Detecting multiscale temporal dynamics of acoustically estimated zooplankton biomass: a case study of high-resolution ocean observatory system in Saanich Inlet (British Columbia, Canada)

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Instrument Platform:
- at seafloor ~100m

**Acoustic Zooplankton Fish Profiler** (made by ASL):
- 200 kHz echosounder: data taken every 2 seconds with 8.5cm vertical bins
- Data resolution was reduced to 1 minute by 1 meter bins

AZFP co-located with a bottom mounted CTD and oxygen sensor

- 10+ year time series
Typical Day in Saanich Inlet (200kHz)

**Challenge:** Single frequency (200kHz) includes targets larger than zooplankton (i.e. fish). How to discriminate?
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- DVM: *Euphausia pacifica* dominates migration backscatter (Sato et al. 2013)
- Zooplankton (*E. pacifica*) Sv: -77 ~ -57 dB
Targeting zooplankton backscatter

10-Jun-2006

- Migration box: within 2 hrs of local sunrise & sunset
- Depth 30m ± 5m
- Exclude surface noise (0-15m)

- Migration zooplankton “biomass” (in Sv):
  (average echo + |min average echo|) * number of echo pixels
Migration Zoop Biomass Time Series

2006.03 ~ 2016.10

ENSOS

“Blob” + ENSO

Weekly (556 observations)

Daily

Weekly

Biweekly (278 observations)

Monthly (128 observations)

Quarterly (43 observations)
How to study dynamical system?

- Studying complex natural dynamical system:
  - Linear statistical approach (based on correlation) → Linear stochastic system
  - Nonlinear analytical approach (based on state space reconstruction) → Nonlinear dynamical system

- State Dependency
  - Relationships among interacting variables change with different states of dynamical system
  - Lorenz butterfly attractor (Lorenz, 1963, J.Atmos.Sci.20:130-141)

The Lorenz system:
\[
\begin{align*}
\frac{dx}{dt} &= -sx + sy \\
\frac{dy}{dt} &= -xz + rx - y \\
\frac{dz}{dt} &= xy - bz
\end{align*}
\]
Non-linear Time Series Analytical Method

- State Space Reconstruction (SSR)
  - Takens’ (1980) embedding theory:
    lagged coordinates state-space reconstruction
    \[ \{x_t, x_{t-	au}, x_{t-2	au} \ldots x_{t-(n-1)	au}\} \]

- Empirical Dynamic Modeling (EDM)
  Methods do not assume any set of equations governing the system but recover the dynamics from time series data
Procedures

- **Time series standardization**
  
  Normalization + Detrend (1st difference)

- **Determining system complexity, Identifying the best embedding dimension**
  
  Simplex-projector (out-of-sample predictability as criterion)

- **Determining nonlinearity of a time series, compare equivalent linear to nonlinear models**
  
  Smap (out-of-sample predictability as criterion)

- **Determining causal variables**
  
  Convergent Cross Mapping (CCM)

- **Forecasting**
  
  Univariate EDM  
  Multivariate EDM

Methods from Sugihara Lab, UCSD
Determining best embedding dimension

Quarterly
BED = 27

Monthly
BED = 28

Biweekly
BED = 2

Weekly
BED = 12
Quantifying nonlinearity

S-map: locally weighted linear regression

\[
\omega(d) = e^{-\theta \bar{d}/d}
\]

- \(d\): distance between the predictee and library points
- \(\bar{d}\): average distance between all library points

Weighting function is determined by \(\theta\)

\[\theta = 1.5\]

control state of dependency

Quarterly

Forecast Skill (thc)

0.63
0.58
0.53
0.49
0.46
0.42
0.38
0.34
0.30
0.26
0.22
0.18
0.14
0.10
0.06
0.02

Nonlinearity (theta)

linear

nonlinear
Quantifying nonlinearity

Quarterly

Monthly

Biweekly

Weekly

θ = 1.5

θ = 1

θ = 2

θ = 1.5
Determining Causal Variables

Temperature at 100m

Salinity at 100m

Oxygen at 100m

Tide height at Pat Bay (Foreman et al 2004)
Environmental Variables

Temperature at 100m

Weekly (556 observations)

Biweekly (278 observations)

Monthly (128 observations)

Quarterly (43 observations)
### Determining Causal Variables

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<th>BED</th>
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Forecasting

Monthly scale

Information on historical trajectories
(reconstructed state space)

Equations assume a mechanistic relationship between variables

✗

✓

Univariate embedding
(time-lagged values of a single variable)

Multivariate embedding
(multiple variables)
Forecasting

Monthly scale

Univariate EDM (biomass)

Library size

Forecasting skill

Forecasting skill

Library

Prediction

Forecasting skill

50 60 70 80 90 100 110

0.197 0.207 0.206 0.228 0.303 0.755 0.71 0.921

0.36 0.38

0.755 0.71 0.921

95 13 0.755

13 8 0.710

100 105 3 0.921

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0

 Library ( # of observations)

Prediction ( # of observations)

Forecasting skill
Forecasting

Monthly scale

Univariate EDM (biomass)

Multivariate EDM (temp, sal, oxy)

Forecasting skill:

$\rho = 0.471$

$p = 0.0002$

lib: 75 observations
pre: 52 predictions
Summary

• Saanich inlet zooplankton biomass time series display nonlinear dynamics on different temporal scales.

• Two adverse events (09-10 ENSO & 15-16 Blob):
  clear on deep water temperature time series
  not clear on zooplankton biomass time series

  No strong correlation

• Nonlinear Dynamics:  CORRELATION ≠ CAUSATION
  quarterly & monthly scales: temperature, salinity & oxygen
  biweekly & weekly scales: tide height

  Significant causal relationship

• Short-term Forecasting:
  univariate embedding: over 70% forecast skill
  multivariate embedding: ~ 50% forecast skill

• Future Suggestion: broad application of EDM to other time series analysis

• All data shown (and much more) is available online at www.oceannetworks.ca
Thank You