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Human-induced intensification of sea surface temperature regime shifts threatens global Large Marine Ecosystems

Zihui Gao, Qinwang Xing, Shin-ichi Ito, Haiqing Yu, Wei Yu, Xinjun Cheno



Zihui GAO

Shanghai Ocean Univ.

The Univ. of Tokyo

Shandong Univ.



Qinwang XING

1. SST regime shifts during 150 years
2. Future SST regime shifts
3. Regime shifts of marine ecosystems

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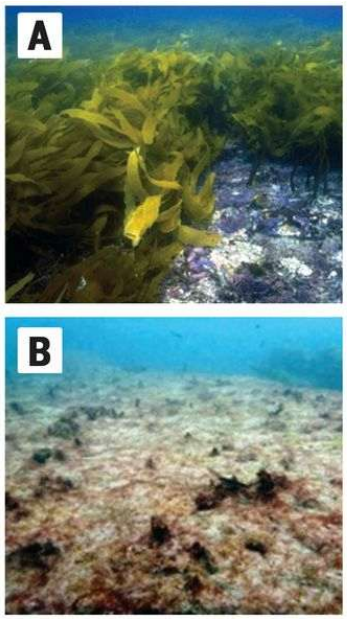
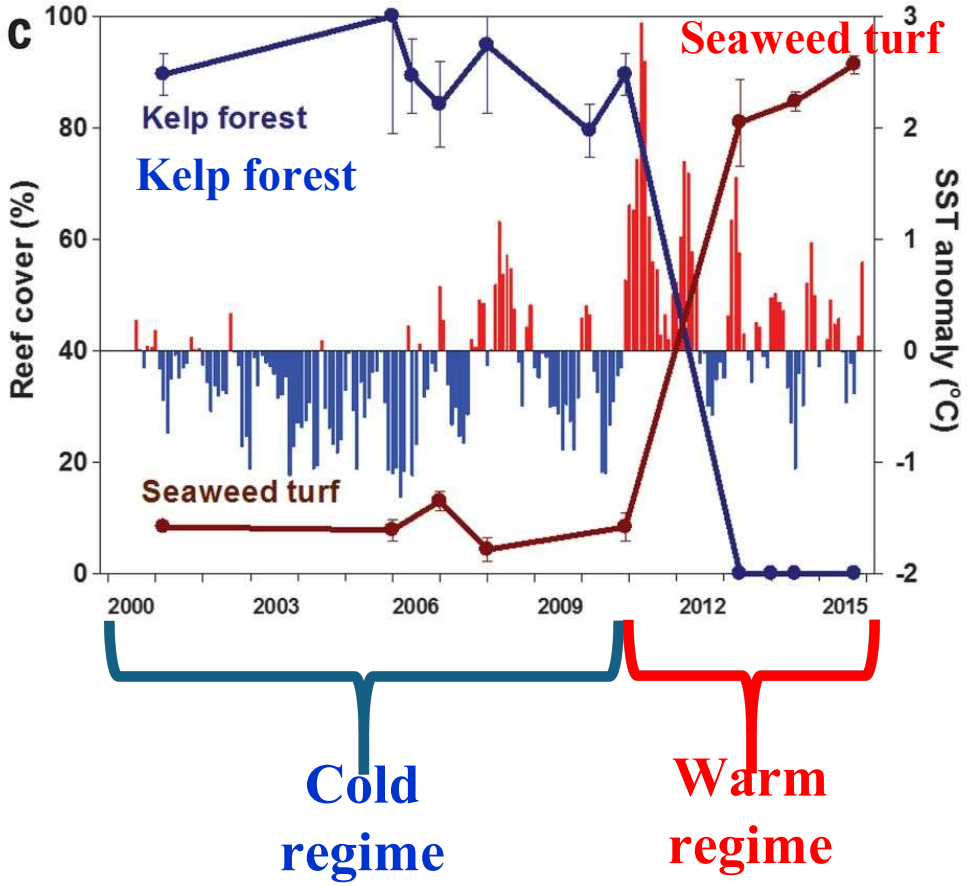
Regime shift



Wernberg et al. (2016, Science)

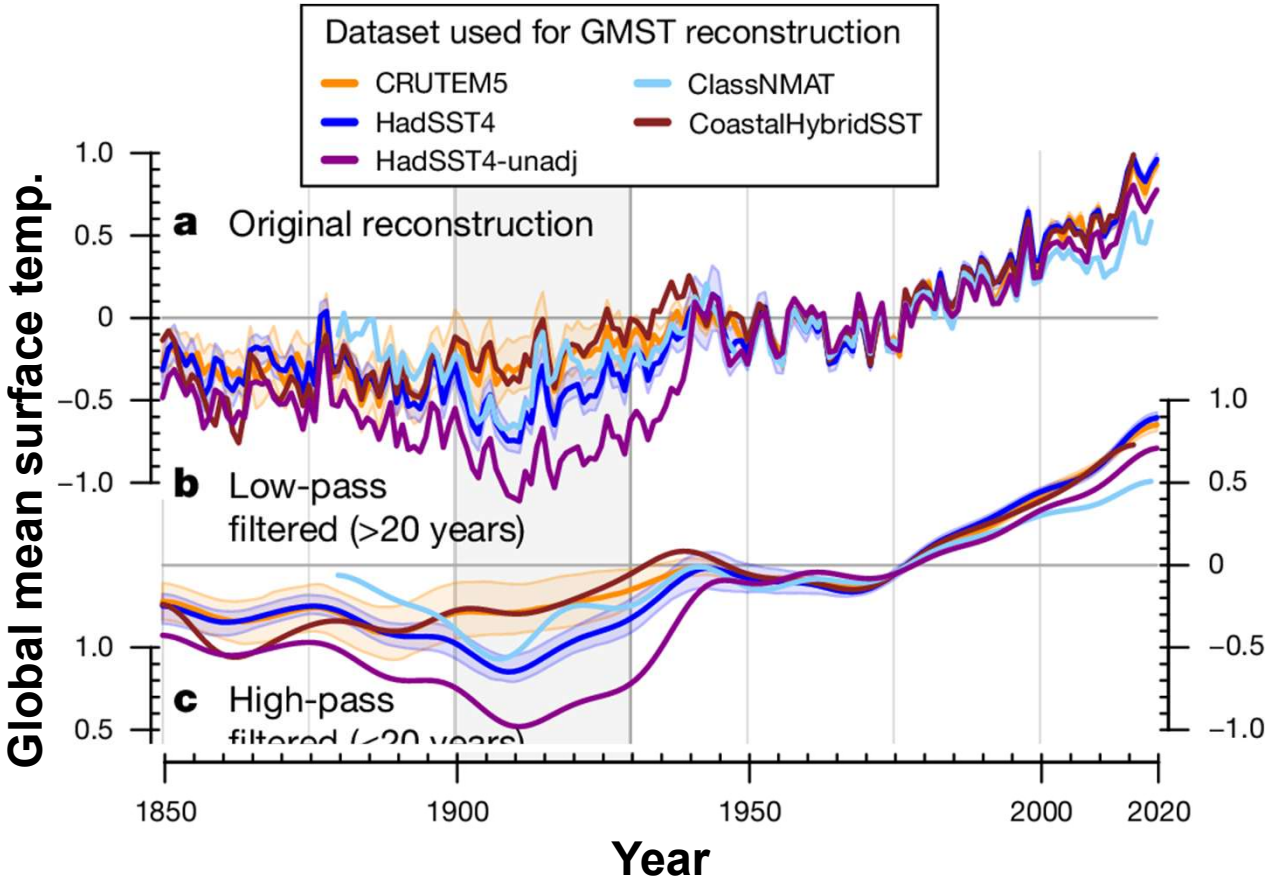
West coast of Australia



Regime shift

- **pronounced, decadal-scale, abrupt transitions between sustained warm and cold states**
- **strongly impacts on marine ecosystems because of the longer timescales**

Global climate change



Sippel et al. (2024, Nature)

Global mean surface temp.

- **Rapid increase since 1980s**
- **Re-acceleration of warming after hiatus in 2000s**
- **Frequency of marine heat waves also increases (Frölicher et al, 2016, Nature)**

When global warming, MHW, and regime shift coincide, the risk on ecosystem becomes severe.

Objectives

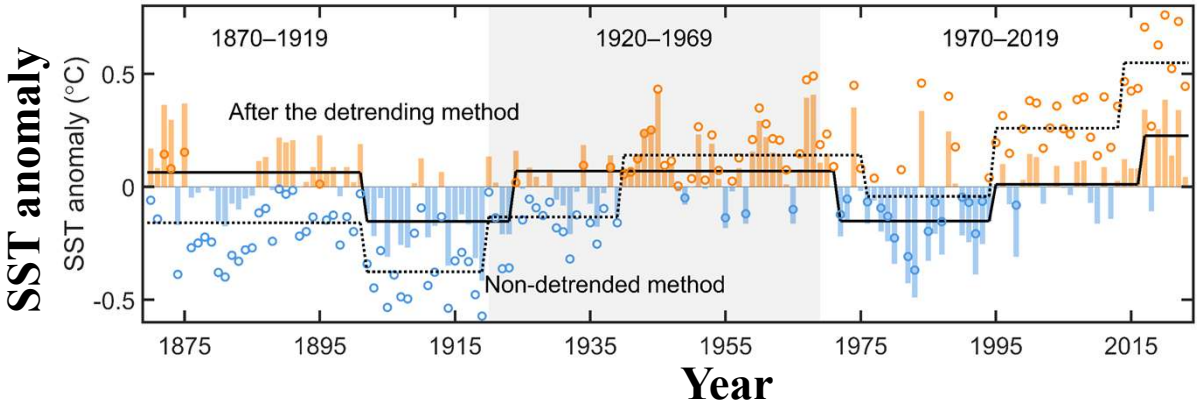
1. **Focus on regime shifts in large marine ecosystems (LME)**
   - **66 large marine ecosystems**
   - **Produce more than 80% of global catch by 22% area of global ocean**

2. **Compare frequency and amplitude of regime shift**
   - **1870-1919 (around Industrial revolution)**
   - **1920-1969 (early warming phase)**
   - **1970-2019 (warming phase)**

3. **Future regime shifts**
   - **1951-2000, 2001-2050, 2051-2100**

Methods

1. **SST observations: 5 datasets**
   - HadISST1 (Hadley Centre Sea Ice and Sea Surface Temperature),
   - ERSSTv5 (Extended Reconstructed Sea Surface Temperature),
   - COBE2 SST (Centennial in situ Observation-Based Estimates, version 2),
   - Berkeley Earth SST, Kaplan SST
2. **Historical hindcast of CMIP6: 51 simulations**
   - 51 hindcasts of 1865-2014
   - 14 natural forcing hindcasts (no anthropogenic forcing)
3. **Future projection of CMIP6**
   - 5 emission scenarios (SSP; 1-1.9, 1-2.6, 2-4.5, 3-7.0, 5-8.5)
   - 19 CMIP6 models for 2015-2100



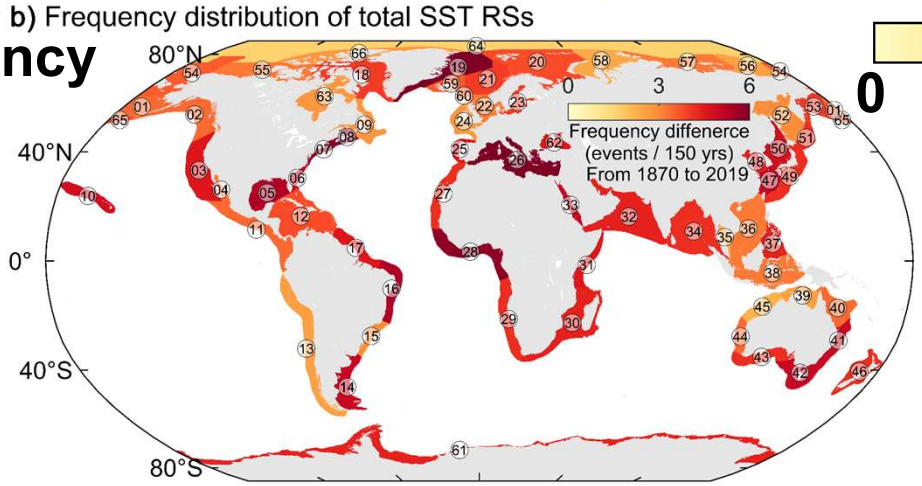
2 analyses
- **raw data**
- **detrended data**

Regime shift detection by STARS and changepoints.

Xing, Gao, et al. (2026)

Results: regime shifts in 150 years

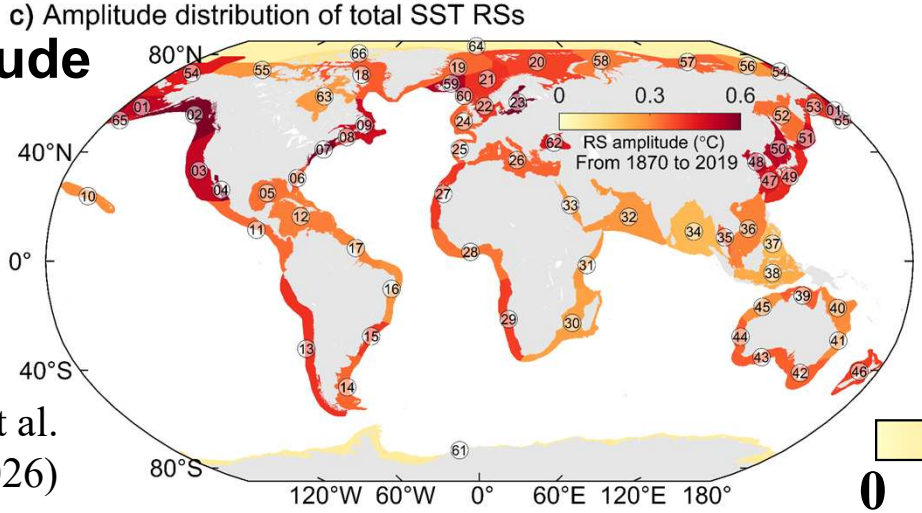
frequency





Global average
- **3.98 times/ 150 years**
- **amplitude: 0.36℃**

amplitude

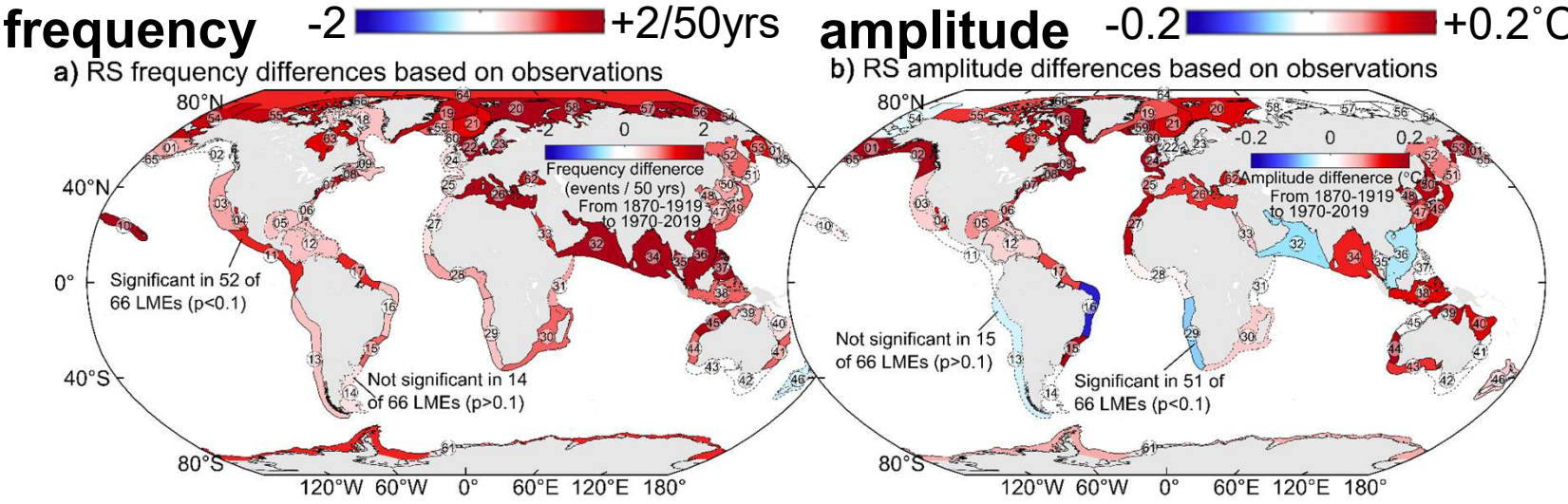


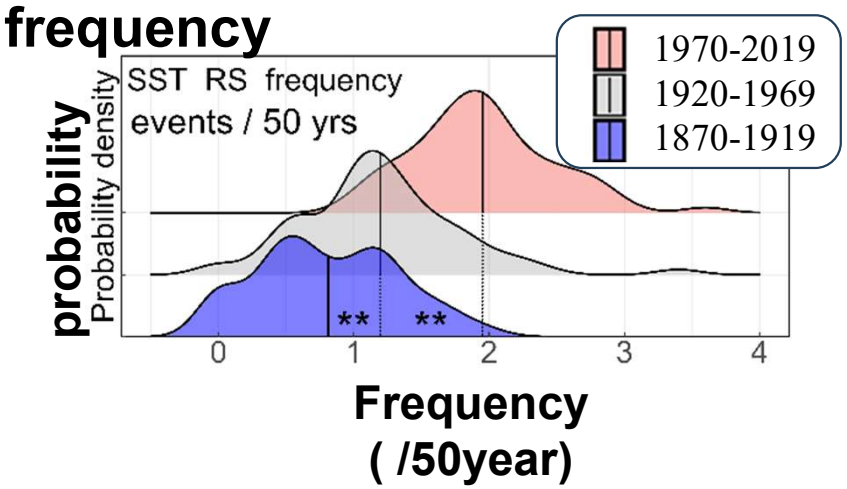


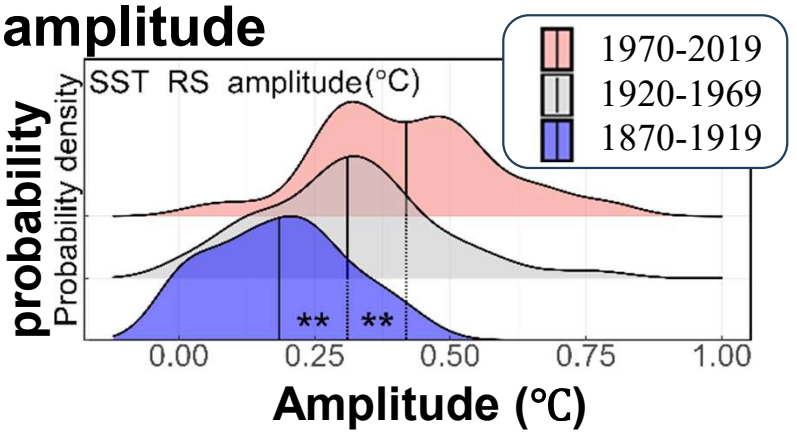
Western boundary is hotspot
- **4.74 times/ 150 years**
- **amplitude: 0.43℃**

Xing, Gao, et al. (2026)

Results: (1970-2019) minus (1870-1919)







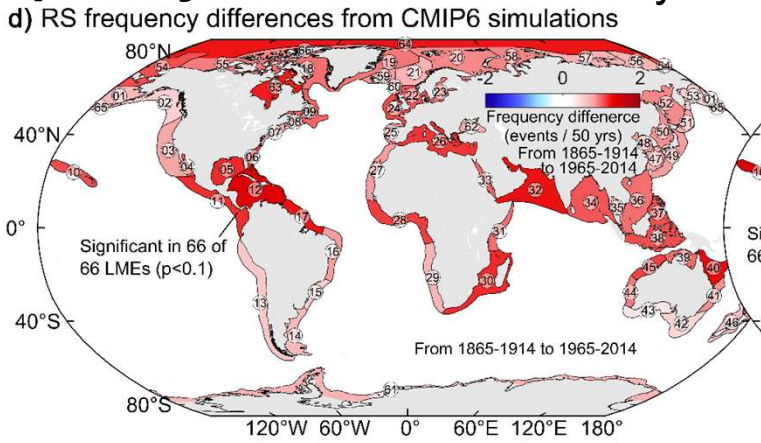
- **frequency: up in 95.45% LME 0.81⇒1.96/50year**
- **amplitude: up in 77.27% LME 0.18⇒0.42℃**

Obvious in Northern hemisphere

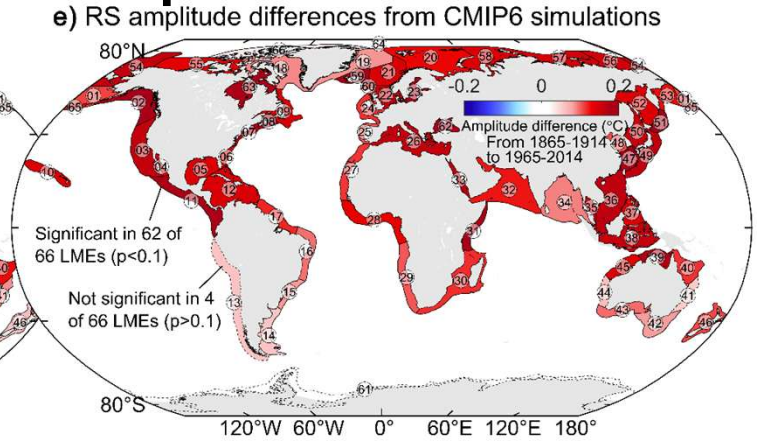
Xing, Gao, et al. (2026)

Simulation: (1965-2014) minus (1865-1914)

frequency -2 +2/50yrs



amplitude -0.2 +0.2˚C

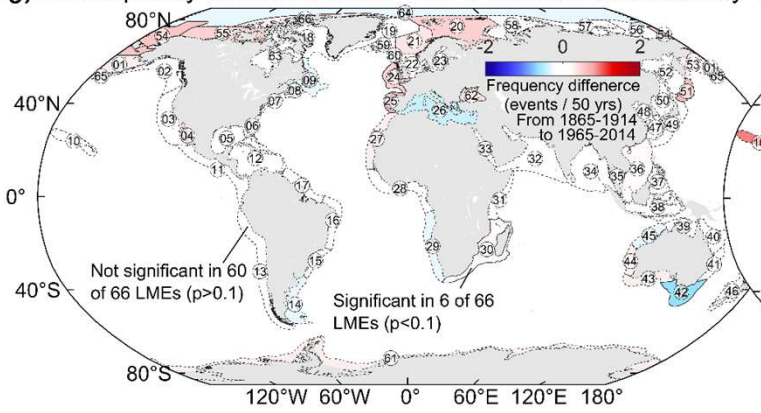


Anthropogenic gas + solar & volcanic effects

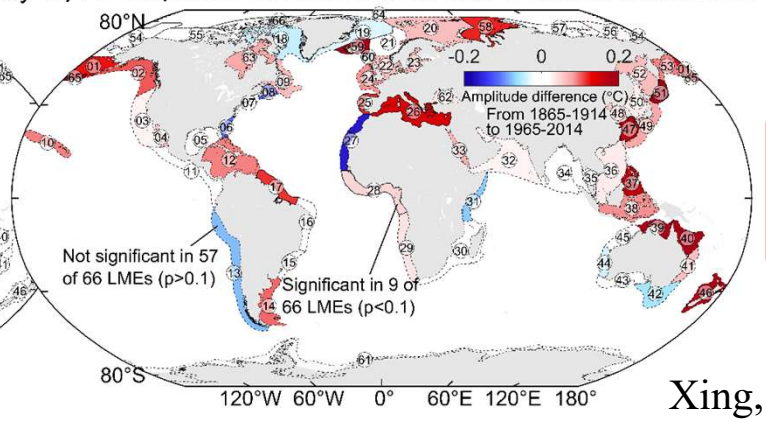
Intensification of regime shifts

Anthropogenic effects induce the intensification

frequency



amplitude



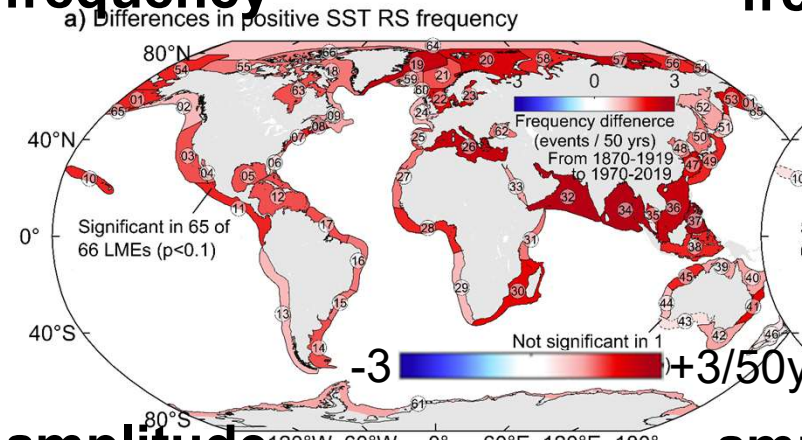
solar & volcanic effects

No significant intensification

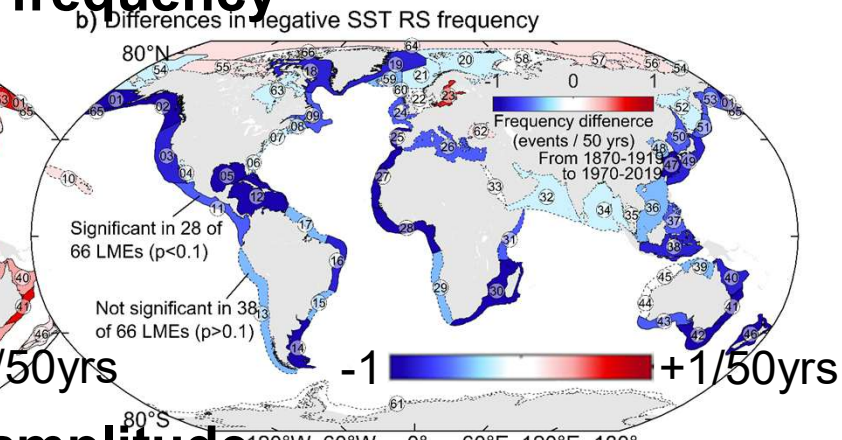
Xing, Gao, et al. (2026)

Warm shift vs Cold shift

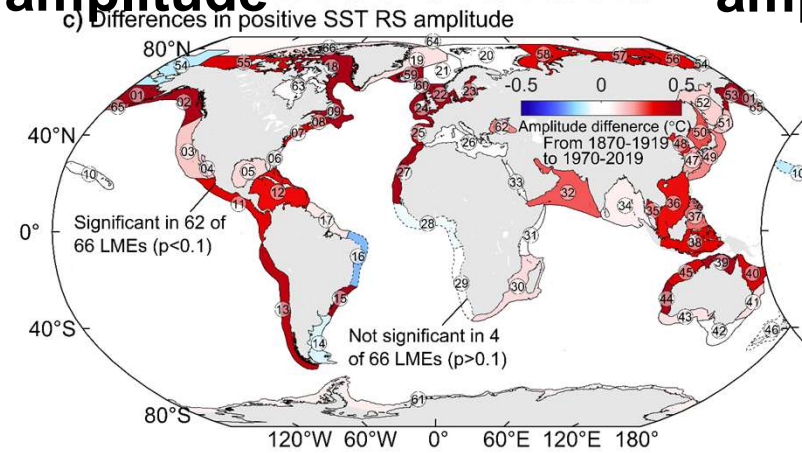
frequency **Warm shift**



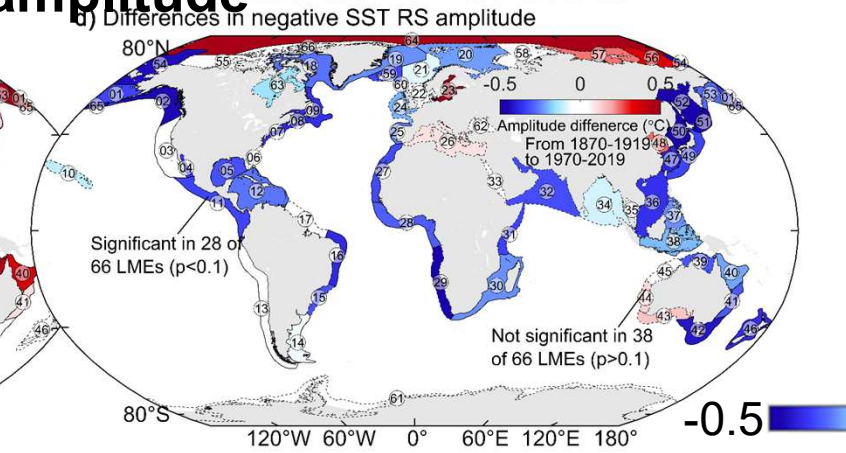
frequency **Cold shift**



amplitude



amplitude



observation (1970-2019) minus (1870-1919)

frequency
warm RS: up
cold RS: down

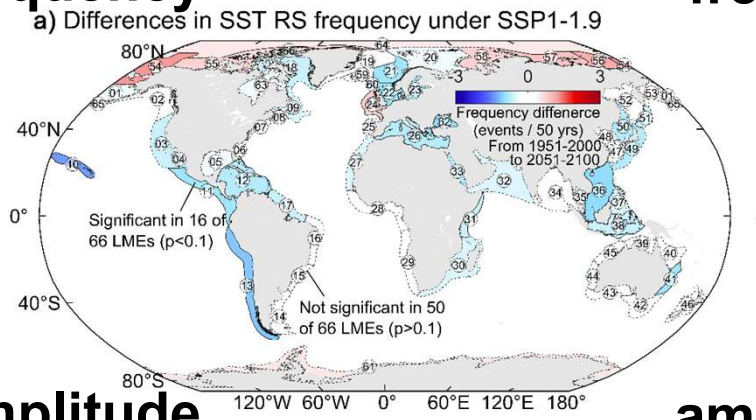
amplitude
warm RS: up
cold RS: donn
(increase in arctic)

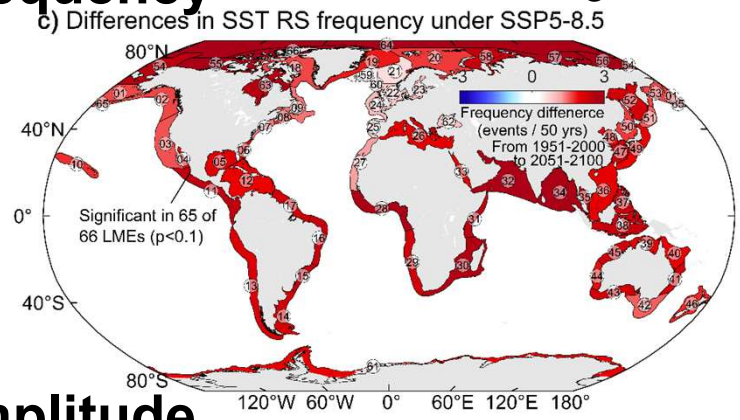
Xing, Gao, et al. (2026)

Future projection (2051-2100) minus (1951-2000)

SSP1-1.9 **SSP5-8.5**

frequency

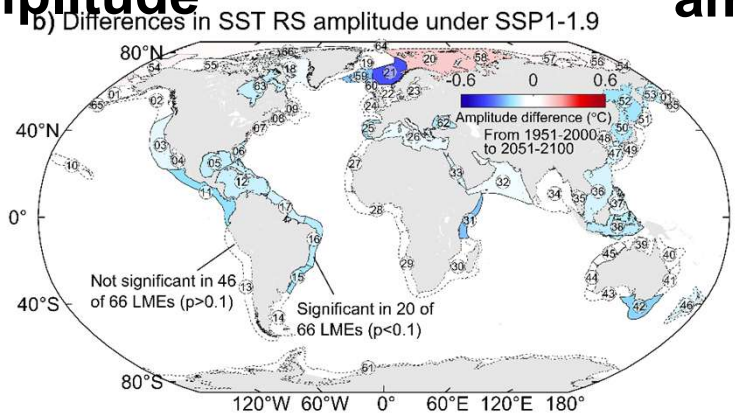


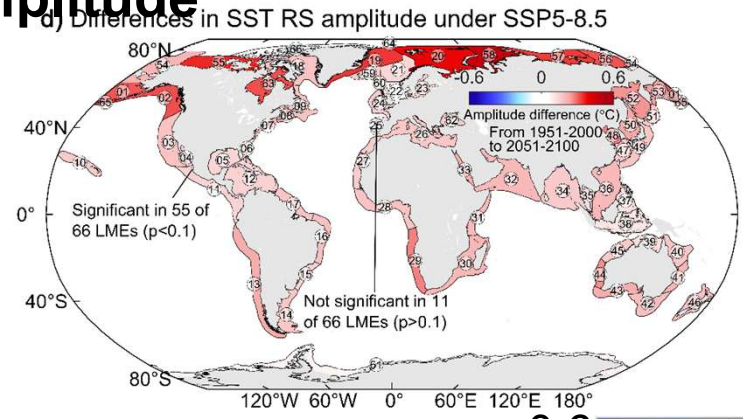


-3 +3/50yrs

- **frequency Regime shift increase under high emission scenario**

amplitude





-0.6 +0.6˚C

- **amplitude RS amplitude increase under high emission scenario**

Regime shift is intensified in Arctic under low emission

Xing, Gao, et al. (2026)

HABITABLE JAPAN
HOTSPOT III

Intensification of regime shift in LMEs

1. **Regime shift frequency and amplitude were intensified by 130-140% during these 150 years**
    a. **Obvious in Northern Hemisphere**
    b. **Intensification of warm-RS & suppression of cold-RS**
2. **Future SST regime shifts**
    a. **Continue to be intensified except for low emission**

Decadal prediction is essential as basement to assess MHVs' impacts on marine ecosystems.

Decadal prediction is essential for investment decision making for fishery industries and related supply chains

- **building ships & new facilities and develop new food processors, etc.**

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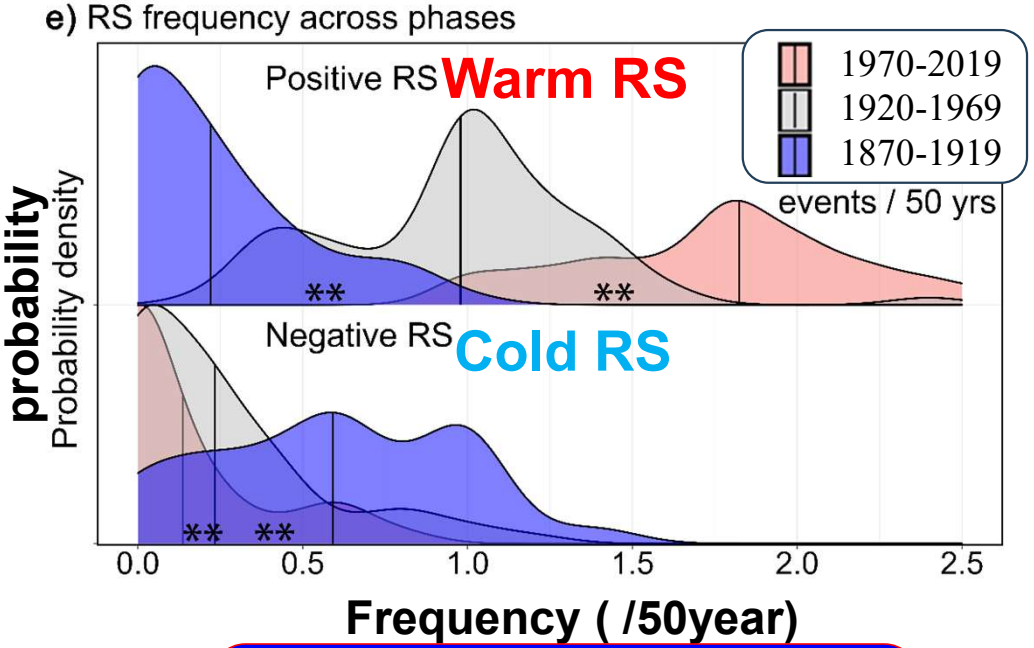
For questions

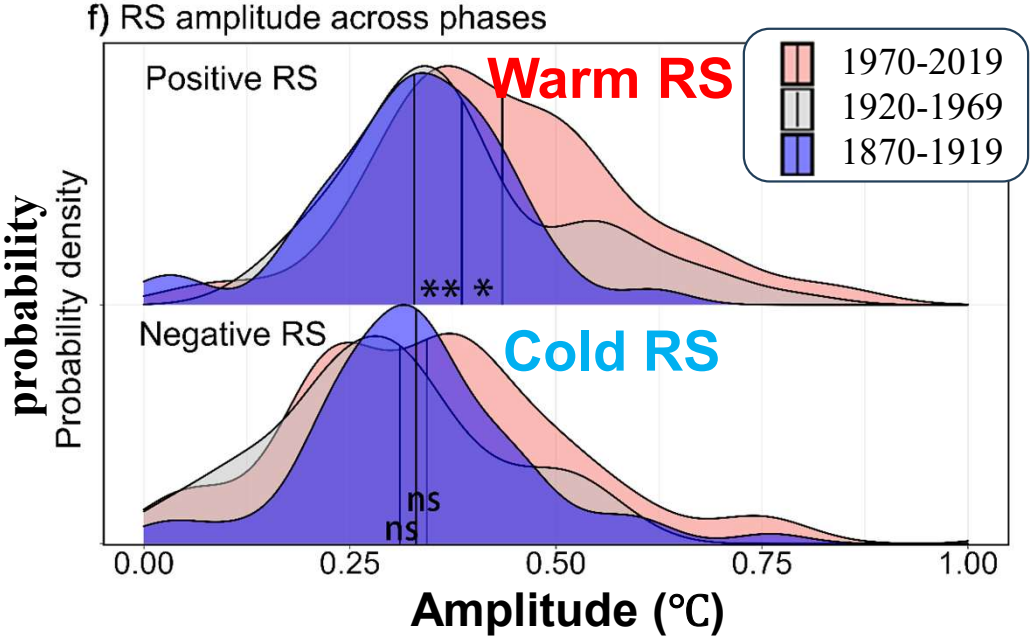
Warm shift vs Cold shift

Xing, Gao, et al. (2026)

frequency



amplitude

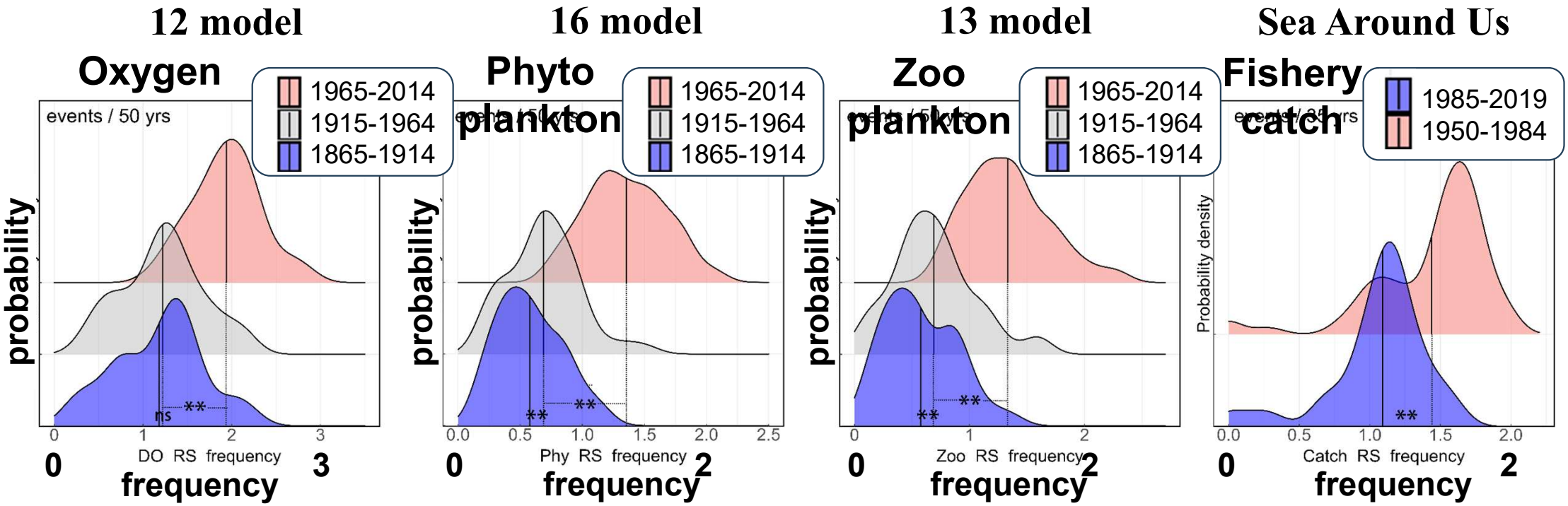


Warm RS: frequency up
Cold RS: frequency down

Warm RS: amplitude up
Cold RS: no change

Intensification of warm RS and suppression of cold RS

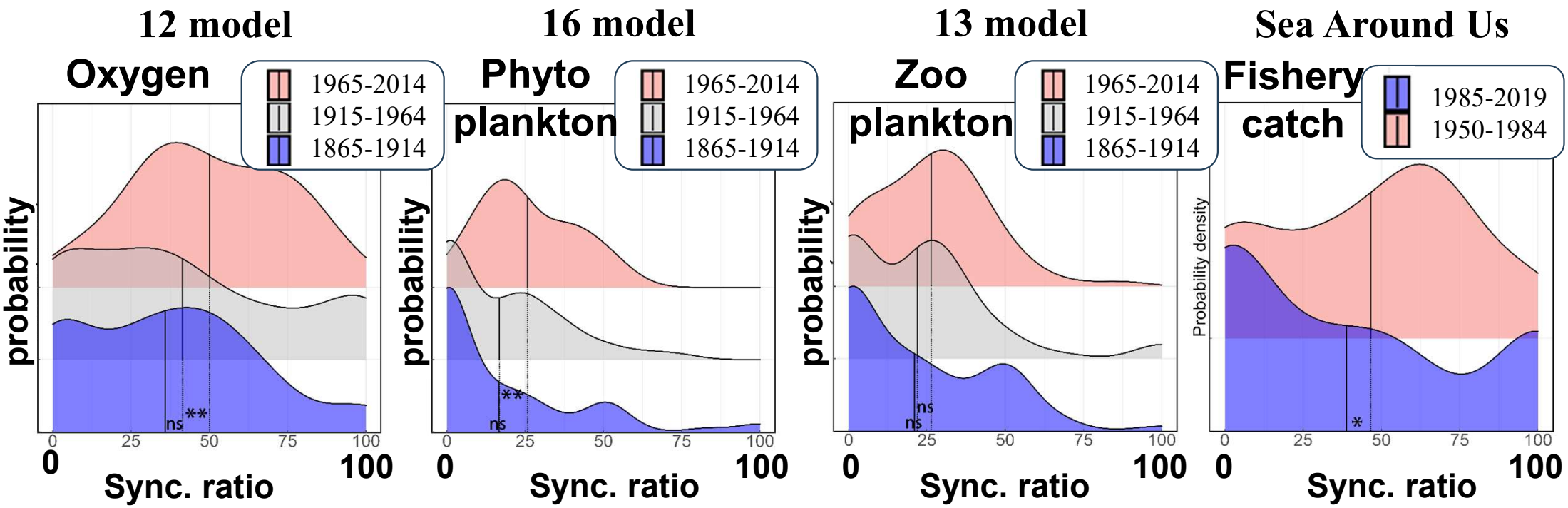
Regime shift in Biogeochemical & Fisheries



Xing, Gao, et al. (2026)

Regime shift frequency increase in DO, planktons, and catch

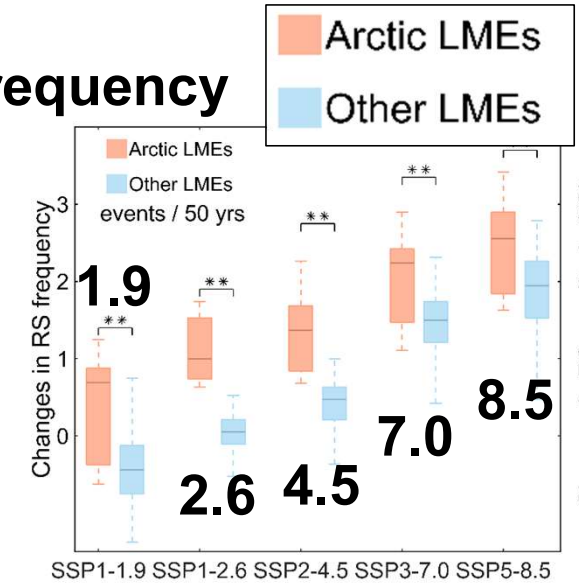
Synchronicity between SST RS and biogeochemical RS



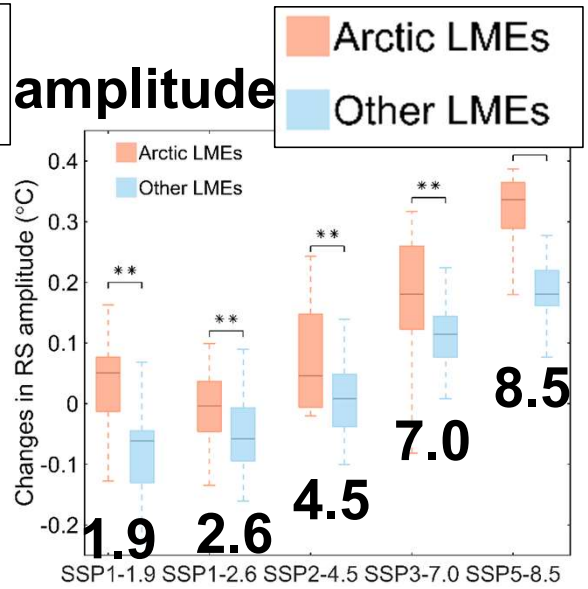
Xing, Gao, et al. (2026)

Synchronicity ratio increase in DO, phytoplankton, and catch

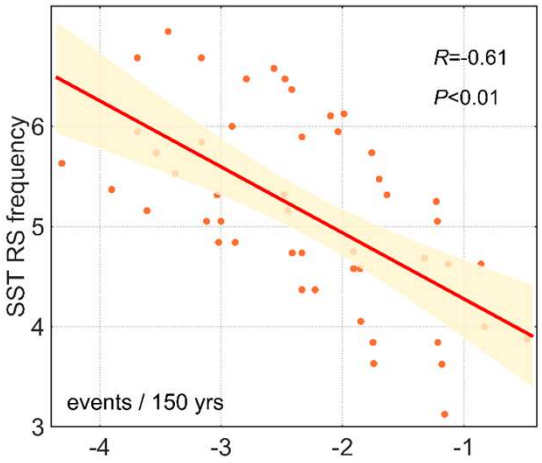
frequency



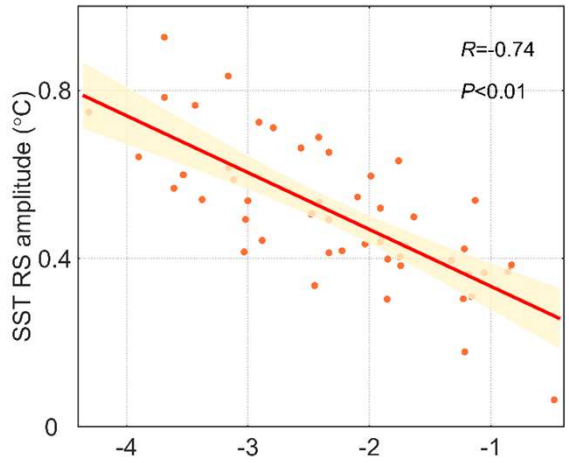
amplitude



frequency



amplitude



Sea ice concentration trend (%/decade)

Future projections

(2051-2100) minus (1951-2000)

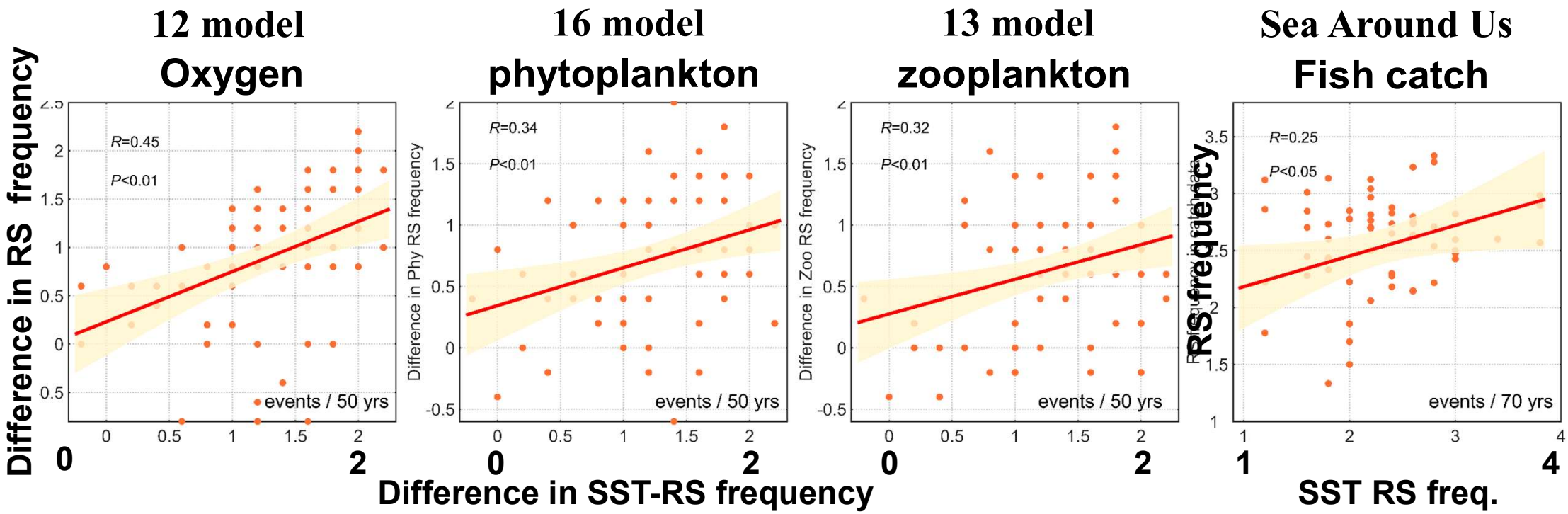
- **Intensification of regime shift is high in Arctic**

Sea ice change in Arctic and RS intensification

- **Both frequency and amplitude show significant correlation.**

Xing, Gao, et al. (2026)

SST-RS vs Biogeochemical-RS



- **RS frequency change in DO and planktons occurs depending on SST-RS frequency change.**
- **Catch-RS frequency increase with SST-RS frequency.**

Xing, Gao, et al. (2026)

Sea-ice simulation (12)

ACCESS-CM2, BCC-CSM2-MR, CAMS-CSM1-0, CMCC-CM2-SR5, CanESM5, EC-Earth3-Veg-LR, EC-Earth3, INM-CM4-8, INM-CM5-0, IPSL-CM6A-LR, MPI-ESM1-2-HR, MPI-ESM1-2-LR

DO simulation (12)

ACCESS-ESM1-5, CMCC-ESM2, CanESM5, GFDL-CM4, GFDLESM4, IPSL-CM5A2-INCA, IPSL-CM6A-LR-INCA, IPSL-CM6A-LR, MPI-ESM-1-2-HAM, MPI-ESM1-2-HR, MPI-ESM1-2-LR, NorESM2-MM

Phytoplankton simulation (16)

ACCESS-ESM1-5, CESM2-FV2, CESM2-WACCM-FV2, CESM2-WACCM, CESM2CMCC-ESM2, CanESM5, GFDL-CM4, GFDL-ESM4, IPSL-CM5A2-INCA, IPSL-CM6A-LR-INCA, IPSL-CM6A-LR, MPIESM-1-2-HAM, MPI-ESM1-2-HR, MPI-ESM1-2-LR, NorESM2-LM, NorESM2-MM

Zooplankton simulation (13)

CESM2-FV2, CESM2-WACCM-FV2, CESM2-WACCM, CESM2, CanESM5, GFDL-ESM4, IPSL-CM5A2-INCA, IPSL-CM6A-LR-INCA, IPSL-CM6A-LR, MPI-ESM-1-2-HAM, MPI-ESM1-2-HR, MPI-ESM1-2-LR, NorESM2-MM

Common model simulations of dissolved oxygen, chlorophyll, and zooplankton (5)

CanESM5, CanESM5-1, CESM2-WACCM, CMCC-ESM2, GFDLESM4