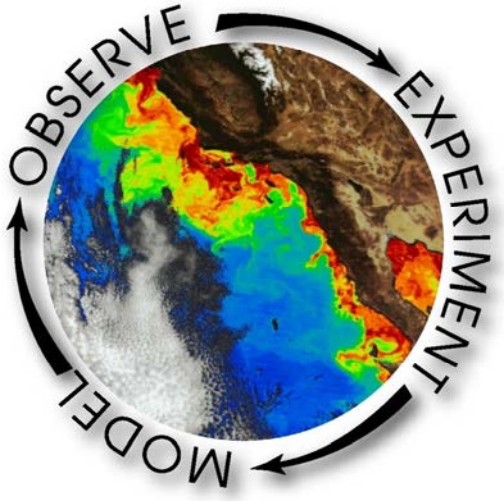
Predictability associated with Pacific Ocean subsurface

Decadal prediction of hypoxia along the US West Coast

Mer Pozo-Buil, Emanuele Di Lorenzo,and Steve Bograd

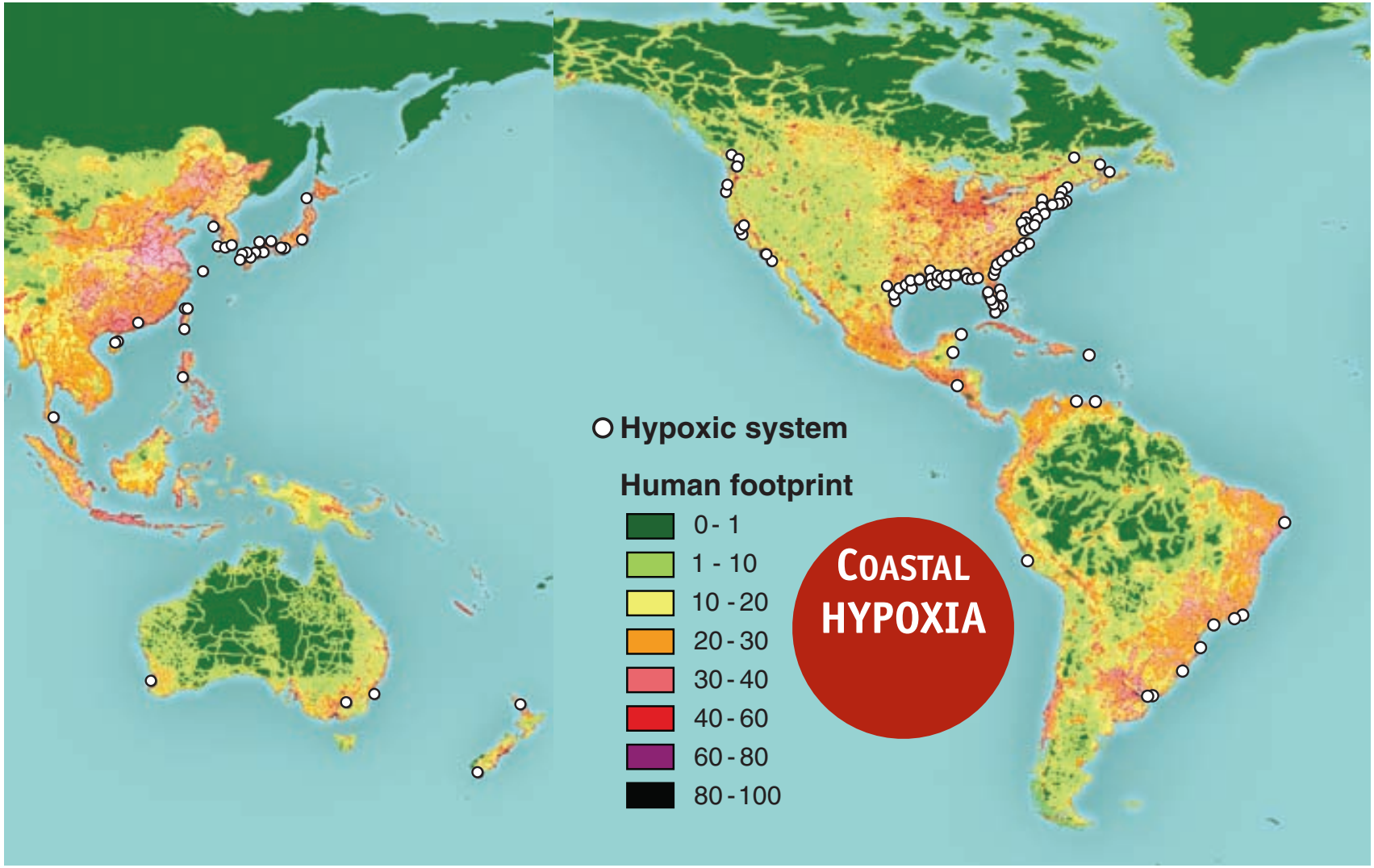
Georgia Institute of Technology



CCE-LTER

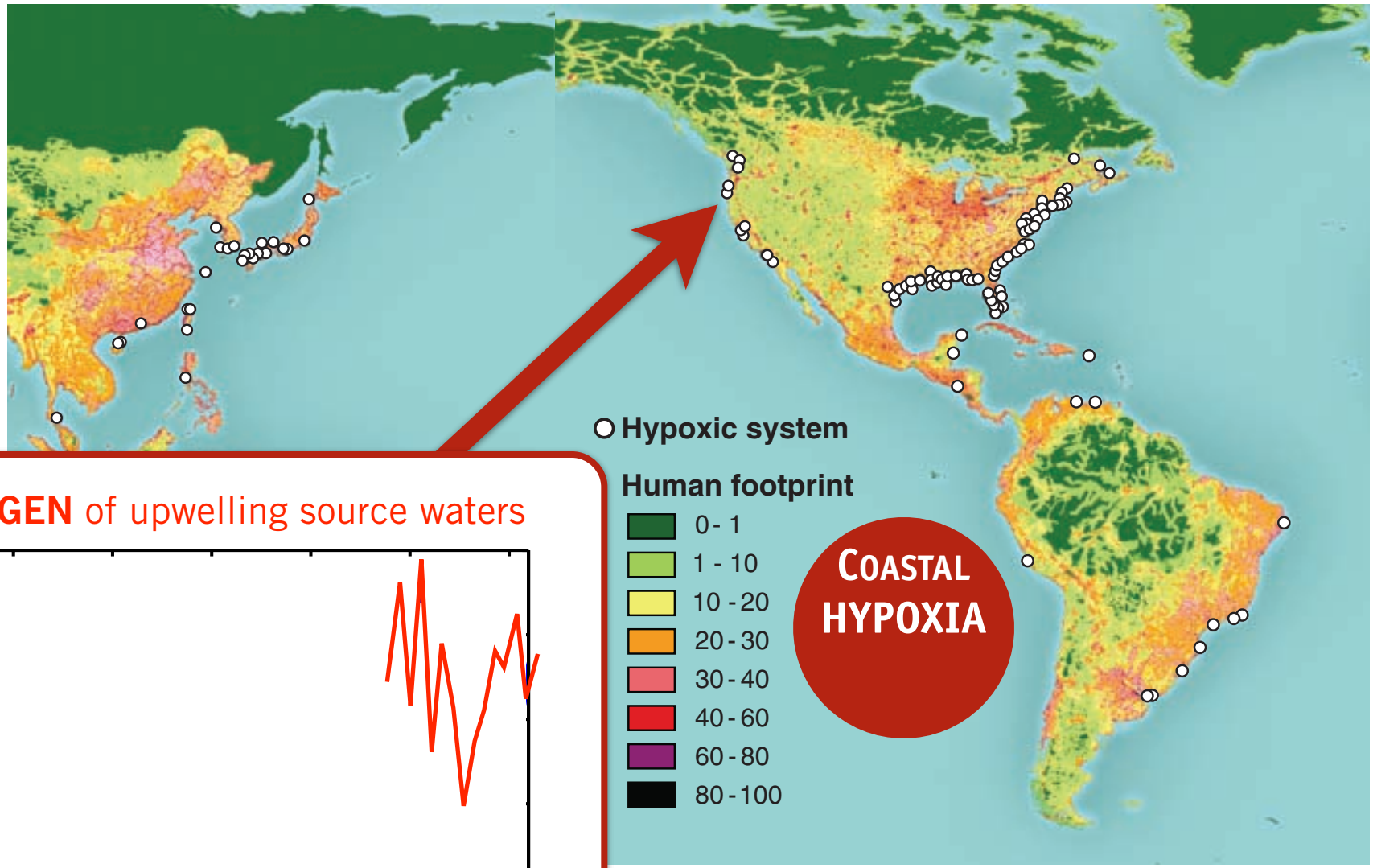
Human vs. physical controls of ***COASTAL HYPOXIA***

Diaz and Rosenberg, Science 2008



Human vs. physical controls of ***COASTAL HYPOXIA***

Diaz and Rosenberg, Science 2008

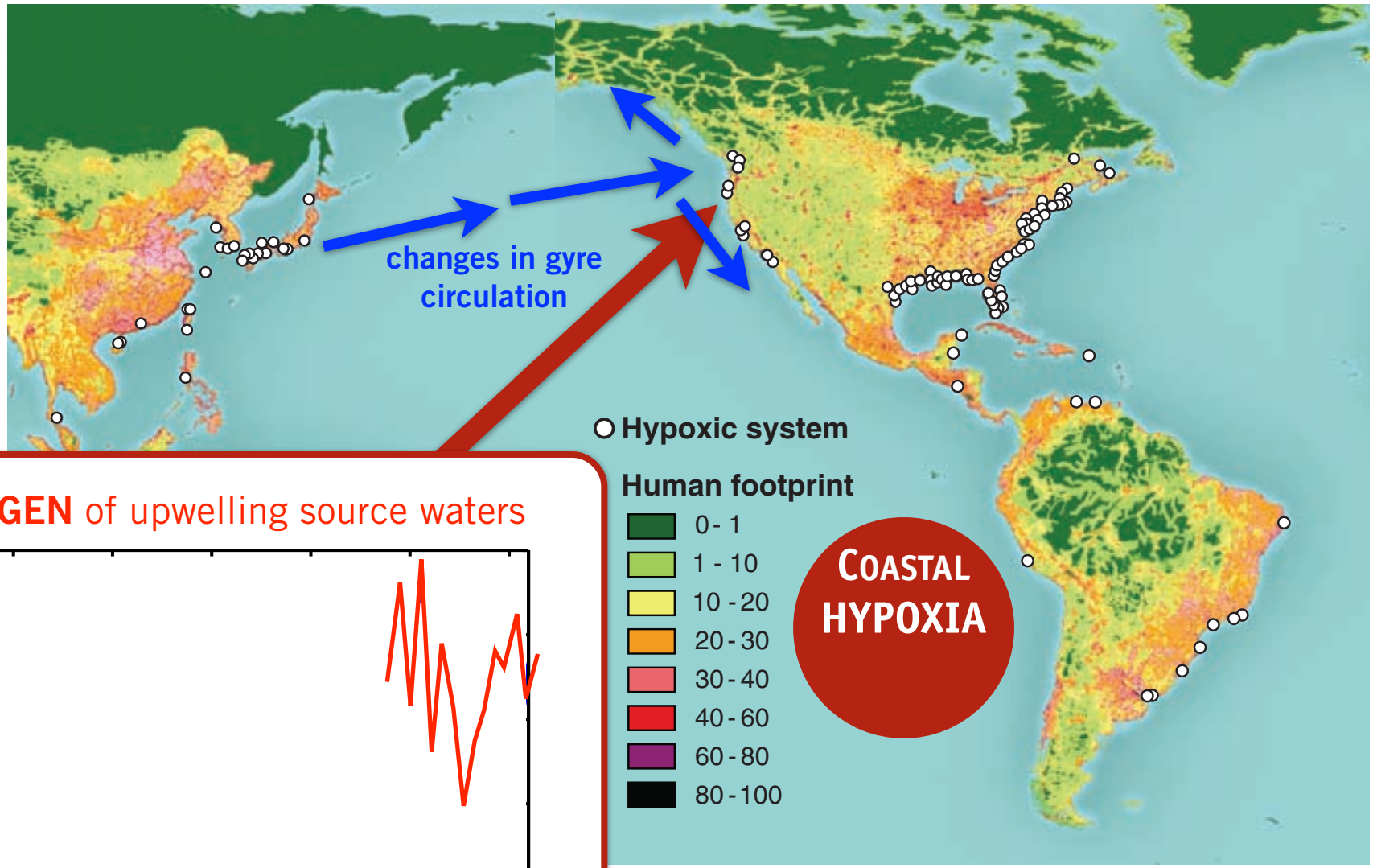


OXYGEN of upwelling source waters

Oregon Shelf, observations by *Peterson et al. 2013*

Human vs. physical controls of ***COASTAL HYPOXIA***

Diaz and Rosenberg, Science 2008

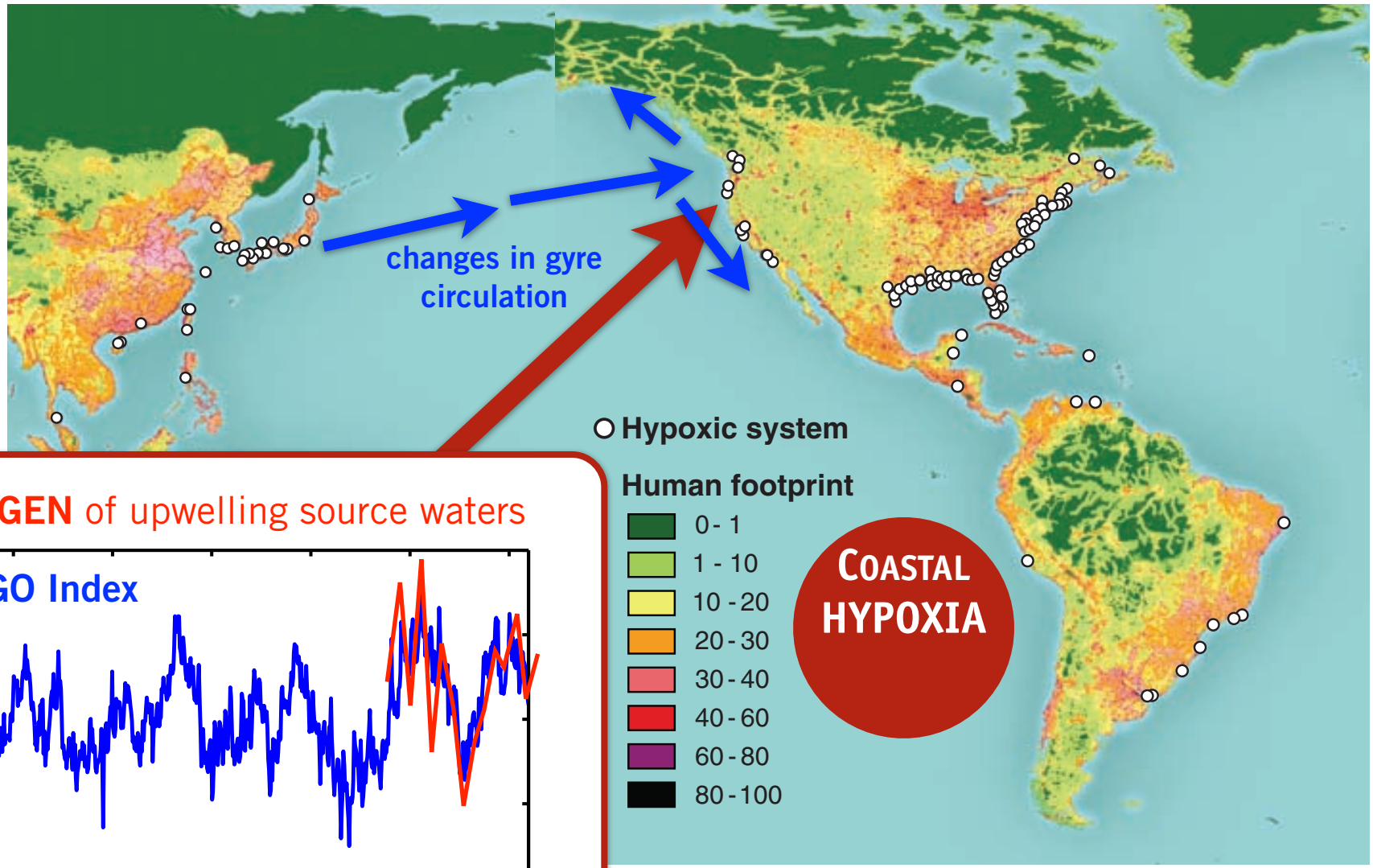


OXYGEN of upwelling source waters

Oregon Shelf, observations by *Peterson et al. 2013*

Human vs. physical controls of ***COASTAL HYPOXIA***

Diaz and Rosenberg, Science 2008



OXYGEN of upwelling source waters

Oregon Shelf, observations by *Peterson et al. 2013*

Human vs. **physical controls** of ***COASTAL HYPOXIA***

QUESTION:

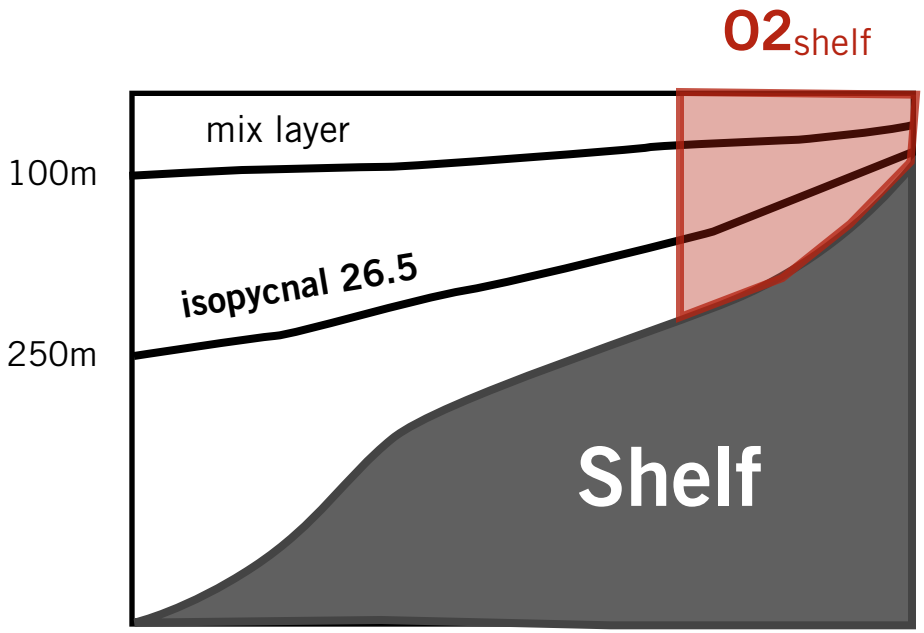
What are the large-scale ocean dynamics that impact ***COASTAL HYPOXIA***?

Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***

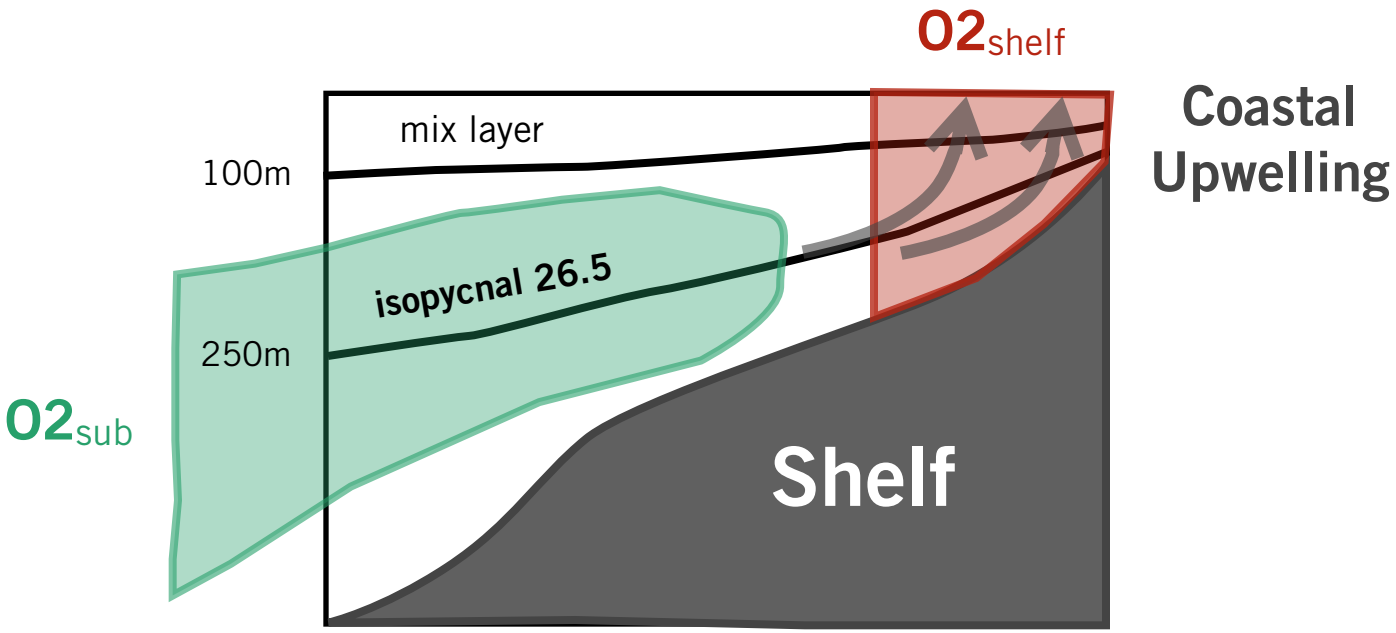
QUESTION:

What are the large-scale ocean dynamics that impact ***COASTAL HYPOXIA***?

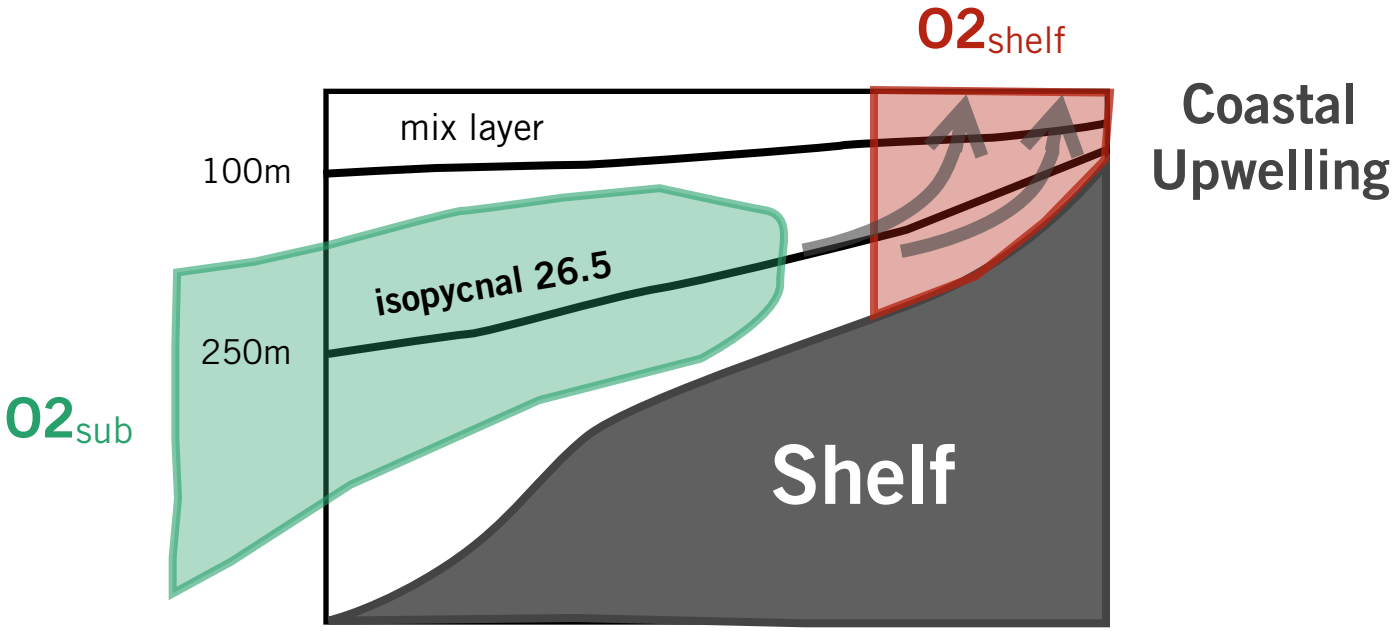
Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***



Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***



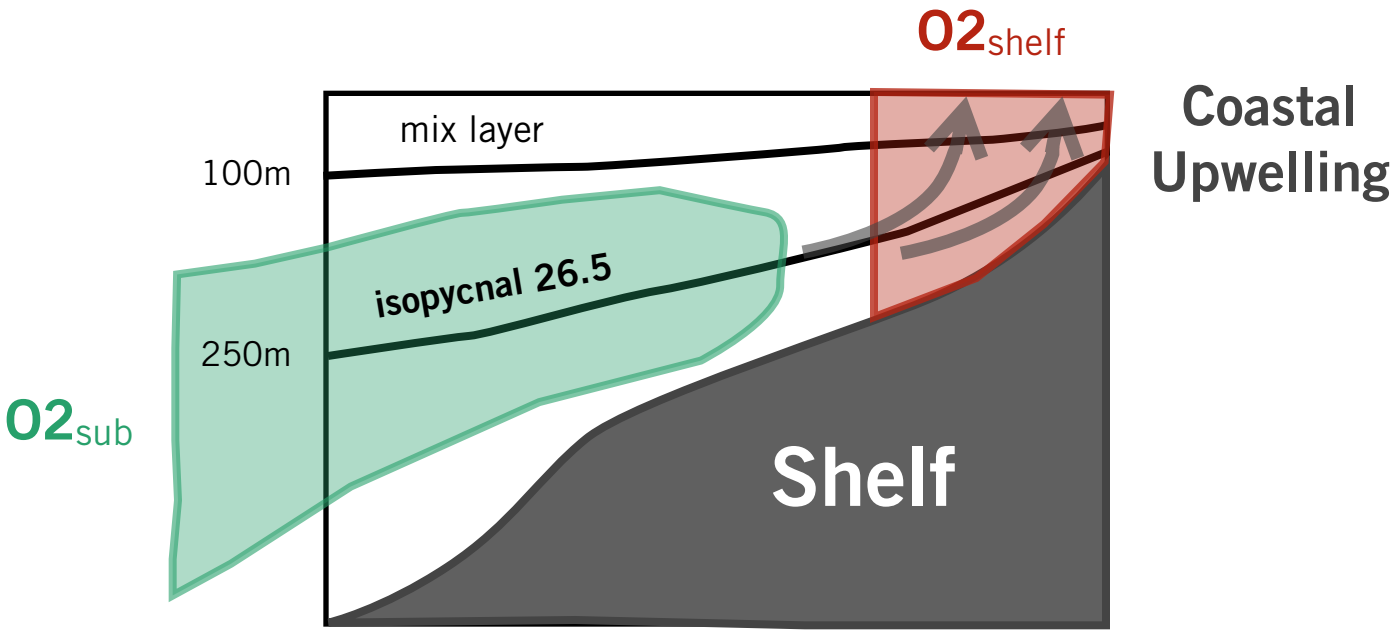
Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***



$$\frac{\partial O'_{shelf}}{\partial t} = -\left(1+\lambda_{bio}\right) w' \cdot \bar{O}_{sub}$$

changes in upwelling
and productivity

Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***

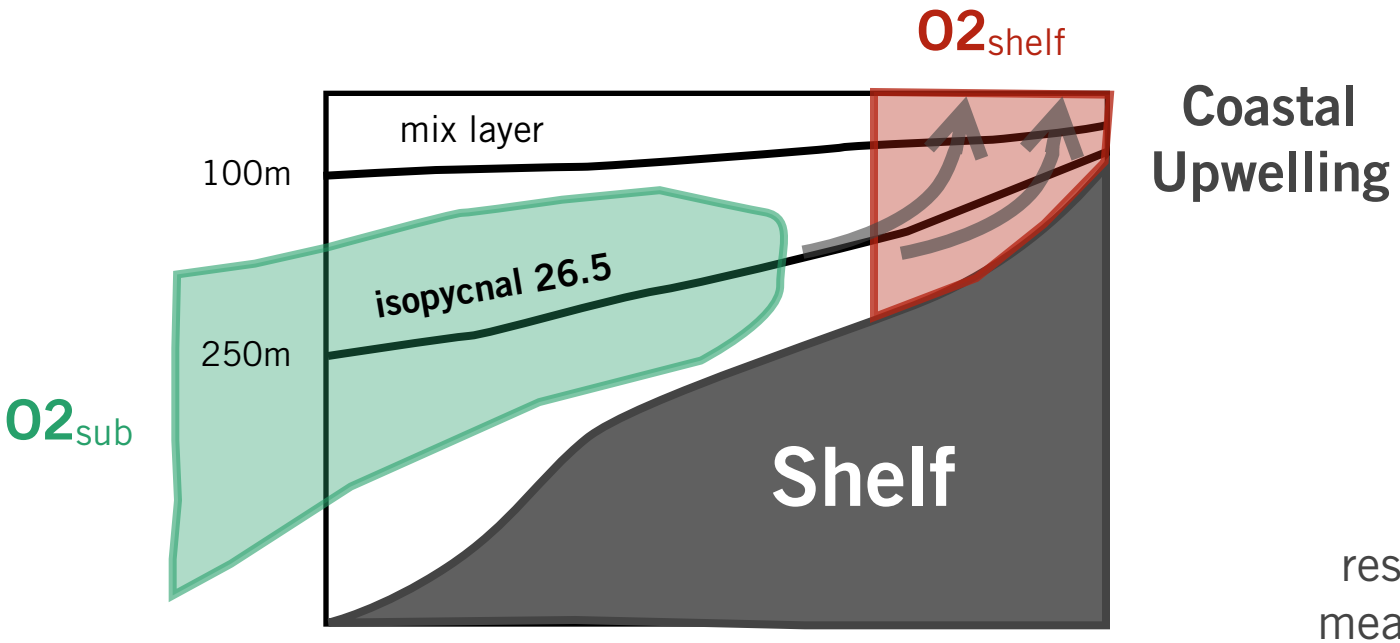


$$\frac{\partial O'_{shelf}}{\partial t} = -\left(1+\lambda_{bio}\right)w' \cdot \bar{O}_{sub} + \bar{w} \cdot O'_{sub}$$

changes in upwelling and productivity

anomalies in source waters that feed mean upwelling

Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***



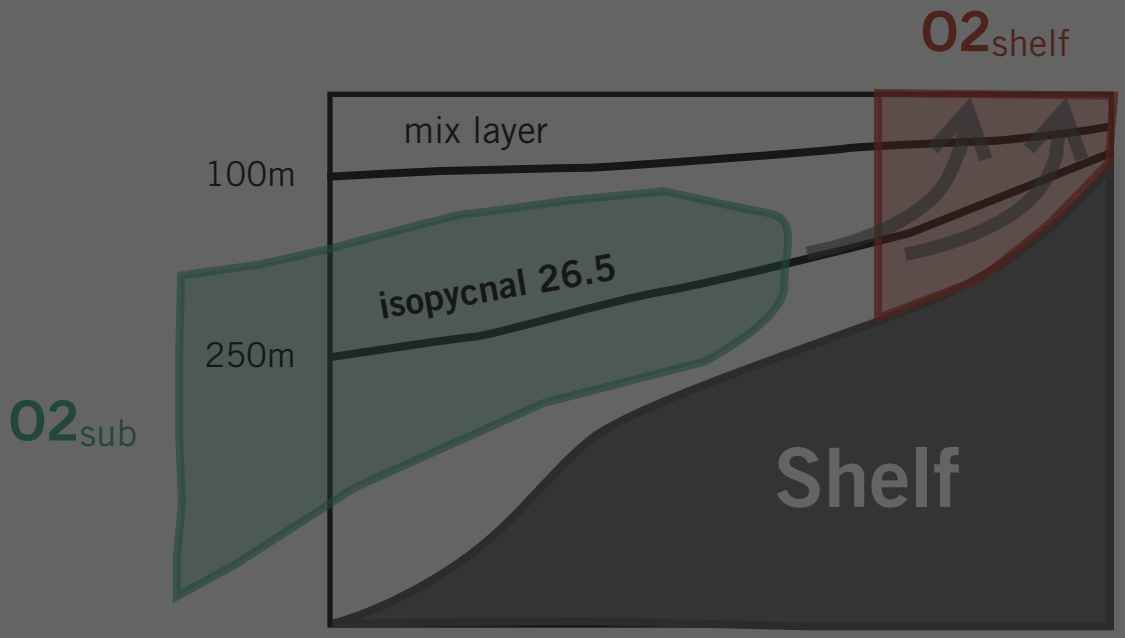
restoration to mean condition

$$\frac{\partial O'_{shelf}}{\partial t} = -\left(1+\lambda_{bio}\right)w' \cdot \bar{O}_{sub} + \bar{w} \cdot O'_{sub} - \varepsilon O'_{shelf}$$

changes in upwelling and productivity

anomalies in source waters that feed mean upwelling

Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***



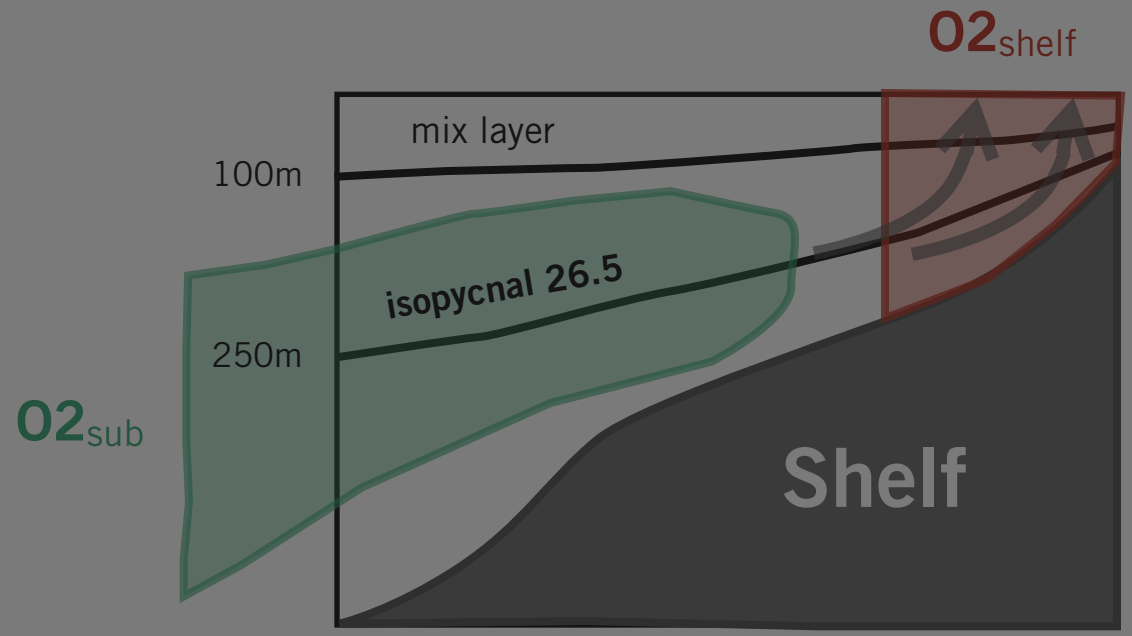
restoration to mean condition

$$\frac{\partial O'_{shelf}}{\partial t} = -\left(1+\lambda_{bio}\right)\overline{w'\cdot O_{sub}} - \bar{w}\cdot O'_{sub} - \varepsilon O'_{shelf}$$

changes in upwelling and productivity

anomalies in source waters that feed mean upwelling

Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***



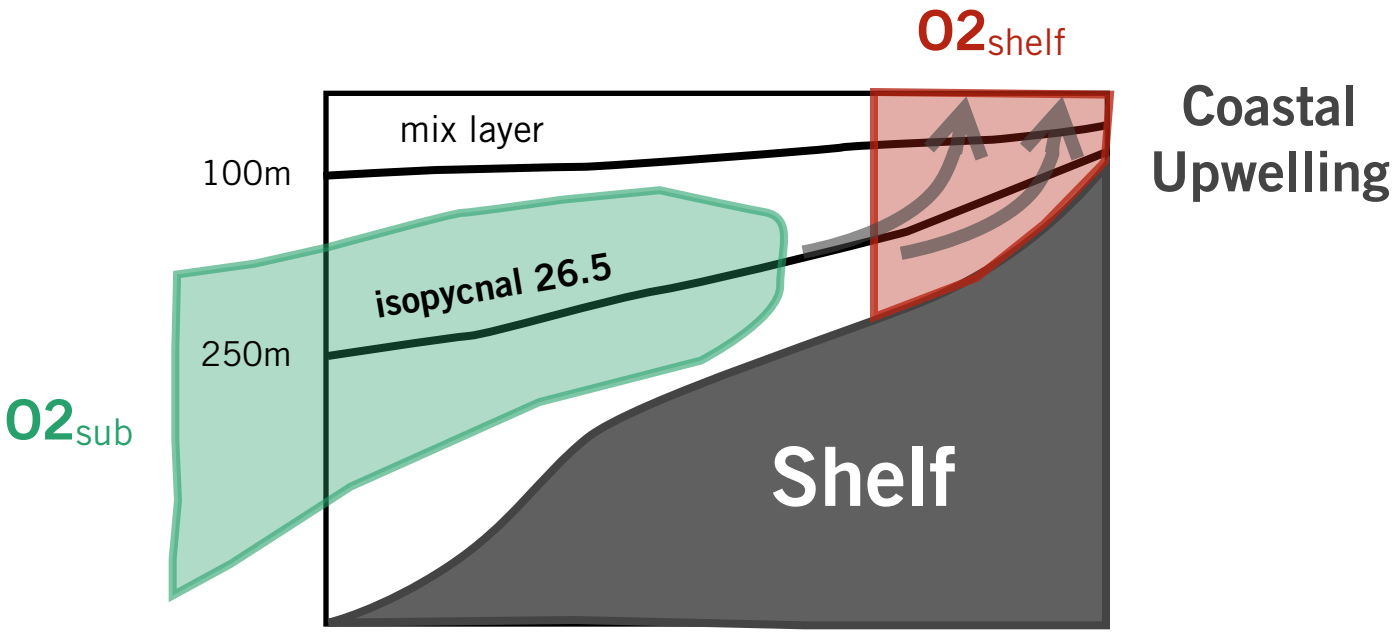
restoration to mean condition

$$\frac{\partial O'_{shelf}}{\partial t} = -(1+\lambda_{bio})w' \cdot \bar{O}_{sub} - \bar{w} \cdot O'_{sub} - \varepsilon O'_{shelf}$$

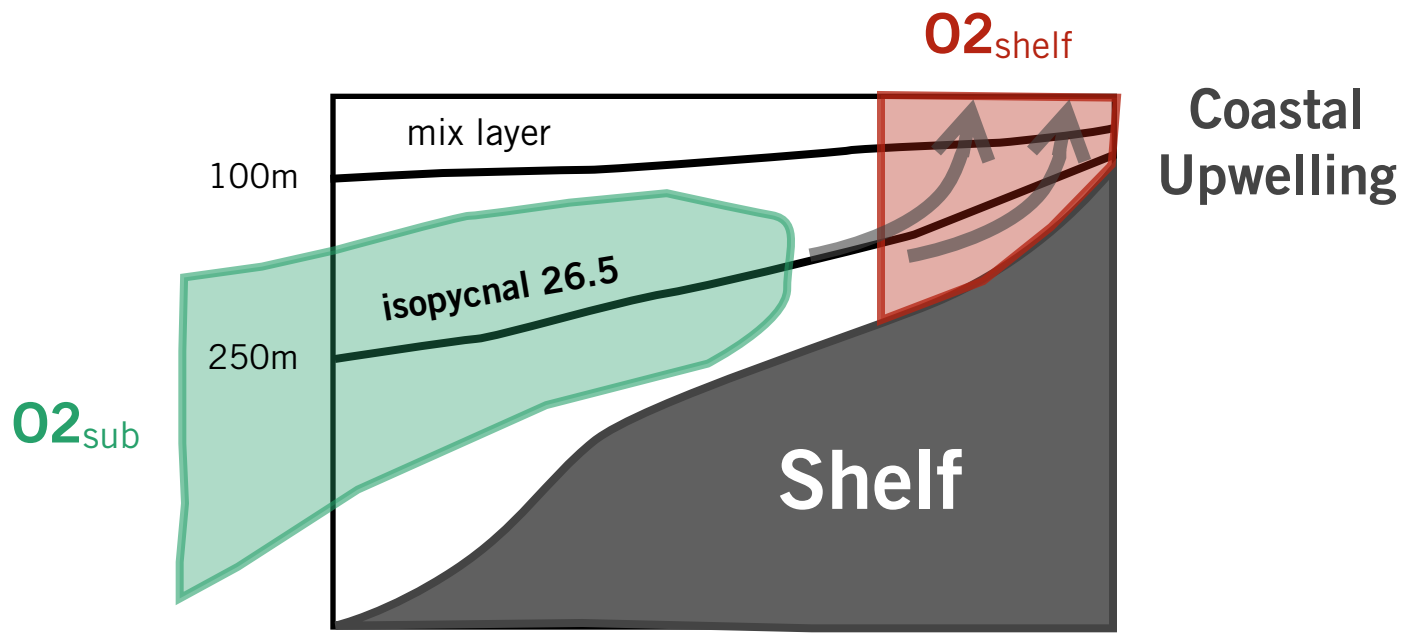
changes in upwelling and productivity

anomalies in source waters that feed mean upwelling

Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***



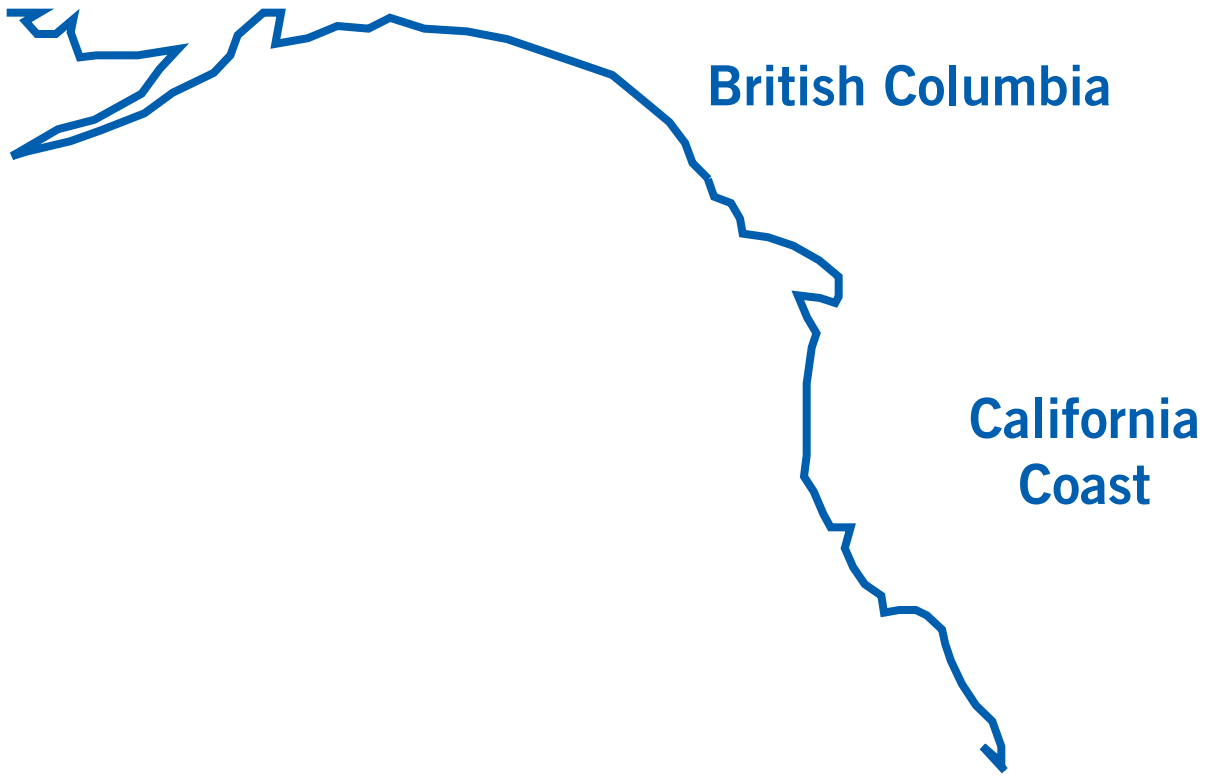
Large-scale ocean dynamics impacting ***COASTAL HYPOXIA***



GOAL:

Develop a conceptual model of the large-scale dynamics controlling $O2_{sub}$

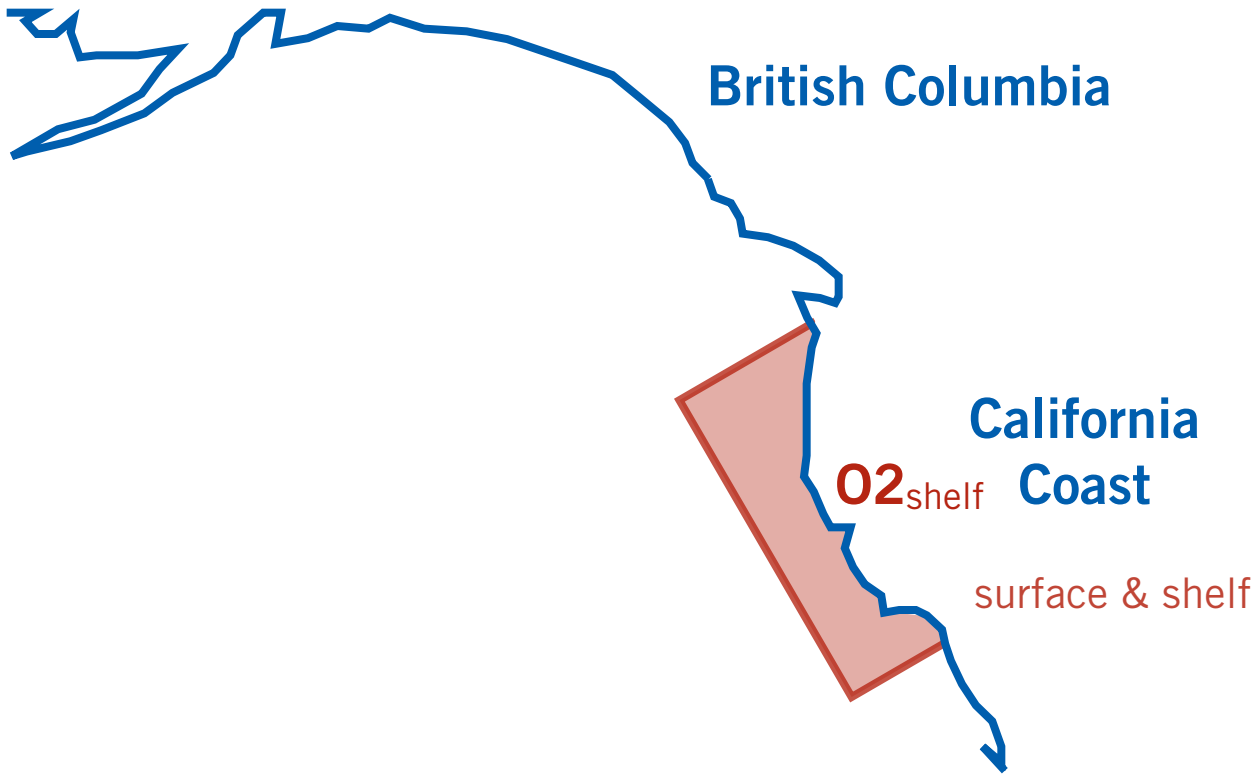
Large-scale ocean dynamics impacting **Coastal Hypoxia**



GOAL:

Develop a conceptual model of the large-scale dynamics controlling $O2_{sub}$

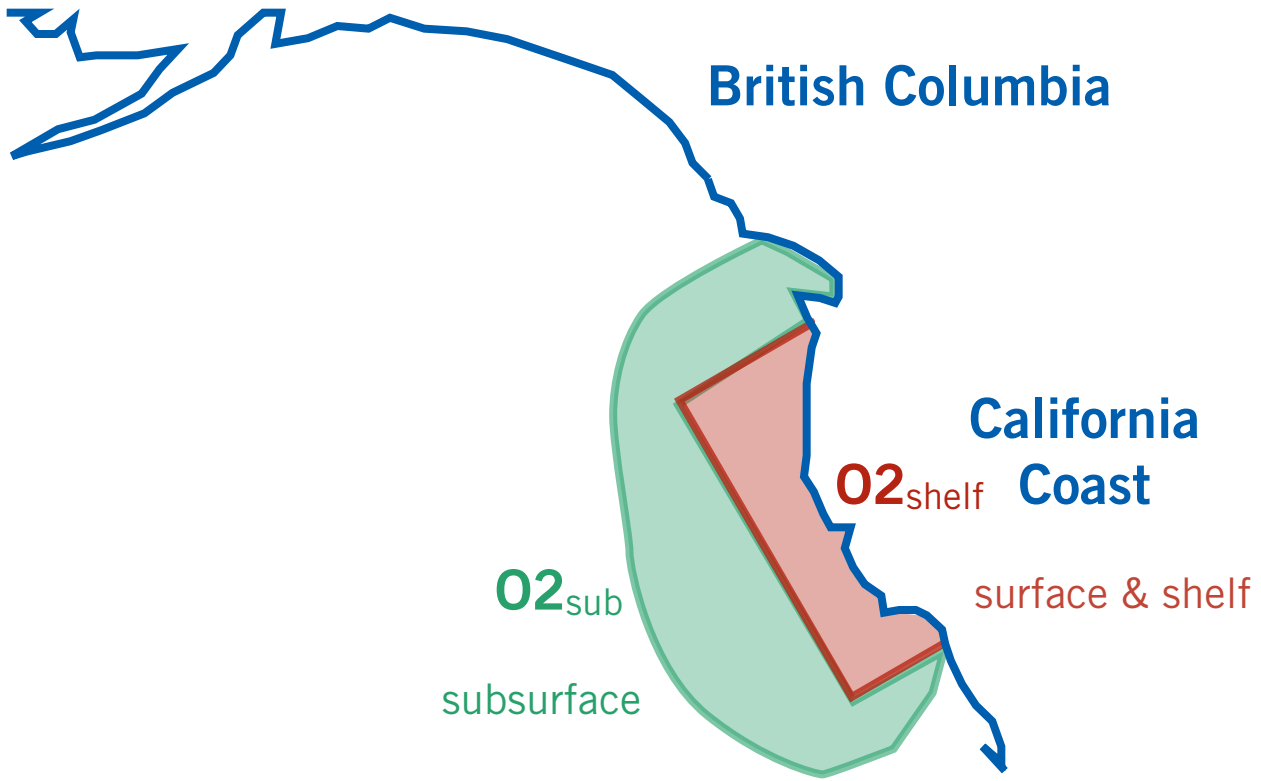
Large-scale ocean dynamics impacting **Coastal Hypoxia**



GOAL:

Develop a conceptual model of the large-scale dynamics controlling $O2_{sub}$

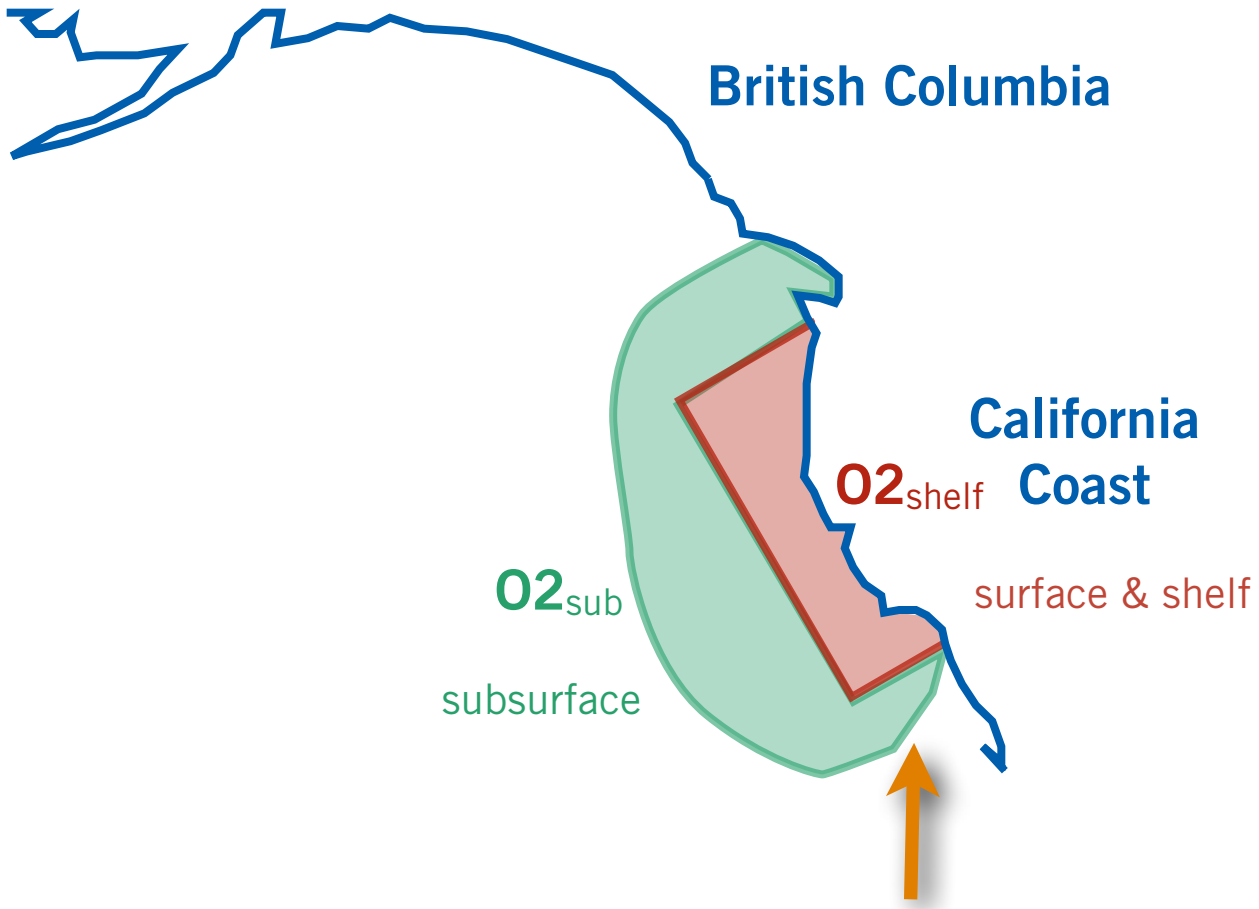
Large-scale ocean dynamics impacting **Coastal Hypoxia**



<u>GOAL</u>:

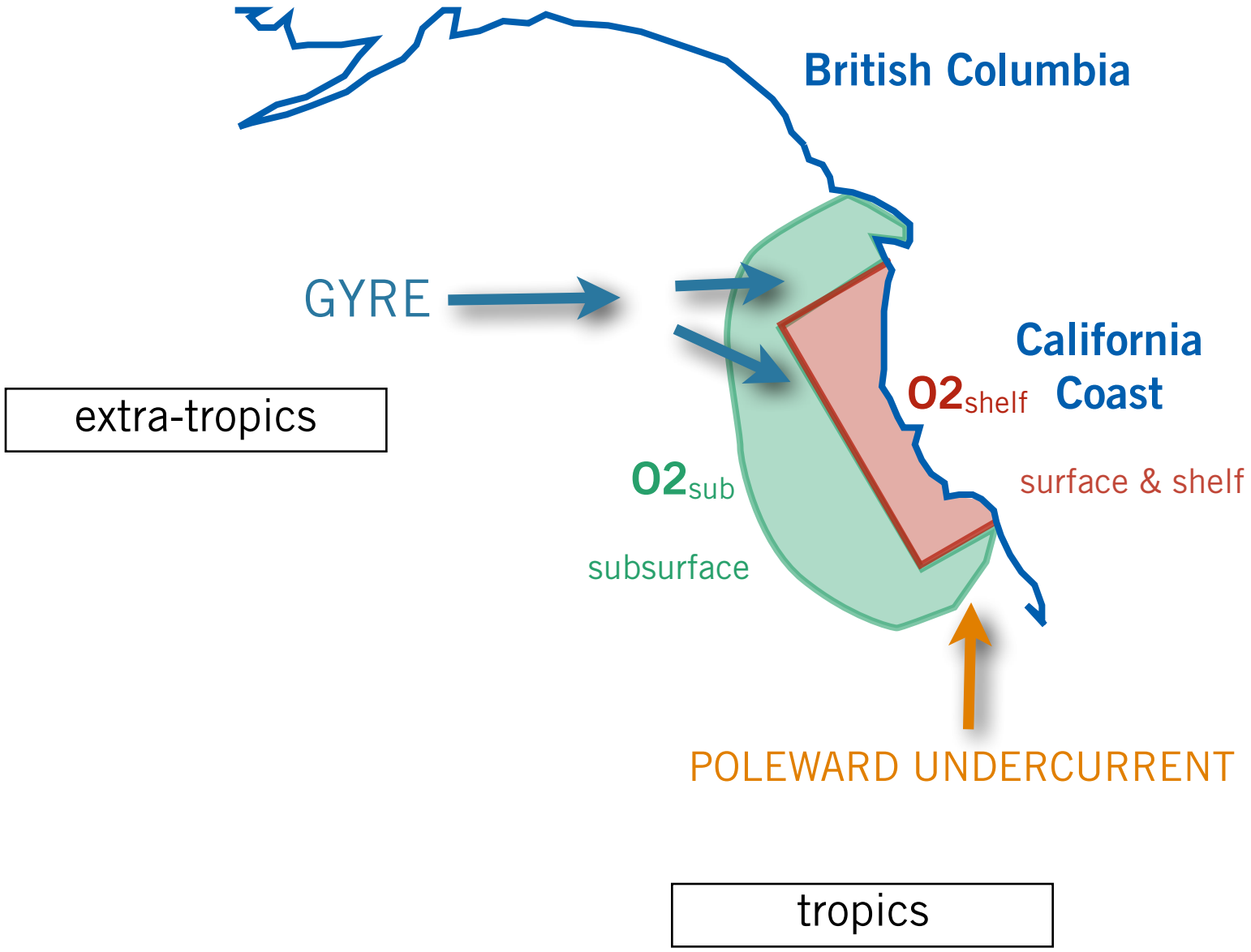
Develop a conceptual model of the large-scale dynamics controlling $O2_{sub}$

Large-scale ocean dynamics impacting **Coastal Hypoxia**



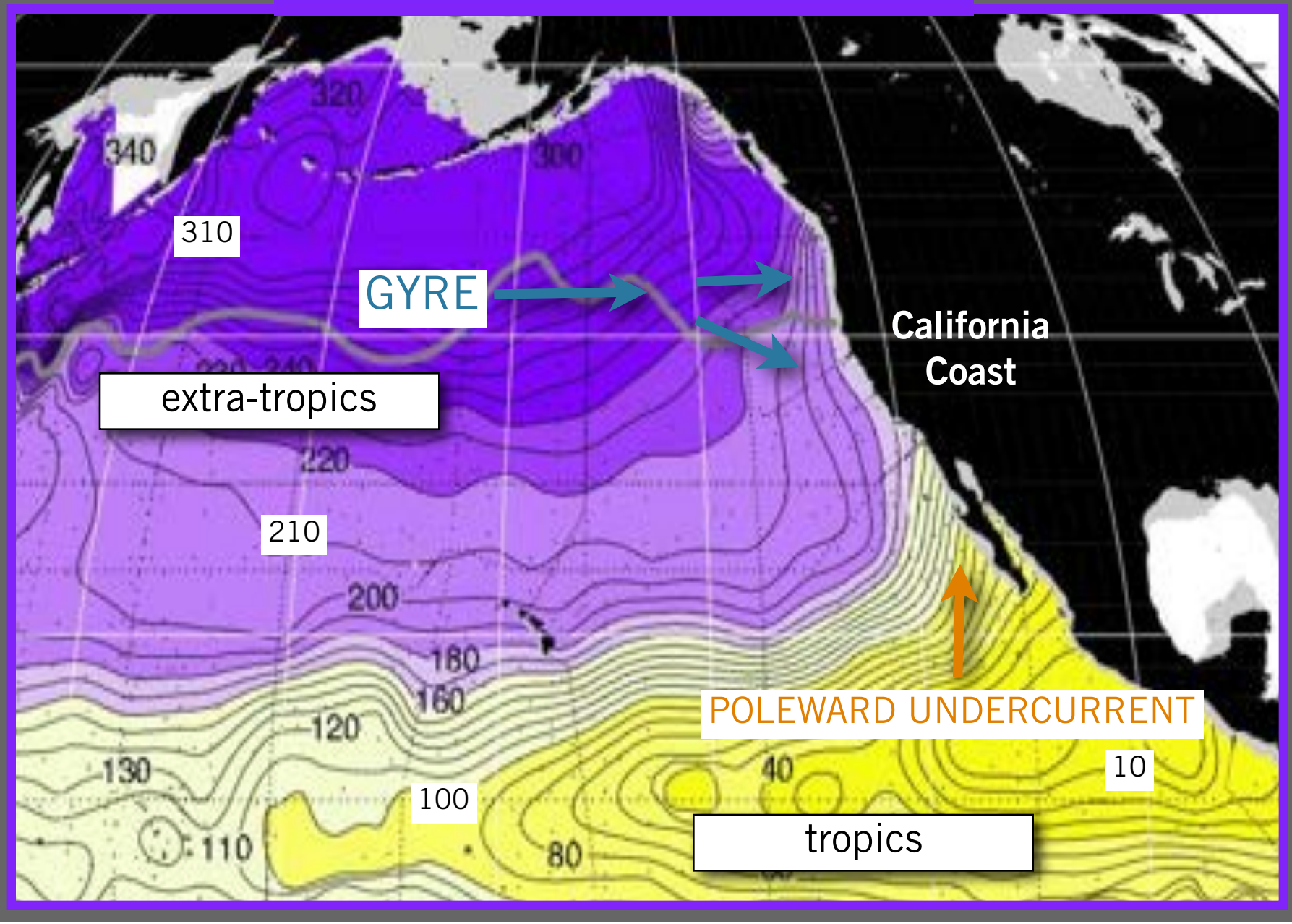
tropics

Large-scale ocean dynamics impacting **Coastal Hypoxia**



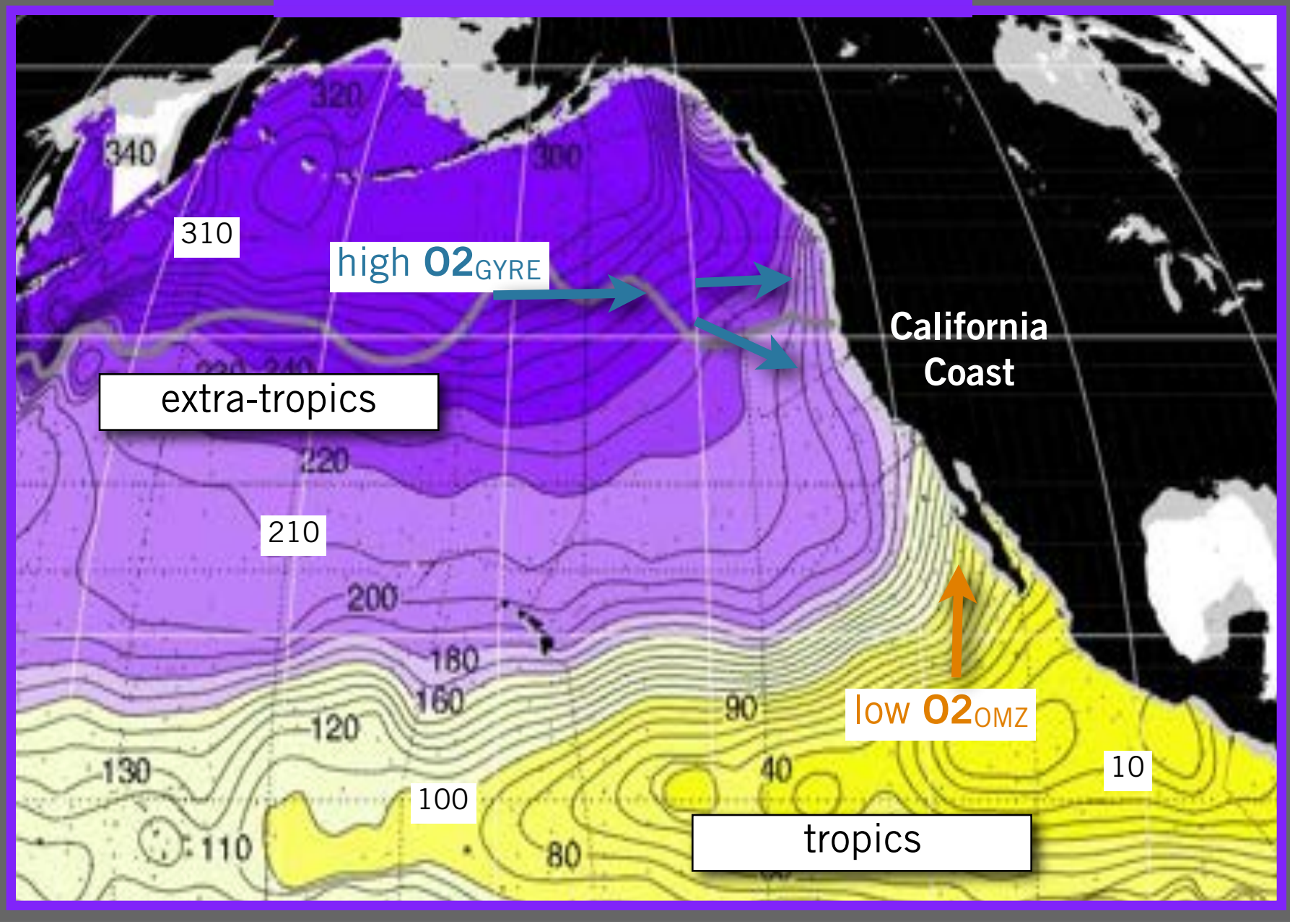
Large-scale ocean dynamics impacting **Coastal Hypoxia**

Oxygen Isopycnal 26.5



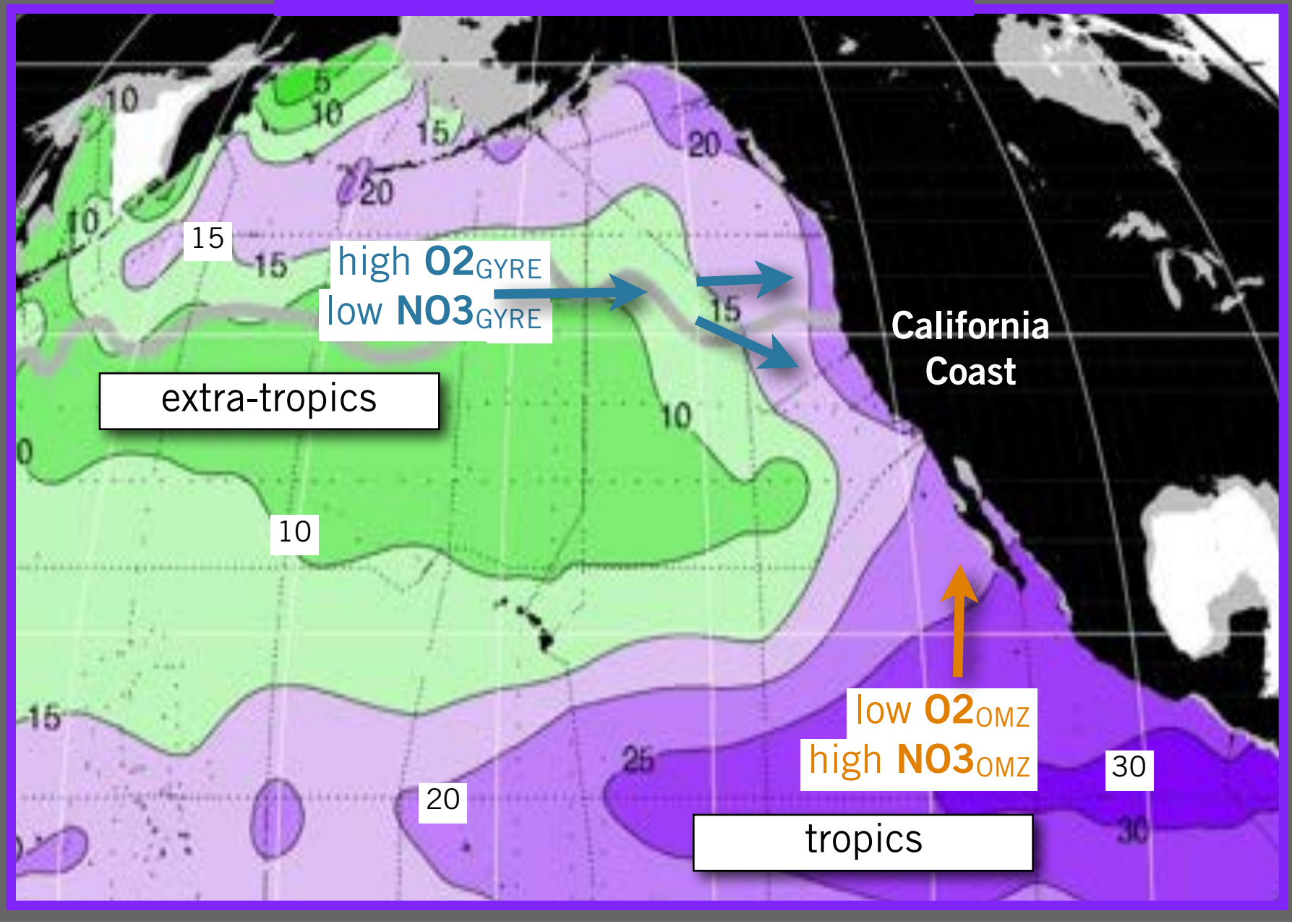
Large-scale ocean dynamics impacting **Coastal Hypoxia**

Oxygen Isopycnal 26.5

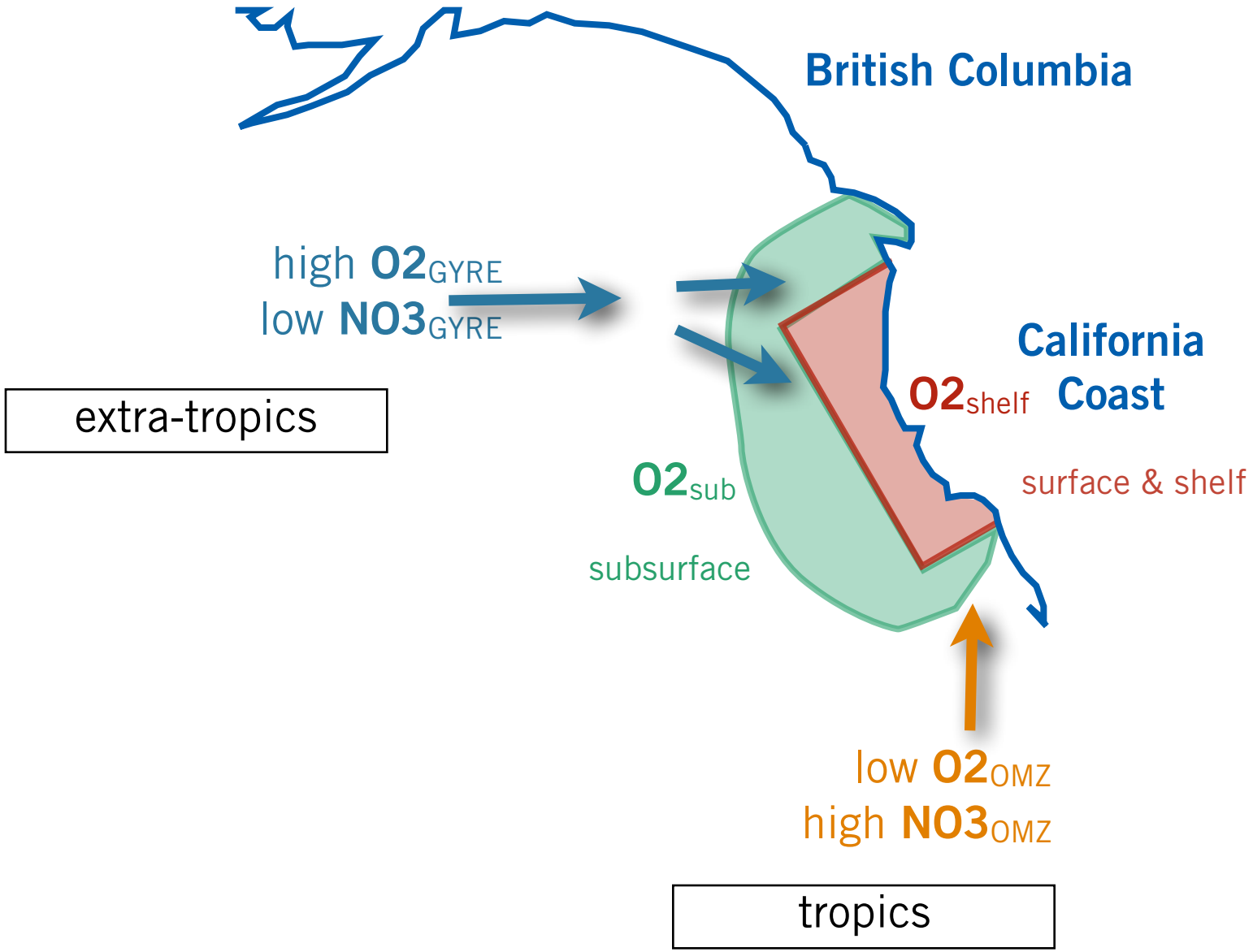


Large-scale ocean dynamics impacting **Coastal Hypoxia**

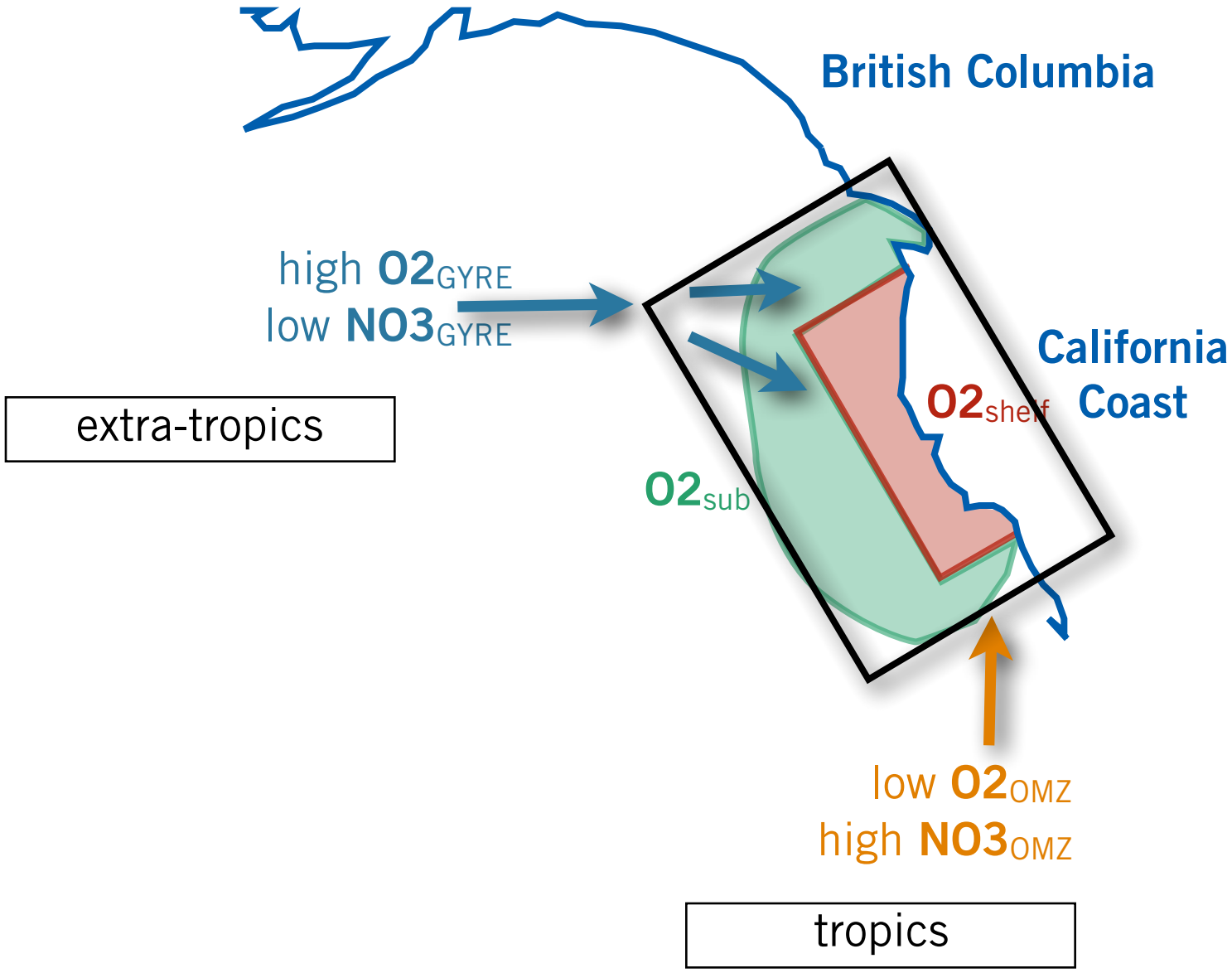
Nitrate Isopycnal 26.5



Large-scale ocean dynamics impacting **Coastal Hypoxia**

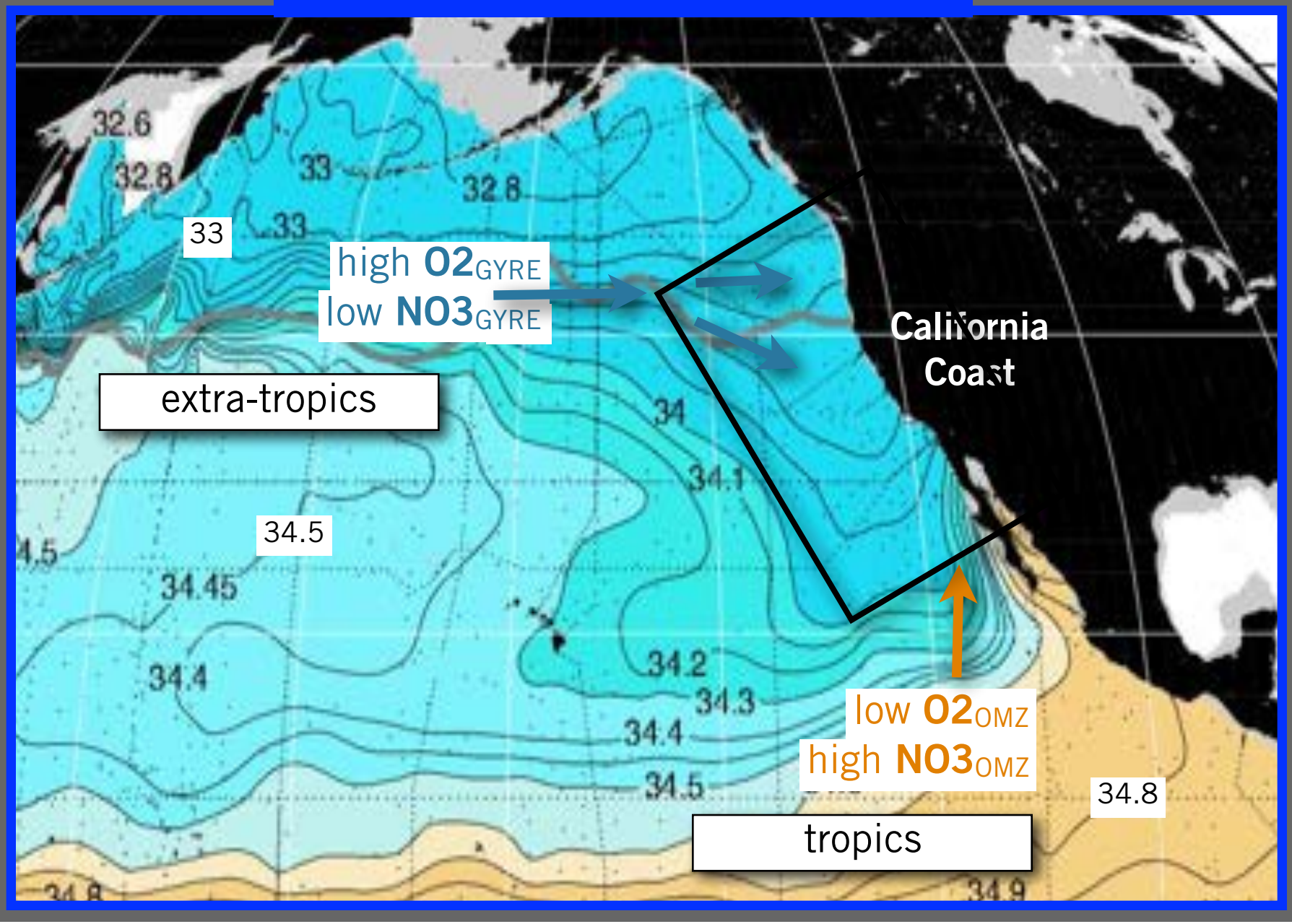


Large-scale ocean dynamics impacting **Coastal Hypoxia**



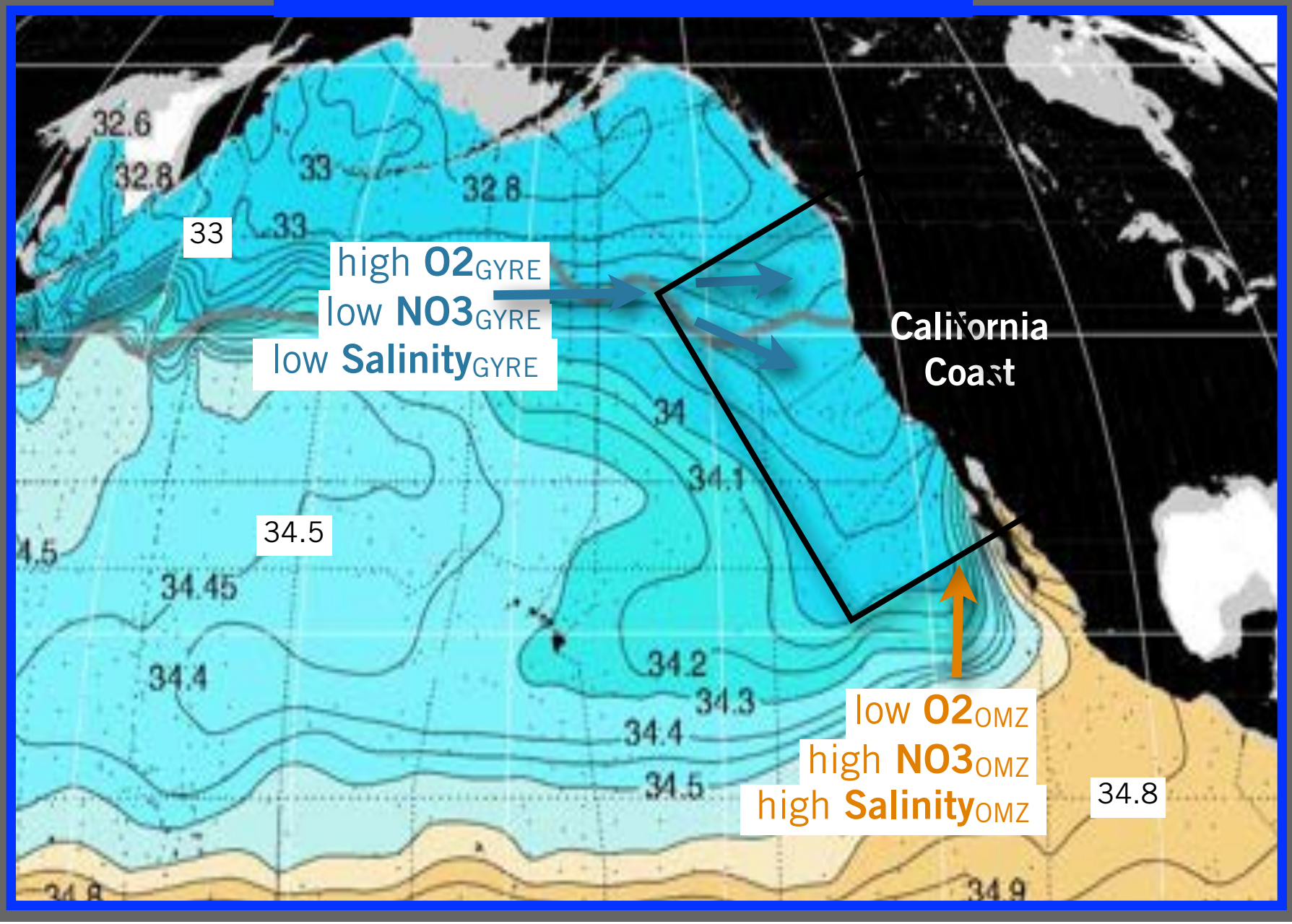
Large-scale ocean dynamics impacting **Coastal Hypoxia**

Salinity Isopycnal 26.5

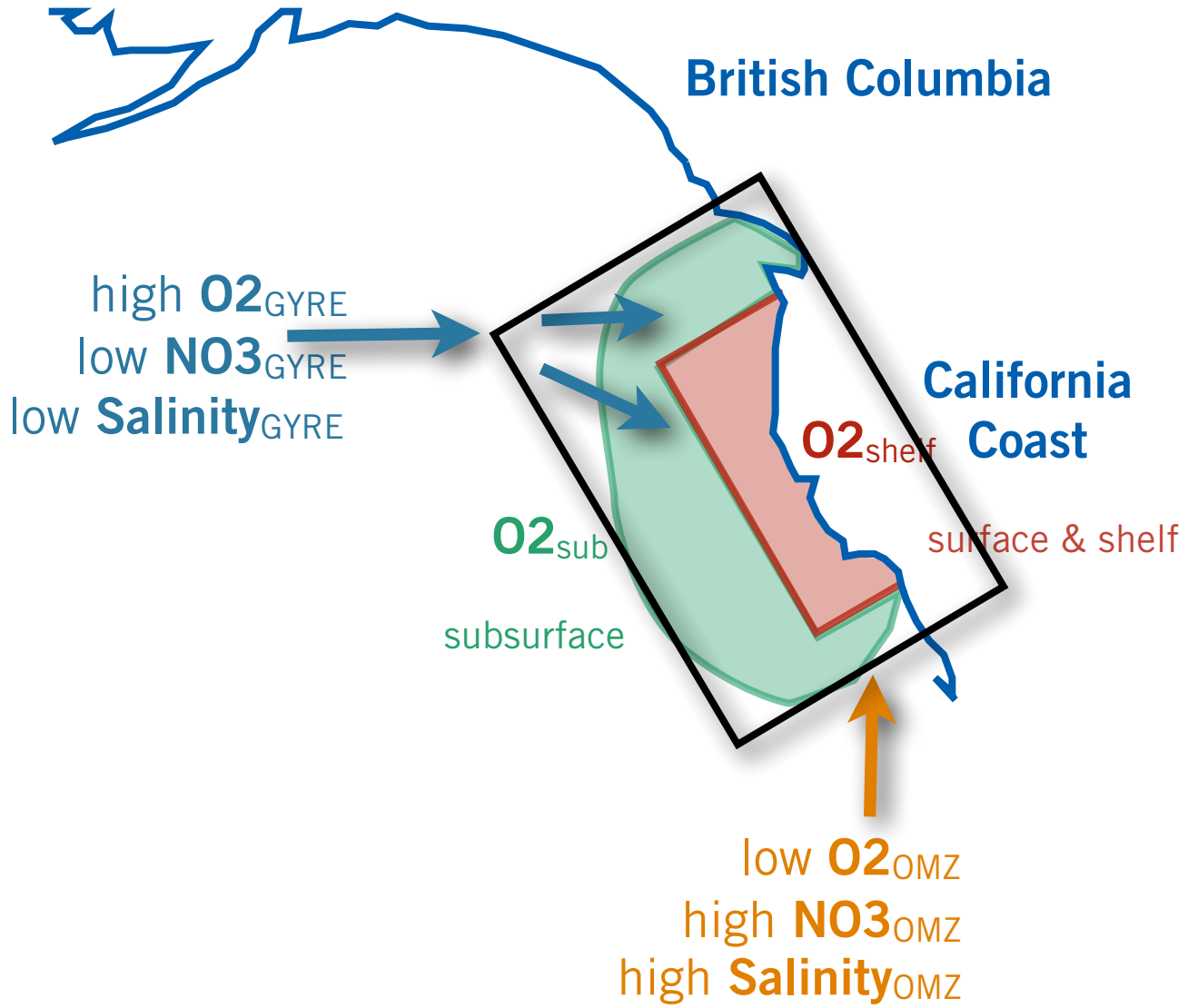


Large-scale ocean dynamics impacting **Coastal Hypoxia**

Salinity Isopycnal 26.5

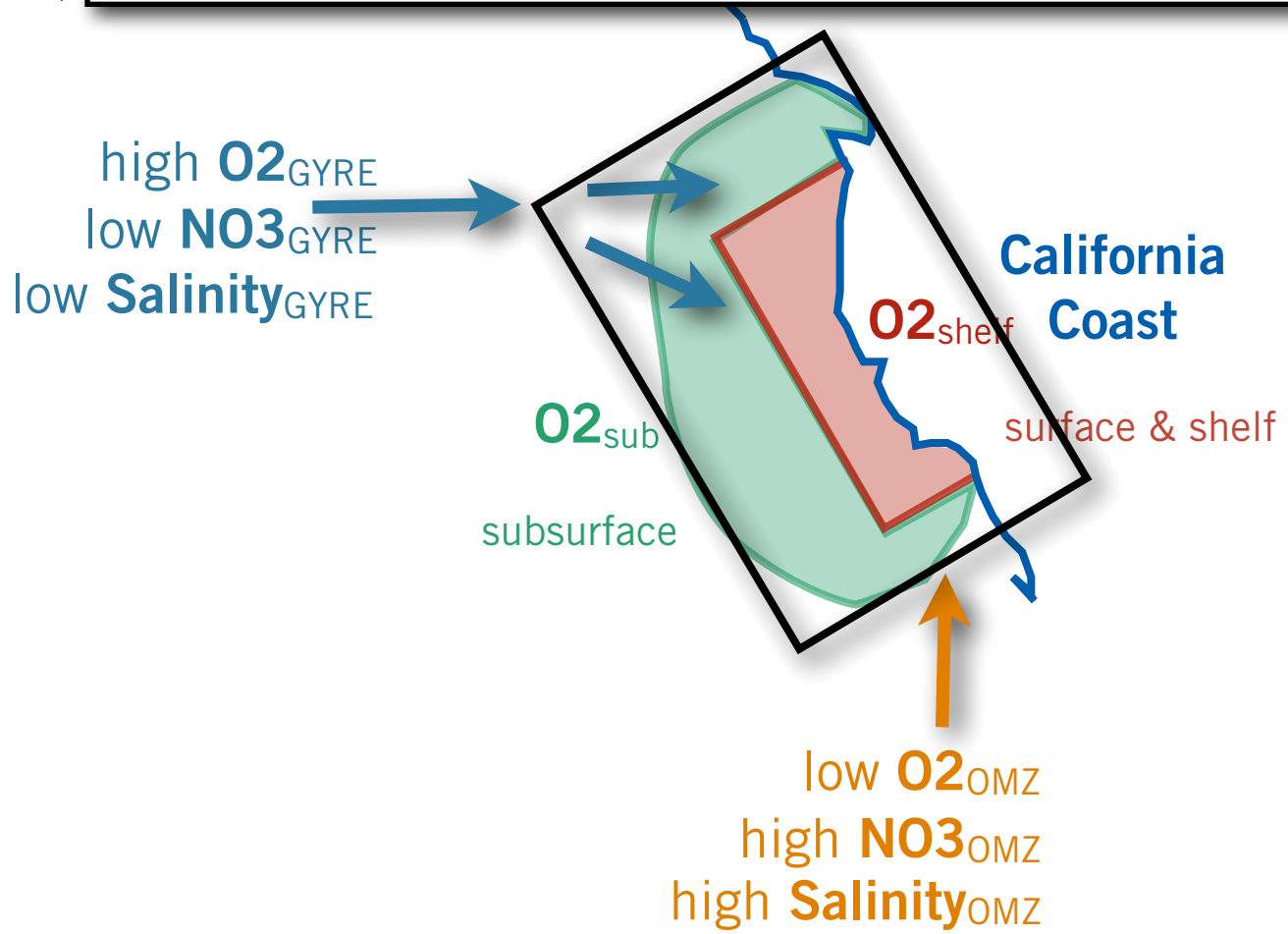


Large-scale ocean dynamics impacting **Coastal Hypoxia**



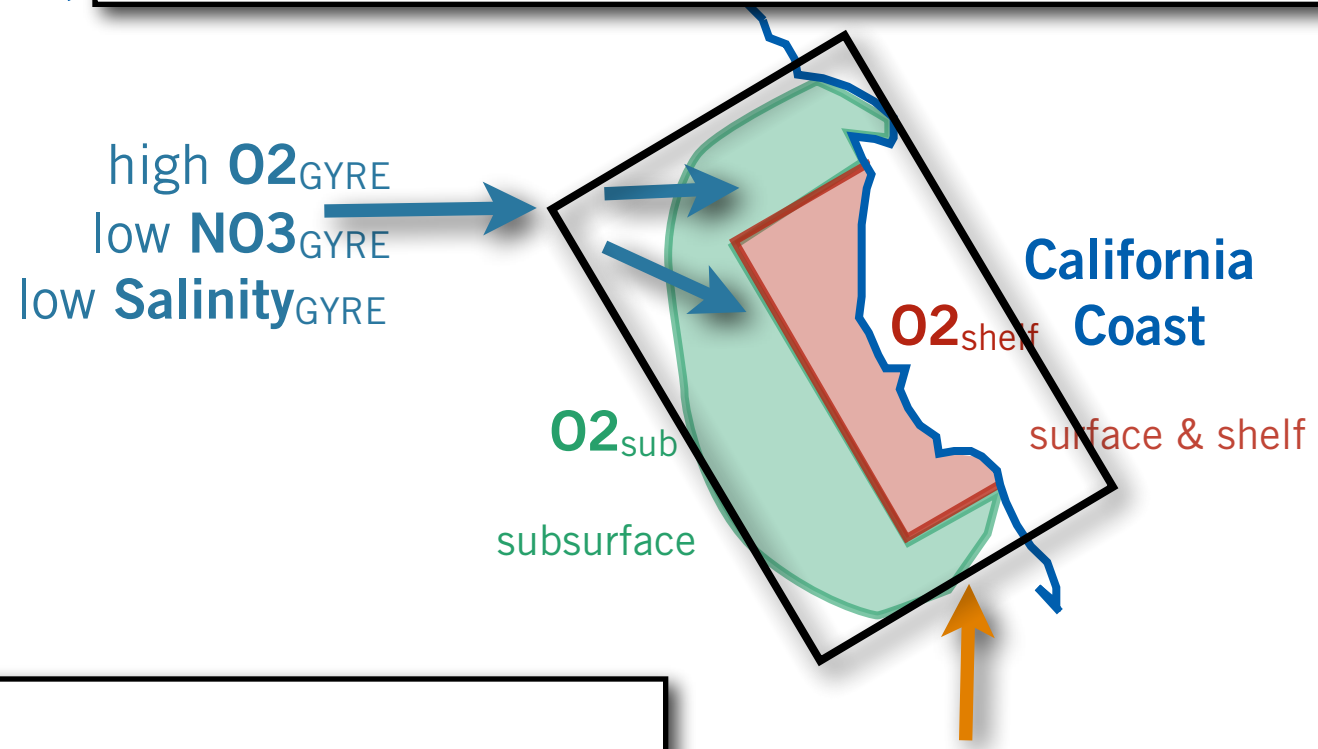
Large-scale ocean dynamics impacting **Coastal Hypoxia**

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)
Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)
California Oxygen (Deutsch et al., 2011)



Large-scale ocean dynamics impacting **Coastal Hypoxia**

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)
Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)
California Oxygen (Deutsch et al., 2011)



salinity anomalies on isopycnal 26.5 = Oxygen Proxy

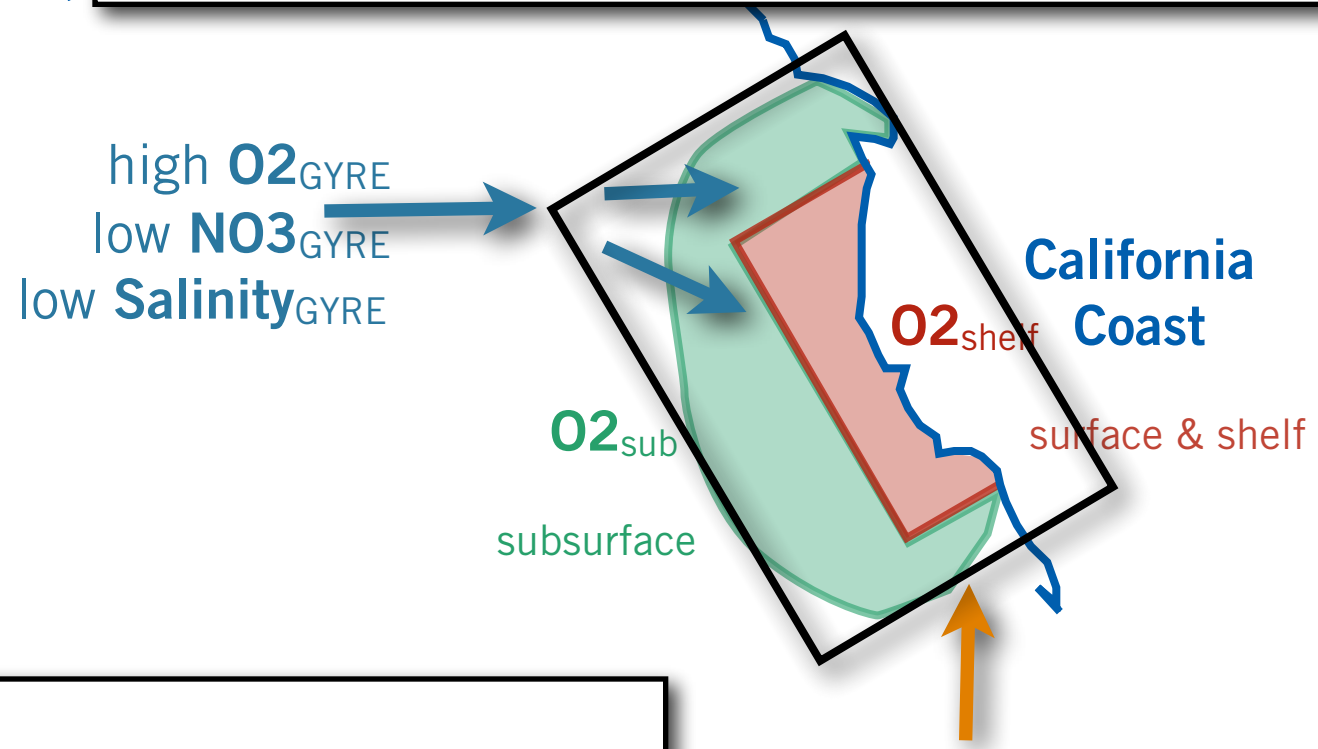
Large-scale ocean dynamics impacting **Coastal Hypoxia**

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)

Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



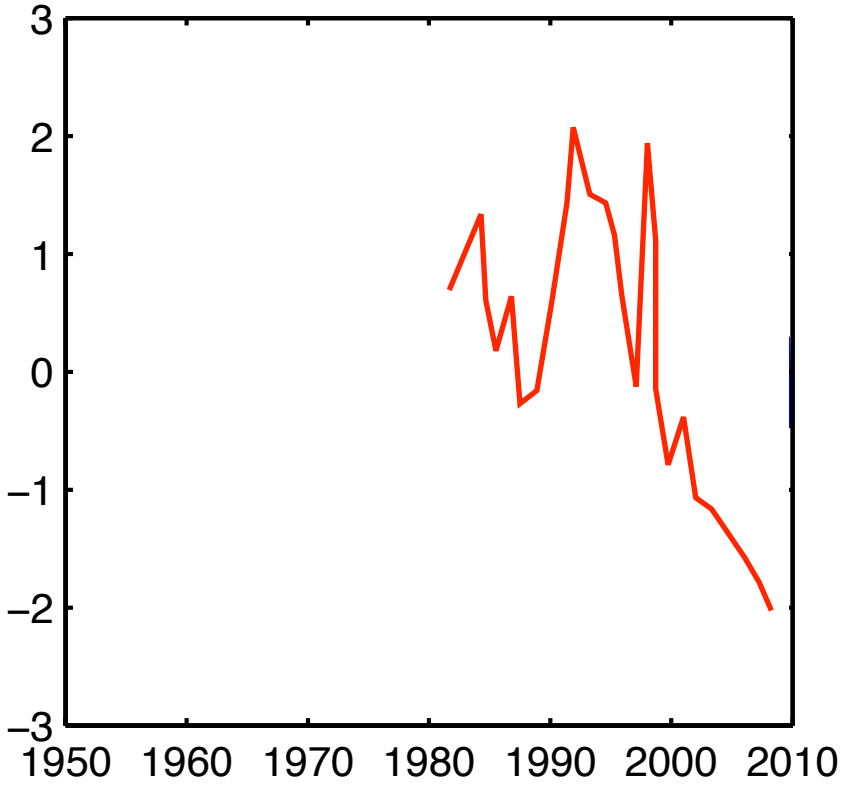
salinity anomalies on isopycnal 26.5 = Oxygen Proxy

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)

Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



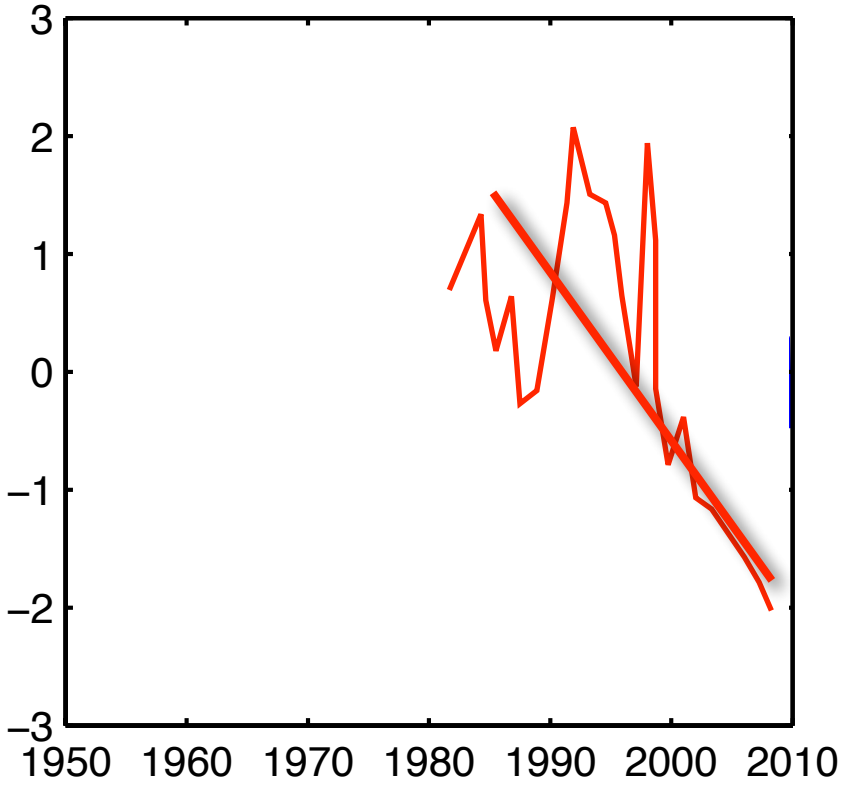
Observations ***SUBSURFACE OXYGEN***
in the California Current System

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)

Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



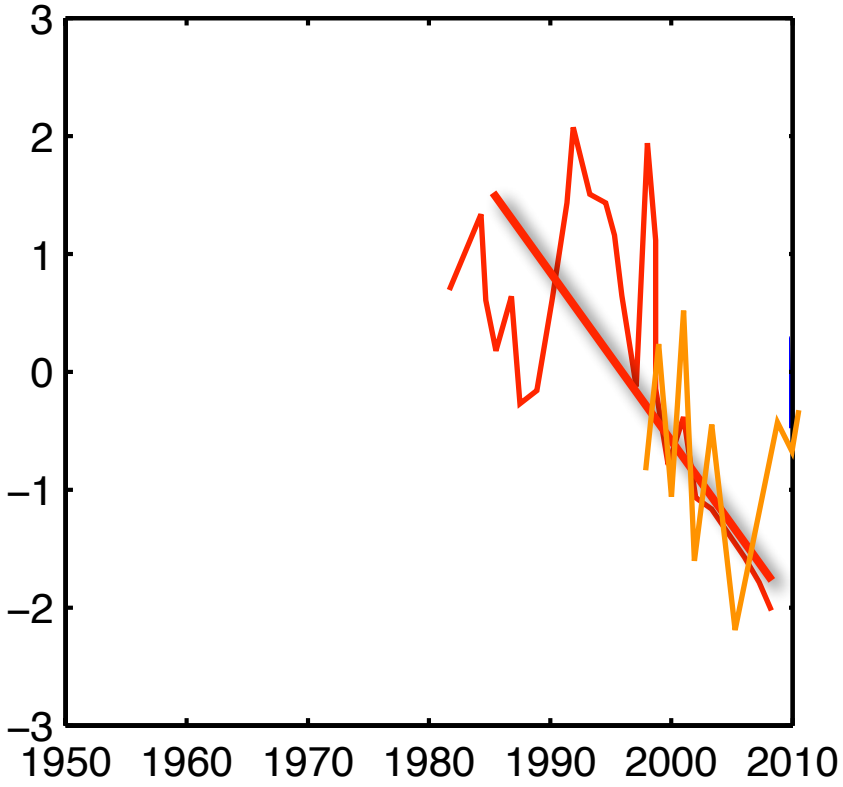
Observations ***SUBSURFACE OXYGEN***
in the California Current System

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)

Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



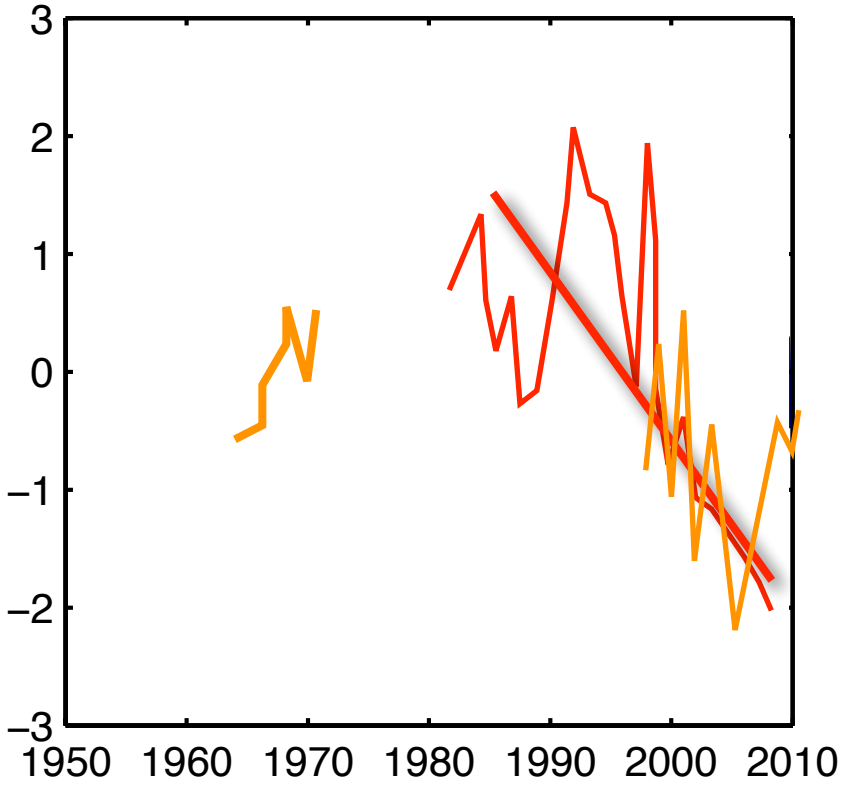
Observations ***SUBSURFACE OXYGEN***
in the California Current System

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)

Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



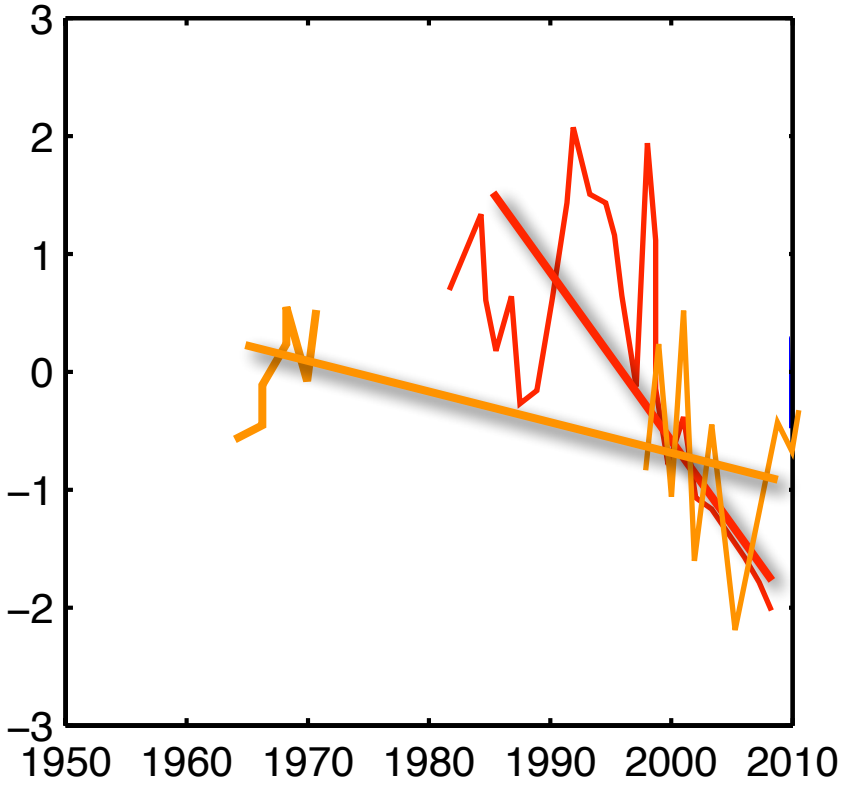
Observations ***SUBSURFACE OXYGEN***
in the California Current System

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)

Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



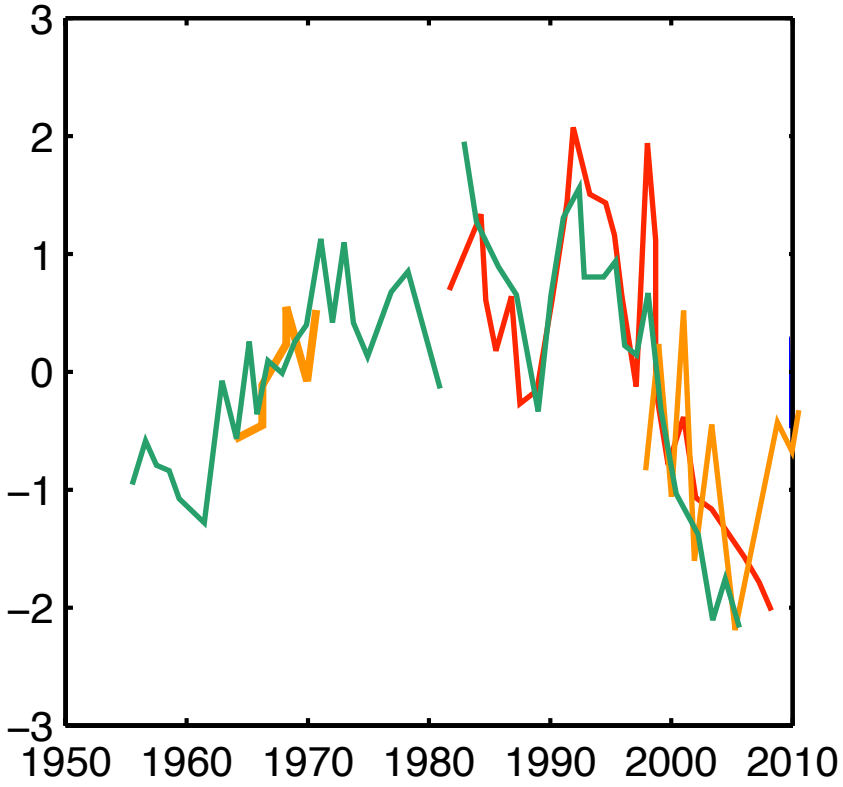
Observations ***SUBSURFACE OXYGEN***
in the California Current System

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)

Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



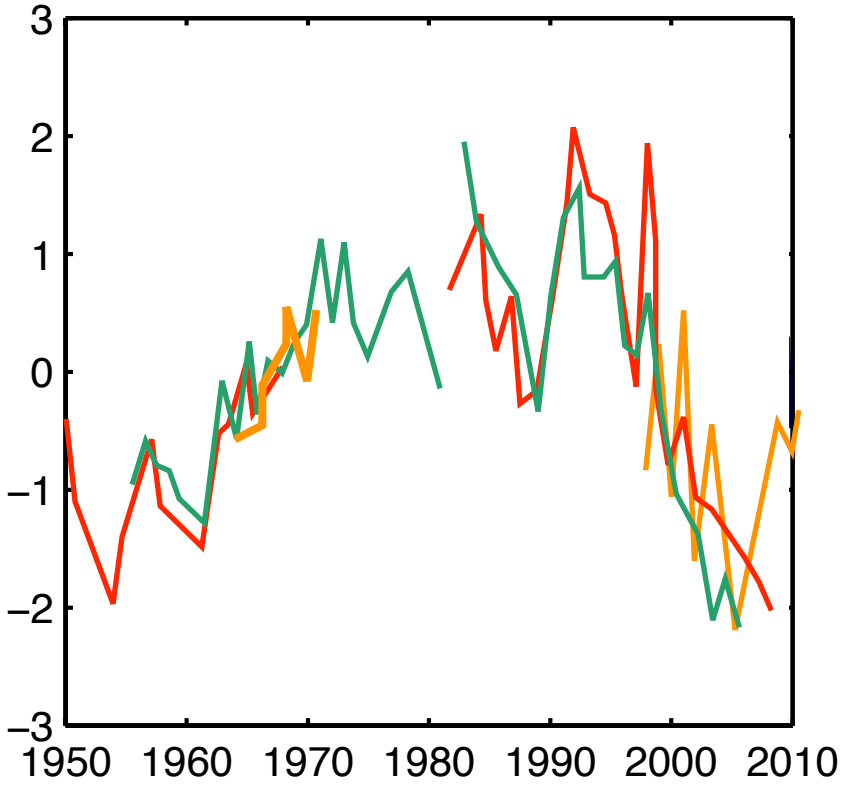
Observations ***SUBSURFACE OXYGEN***
in the California Current System

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)

Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



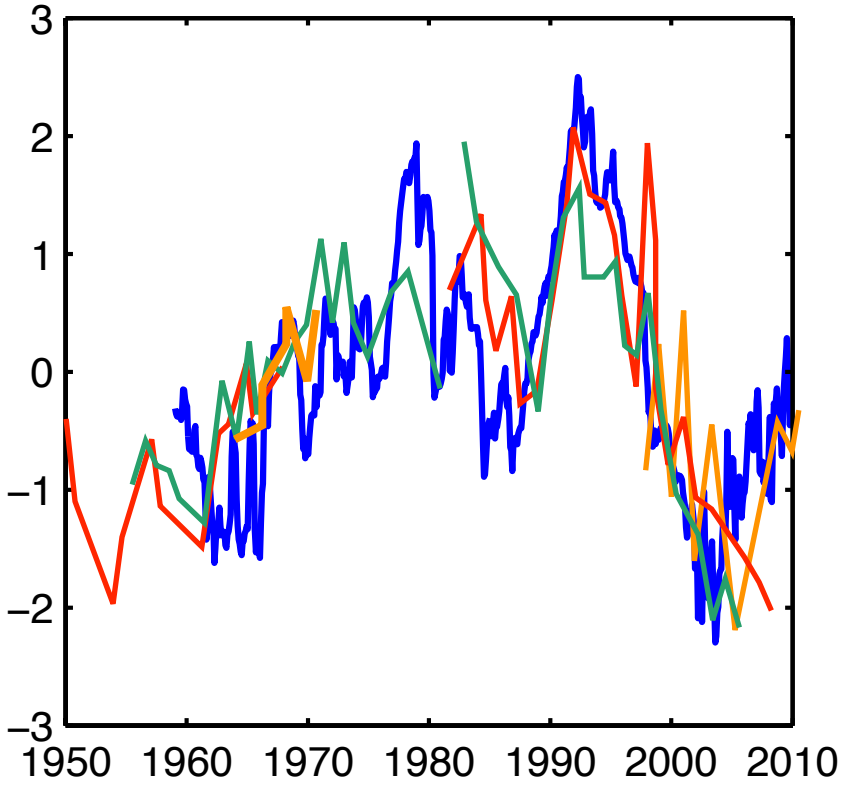
Observations ***SUBSURFACE OXYGEN***
in the California Current System

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Bograd et al. 2008; Koslow et al., 2011)

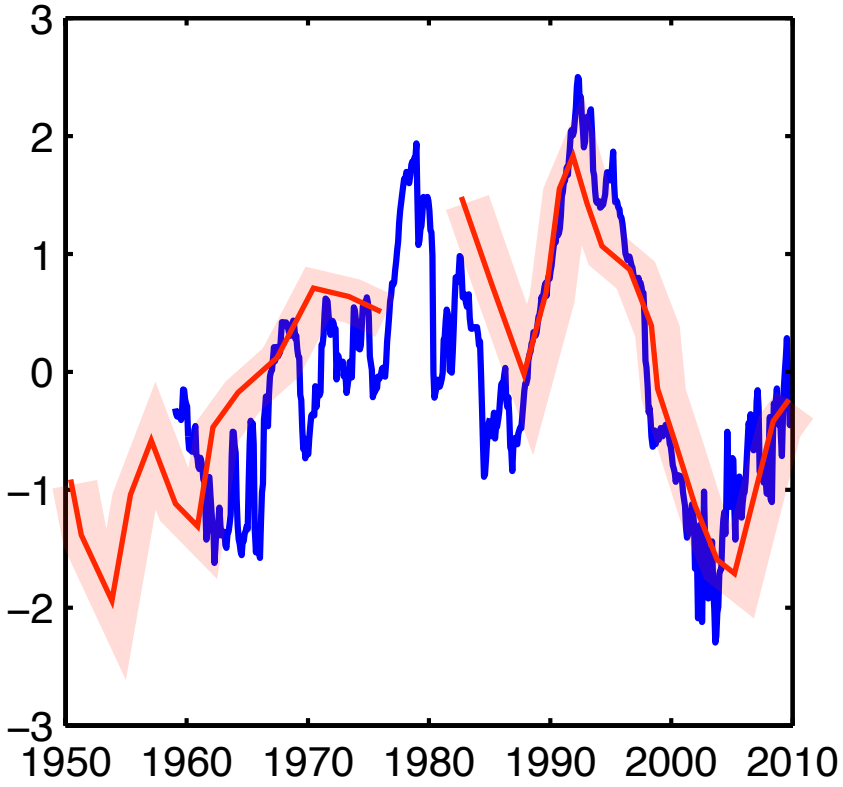
Newport Oxygen (Pierce et al., 2012; Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)

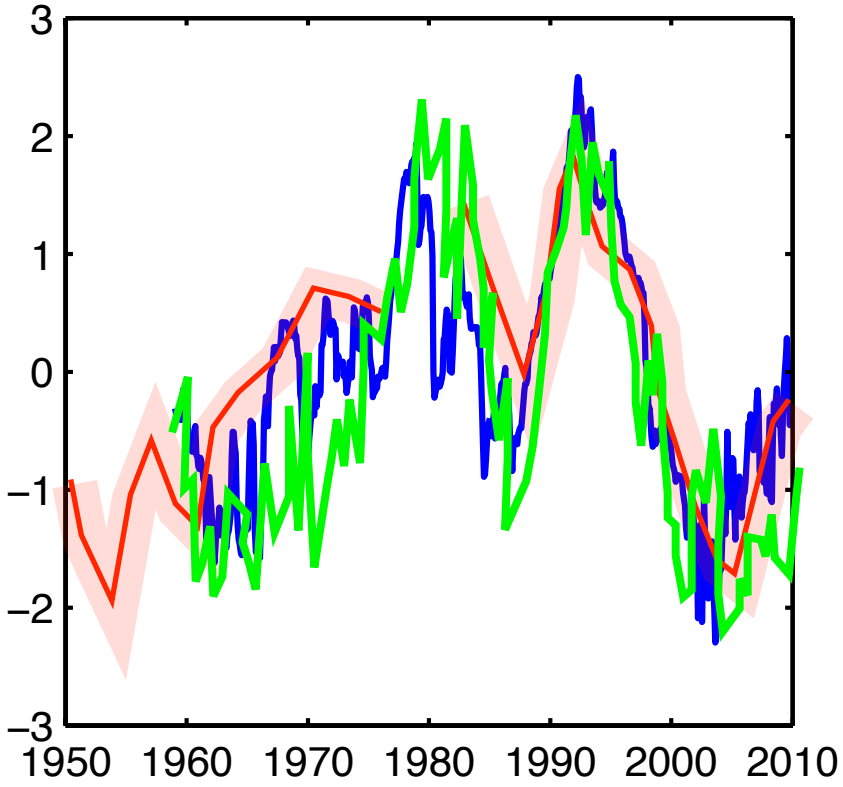


Observations ***SUBSURFACE OXYGEN***
in the California Current System

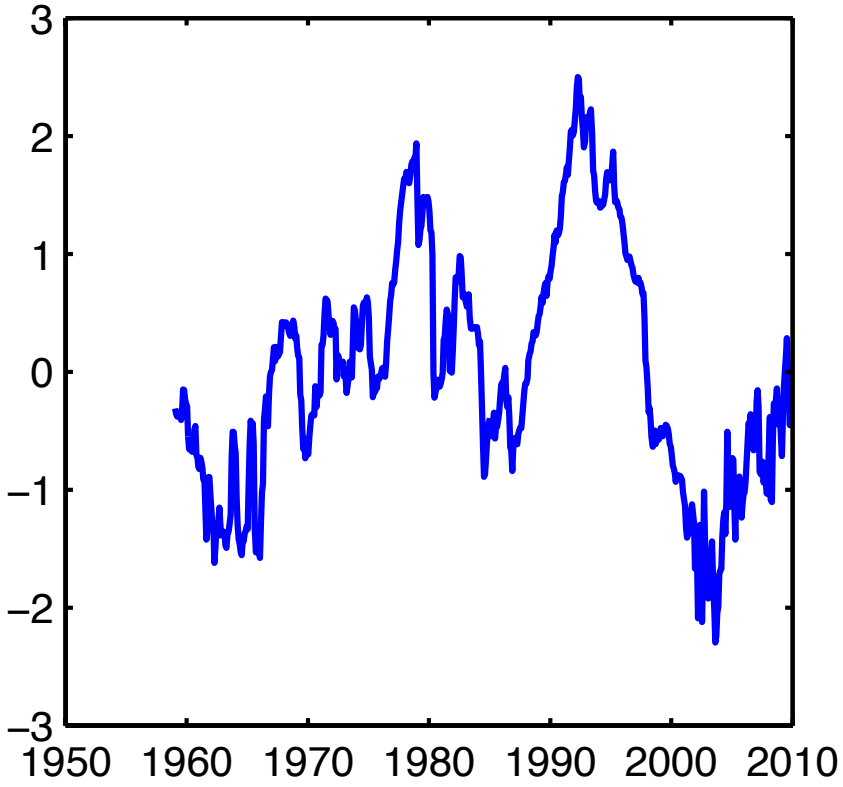
ECMWF ORA3 Oxygen Proxy
Observations Oxygen



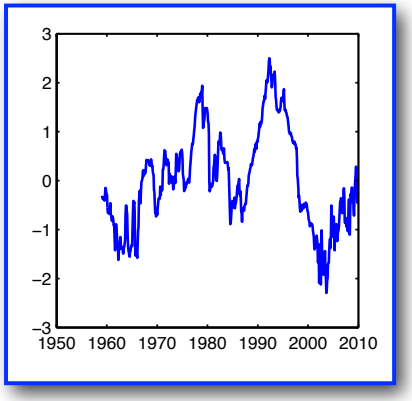
ECMWF ORA3 Oxygen Proxy
Observations Oxygen
SODA Reanalysis Oxygen Proxy



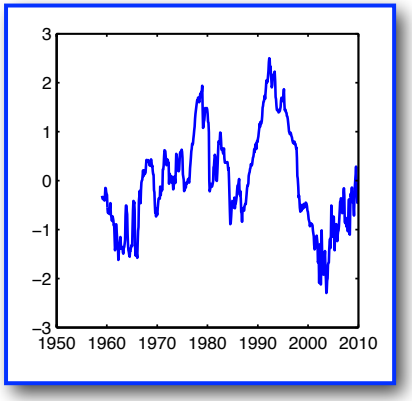
ECMWF ORA3 Oxygen Proxy Index

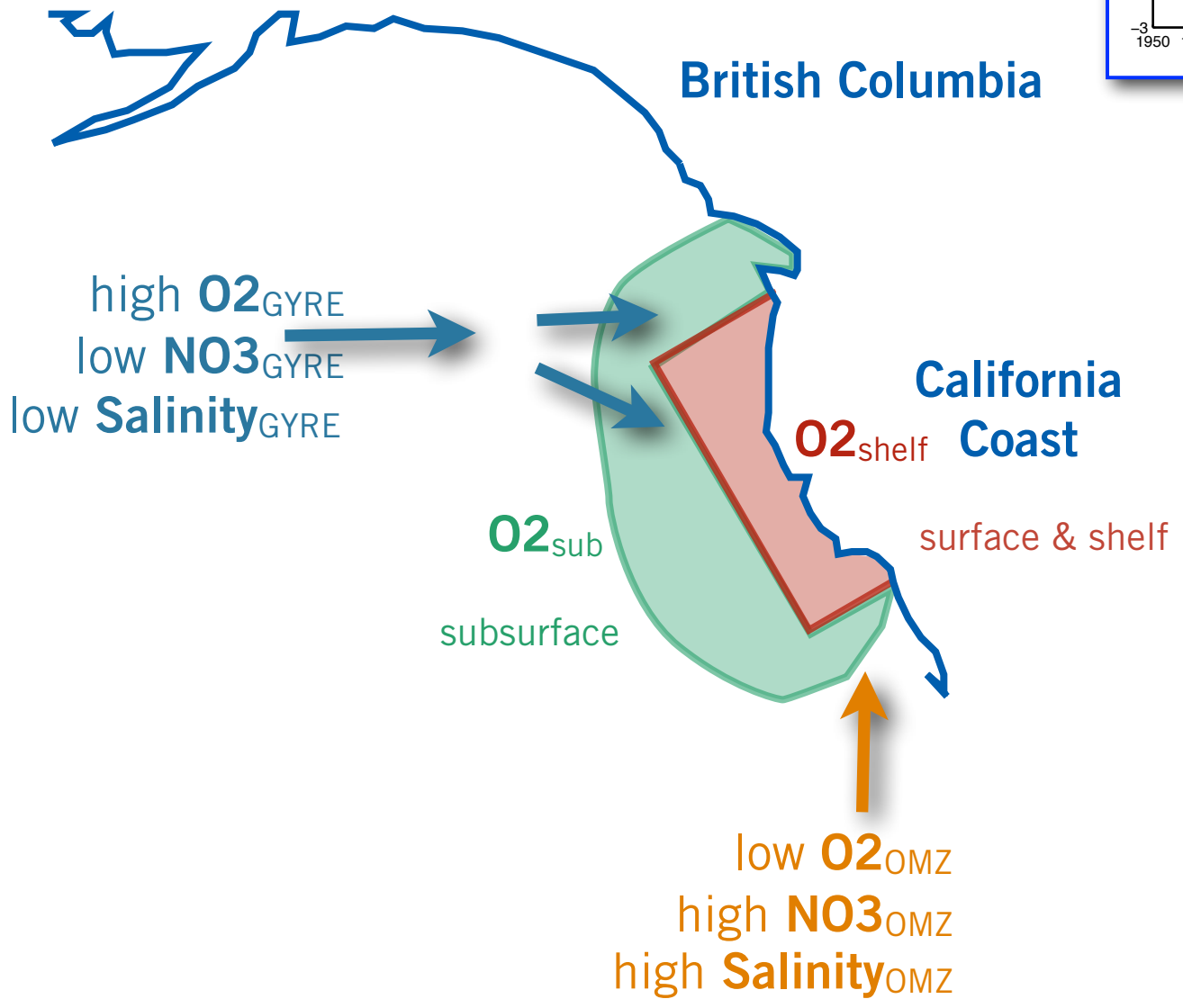


ECMWF ORA3 Oxygen Proxy Index

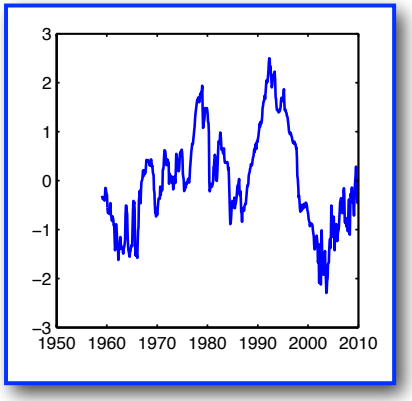


ECMWF ORA3 Oxygen Proxy Index

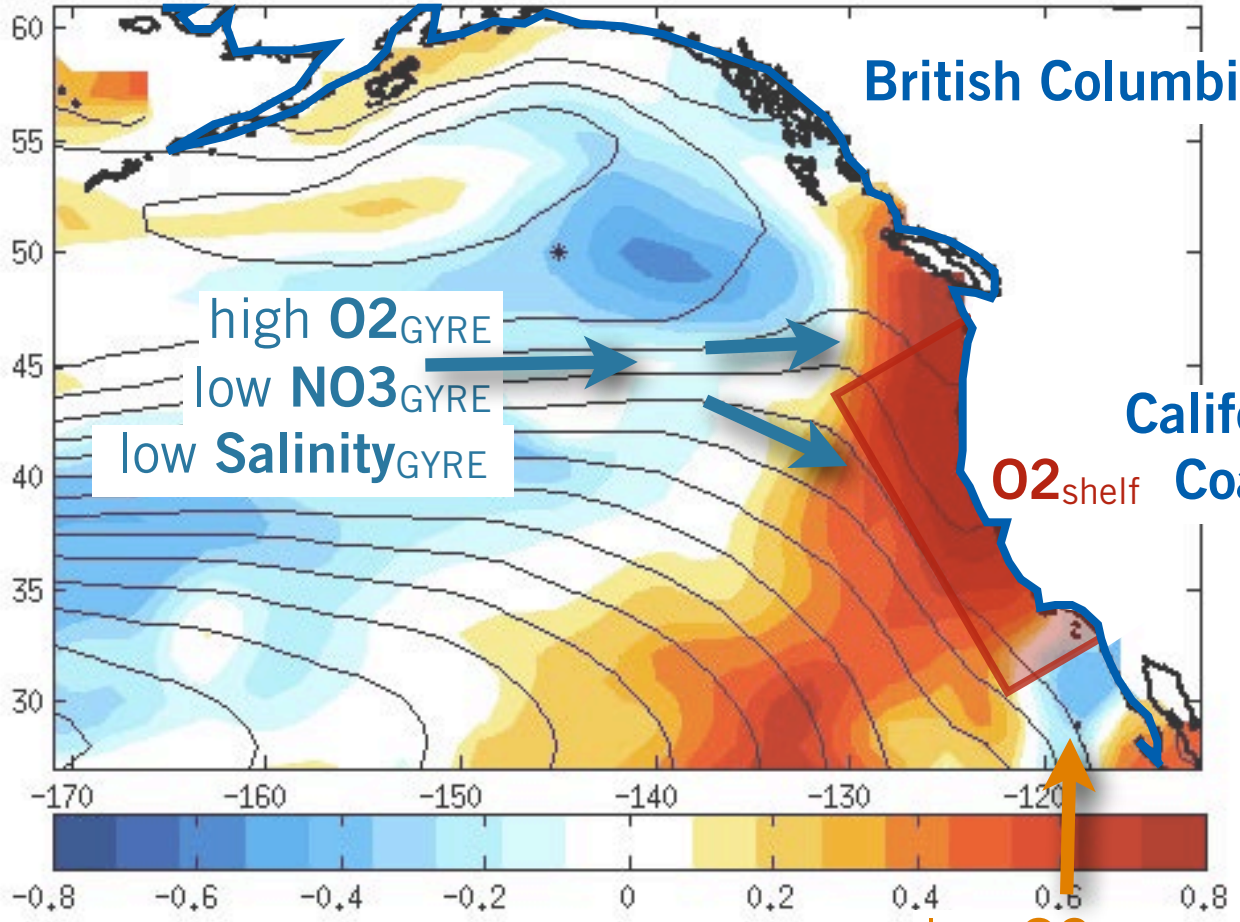




ECMWF ORA3 Oxygen Proxy Index



Correlation with Salinity ISO=26.5



British Columbia

high $O2_{GYRE}$
low $NO3_{GYRE}$
low $Salinity_{GYRE}$

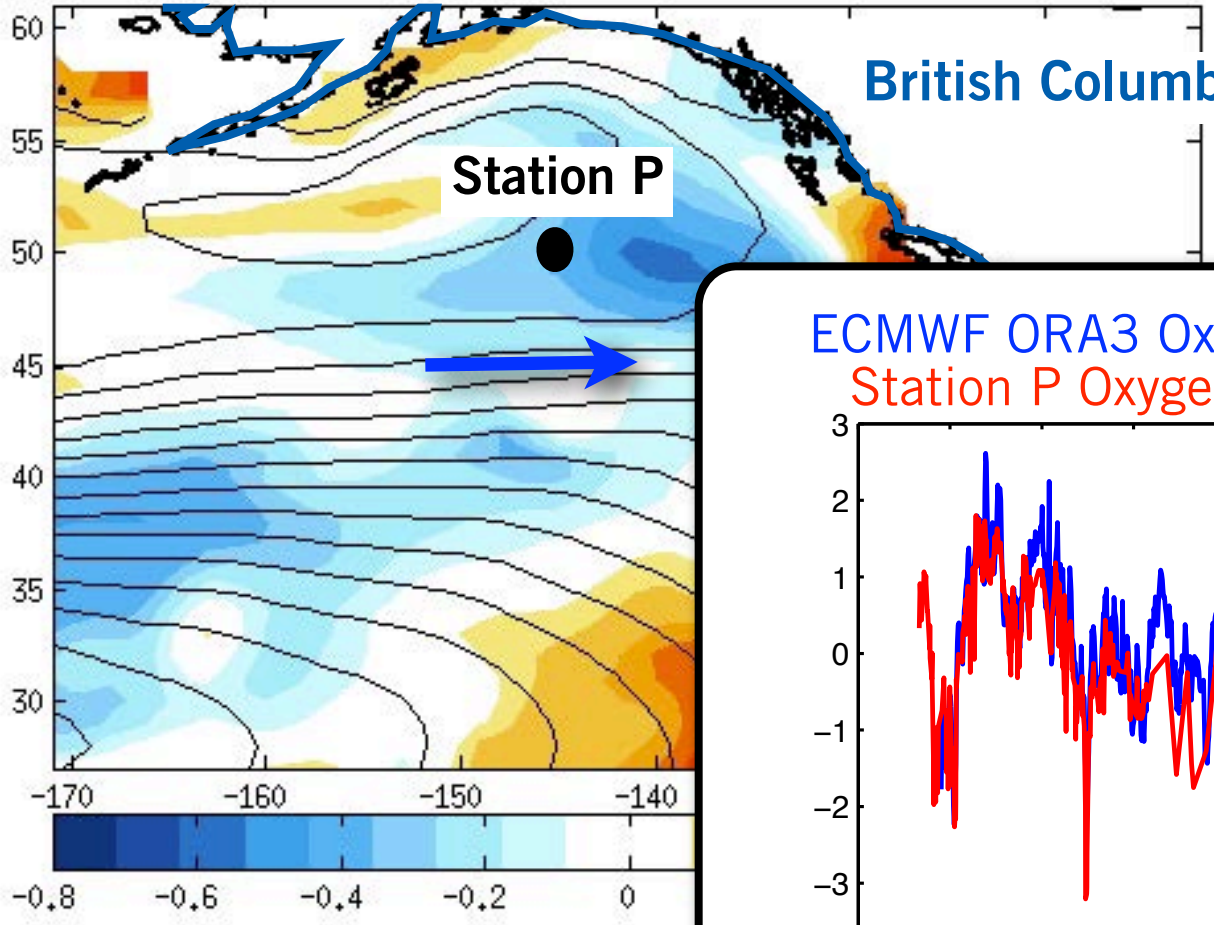
California Coast

$O2_{shelf}$

low $O2_{OMZ}$
high $NO3_{OMZ}$
high $Salinity_{OMZ}$

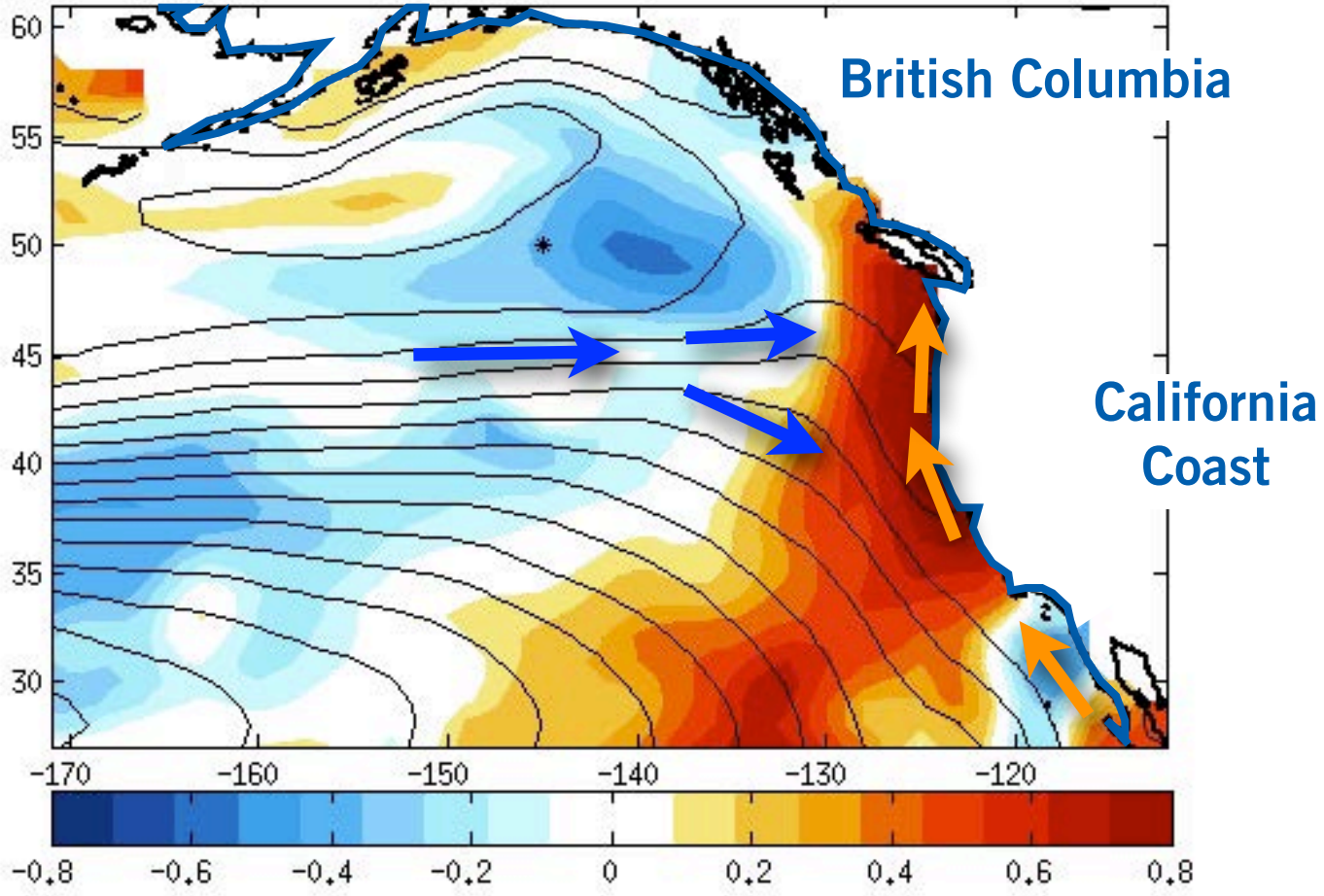
ECMWF ORA3 Oxygen Proxy Index

Correlation with Salinity ISO=26.5

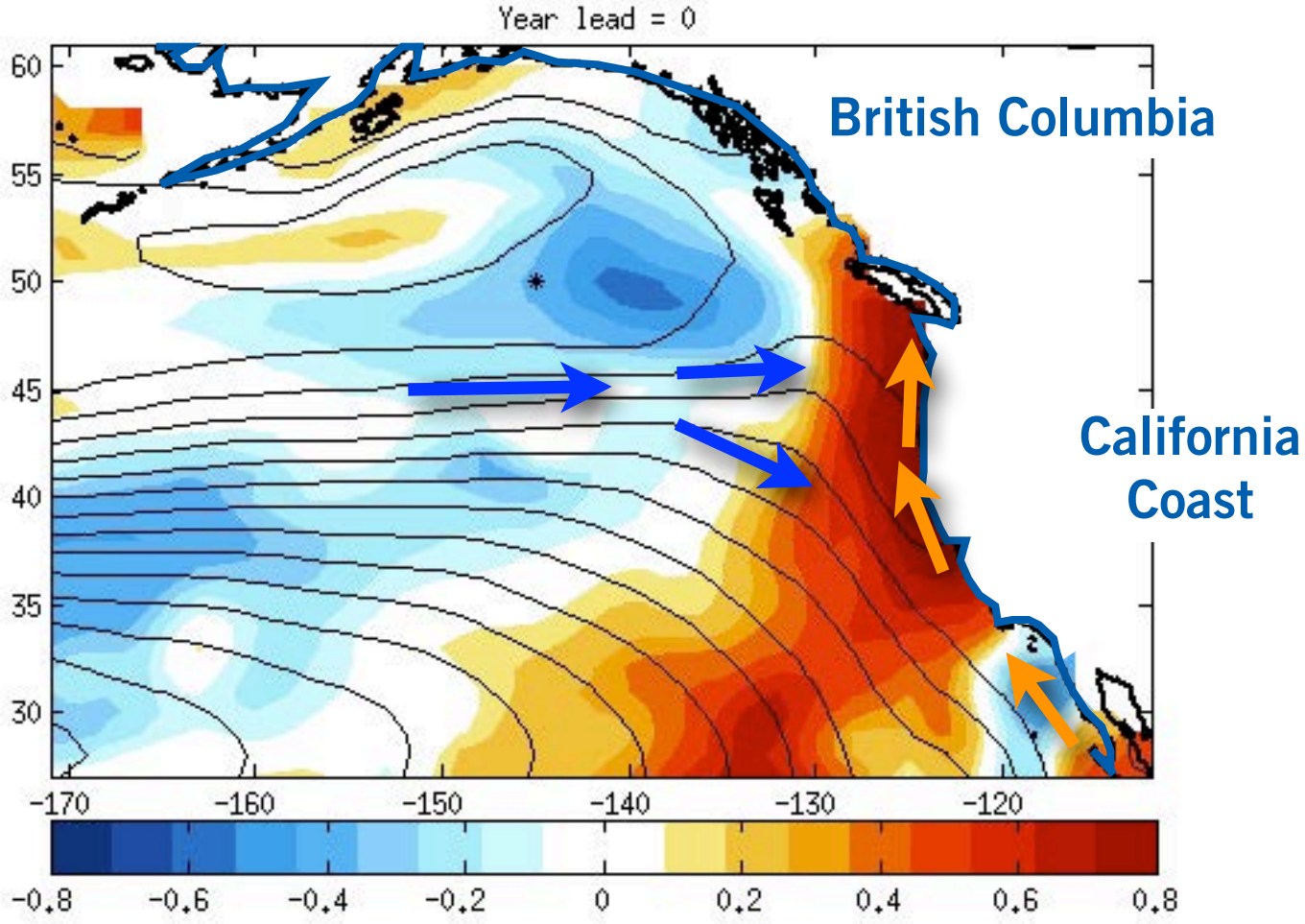


ECMWF ORA3 Oxygen Proxy Index

Correlation with Salinity ISO=26.5



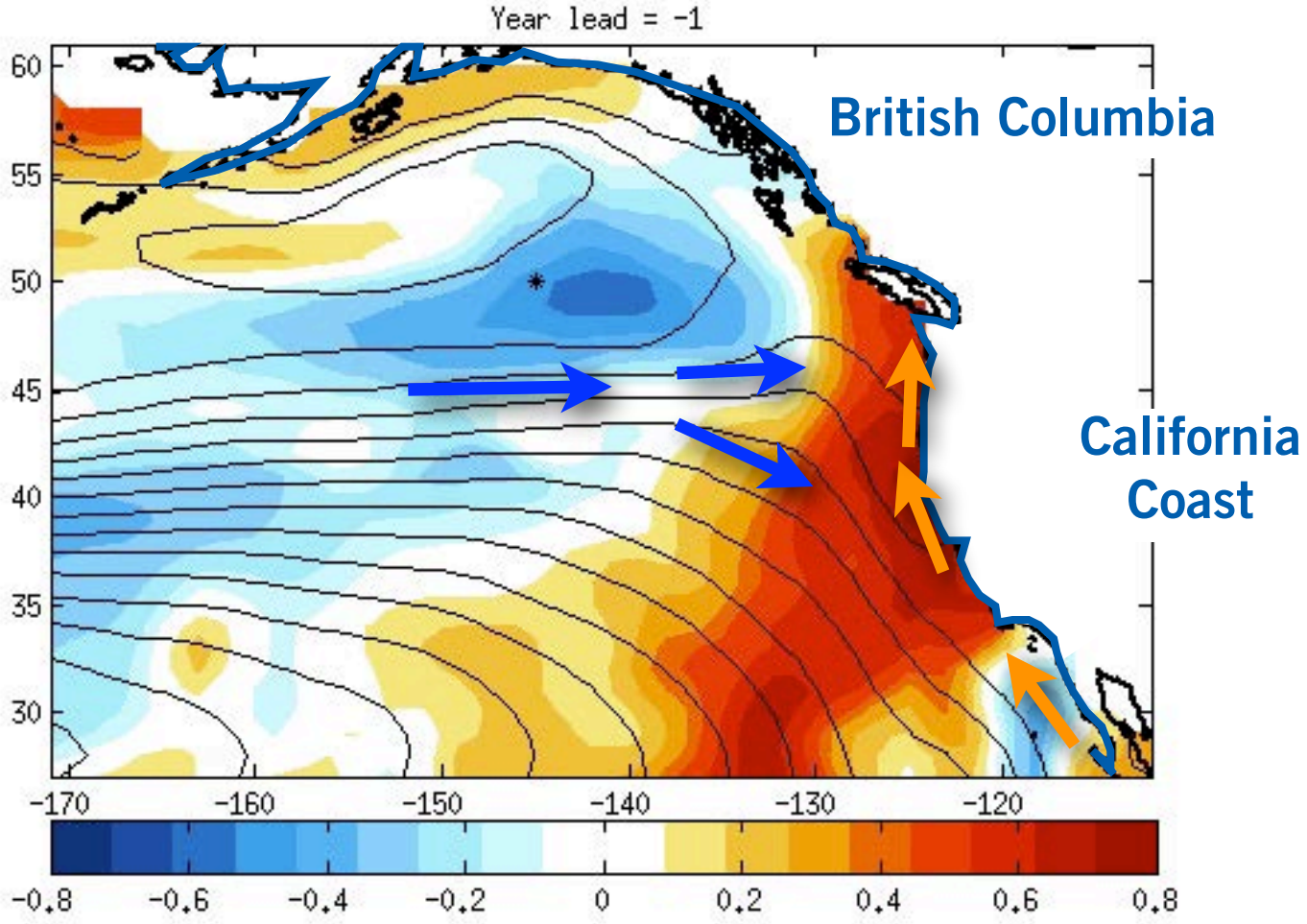
ECMWF ORA3 Oxygen Proxy Index



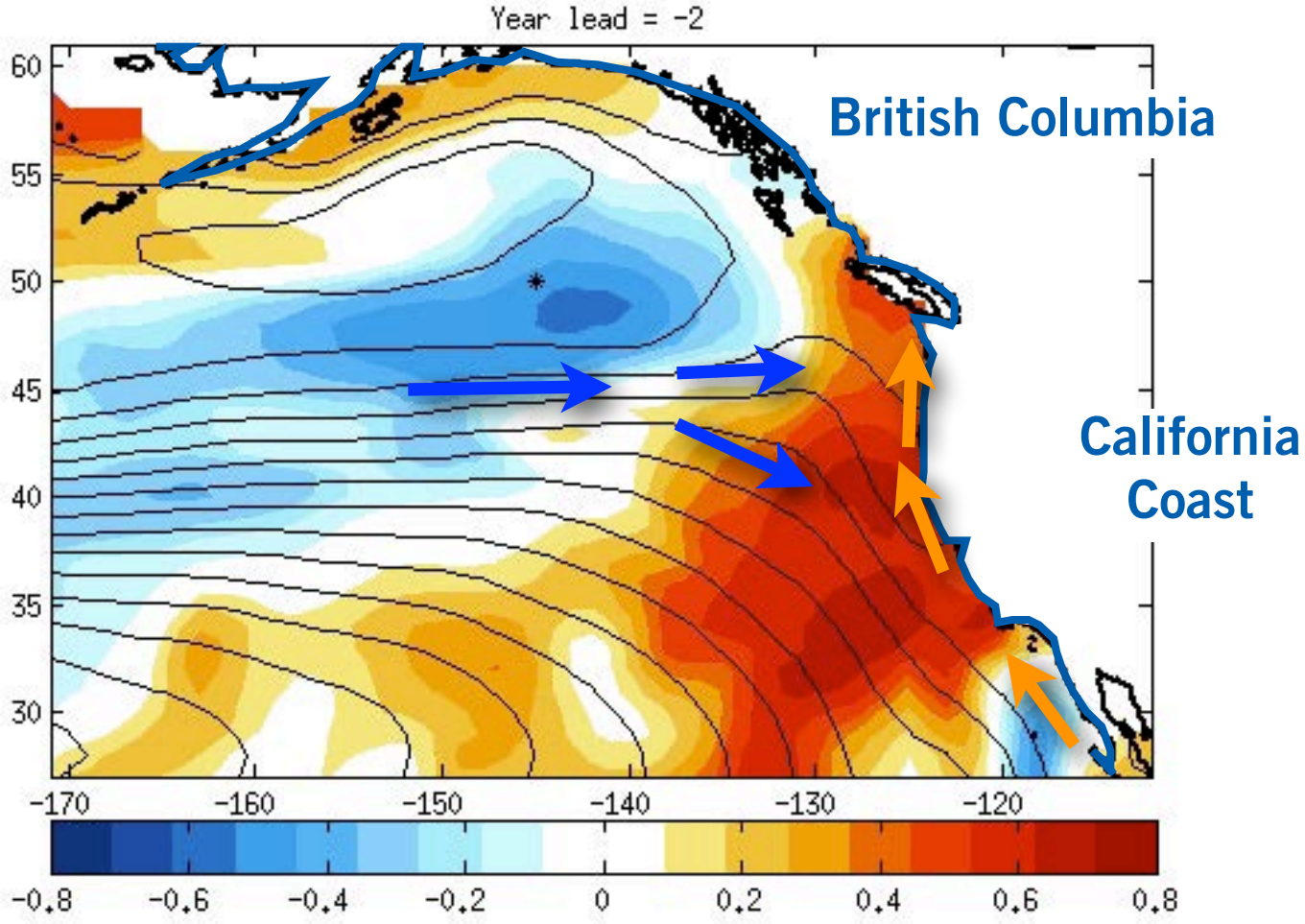
QUESTION:

Where did these anomalies come from?

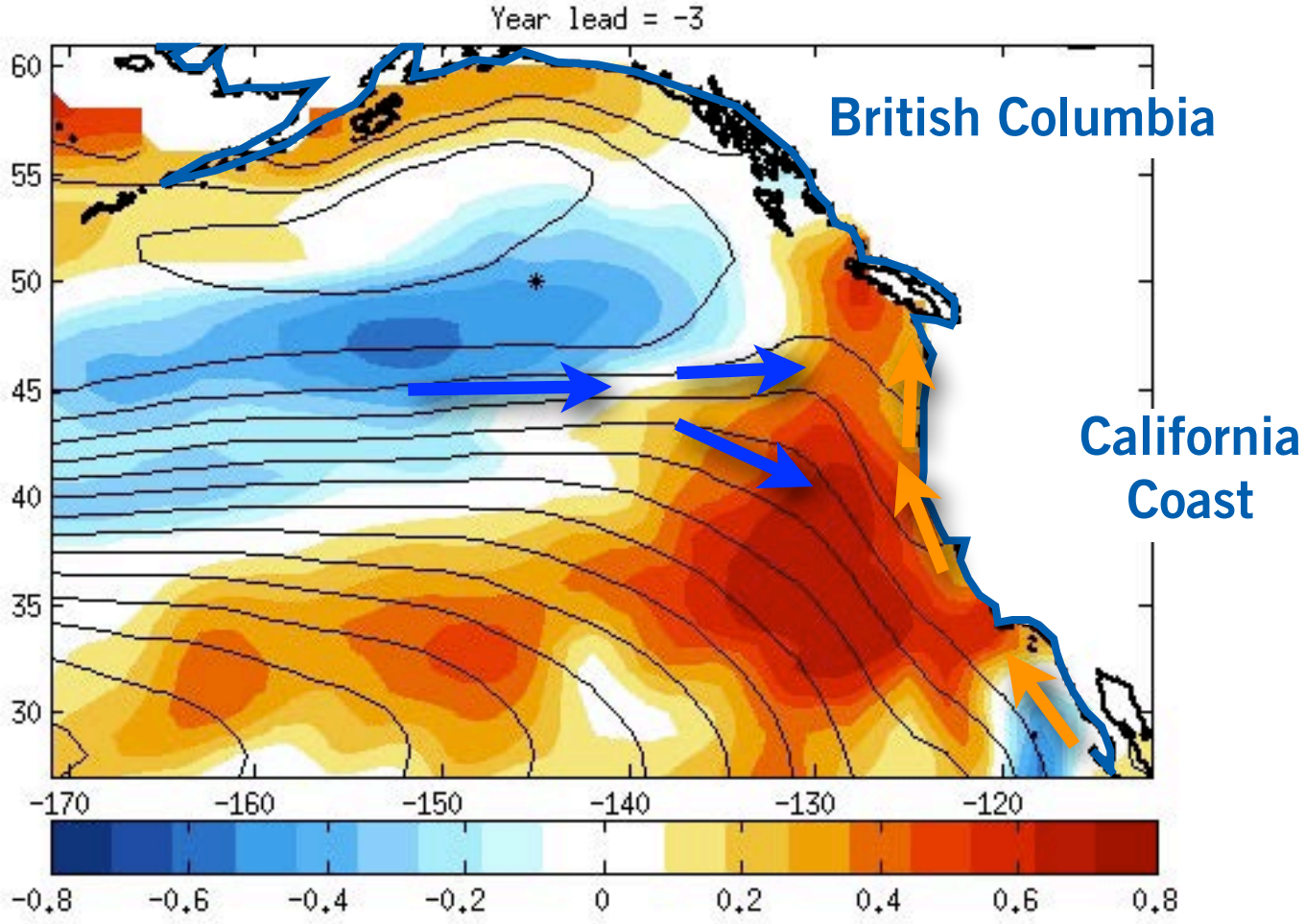
ECMWF ORA3 Oxygen Proxy Index



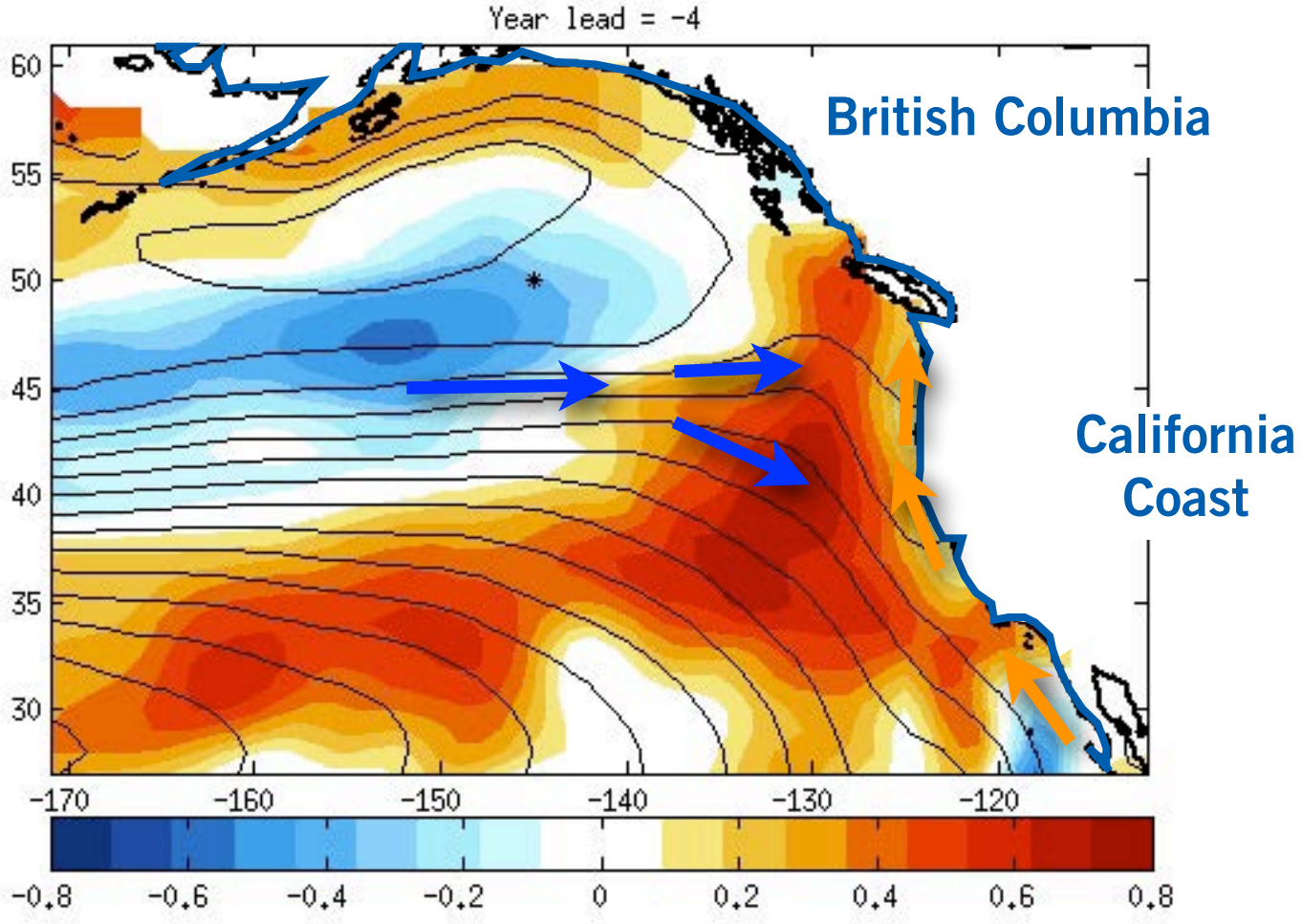
ECMWF ORA3 Oxygen Proxy Index



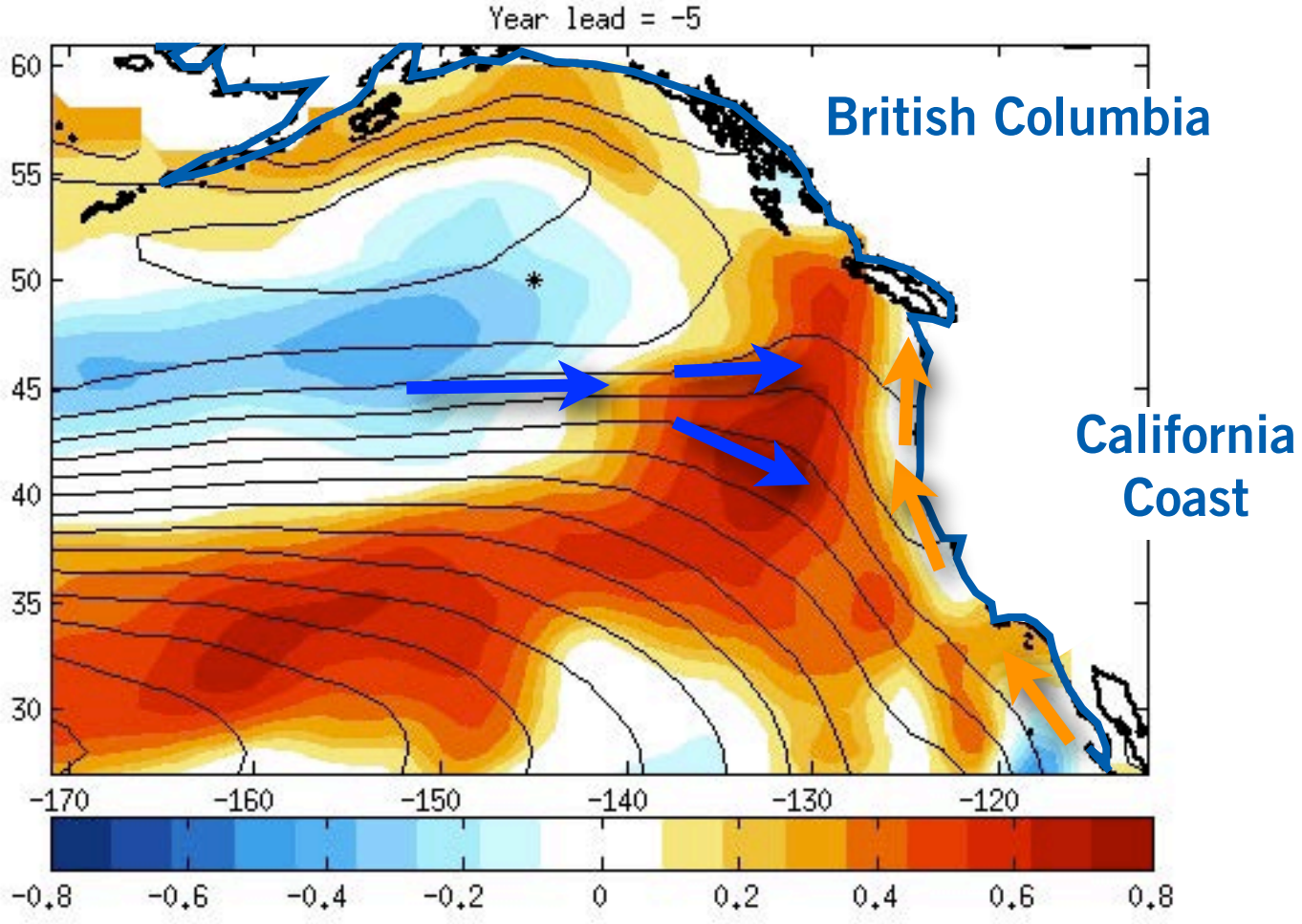
ECMWF ORA3 Oxygen Proxy Index



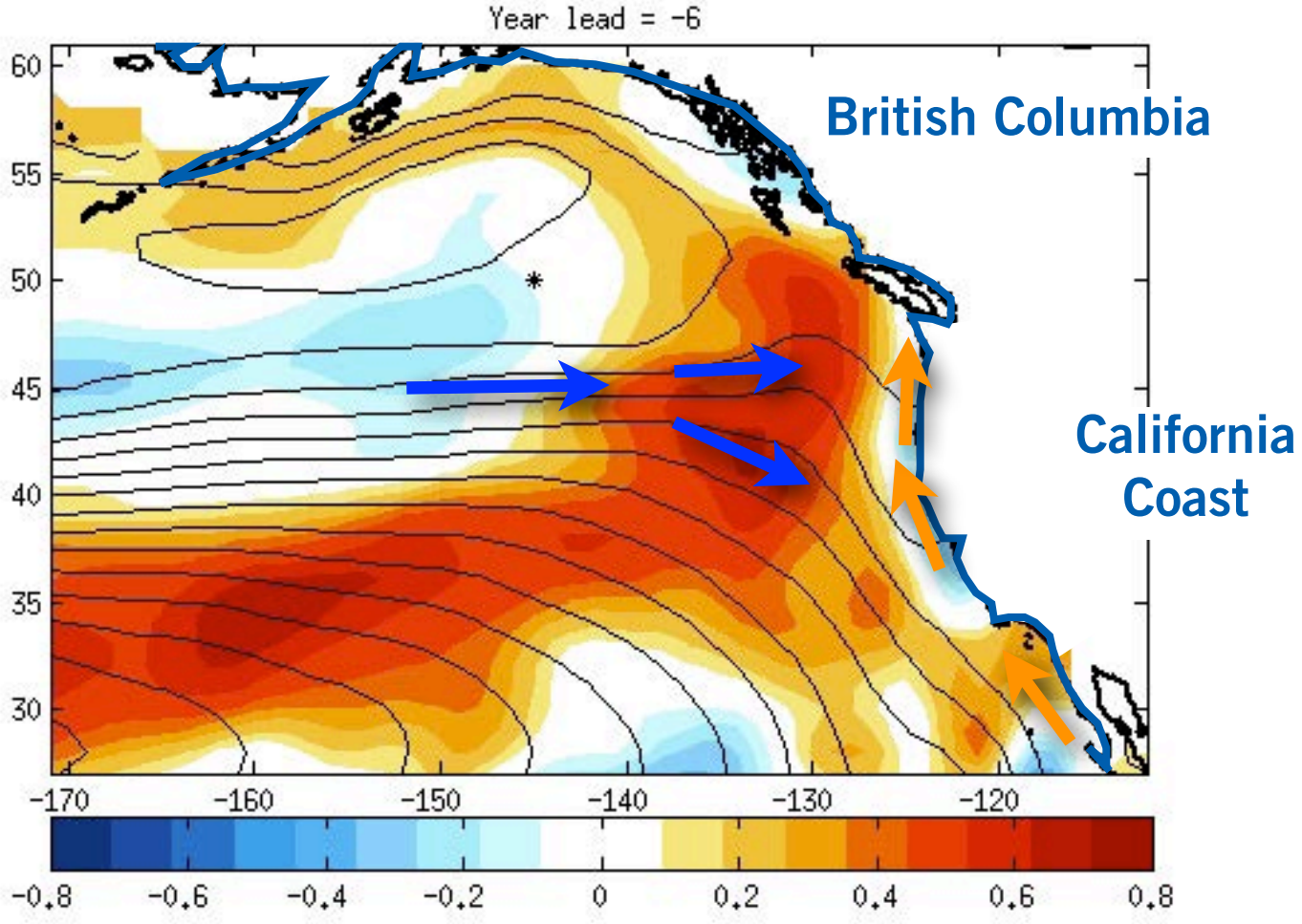
ECMWF ORA3 Oxygen Proxy Index



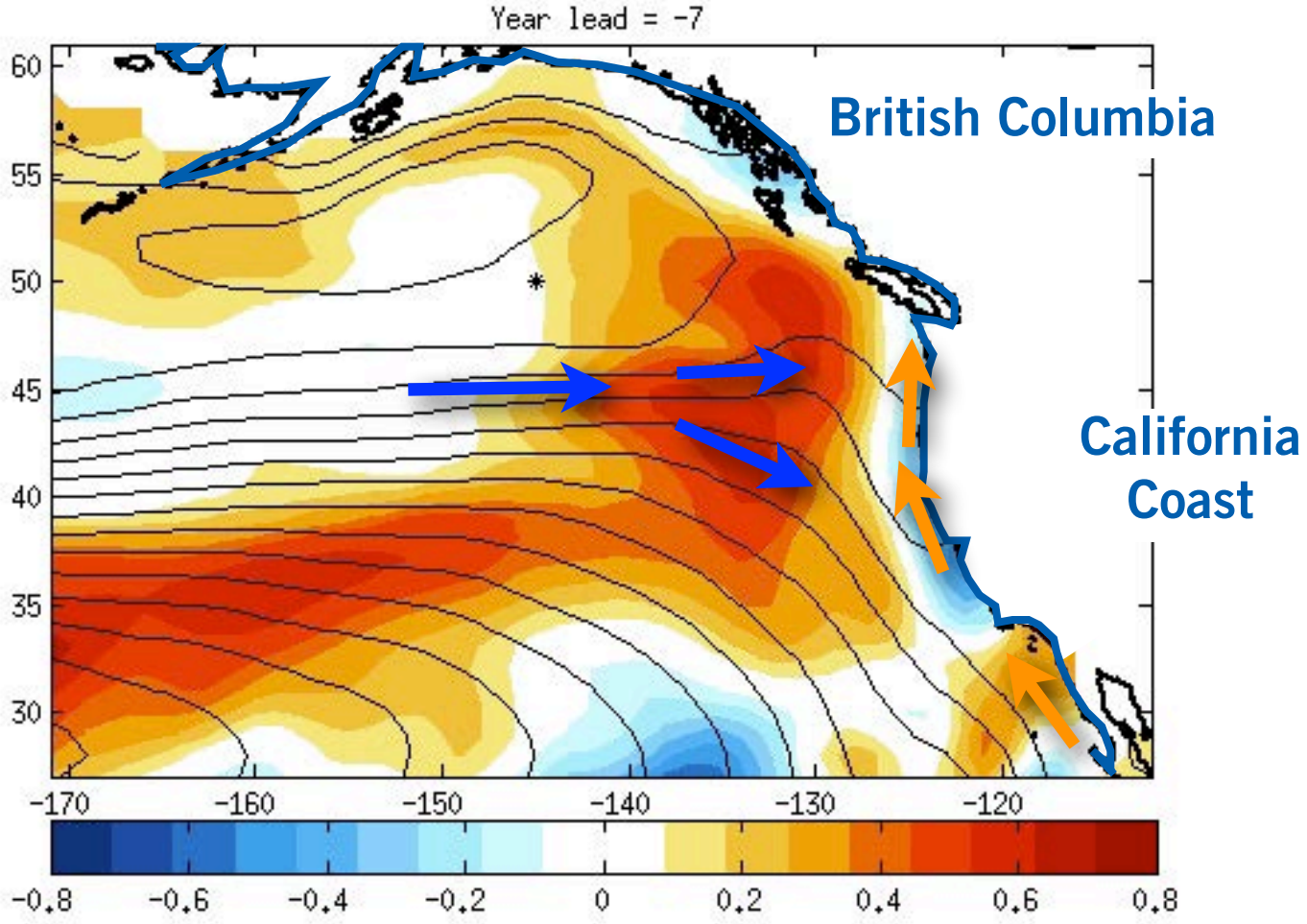
ECMWF ORA3 Oxygen Proxy Index



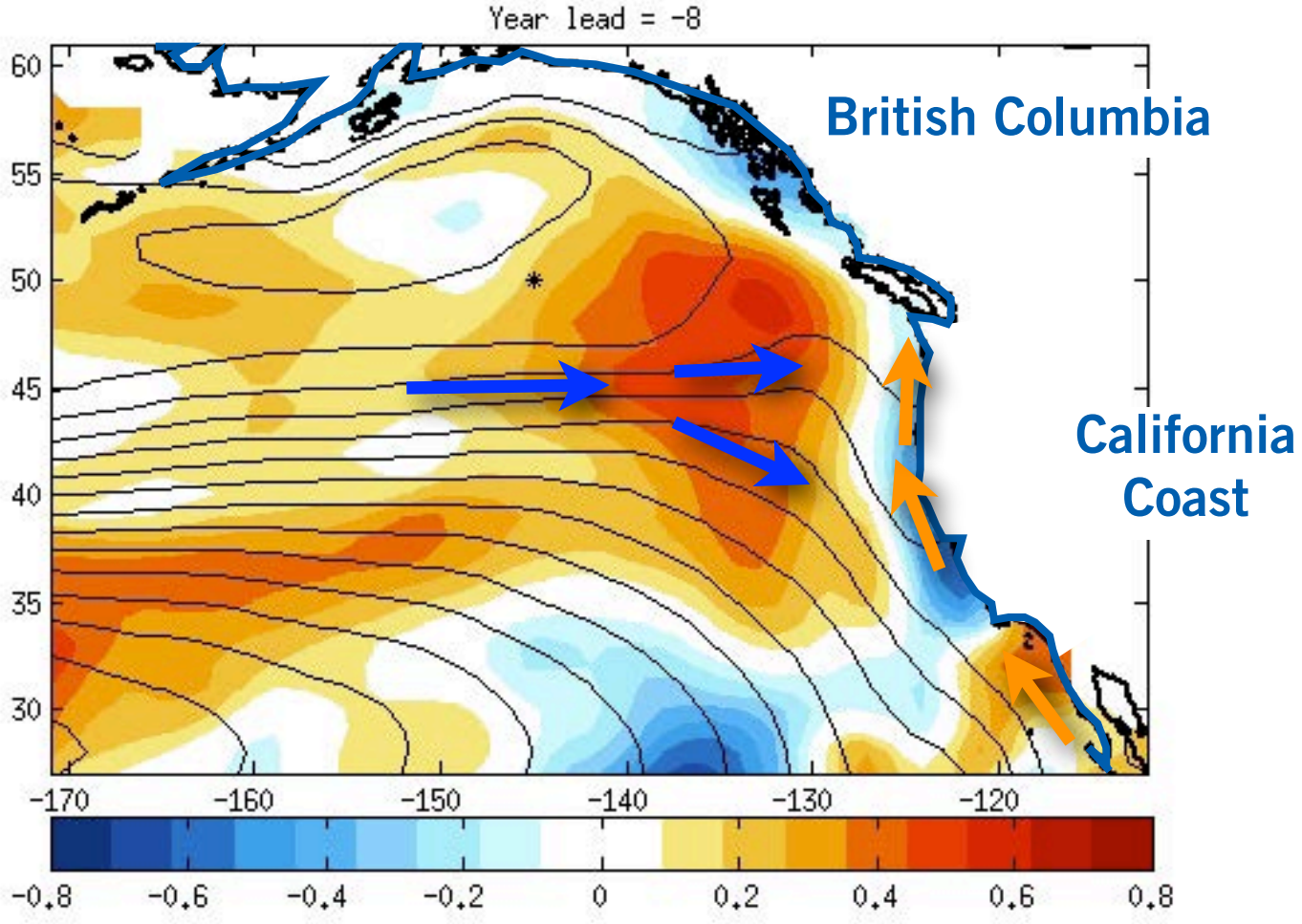
ECMWF ORA3 Oxygen Proxy Index



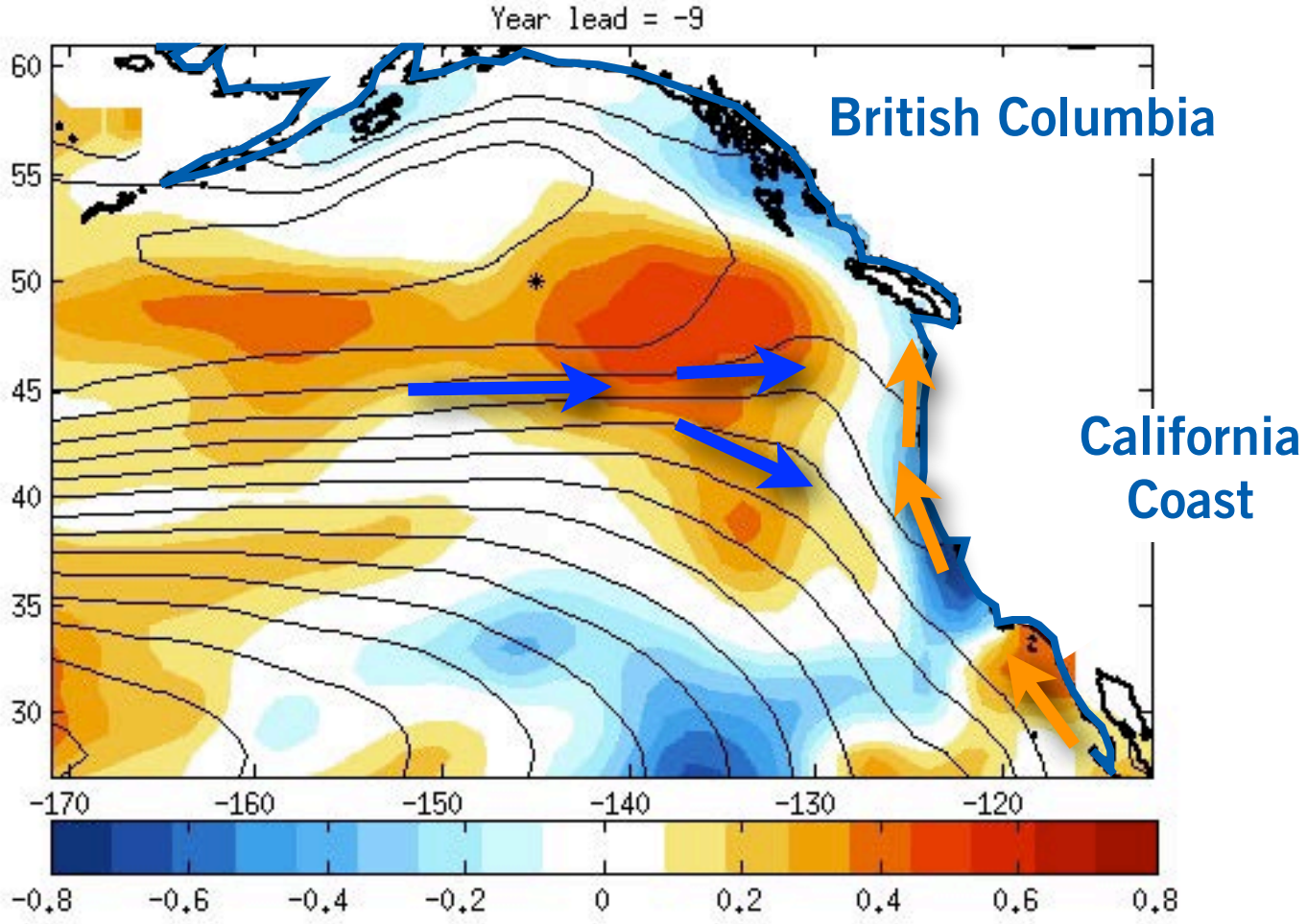
ECMWF ORA3 Oxygen Proxy Index



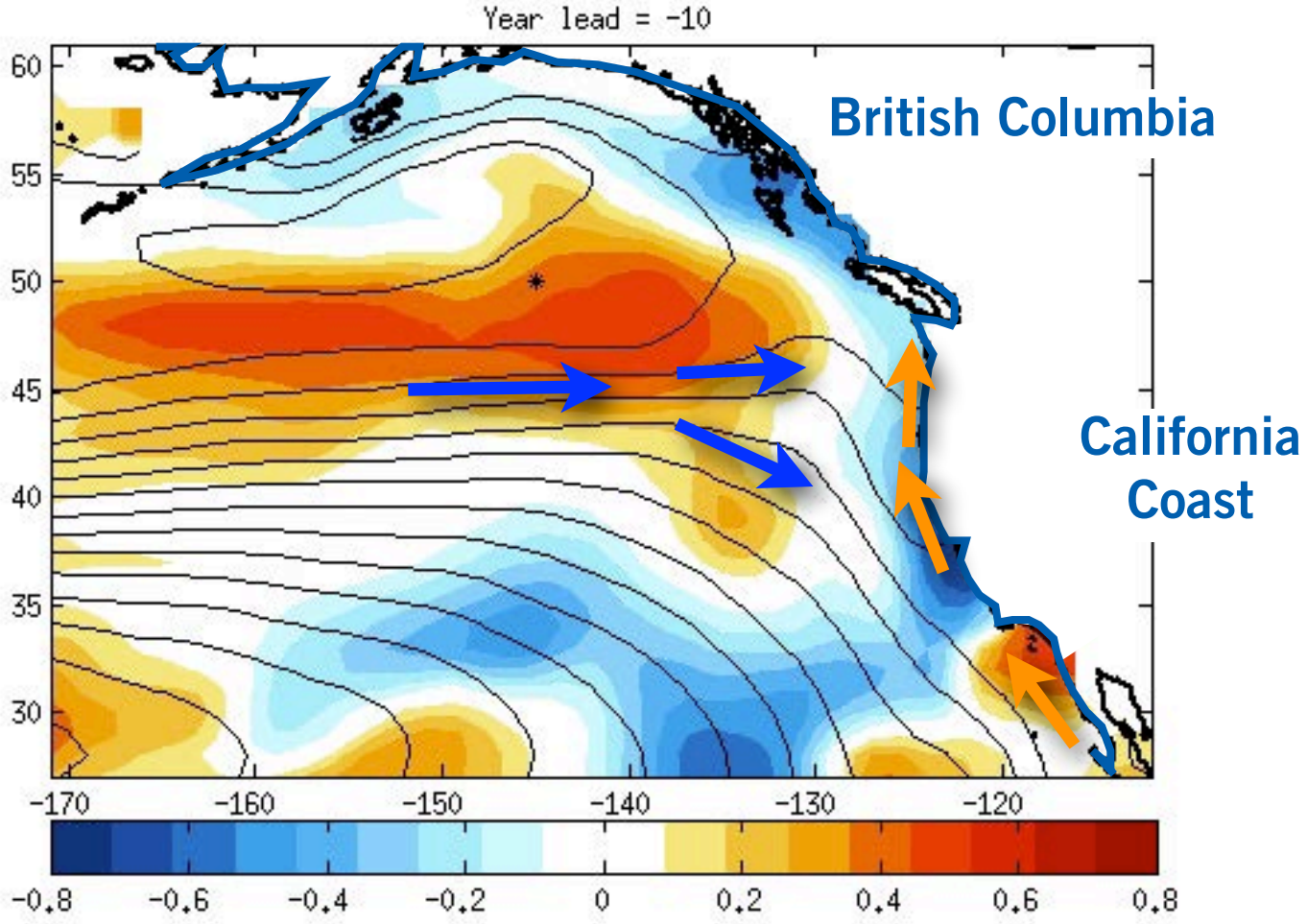
ECMWF ORA3 Oxygen Proxy Index



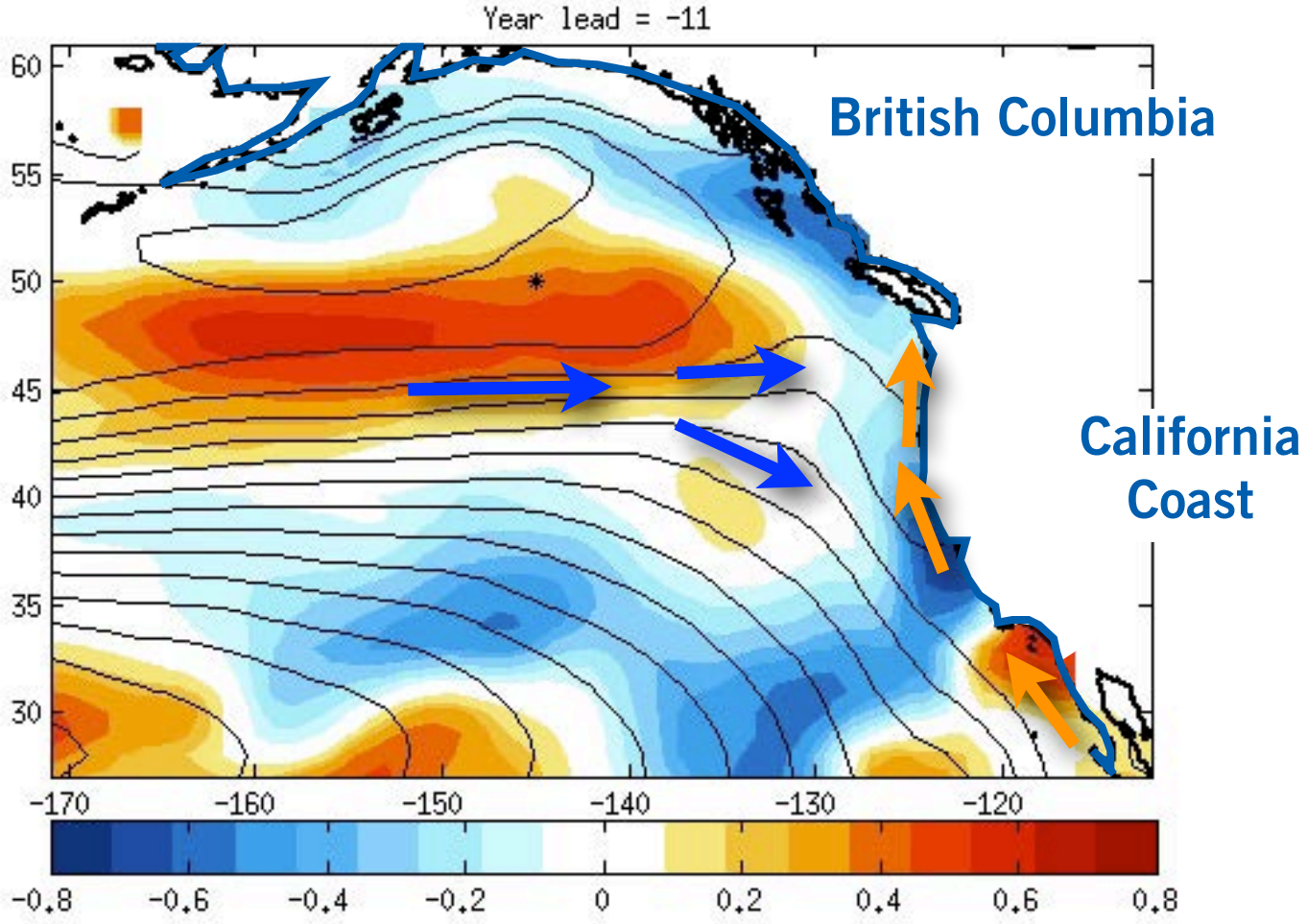
ECMWF ORA3 Oxygen Proxy Index



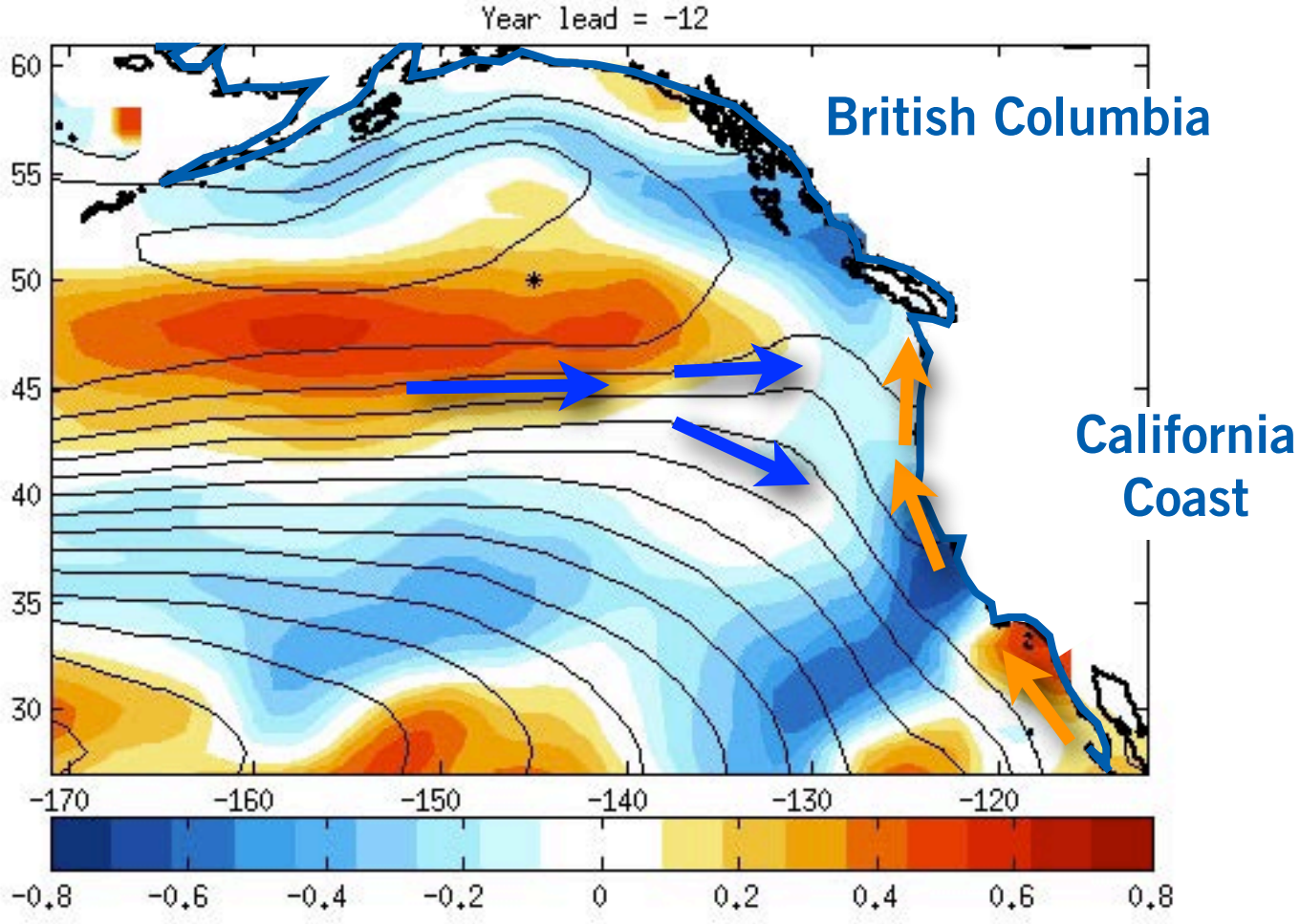
ECMWF ORA3 Oxygen Proxy Index



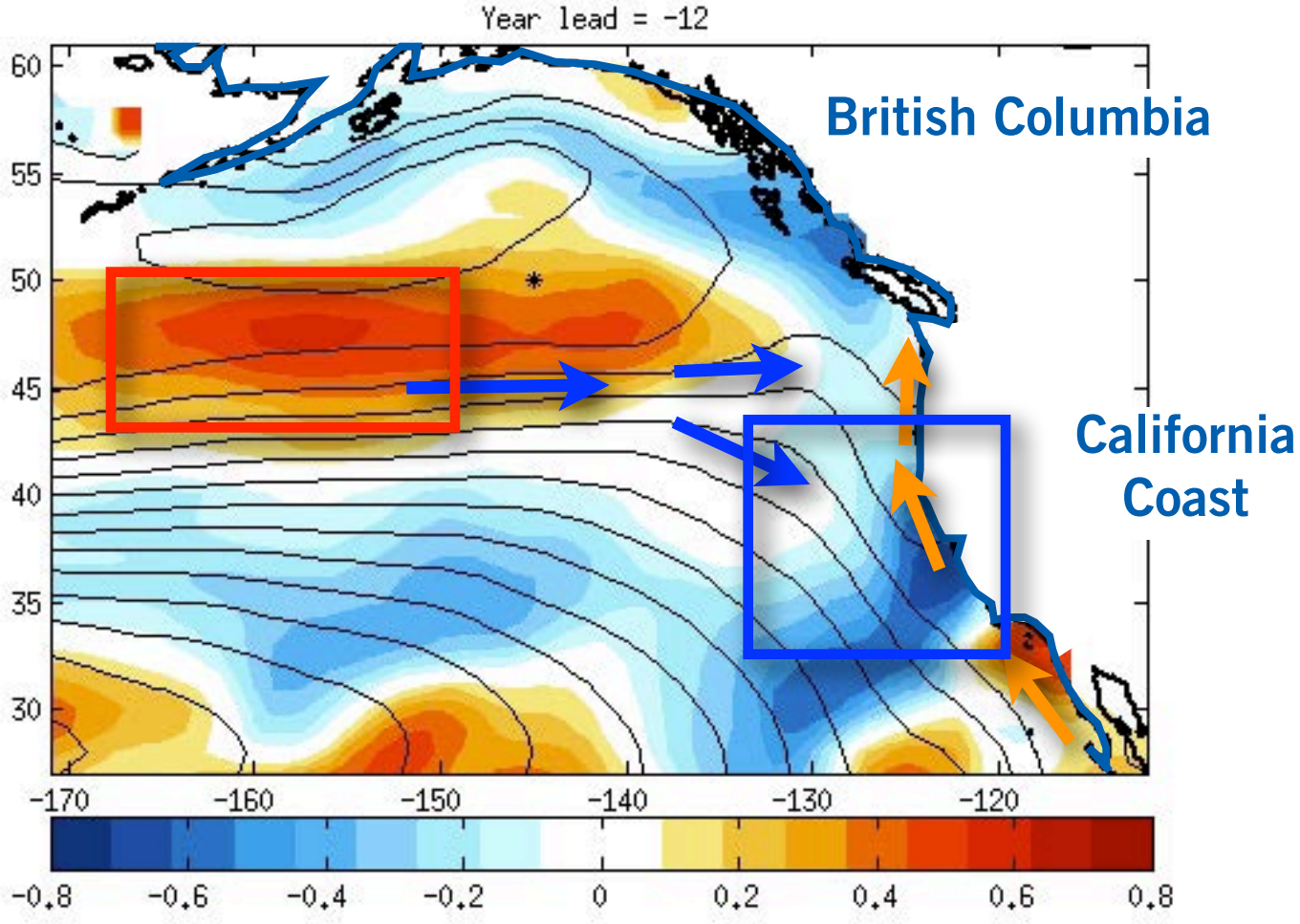
ECMWF ORA3 Oxygen Proxy Index



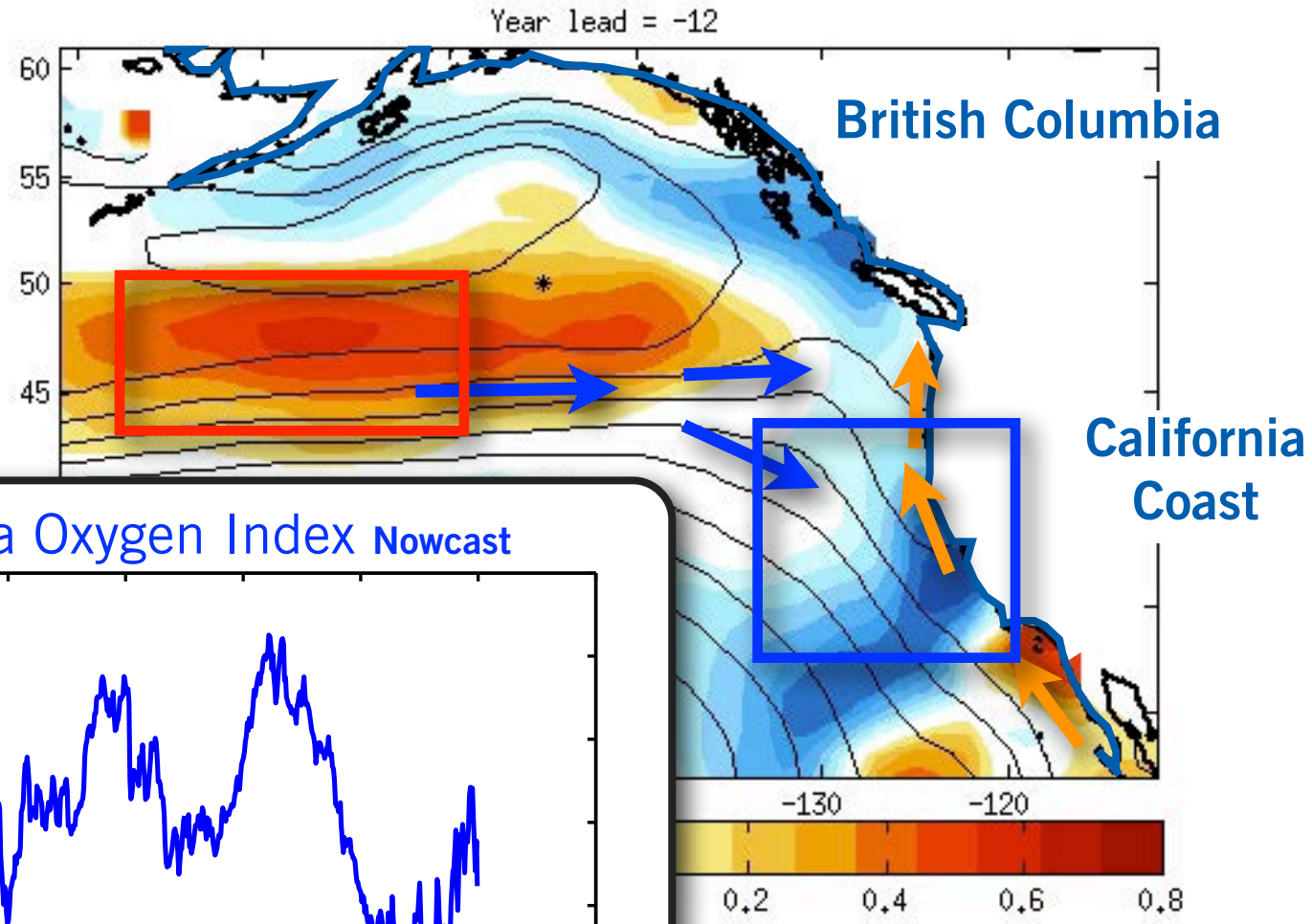
ECMWF ORA3 Oxygen Proxy Index

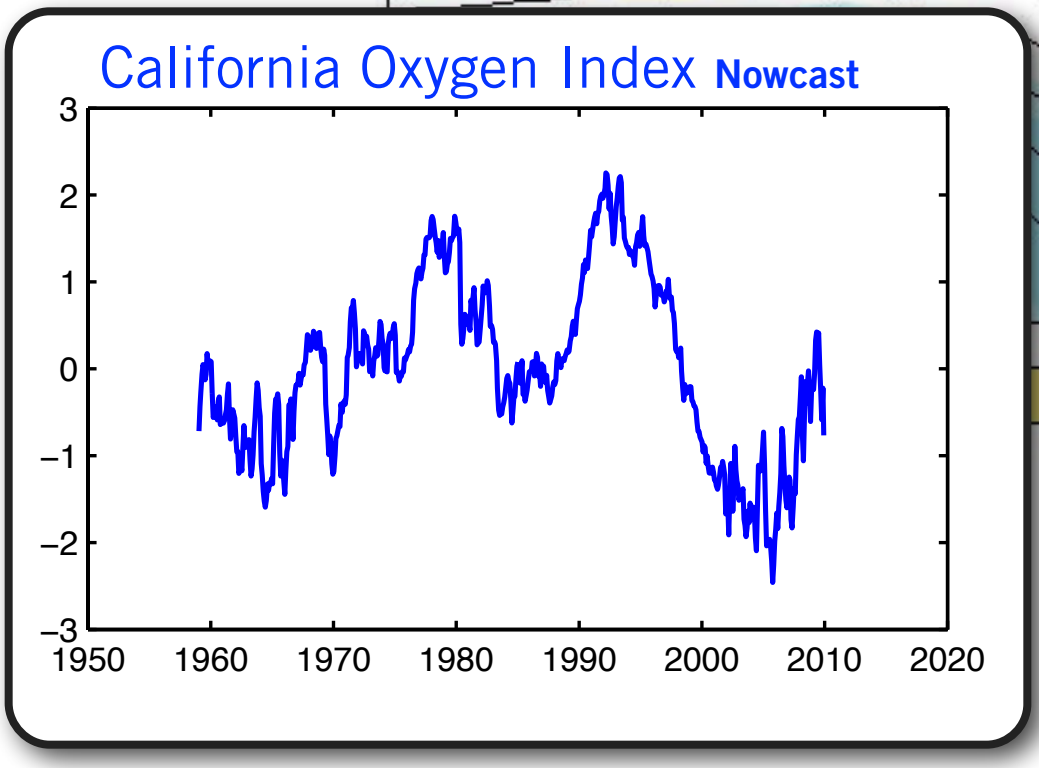


ECMWF ORA3 Oxygen Proxy Index

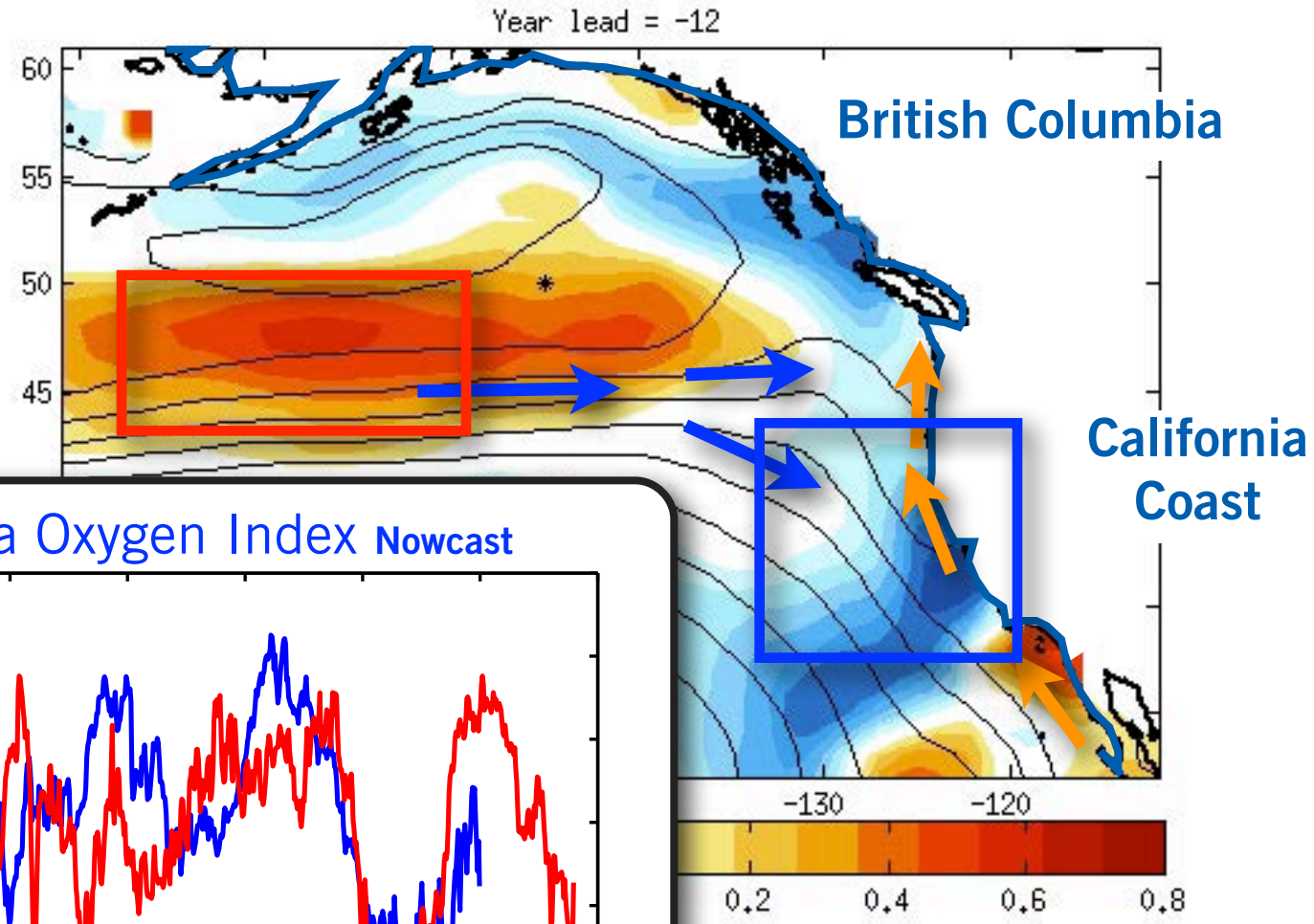


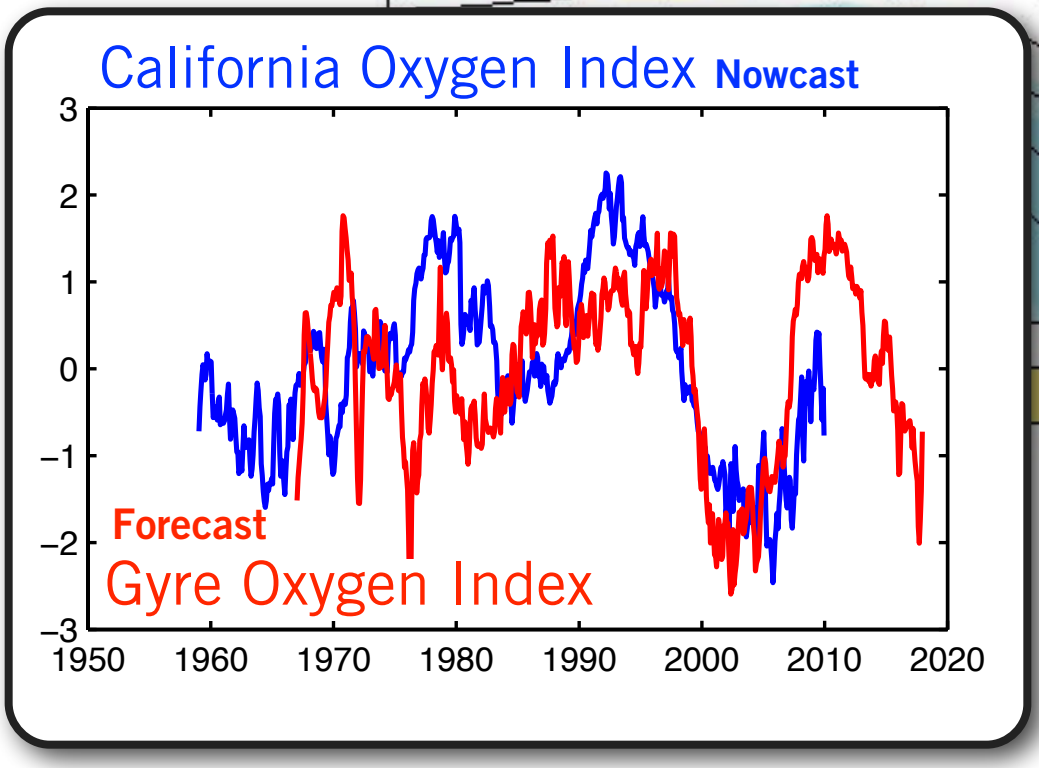
ECMWF ORA3 Oxygen Proxy Index



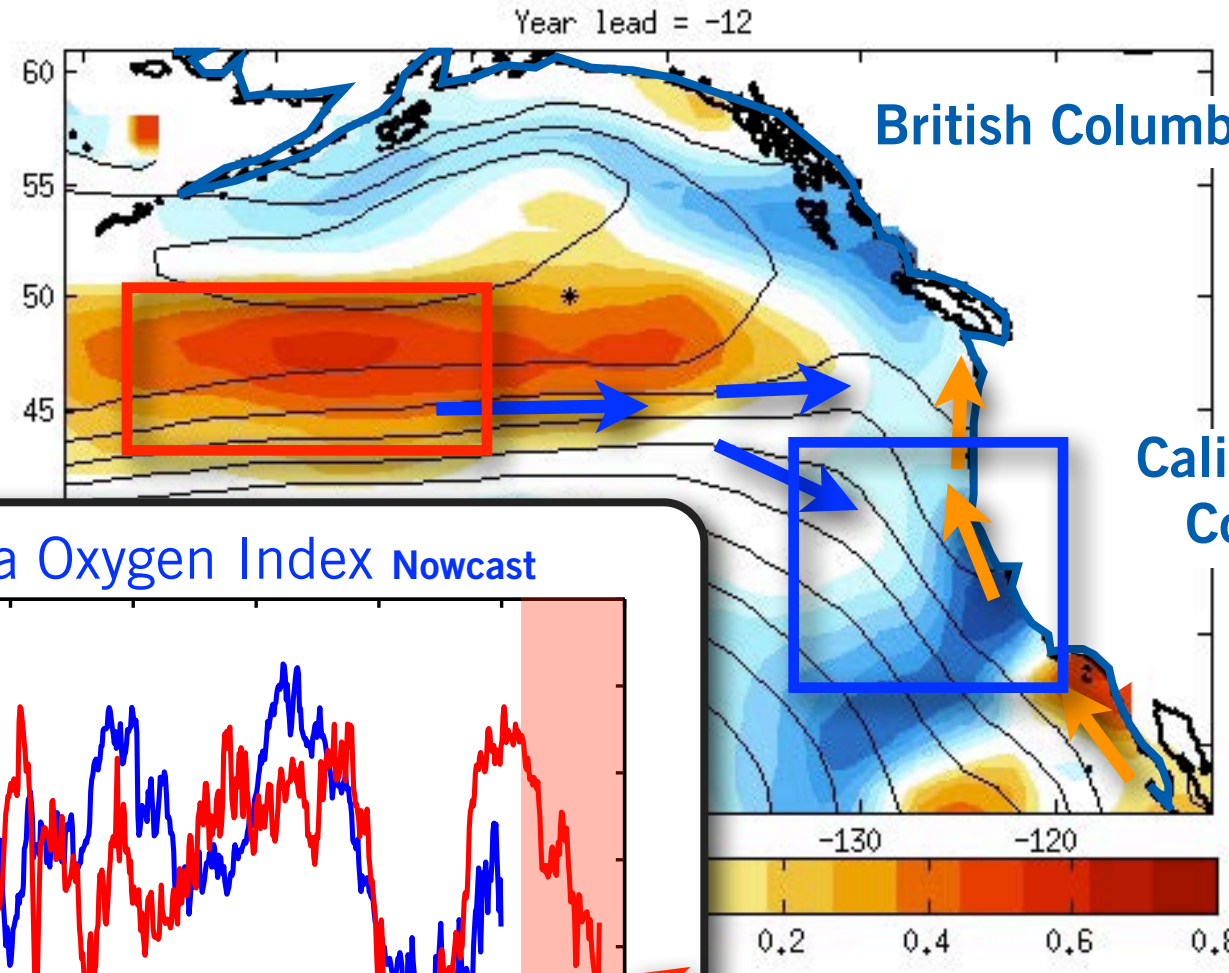


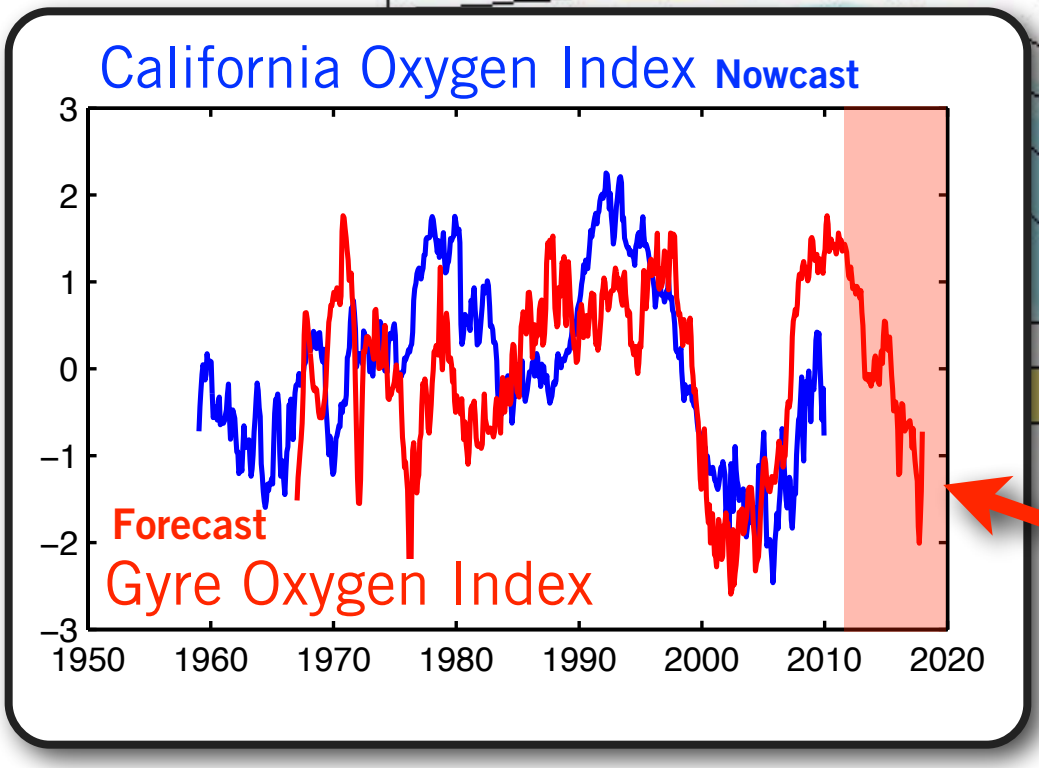
ECMWF ORA3 Oxygen Proxy Index





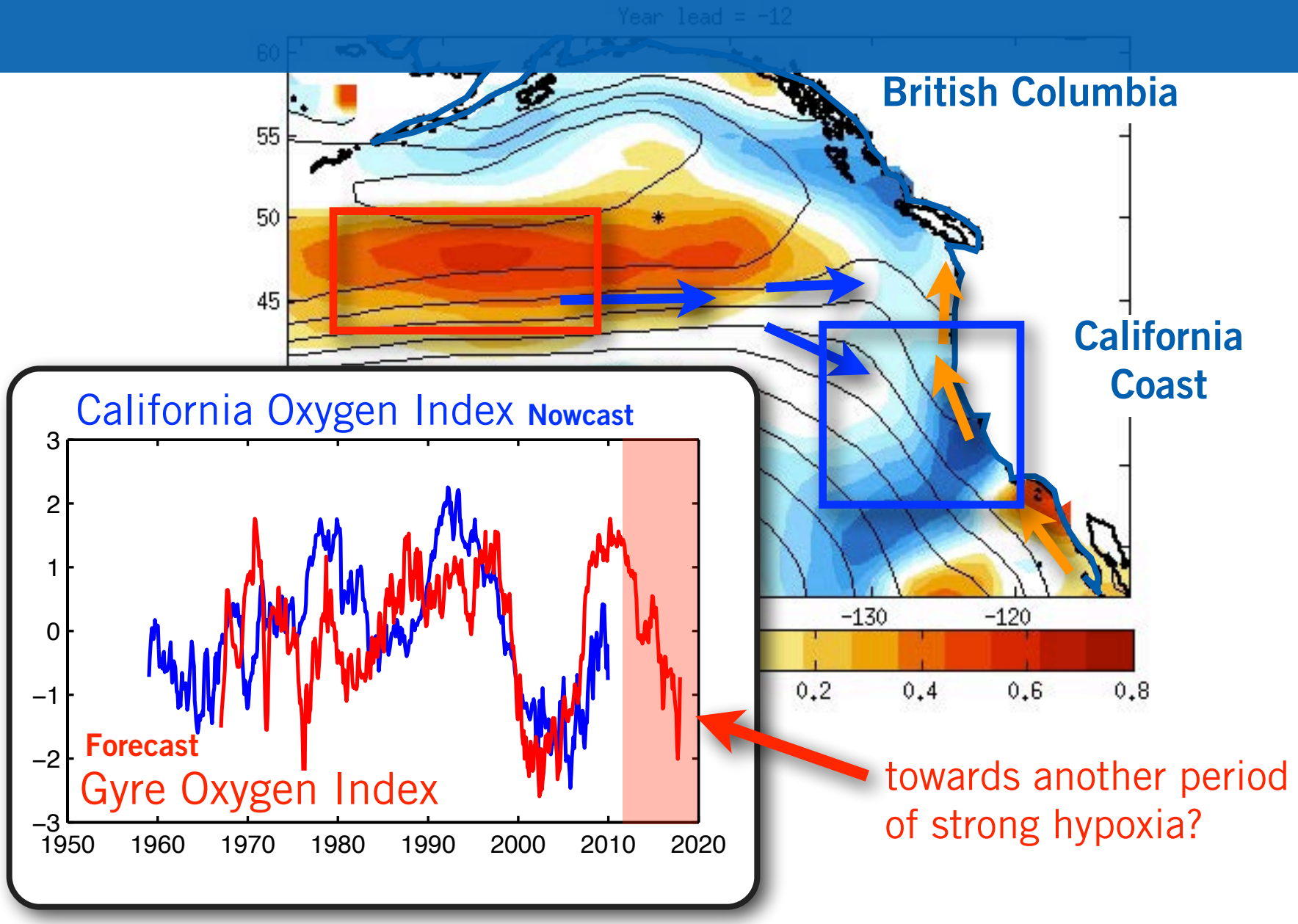
ECMWF ORA3 Oxygen Proxy Index





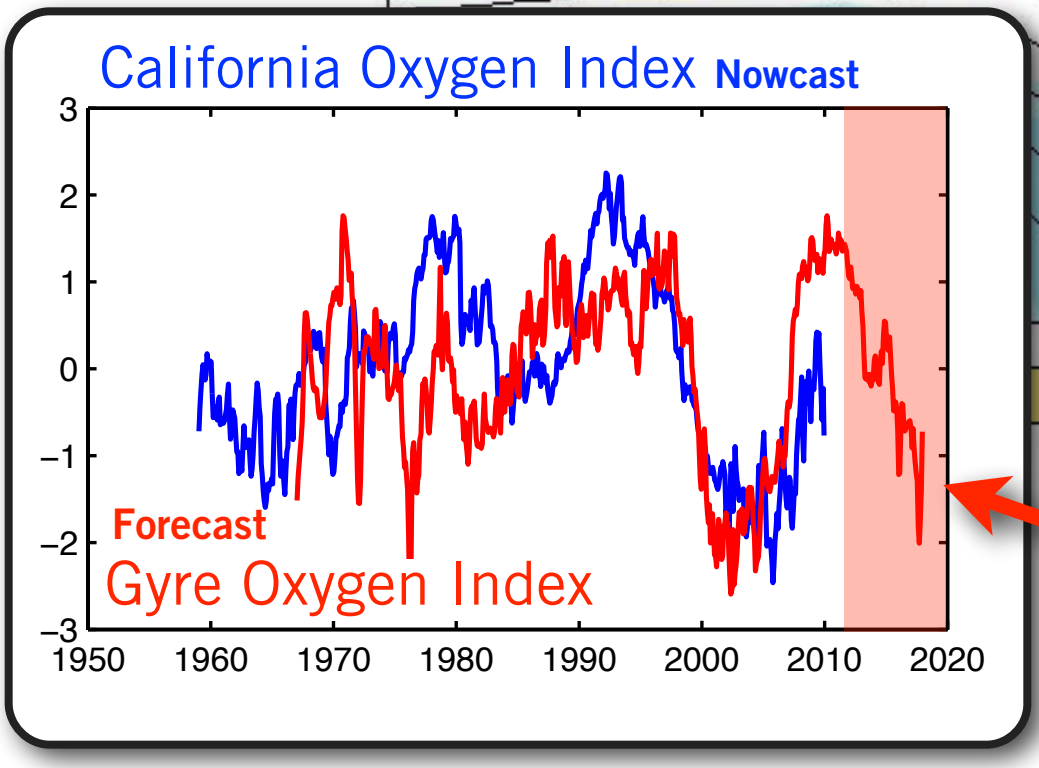
towards another period of strong hypoxia?

COMMENTS & CHALLENGES

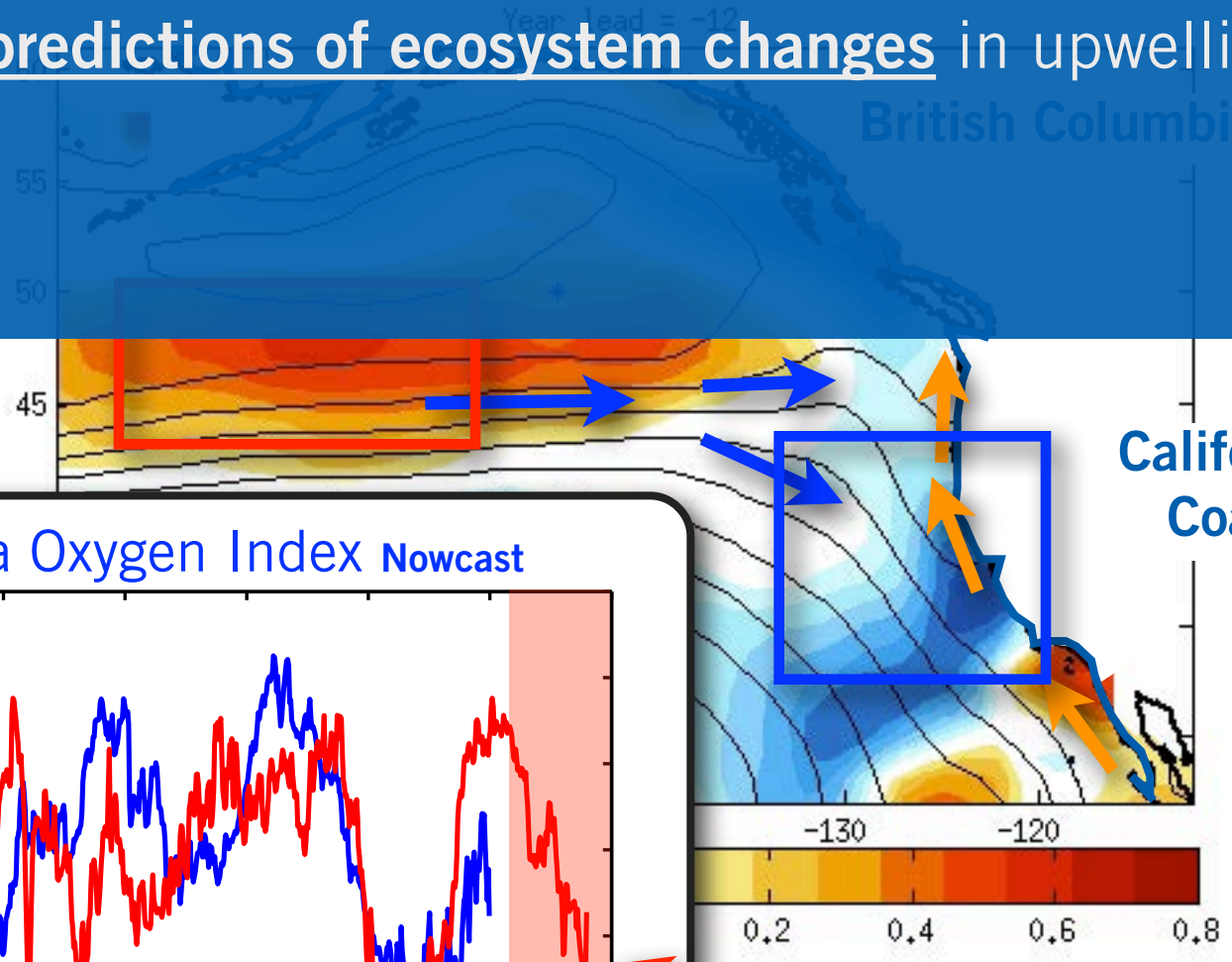


COMMENTS & CHALLENGES

1. strong decadal variability in subsurface may be exploited for **<u>decadal predictions of ecosystem changes</u>** in upwelling regions



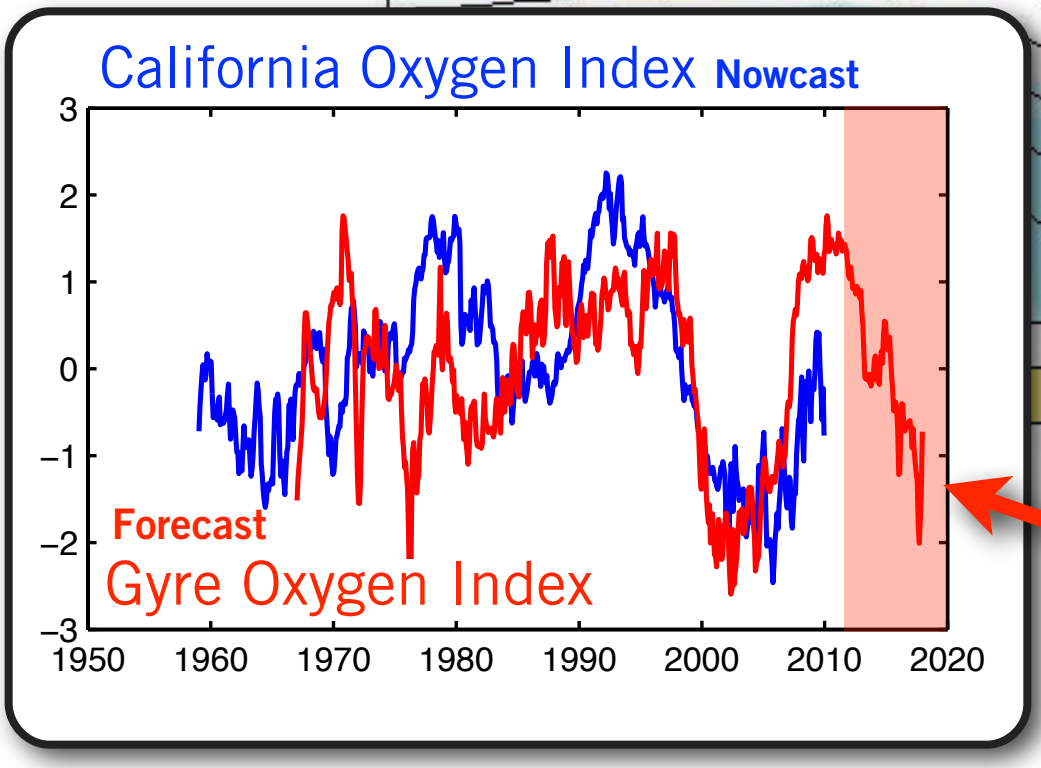
towards another period of strong hypoxia?

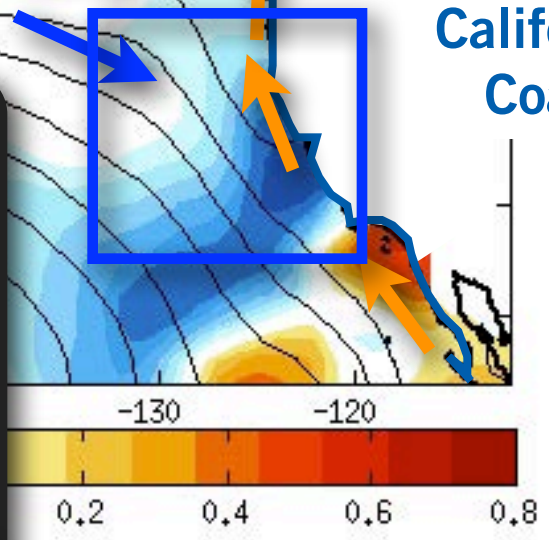


COMMENTS & CHALLENGES

1. strong decadal variability in subsurface may be exploited for **<u>decadal predictions of ecosystem changes</u>** in upwelling regions

2. constrain subsurface dynamics and **<u>potential for predictability</u>** by combining models and observations





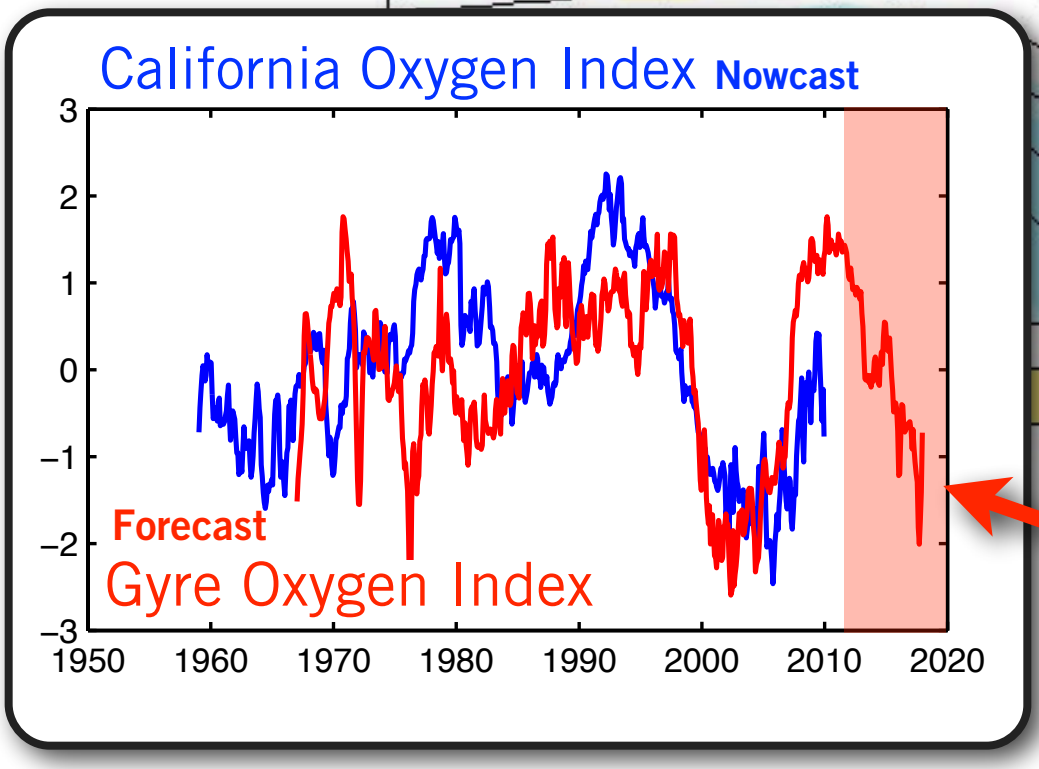
towards another period of strong hypoxia?

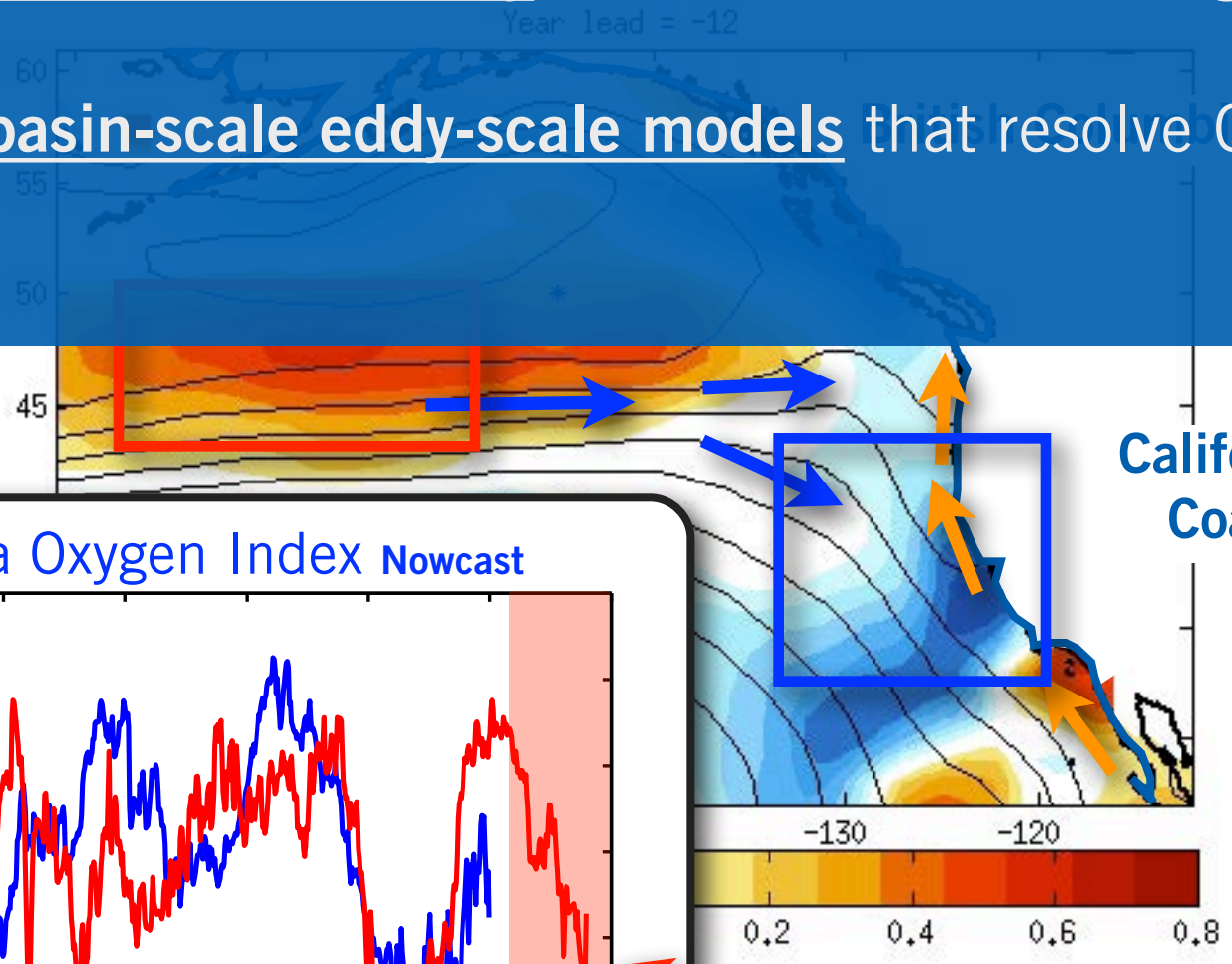
END

COMMENTS & CHALLENGES

1. **strong decadal variability** in subsurface O2 from gyre dynamics

2. need **basin-scale eddy-scale models** that resolve O2 dynamics





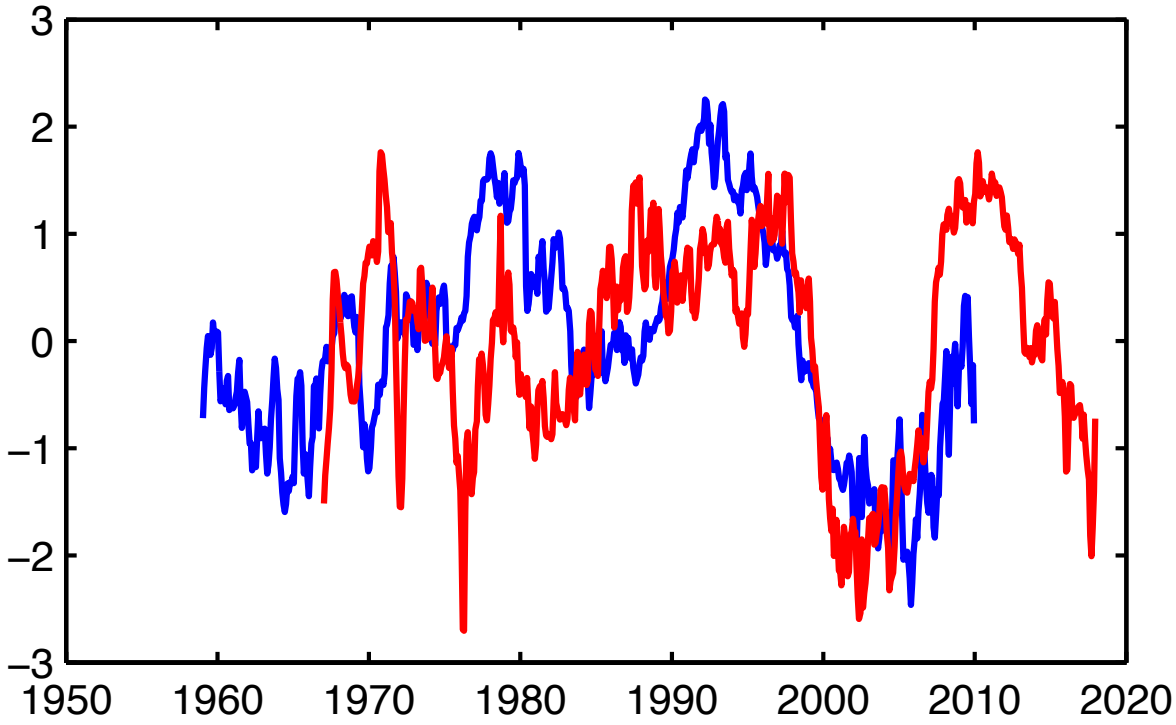
towards another period
of strong hypoxia?

COMMENTS & CHALLENGES

1. strong decadal variability in subsurface O2 from gyre dynamics

2. need basin-scale eddy-scale models that resolve O2 dynamics

3. constrain subsurface dynamics by combining model and observations


3
2
1
0
−1
−2
−3
1950
1960
1970
1980
1990
2000
2010
2020

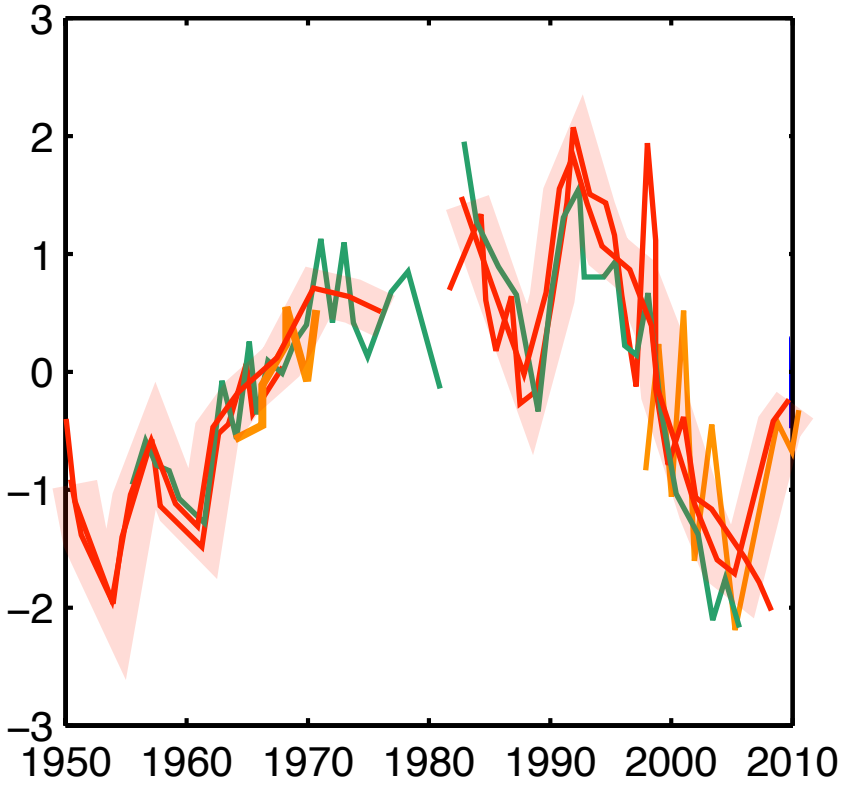
END

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



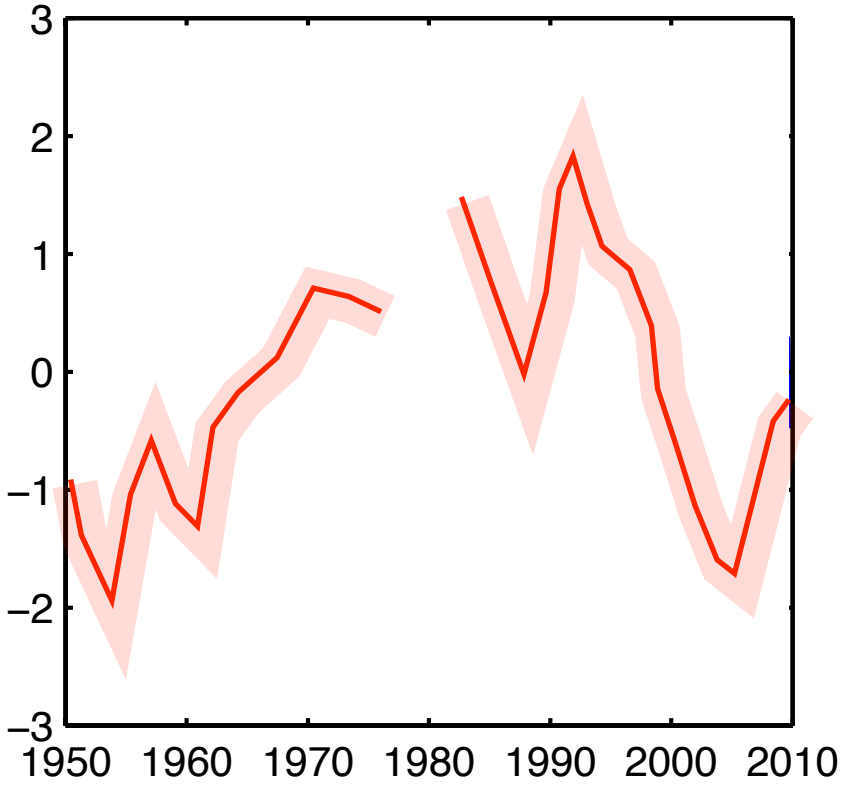
good

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



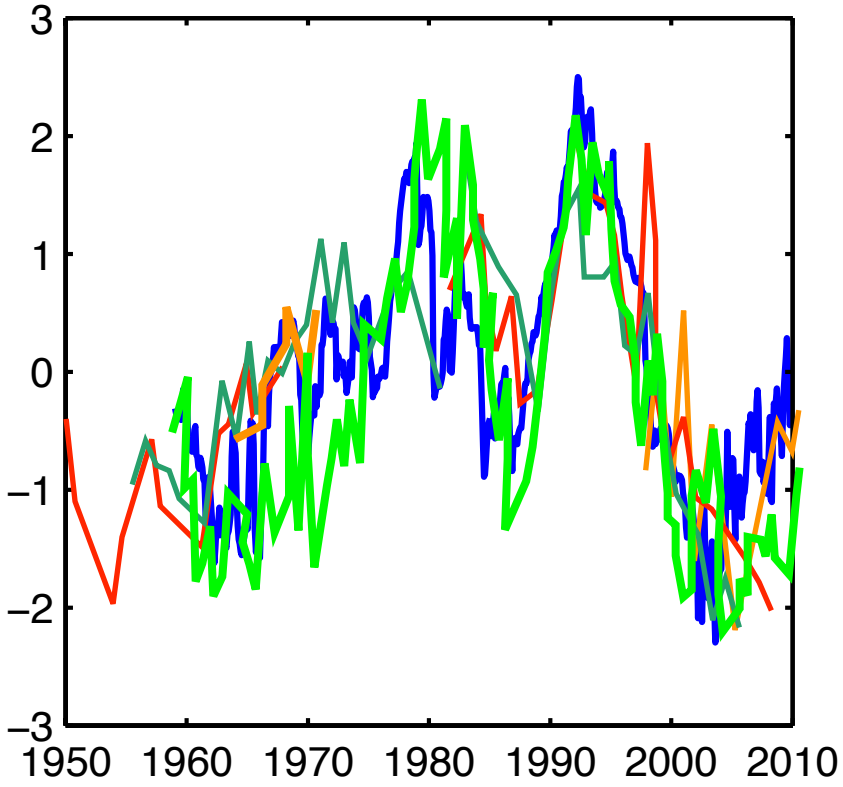
good

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

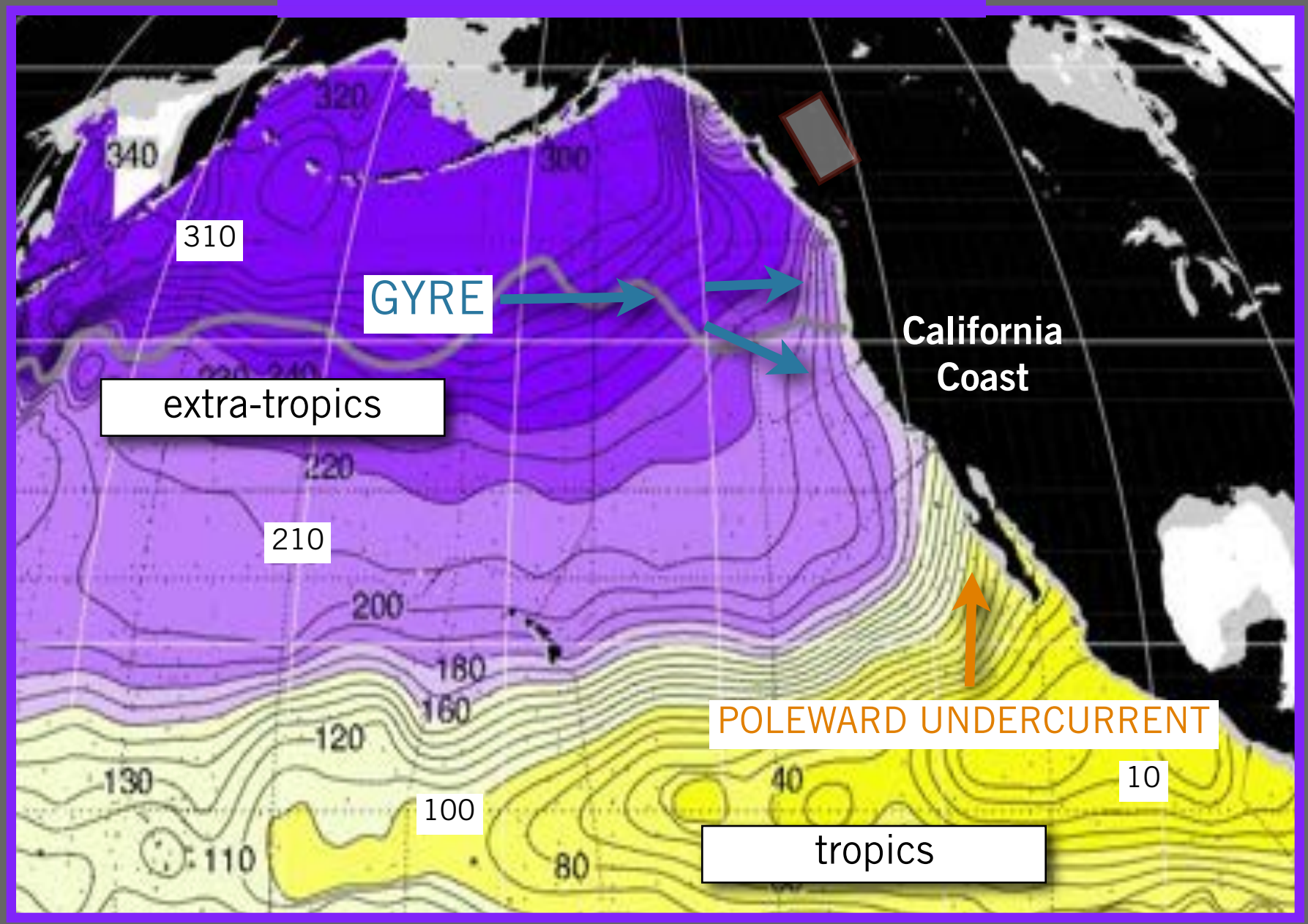
Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)

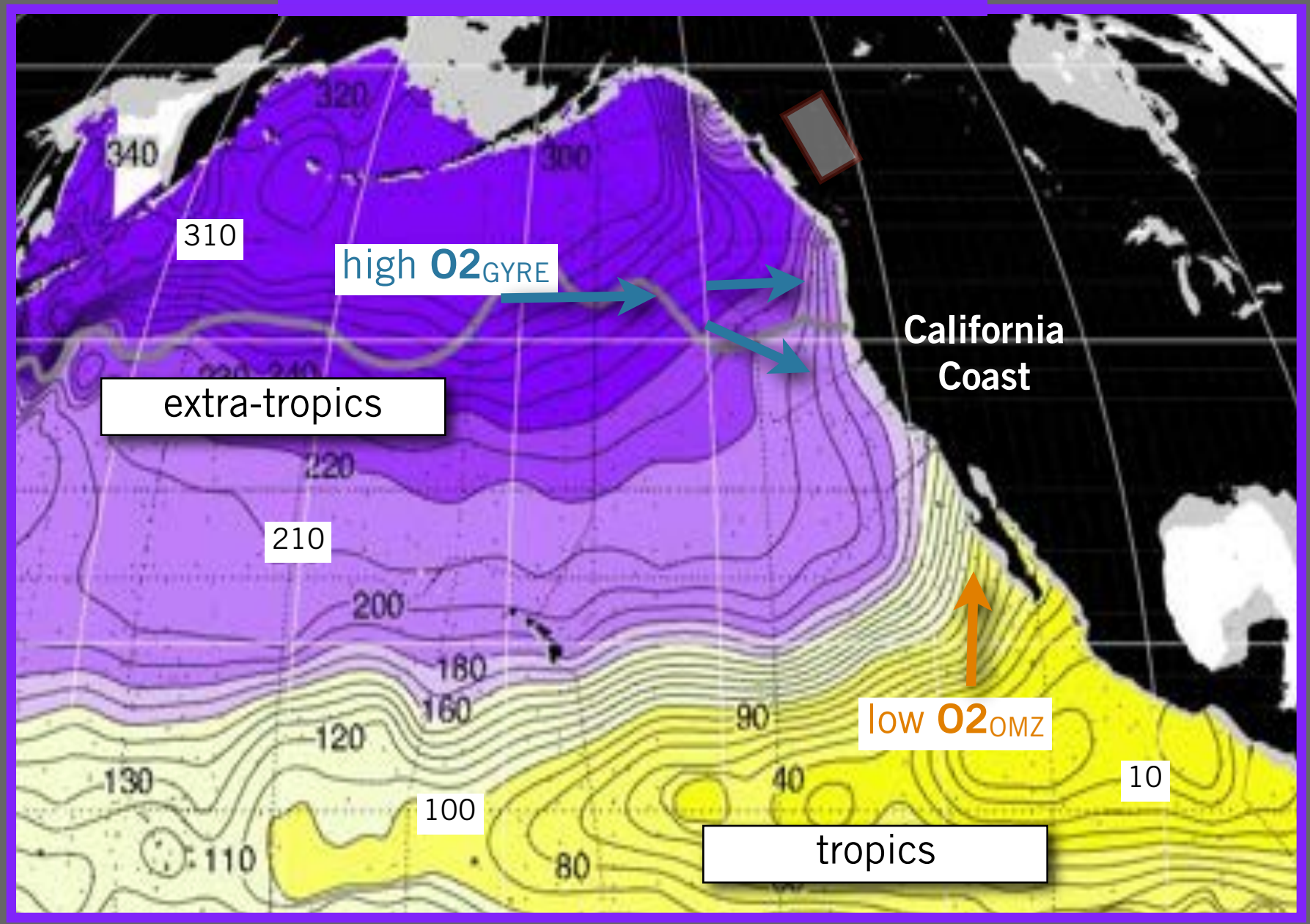


good

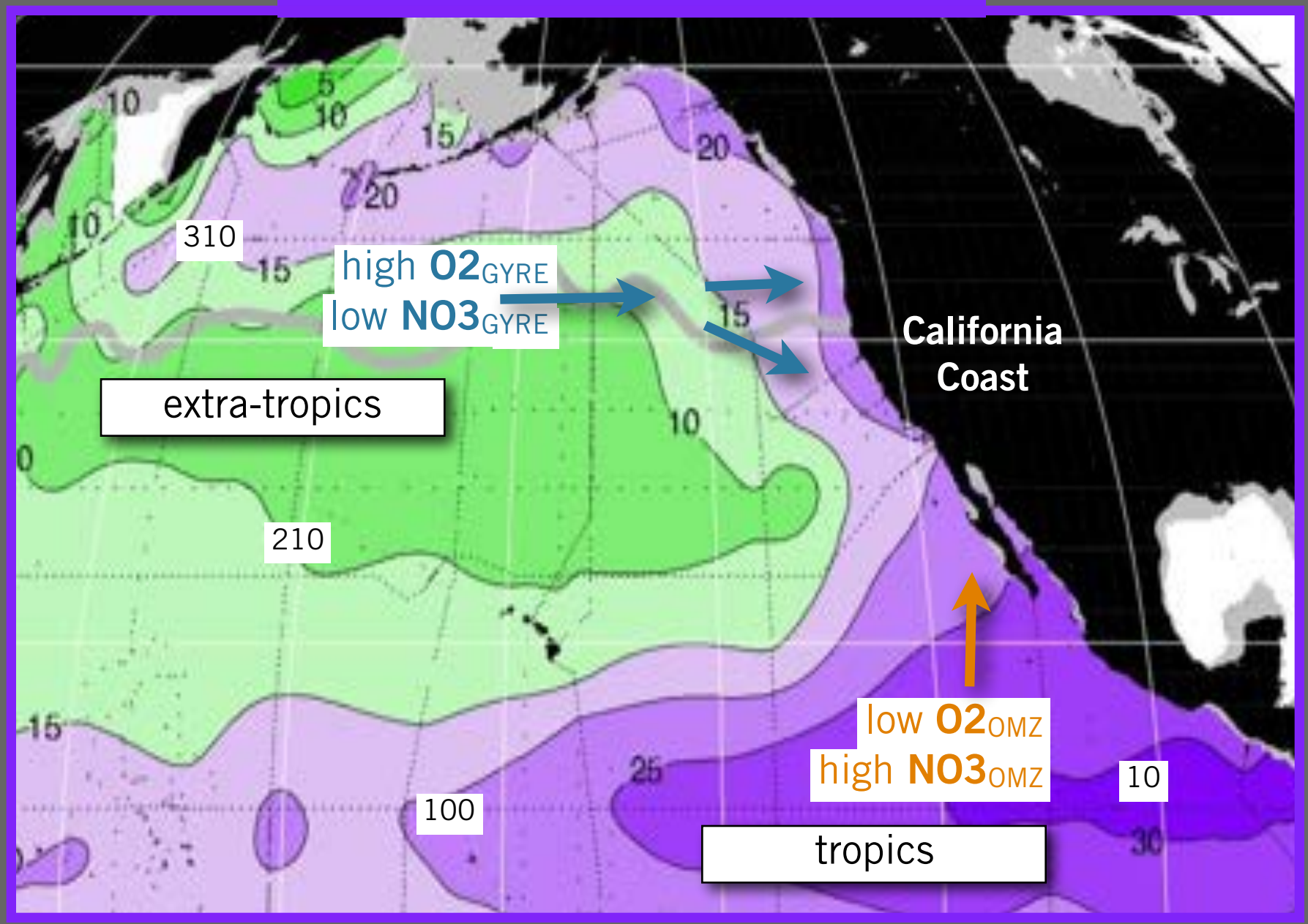
Oxygen Isopycnal 26.5



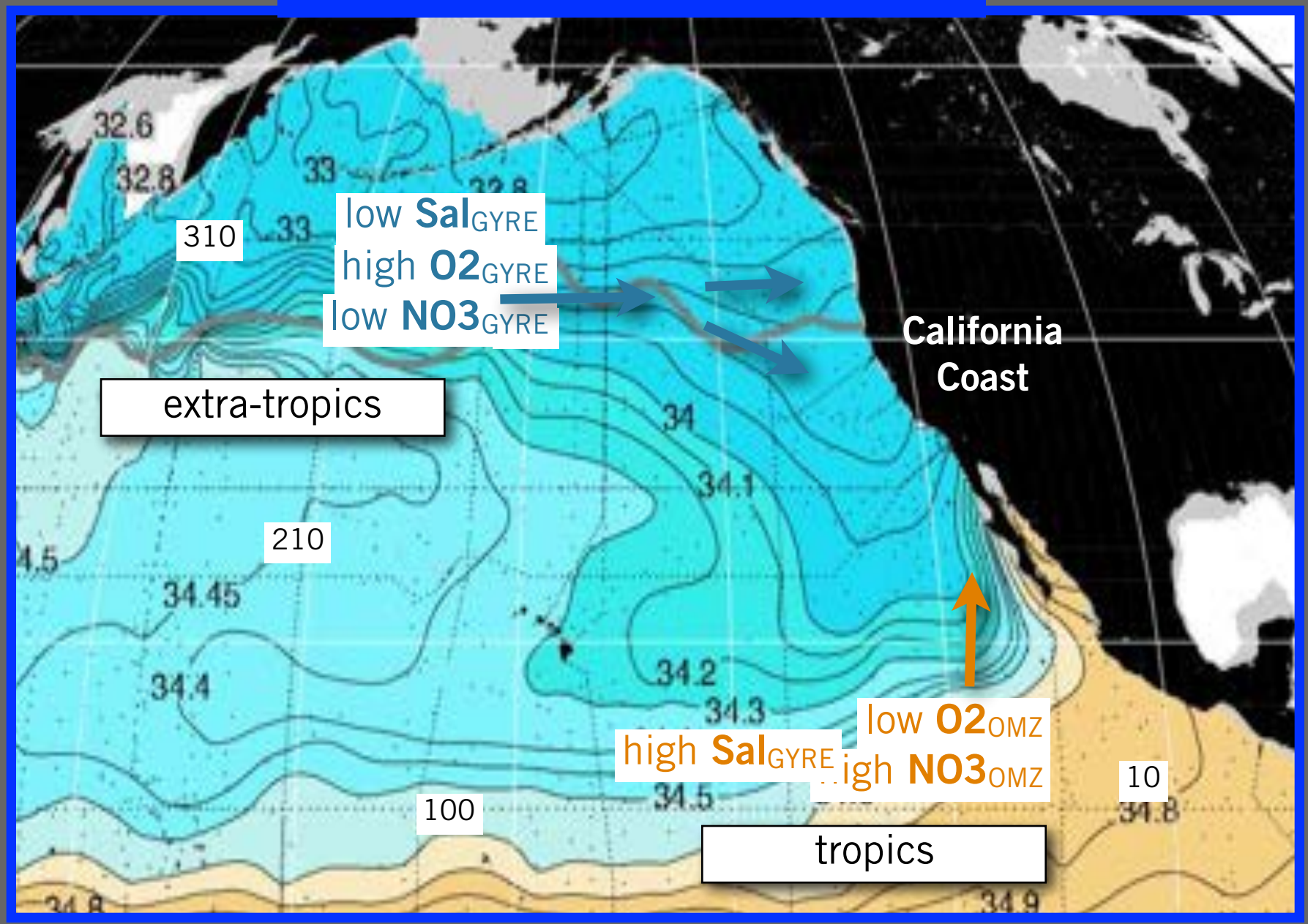
Oxygen Isopycnal 26.5

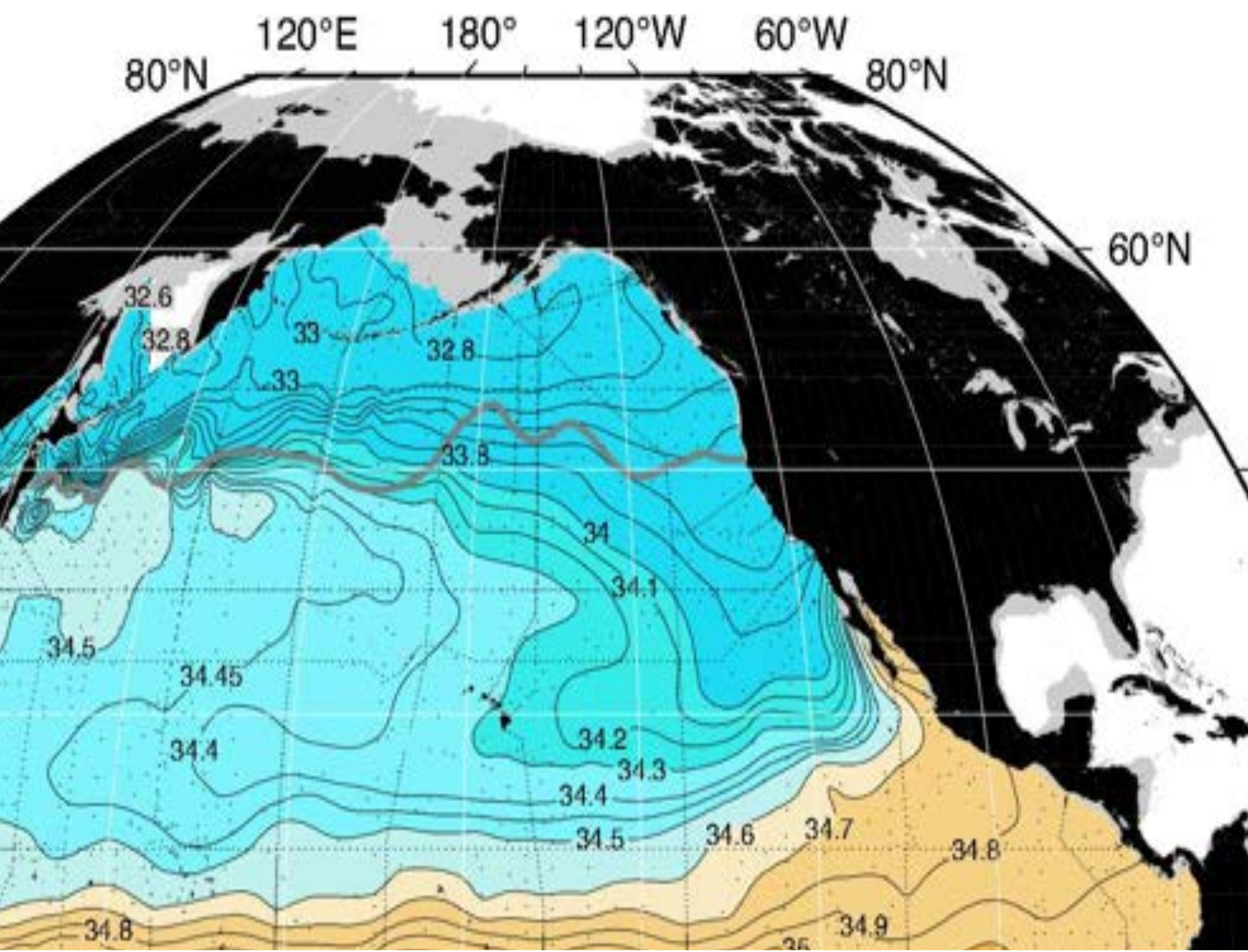


Nitrate Isopycnal 26.5

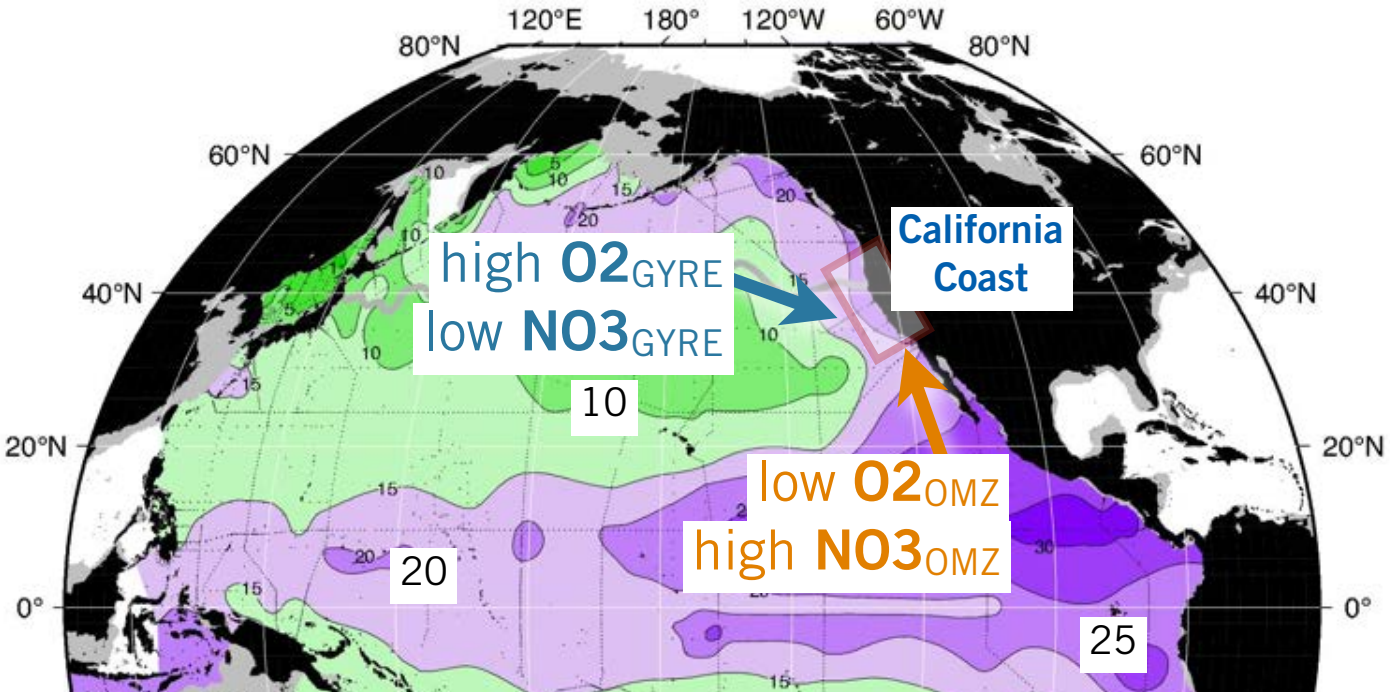


Salinity Isopycnal 26.5

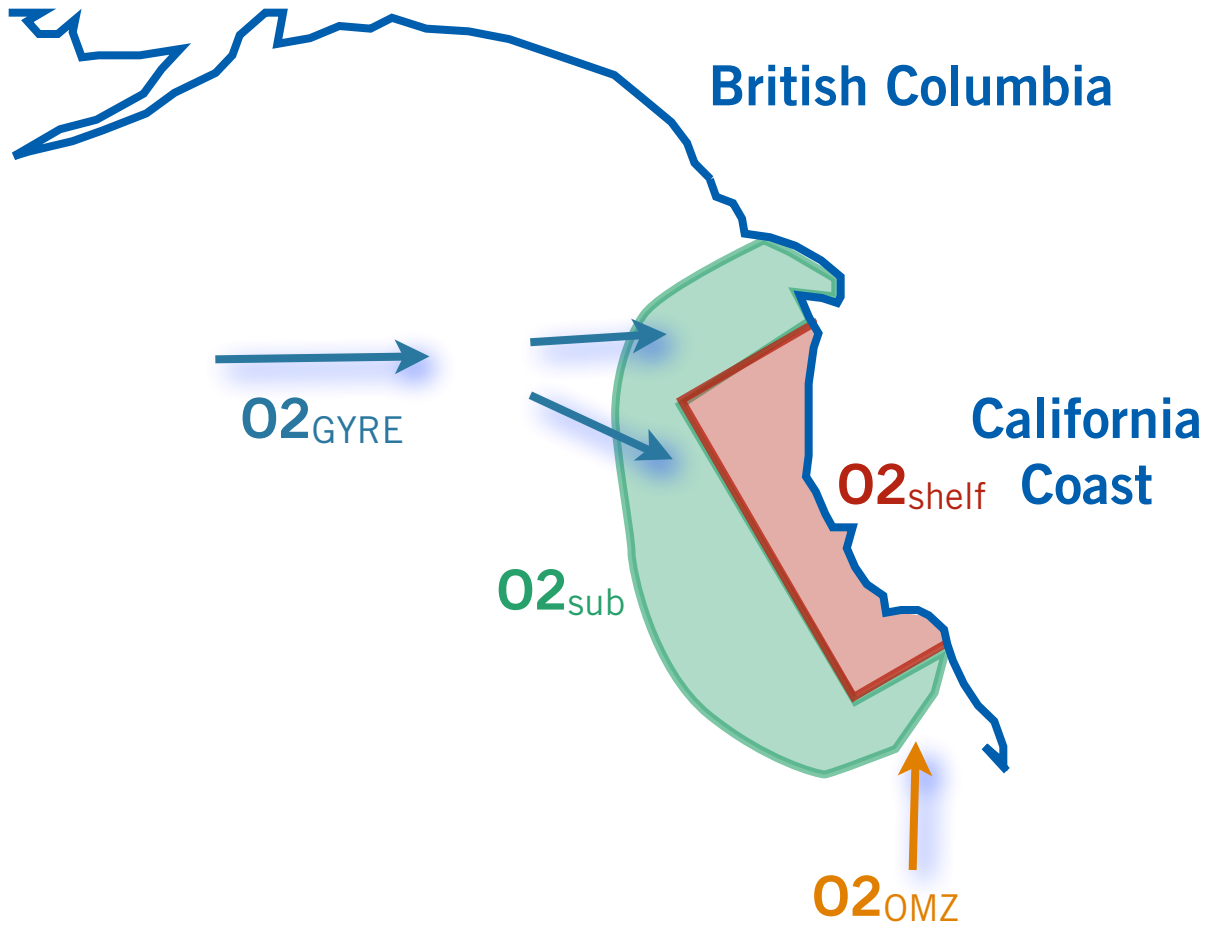



120°E
180°
120°W
60°W
80°N
80°N
60°N
32.6
32.8
33
32.8
33
33.8
34
34.1
34.5
34.45
34.4
34.2
34.3
34.4
34.5
34.6
34.7
34.8
34.8
34.9

Nitrate Isopycnal 26.5



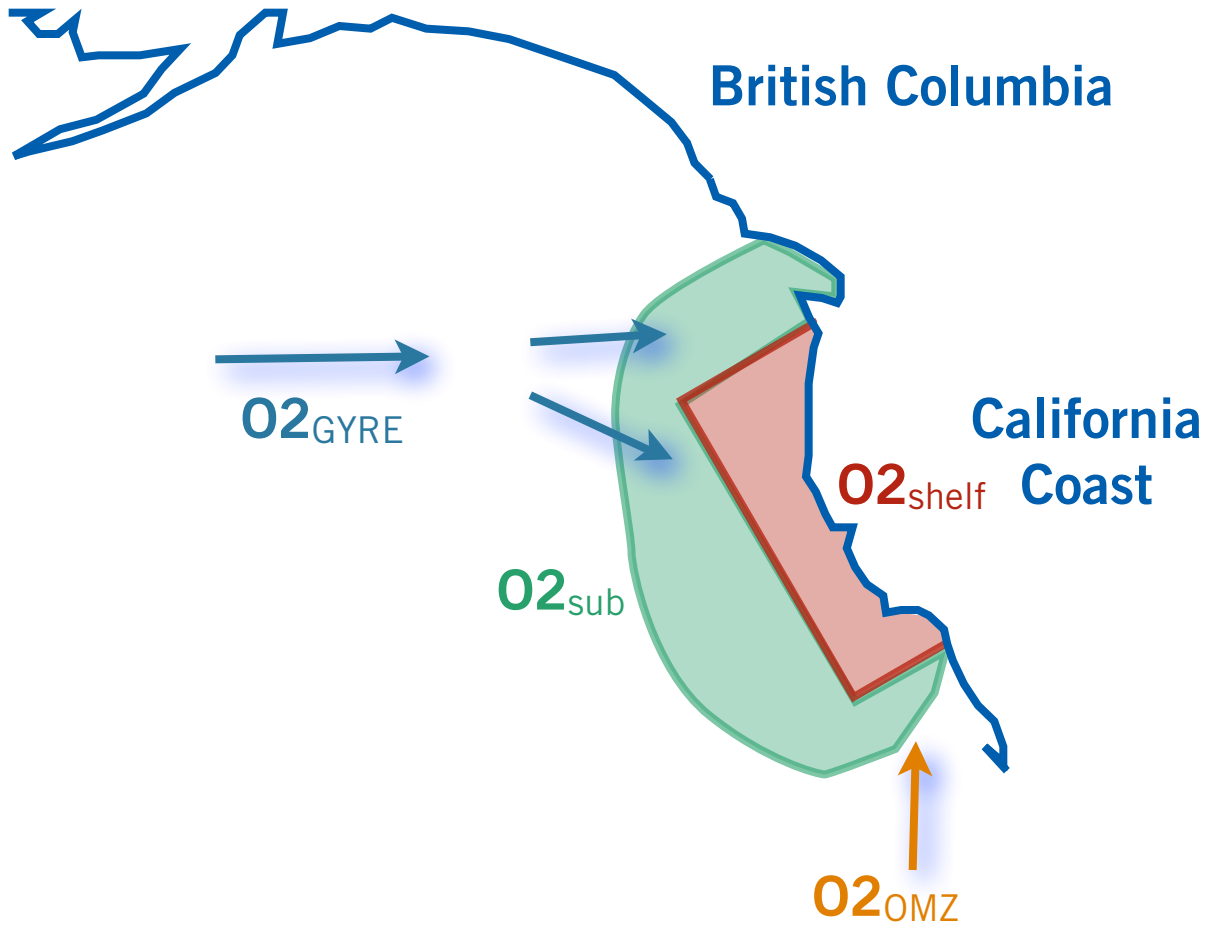
Large-scale ocean dynamics impacting **Coastal Hypoxia**



<u>GOAL</u>:

Develop a conceptual model of the large-scale dynamics controlling

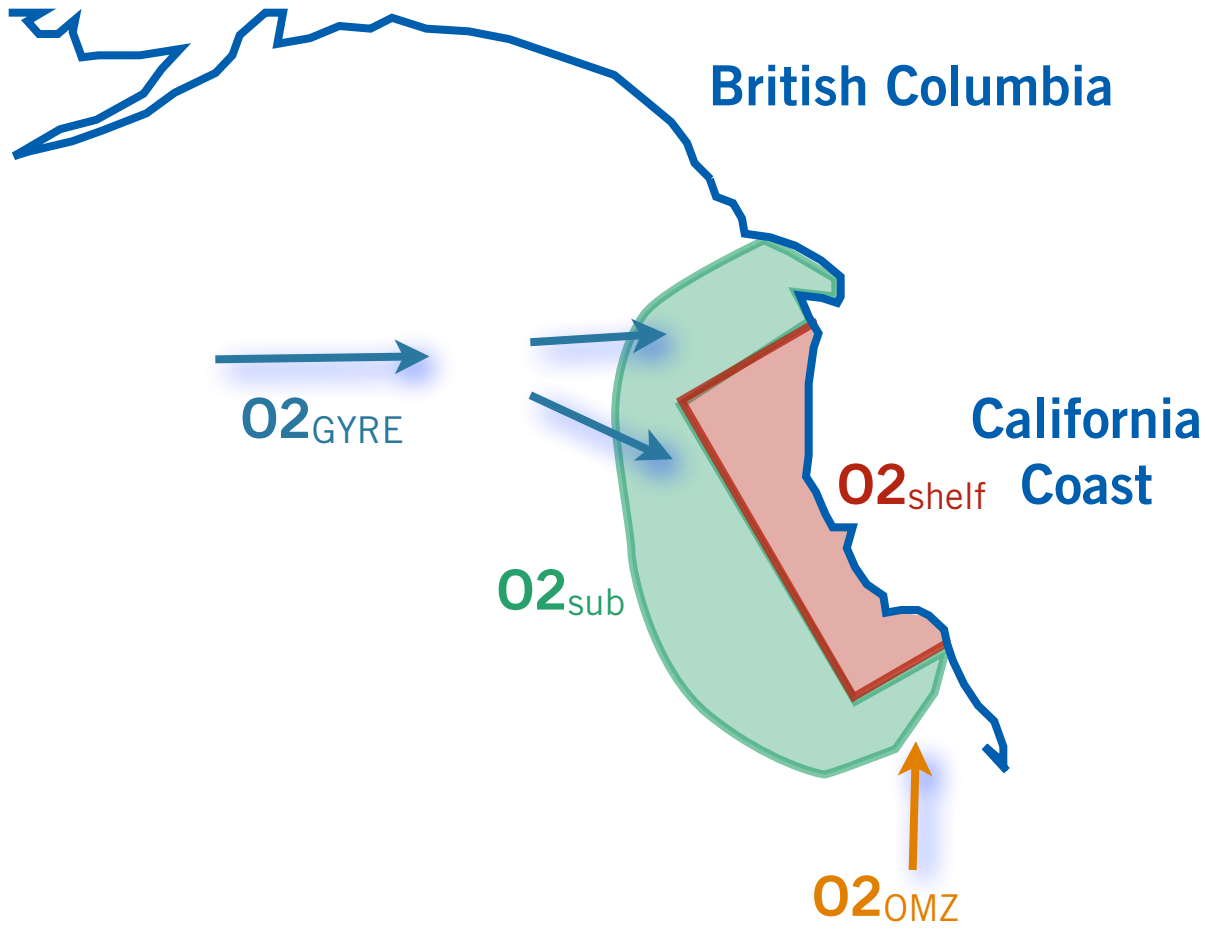
Large-scale ocean dynamics impacting **Coastal Hypoxia**



<u>GOAL</u>:

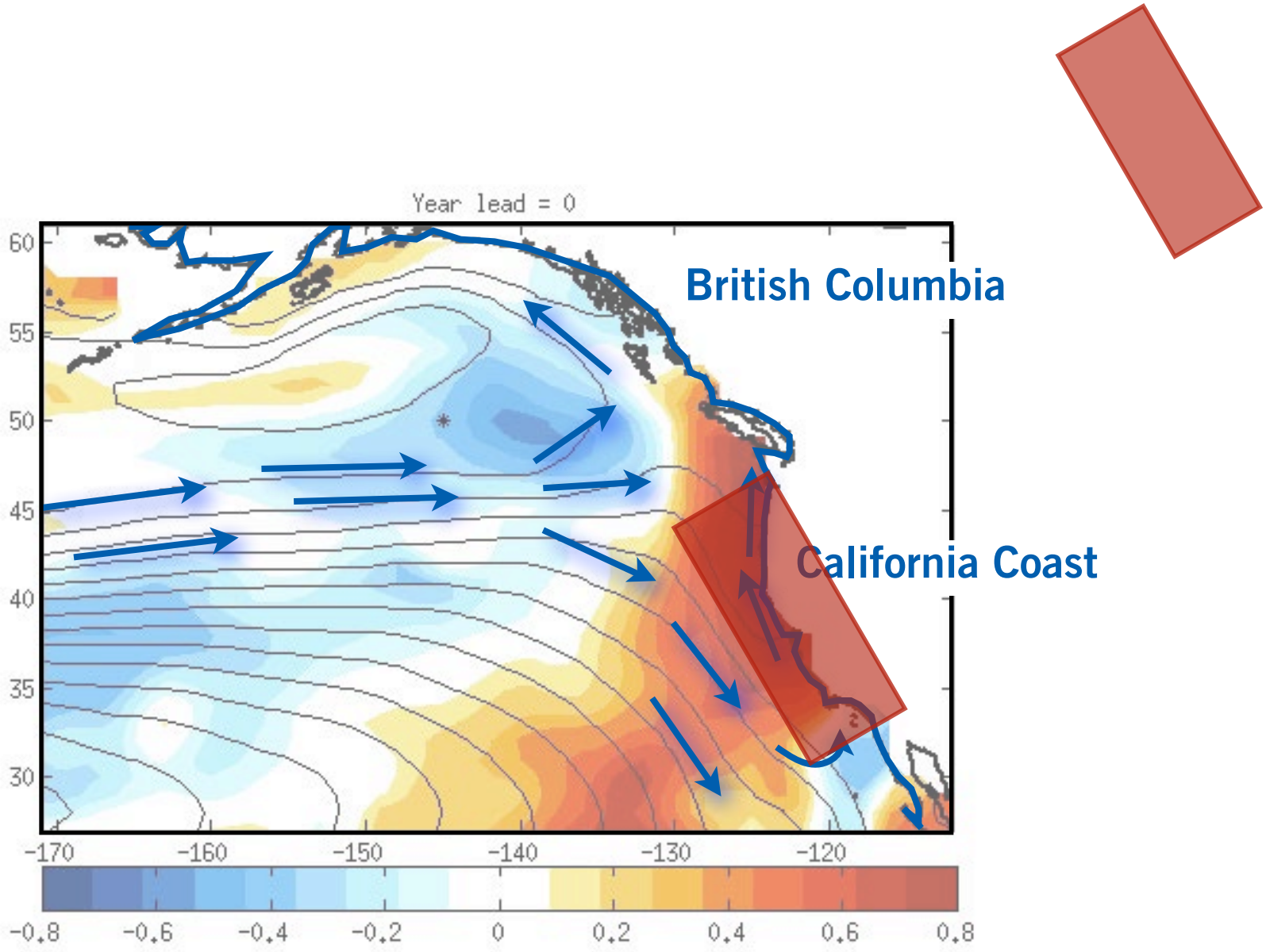
Develop a conceptual model of the large-scale dynamics controlling

Large-scale ocean dynamics impacting **Coastal Hypoxia**

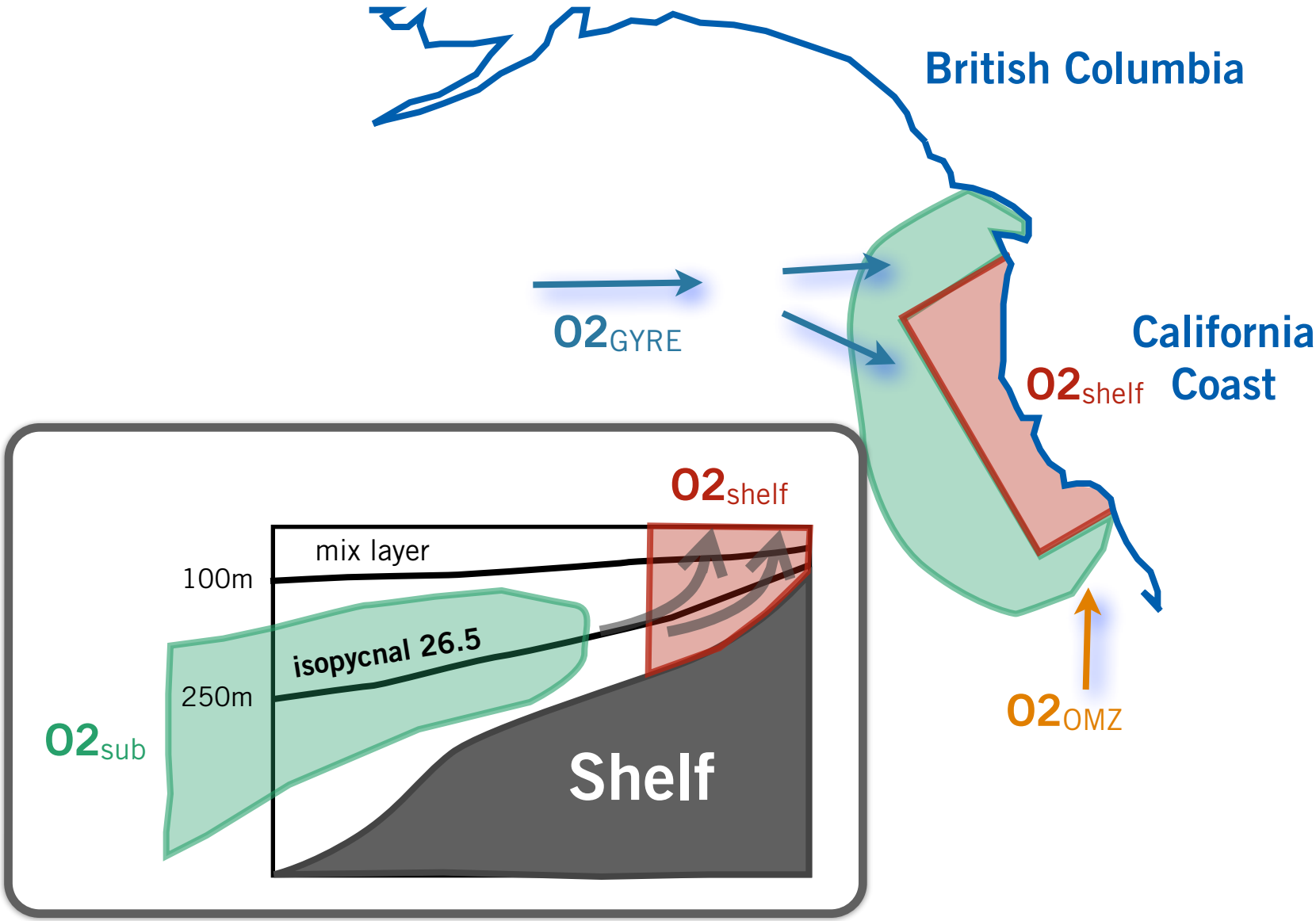


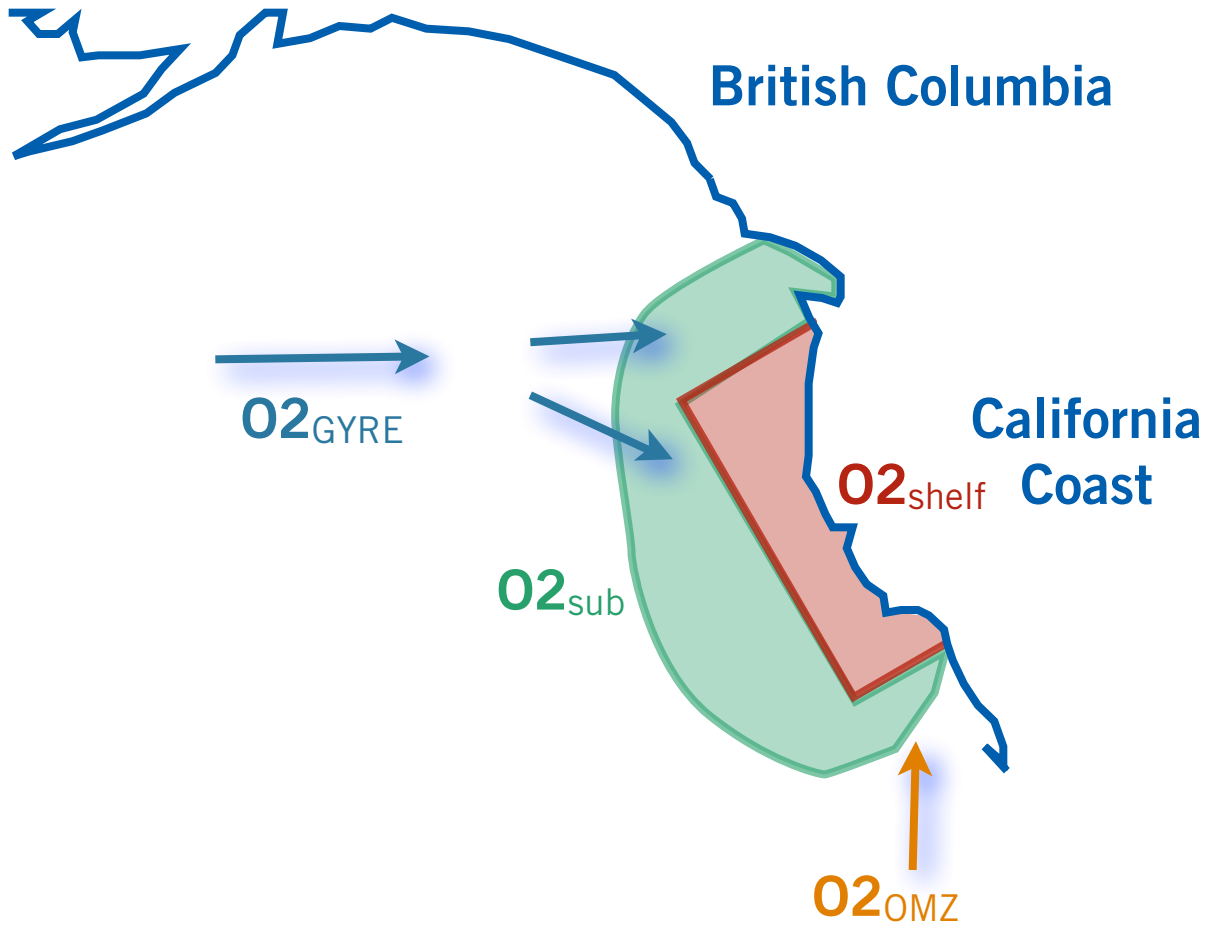
<u>GOAL</u>:

Develop a conceptual model of the large-scale dynamics controlling

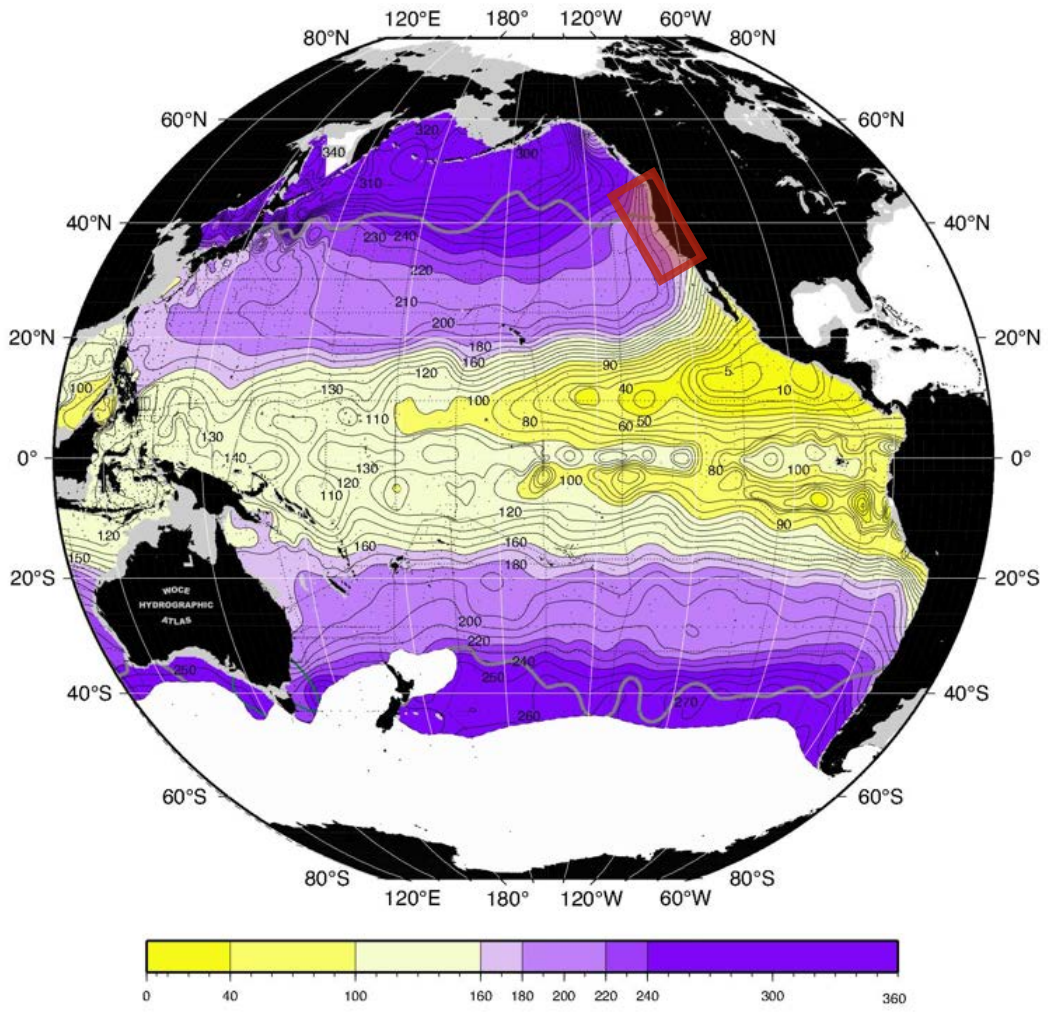

Year lead = 0
60
55
50
45
40
35
30
-170
-160
-150
-140
-130
-120
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
British Columbia
California Coast

Large-scale ocean dynamics impacting **Coastal Hypoxia**

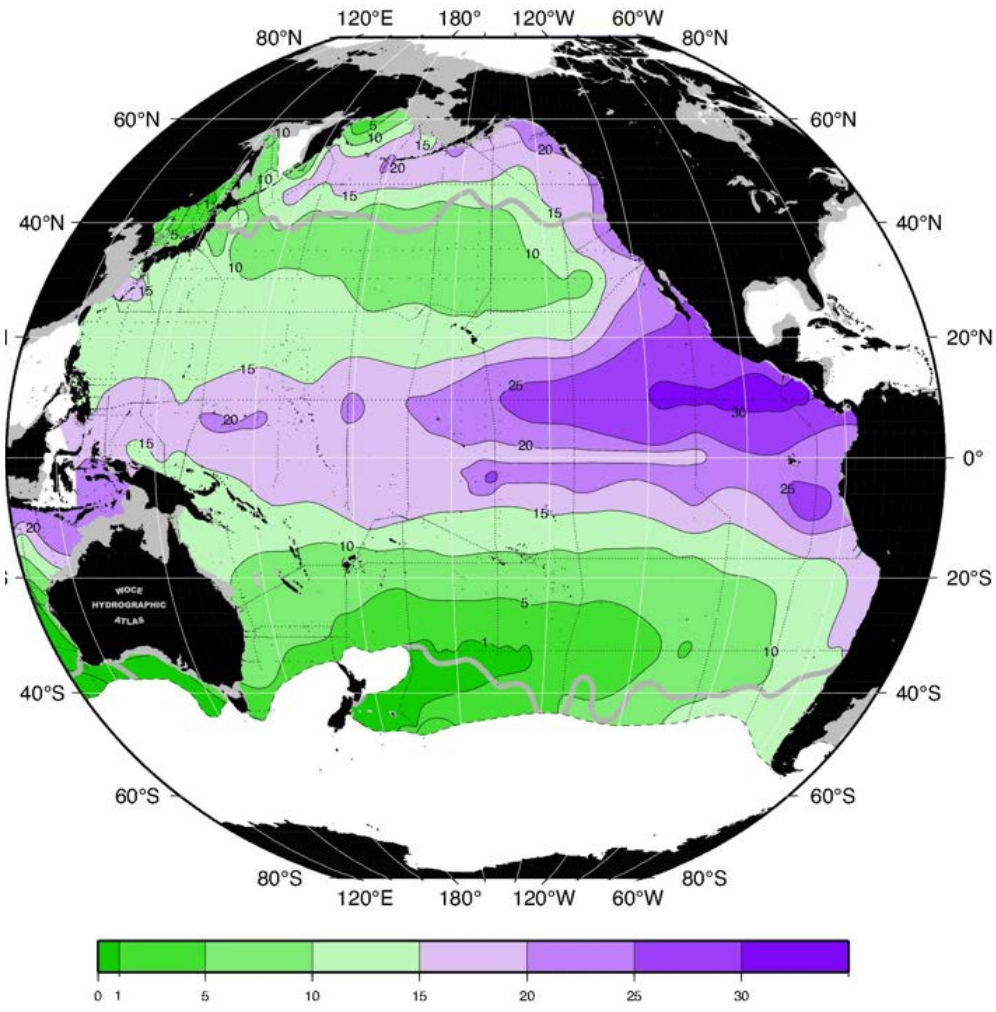



British Columbia
O2GYRE
California
Coast
O2shelf
O2sub
O2OMZ

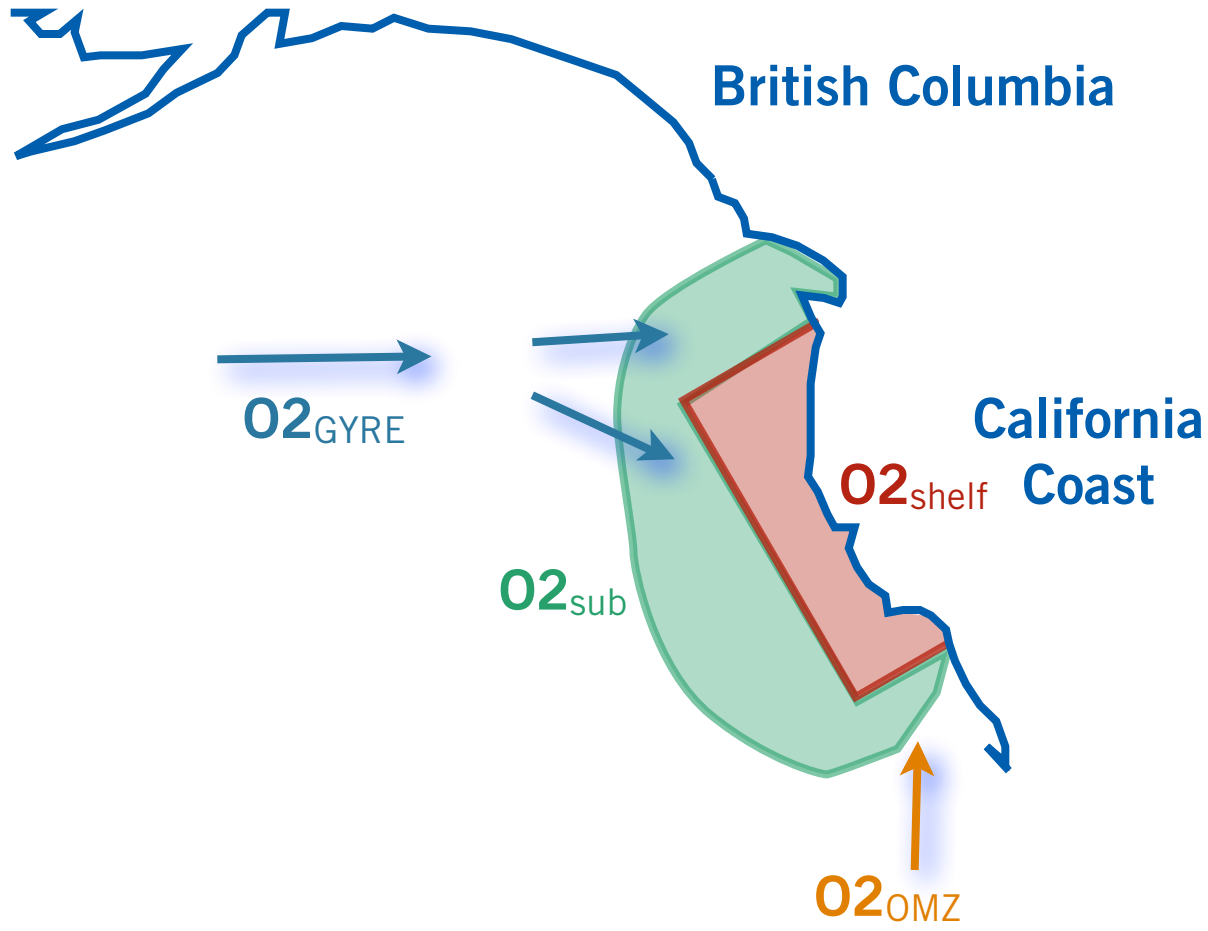
Oxygen (µmol/kg) 26.0 γ^n (kg/m^3)



Nitrate (µmol/kg) 26.0 γ^n (kg/m^3)



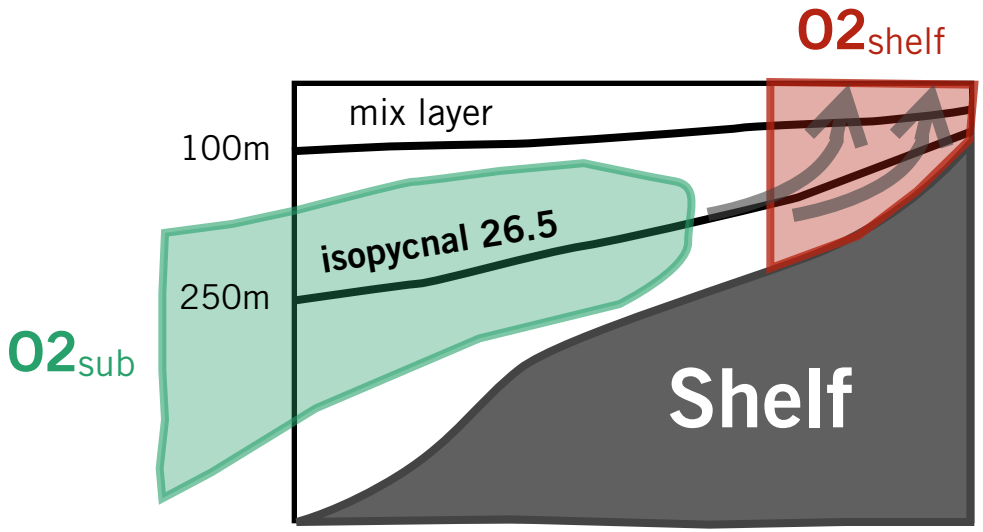
Large-scale ocean dynamics impacting **Coastal Hypoxia**



changes in upwelling

changes in source waters

$$\frac{\partial O'_{shelf}}{\partial t} = -\left(1+\lambda_{bio}\right) w' \cdot \bar{O}_{sub} + \bar{w} \cdot O'_{sub} - \varepsilon O'_{shelf}$$



Upwelling (w)

$$\frac{\partial O'_{sub}}{\partial t} = u' \cdot \bar{O}_{gyre} + \bar{u} \cdot O'_{gyre} + v' \cdot \bar{O}_{OMZ} + \bar{v} \cdot O'_{OMZ}$$

changes in gyre circulation

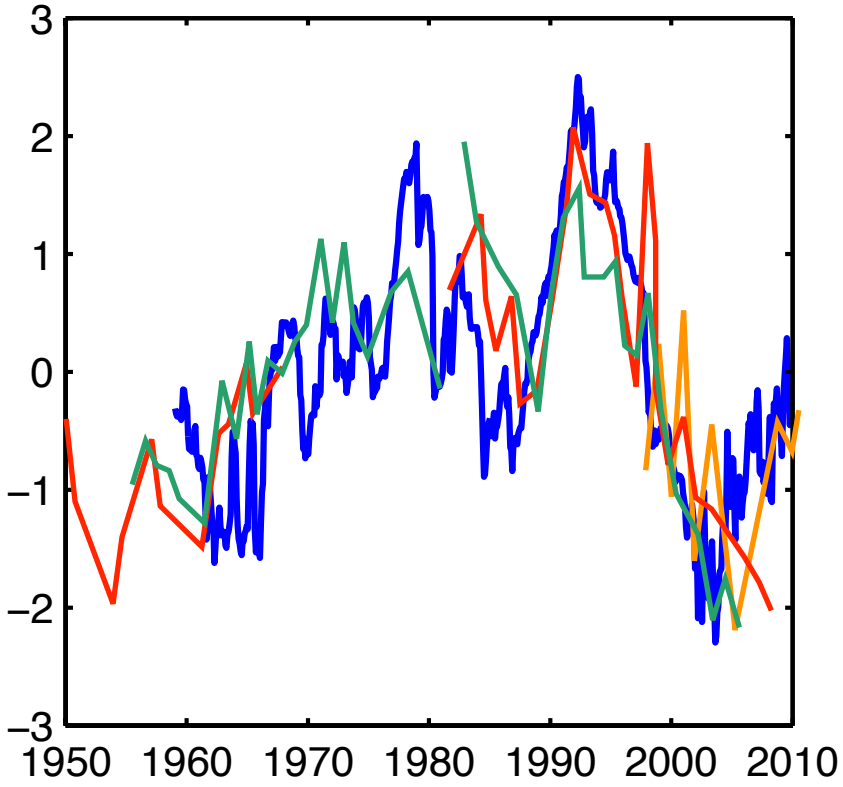
changes in poleward flow advection

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



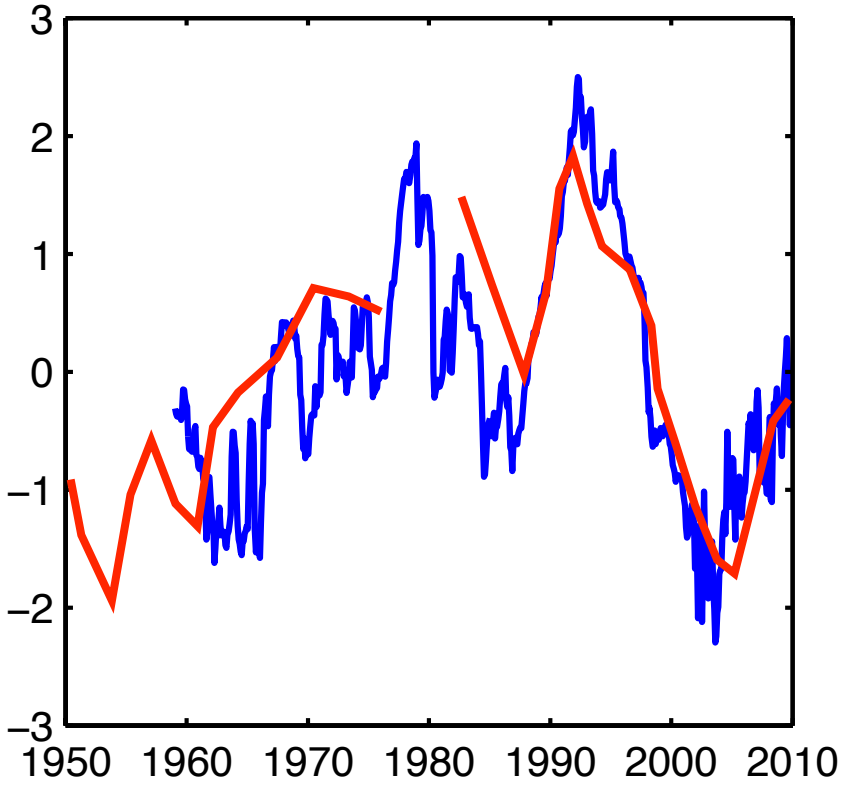
good

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

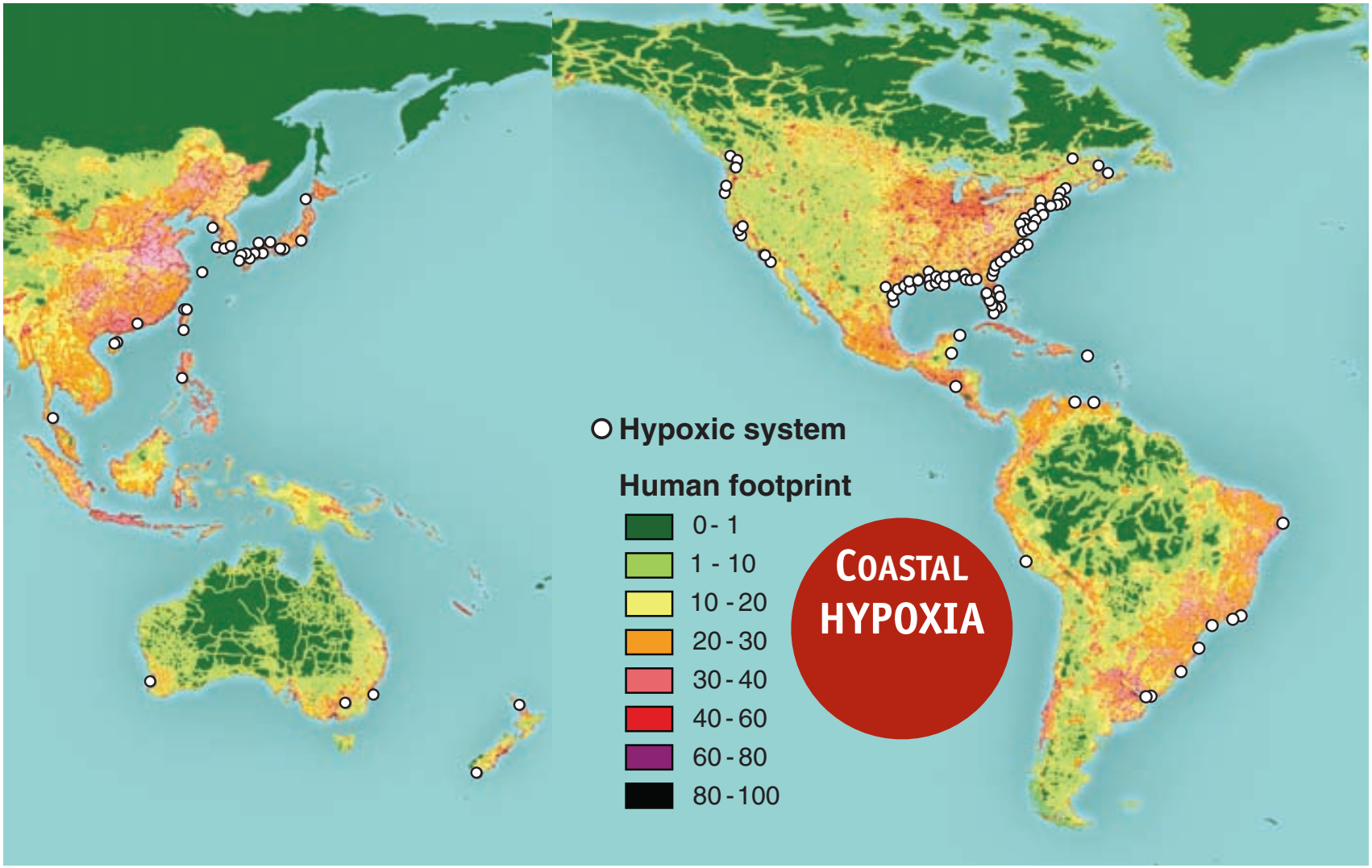
Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)

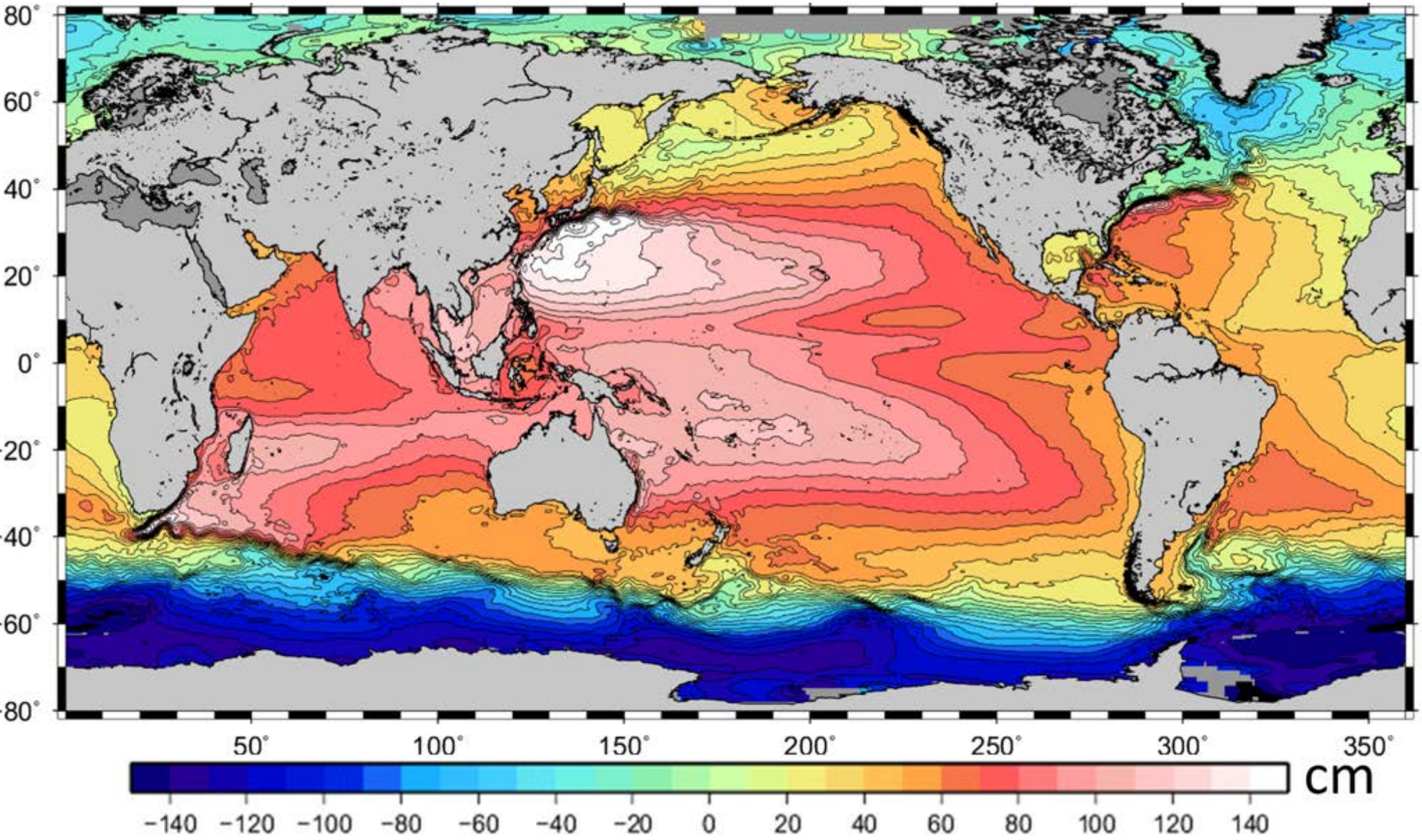


good

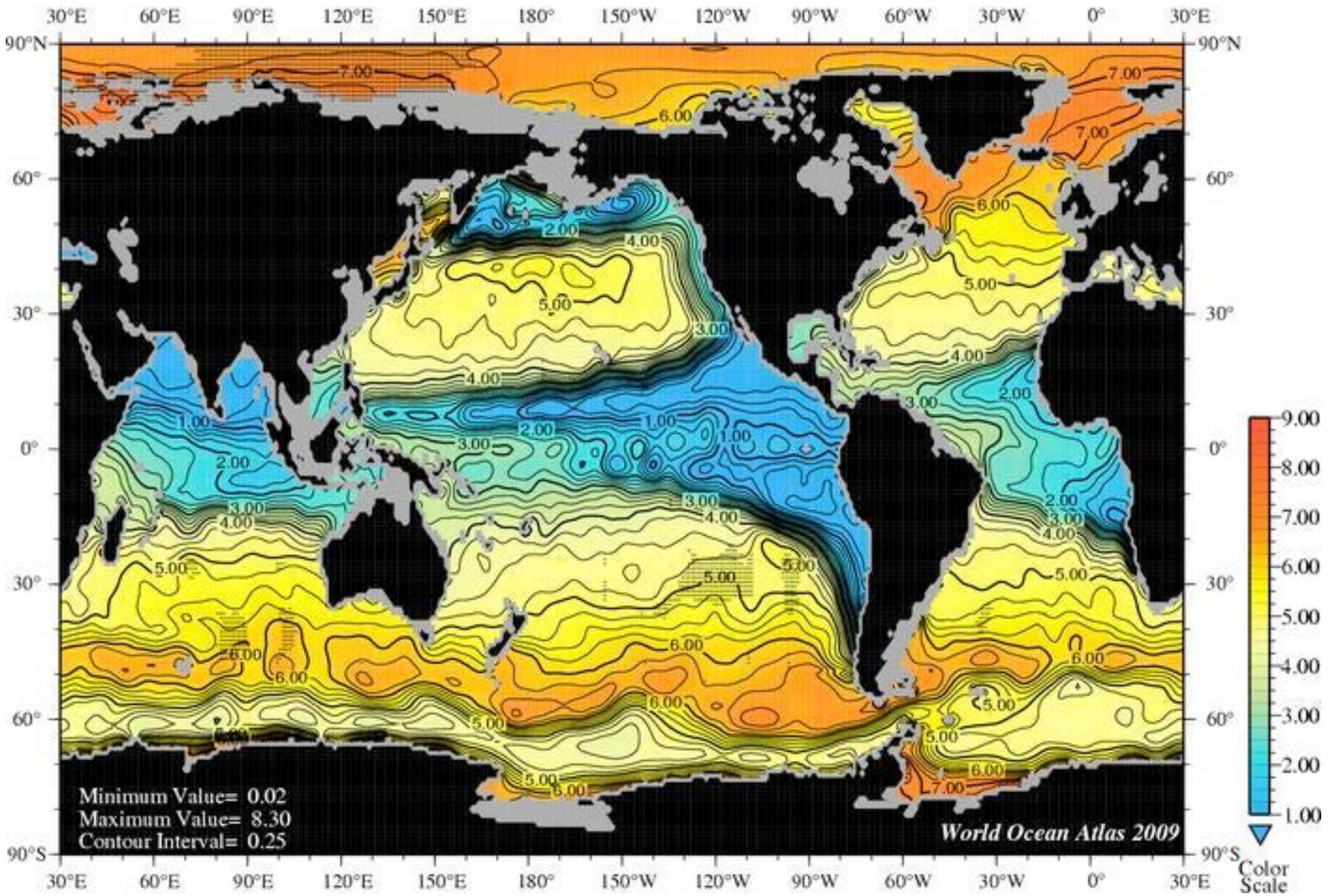
Diaz and Rosenberg, Science 2008



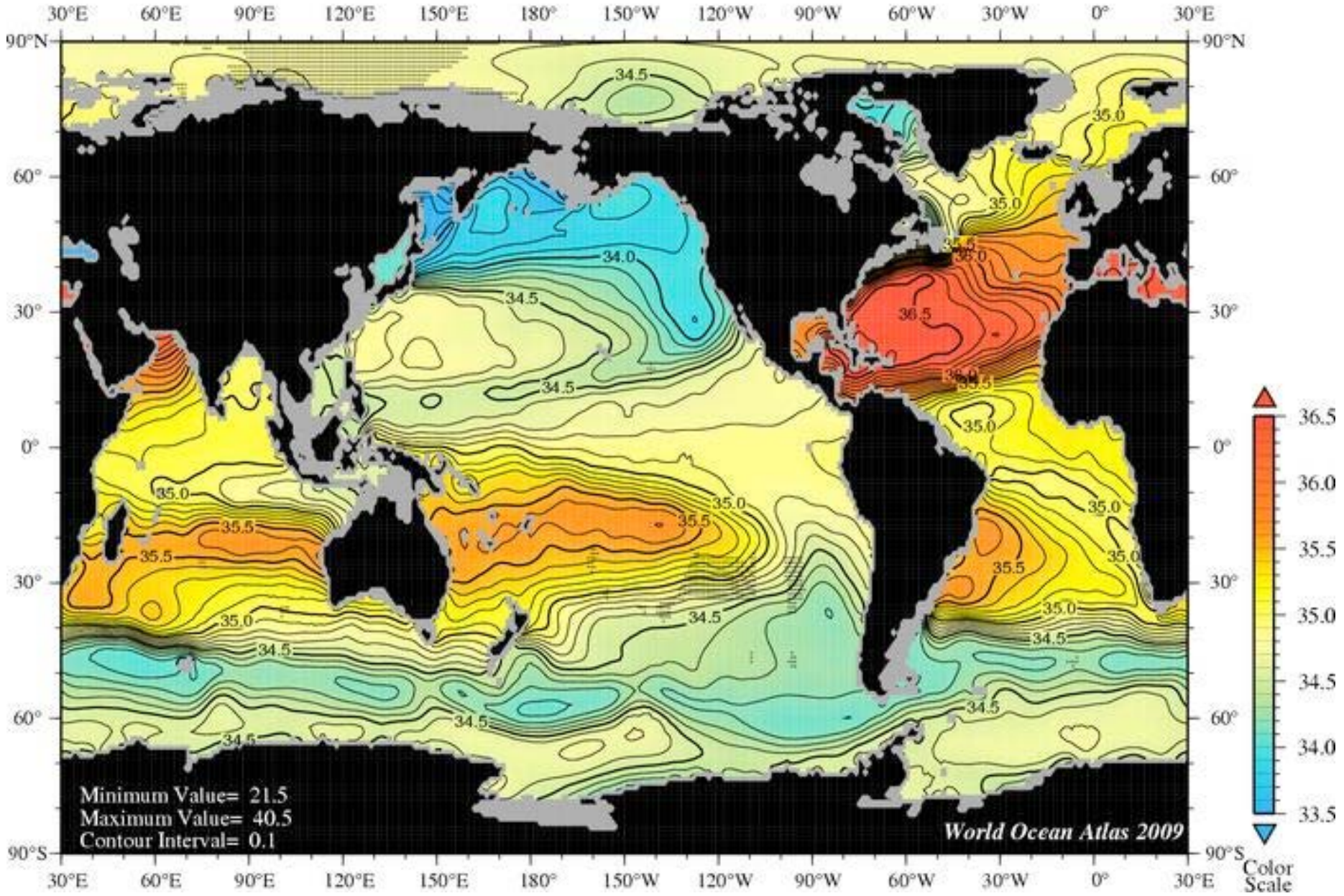
Oregon Shelf, observations by *Peterson et al. 2013*


80°
60°
40°
20°
0°
-20°
-40°
-60°
-80°
50°
100°
150°
200°
250°
300°
350°
−140 −120 −100 −80 −60 −40 −20 0 20 40 60 80 100 120 140
cm

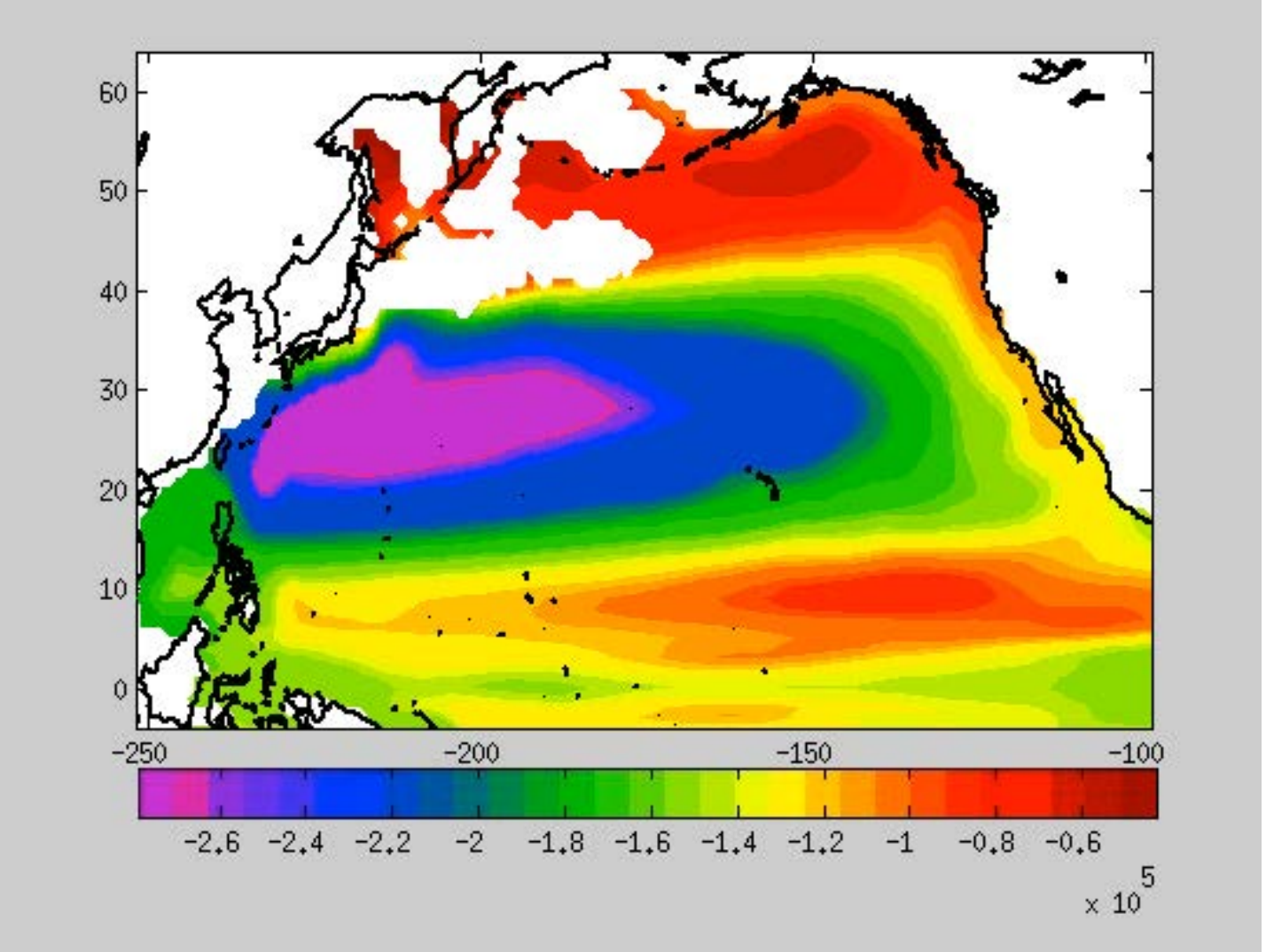
Winter (Jan.-Mar.) oxygen [ml/l] at 250 m. depth.



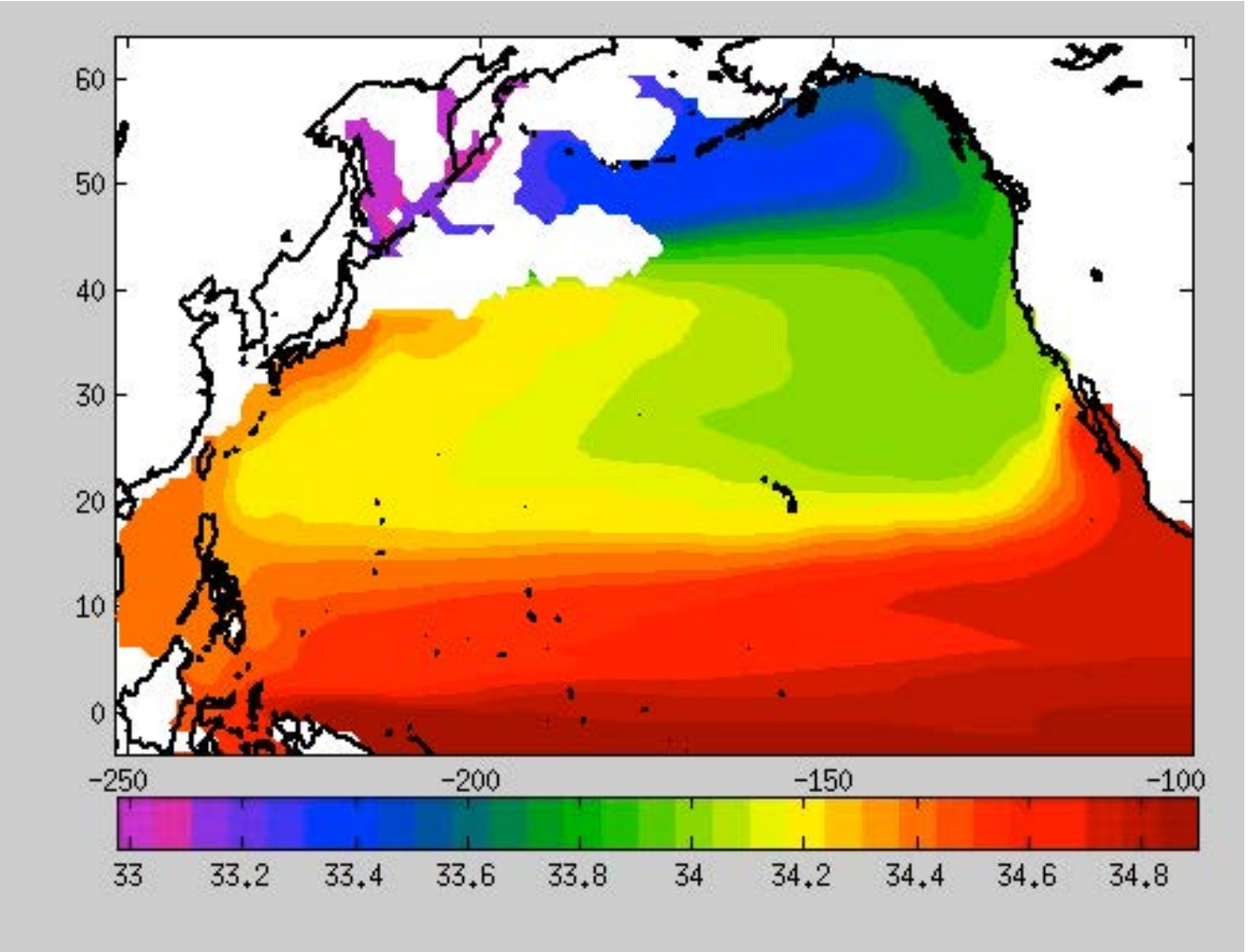
Winter (Jan.-Mar.) salinity [PSS] at 250 m. depth.



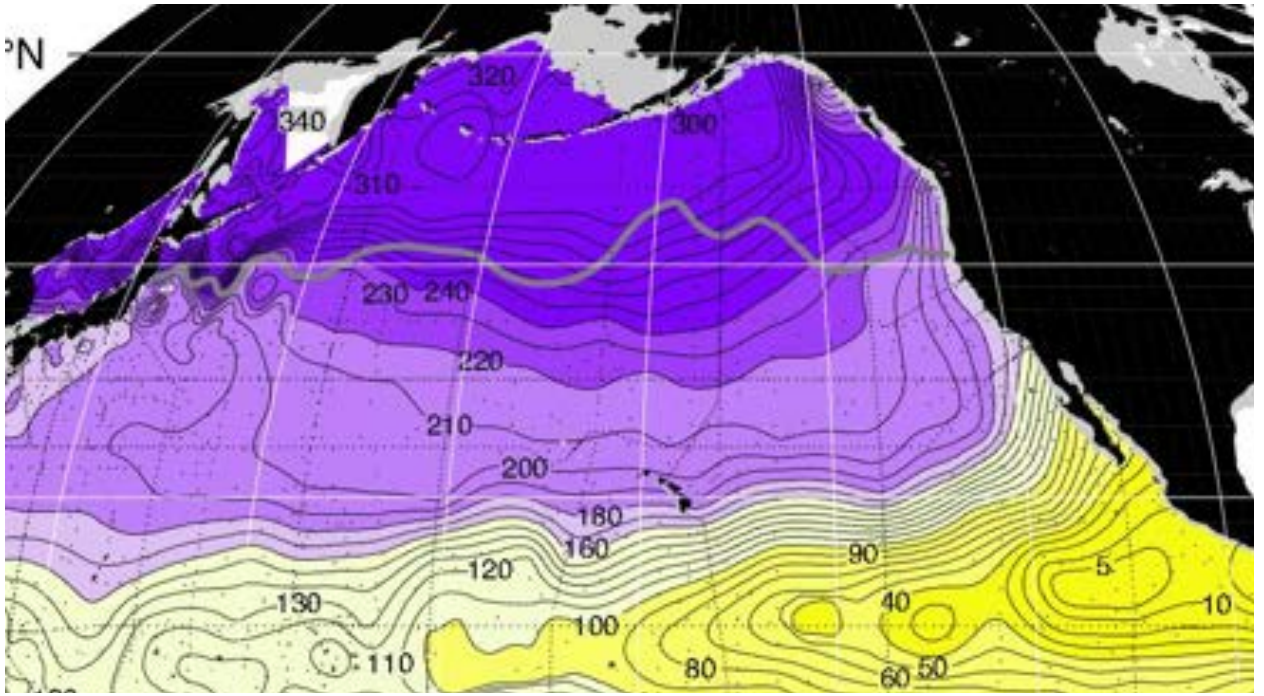
ORA3 Bernoulli Stream function ISO=26.5



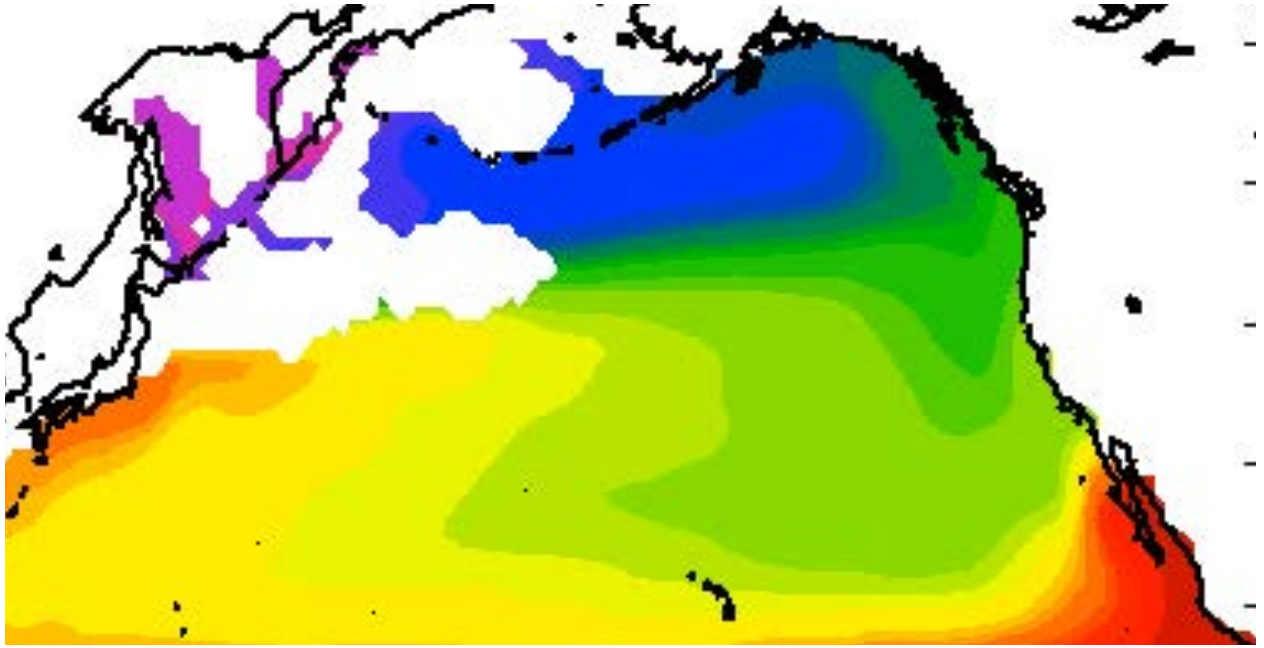
ORA3 Spice ISO=26.5

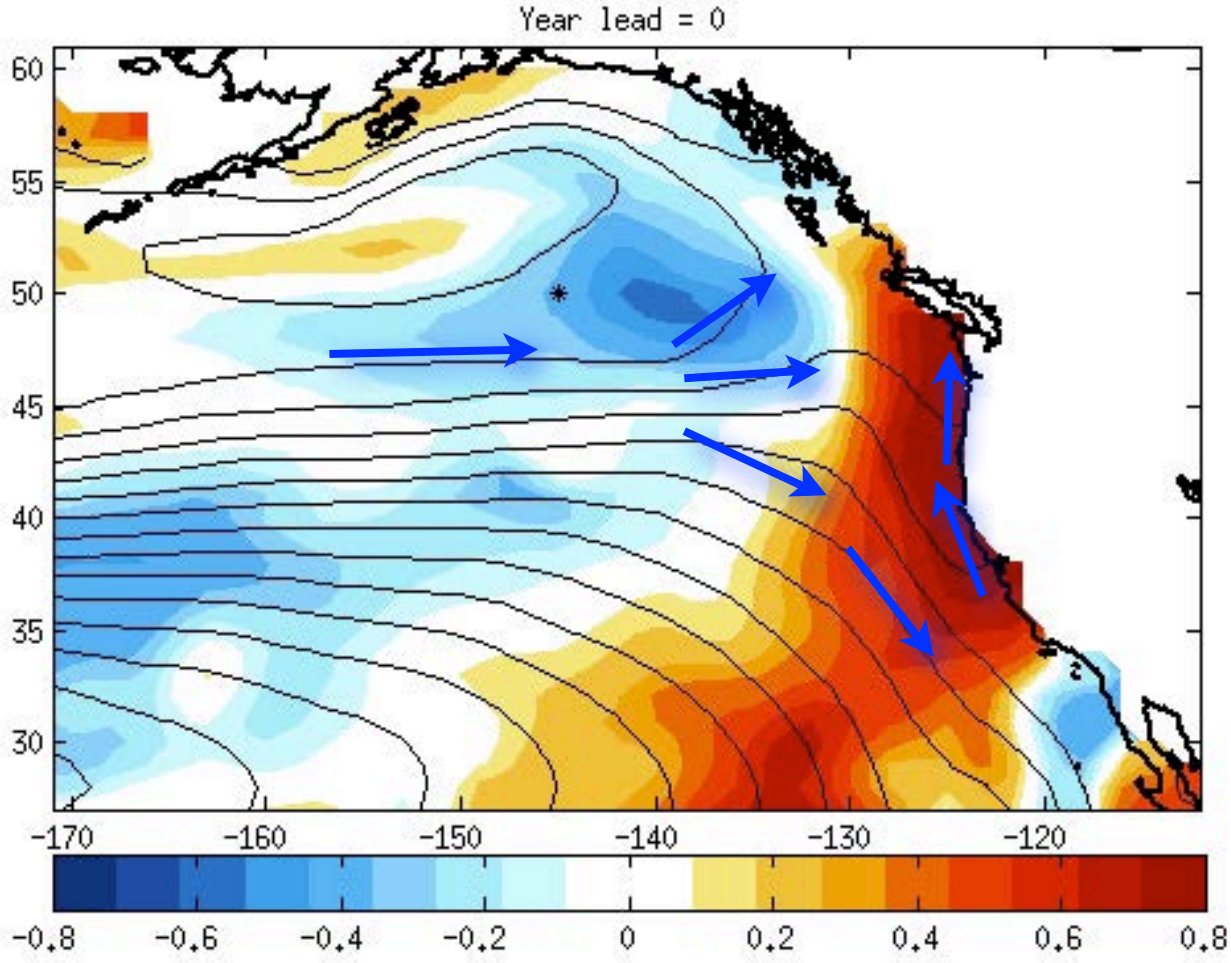


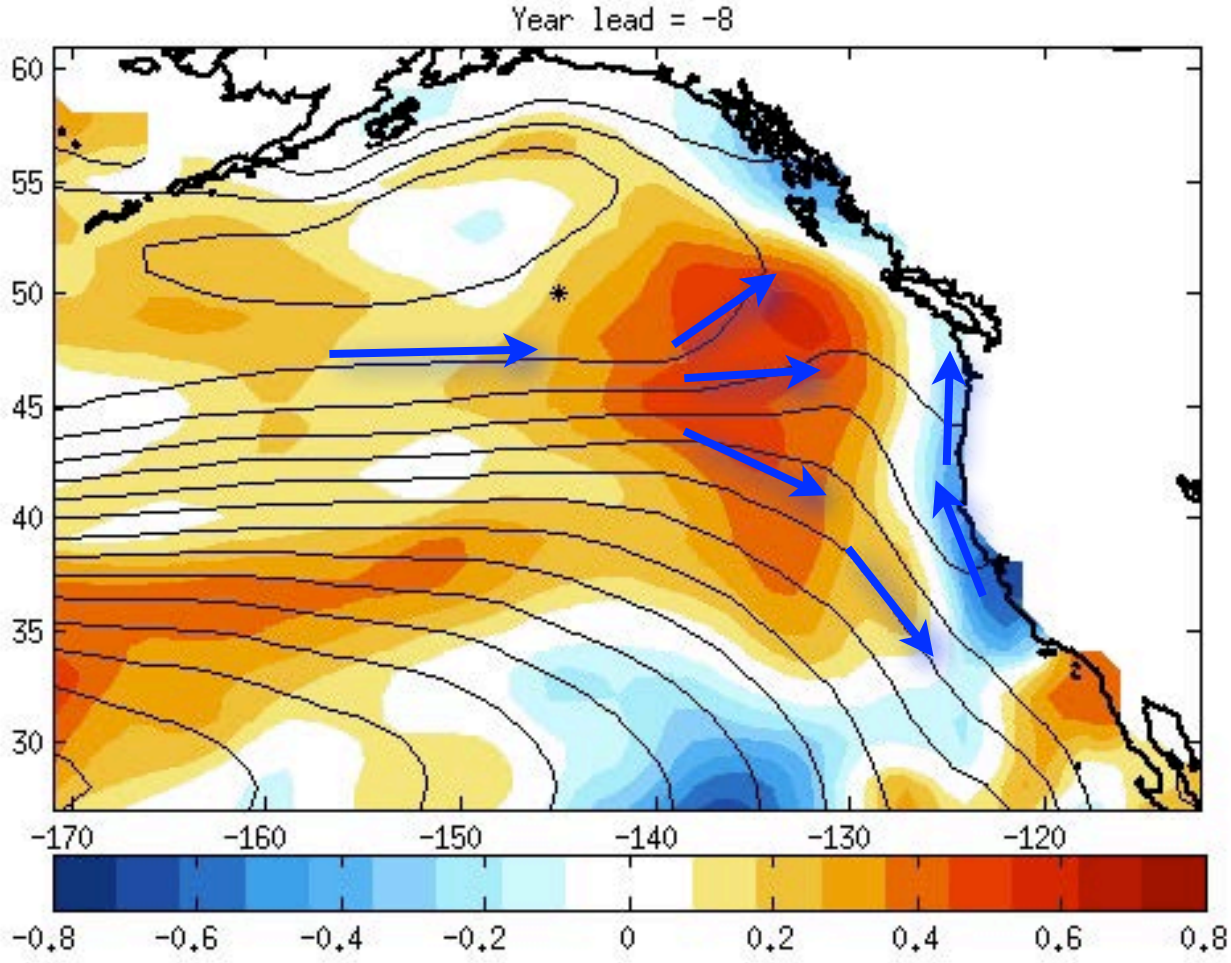
Mean WOA O2
ISO=26.5

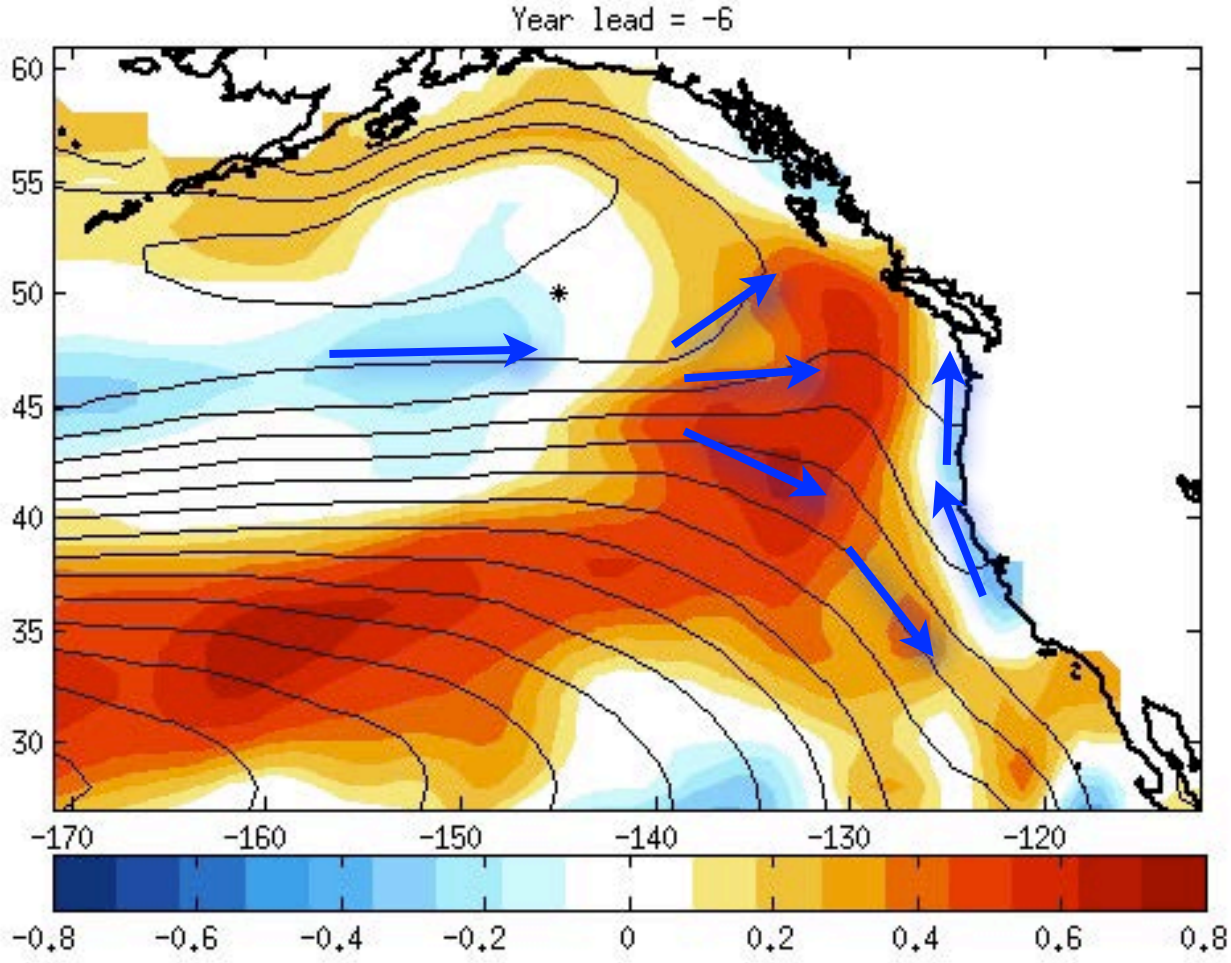


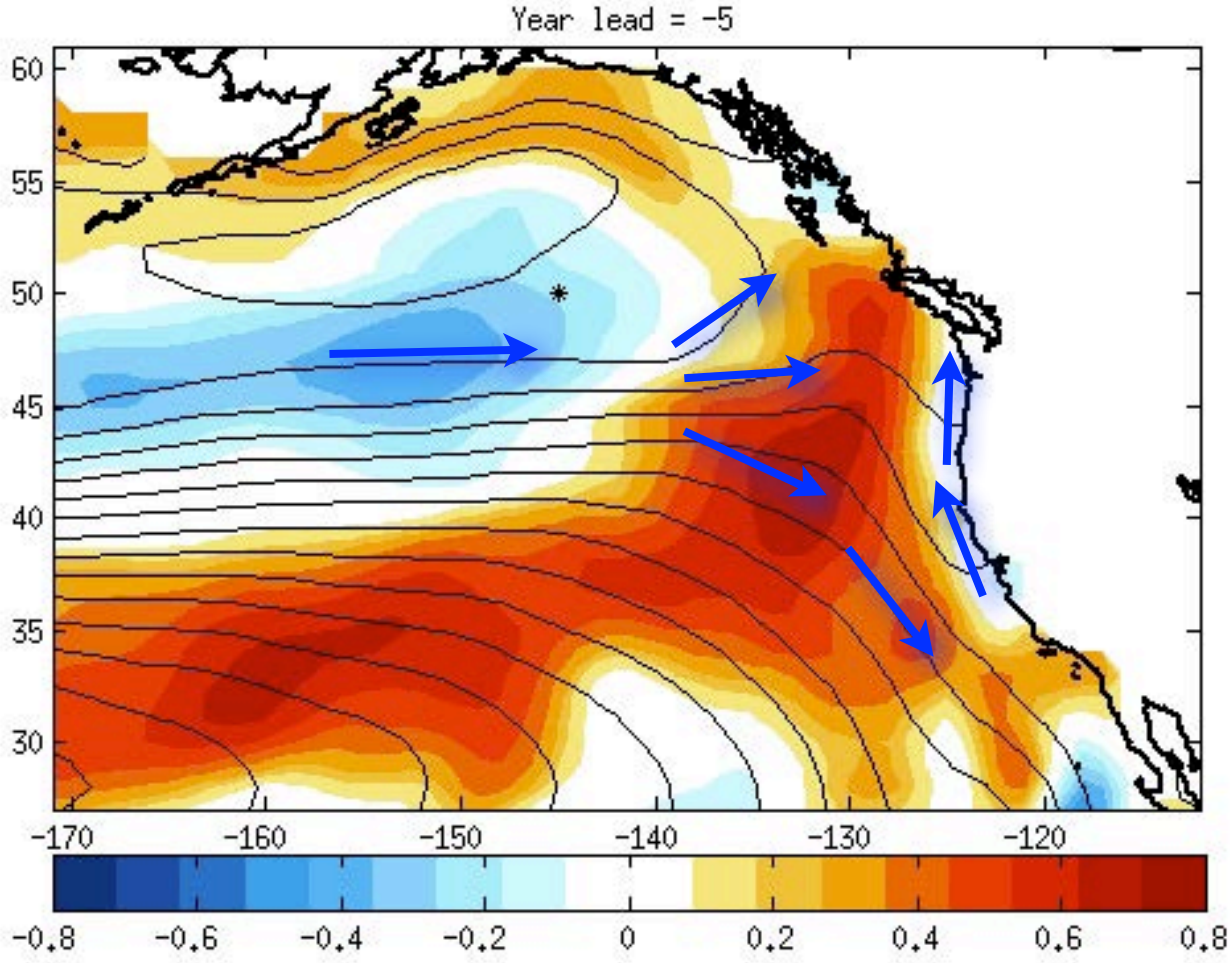
Mean ORA3 Spice
ISO=26.5

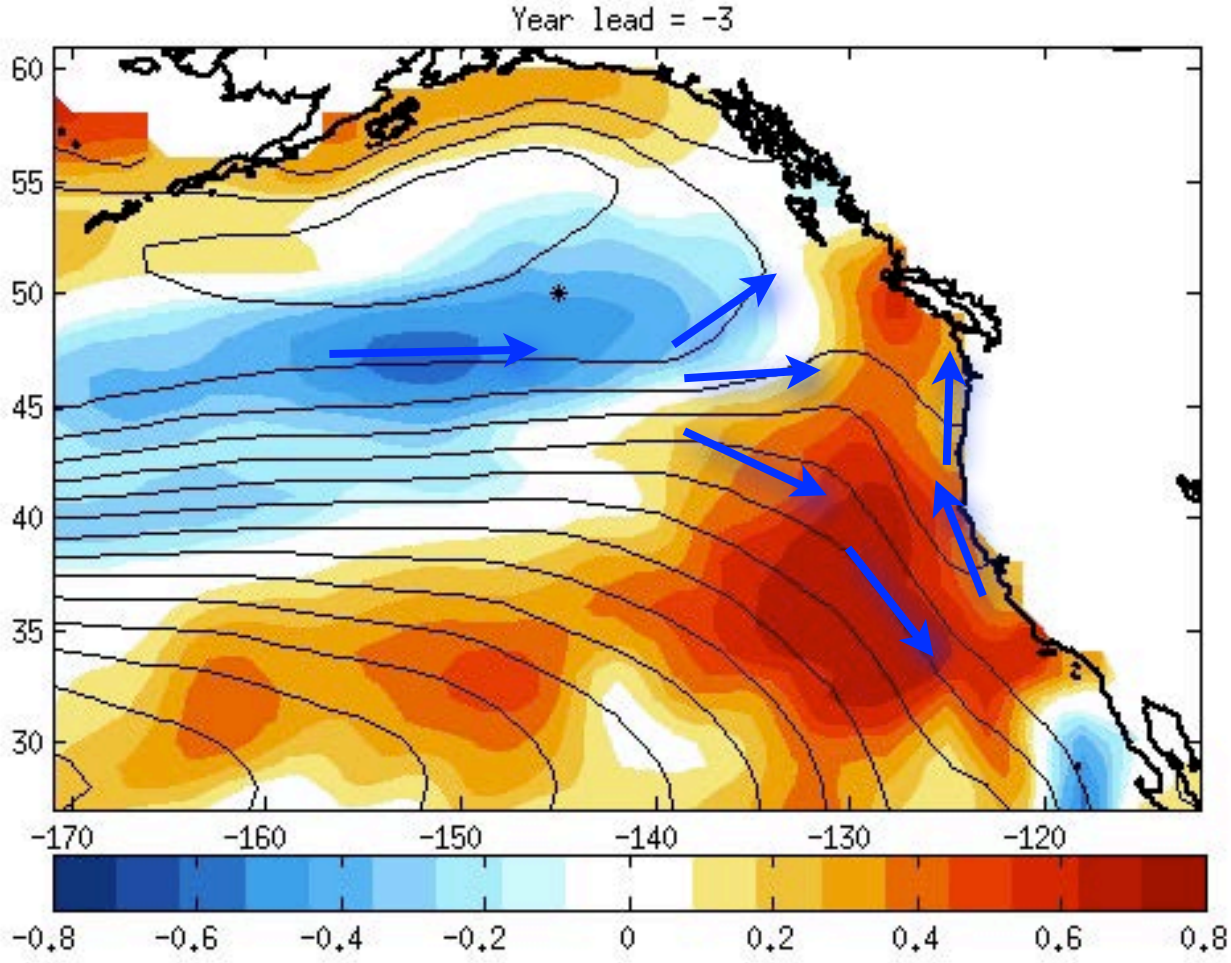


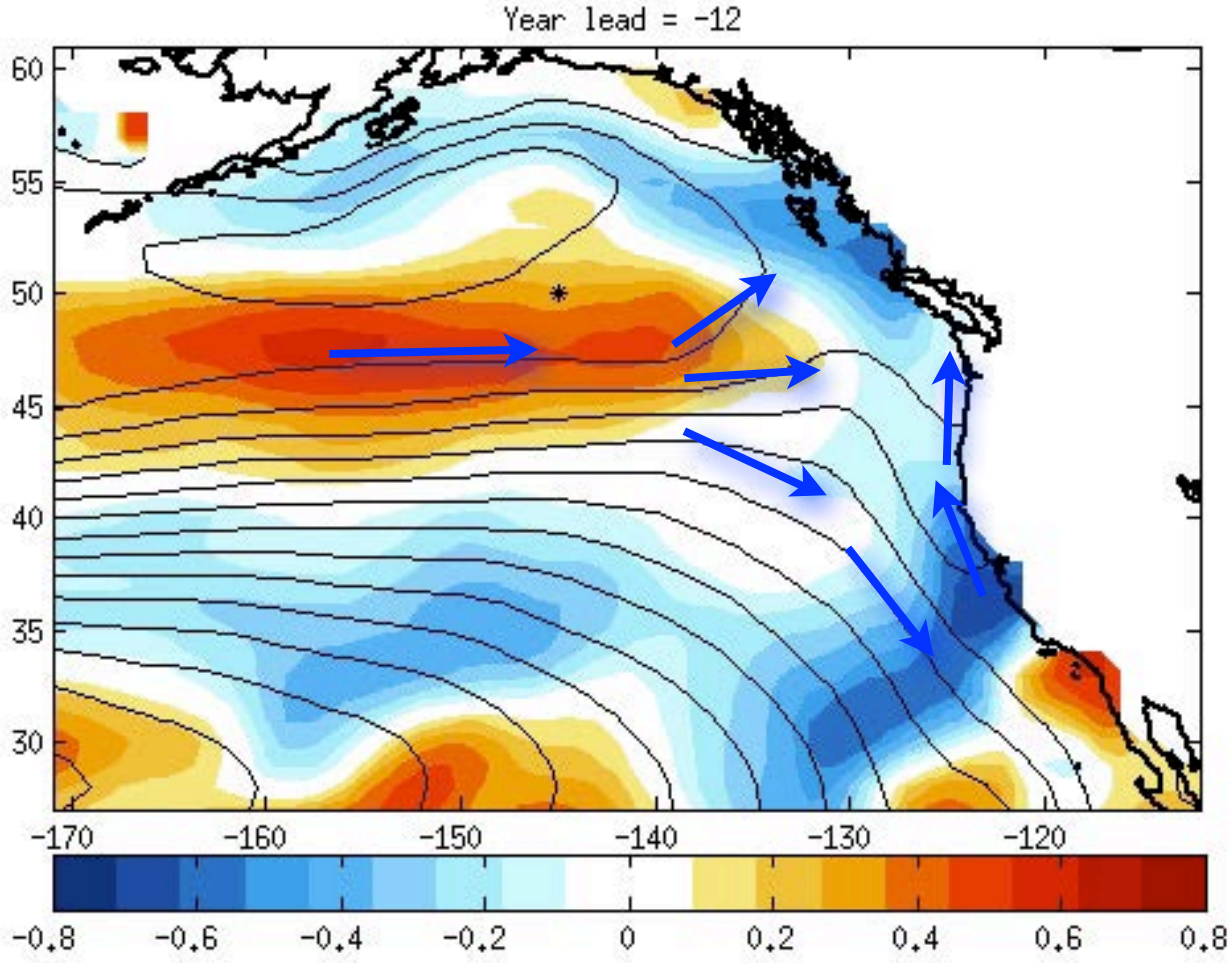

Year lead = 0
60
55
50
45
40
35
30
-170
-160
-150
-140
-130
-120
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8


Year lead = -8
60
55
50
45
40
35
30
-170
-160
-150
-140
-130
-120
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8

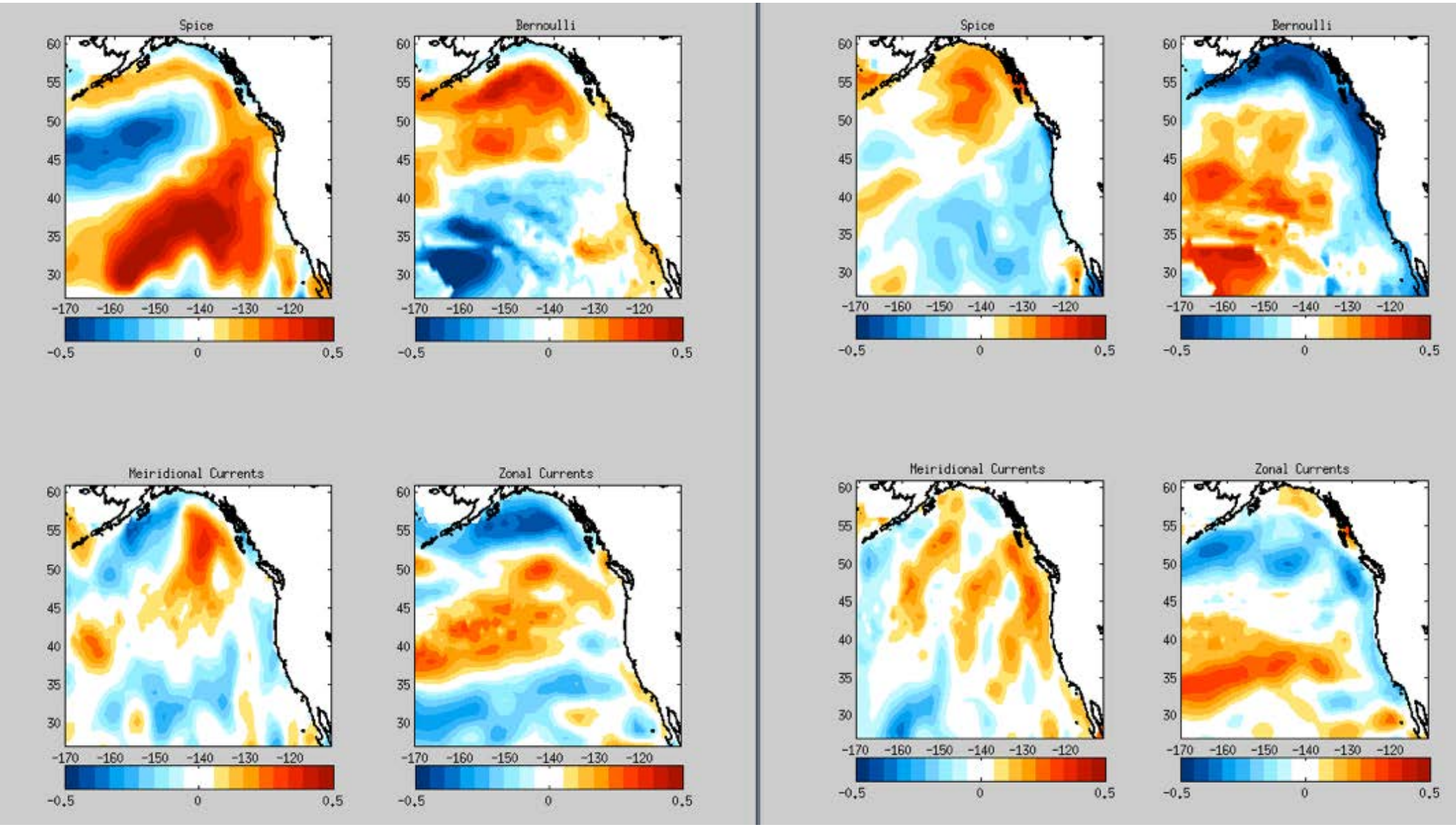

Year lead = -6
60
55
50
45
40
35
30
-170
-160
-150
-140
-130
-120
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8


Year lead = -5
60
55
50
45
40
35
30
-170
-160
-150
-140
-130
-120
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8

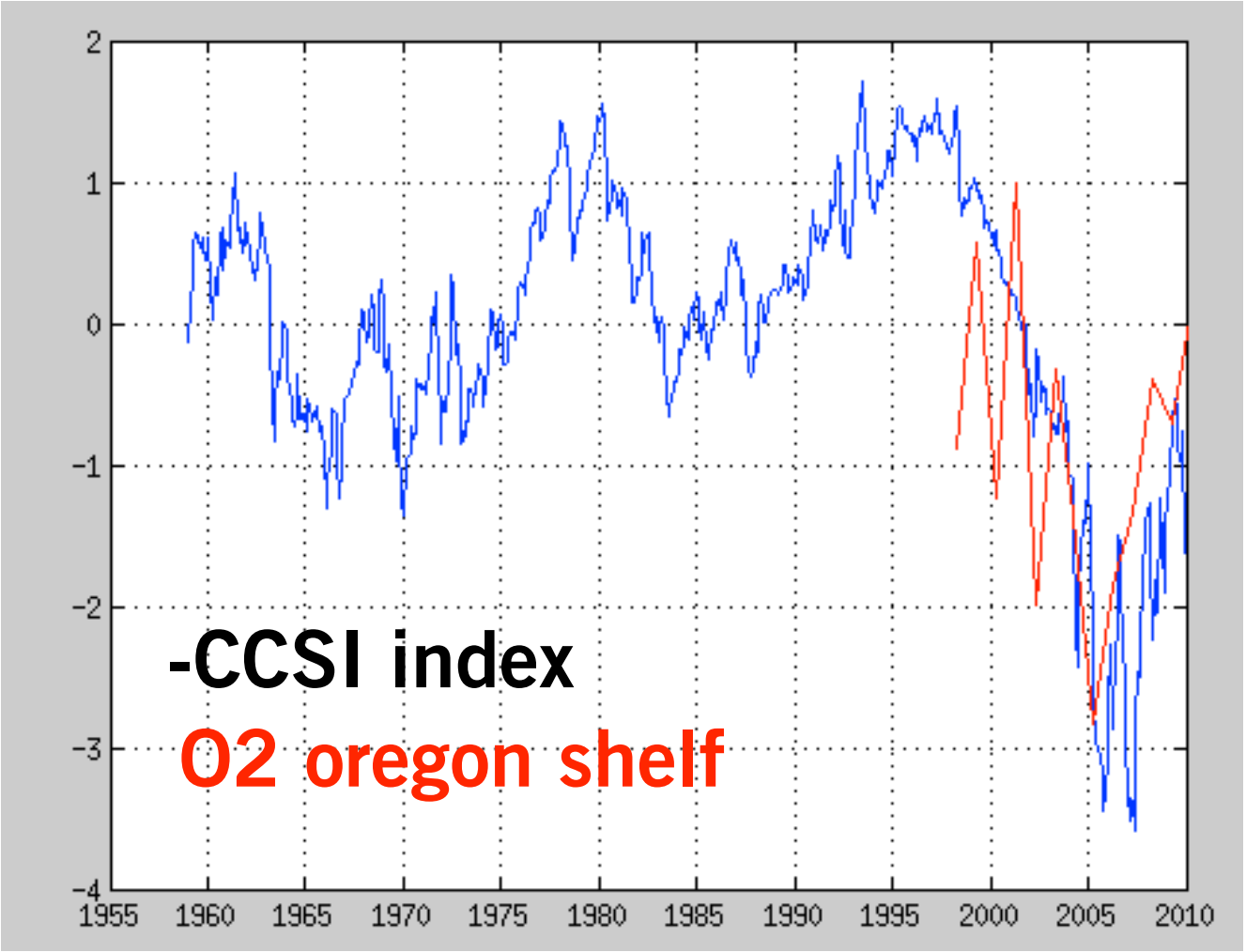

Year lead = -3
60
55
50
45
40
35
30
-170
-160
-150
-140
-130
-120
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8


Year lead = -12
60
55
50
45
40
35
30
-170
-160
-150
-140
-130
-120
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8

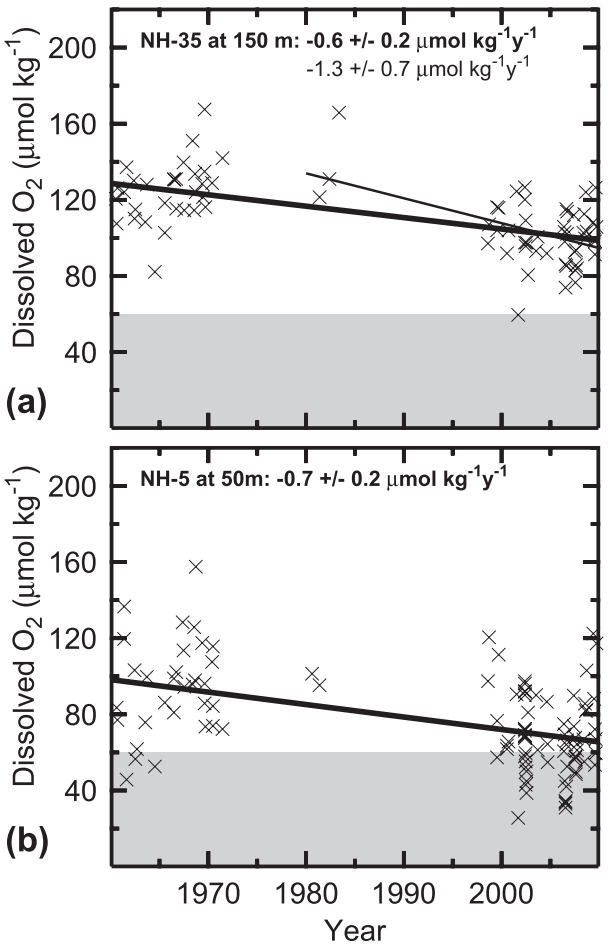
Correlation with NPGO and PDO

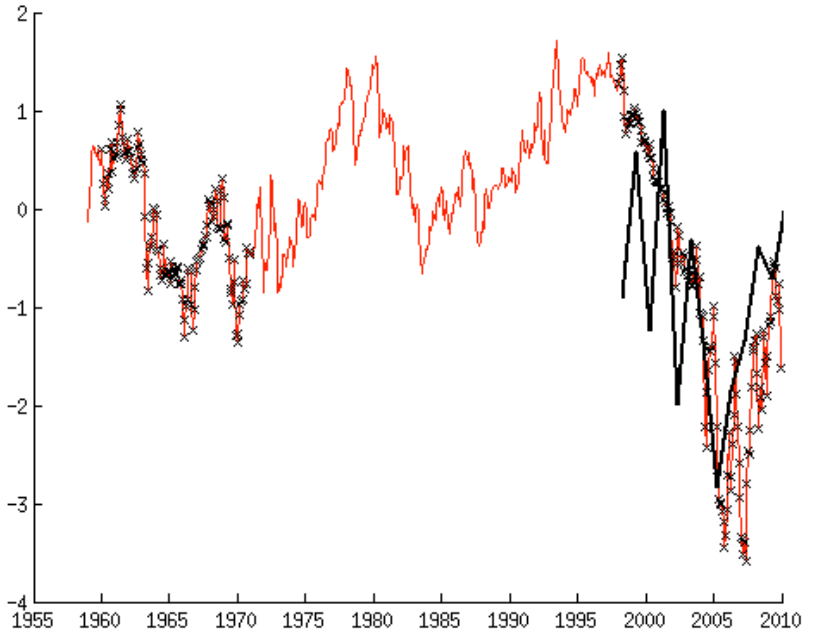


Spice variation along the CCS

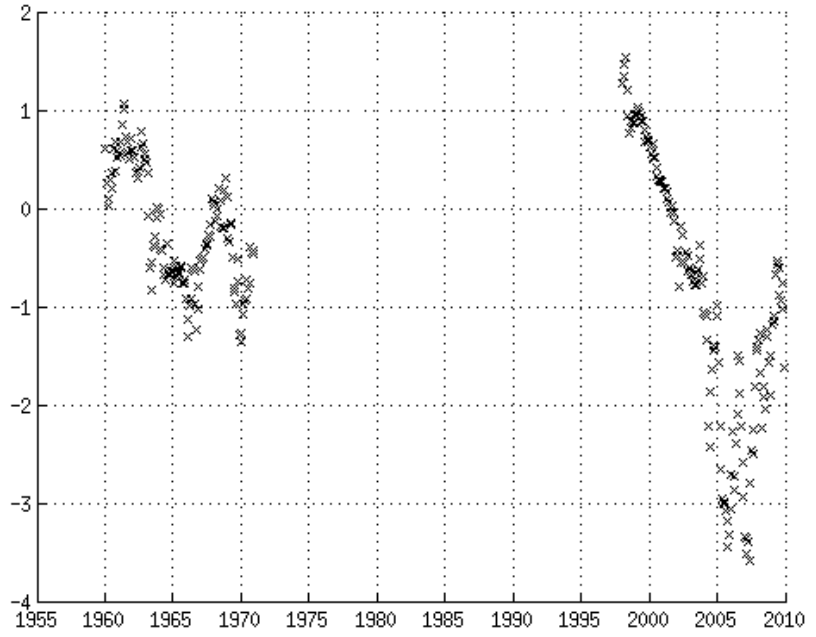


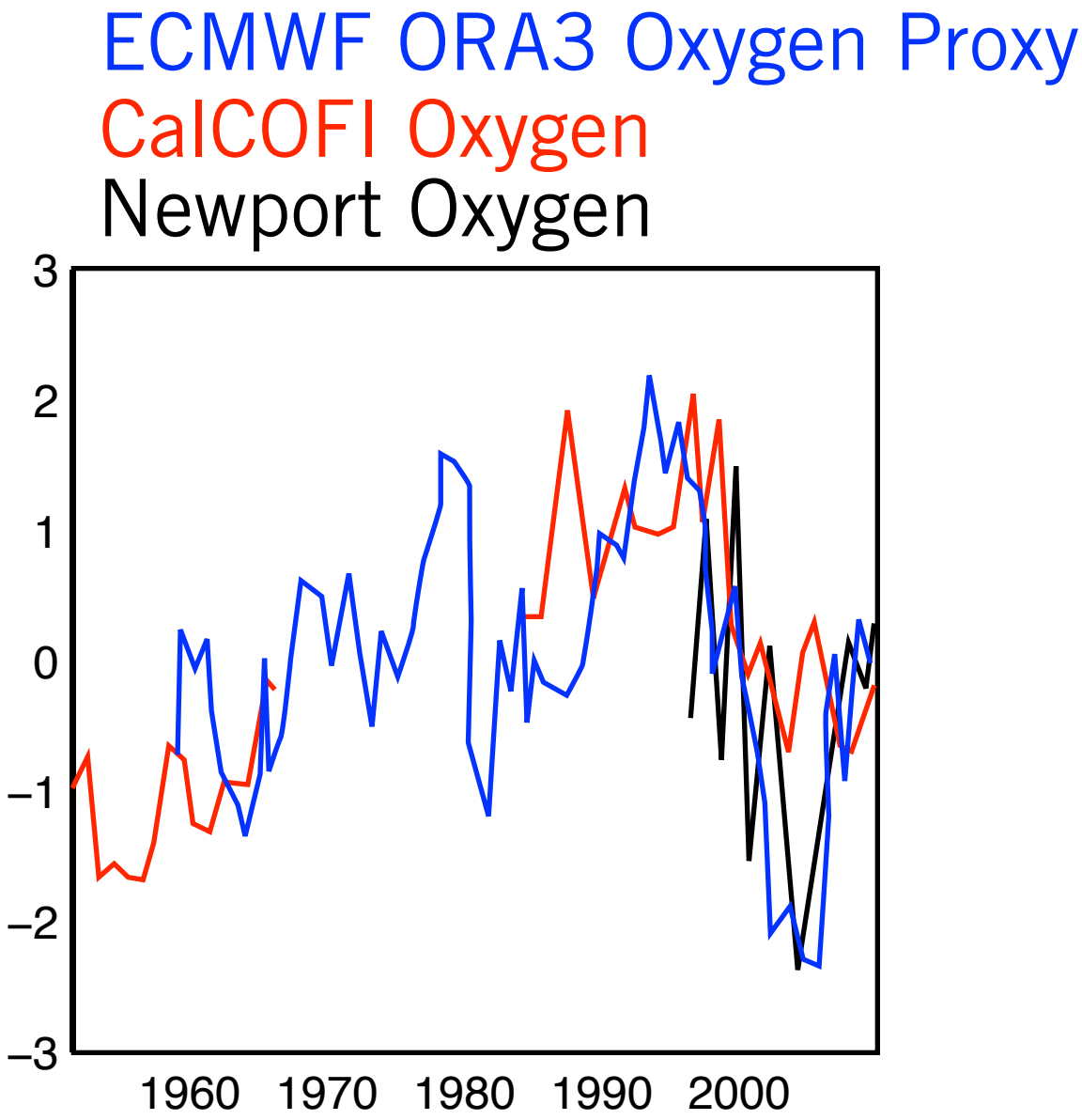
Spice = temperature + salinity

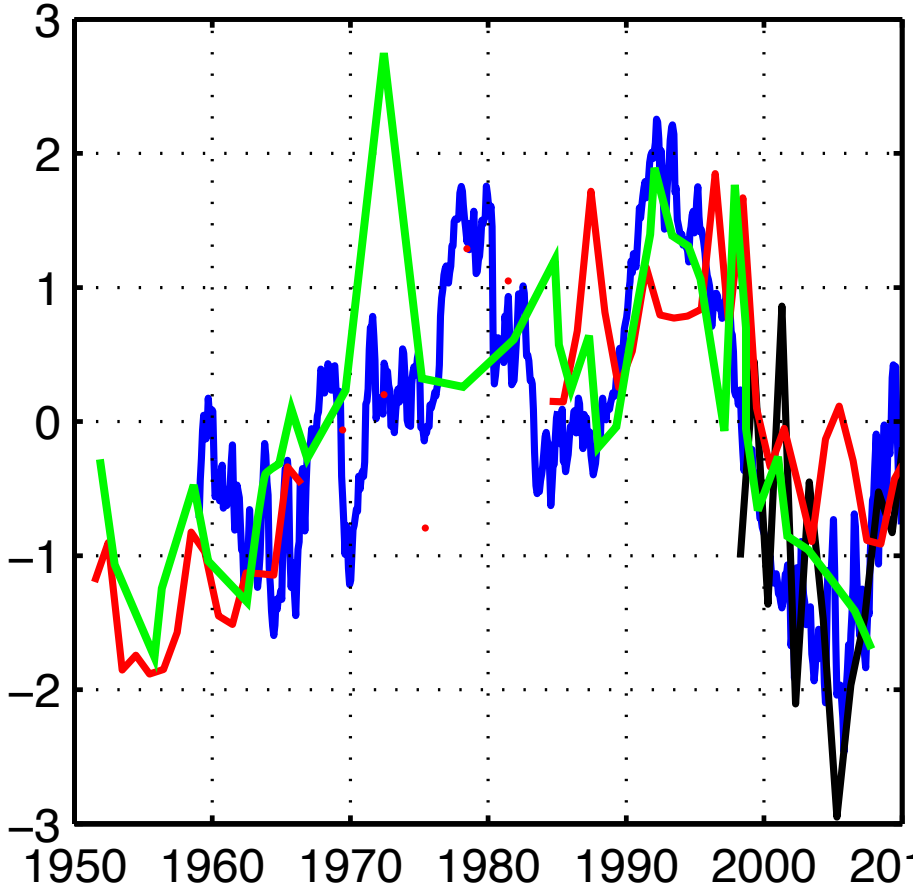

NH-35 at 150 m: -0.6 +/- 0.2 μmol kg-1y-1
-1.3 +/- 0.7 μmol kg-1y-1
Dissolved O2 (μmol kg-1)
200
160
120
80
40
(a)
NH-5 at 50m: -0.7 +/- 0.2 μmol kg-1y-1
Dissolved O2 (μmol kg-1)
200
160
120
80
40
(b)
1970
1980
1990
2000
Year

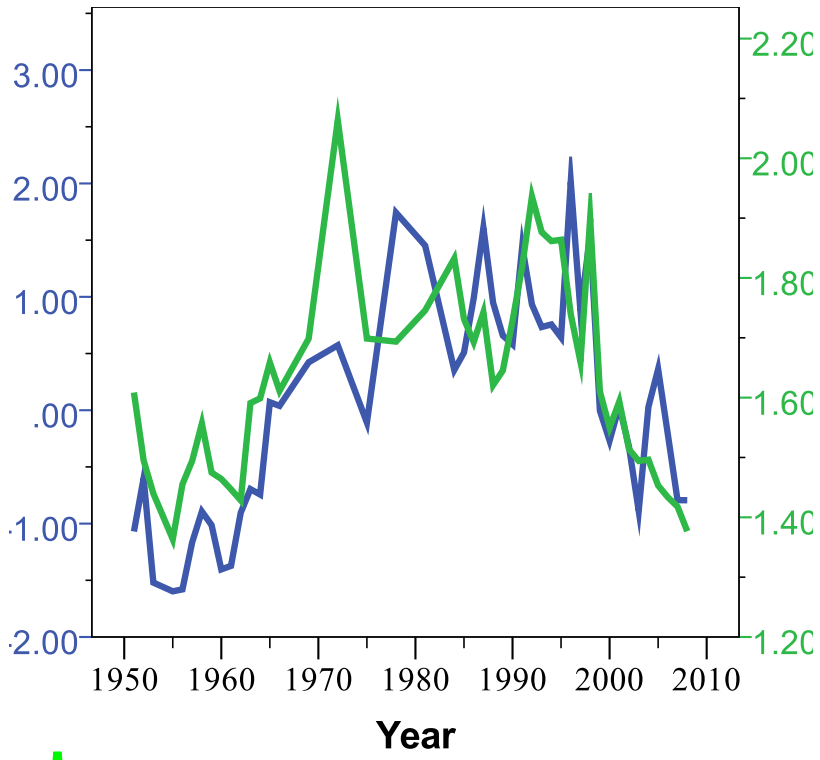

2
1
0
-1
-2
-3
-4
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

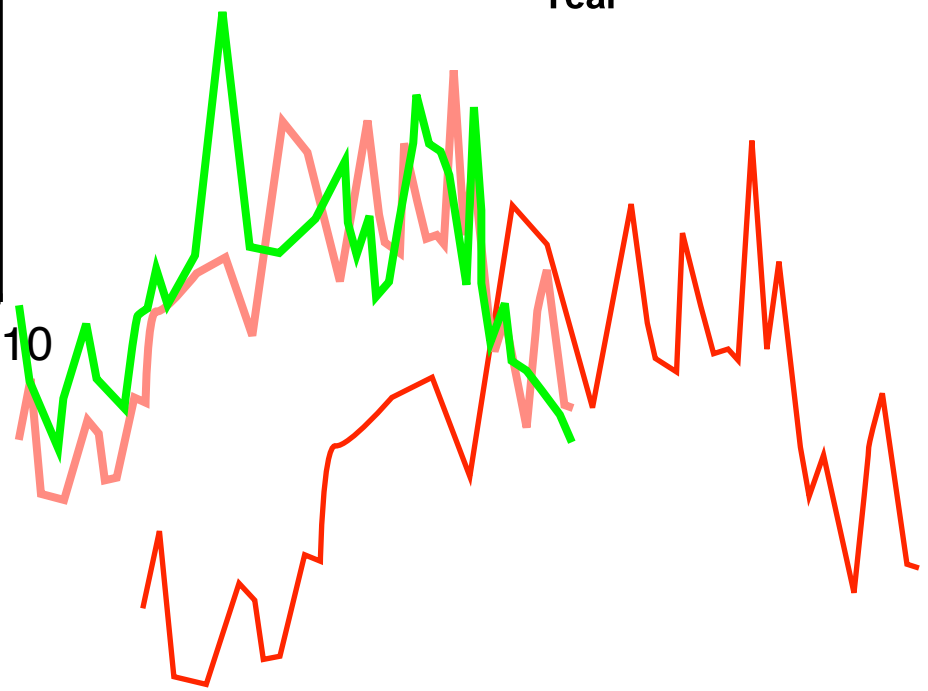
igure 2


2
1
0
-1
-2
-3
-4
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010


ECMWF ORA3 Oxygen Proxy
CalCOFI Oxygen
Newport Oxygen
3
2
1
0
−1
−2
−3
1960
1970
1980
1990
2000


3
2
1
0
−1
−2
−3
1950
1960
1970
1980
1990
2000
2010

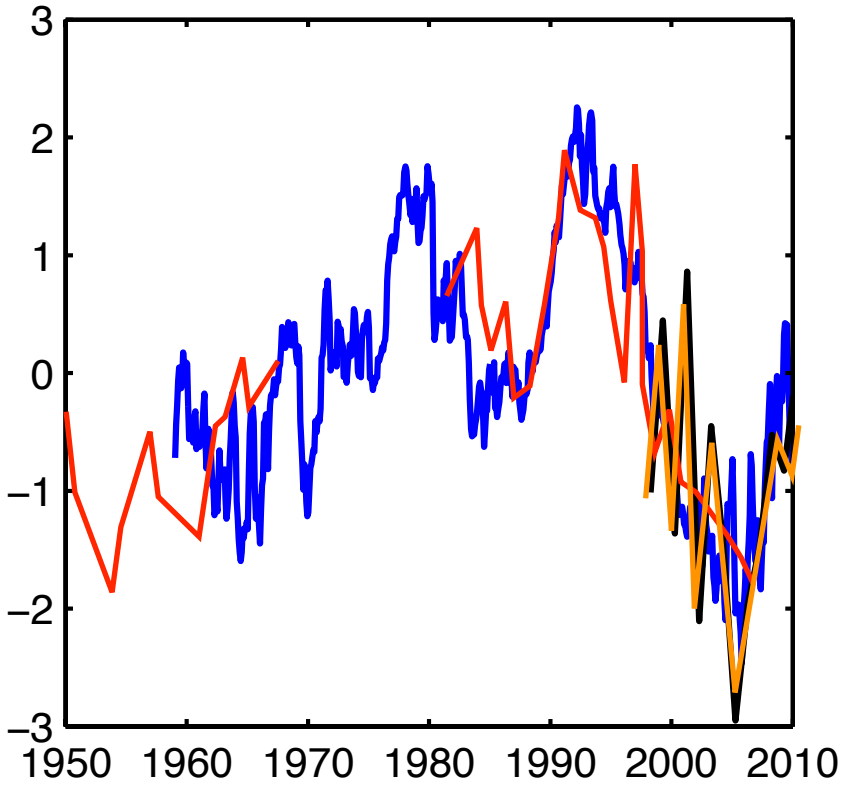

3.00
2.00
1.00
.00
-1.00
-2.00
2.20
2.00
1.80
1.60
1.40
1.20
1950
1960
1970
1980
1990
2000
2010
Year



ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen

Newport Oxygen

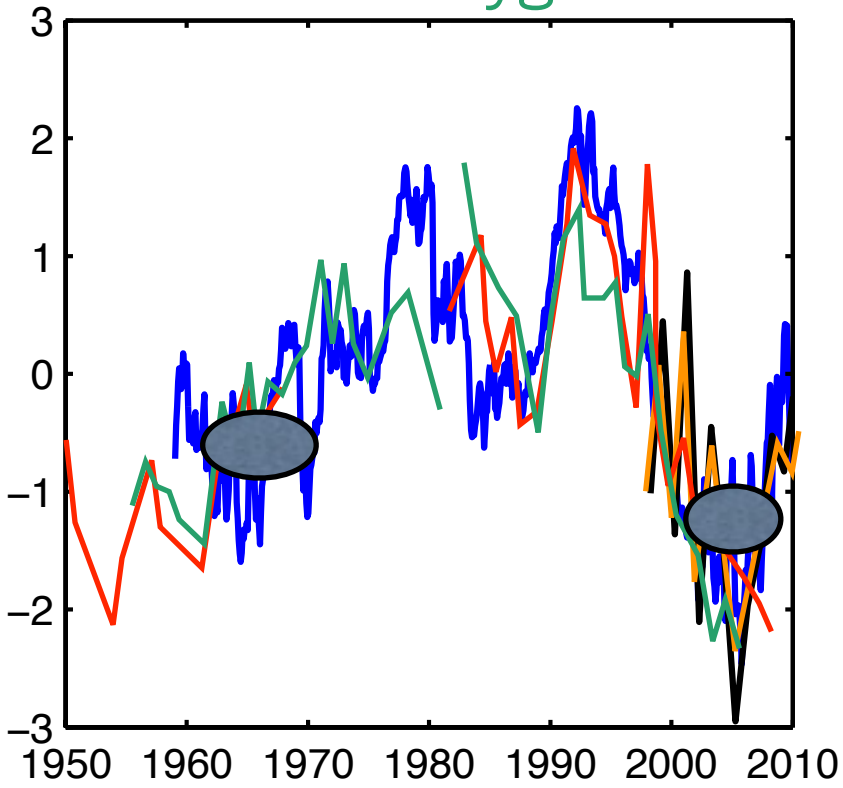


ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



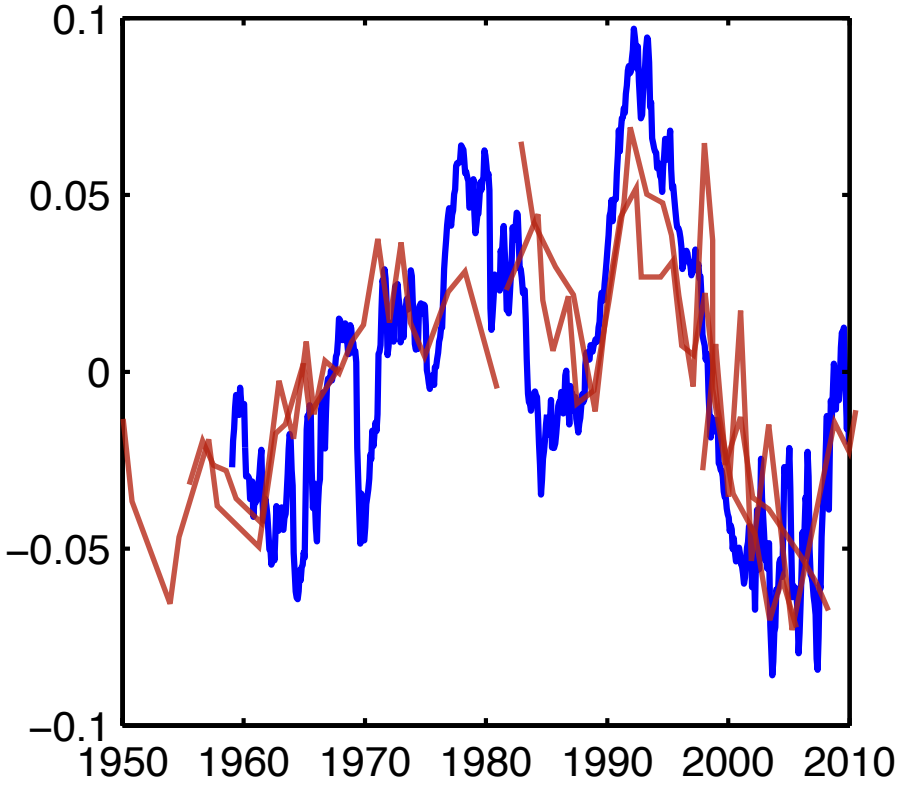
good

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



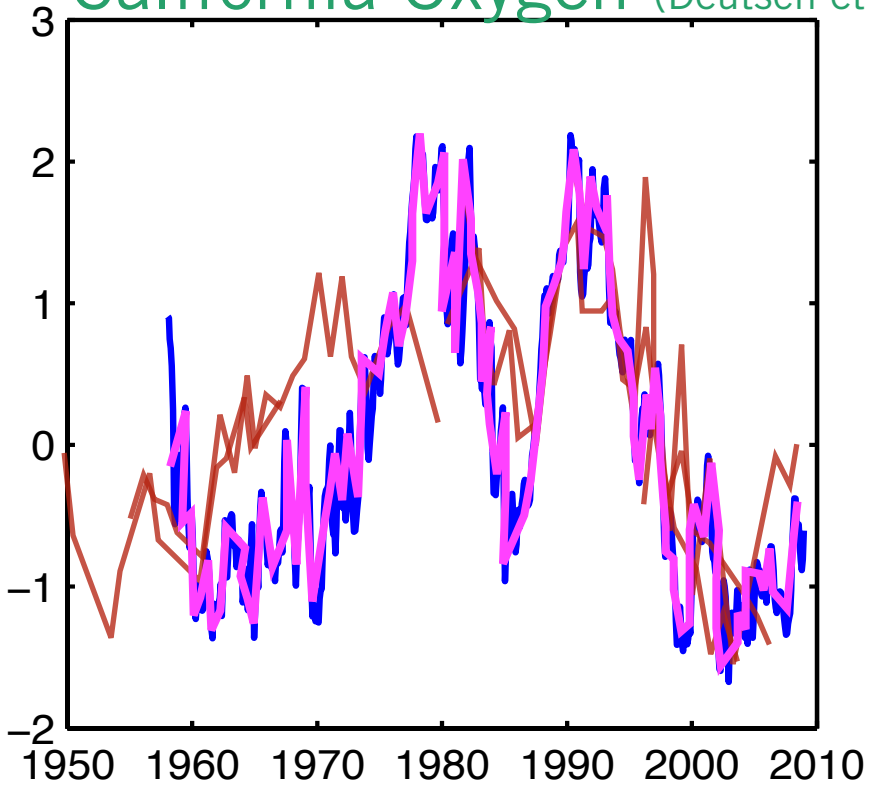
SPICE PC1

SODA offshore Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



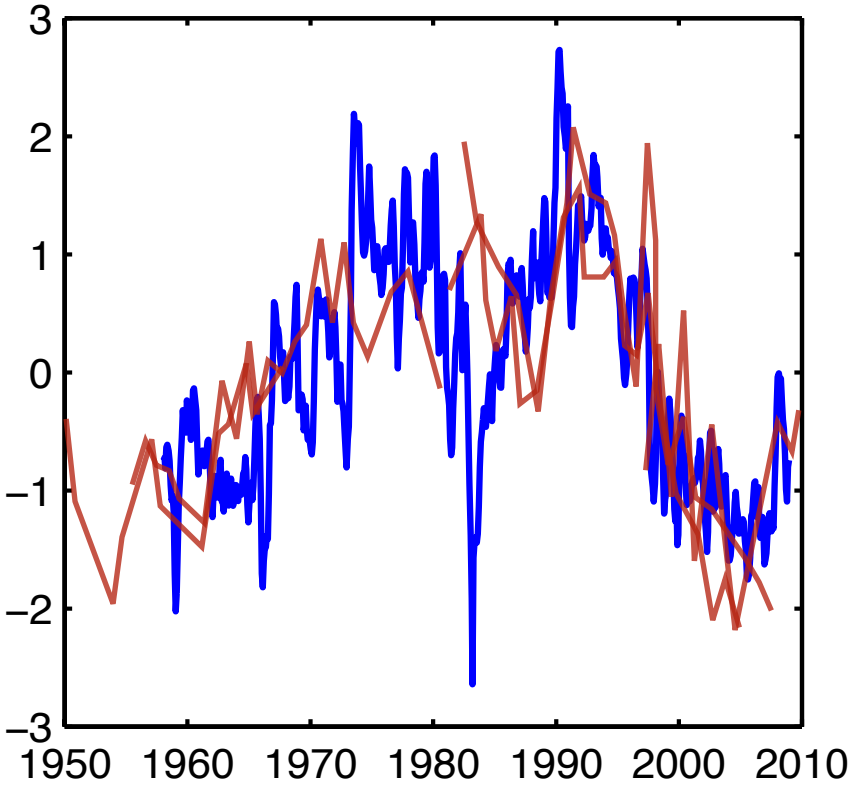
SPICE PC1

SODA inshore Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



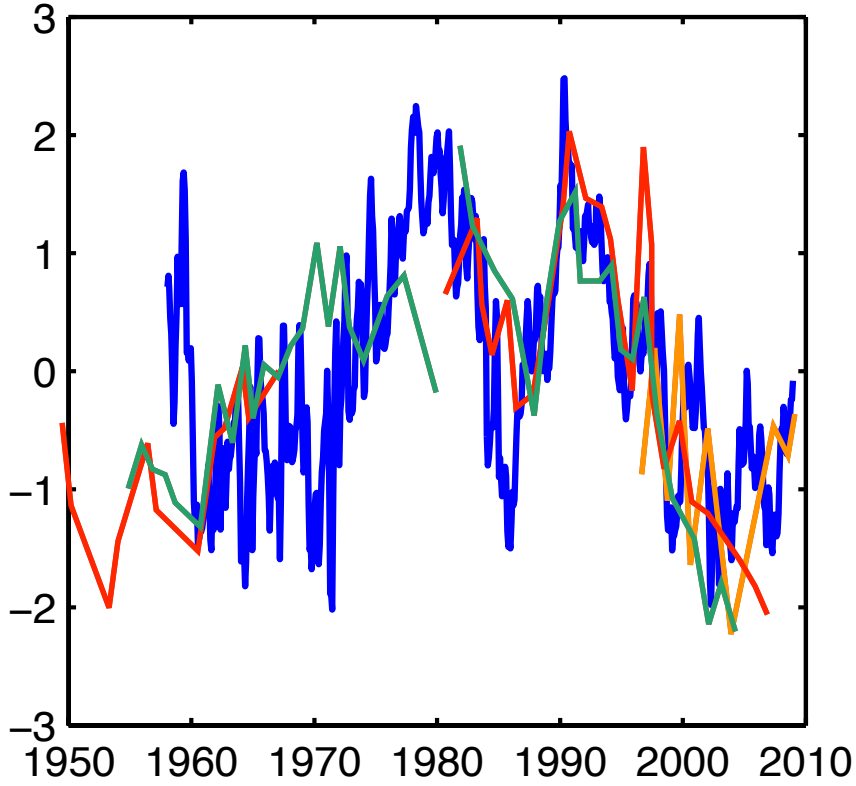
SPICE PC1

SODA inshore Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



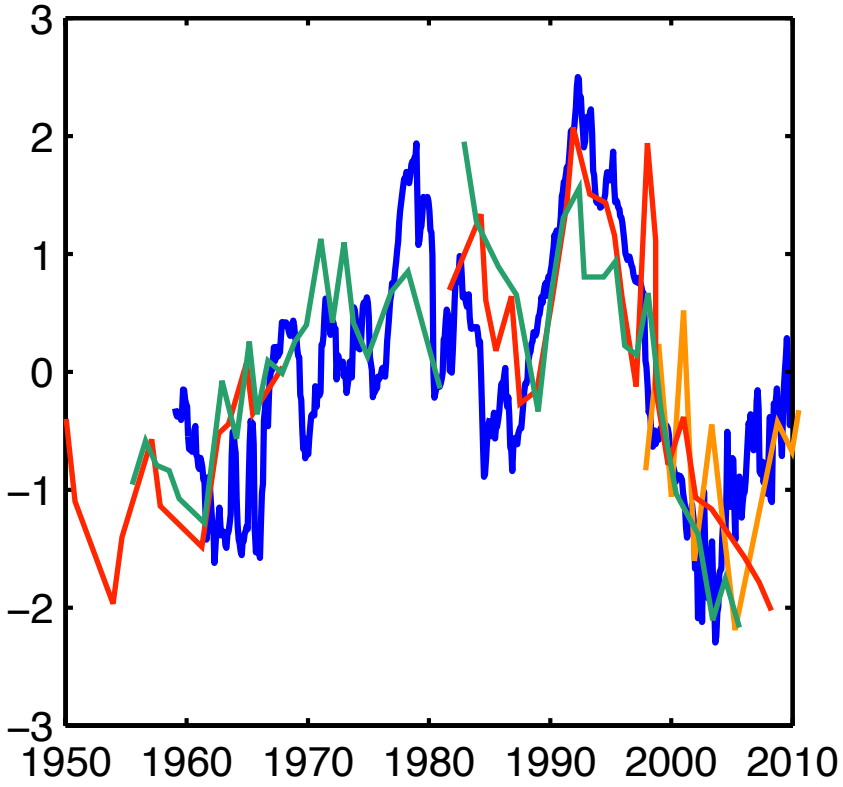
SPICE PC1

ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)

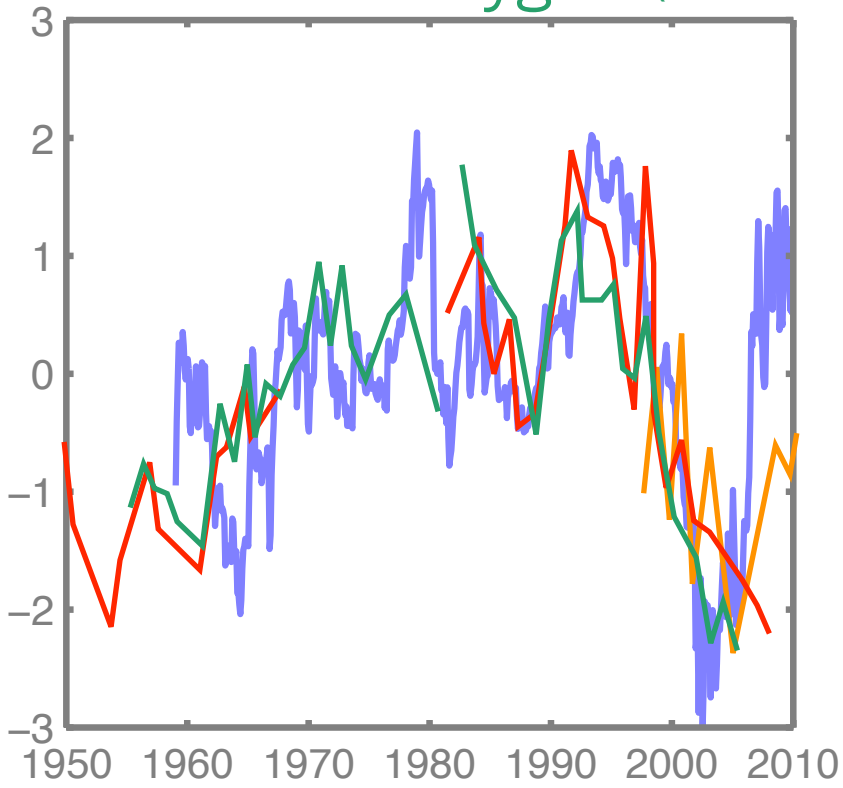


ECMWF ORA3 Oxygen Proxy

CalCOFI Oxygen (Koslow et al., 2011)

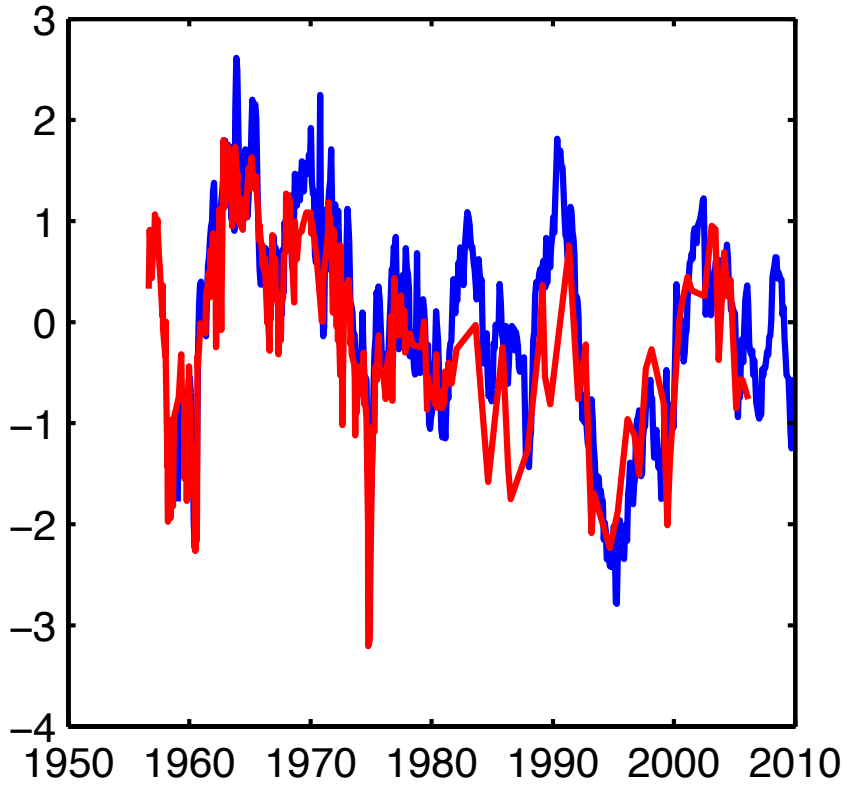
Newport Oxygen (Peterson et al., 2013)

California Oxygen (Deutsch et al., 2011)



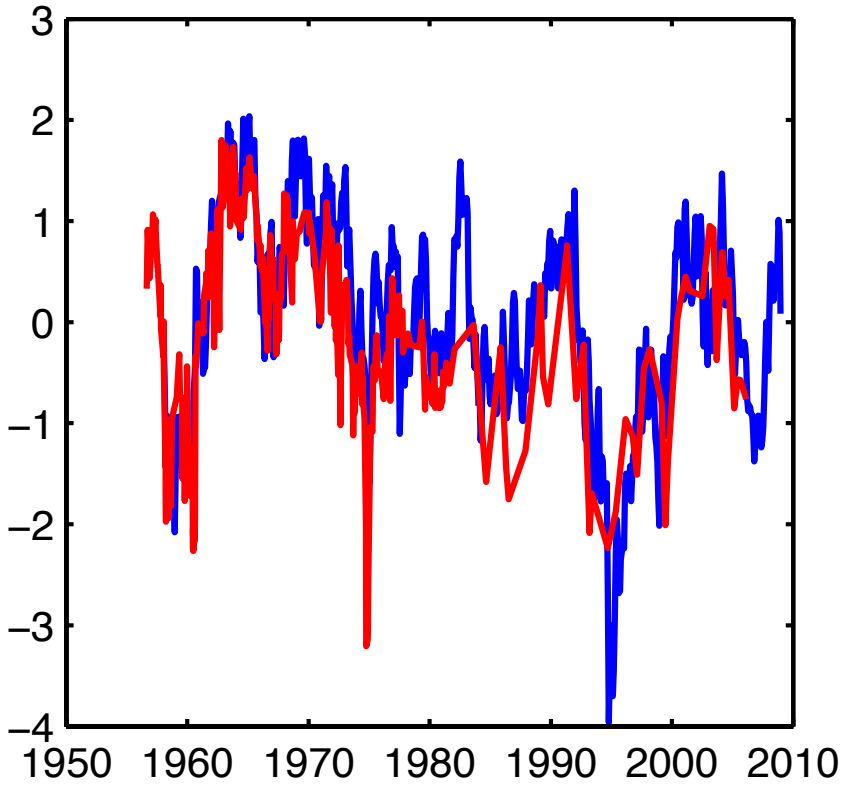
ECMWF ORA3 Oxygen Proxy (Station P)

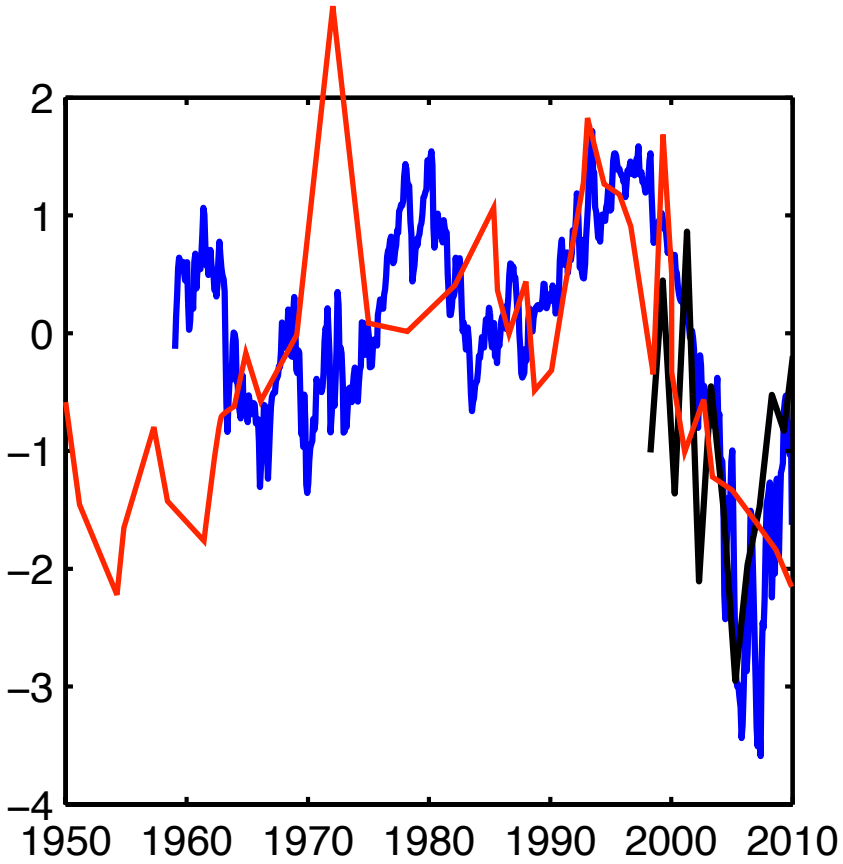
Station P Oxygen (Whitney et al., 2011)



SODA Oxygen Proxy (Station P)

Station P Oxygen (Whitney et al., 2011)




2
1
0
−1
−2
−3
−4
1950
1960
1970
1980
1990
2000
2010

Correlation with **CCSI index**