OCEAN NETWORKS CANADA SCIENCE

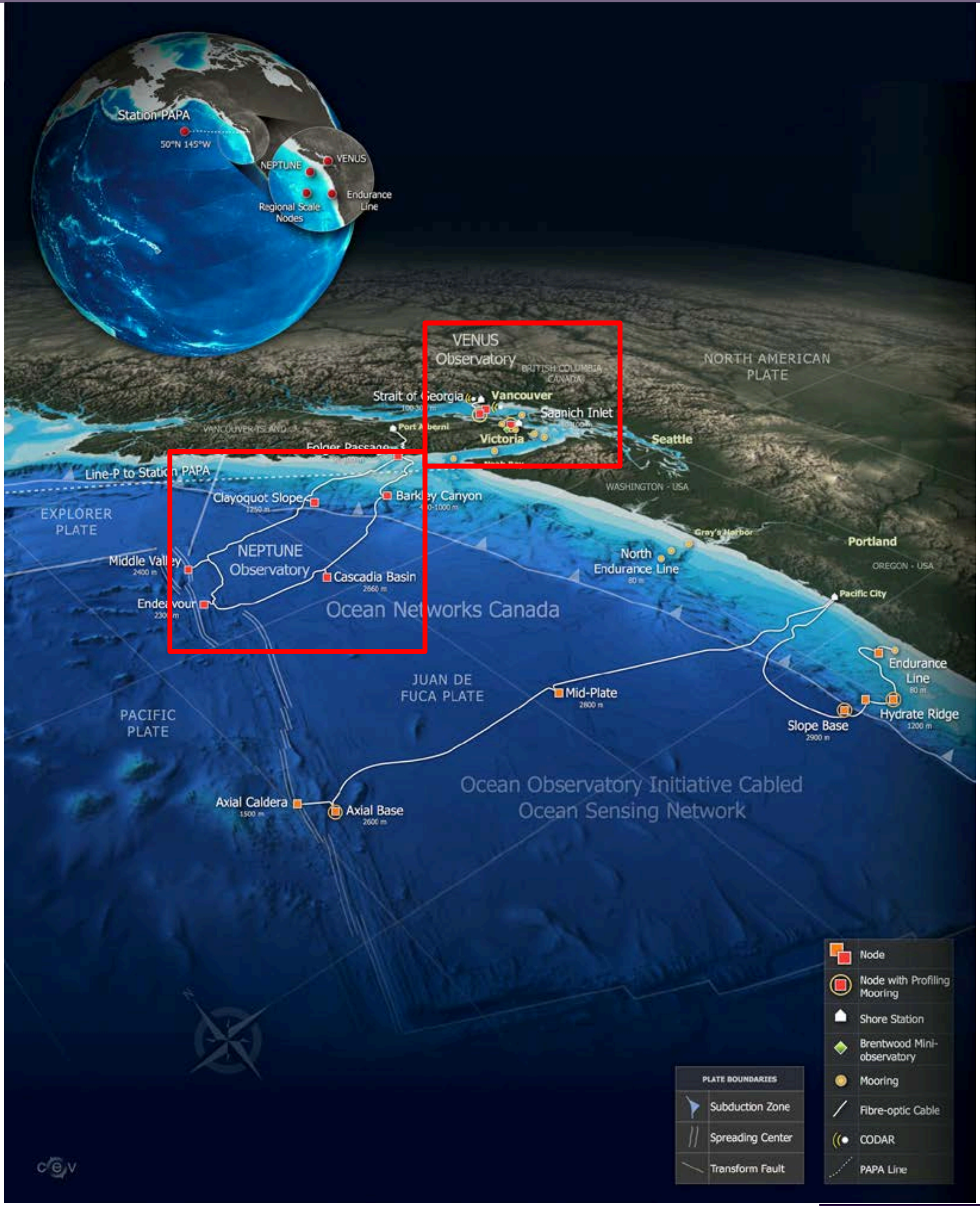
# Detecting multiscale temporal dynamics of acoustically estimated zooplankton biomass: a case study of high-resolution ocean observatory system in Saanich Inlet (British Columbia, Canada)

Lu Guan[1], Akash Sastri[2], Chih-hao Hsieh[3], Kim Juniper[1,2], John Dower[1], Richard Dewey[2], Stephane Gauthier[4]

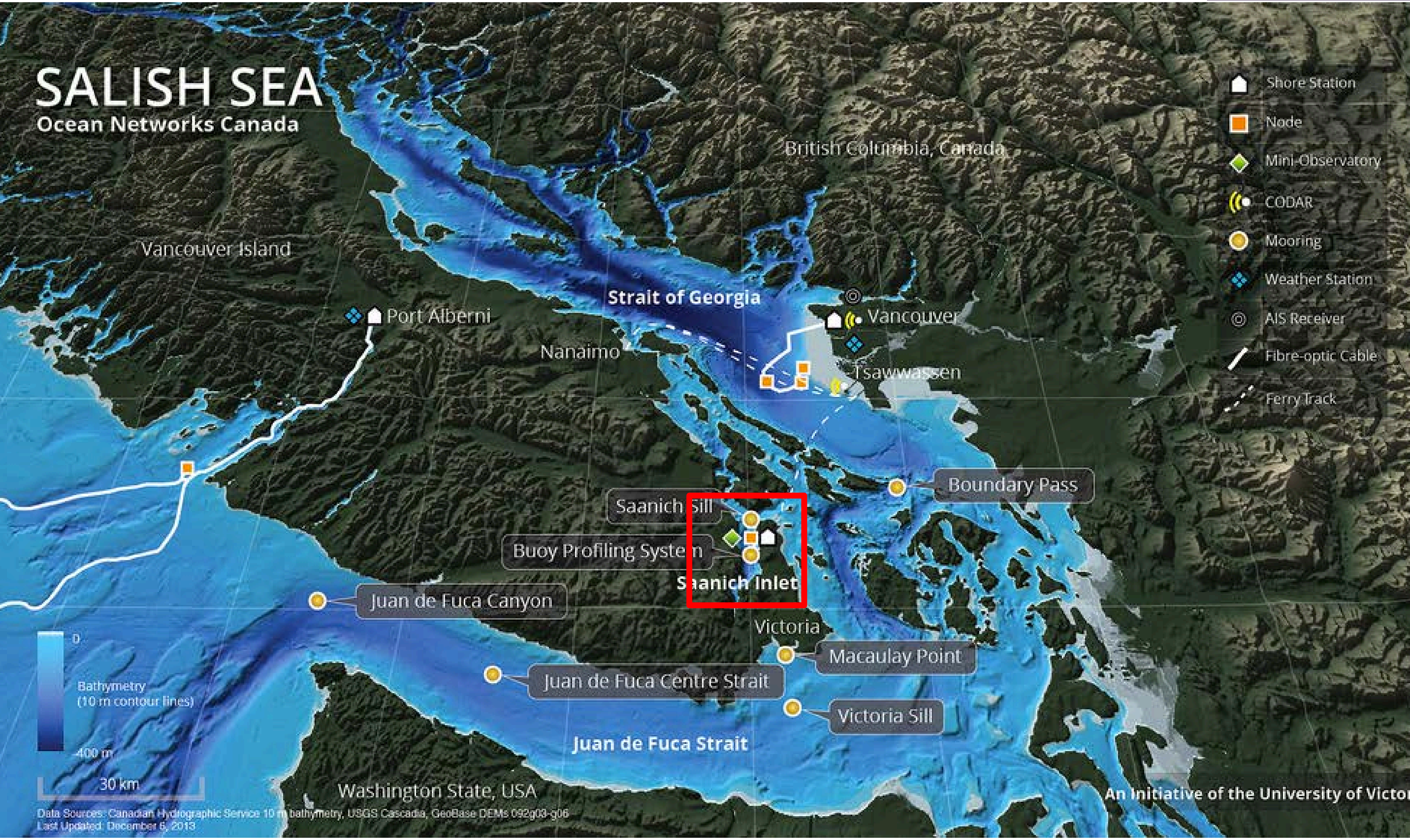
1. University of Victoria (UVic)
2. Ocean Networks Canada (ONC)
3. National Taiwan University (NTU)
4. Fisheries and Oceans Canada (DFO)

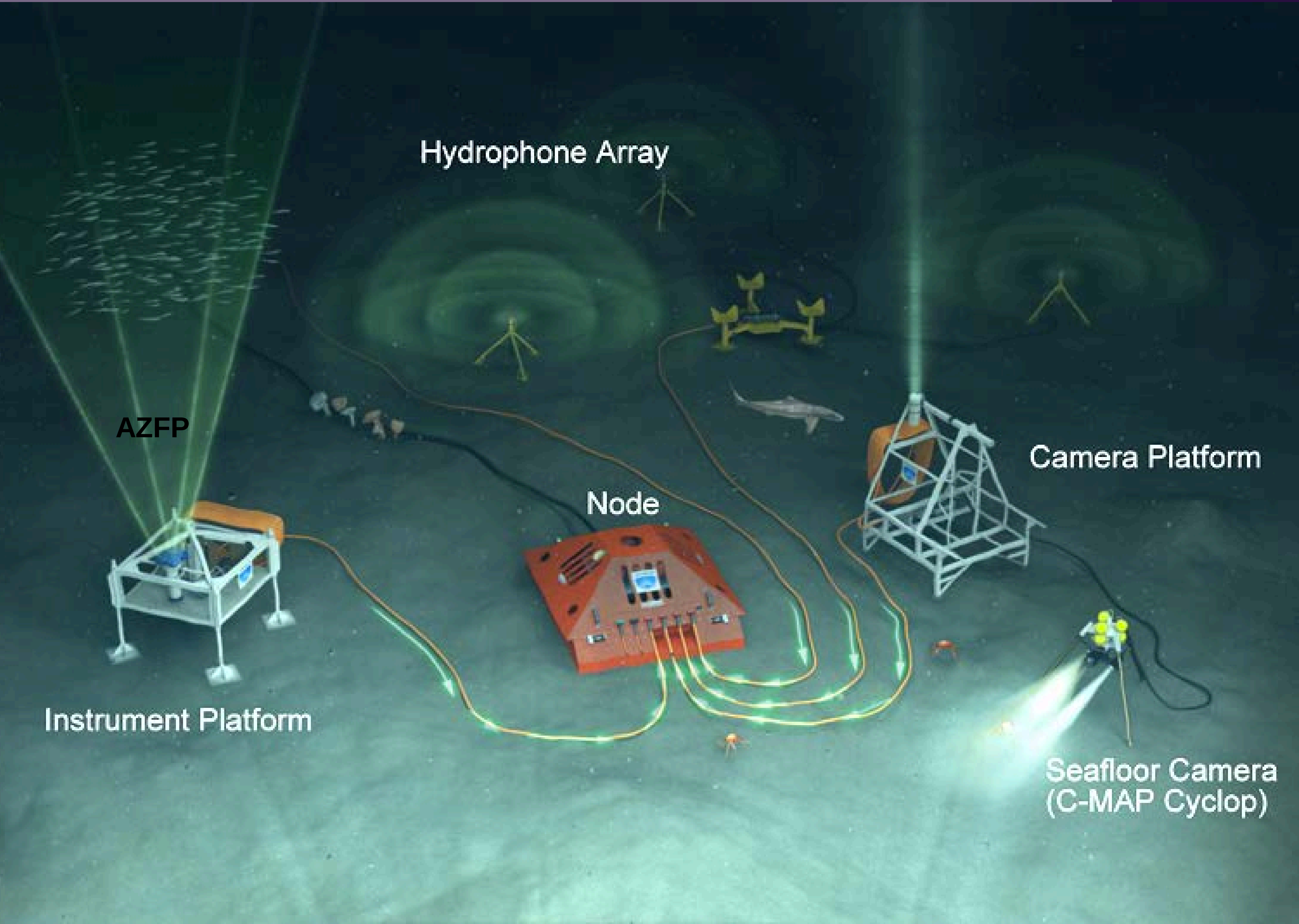
University of Victoria

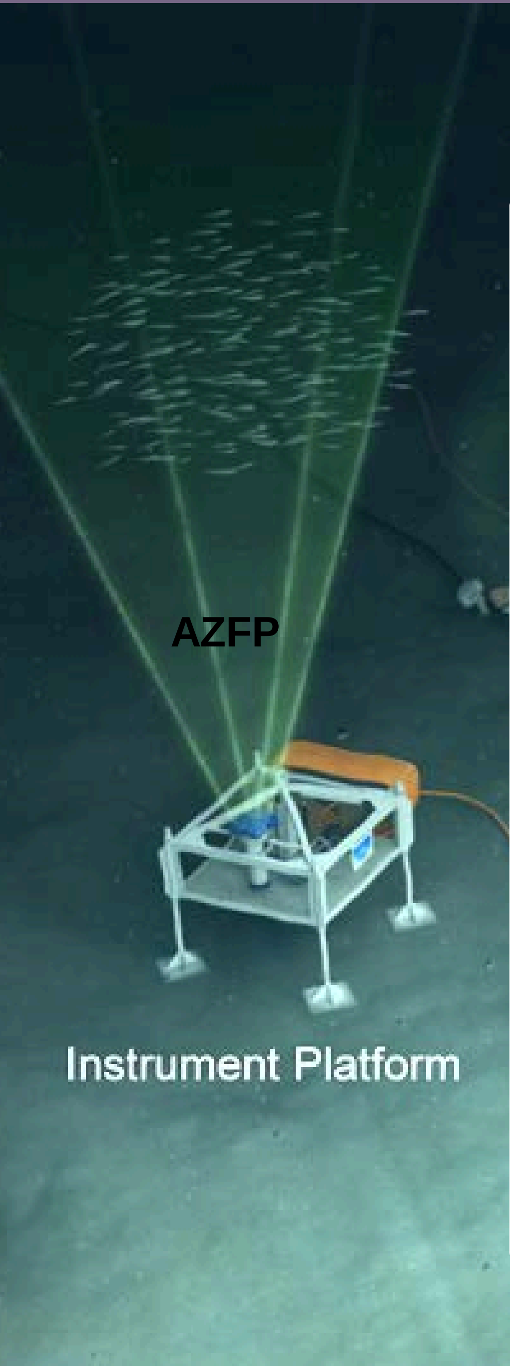
OCEAN NETWORKS CANADA SCIENCE



OCEAN NETWORKS CANADA SCIENCE




Hydrophone Array
AZFP
Camera Platform
Node
Instrument Platform
Seafloor Camera
(C-MAP Cyclop)




Instrument Platform:
- at seafloor ~100m

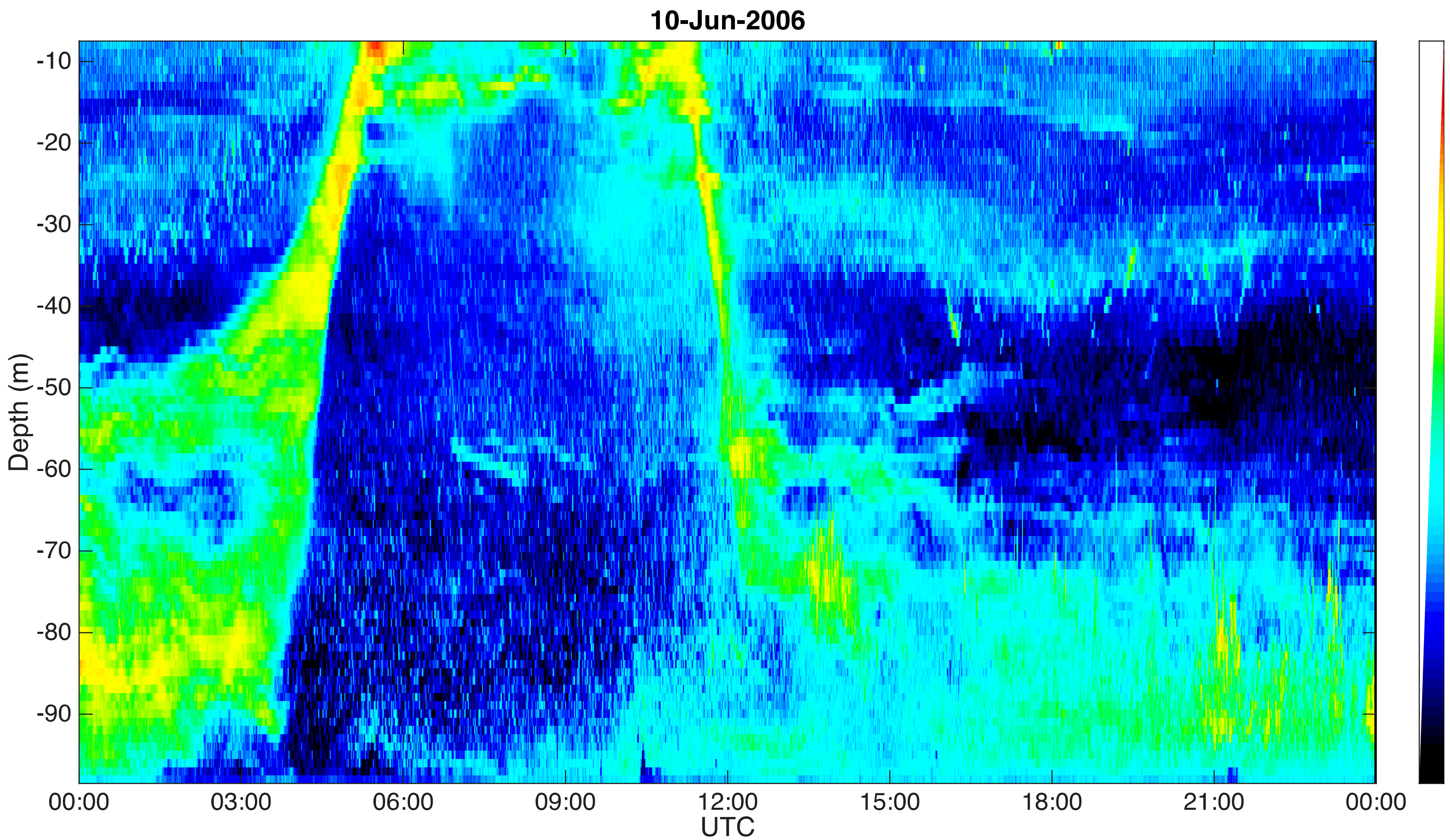
Acoustic Zooplankton Fish Profiler (made by ASL) :
- 200 kHz echosounder: data taken every 2 seconds with 8.5cm vertical bins
- Data resolution was reduced to 1 minute by 1 meter bins

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

➢ 10+ year time series

OCEAN NETWORKS CANADA

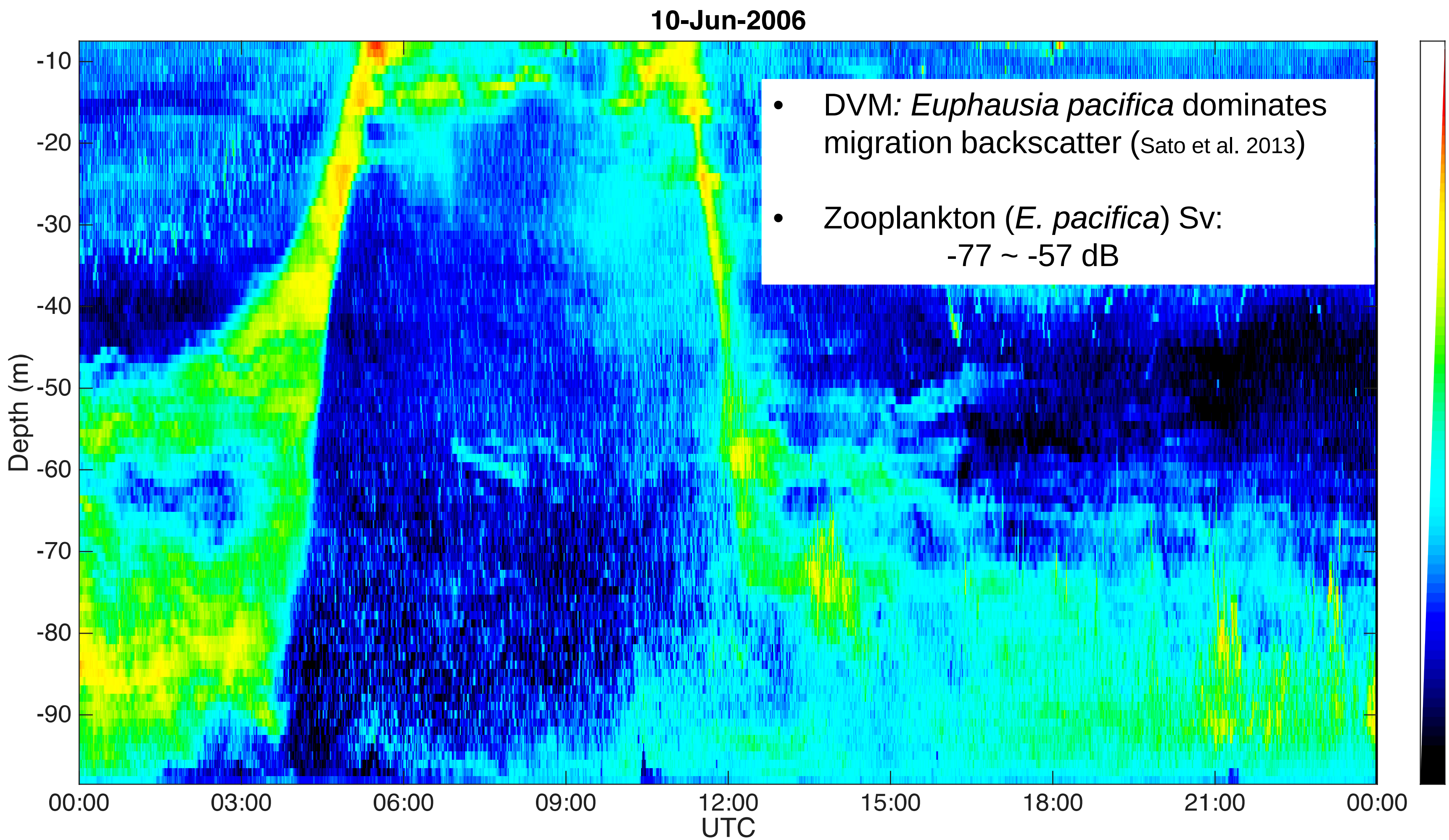
# Typical Day in Saanich Inlet (200kHz)




**Challenge:** Single frequency (200kHz) includes targets larger than zooplankton (i.e. fish). How to discriminate?

# Typical Day in Saanich Inlet (200kHz)

OCEAN NETWORKS CANADA

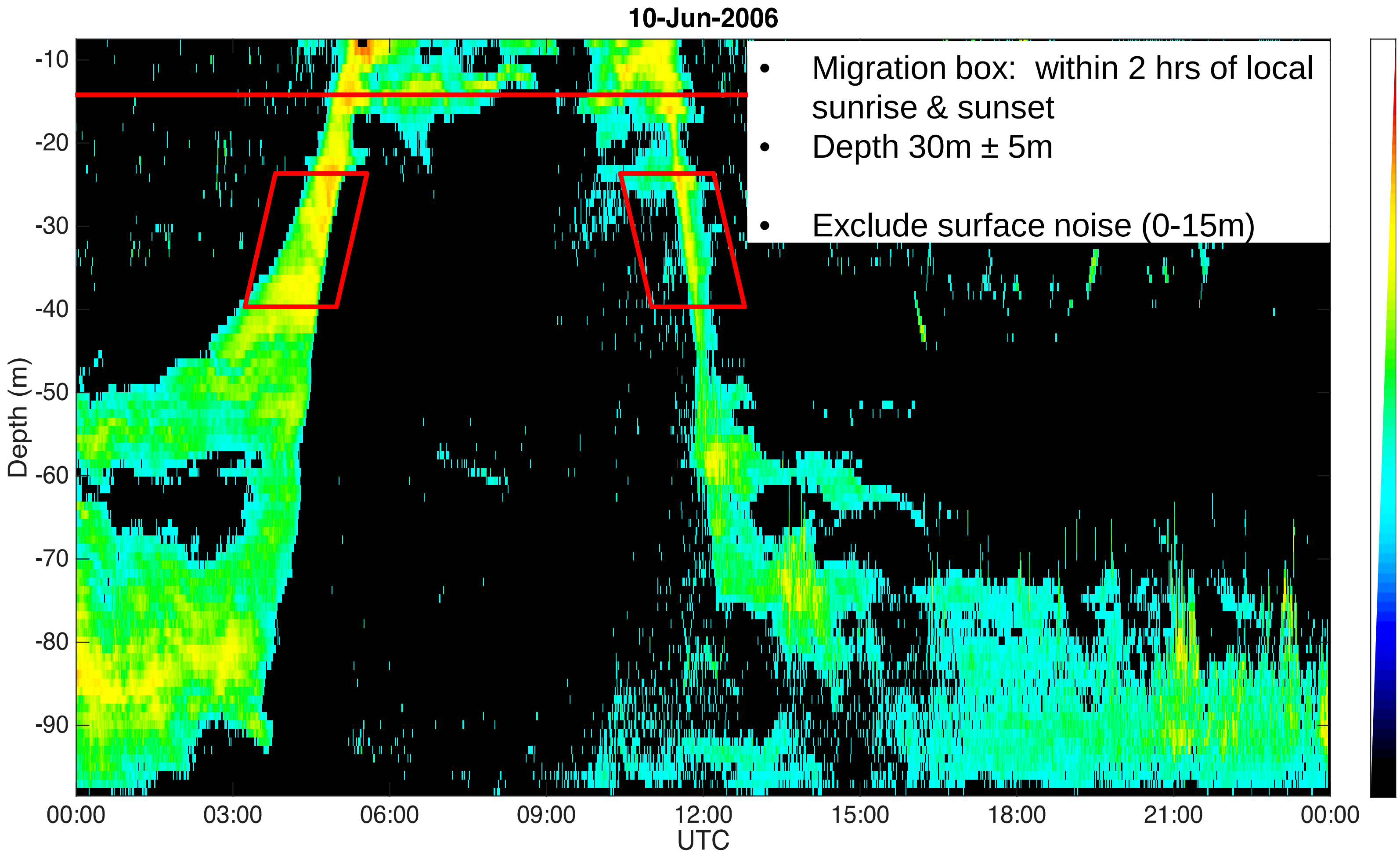



- DVM*: Euphausia pacifica* dominates migration backscatter (Sato et al. 2013)
- Zooplankton (*E. pacifica*) Sv: -77 ~ -57 dB

**<u>Challenge</u>:** Single frequency (200kHz) includes targets larger than zooplankton (i.e. fish). How to discriminate?

OCEAN NETWORKS CANADA SCIENCE

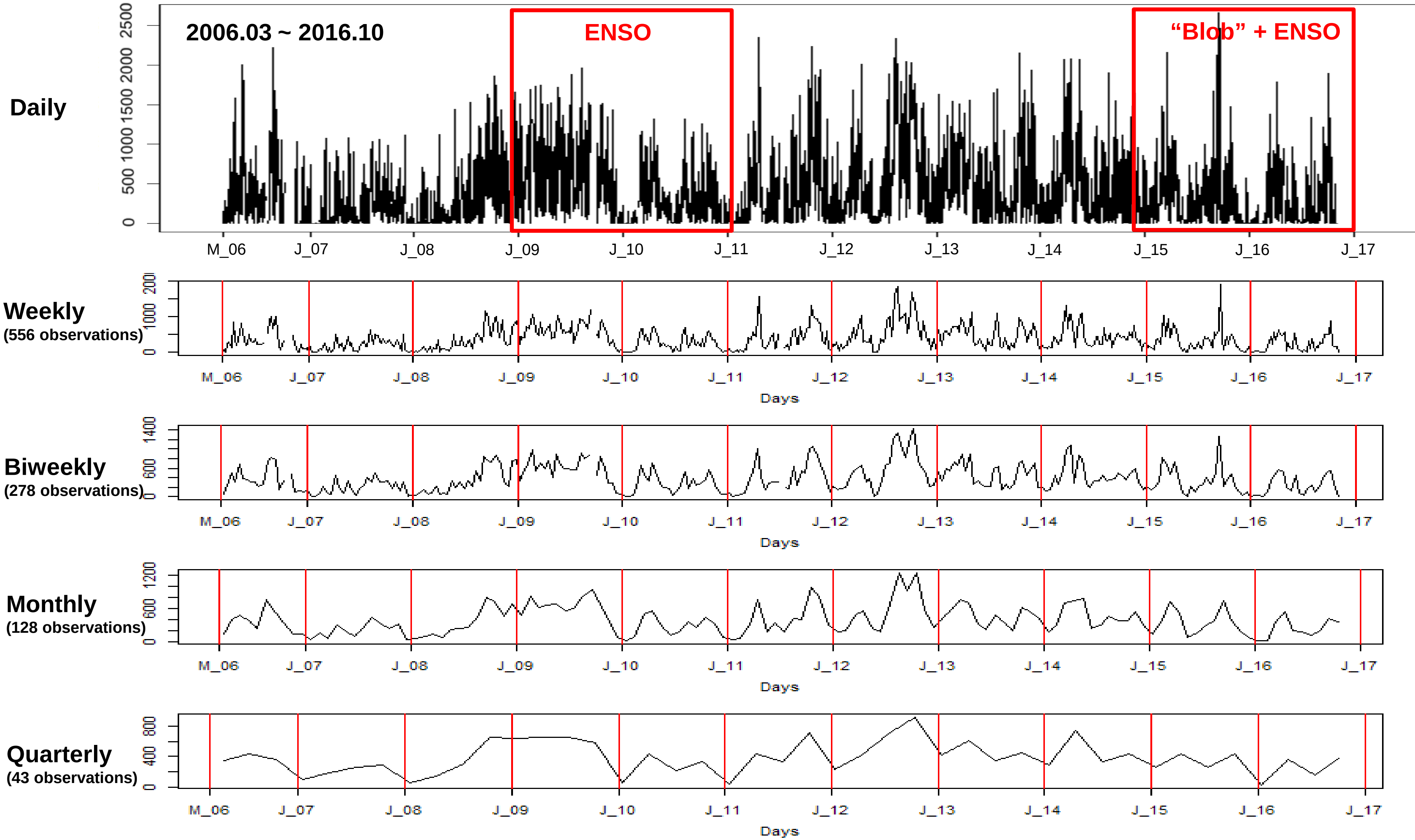
# Targeting zooplankton backscatter




- Migration zooplankton "biomass" (in Sv):

(average echo + |min average echo|) * number of echo pixels

# Migration Zoop Biomass Time Series



OCEAN NETWORKS CANADA SCIENCE

# 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

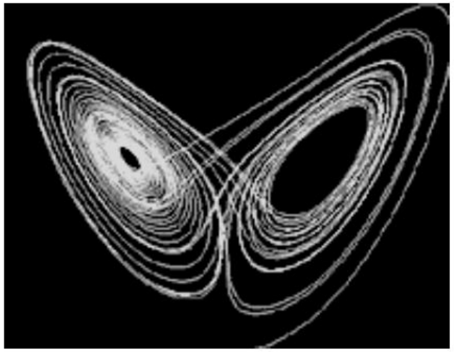
- State Dependency
  - Relationships among interacting variables change with different states of dynamical system
  - Lorenz butterfly attractor (Lorenz, 1963, J.Atmos.Sci.20:130-141)

The Lorenz system:

$$\frac{dx}{dt} = -sx + sy$$

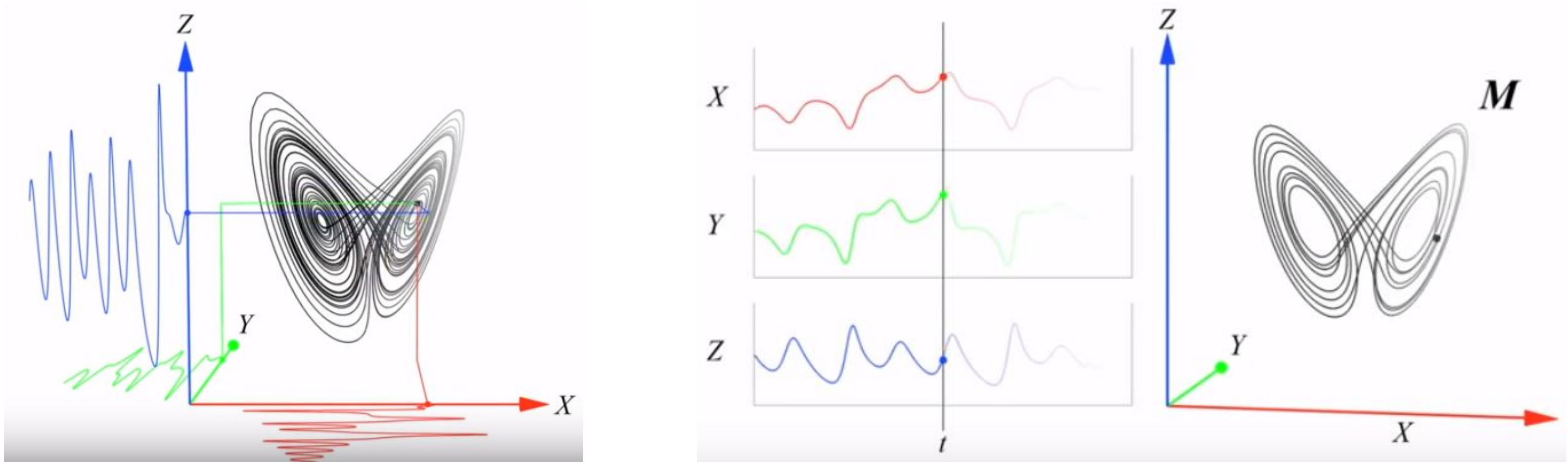
$$\frac{dy}{dt} = -xz + rx - y$$

$$\frac{dz}{dt} = xy - bz$$



OCEAN NETWORKS CANADA SCIENCE

# Non-linear Time Series Analytical Method




- State Space Reconstruction (SSR)

  - Takens' (1980) embedding theory:

    lagged coordinates state-space reconstruction

    (e.g. $\{x_t, x_{t-\tau}, x_{t-2\tau} \ldots x_{t-(E-1)\tau}\}$ ).

    (Takens 1980 in *Dynamic systems and turbulence* p366-381)

- Empirical Dynamic Modeling (EDM)

  Methods do not assume any set of equations governing the system but recover the dynamics from time series data

OCEAN NETWORKS CANADA SCIENCE

# 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 (our-of-sample predictability as criterion)

- Determining causal variables

  Convergent Cross Mapping (CCM)

- Forecasting

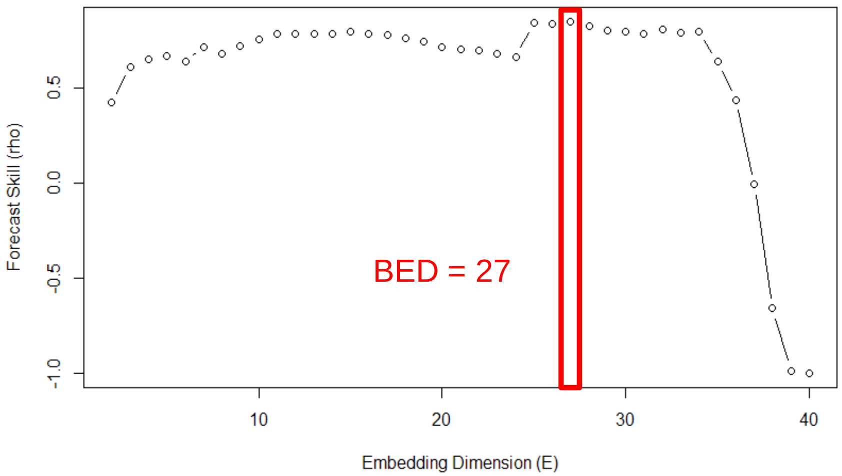
  Univariate EDM
  Multivariate EDM

Methods from Sugihara Lab, UCSD
Simplex: Sugihara and May, 1990, Nature, 344: 734-741
S-map: Sugihara, 1994, Philo. Trans.R.Soc.Lond.A, 348:477-495
CCM: Sugihara et al, 2012, Science, 338:496-500

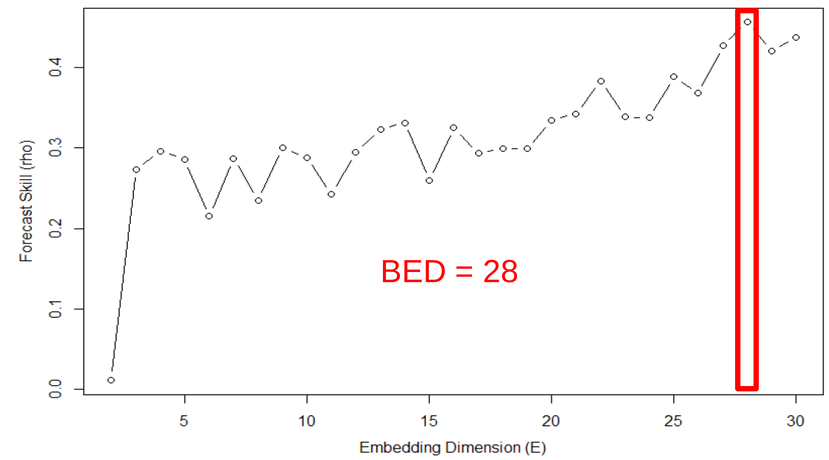
OCEAN NETWORKS CANADA SCIENCE

# Determining best embedding dimension

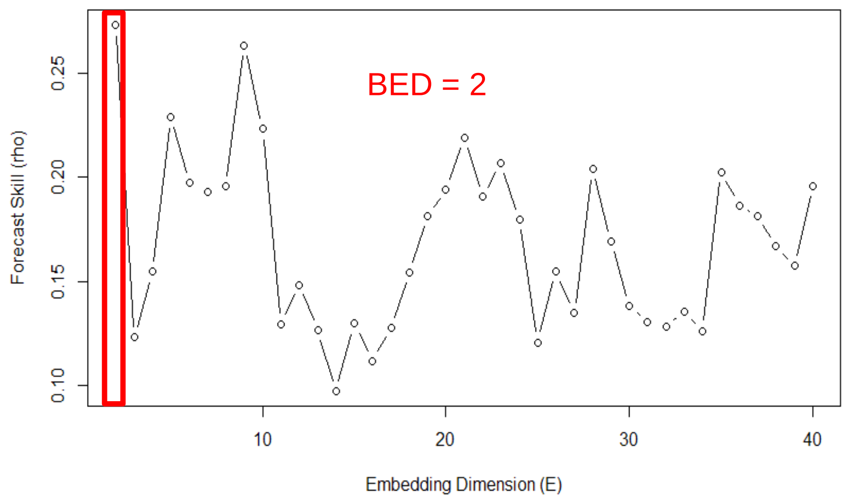
Quarterly



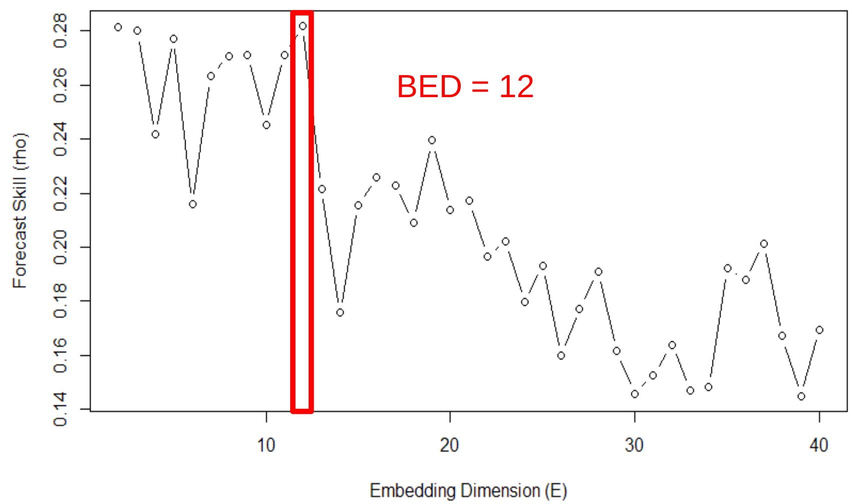

Monthly




Biweekly



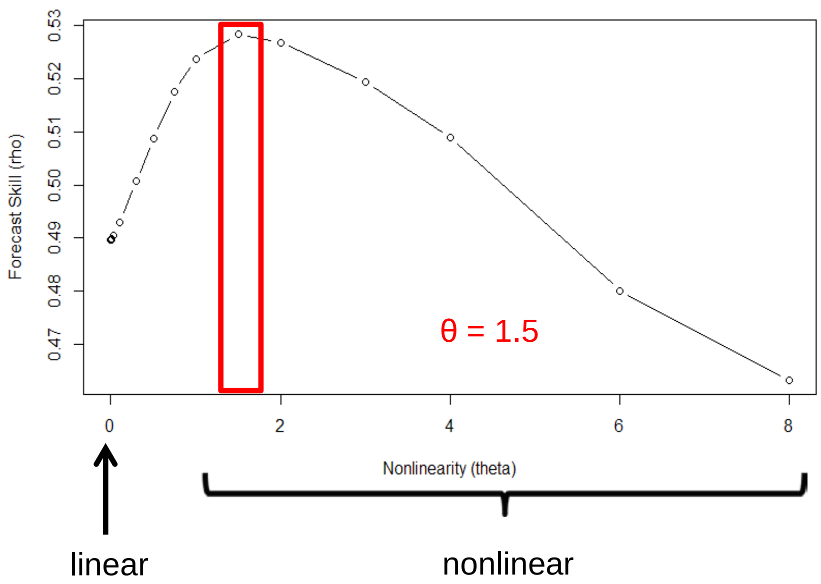

Weekly



OCEAN NETWORKS CANADA SCIENCE

# Quantifying nonlinearity

Quarterly




S-map:

locally weighted linear regression

**control state of dependency**

Weighting function is determined by θ

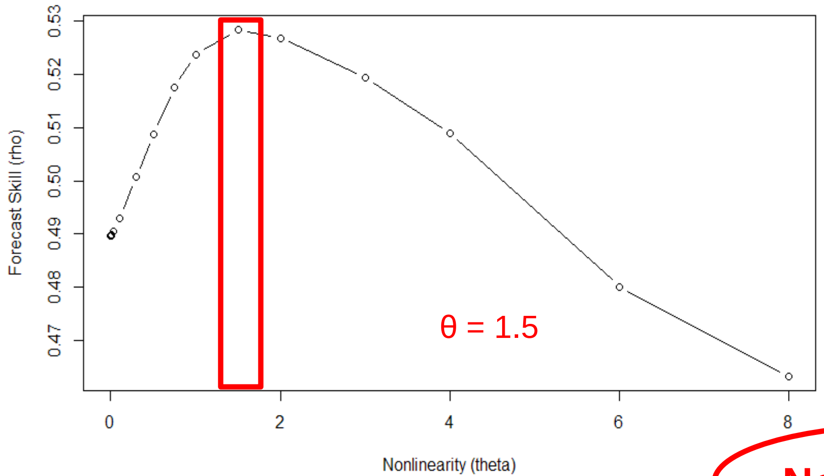
$$\omega(d) = e^{-\theta d / \bar{d}}$$

d: distance between the predictee and library points

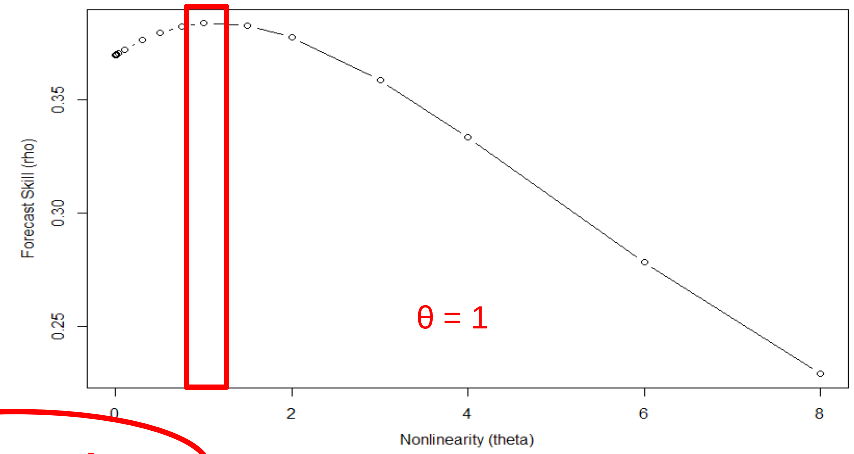
$\bar{d}$ : average distance between all library points

# Quantifying nonlinearity

Quarterly

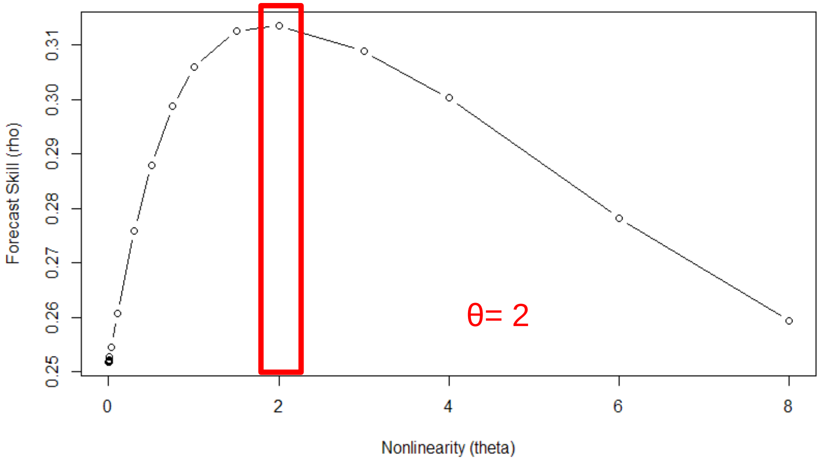



Monthly

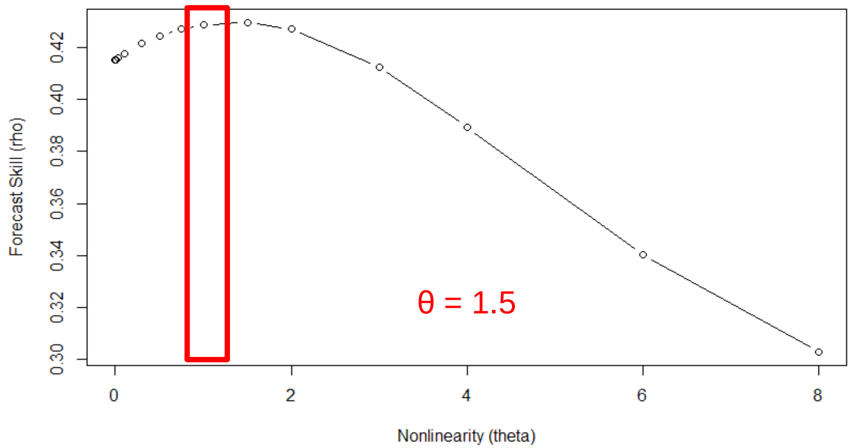



Nonlinearity

Biweekly




Weekly



OCEAN NETWORKS CANADA SCIENCE

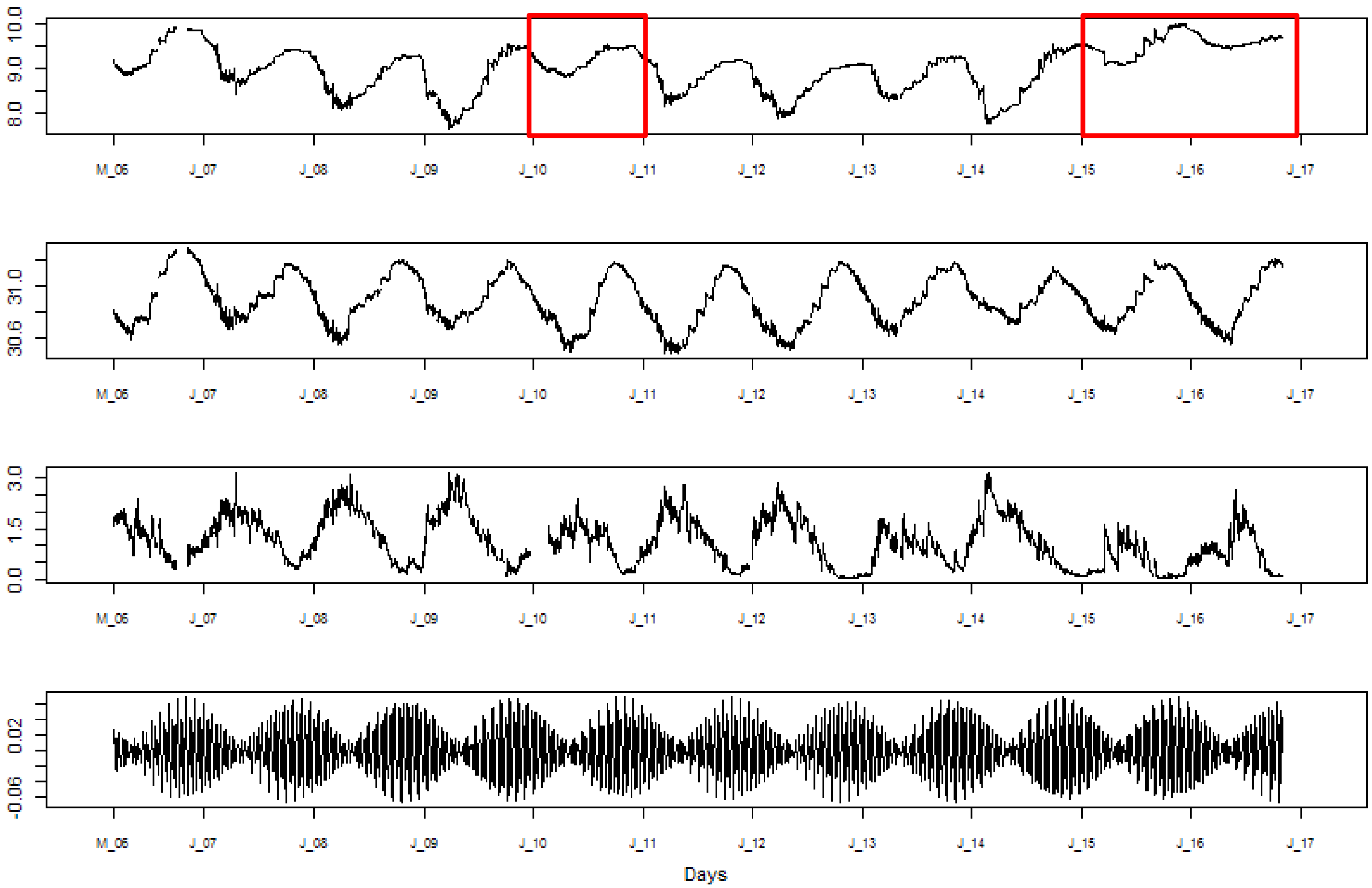
# Determining Causal Variables

**Temperature at 100m**

**Salinity at 100m**

**Oxygen at 100m**

**Tide height at Pat Bay**
(Foreman et al 2004)



OCEAN NETWORKS CANADA SCIENCE

# Environmental Variables

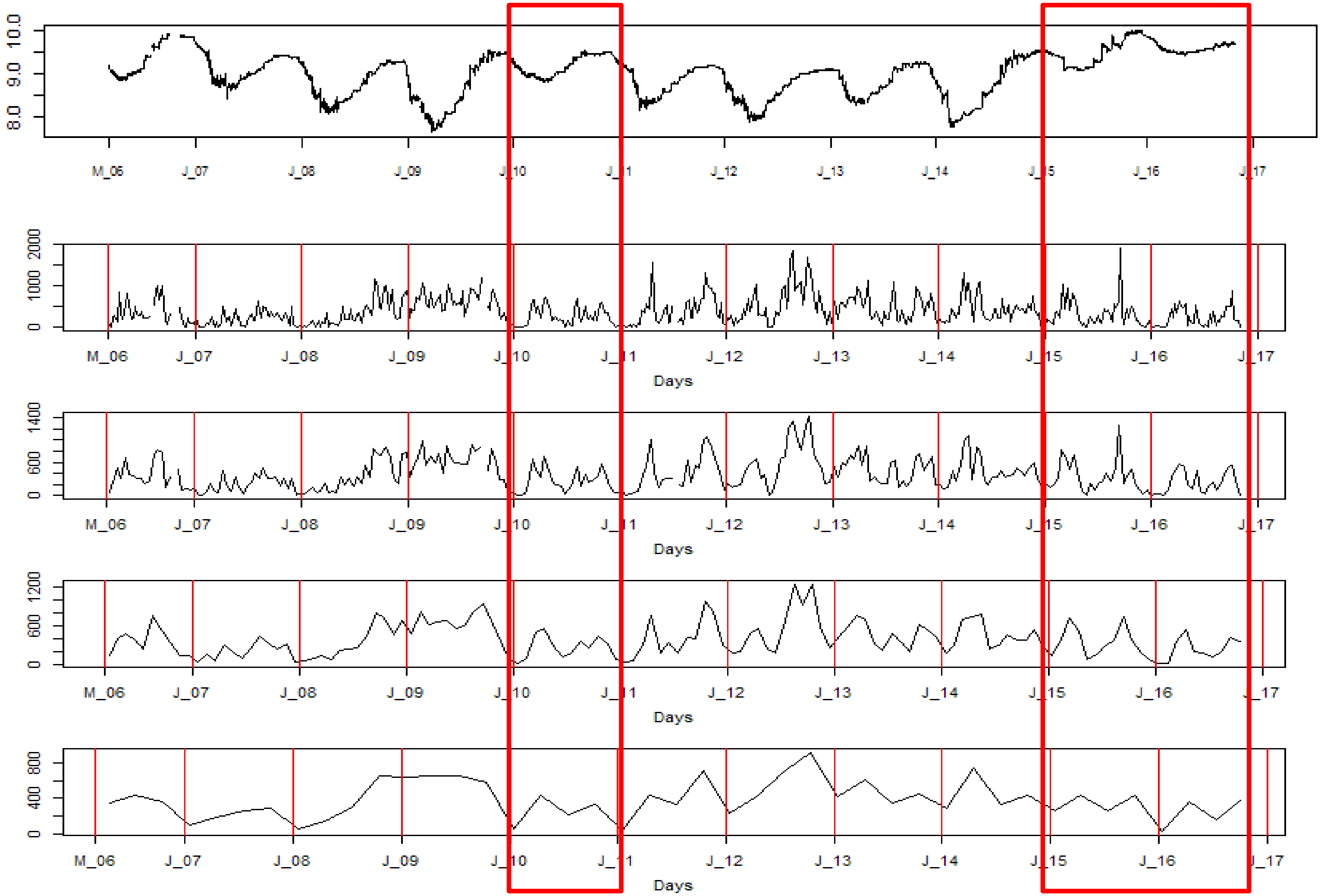
**Temperature at 100m**

**Weekly**
**(556 observations)**

**Biweekly**
**(278 observations)**

**Monthly**
**(128 observations)**

**Quarterly**
**(43 observations)**



OCEAN NETWORKS CANADA SCIENCE

# Determining Causal Variables

**Quarterly**

| Effect | Cause | BED | ρ_max | ρ_min | z | p_z | Kendall_tau | Kendll_p | Convergence |
|---|---|---|---|---|---|---|---|---|---|
| Biomass | **Temperature** | 11 | 0.509 | 0 | 2.478 | **0.007** | 1 | **<0.001** | YES |
| | **Salinity** | 7 | 0.597 | 0.037 | 2.874 | **0.002** | 1 | **<0.001** | YES |
| | **Oxygen** | 11 | 0.405 | 0 | 1.898 | **0.029** | 0.909 | **0.003** | YES |
| | Tide height | 33 | 0.284 | 0.051 | 1.067 | 0.143 | 0.642 | **0.035** | NO |

**Monthly**

| Effect | Cause | BED | ρ_max | ρ_min | z | *p*_z | Kendall_tau | Kendll_*p* | Convergence |
|---|---|---|---|---|---|---|---|---|---|
| Biomass | **Temperature** | 18 | 0.332 | 0 | 2.721 | **0.003** | 0.972 | **<0.001** | YES |
| | **Salinity** | 11 | 0.309 | 0 | 2.519 | **0.006** | 0.970 | **<0.001** | YES |
| | **Oxygen** | 13 | 0.323 | 0 | 2.613 | **0.005** | 0.992 | **<0.001** | YES |
| | Tide height | 2 | 0.038 | 0 | 0.3 | 0.382 | 0.487 | **0.024** | NO |

**Biweekly**

| Effect | Cause | BED | ρ_max | ρ_min | z | *p*_z | Kendall_tau | Kendll_*p* | Convergence |
|---|---|---|---|---|---|---|---|---|---|
| Biomass | Temperature | 10 | 0.059 | 0 | 0.678 | 0.249 | 1 | **0.003** | NO |
| | Salinity | 8 | 0.083 | 0 | 0.963 | 0.168 | 0.709 | **<0.001** | NO |
| | Oxygen | 22 | 0.073 | 0 | 0.85 | 0.198 | 0.964 | **<0.001** | NO |
| | **Tide height** | 9 | 0.248 | 0.104 | 1.817 | **0.043** | 0.524 | **0.029** | YES |

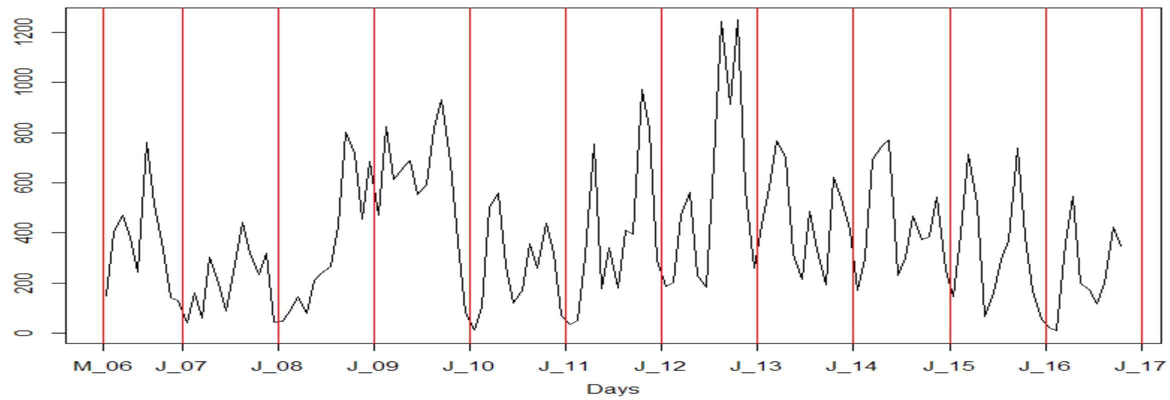
**Weekly**

| Effect | Cause | BED | ρ_max | ρ_min | z | *p*_z | Kendall_tau | Kendll_*p* | Convergence |
|---|---|---|---|---|---|---|---|---|---|
| Biomass | Temperature | 7 | 0.119 | 0.045 | 0.109 | 0.113 | 0.524 | **0.008** | NO |
| | **Salinity** | 12 | 0.122 | 0.014 | 1.788 | **0.037** | 0.876 | **<0.001** | YES |
| | Oxygen | 2 | 0 | 0 | 0 | 0.500 | -0.79 | 0.083 | NO |
| | **Tide height** | 8 | 0.123 | 0.0007 | 0.022 | **0.022** | 0.657 | **<0.001** | YES |

OCEAN NETWORKS CANADA SCIENCE

# Forecasting

**Monthly scale**




✓ **Information on historical trajectories (reconstructed state space)**

✗ Equations assume a mechanistic relationship between variables

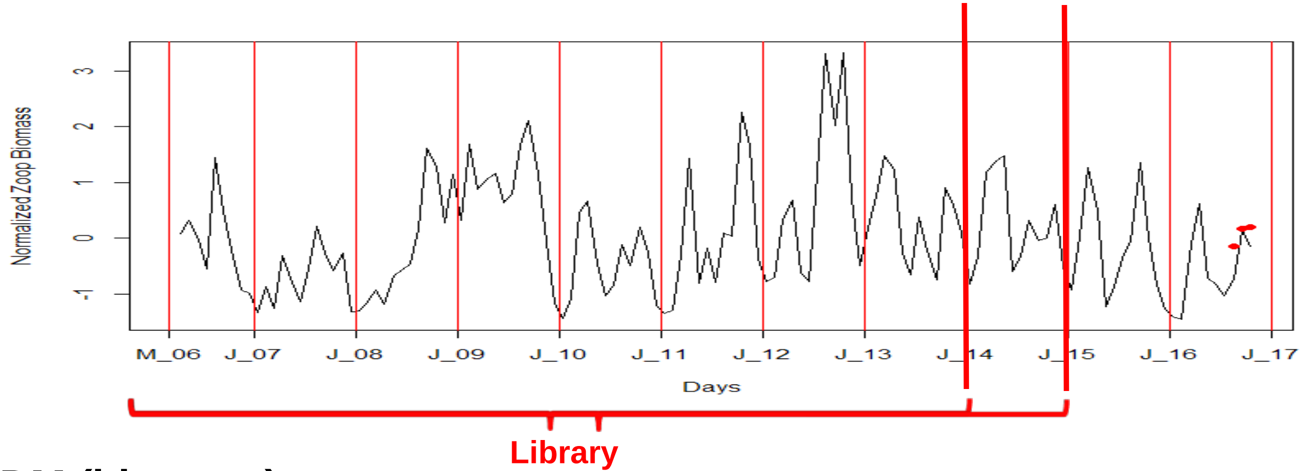
→ Forecasting

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

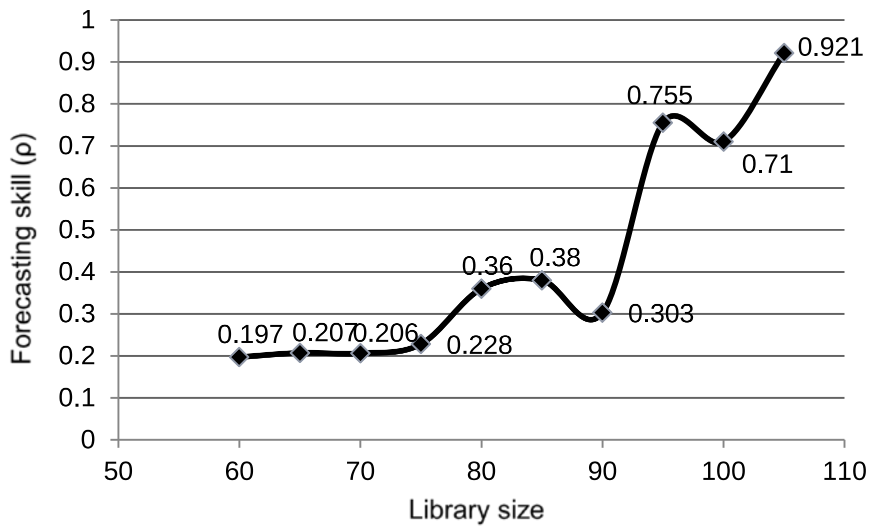
→ Multivariate embedding (multiple variables)

# Forecasting

## Monthly scale




## Univariate EDM (biomass)

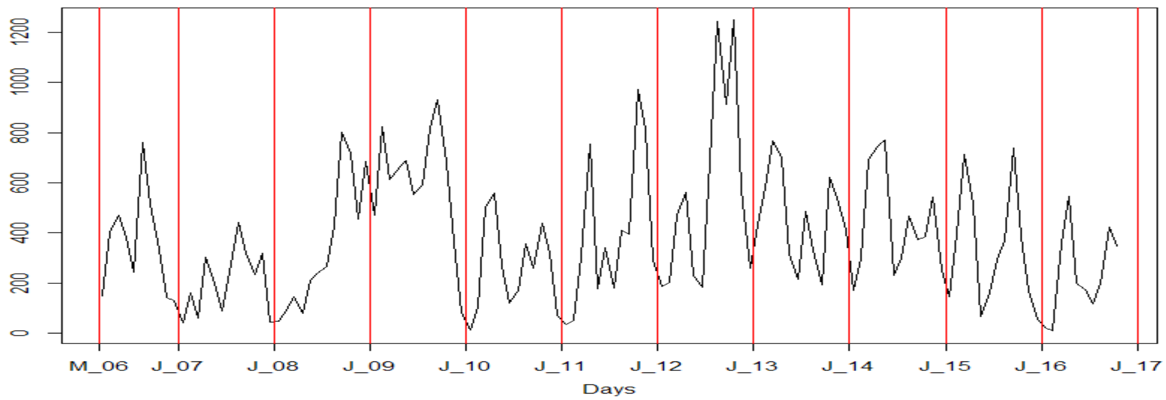



| Library (# of observations) | Prediction (# of observations) | Forecasting skill |
|---|---|---|
| 95 | 13 | 0.755 |
| 100 | 8 | 0.710 |
| 105 | 3 | 0.921 |

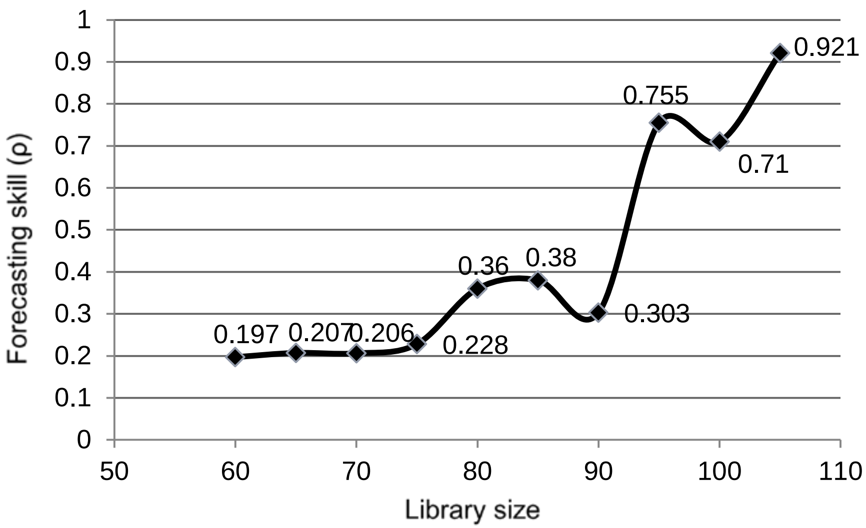
OCEAN NETWORKS CANADA SCIENCE

# Forecasting

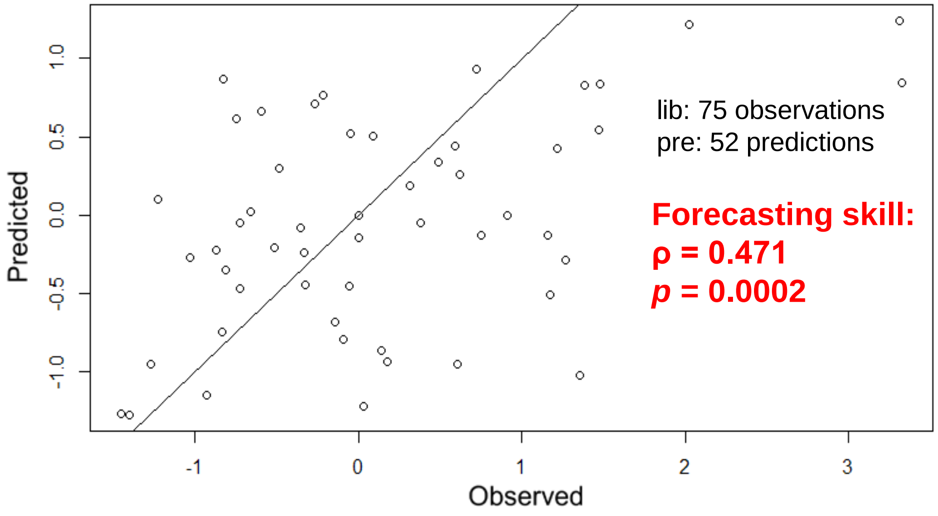
**Monthly scale**




## Univariate EDM (biomass)




## Multivariate EDM (temp, sal, oxy)



OCEAN NETWORKS CANADA SCIENCE

# 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**

**CORRELATION ≠ CAUSATION**

- Nonlinear Dynamics:
  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