# Advection of deep-sea and coastal water into the HNLC region of the northeast Pacific Ocean

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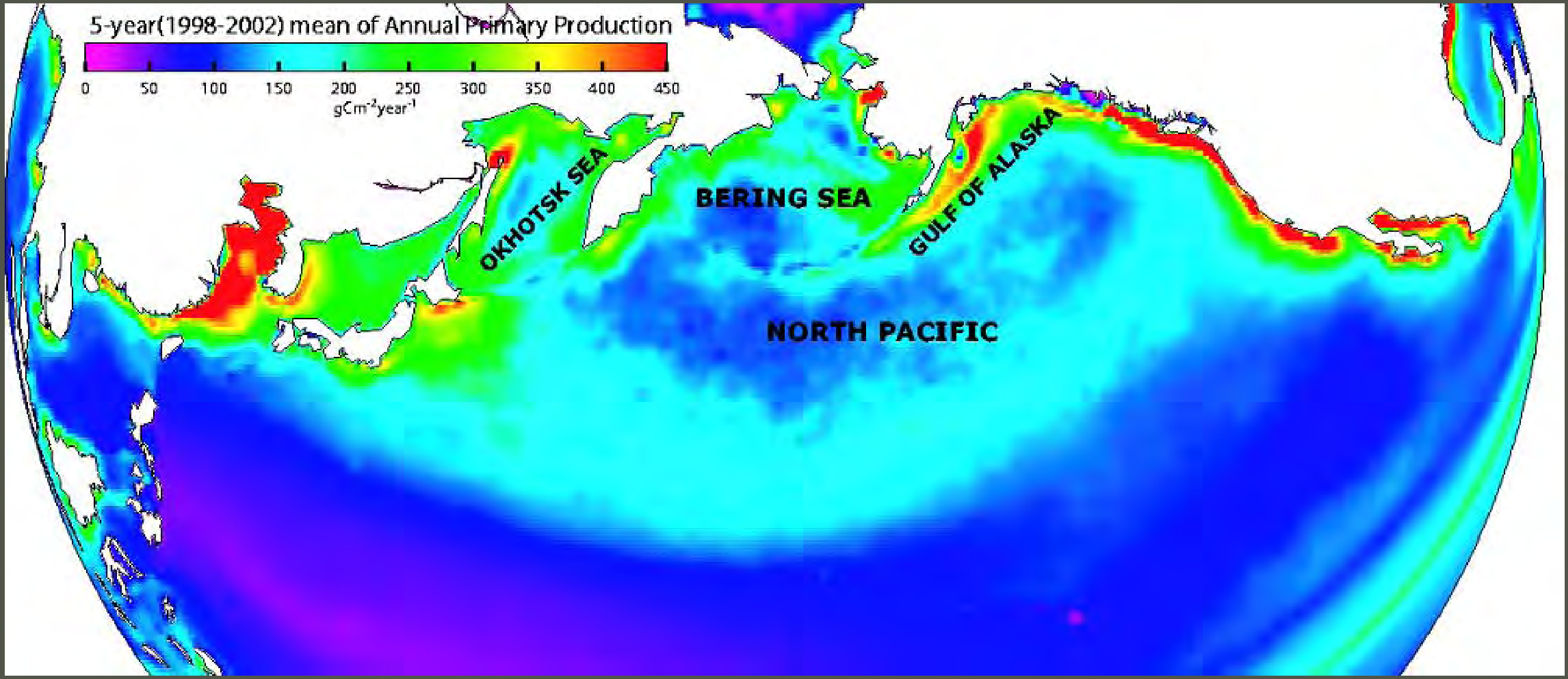
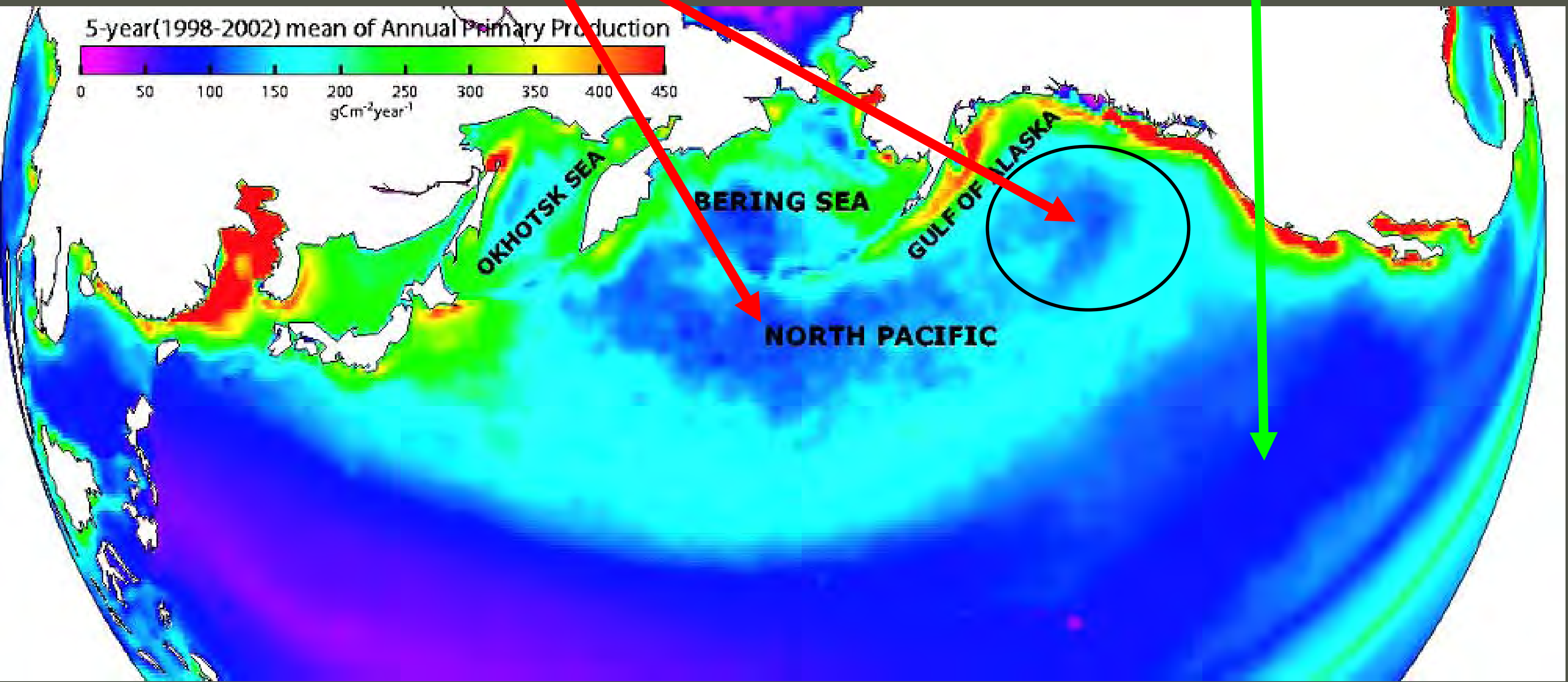
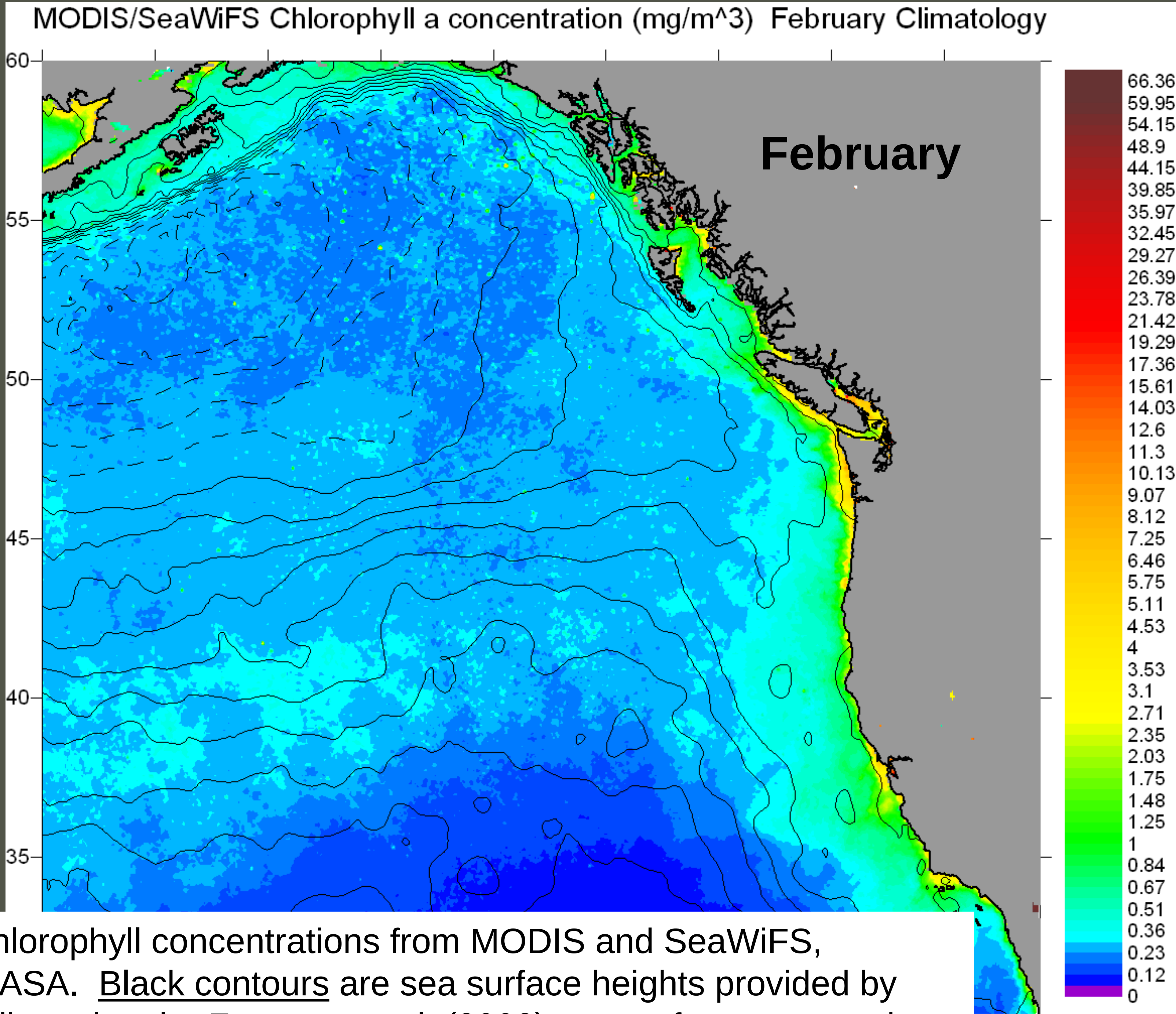
Fisheries and Oceans Canada | Pêches et Océans Canada
Canadian Space Agency | Agence spatiale canadienne



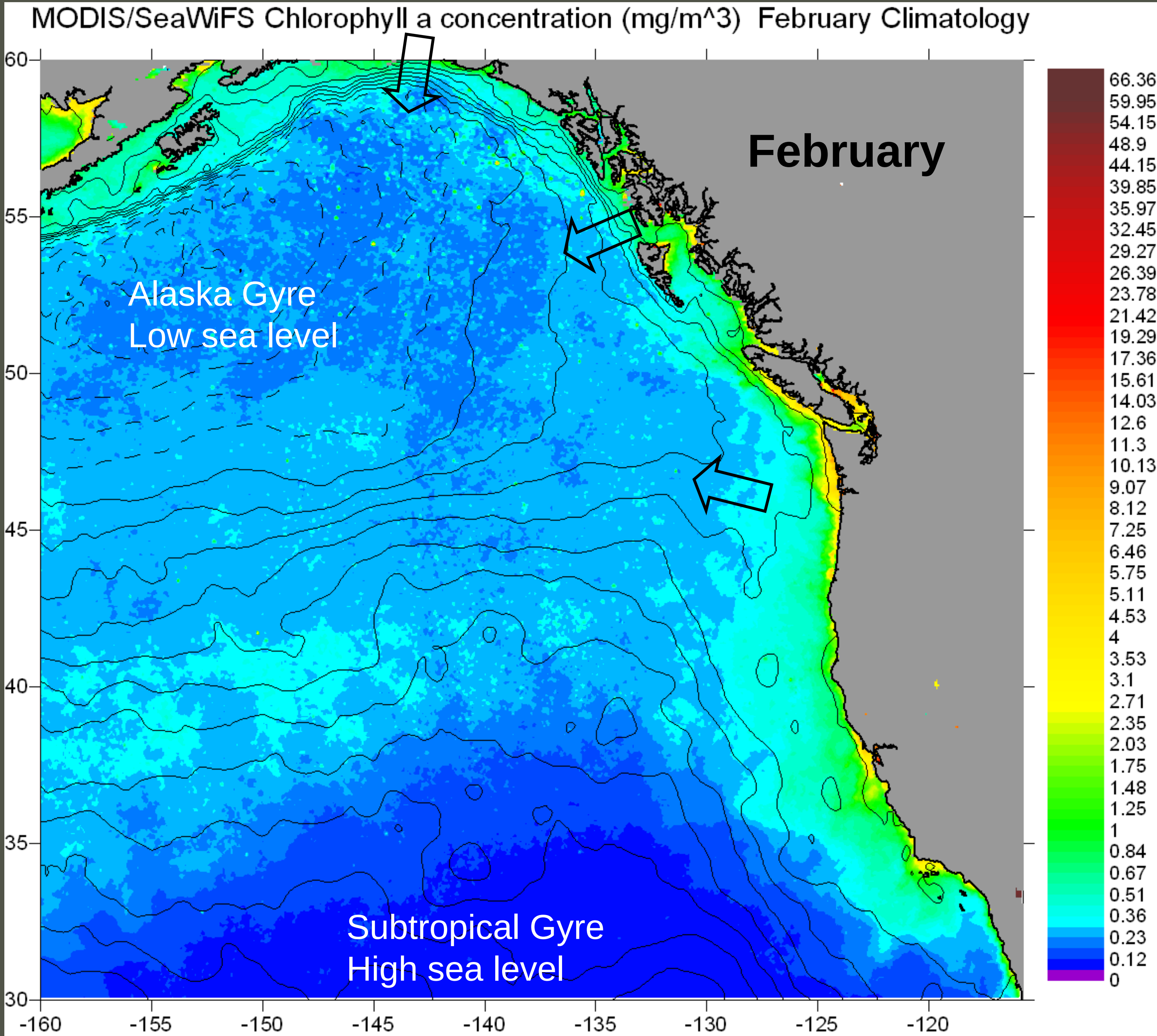
Low-Nutrient, Low-Chlorophyll due mainly to nitrate limitation

High-Nutrient, Low-Chlorophyll due mainly to iron limitation

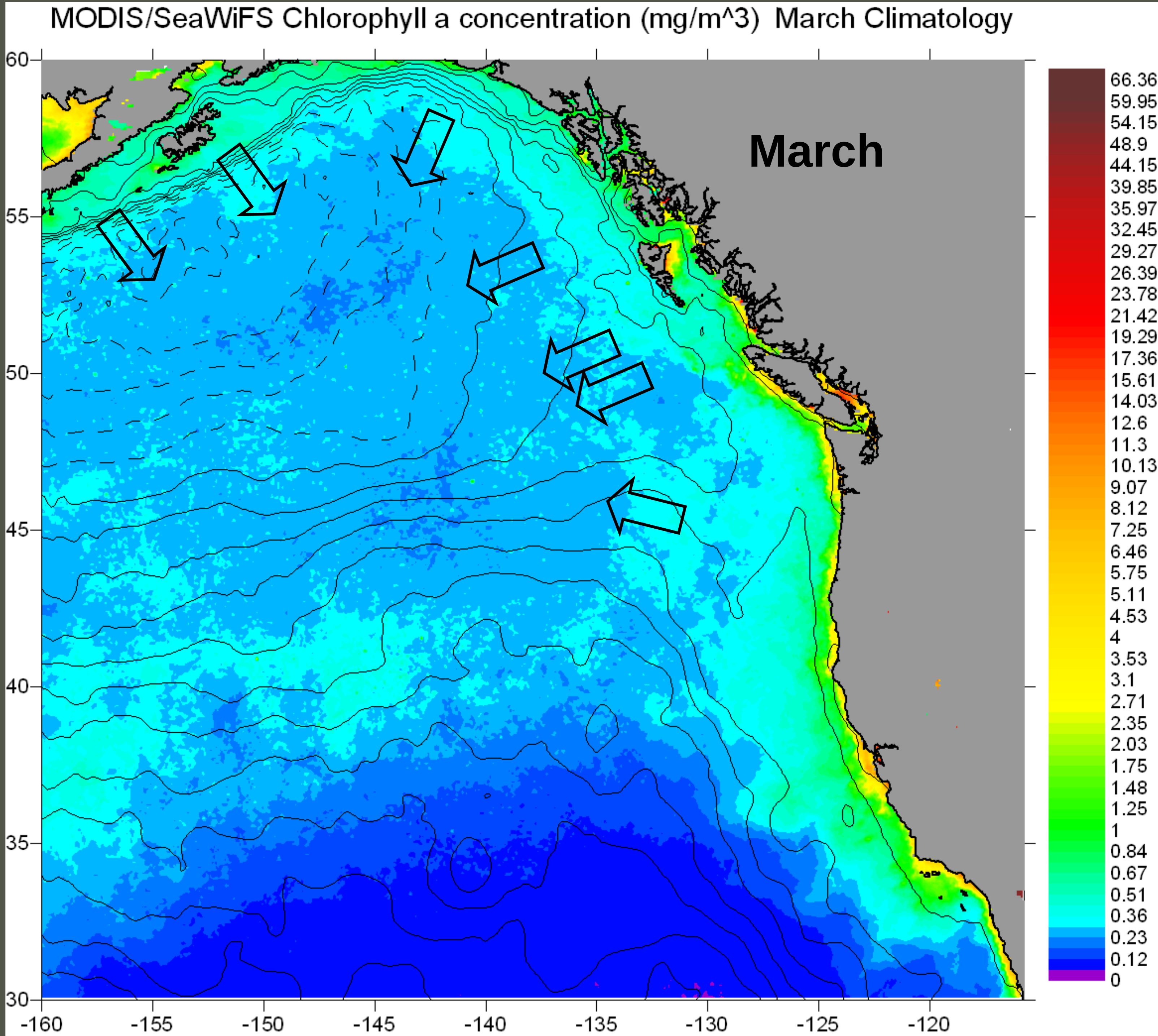


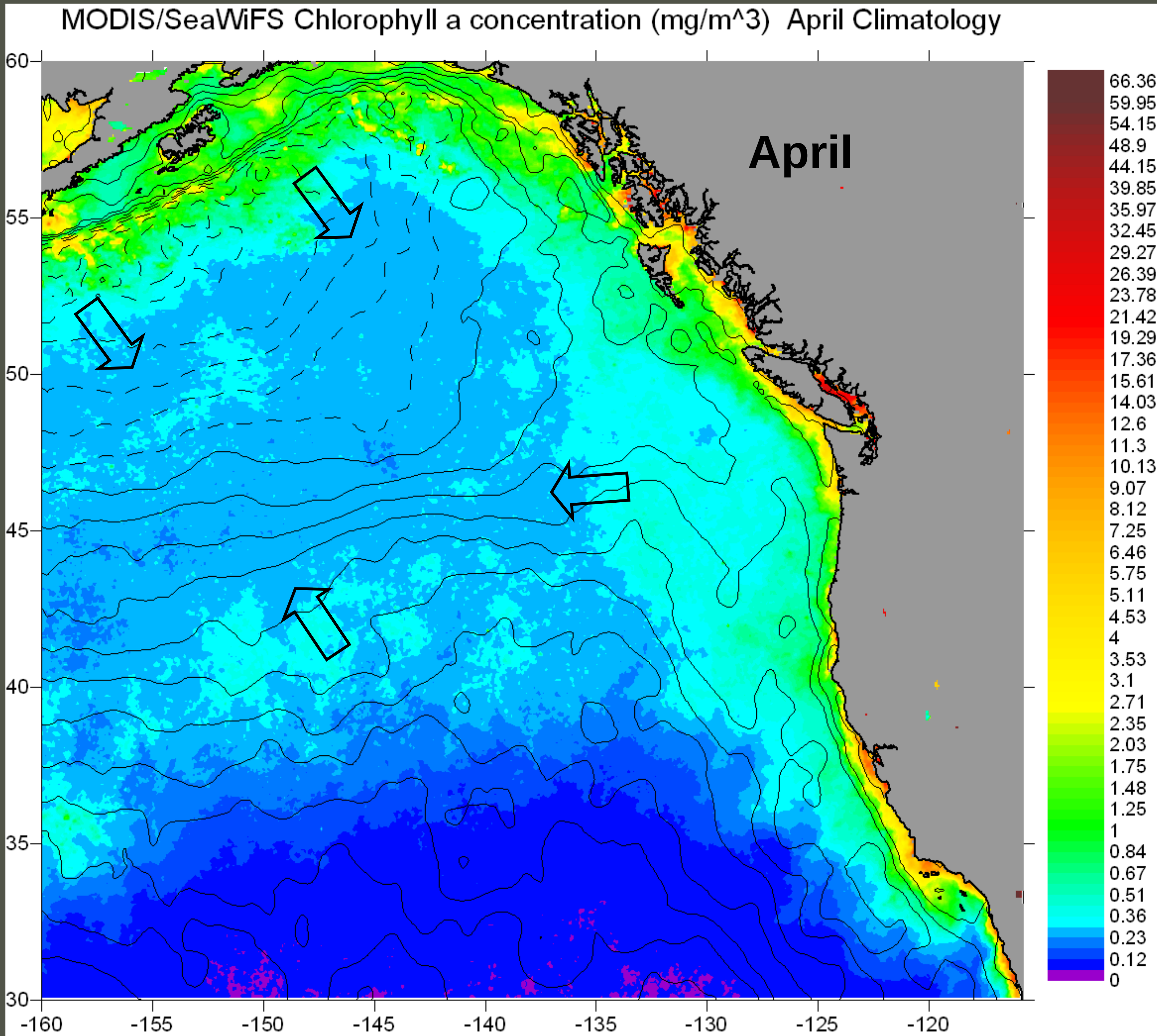


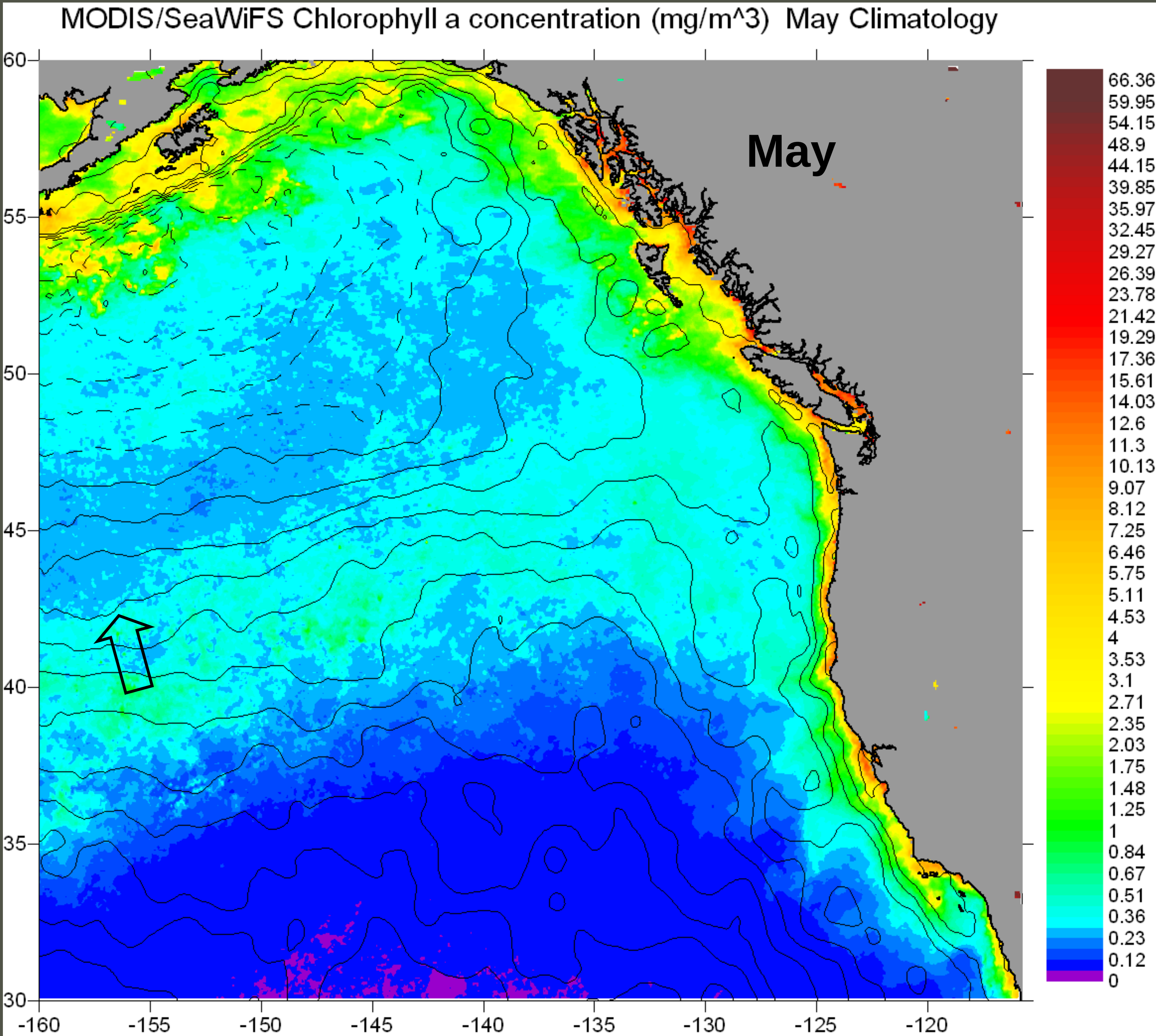

Colours are chlorophyll concentrations from MODIS and SeaWiFS, provided by NASA. Black contours are sea surface heights provided by AVISO and adjusted to the Foreman et al. (2008) sea surface topography.



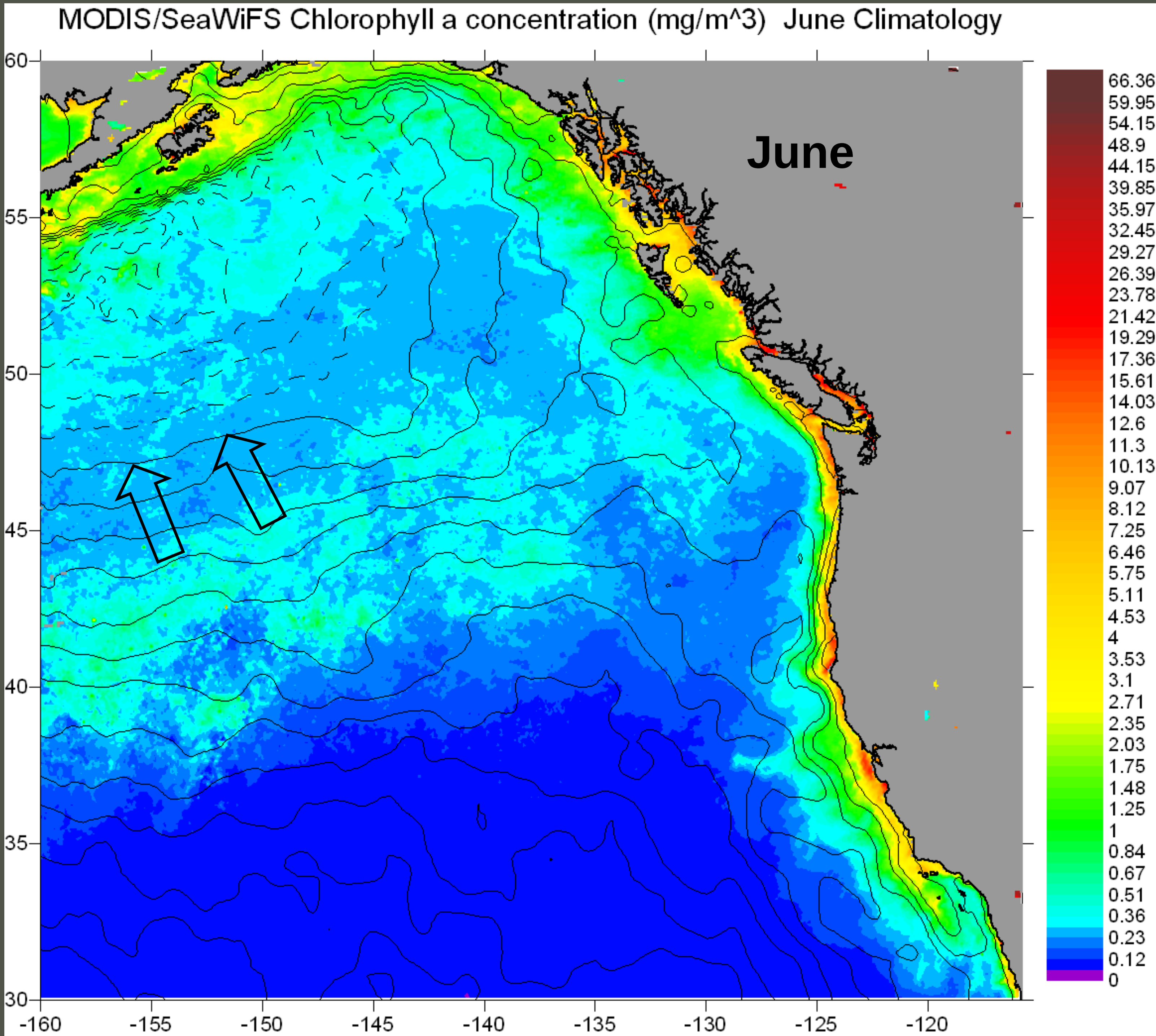
MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) February Climatology
February
Alaska Gyre
Low sea level
Subtropical Gyre
High sea level
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0

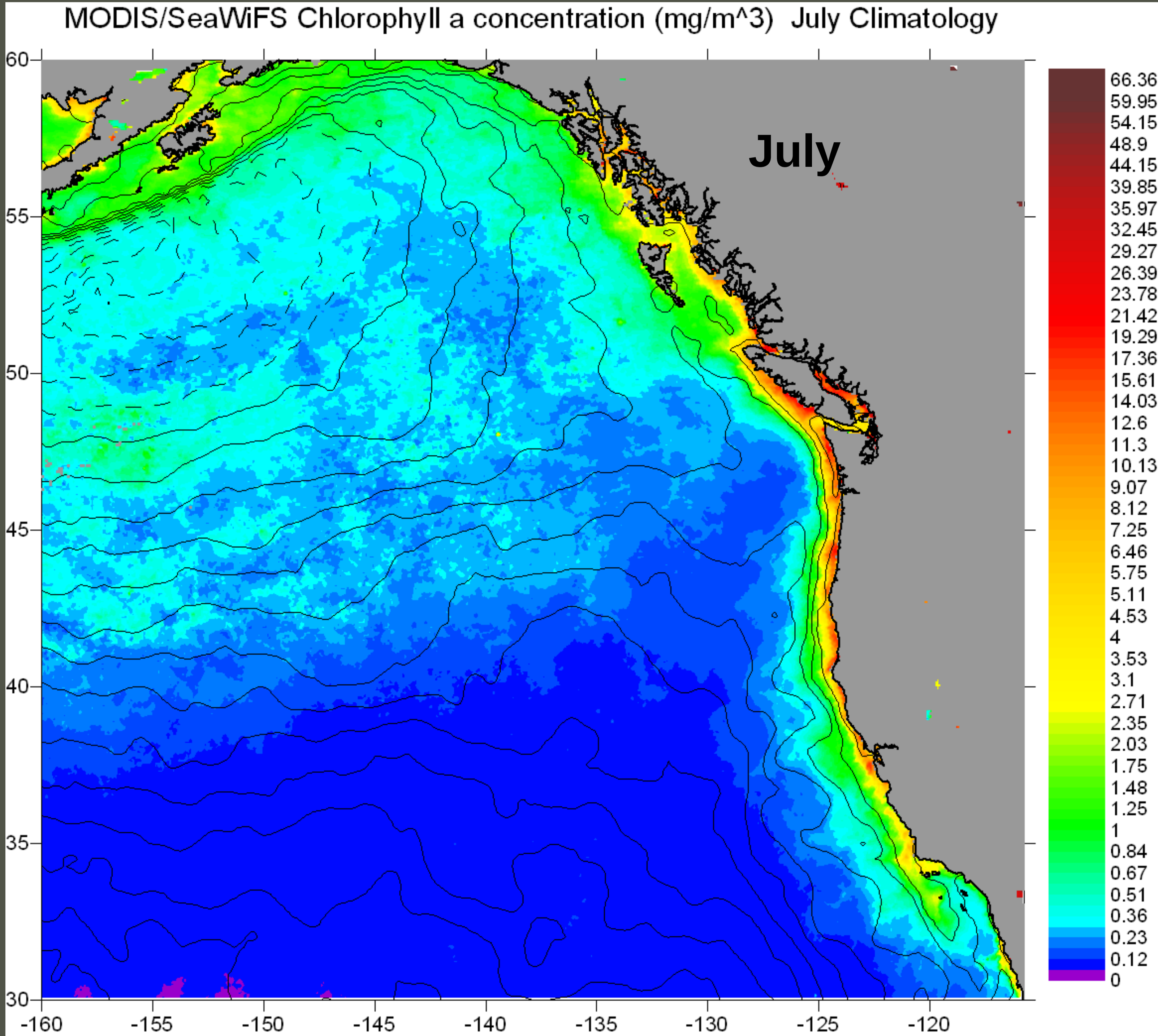

MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) March Climatology
March
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0


MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) April Climatology
April
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0



MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) May Climatology
May
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0


MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) June Climatology
June
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0


MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) July Climatology
July
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0

**Parsons, T. R.,** LeBrasseur, R.J. (1968).

"A discussion of some critical indices of primary and secondary production for large-scale ocean surveys."

*California Marine Research Communications,*

*CalCOFI* Report 12: 54-63.



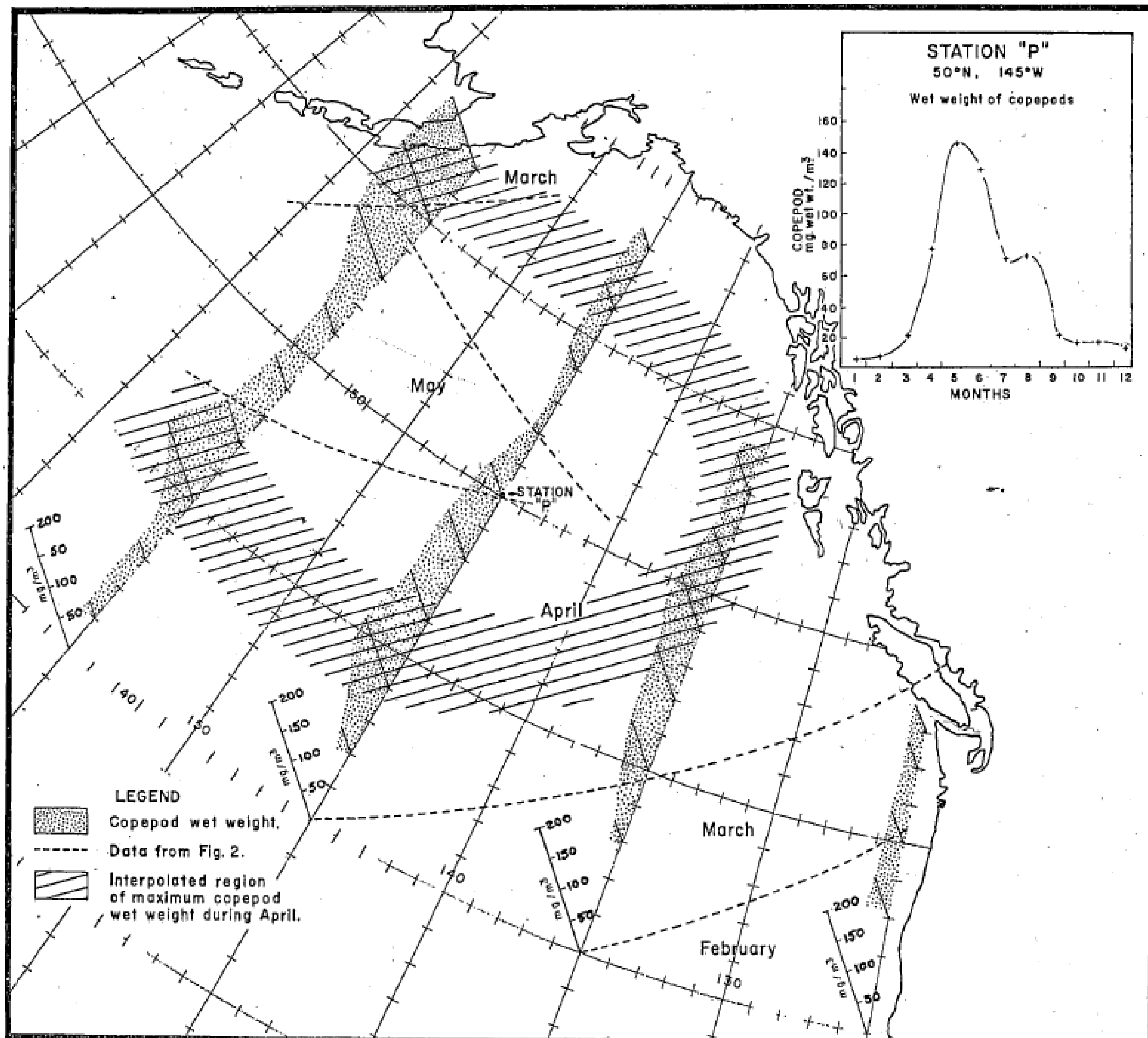
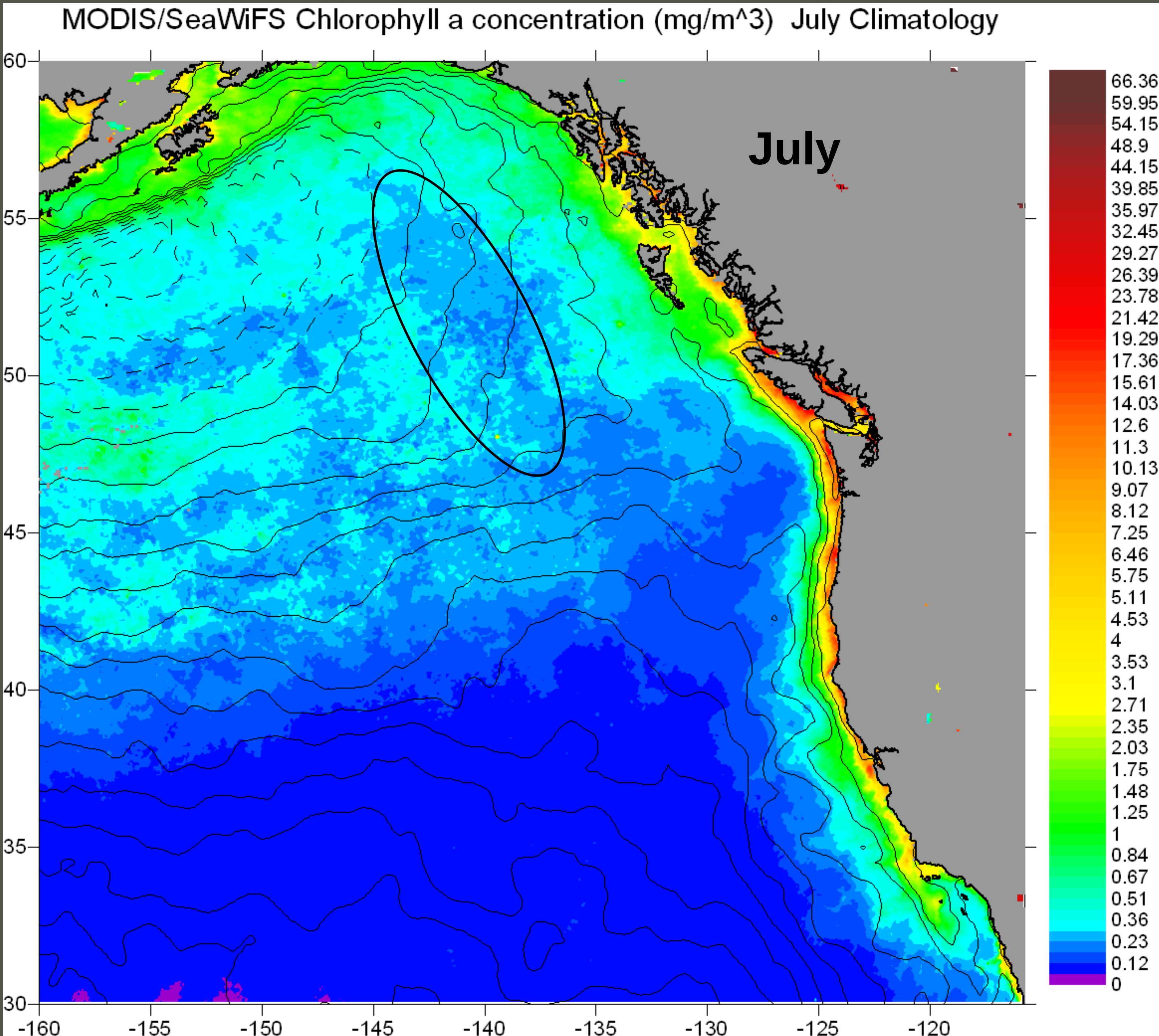
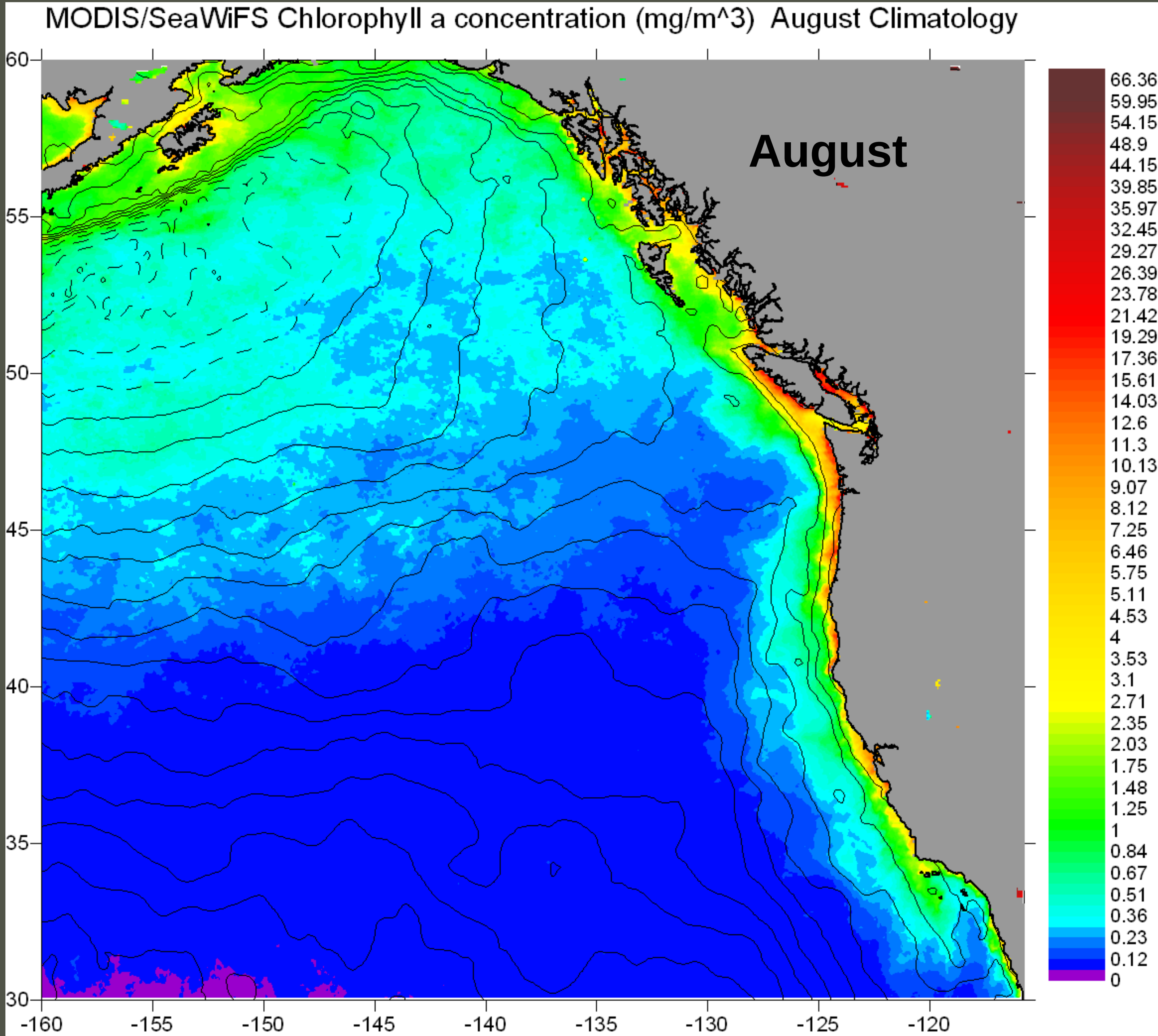
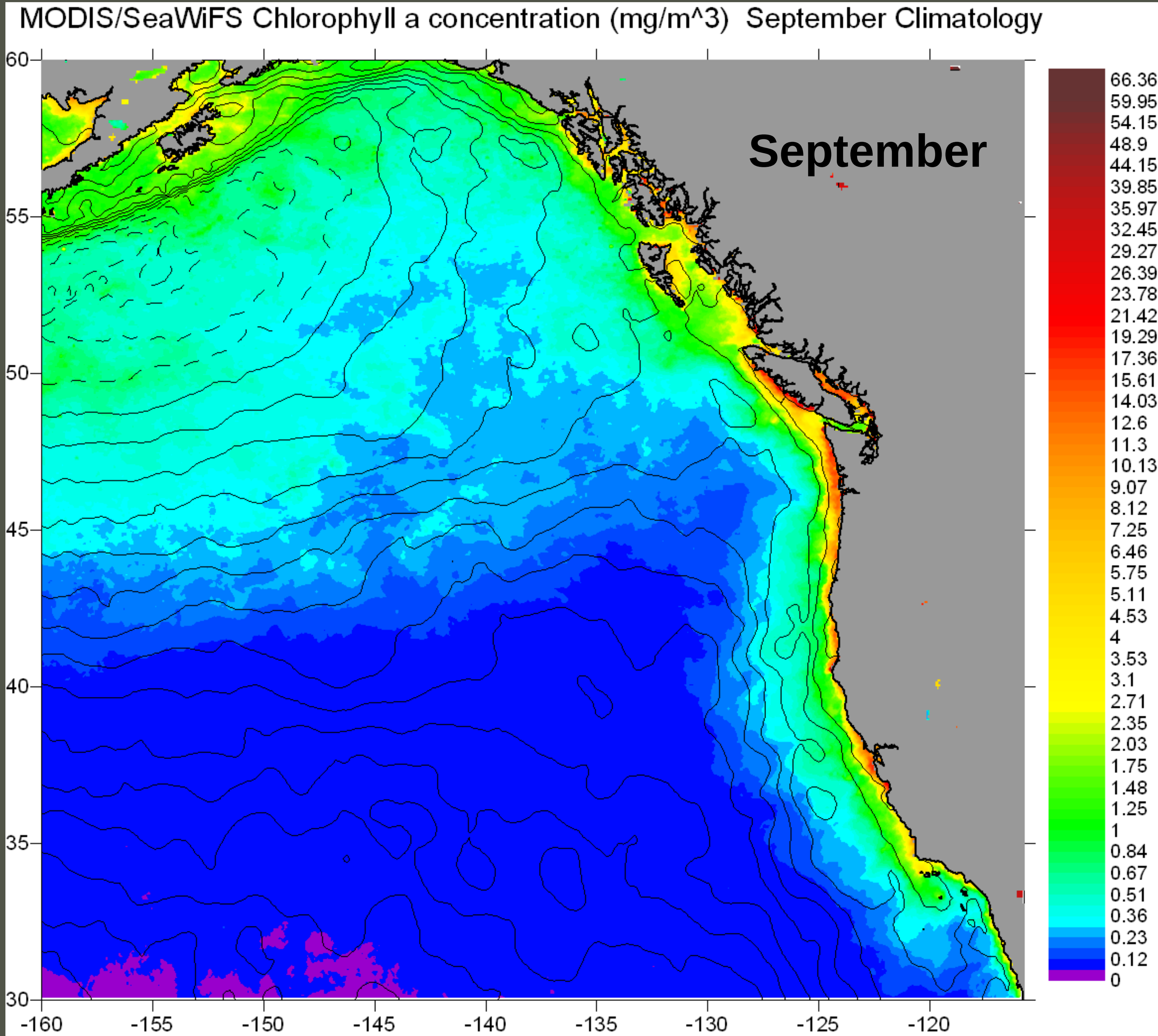


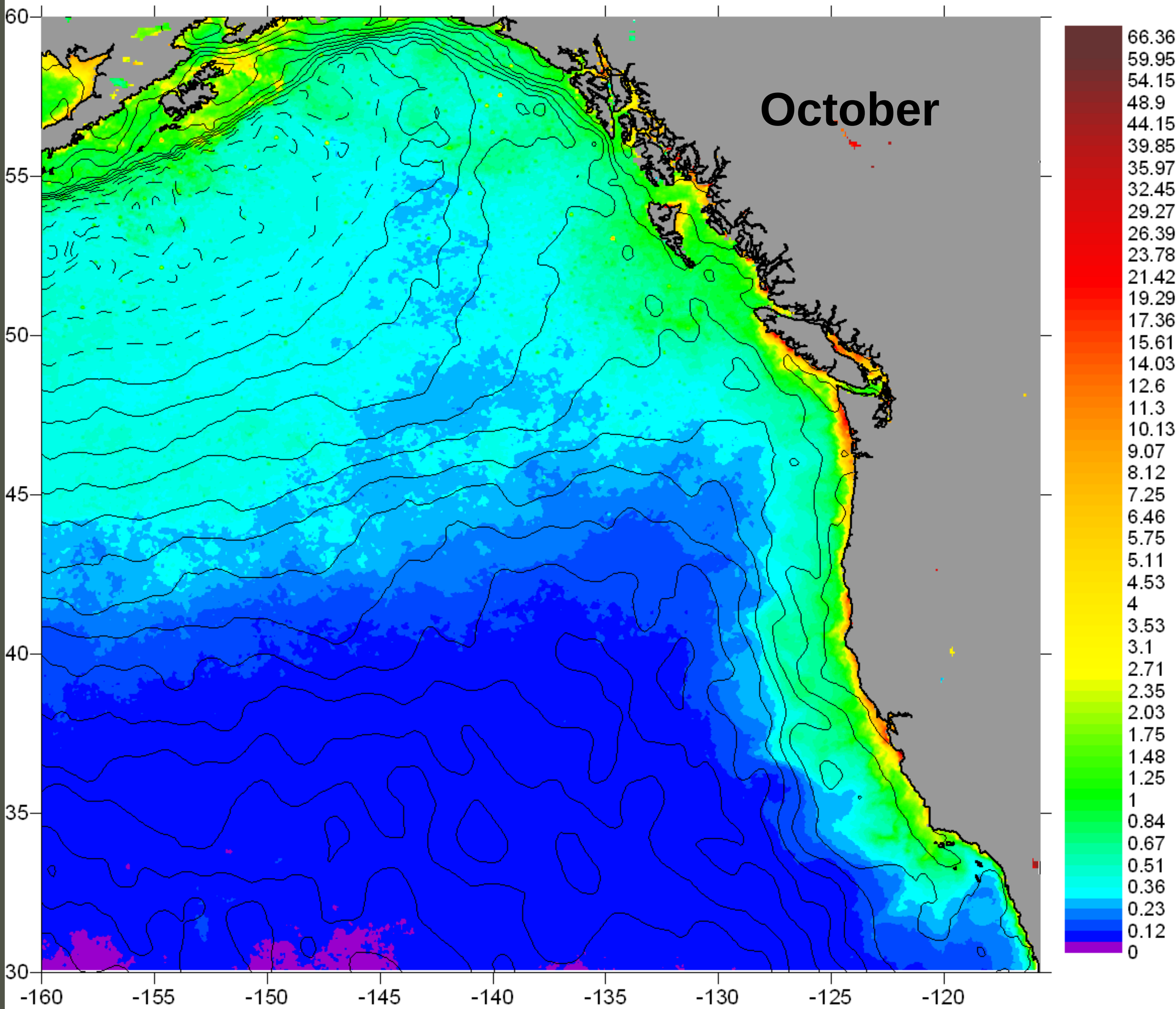

Figure 5. A comparison of copepod wet weights during April and the occurrence of the spring phytoplankton bloom in the eastern Subarctic Pacific Ocean, February to May.

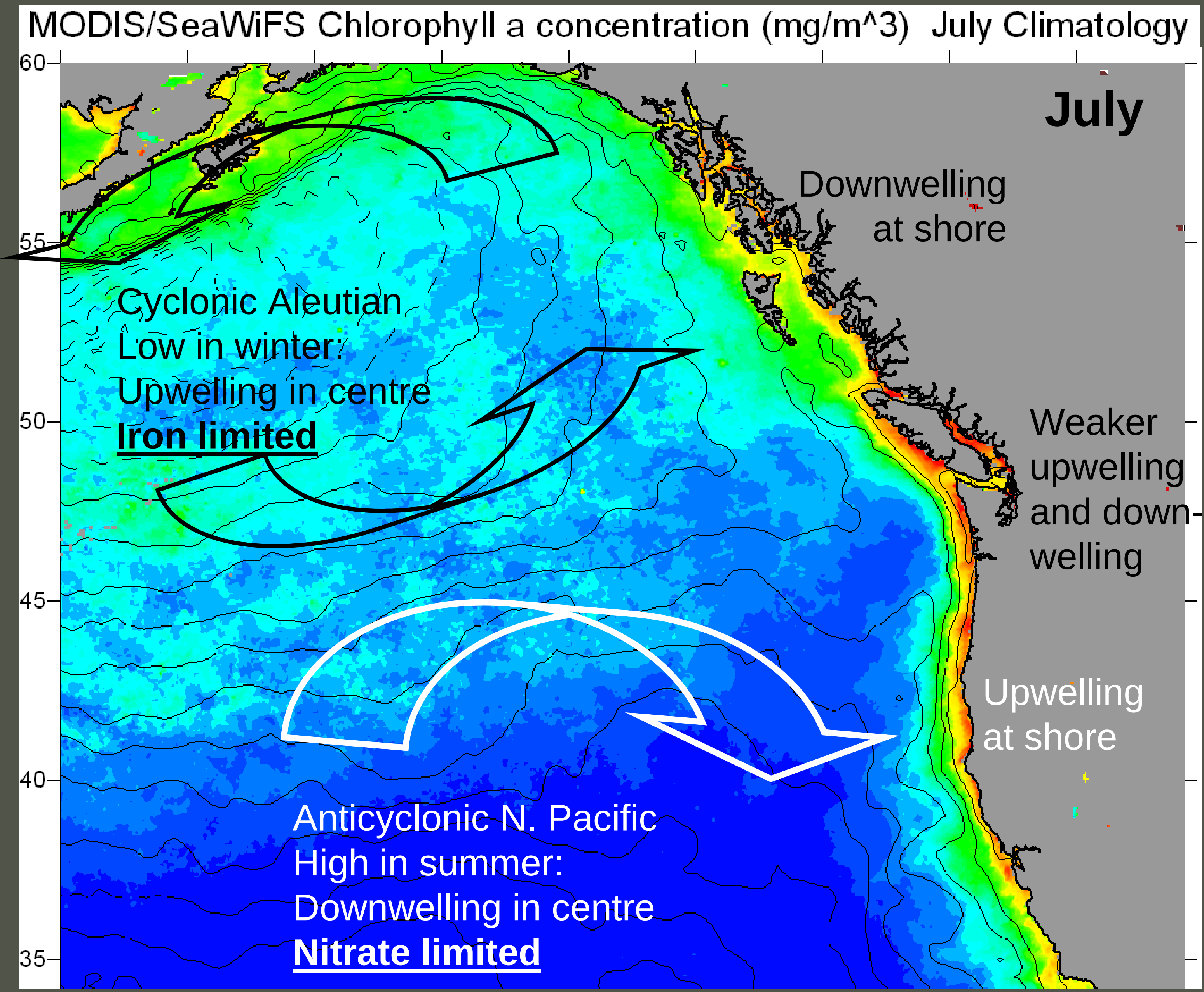

MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) July Climatology
July
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0


MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) August Climatology
August
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0


MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) September Climatology
September
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0

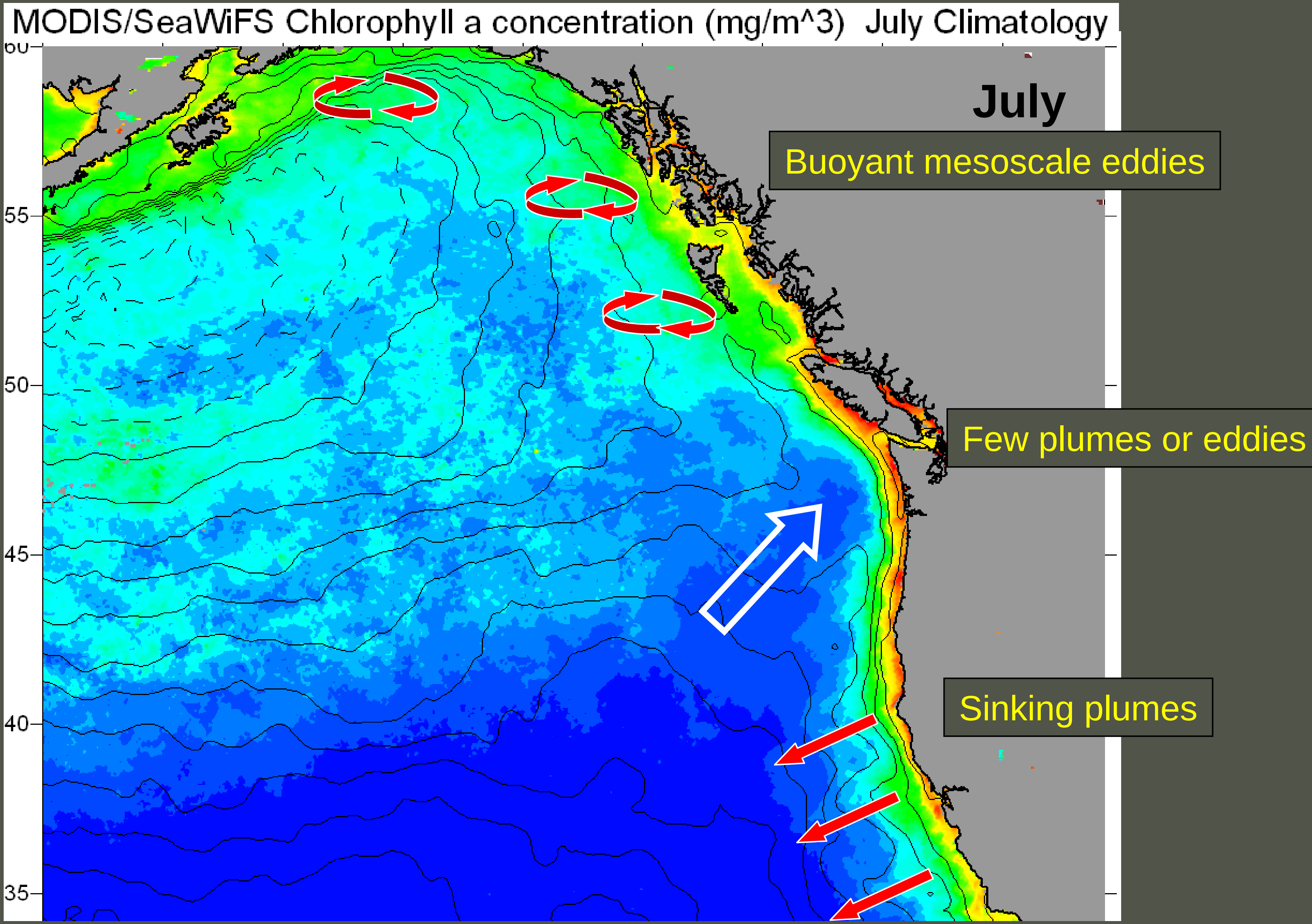
MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) October Climatology



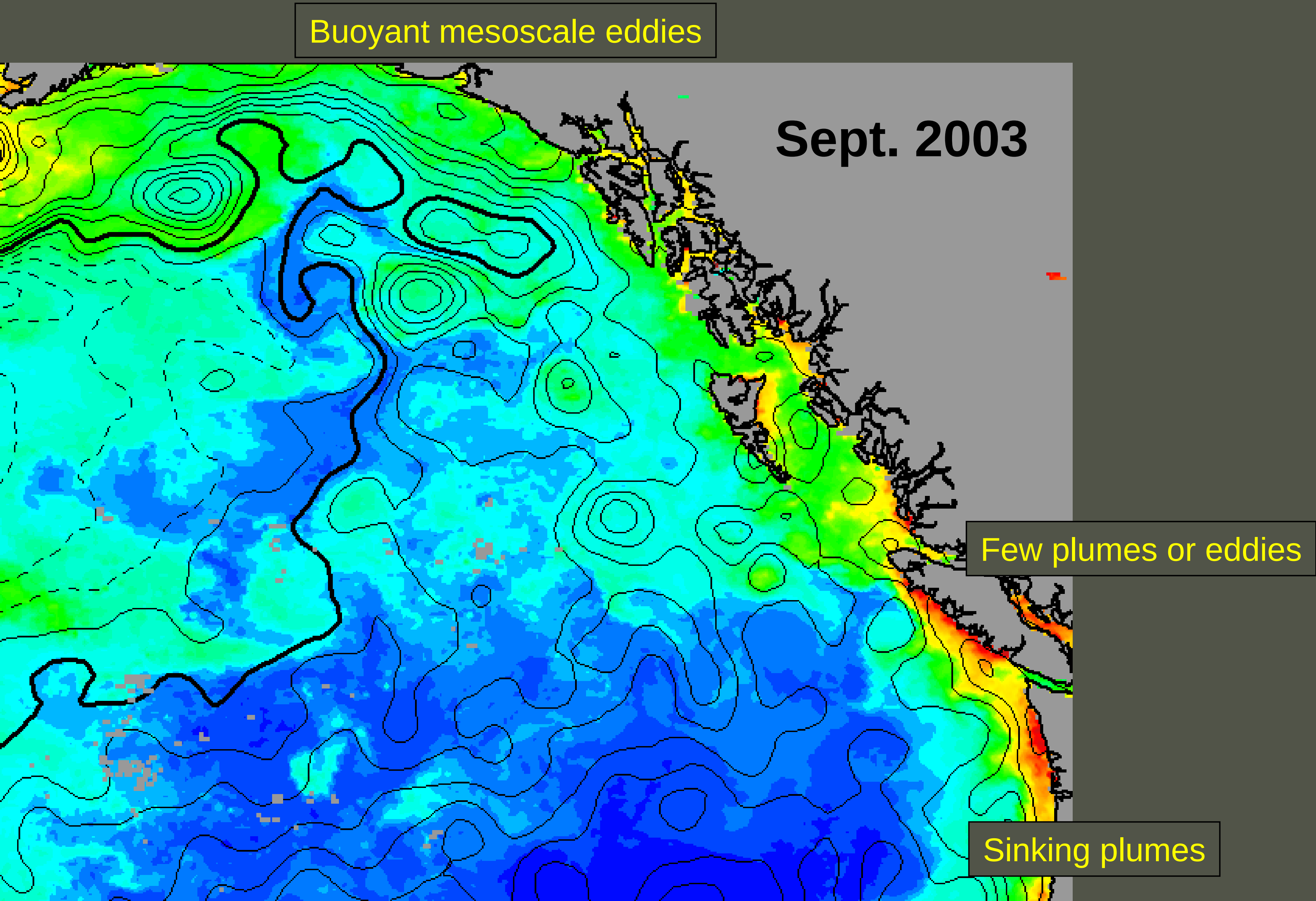


MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) July Climatology
60
55
50
45
40
35
July
Downwelling at shore
Cyclonic Aleutian Low in winter: Upwelling in centre **Iron limited**
Weaker upwelling and down-welling
Upwelling at shore
Anticyclonic N. Pacific High in summer: Downwelling in centre **Nitrate limited**

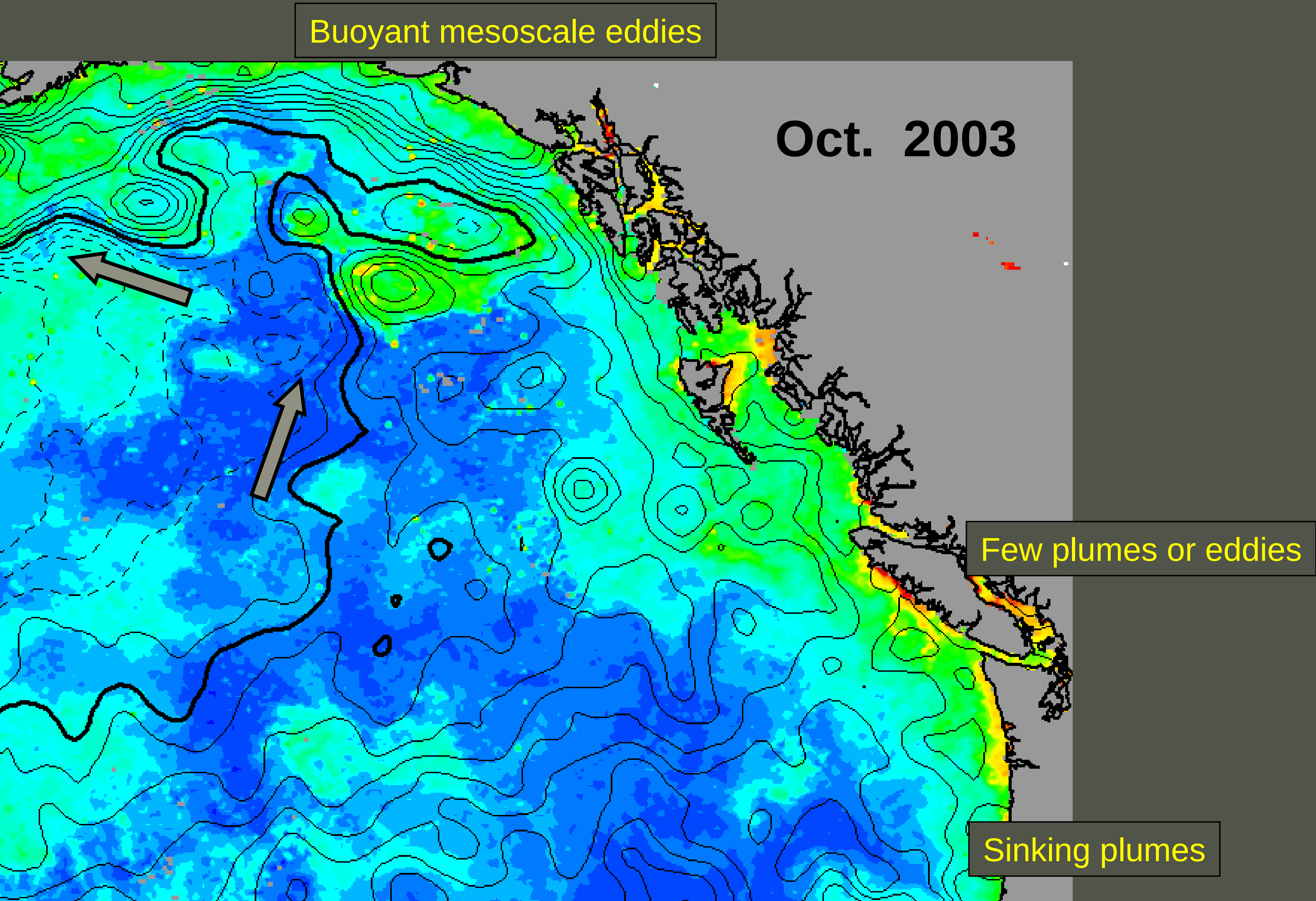
# 1 Nutrients from the east and north

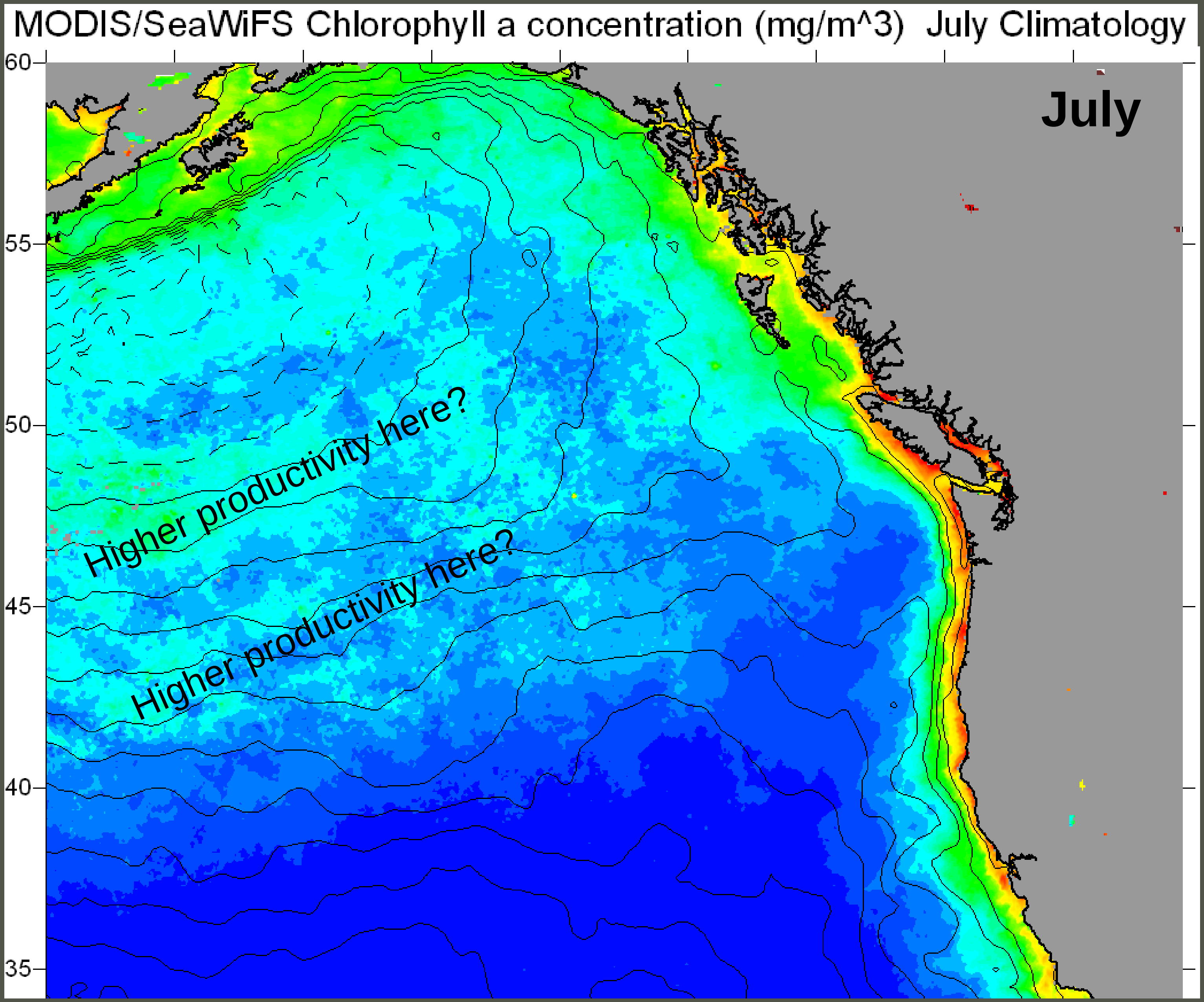


# Iron from the east and north



# Iron from the east and north

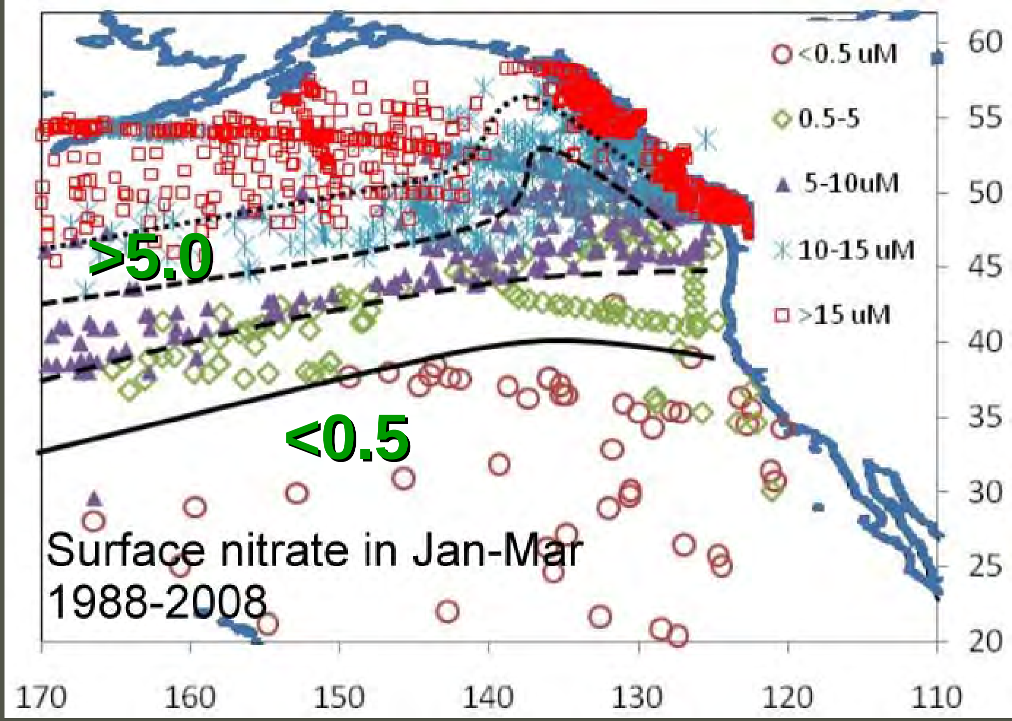




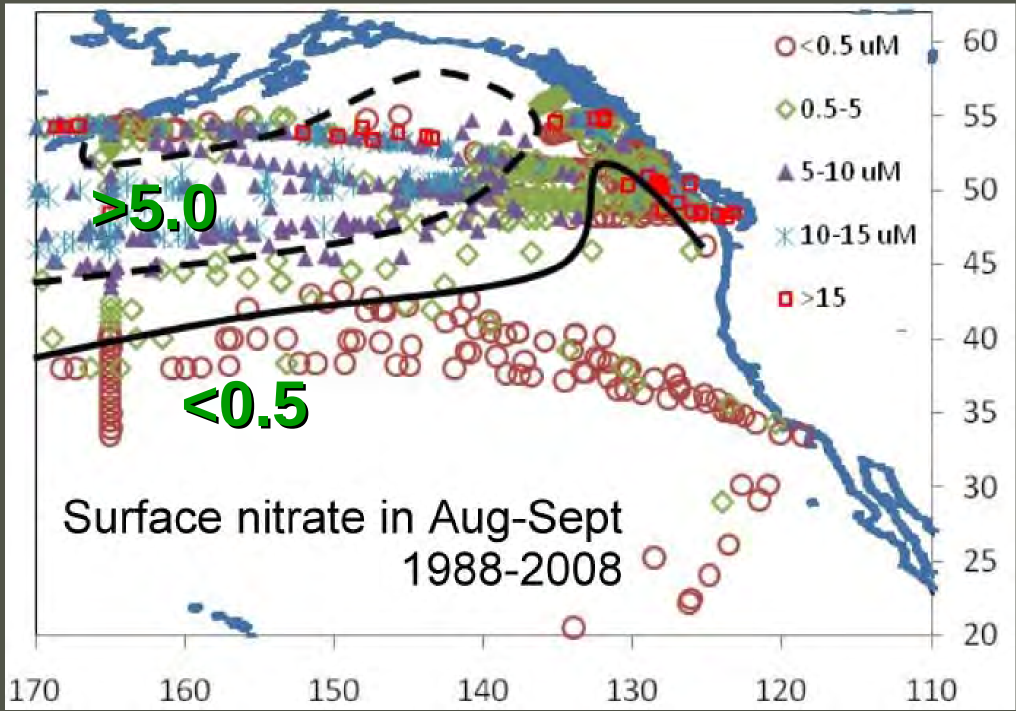
MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) July Climatology
July
Higher productivity here?
Higher productivity here?
60
55
50
45
40
35

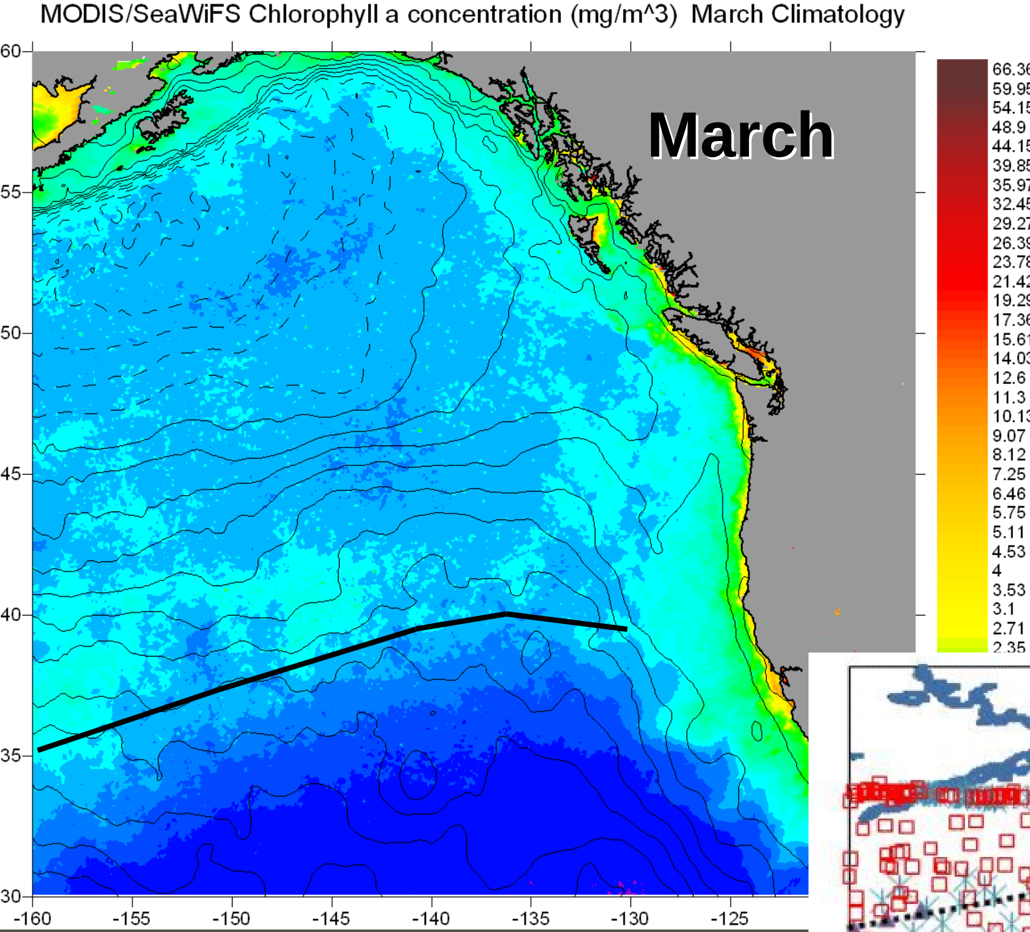
Surface nitrate
all data 1988-2008
Frank Whitney, DFO
Pers. Communication

January-March

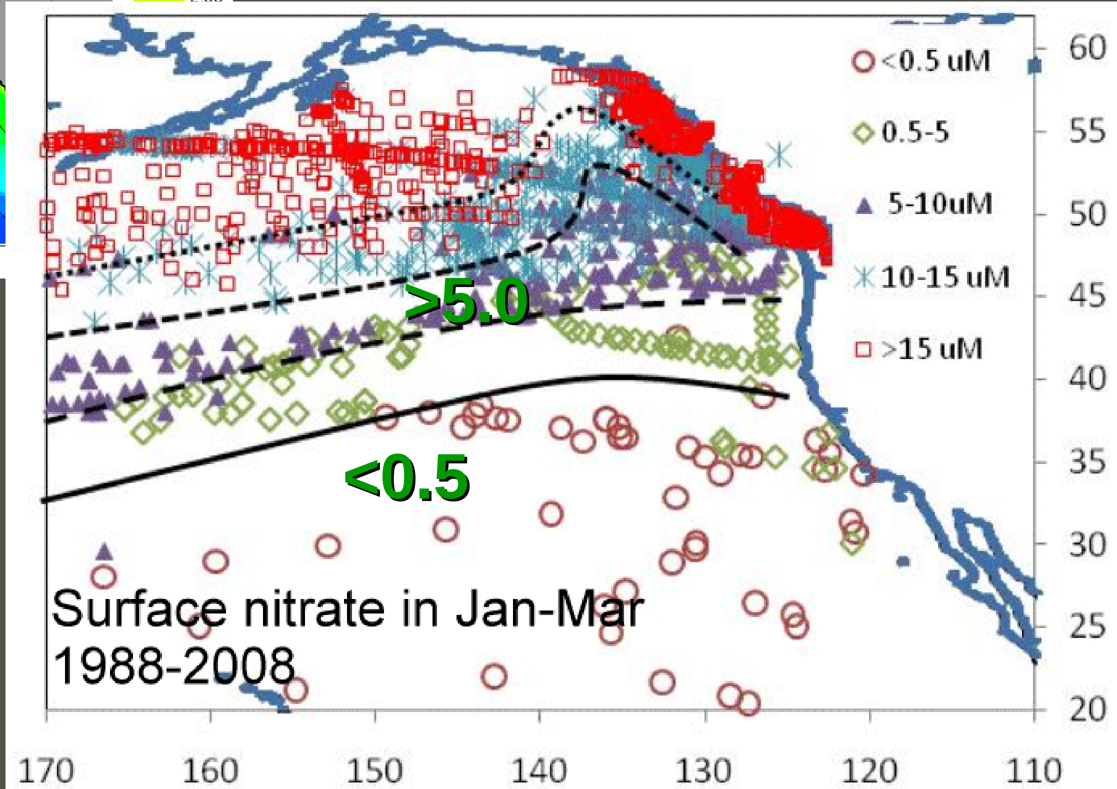



August-September

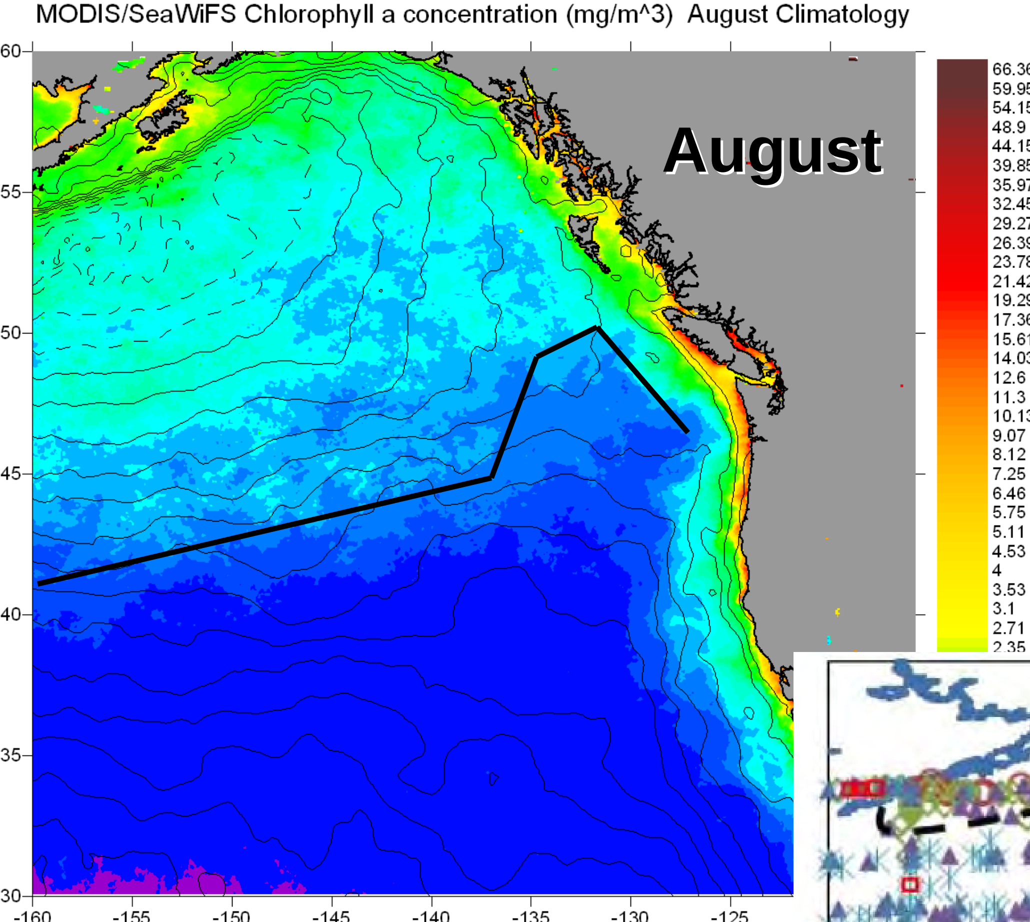





Southern "bloom" possibly due to sufficient iron plus a winter supply of macro-nutrients.

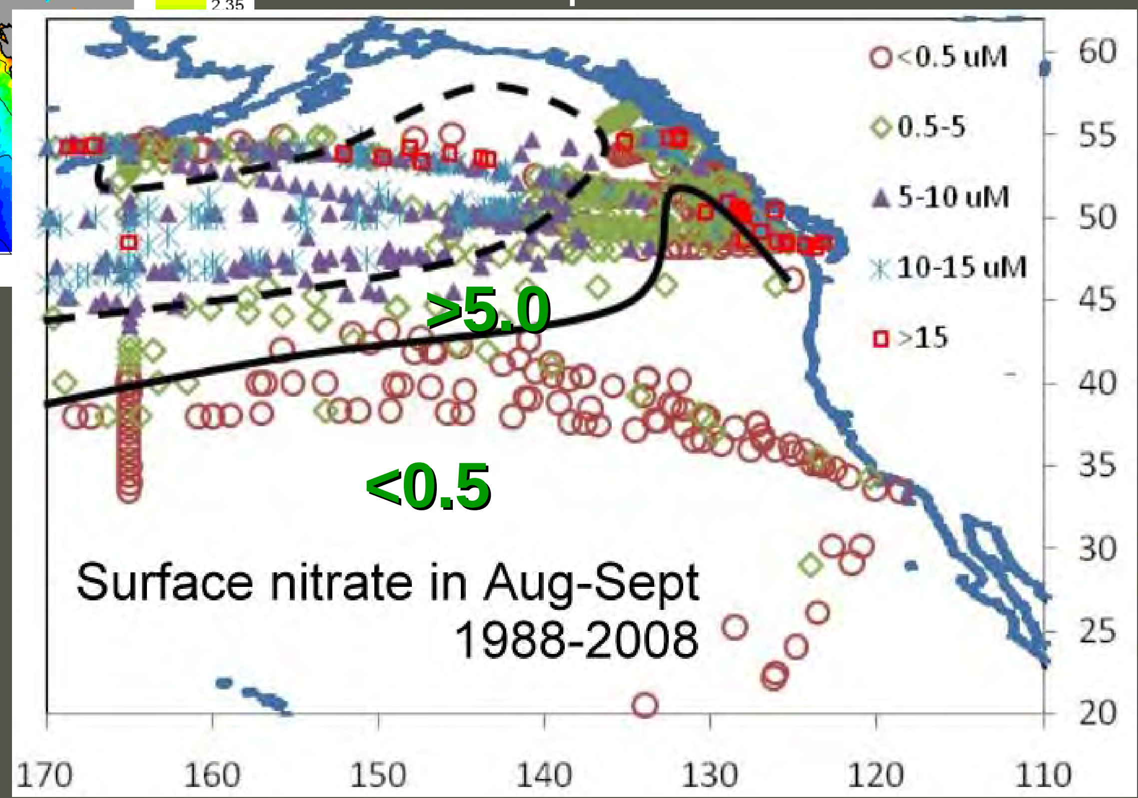


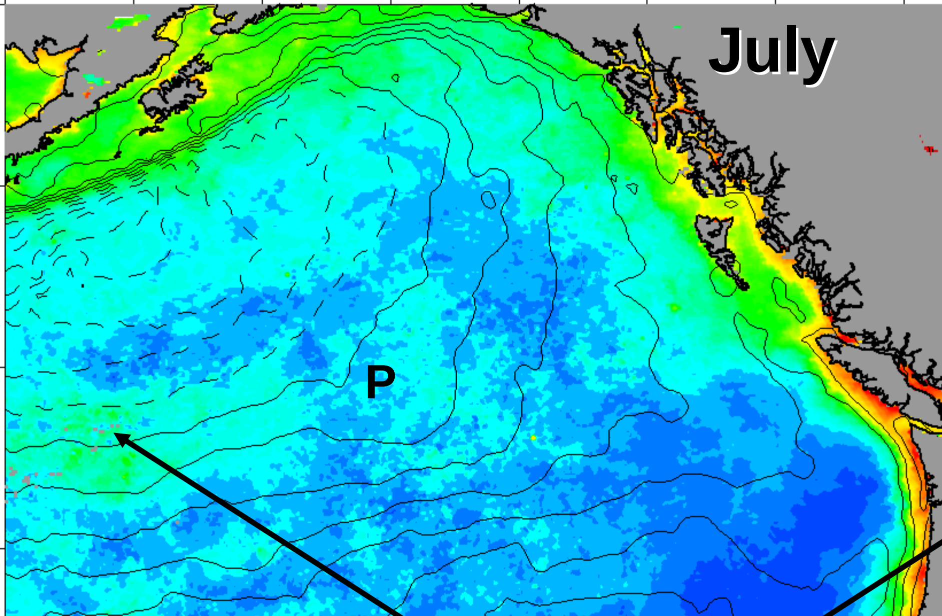

Surface nitrate
all data 1988-2008
Jan/Feb/Mar
Frank Whitney,
Pers. Communication

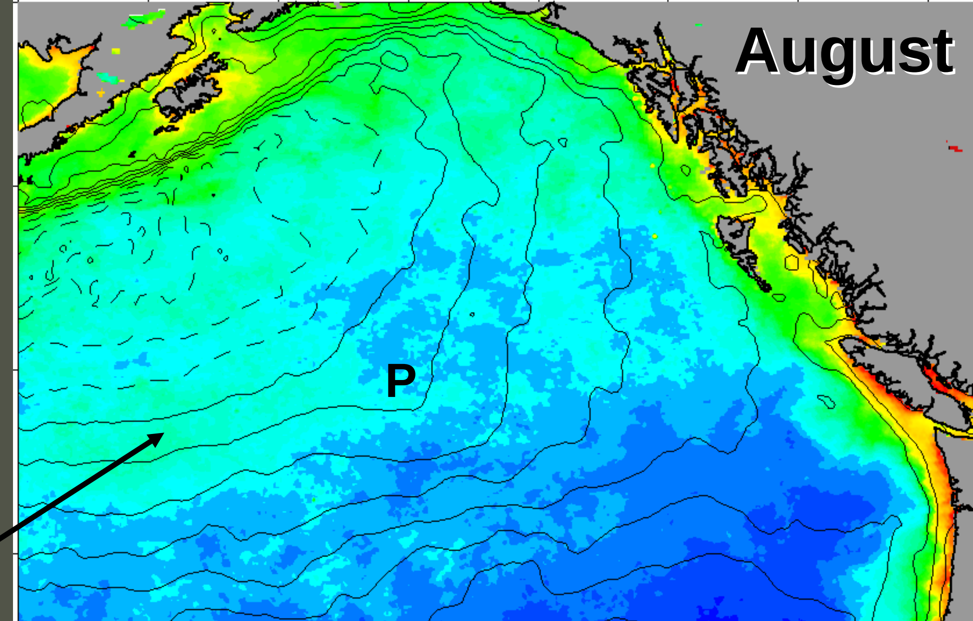


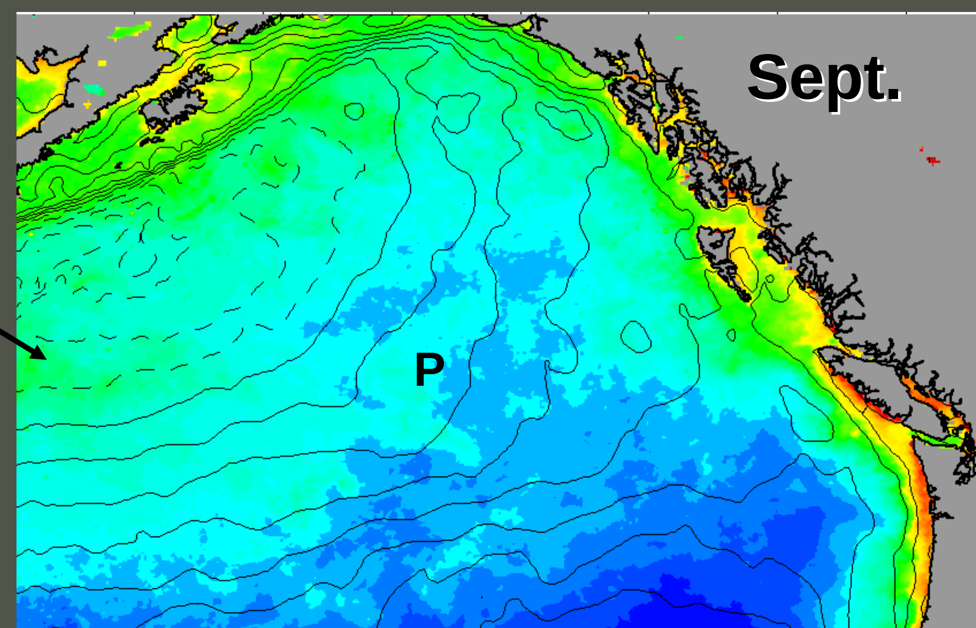

- Note how the southern limit of chlorophyll seems to follow the transition line from >5 to <0.5 micromoles of Nitrate.
- The low-$NO_3$ region west of Vancouver Island varies from year to year.
- Borgrad et al. (2004) note the boundary aligns with the 18°C surface temperature.

Surface nitrate
all data 1988-2008
Aug/Sept
Frank Whitney,
Pers. Communication

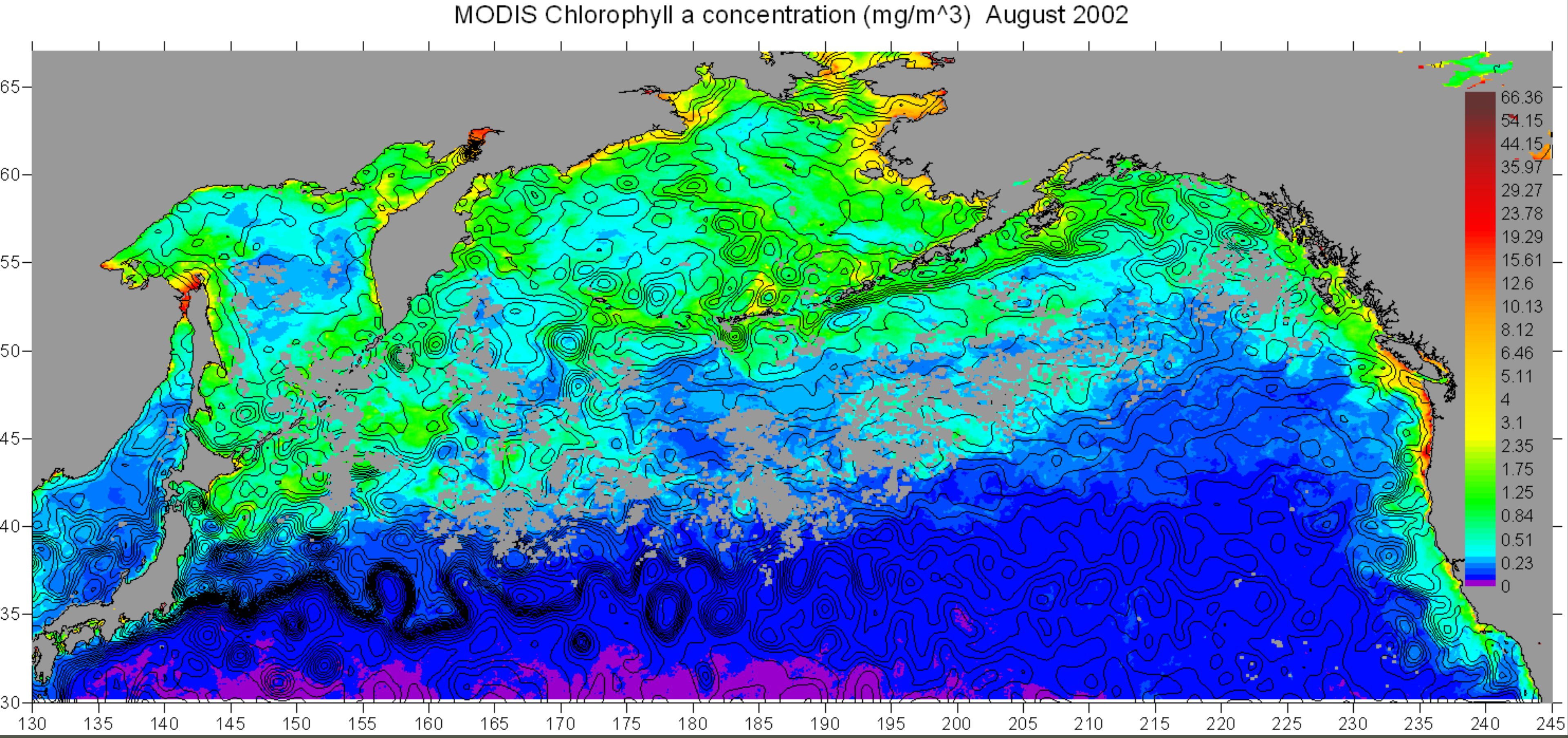


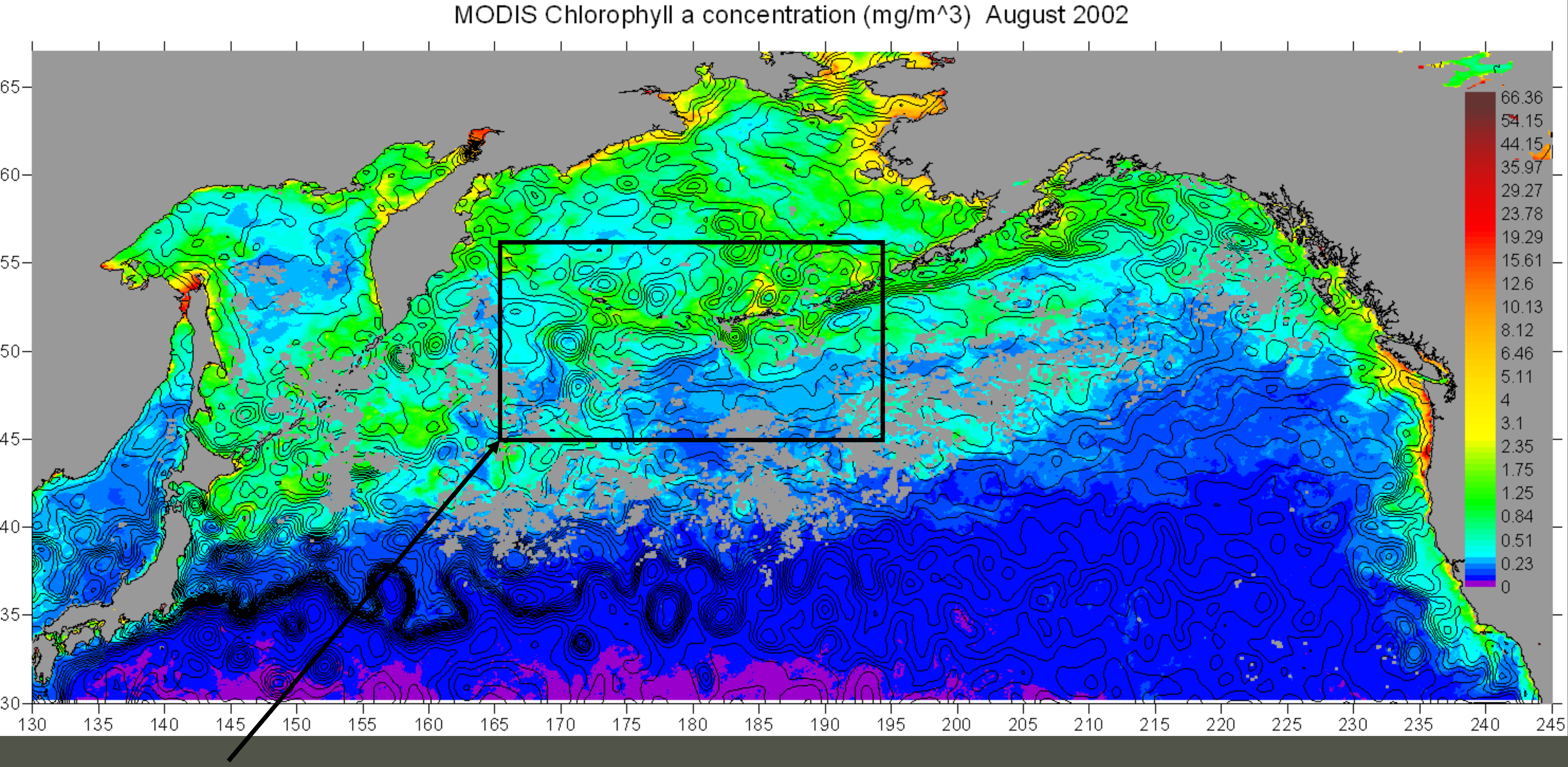


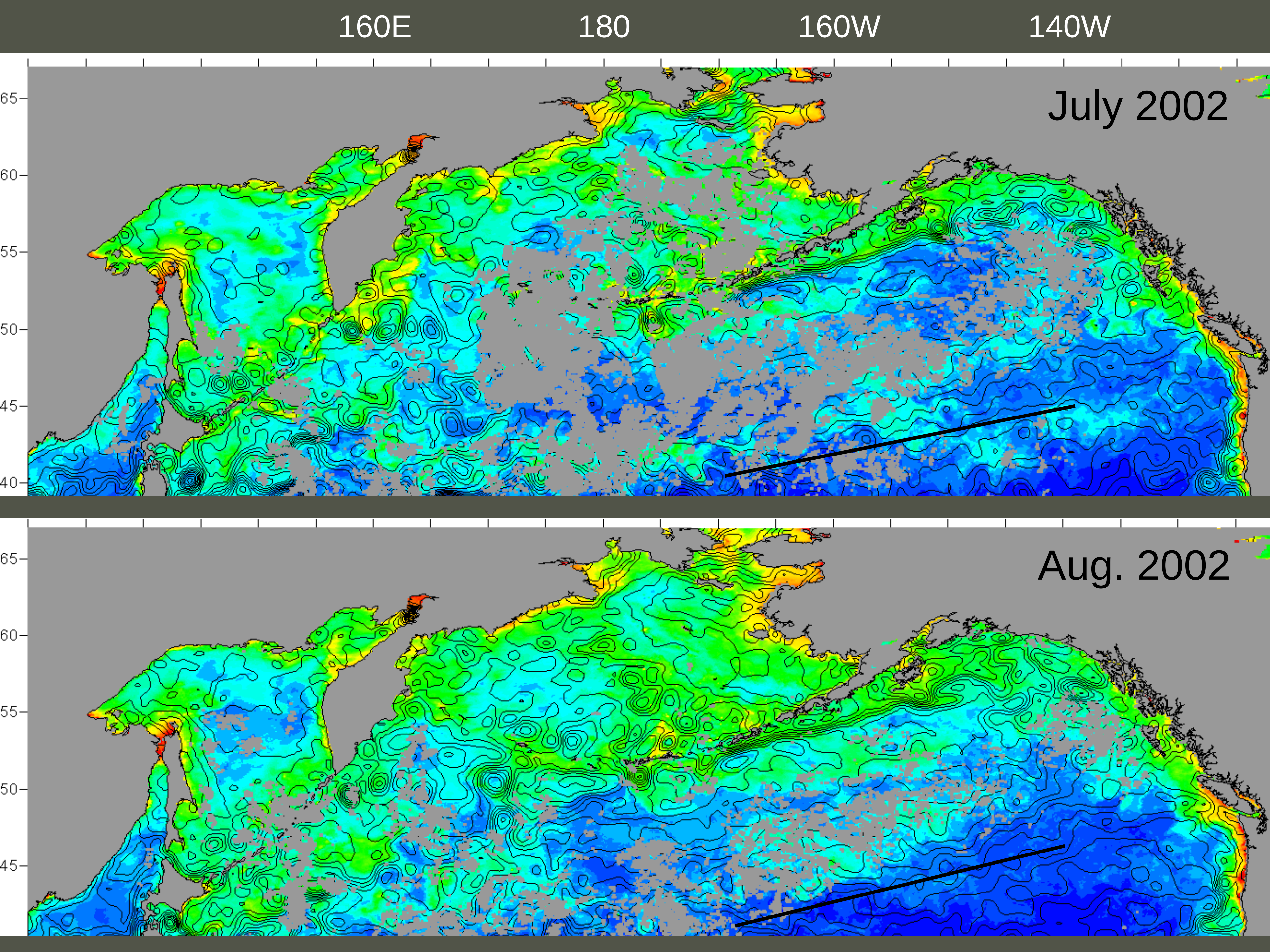

Why relatively higher chlorophyll here?

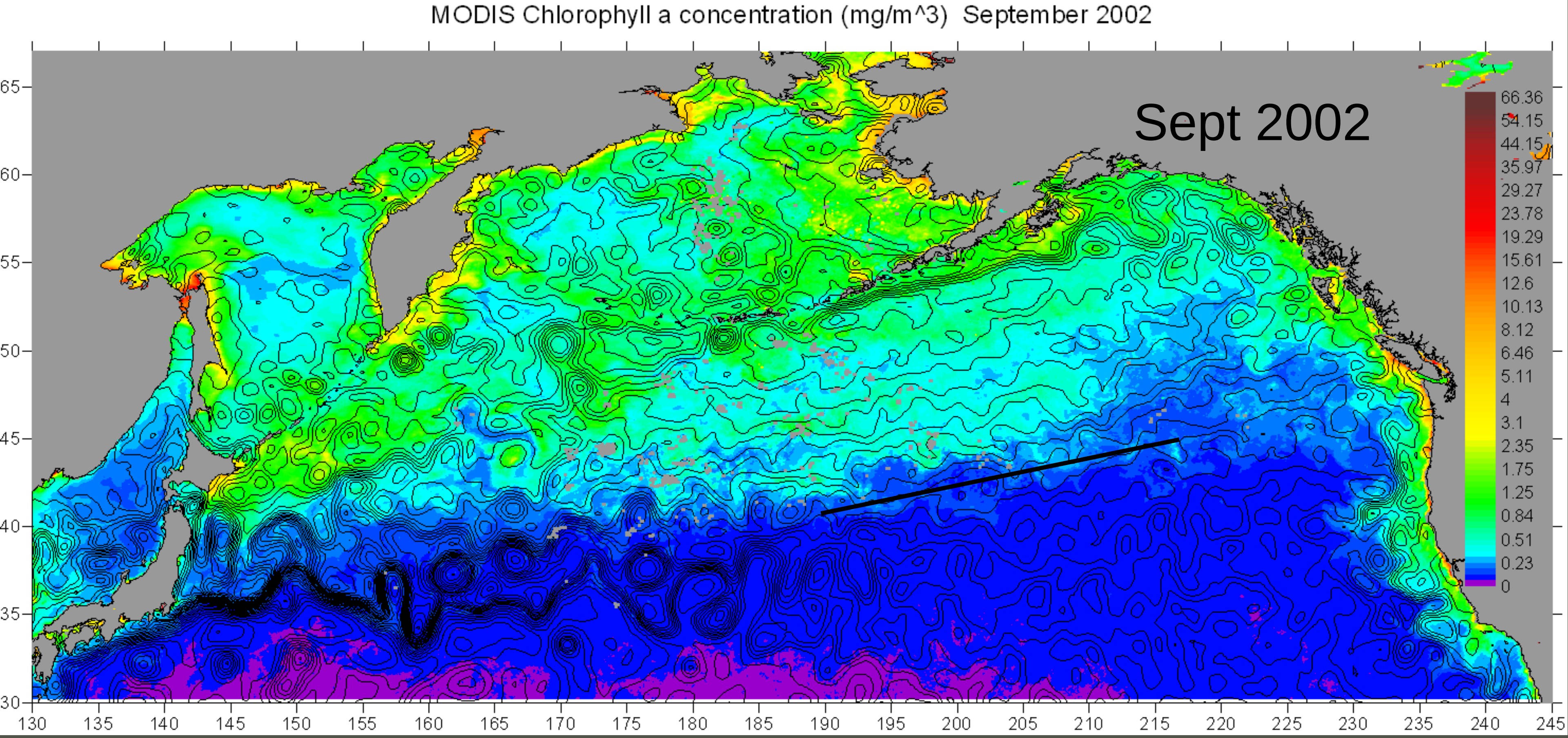

MODIS Chlorophyll a concentration (mg/m^3) August 2002
65
60
55
50
45
40
35
30
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
205
210
215
220
225
230
235
240
245
66.36
54.15
44.15
35.97
29.27
23.78
19.29
15.61
12.6
10.13
8.12
6.46
5.11
4
3.1
2.35
1.75
1.25
0.84
0.51
0.23
0




UENO, CRAWFORD and ONISHI (2010)
*Journal of Oceanography*, Vol. 66, pp. 319 to 328

More chlorophyll to the south of the  Alaskan Stream when eddies present, based on SeaWiFS chlorophyll + altimetry from 1997 to 2007.

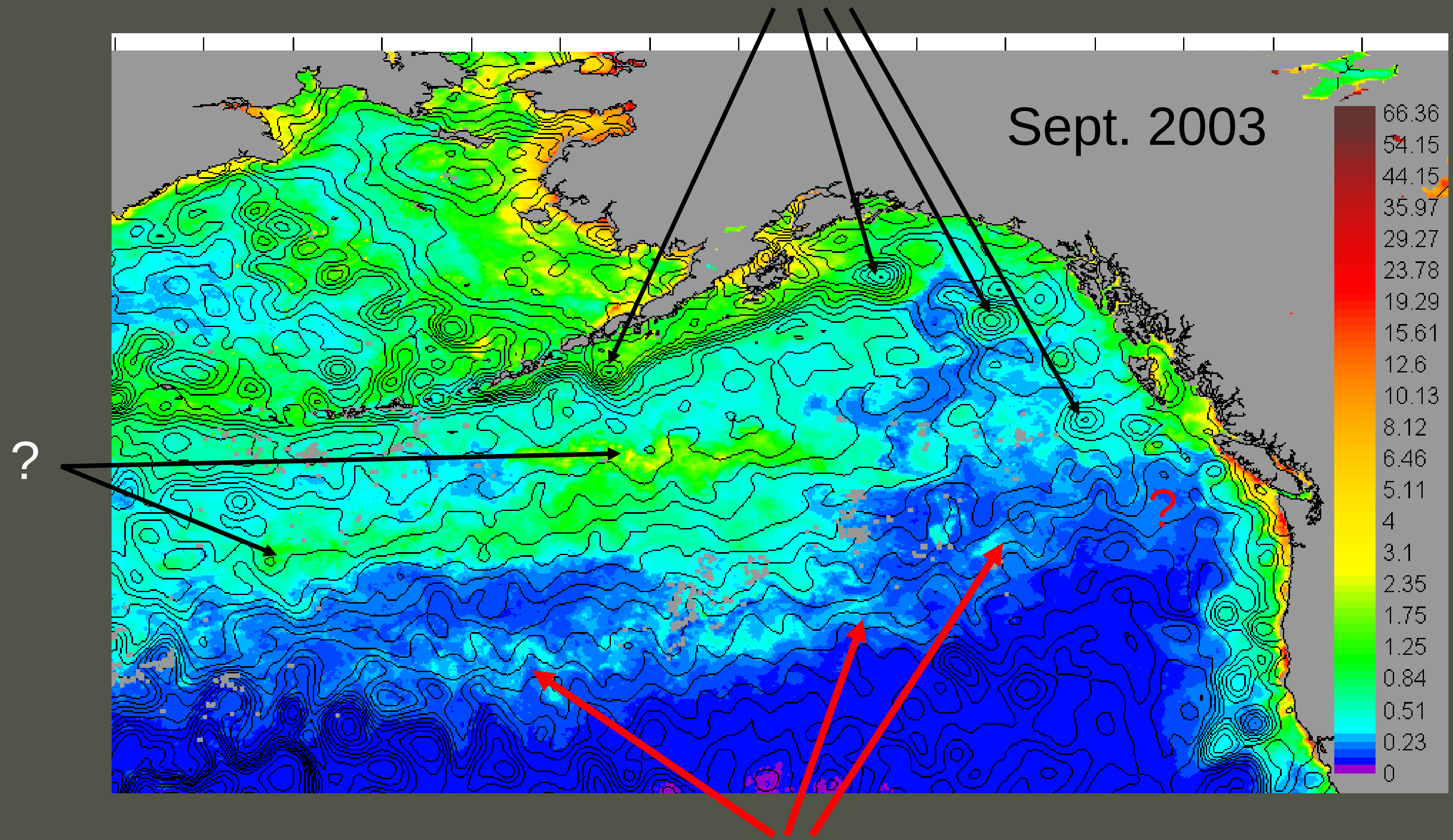

160E
180
160W
140W
July 2002
Aug. 2002
65
60
55
50
45
40



MODIS Chlorophyll a concentration (mg/m^3) September 2002
Sept 2002
66.36
54.15
44.15
35.97
29.27
23.78
19.29
15.61
12.6
10.13
8.12
6.46
5.11
4
3.1
2.35
1.75
1.25
0.84
0.51
0.23
0
65
60
55
50
45
40
35
30
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
205
210
215
220
225
230
235
240
245

# Summary

Anticyclonic Mesoscale eddies inject nutrients into the Alaskan Gyre. Lowest chlorophyll concentrations are between the eastern end of the gyre and SE Alaska, following streamlines of the Alaska Current




Higher concentrations of chlorophyll here are possibly due to mixing iron-rich water from the south with nitrate-rich water from the north . This band of chlorophyll migrates north and south through the year.

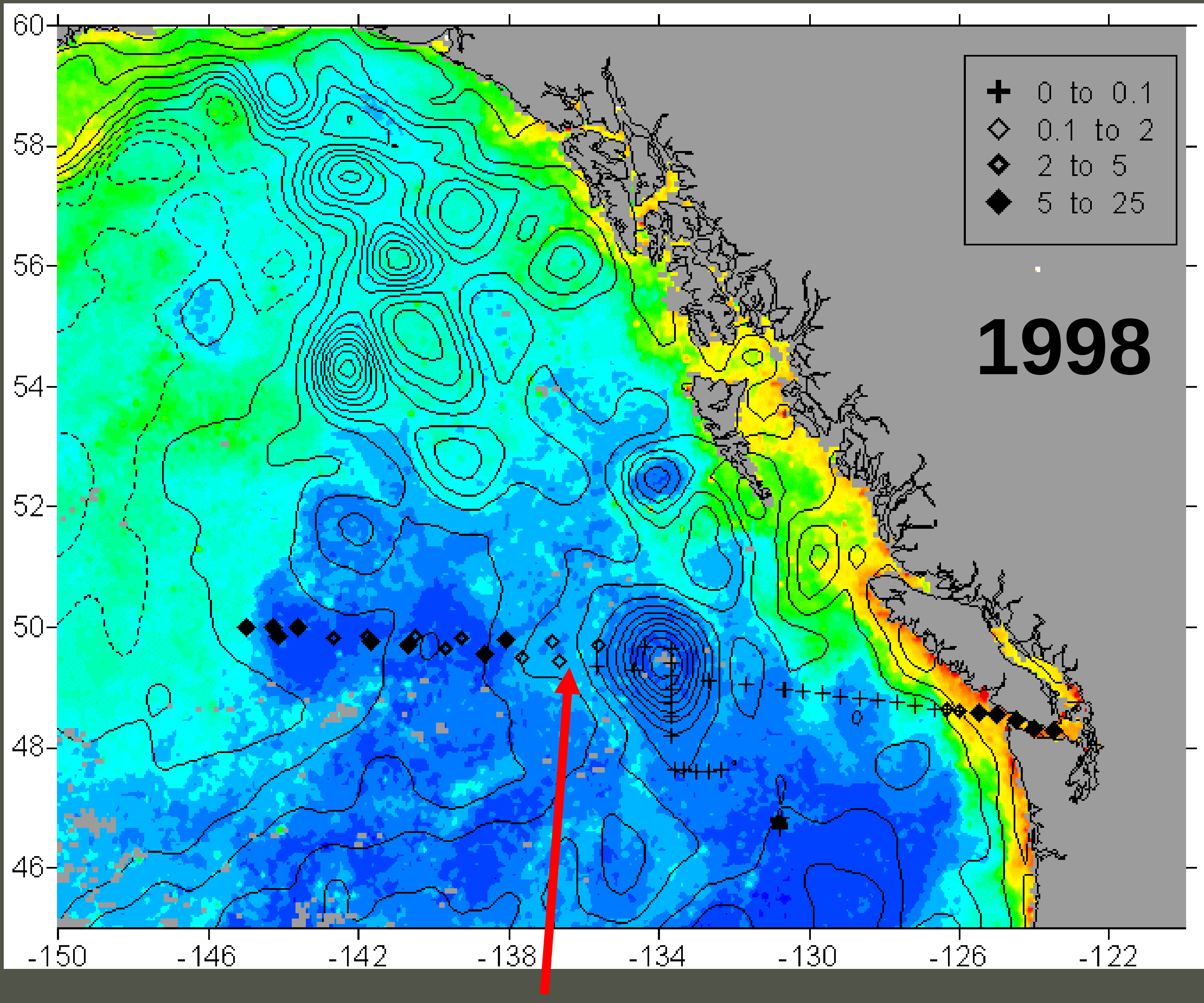
Observations in 1998, following intense El Niño with deep Aleutian Low in previous winter.

Chl and nitrate in Aug-Sep

Sea level from AVISO.

Chl from NASA.

Nitrate from DFO Line P program.



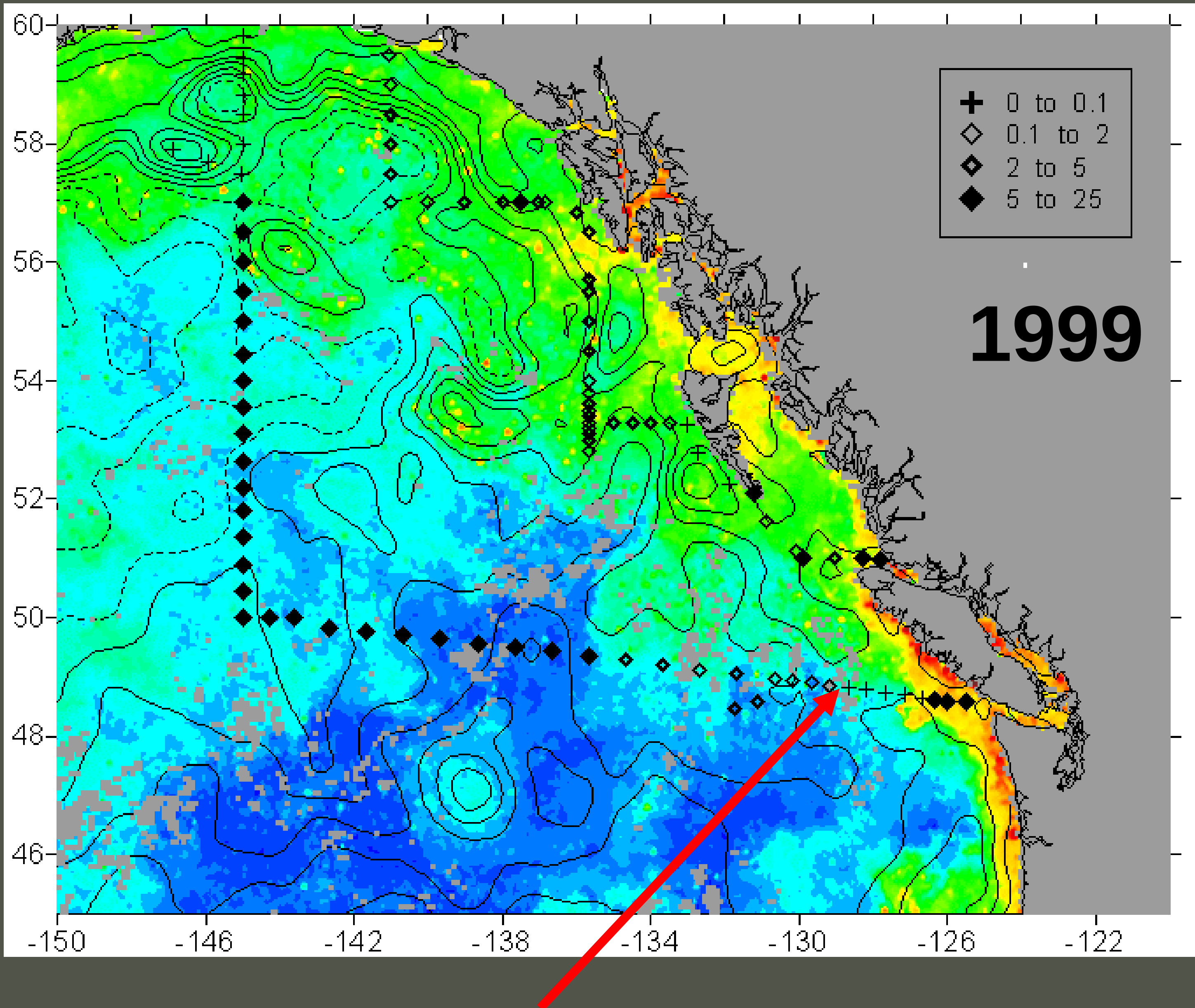
Observations in **1999**, during La Niña with strong westerlies.

Chl and nitrate in Aug-Sep

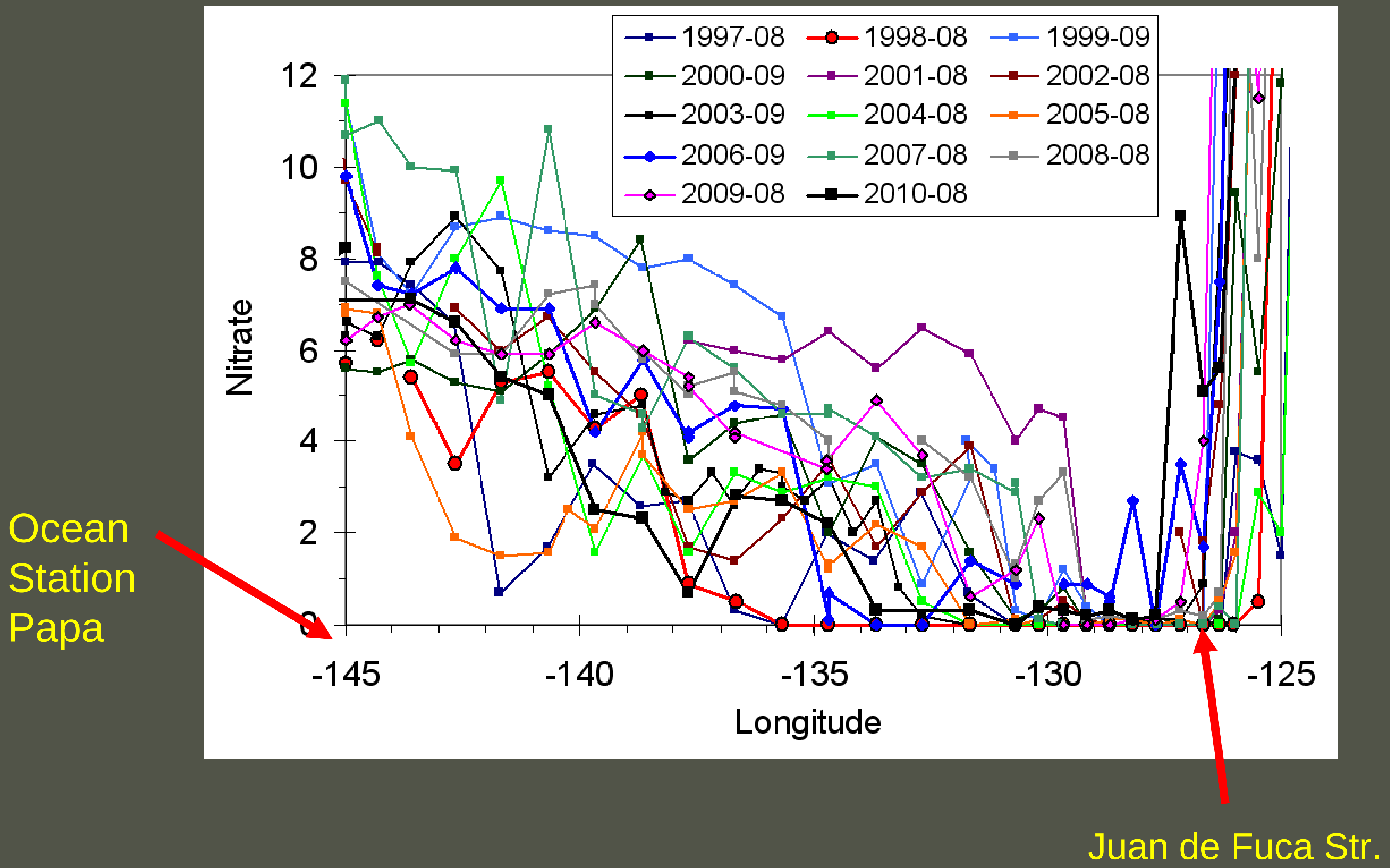
Sea level from Aviso.

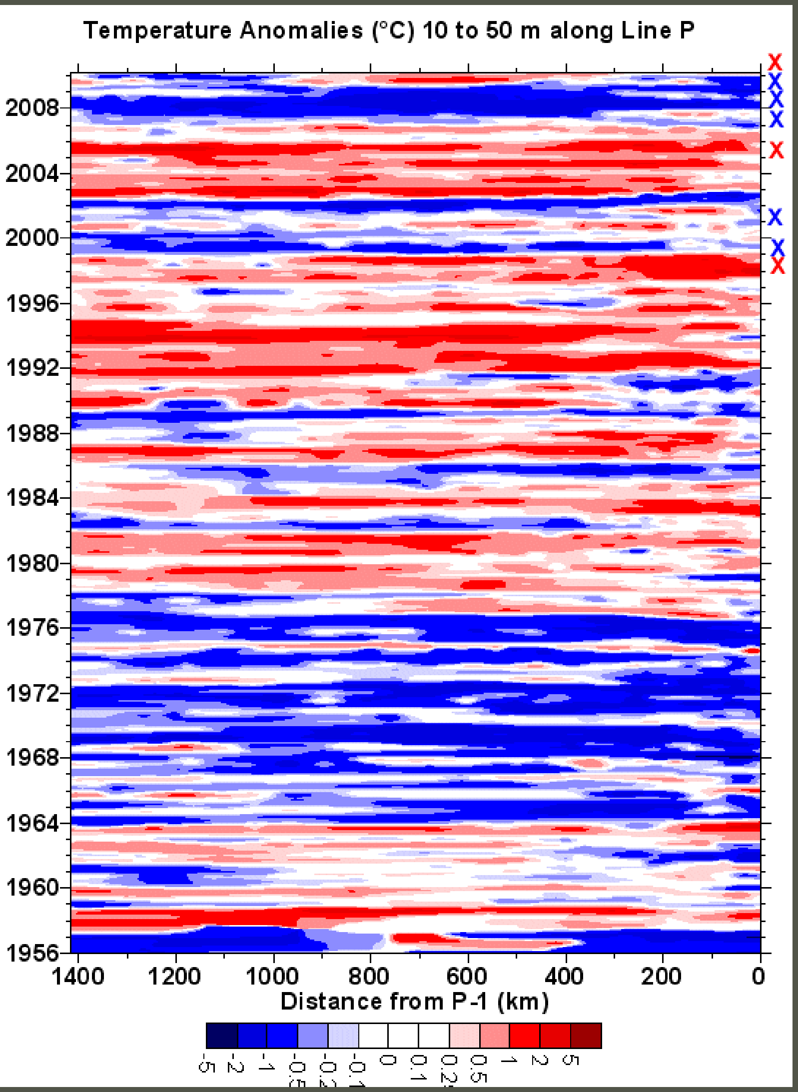
Chl from NASA.

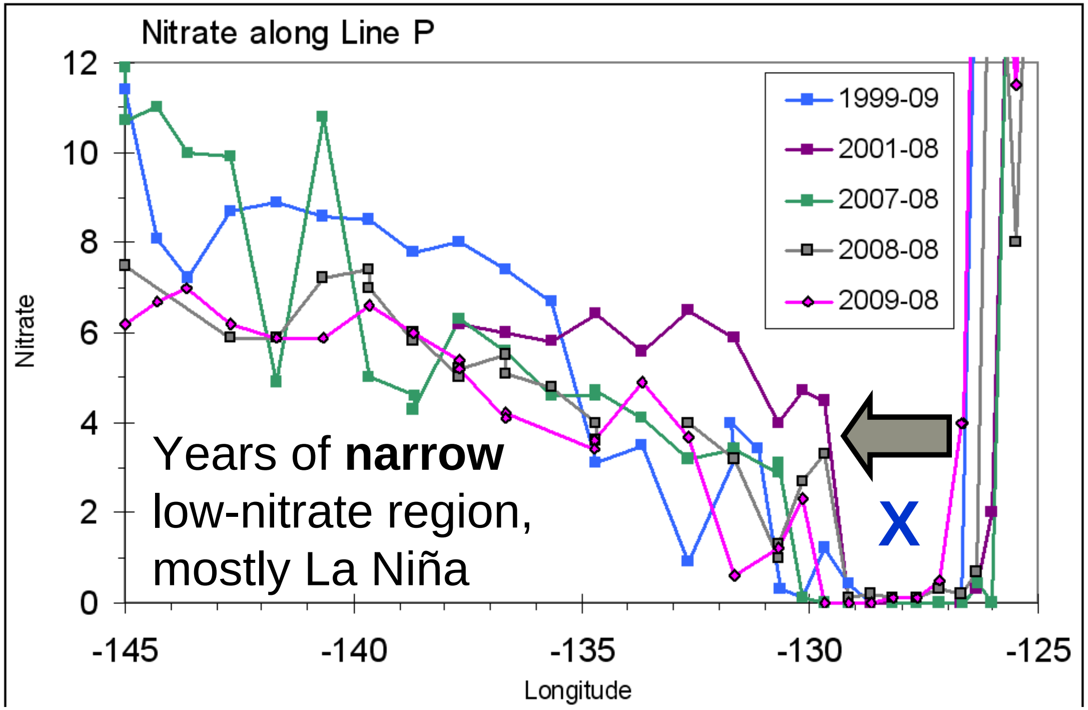
Nitrate from DFO Line P program.

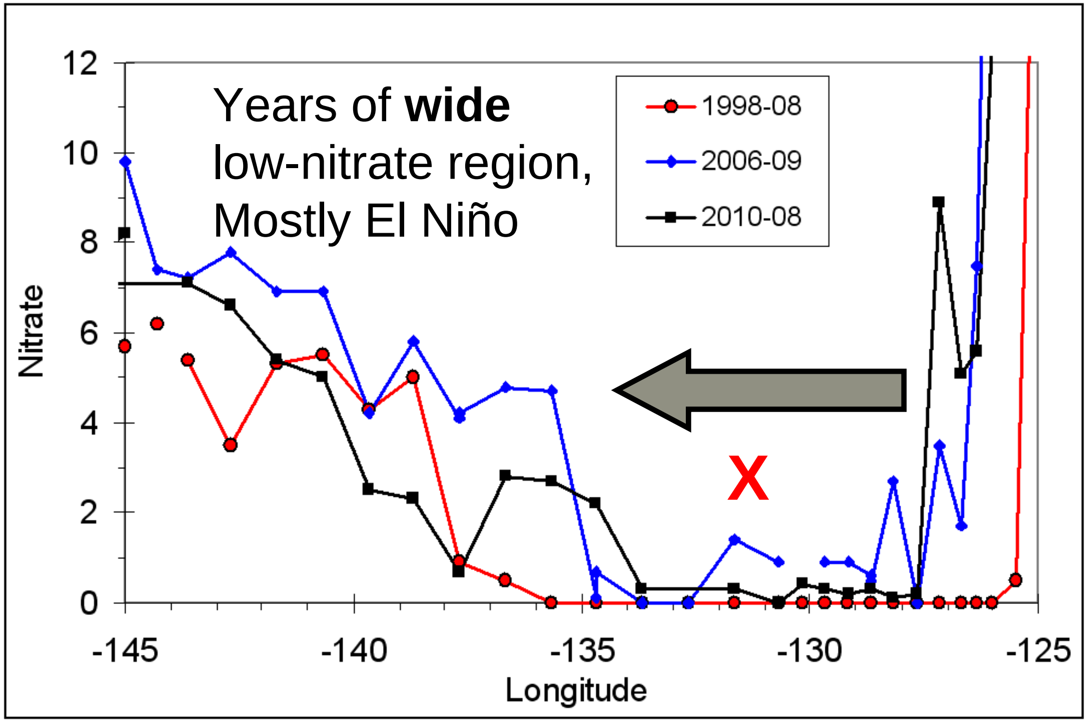


Graph of nutrient levels along Line P in August and September in each year, 1997 to 2010.



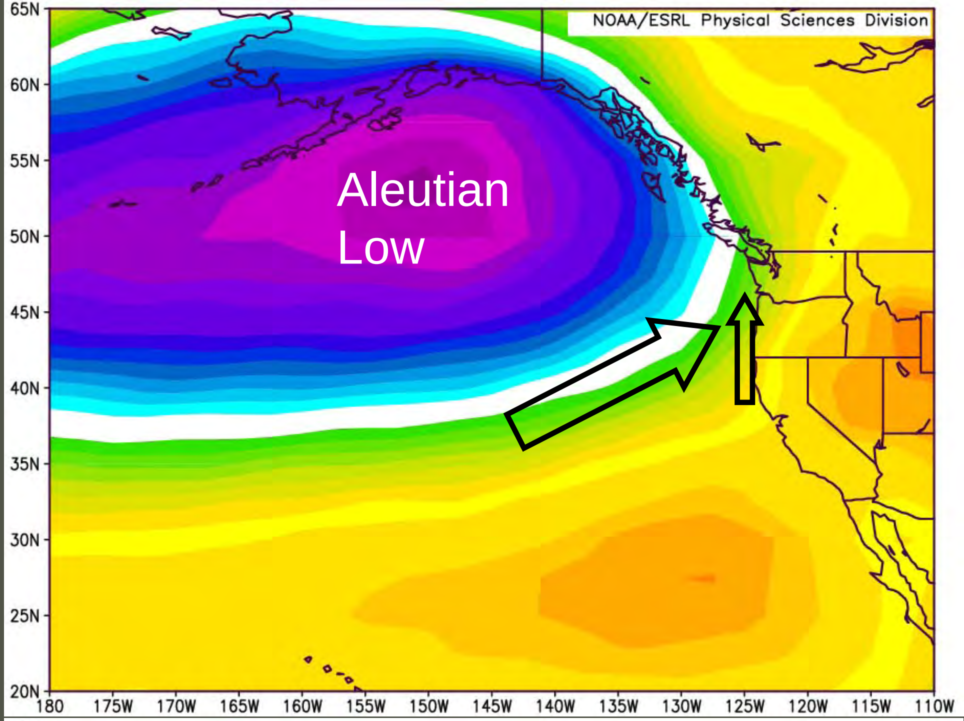

Temperature Anomalies (°C) 10 to 50 m along Line P
2008
2004
2000
1996
1992
1988
1984
1980
1976
1972
1968
1964
1960
1956
1400 1200 1000 800 600 400 200 0
Distance from P-1 (km)


Nitrate along Line P
1999-09
2001-08
2007-08
2008-08
2009-08
Years of **narrow** low-nitrate region, mostly La Niña
X
Nitrate
Longitude


Years of **wide** low-nitrate region, Mostly El Niño
1998-08
2006-09
2010-08
X
Nitrate
Longitude

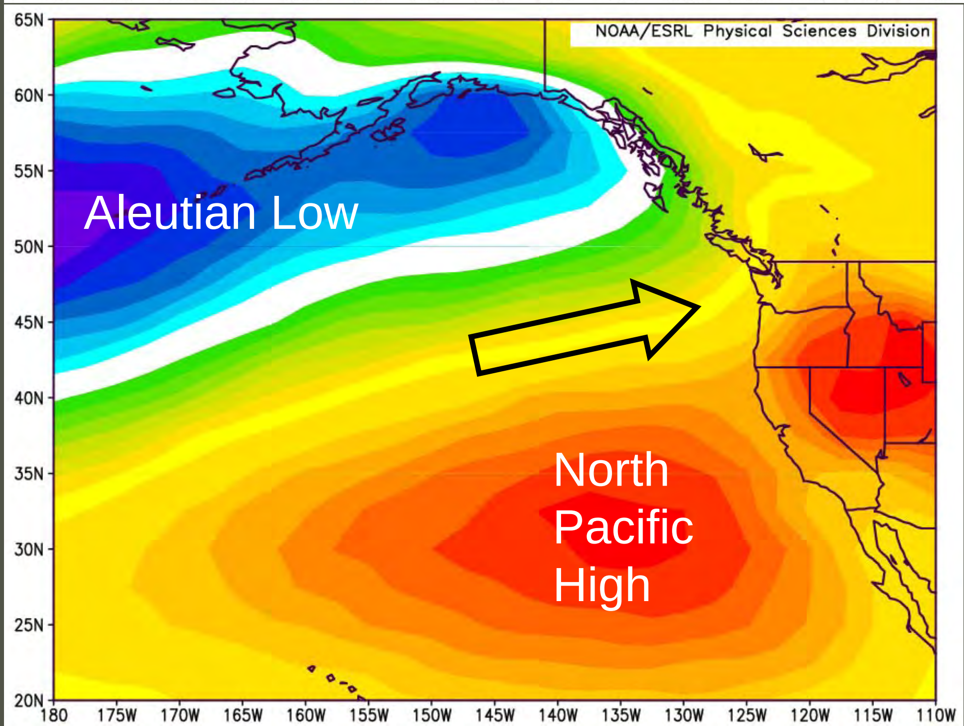
January-February
Average sea-level air pressure
1998 2006 2010
Mostly El Niño

**Wide** low-nitrate region



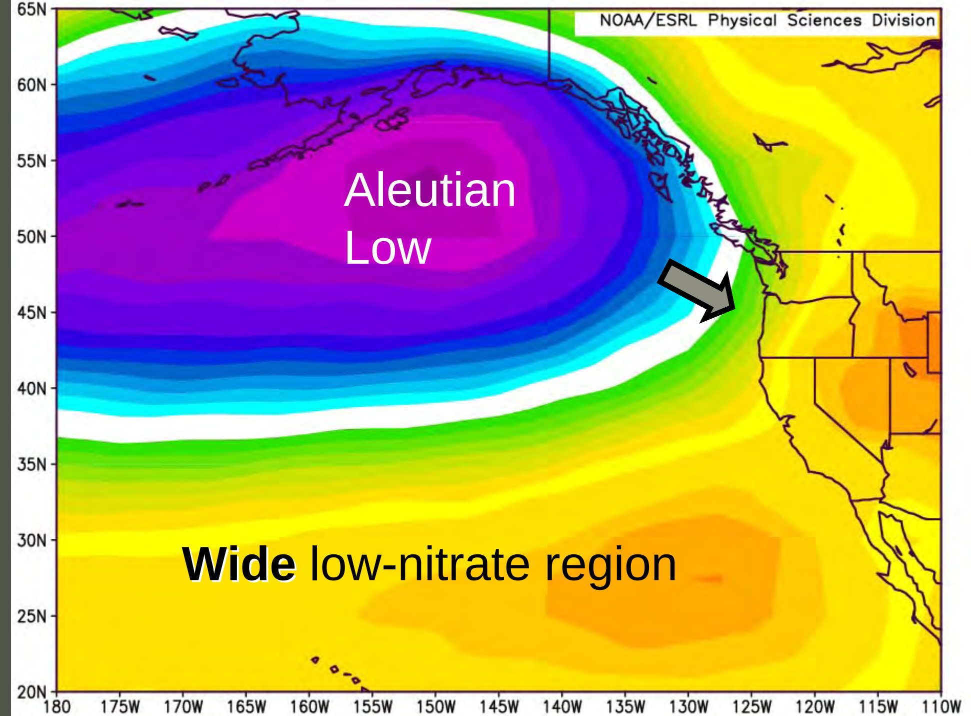

January-February
Average sea-level air pressure
1999 2001 2007 2008 2009
Mostly La Niña

**Narrow** low-nitrate region



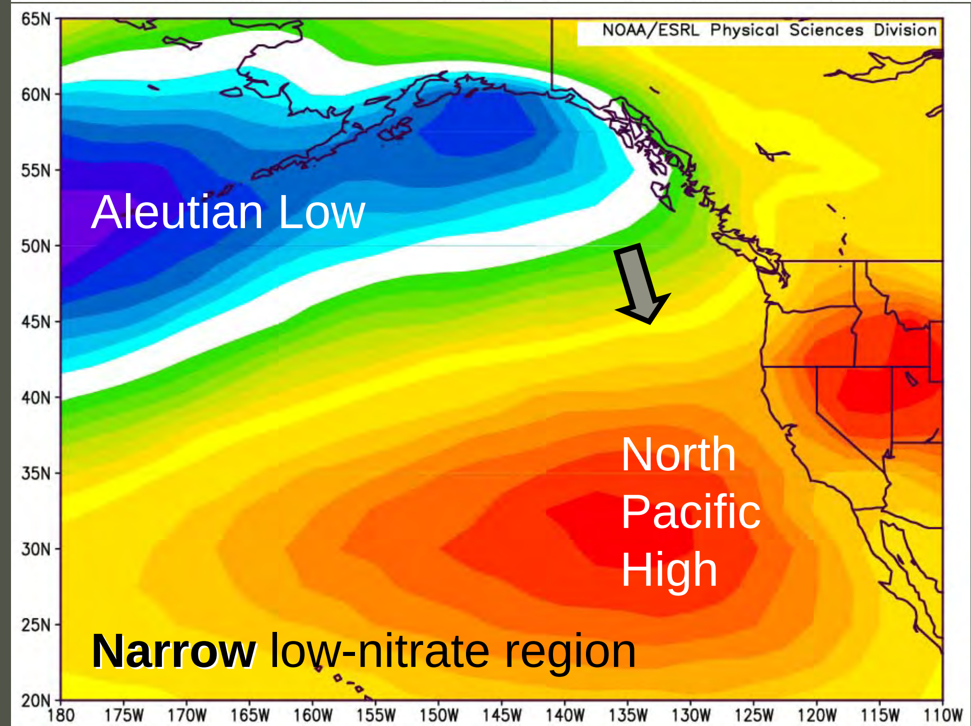
January-February
Average sea-level air pressure
1998 2006 2010
Mostly El Niño

**Wide** low-nitrate region




January-February
Average sea-level air pressure
1999 2001 2007 2008 2009
Mostly La Niña

**Narrow** low-nitrate region



# Conclusions:

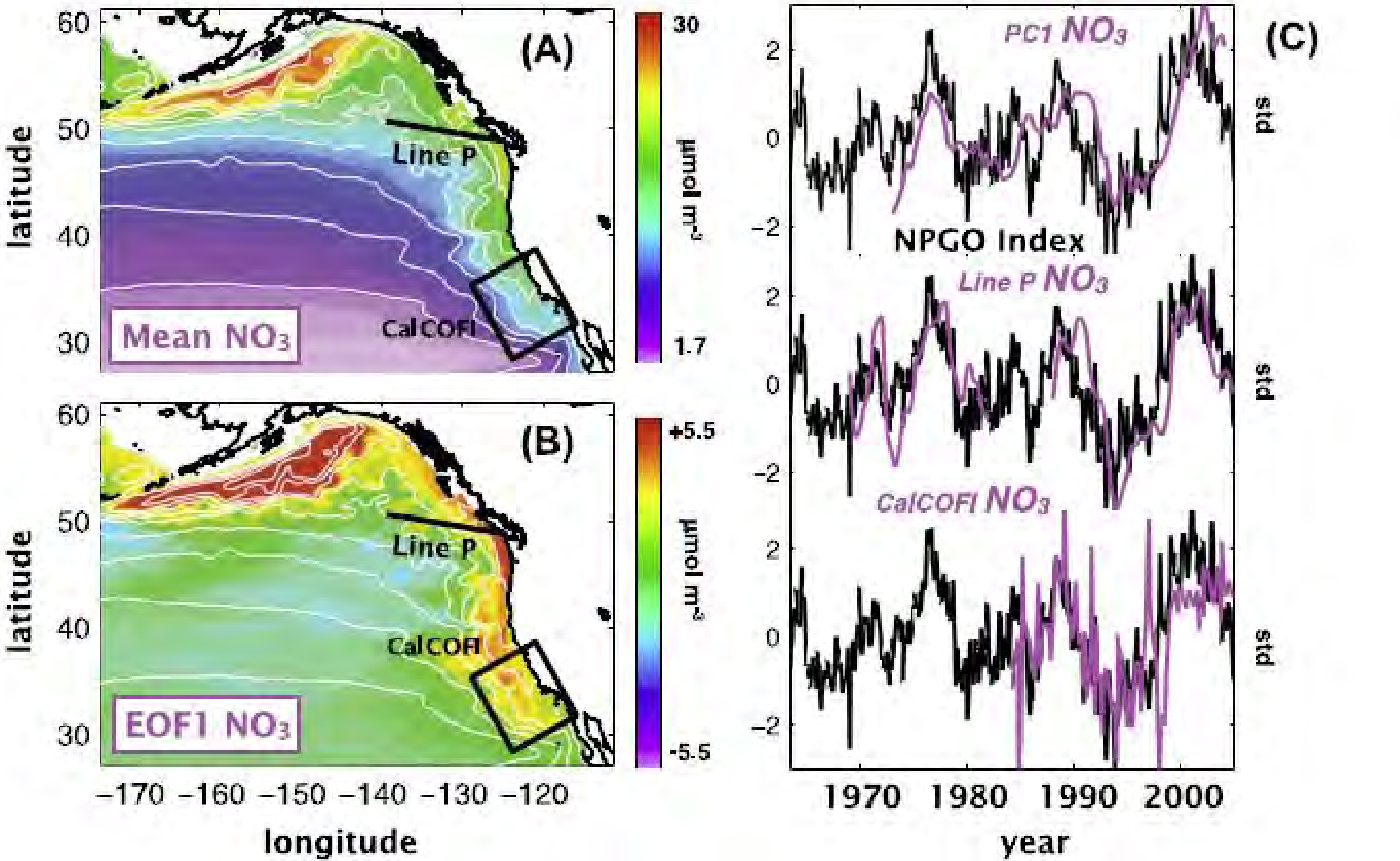
Within the HNLC region there is seasonal and regional variability in chlorophyll concentration as determined by SeaWiFS and MODIS satellites.

A weak spring bloom begins close to shore and progresses into mid-gulf through spring, much as described by Parsons and LeBrasseur (1968).

A chlorophyll-minimum region develops in mid-gulf in summer, due to:
(1) a local minimum in iron transport from coastal regions, and
(2) distance from the boundary between subtropical and subarctic water.

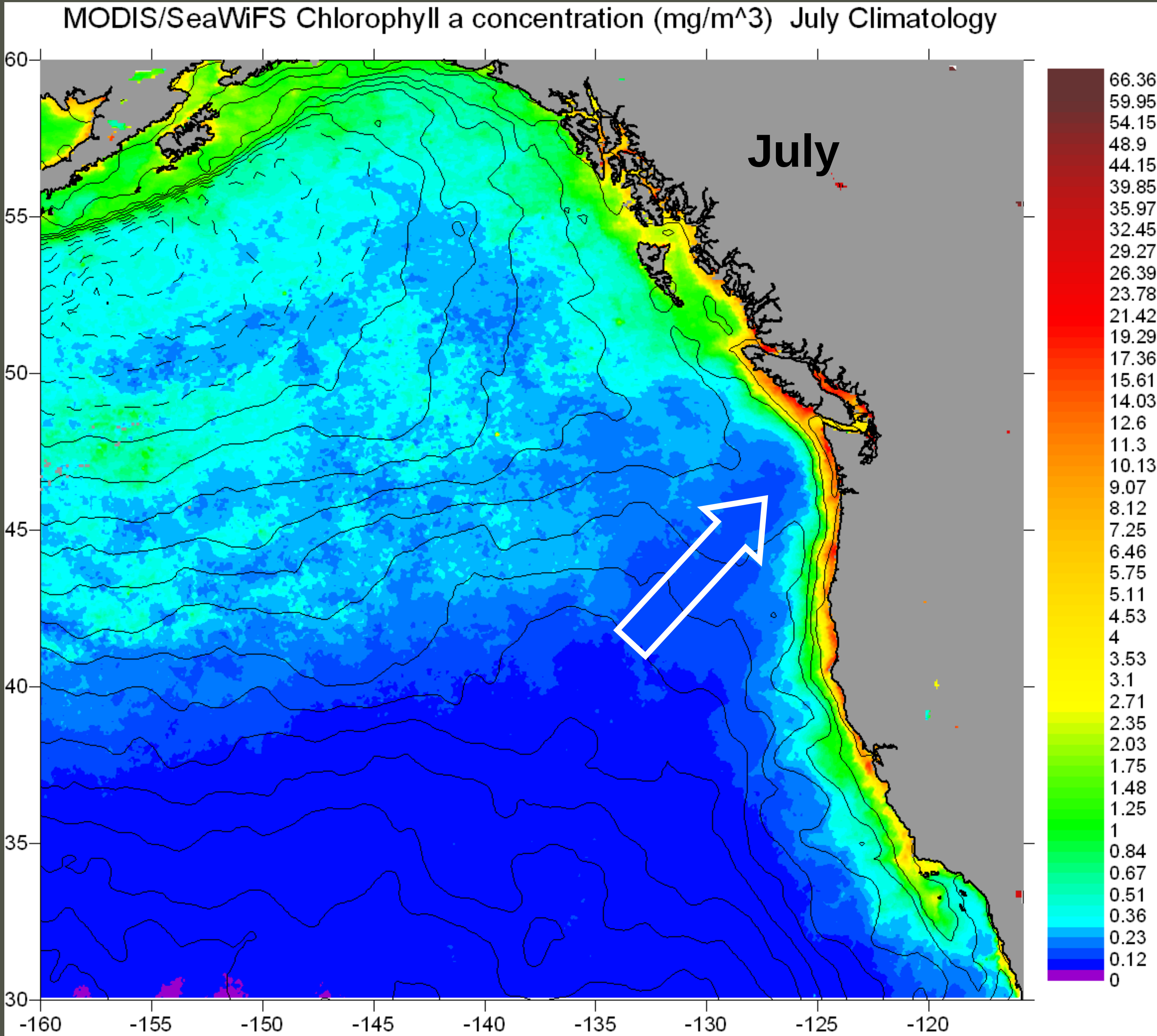
The sharp edges of the low-chlorophyll region suggests that oceanic transport of iron is more important in summer than is atmospheric transport.

An apparent tongue of low-nitrate water extends toward Vancouver Island from the southwest.  Low nitrate in summer in this tongue depends on nearby upwelling and Ekman transport as well as movement of subarctic water itself.

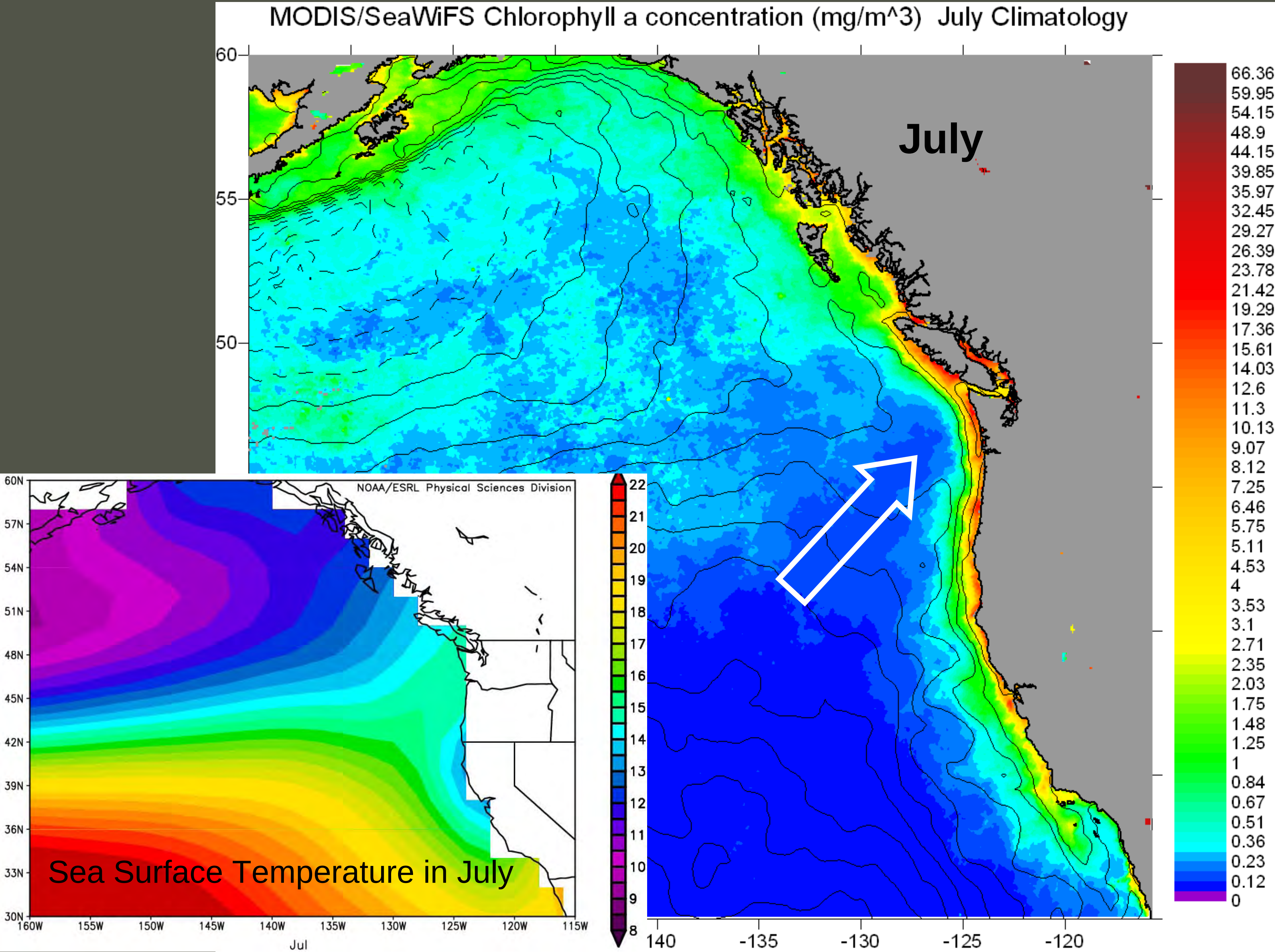


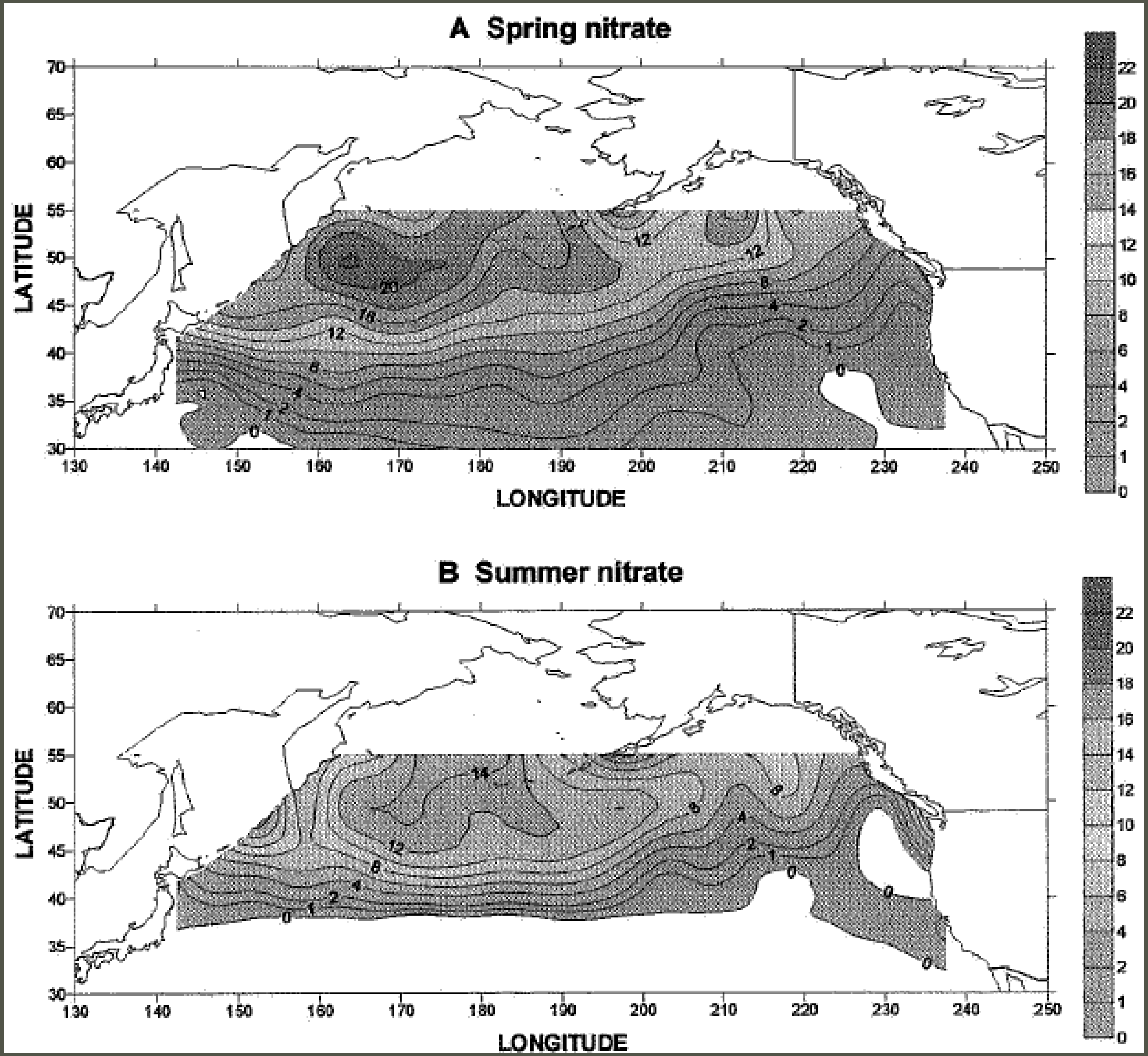

$NO_3$ at 150 m depth

NO3 at ocean surface

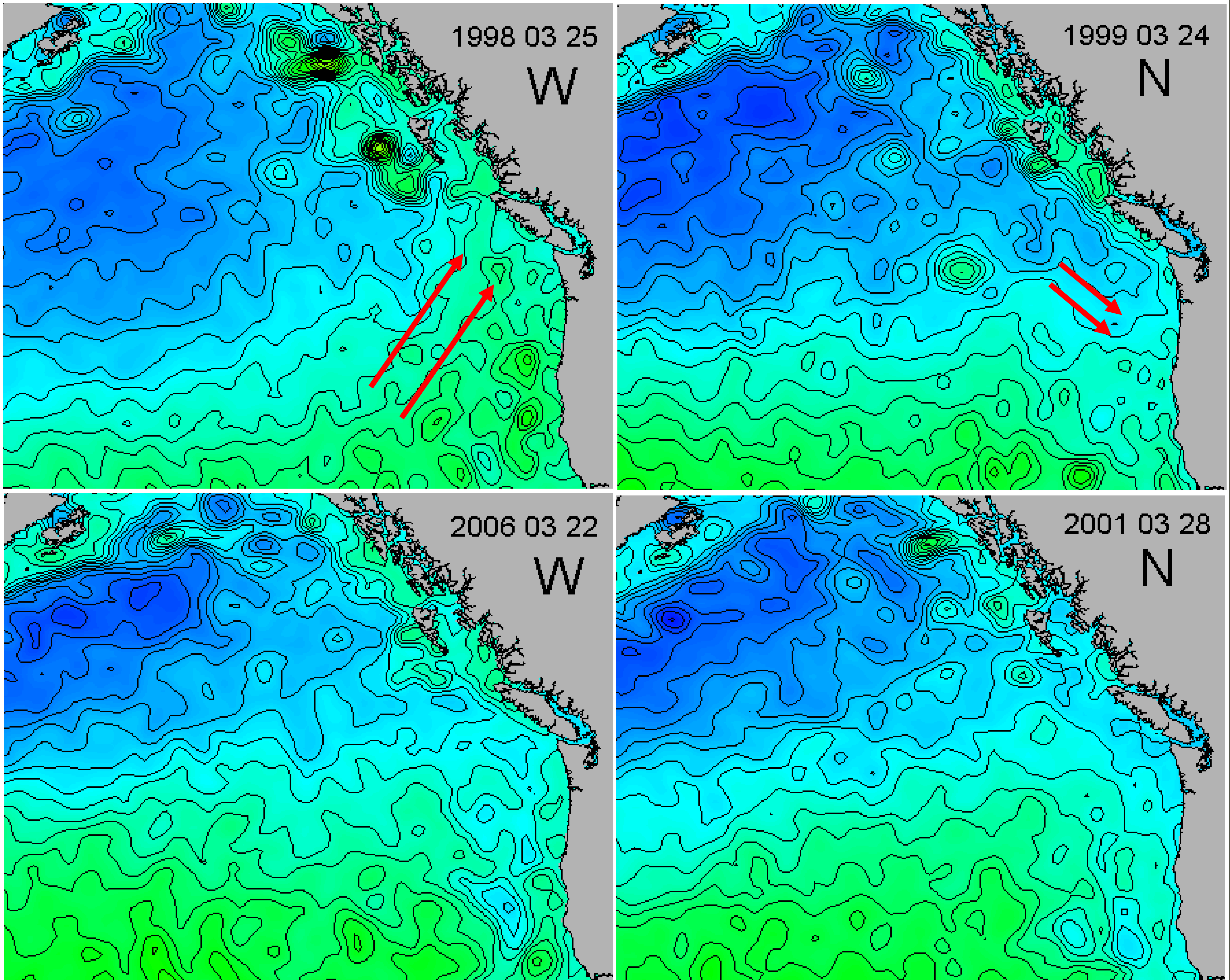


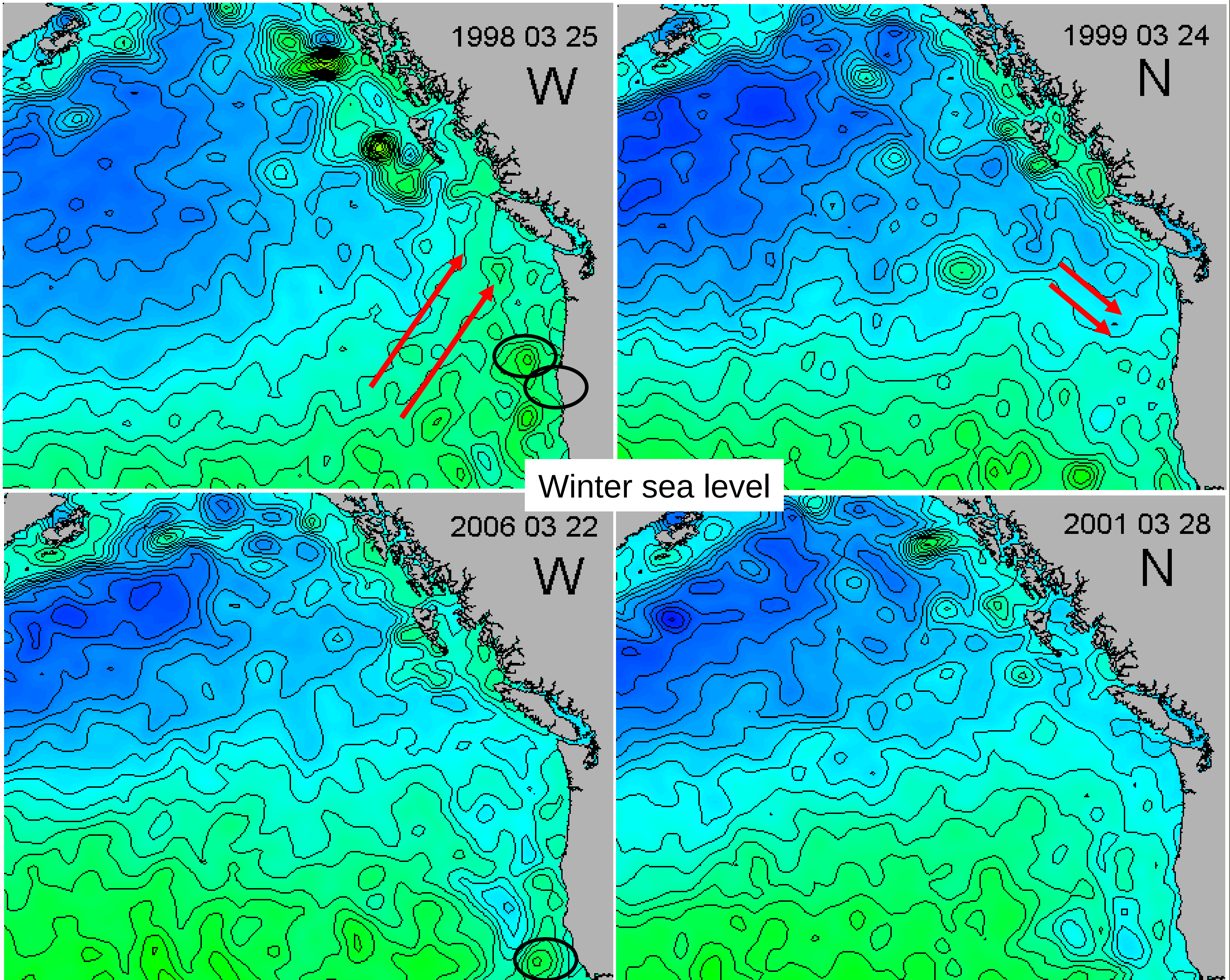
MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) July Climatology
July
60
55
50
45
40
35
30
-160
-155
-150
-145
-140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0

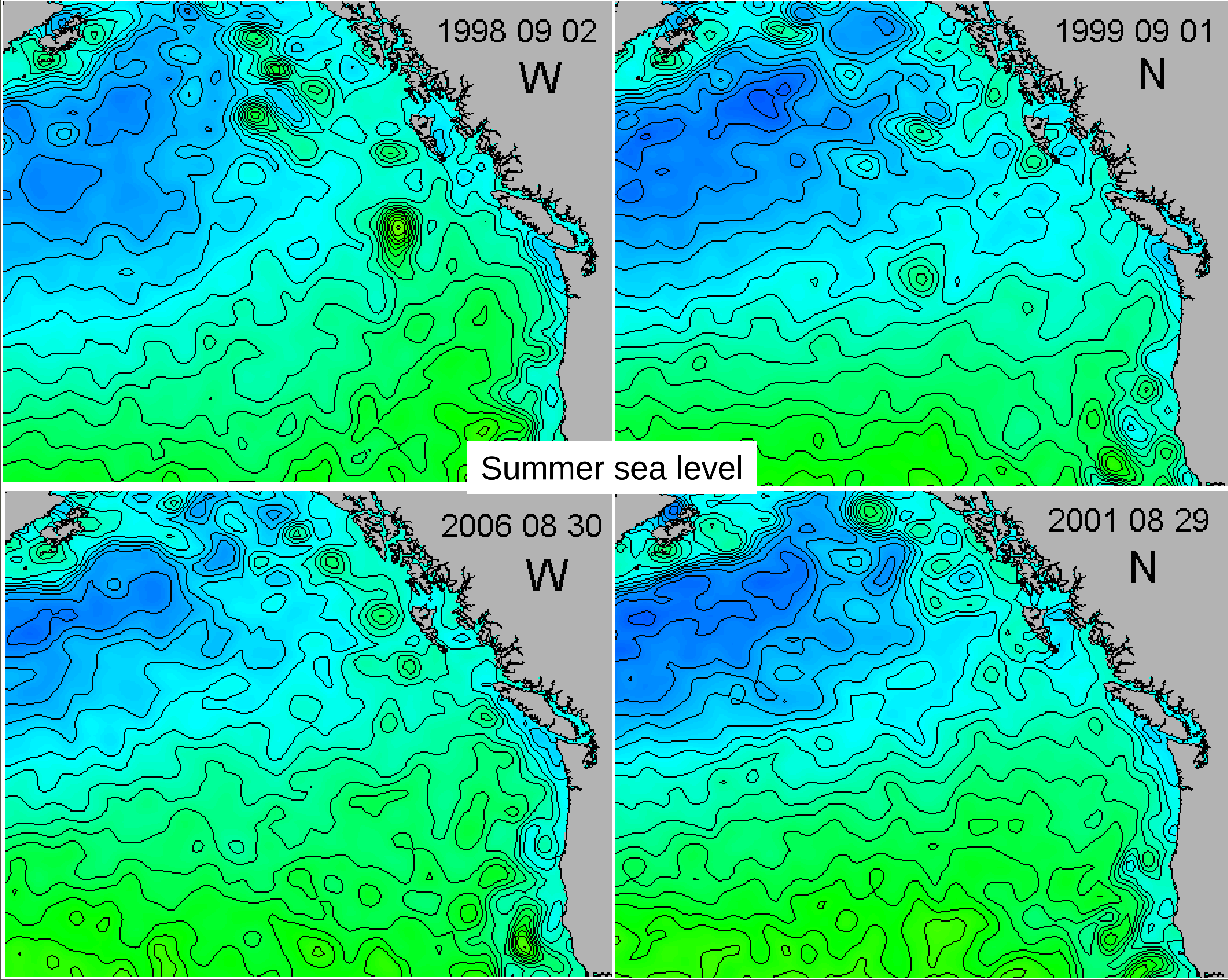

MODIS/SeaWiFS Chlorophyll a concentration (mg/m^3) July Climatology
July
60
55
50
140
-135
-130
-125
-120
66.36
59.95
54.15
48.9
44.15
39.85
35.97
32.45
29.27
26.39
23.78
21.42
19.29
17.36
15.61
14.03
12.6
11.3
10.13
9.07
8.12
7.25
6.46
5.75
5.11
4.53
4
3.53
3.1
2.71
2.35
2.03
1.75
1.48
1.25
1
0.84
0.67
0.51
0.36
0.23
0.12
0
NOAA/ESRL Physical Sciences Division
Sea Surface Temperature in July
60N
57N
54N
51N
48N
45N
42N
39N
36N
33N
30N
160W
155W
150W
145W
140W
135W
130W
125W
120W
115W
Jul
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8




Wong et al. 2002. Seasonal and Interannual variability in the distribution of surface nutrients and dissolved inorganic carbon in the northern North Pacific: Influence of El Niño. Journal of Oceanography.


1998 03 25
W
1999 03 24
N
2006 03 22
W
2001 03 28
N


1998 03 25
W
1999 03 24
N
Winter sea level
2006 03 22
W
2001 03 28
N


1998 09 02
W
1999 09 01
N
Summer sea level
2006 08 30
W
2001 08 29
N

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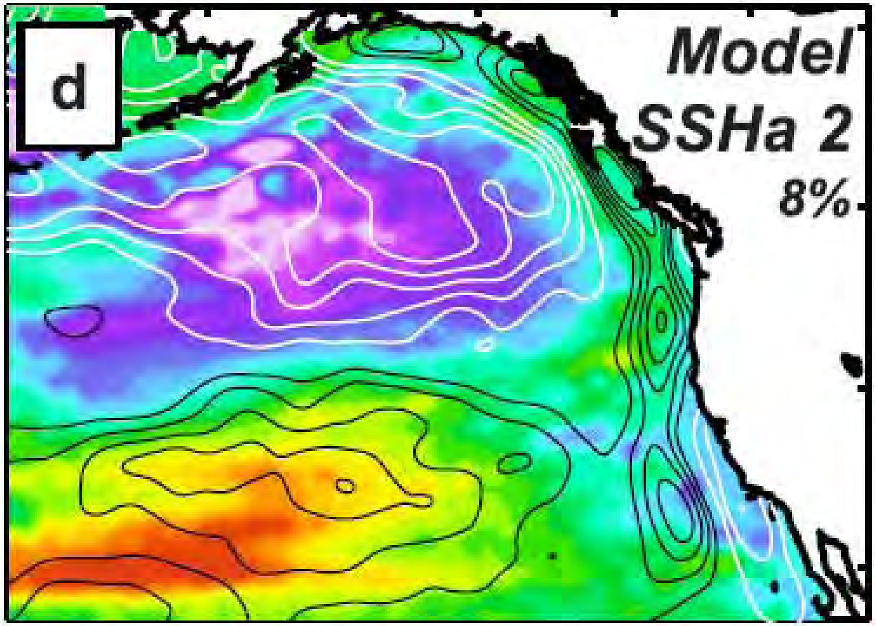


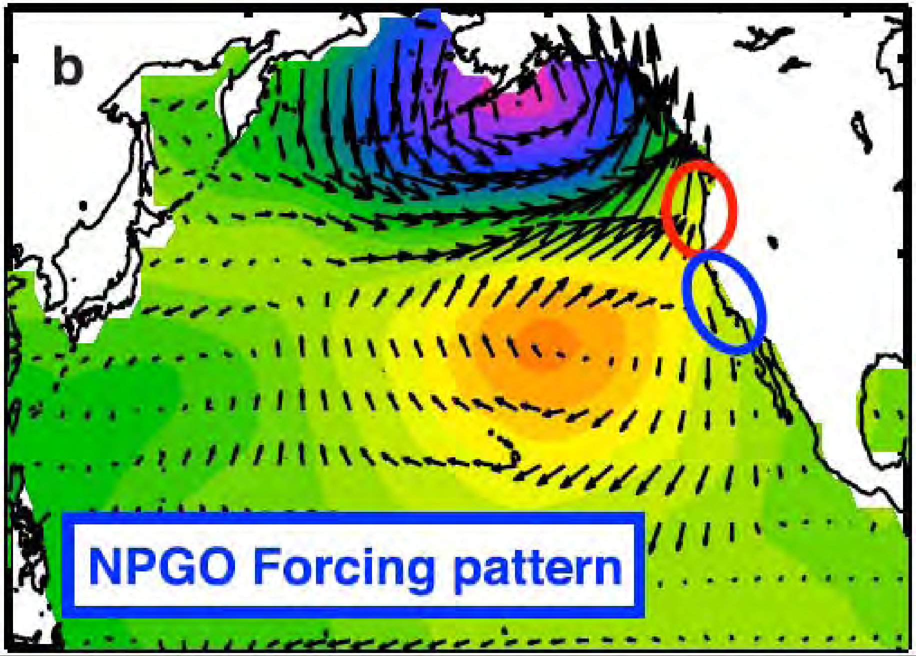


Colour: Sea surface height anomaly in numerical model.

Black & white contours: wind stress curl. Upwelling inside white contours

Colour: NCEP air pressure associated with NPGO.

Vectors: NCEP wind stress associated with NPGO.

Suspect the narrow region of low-nutrient along Line P is associated with positive NPGO, due to strong upwelling and Ekman flow in this region.