Accelerating Salinity Trends at Station ALOHA in the North Pacific Subtropical Gyre

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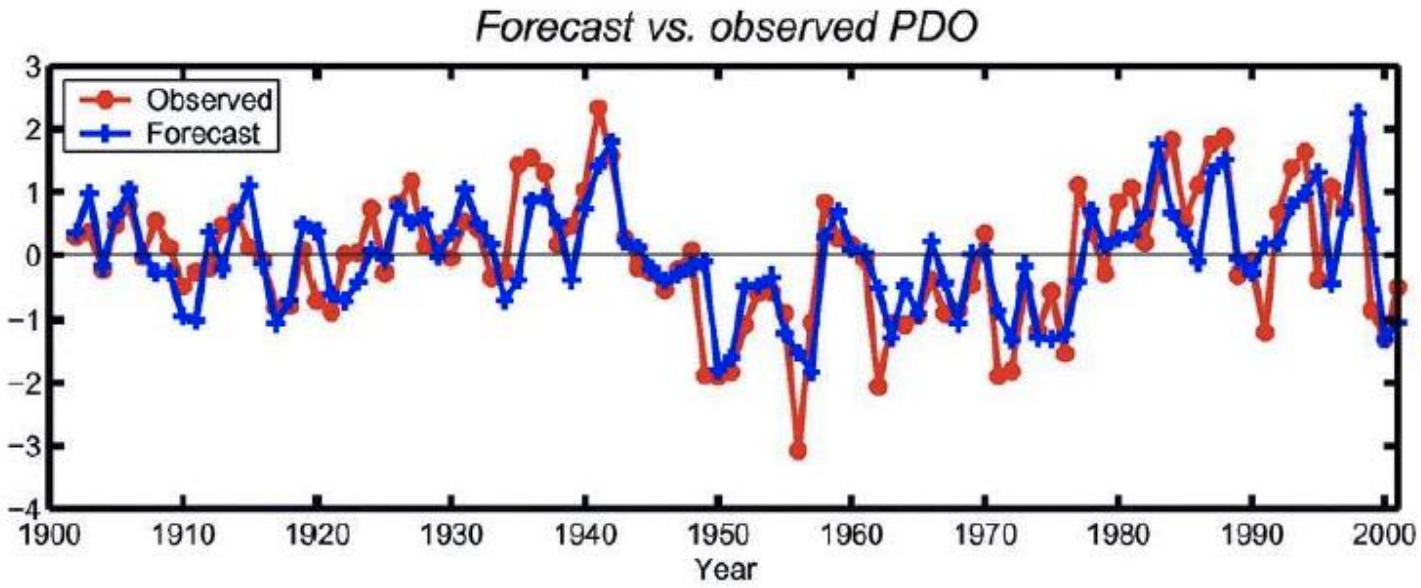
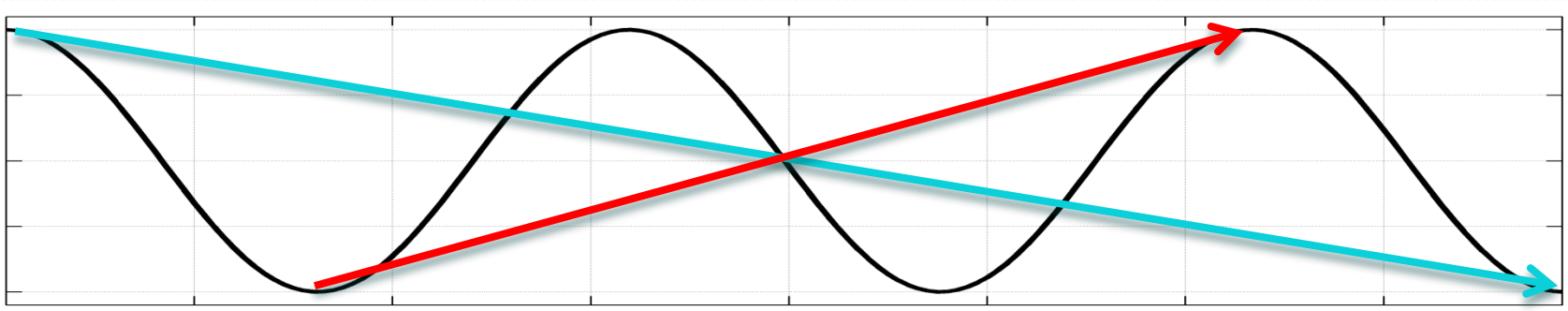
Motivation

- Intensification of hydrological cycle → salinity trends
- We also observe natural decadal to multi-decadal climate variations (like PDO, NAO)
- **How do we detect and separate long-term trends?**



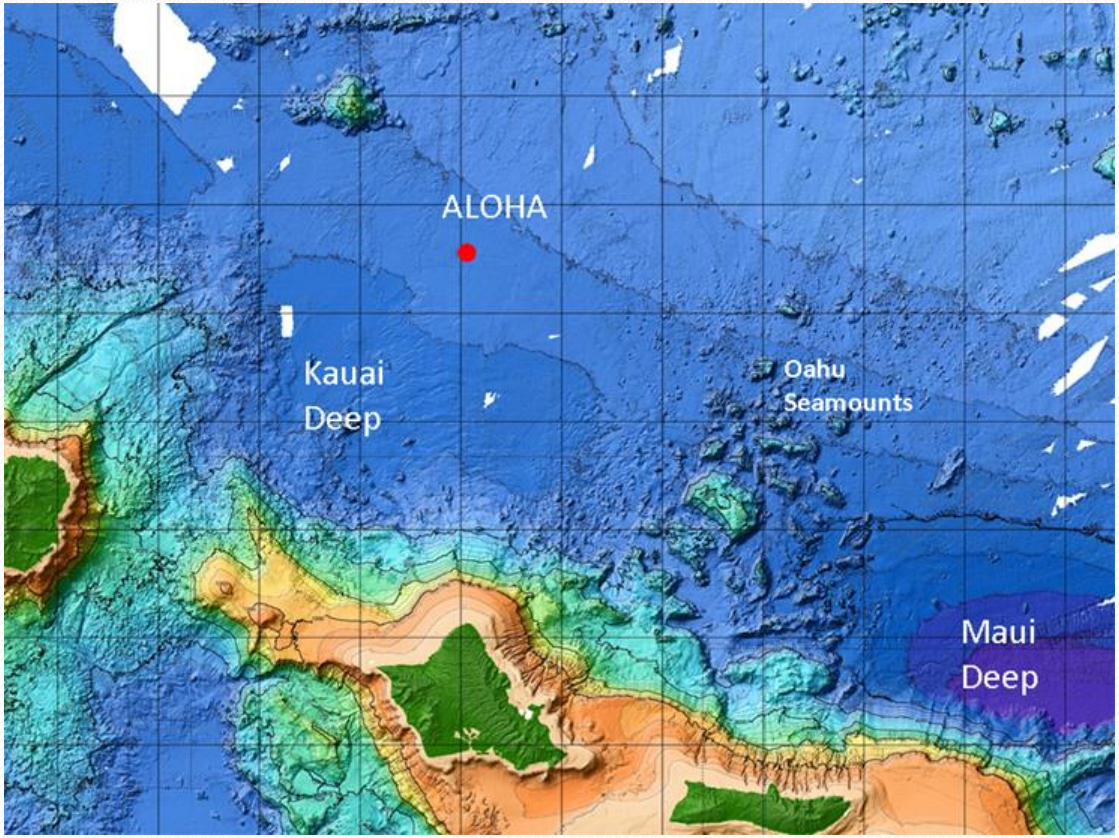
Trend Estimation

- **What do we mean by "trend"?**
  - Secular variation, though rate may change
  - Usually linear approximation (constant change) with least squares regression; sensitive to outliers and end points
- **How to separate trends from "noise" and other climate variability?**
  - Model natural variability to reduce end effects
  - Long, high-resolution observations



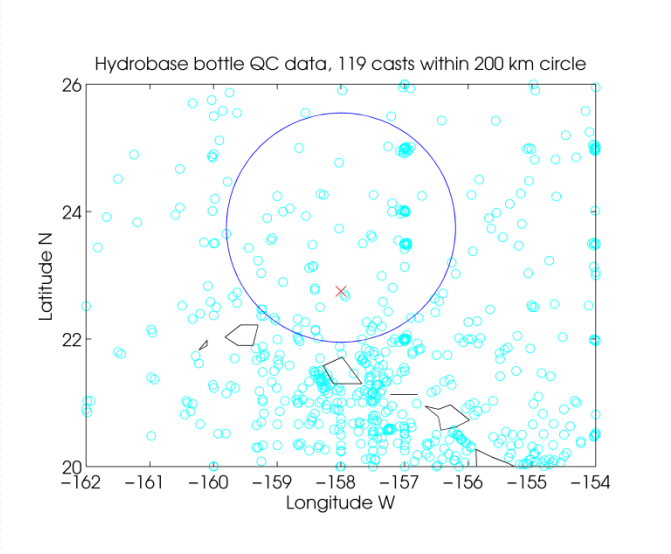
Hawaii Ocean Time-series at Station ALOHA

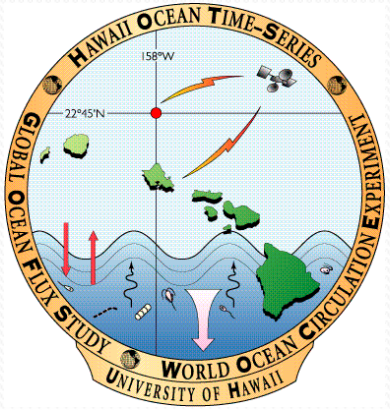
- Located within North Pacific Subtropical Gyre
- 10 km radius circle
  - 22°45' N 158° W
  - 4800 m deep
- Occupied ~monthly since late 1988

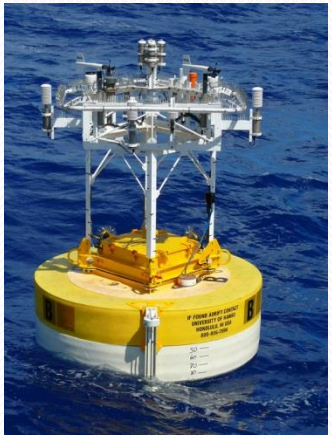


Station ALOHA Salinity Record

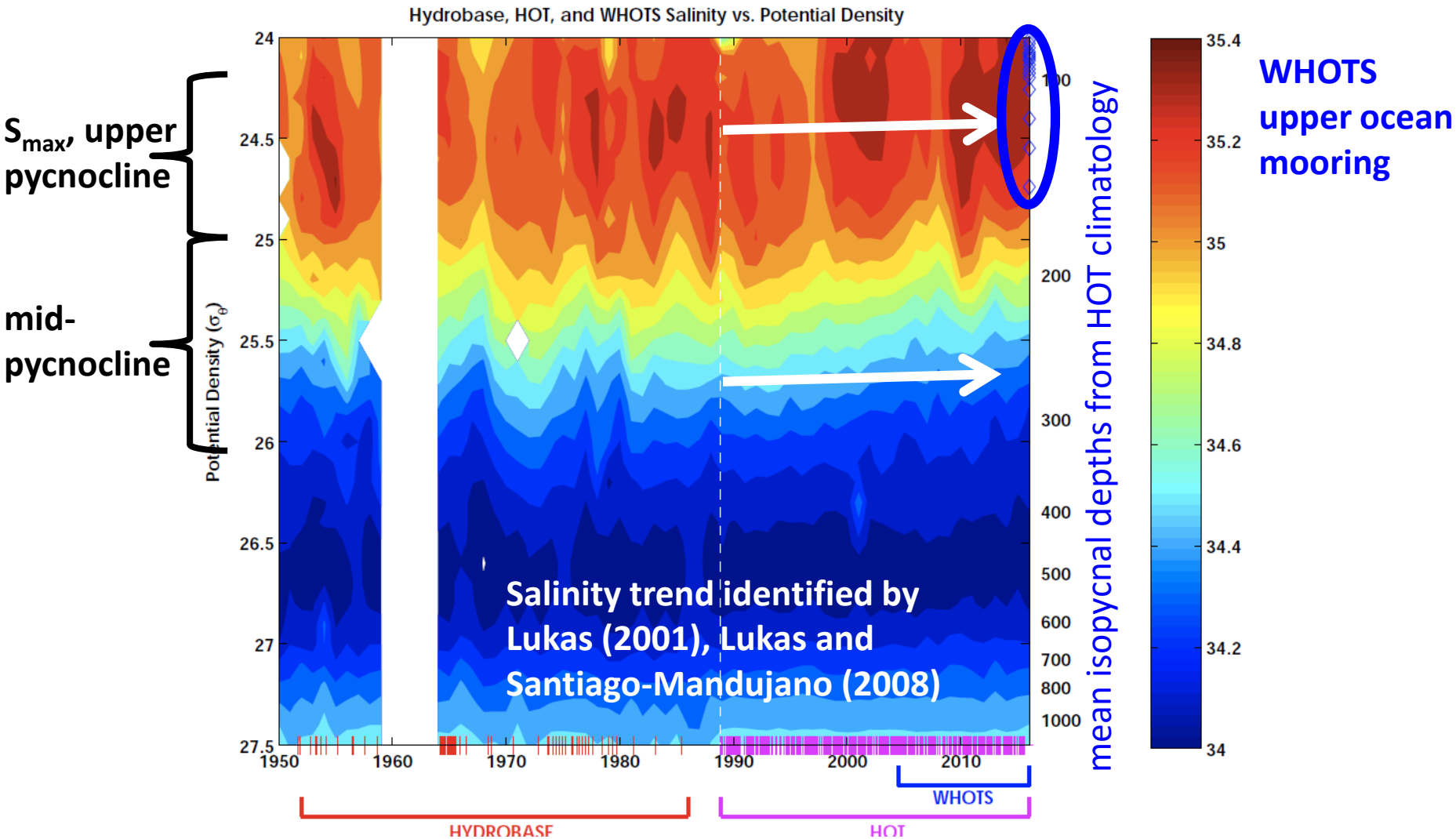
- **Hydrobase**
  - Bottle and CTD salinity from 200 km radius around ALOHA
  - 1952 to 1987
- **Hawaii Ocean Time-series**
  - Near-monthly sampling of the upper 1000m of the ocean at ALOHA
  - 1988 to present
- **WHOTS Mooring**
  - Continuous hydrological measurements (0 – 150m)
  - 2004 to present



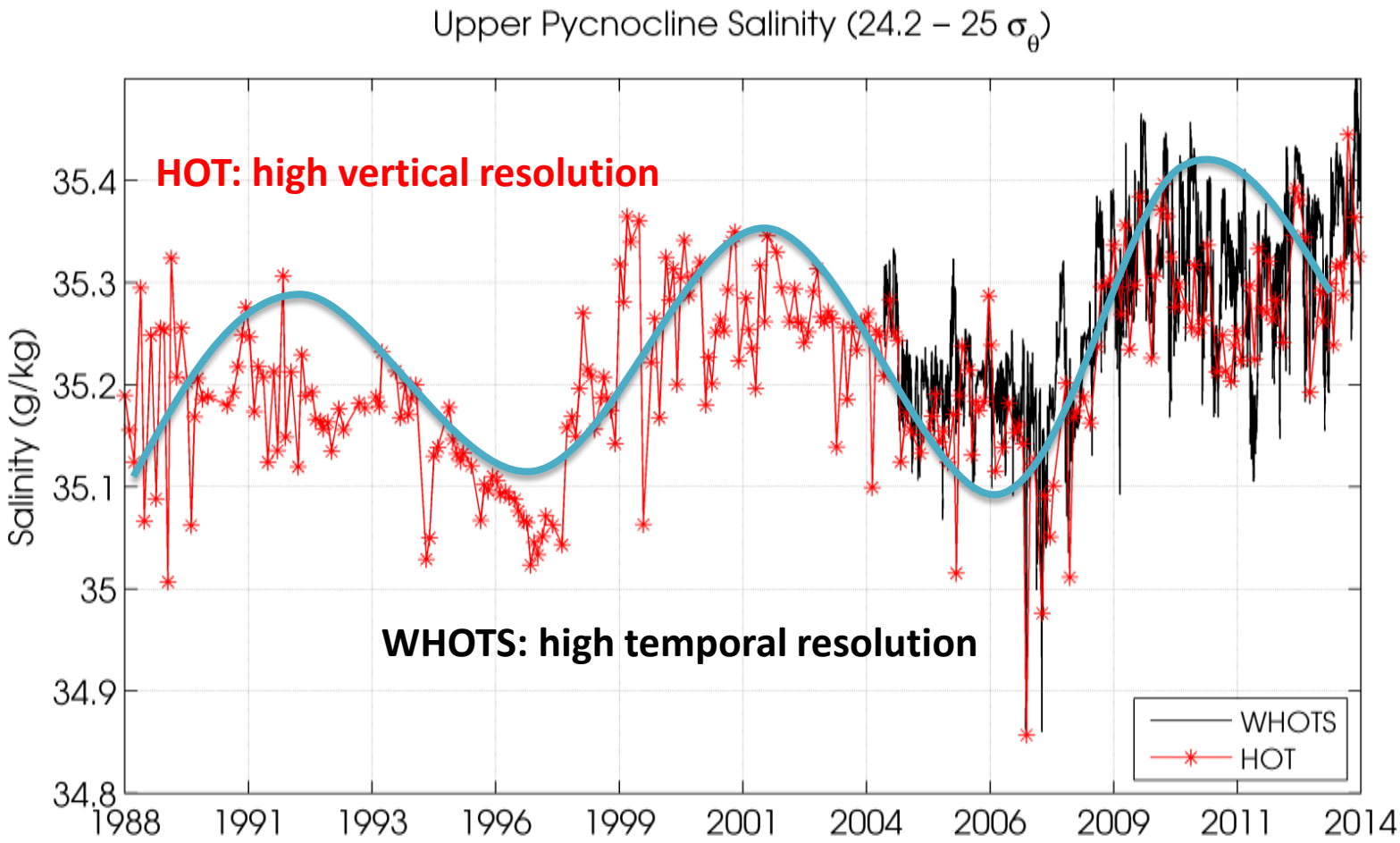




Station ALOHA Salinity Record



HOT and WHOTS Observations



Decadal trend?

Multiple Linear Regression

Full Model:

- Mean, Trend
- Annual Harmonics
  - 1, 1/2, 1/3
- Interannual
  - 2, 4 years
- Decadal

Sub-models:

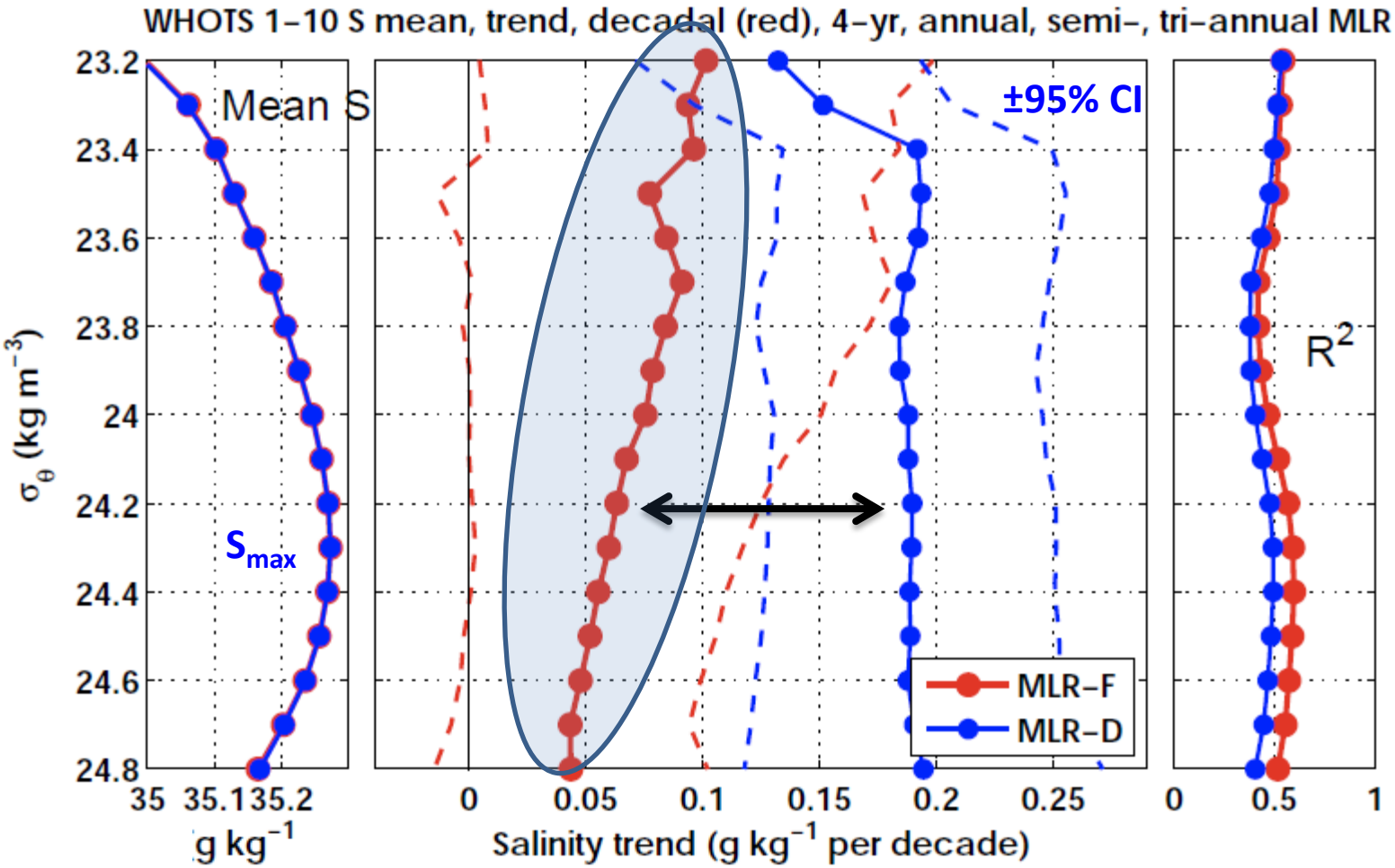
- Exclude decadal
- Add 20 year?

$$y(t) = a_0 + a_1 t + \sum_{i=2}^{M} (a_i \cos \omega_i \mathrm{t} + b_i \sin \omega_i \mathrm{t})$$

$$A_i = \sqrt{{a_i}^2 + {b_i}^2}, \qquad \varphi_i = \tan^{-1}(b_i/a_i)$$

Where t is time, and ω_i, A_i, and φ_i are the harmonics frequency, amplitude and phase respectively.

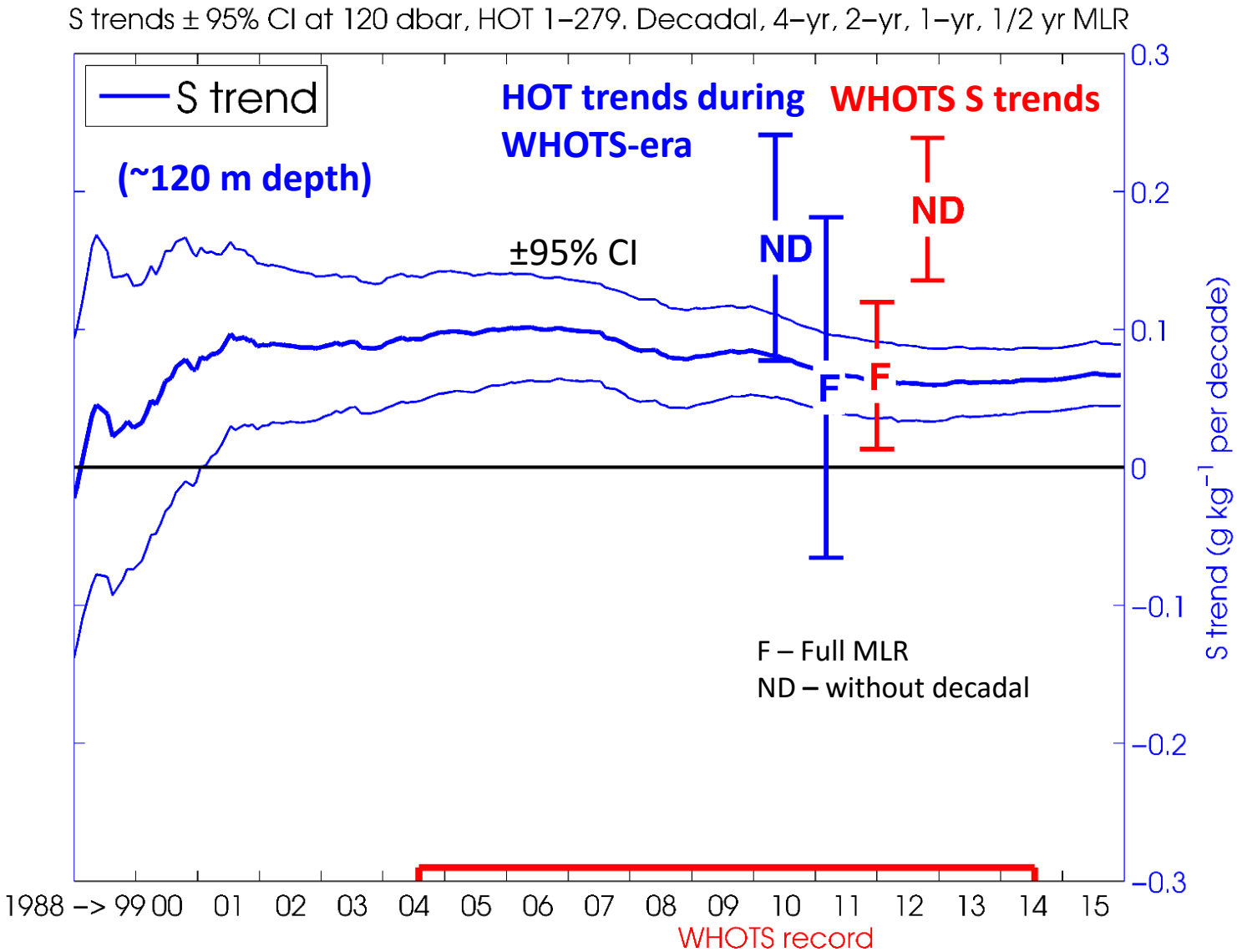
WHOTS Salinity Trends 2004 - 2014



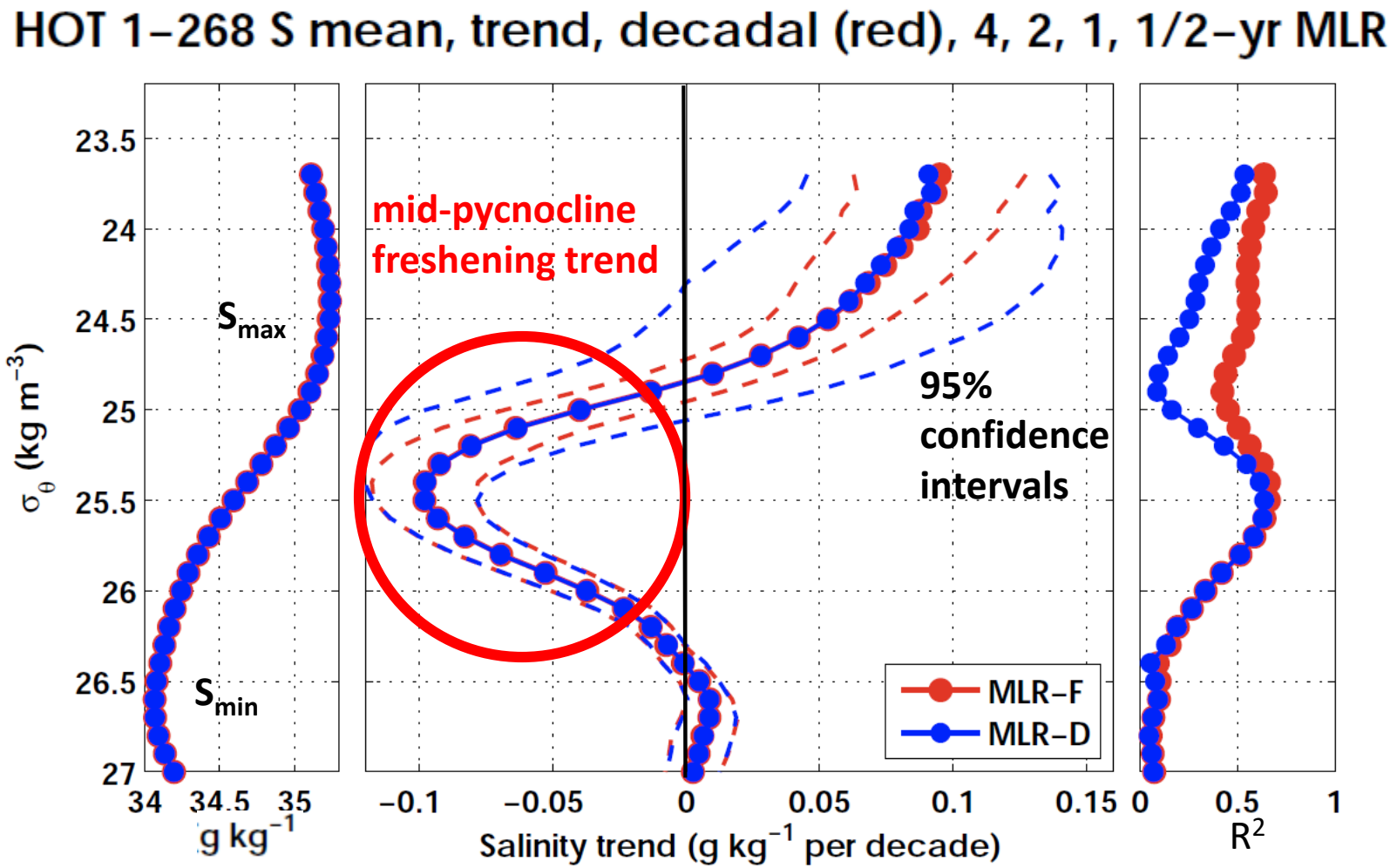
Increasing salinity in mixed-layer and Upper Pycnocline/S_{max}

2-4X larger trends from MLR w/o decadal cycle

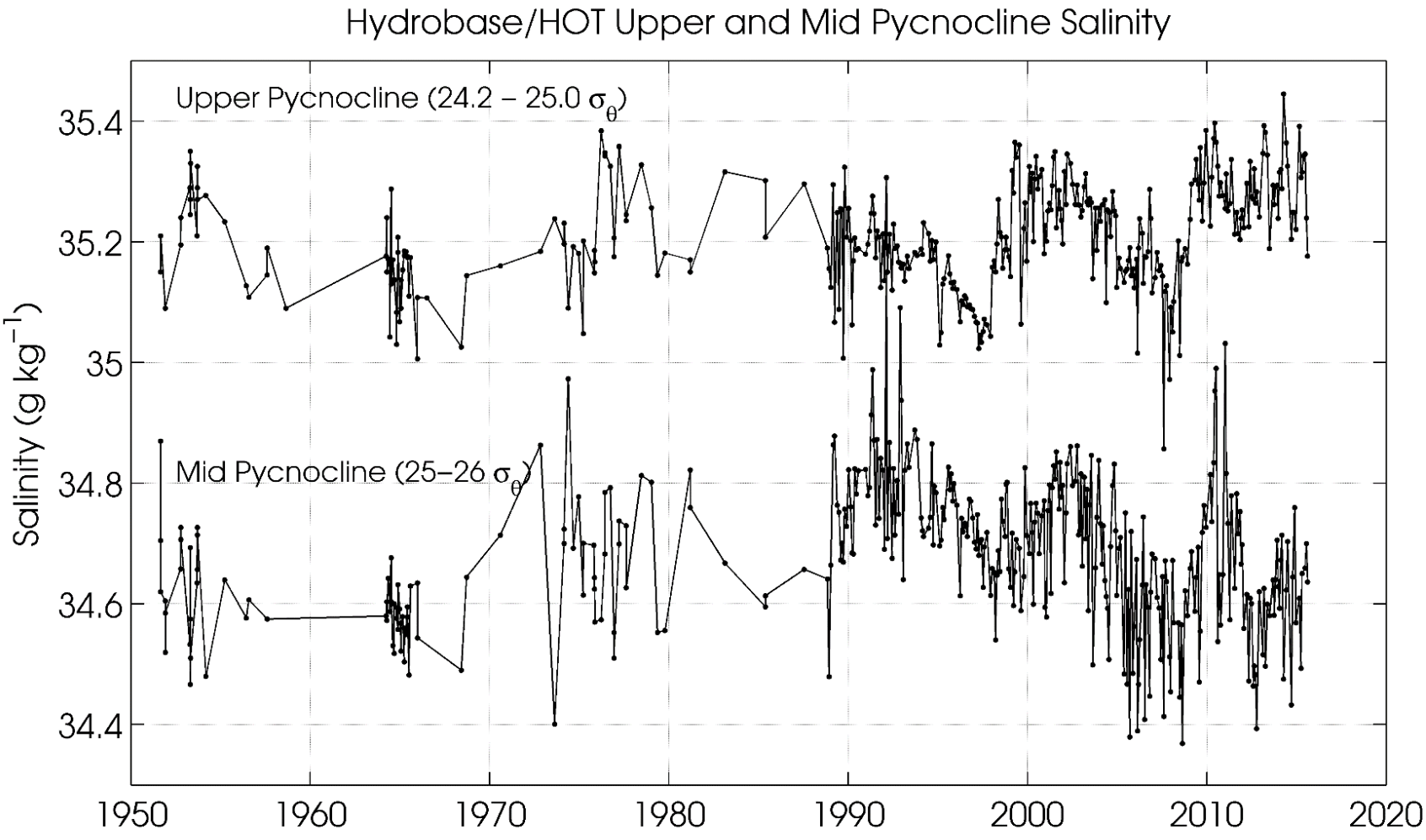
Salinity Trends in the Upper Pycnocline



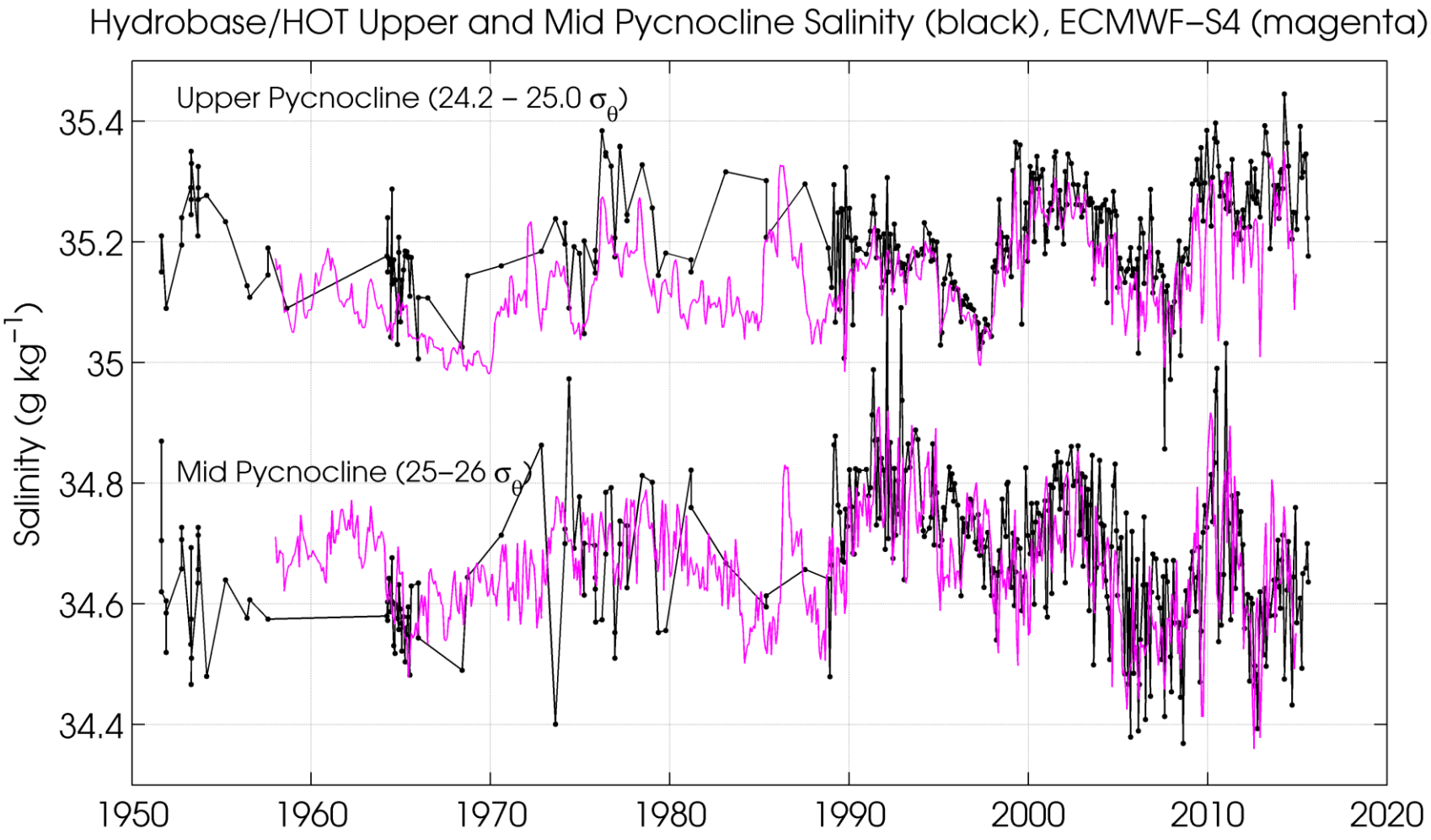
HOT Salinity Trends 1988 – 2015



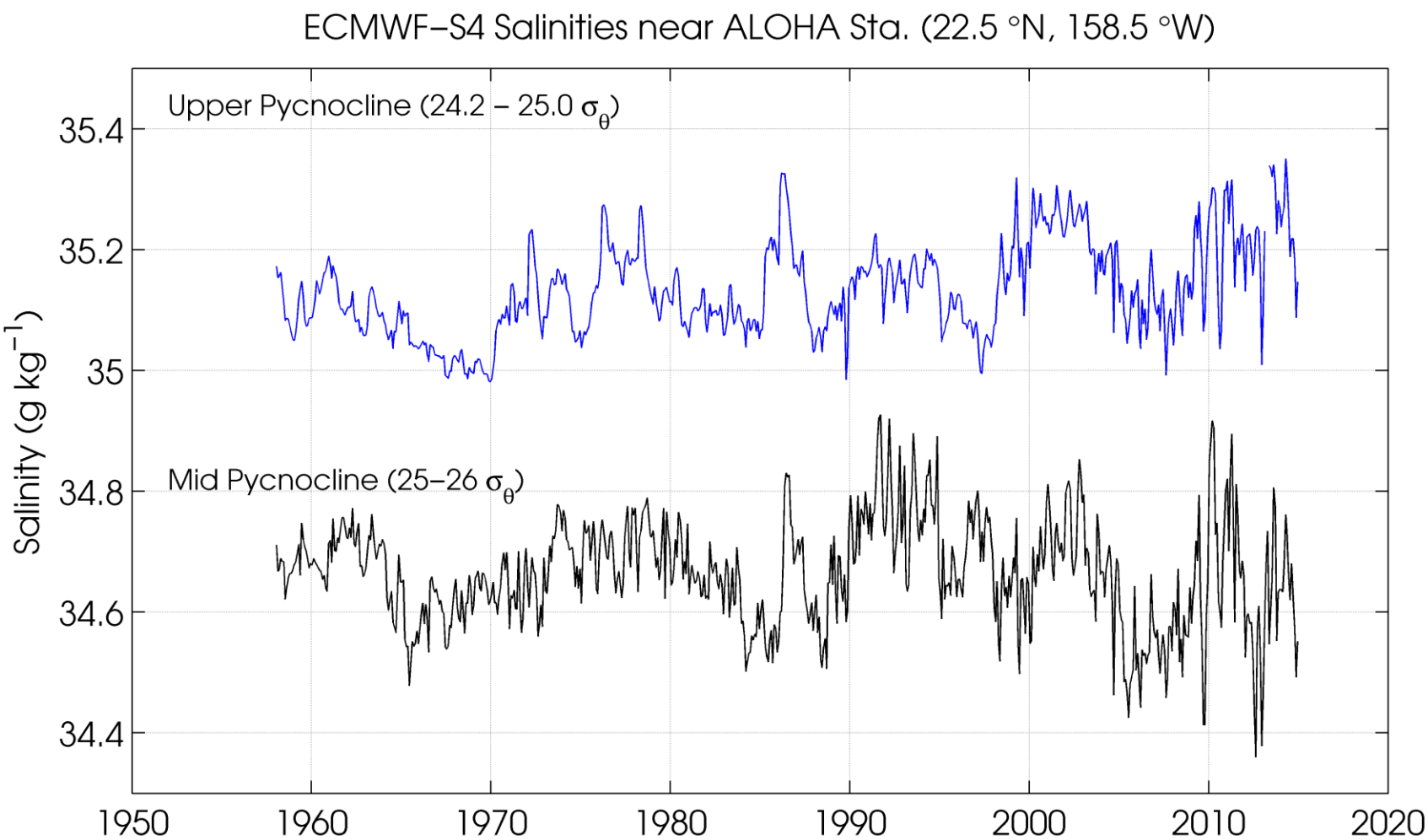
Hydrographic Record for Station ALOHA



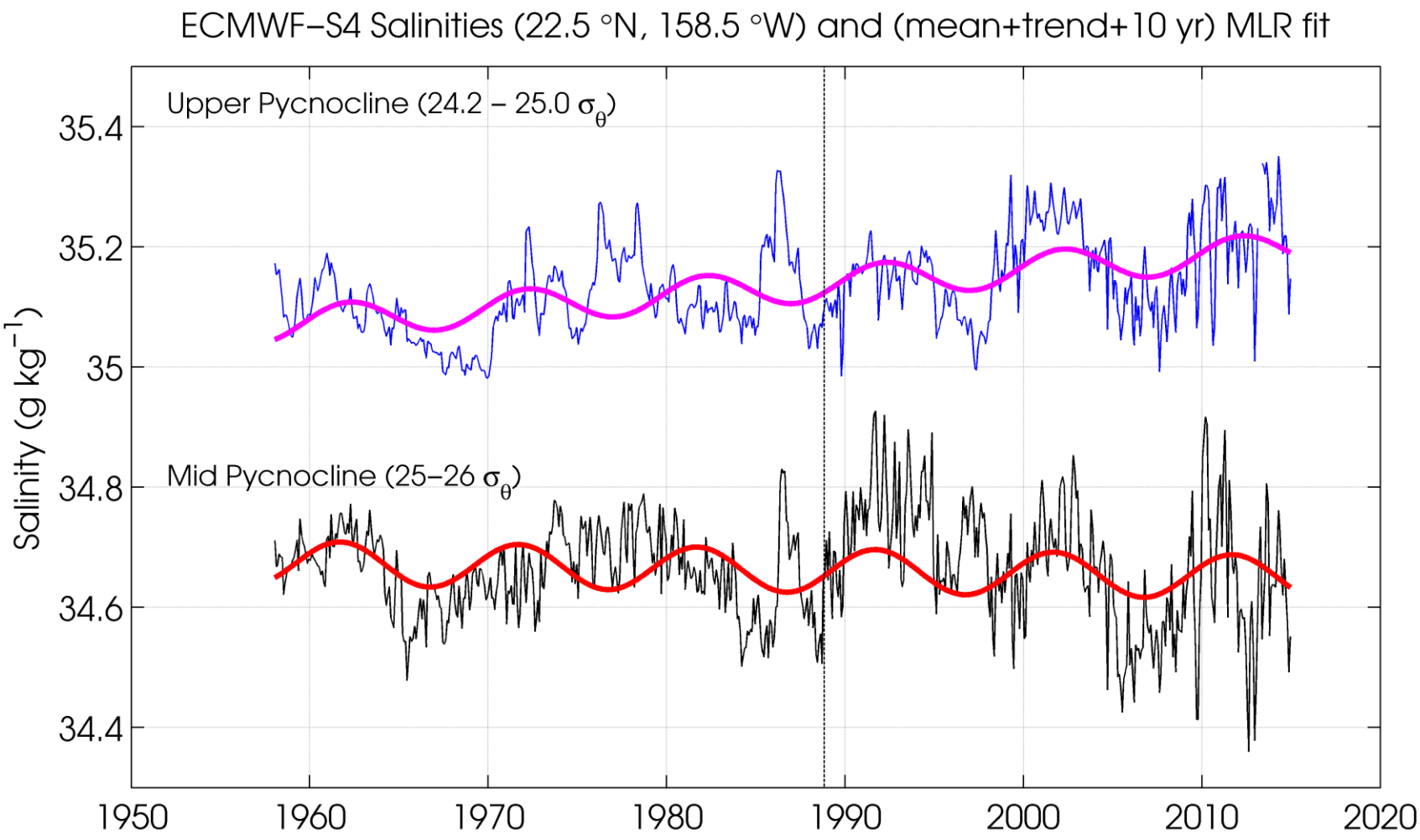
ECMWF S4 Reanalysis



ECMWF Reanalysis S4 at Station ALOHA



MLR Linear Trend + Decadal



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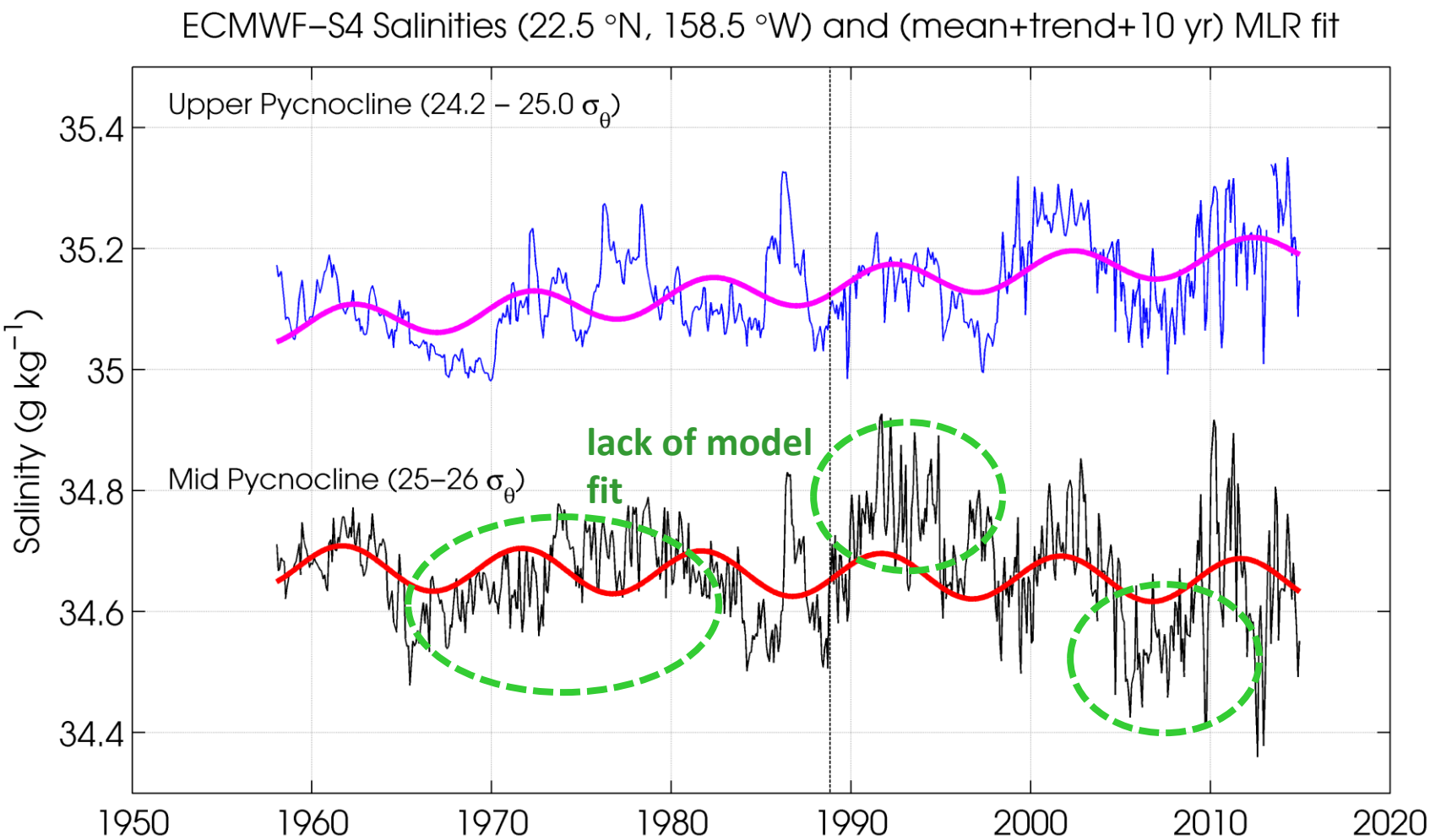
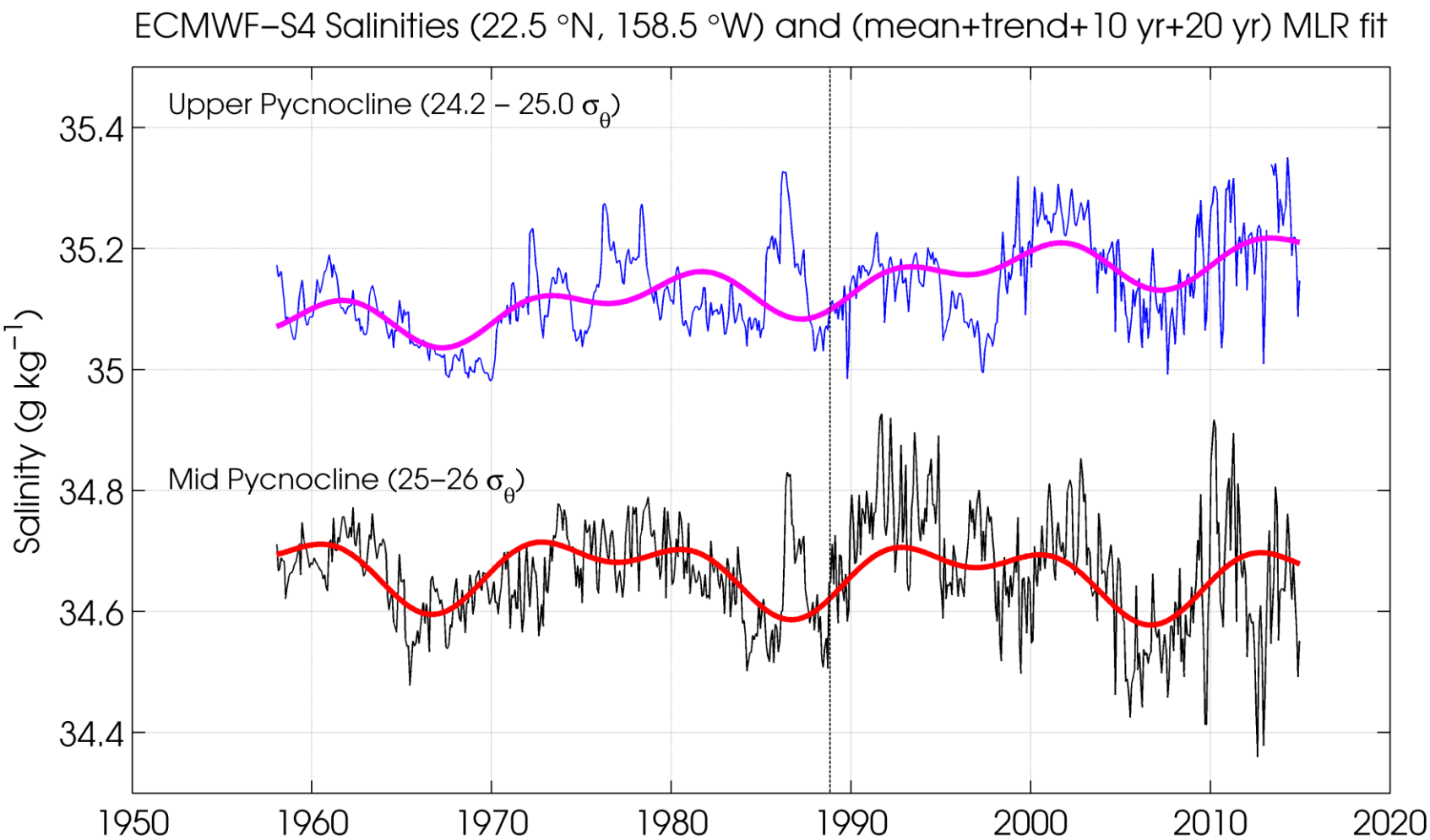
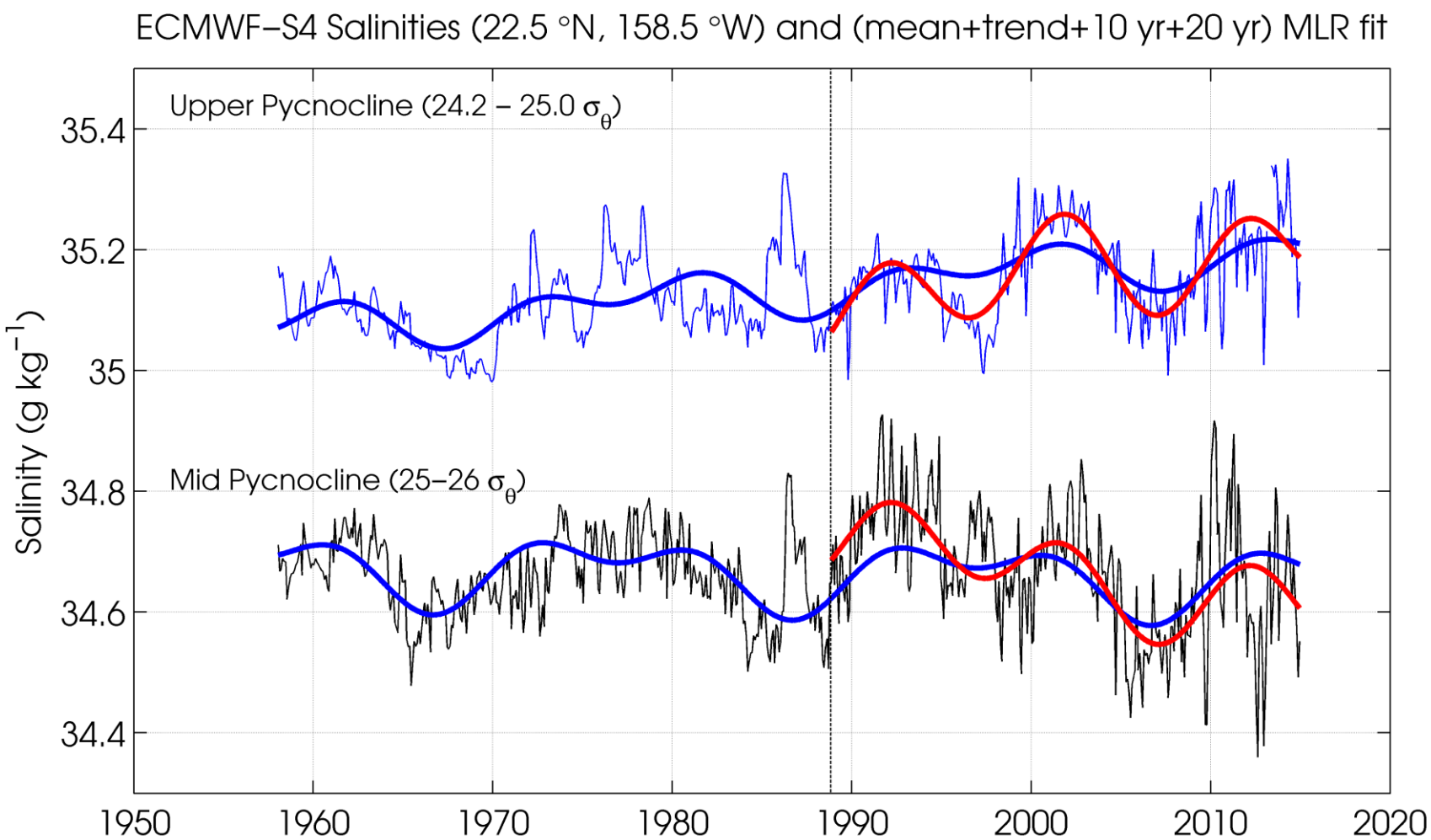


Adding 20-Year Cycle



Comparing HOT-era with Whole Record



ECMWF S4 Salinity Trends at ALOHA

Upper pycnocline with (without) 20-year cycle

S-Trend g kg^{-1} $decade^{-1}$	Pre-HOT	HOT-era	Whole Record
Linear trend	0.023(0.020)	0.037 (0.033)	0.024(0.022)
95% CI	0.027(0.034)	0.019 (0.021)	0.012(0.013)
R^2	0.29(0.08)	0.55 (0.48)	0.36(0.30)

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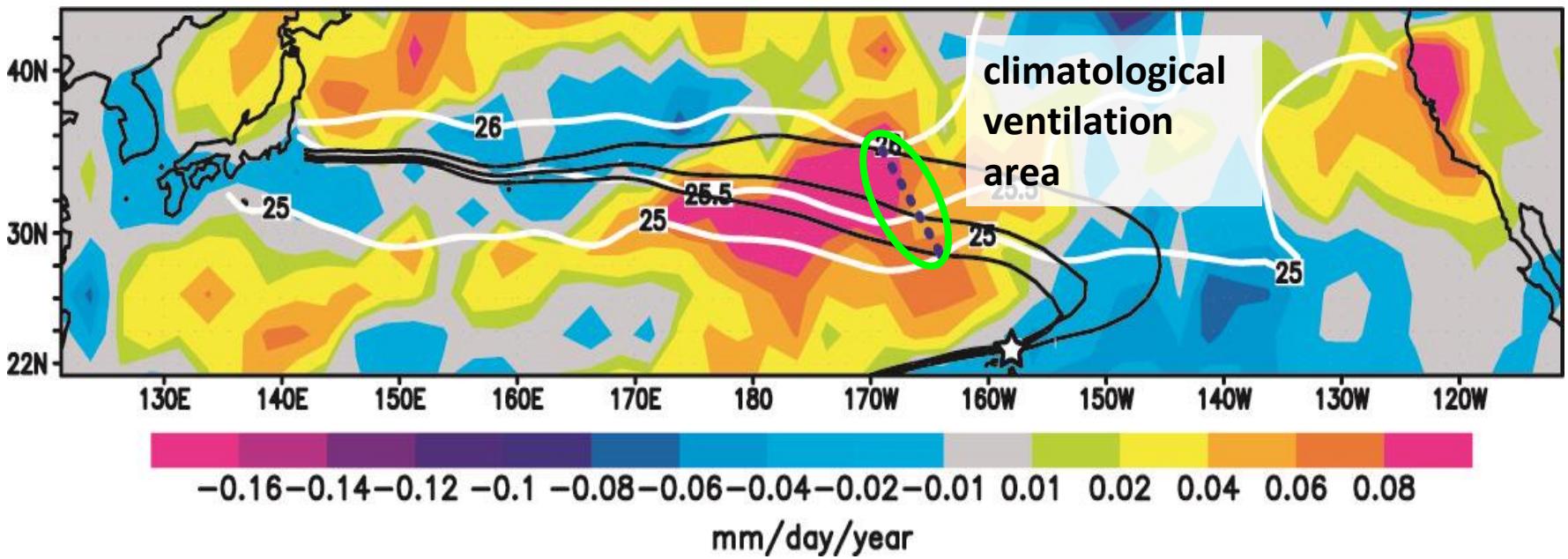
Mid pycnocline with (without) 20-year cycle

S-Trend g kg^{-1} decade^{-1}	pre-HOT	HOT-era	Whole Record
Linear trend	-0.019(-0.006)	-0.052 (-0.059)	0.004(-0.004)
95% CI	0.019(0.033)	0.033 (0.33)	0.011(0.140)
R^2	0.31(0.05)	0.35 (0.32)	0.22(0.09)

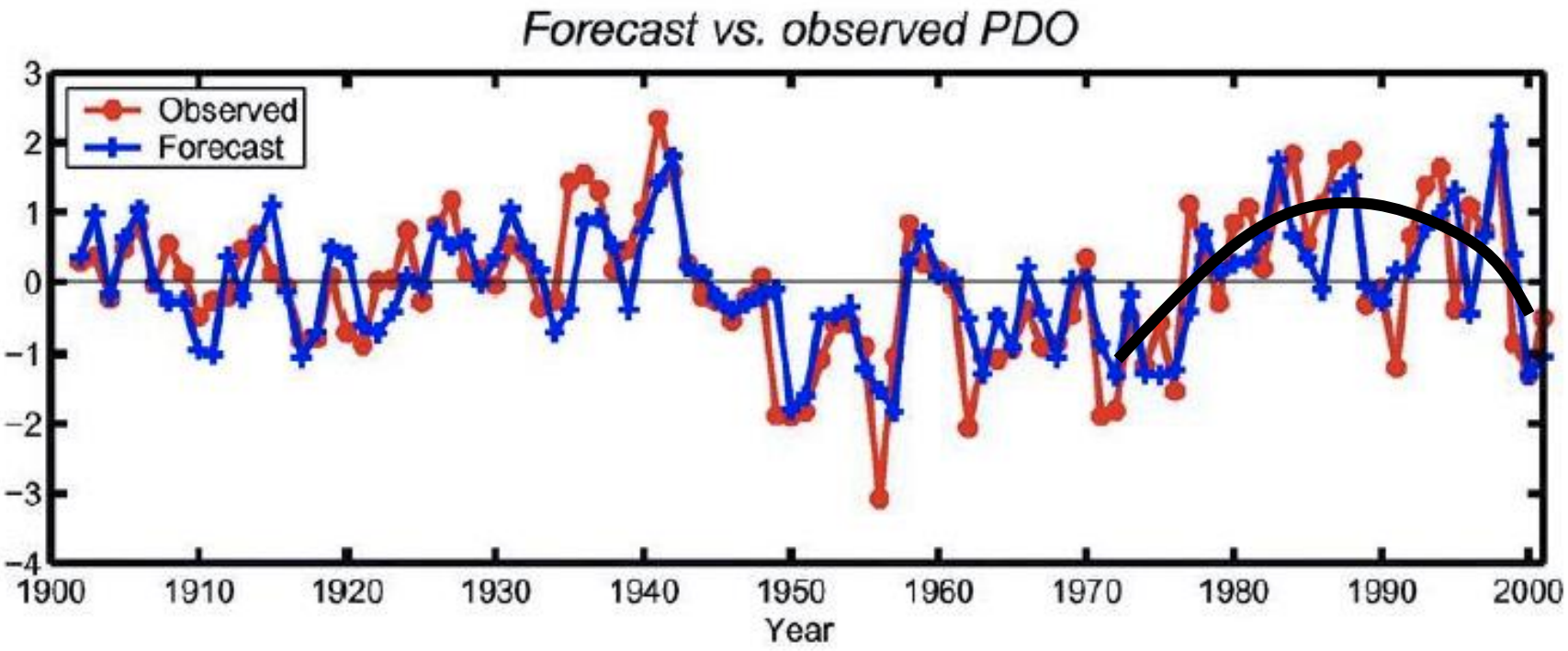
Rainfall Trends for Winter Isopycnal Outcrop Region for 25-26 σ_θ



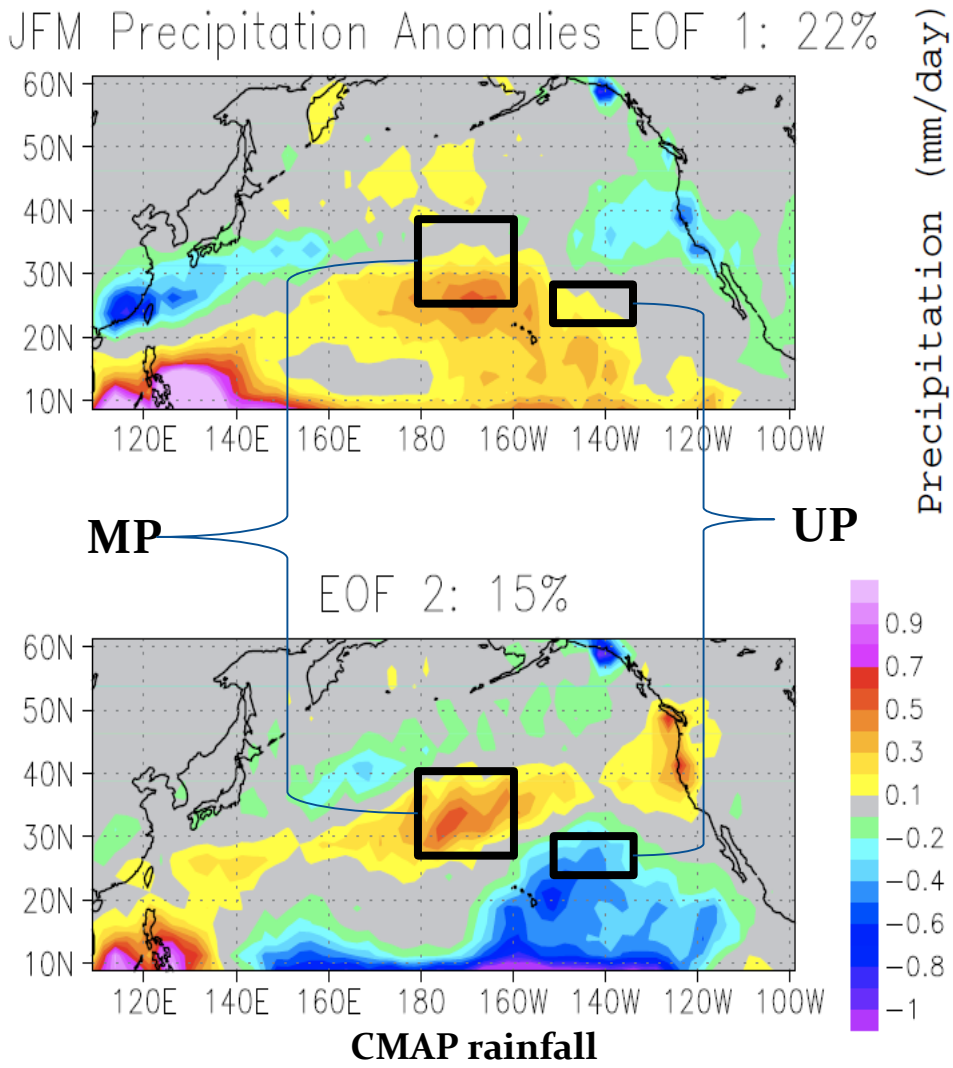
- **Colors are rainfall (CMAP) linear trends for 1986-2001, without decadal variability**
- **White lines are mean March surface locations of selected isopycnals**
- **Black lines are mean geostrophic streamlines (from WOA) for selected isopycnals that pass through Station ALOHA (★)**

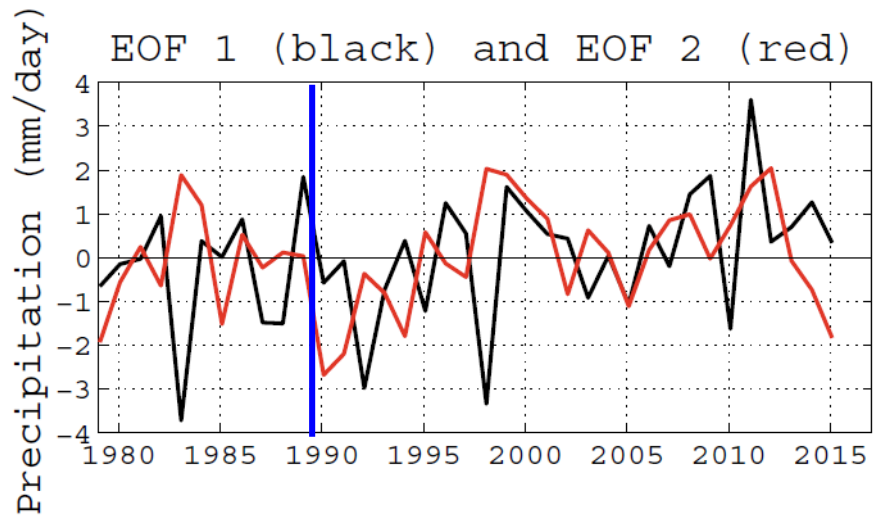
from Lukas and Santiago-Mandujano (2008; Oceanography)

Multi-decadal Peak of PDO: Late 1980s



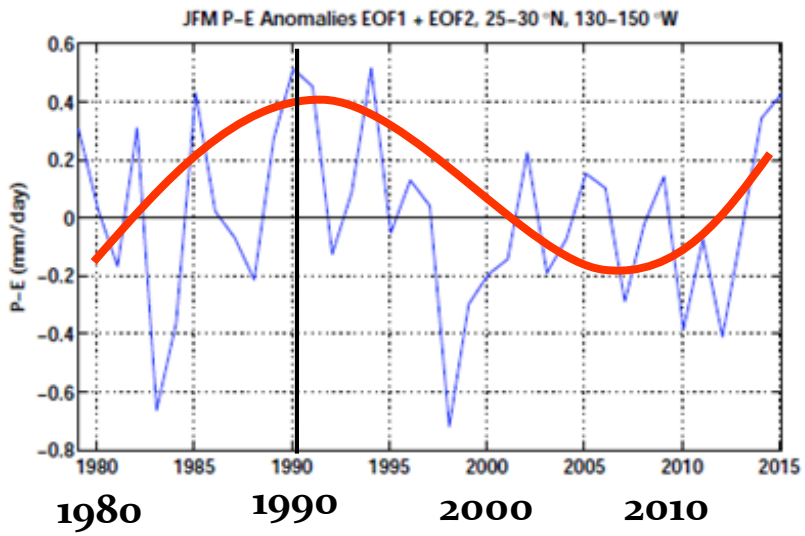
North Pacific Rainfall Anomalies



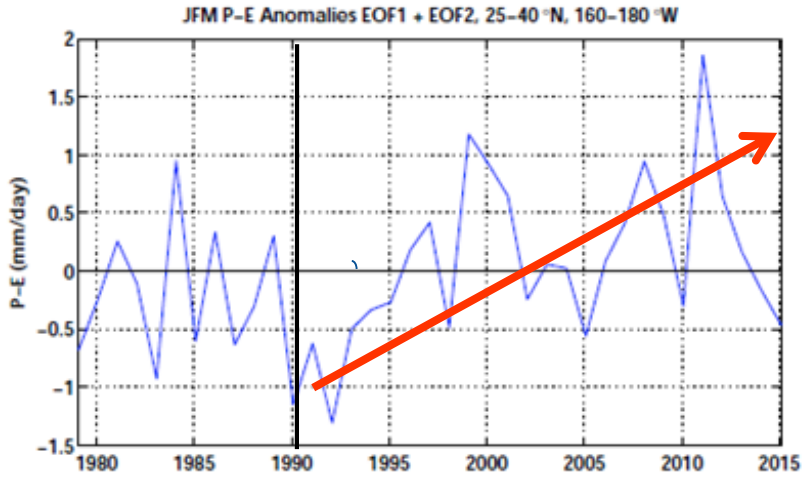


- **Storm-track and intensity changes associated with El Niño and Pacific decadal variability**
- **Reinforcing anomalies in Central North Pacific (mid pycnocline);**
- **Opposing in surface S_{max} (upper pycnocline) region to NE of Hawaii**

EOF Filtered JFM P-E Anomolies: EOFS 1+2



Upper Pycnocline Ventilation Region 25-30°N, 130-150°W



Mid Pycnocline Ventilation Region 25-40°N, 160-180°W

Results and Conclusions

- During HOT/WHOTS Station ALOHA salinity increasing in the upper-pycnocline, while decreasing in mid-pycnocline, with strong decadal variations
- Upper-pycnocline salinification appears to trace back to the mid-1960s using ocean reanalysis, but is more rapid in the HOT-era
- Mid-pycnocline freshening trend appears to have started in the late 1980s-early 1990s
- Multi-decadal variability is currently a confounding factor for quantifying secular trends and any accelerations associated with anthropogenic global warming

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