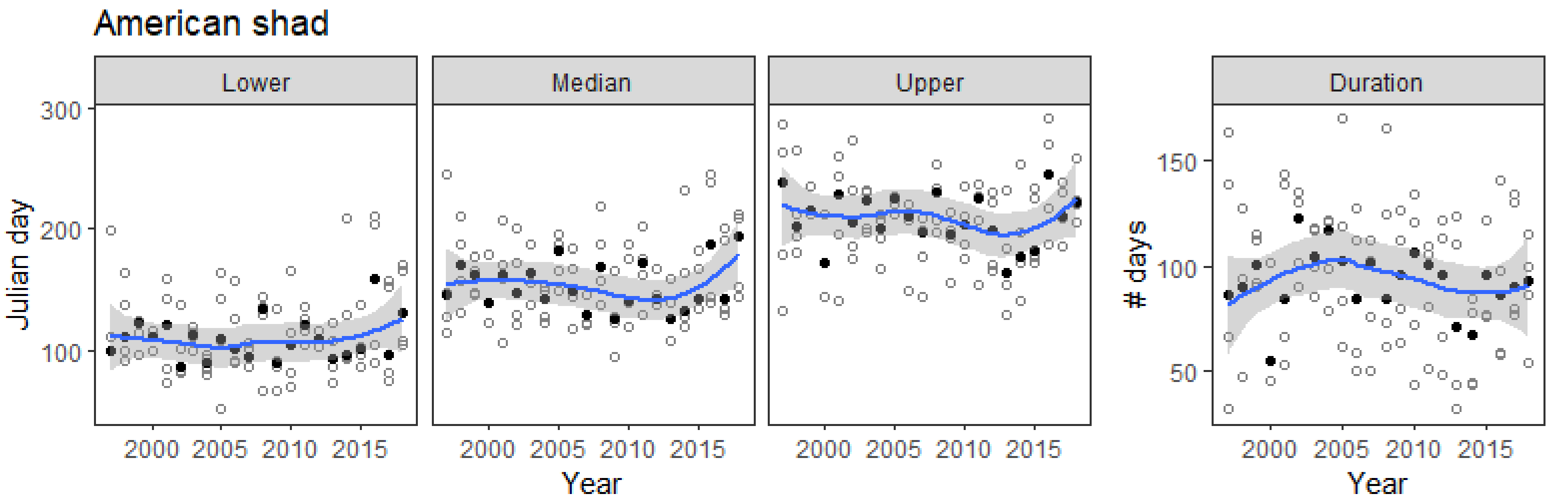
Environmental covariates (e.g., temperature, salinity) for each site

Observation error (e.g., gear effects)

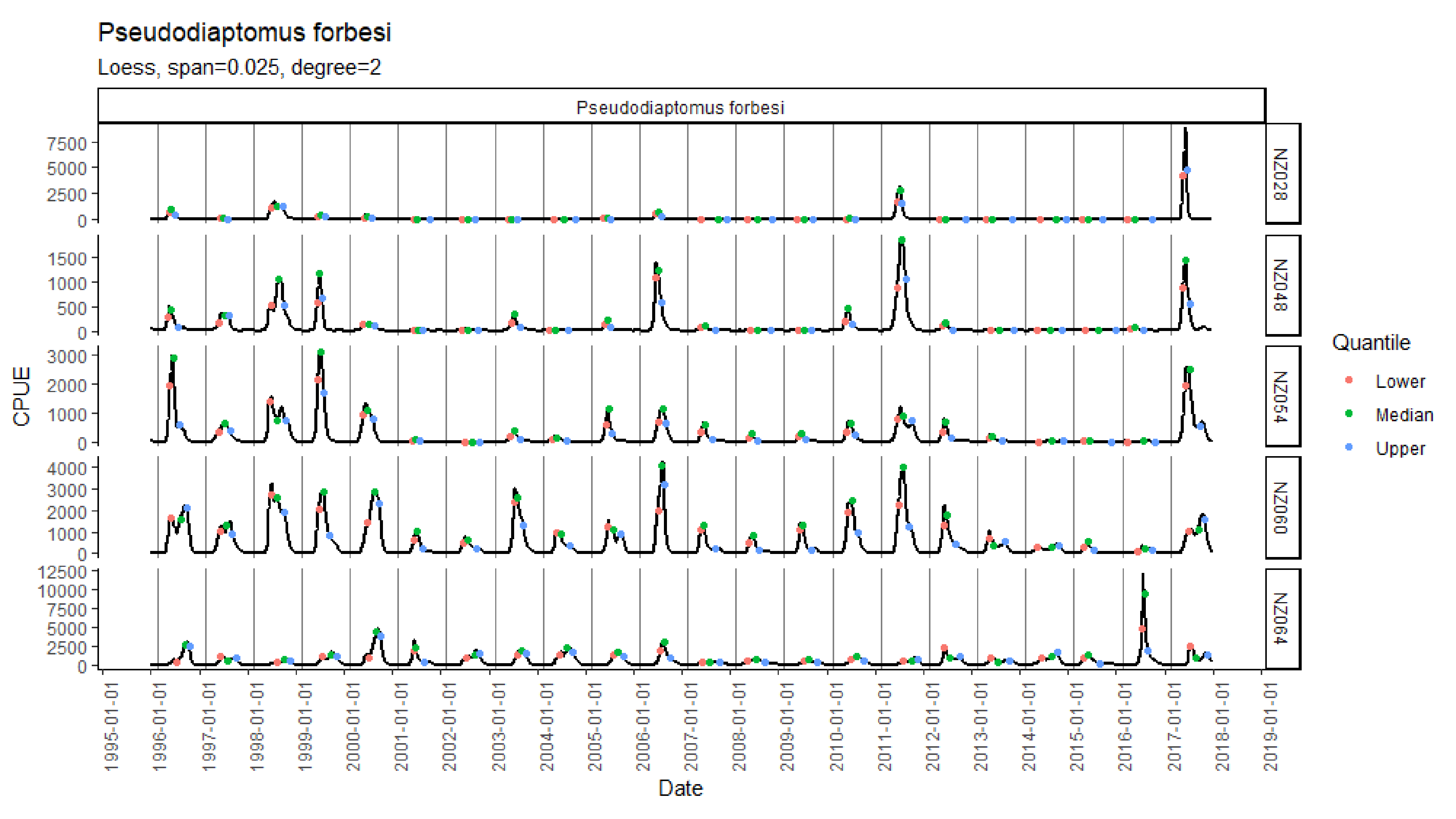


Water quality anomalies
200
100
0
-100
Secchi
Clearer
40
20
0
-20
-40
SurfSal
Saltier
10
5
0
-5
-10
SurfTemp
Warmer
sum anomalies (3 mos prior)
1995
2000
2005
2010
2015
Date
StationPair
Station1
Station2
Station3
Station4
Station5
Station6


Age-0 AMESHA
Loess, span=0.025, degree=2
Alosa sapidissima
CPUE
Date
430
433
535
736
750
Quantile
Lower
Median
Upper



When the timing of the quantiles shift,
the duration of the peak can narrow or widen



Pseudodiaptomus forbesi
Loess, span=0.025, degree=2
Pseudodiaptomus forbesi
NZ028
NZ048
NZ054
NZ060
NZ064
CPUE
Date
Quantile
Lower
Median
Upper
7500
5000
2500
0
1500
1000
500
3000
2000
4000
12500
10000
1995-01-01
1996-01-01
1997-01-01
1998-01-01
1999-01-01
2000-01-01
2001-01-01
2002-01-01
2003-01-01
2004-01-01
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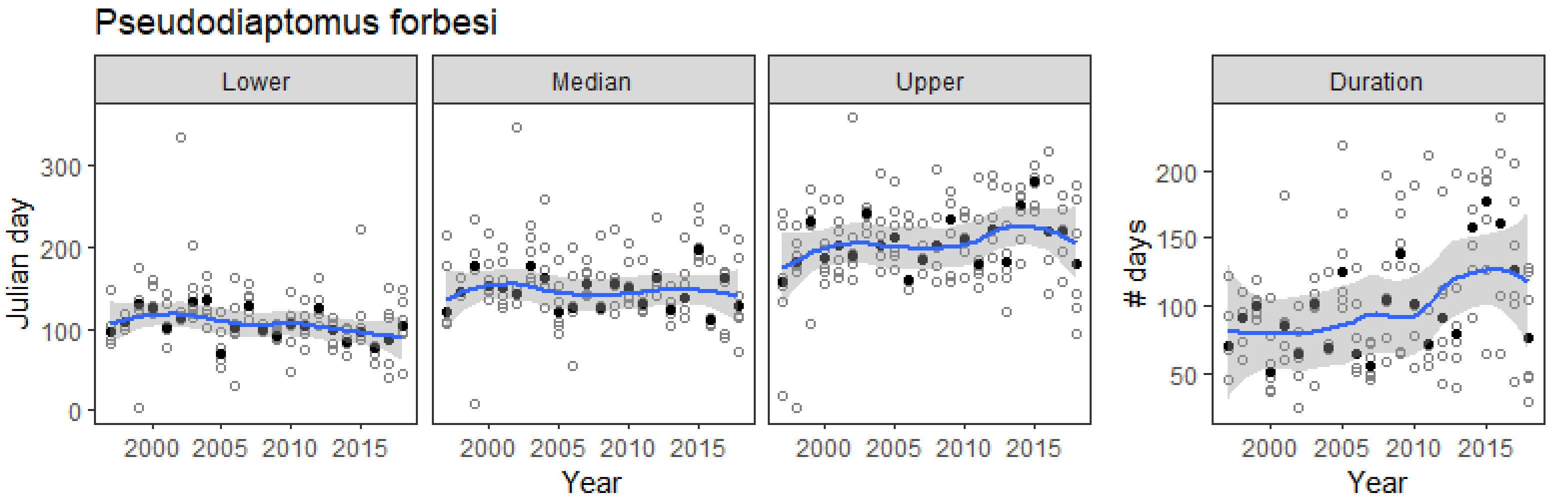
2018-01-01
2019-01-01



Prey species widening its peak

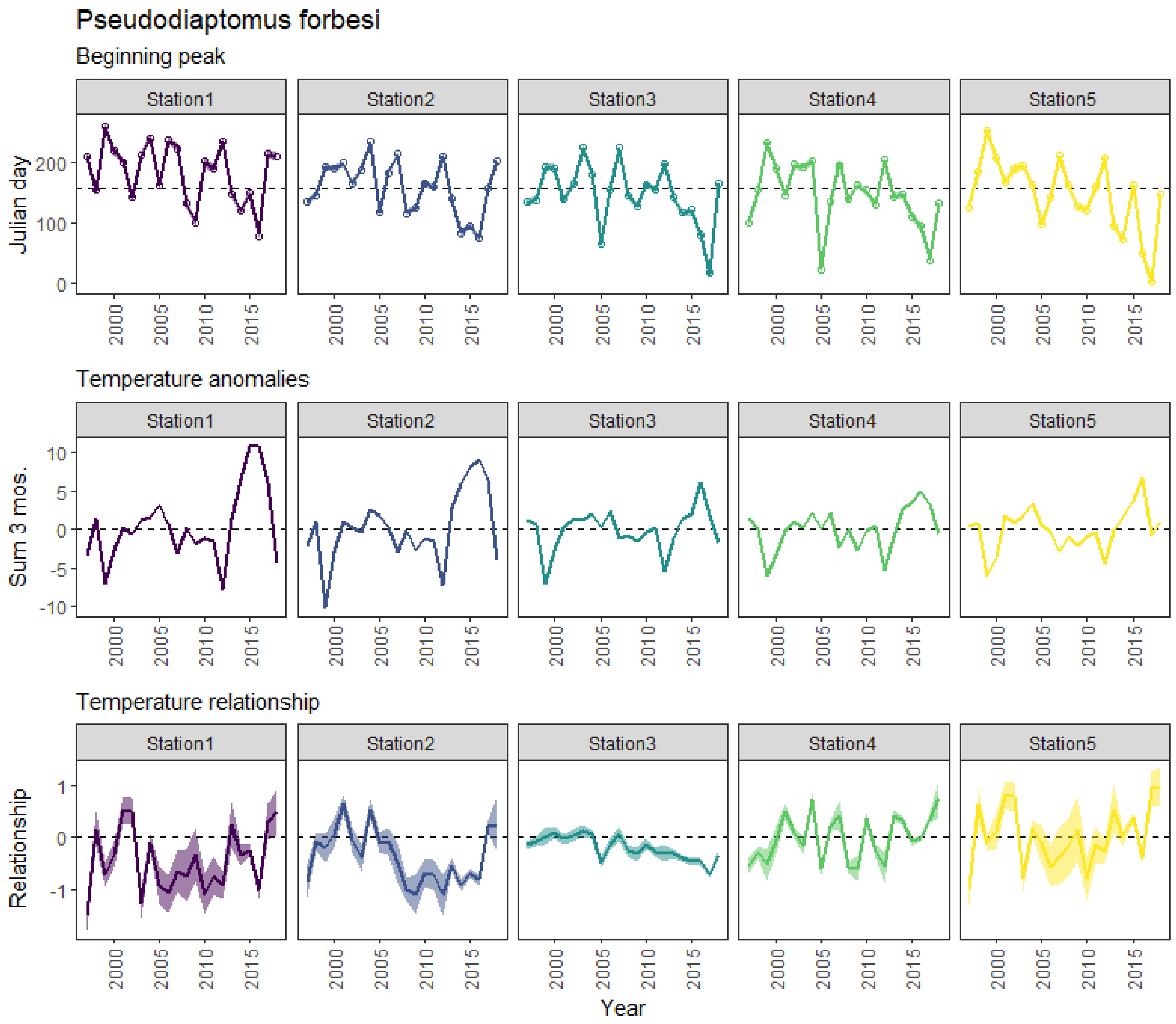
Specific study questions

- Is there evidence of directional shifts in species’ phenology?
- Is there evidence of time-varying relationships between species’ phenology and environmental conditions?
- Are the time-varying relationships consistent across space and time?

Timing

Temperature

Relationships (slope)

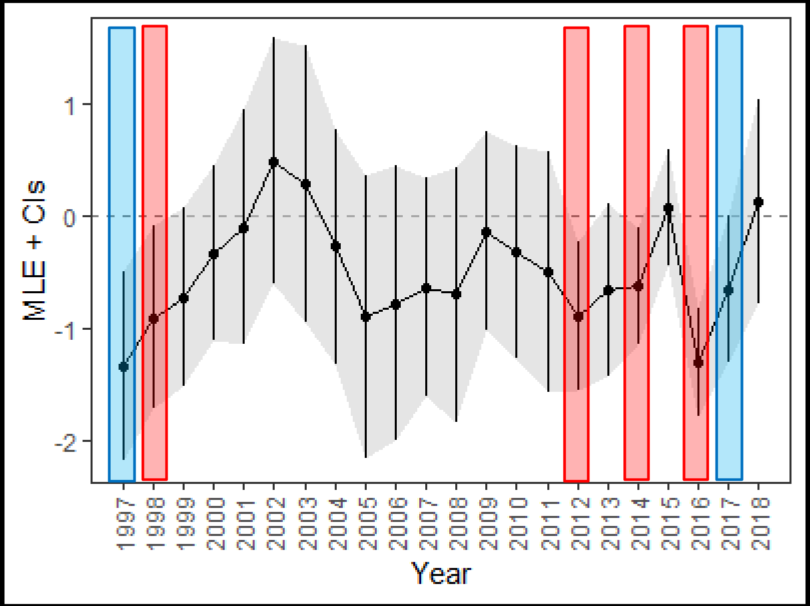


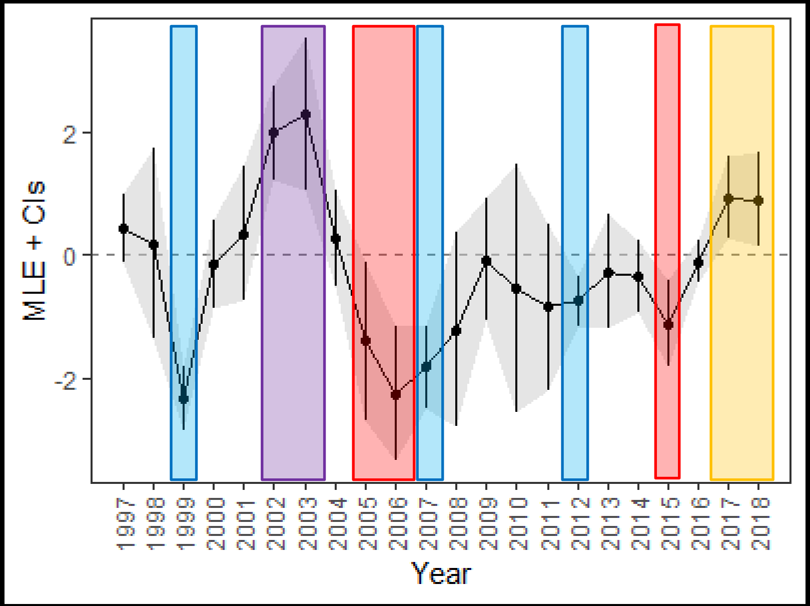
Significant shifts earlier, stronger downstream

Temperature variability greater upstream

Time-varying, predominantly negative upstream

Time-varying relationships examples





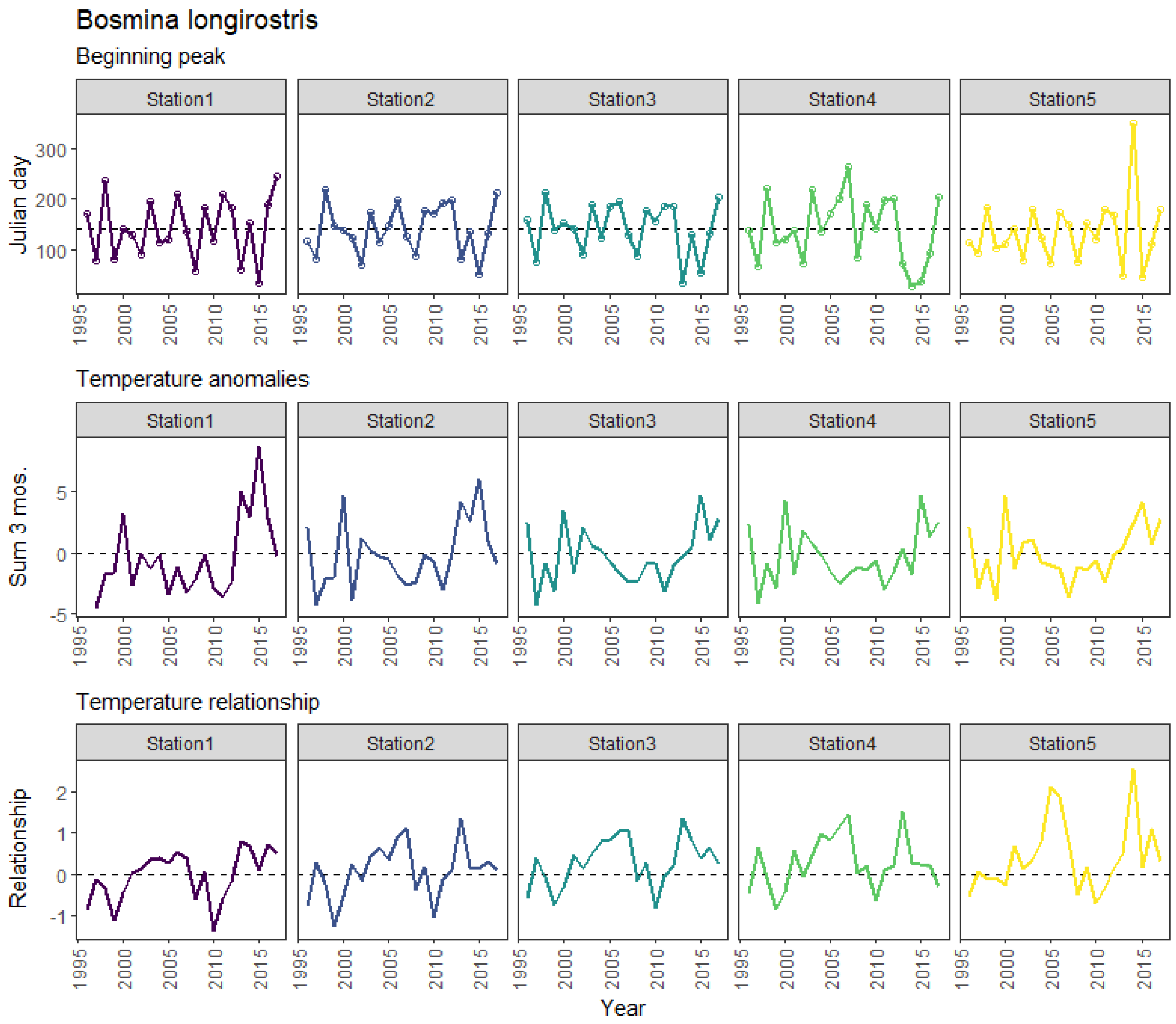
(-) Cooler temperatures and later timing
(-) Warmer temperatures and earlier timing

(+) Cooler temperatures and earlier timing
(+) Warmer temperatures and later timing

Timing

Temperature

Relationships (slope)



No significant shifts

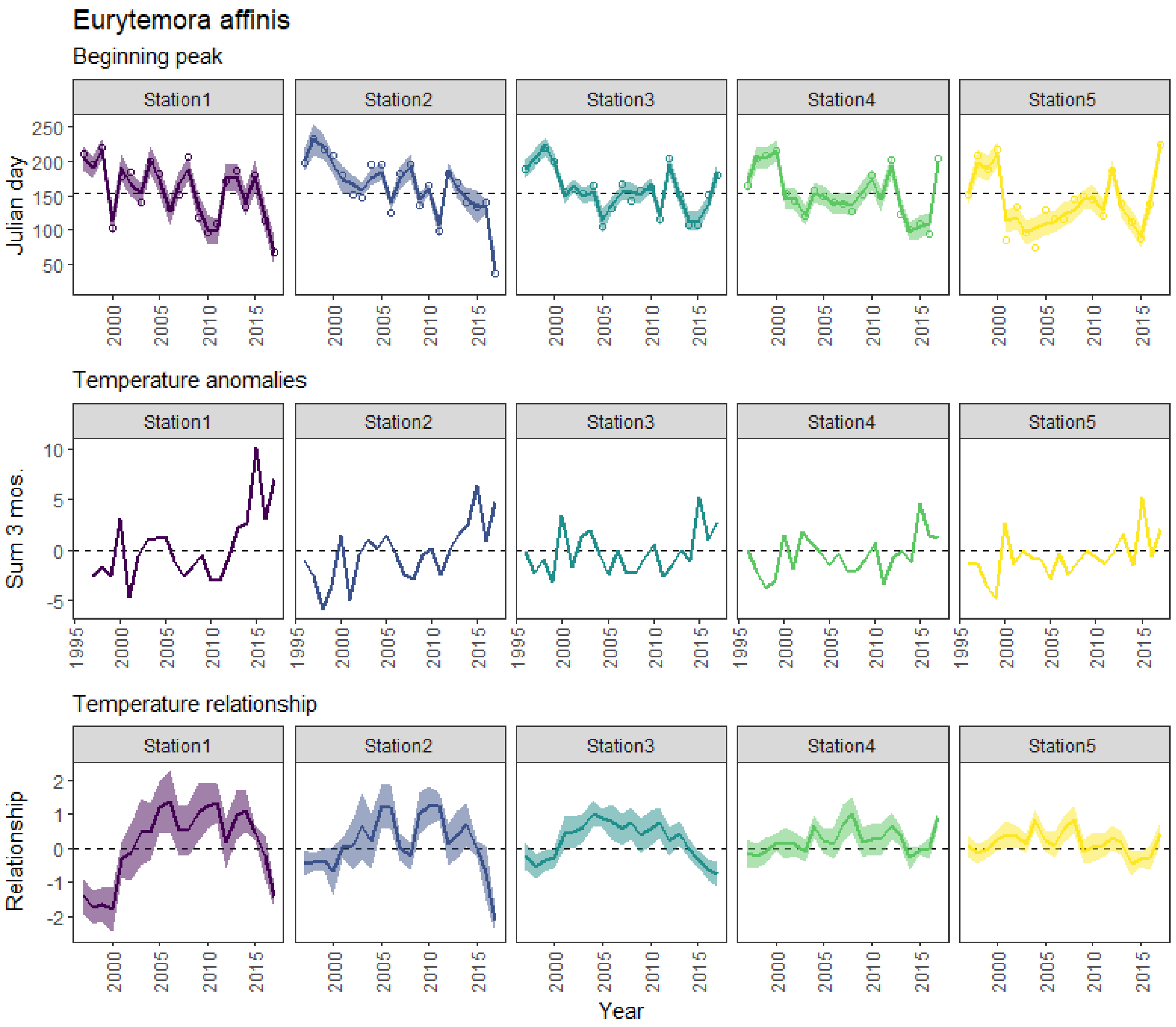
Temperature variability greater upstream

Time-varying, increasingly positive downstream

Timing

Temperature

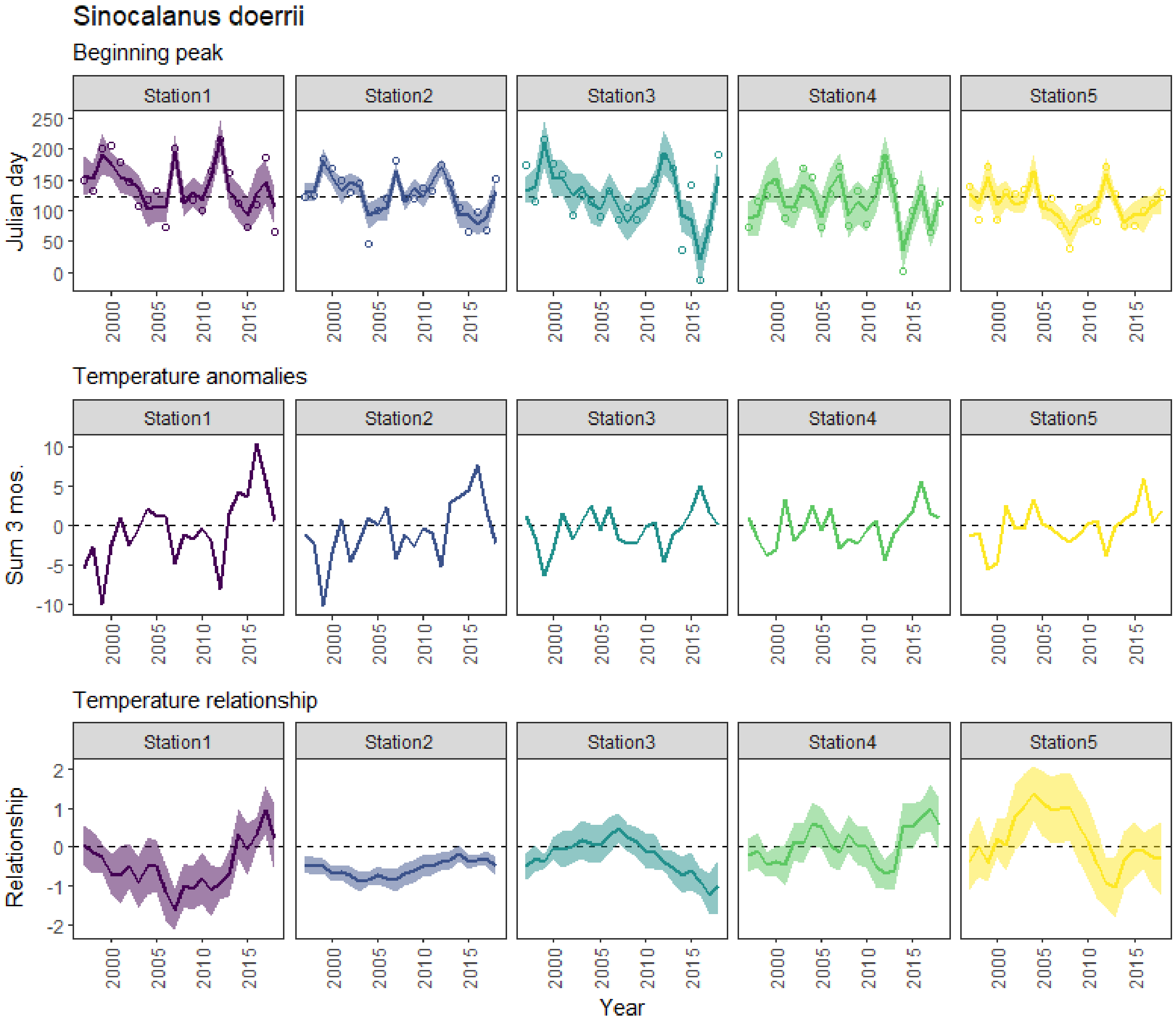
Relationships (slope)



Significant shifts earlier upstream

Temperature variability greater upstream

Time-varying, stronger upstream, predominantly positive



Significant shifts earlier in stations 2,3,5

Temperature variability greater upstream

Time-varying, inverse upstream vs. downstream

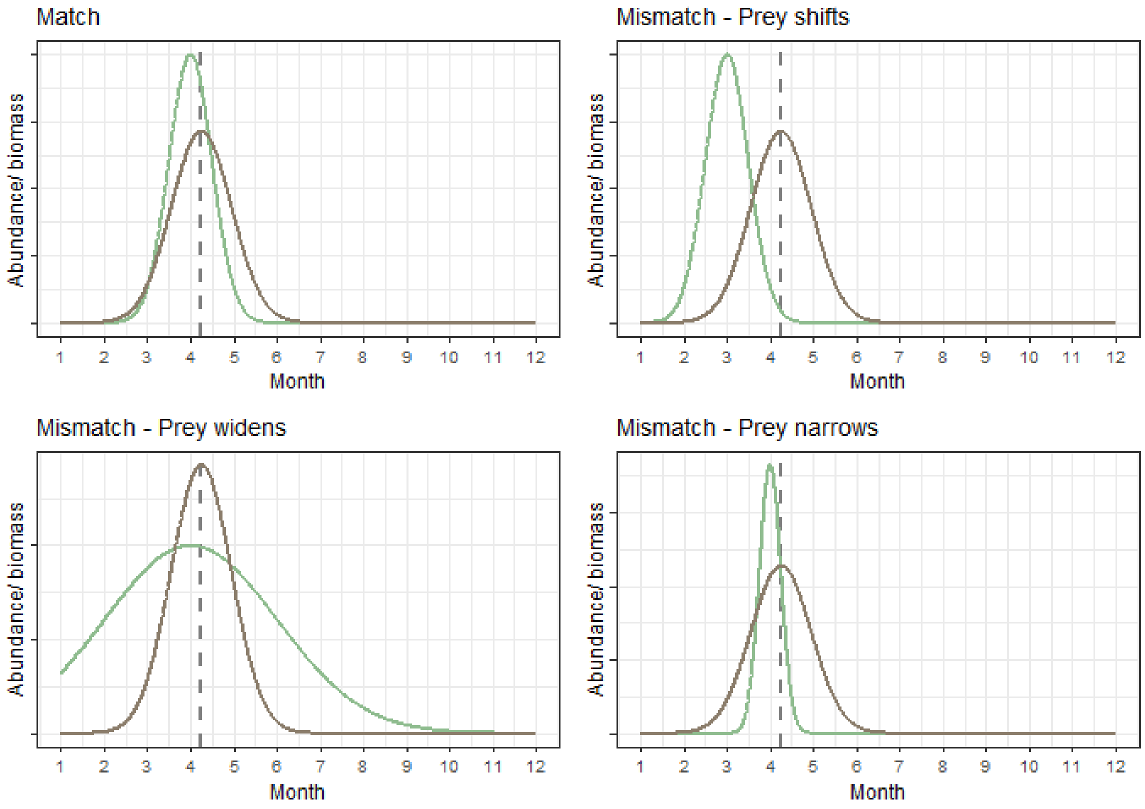
What we've learned from the DLMs so far…

- Phenological shifts
  - Phenology varied throughout the time series
  - Most species shifted the beginning of their peaks earlier over time in at least some stations; commonly upstream where there was greater temperature variability and anomalies
- Time-varying relationships
  - More consistent for some species than others (negative vs. positive); others switched the direction and magnitude in space and time
  - Sensitivity to changes in temperature often varied as a function of the estuarine gradient; some species were more sensitive upstream vs. downstream

Next steps...

- Repeat analysis for other variables
  - Day of median catch
  - Duration
  - Abundance
  - Salinity
  - Secchi
- Repeat analysis for macrozooplankton and age-0 forage fishes
- Model selection via AIC

Finally, assess the potential for matches/ mismatches



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- 'Zooper' package
- 'Deltafish' package

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- Environmental Monitoring Program – Zooplankton Study

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Literature with methods

- Data wrangling methods:
  - Thaxton, W.C., Taylor, J.C. and Asch, R.G., 2020. Climate-associated trends and variability in ichthyoplankton phenology from the longest continuous larval fish time series on the east coast of the United States. *Marine Ecology Progress Series*, 650, pp.269-287.

- Multivariate DLM methods:
  - Leathers, K., Herbst, D., Safeeq, M. and Ruhi, A., 2022. Dynamic, downstream-propagating thermal vulnerability in a mountain stream network: Implications for biodiversity in the face of climate change. *Limnology and Oceanography.*

Questions?

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