Origin of the mesoscale eddies and year-to-year changes of the chlorophyll-*a* concentration in the Kuril Basin of the Okhotsk Sea

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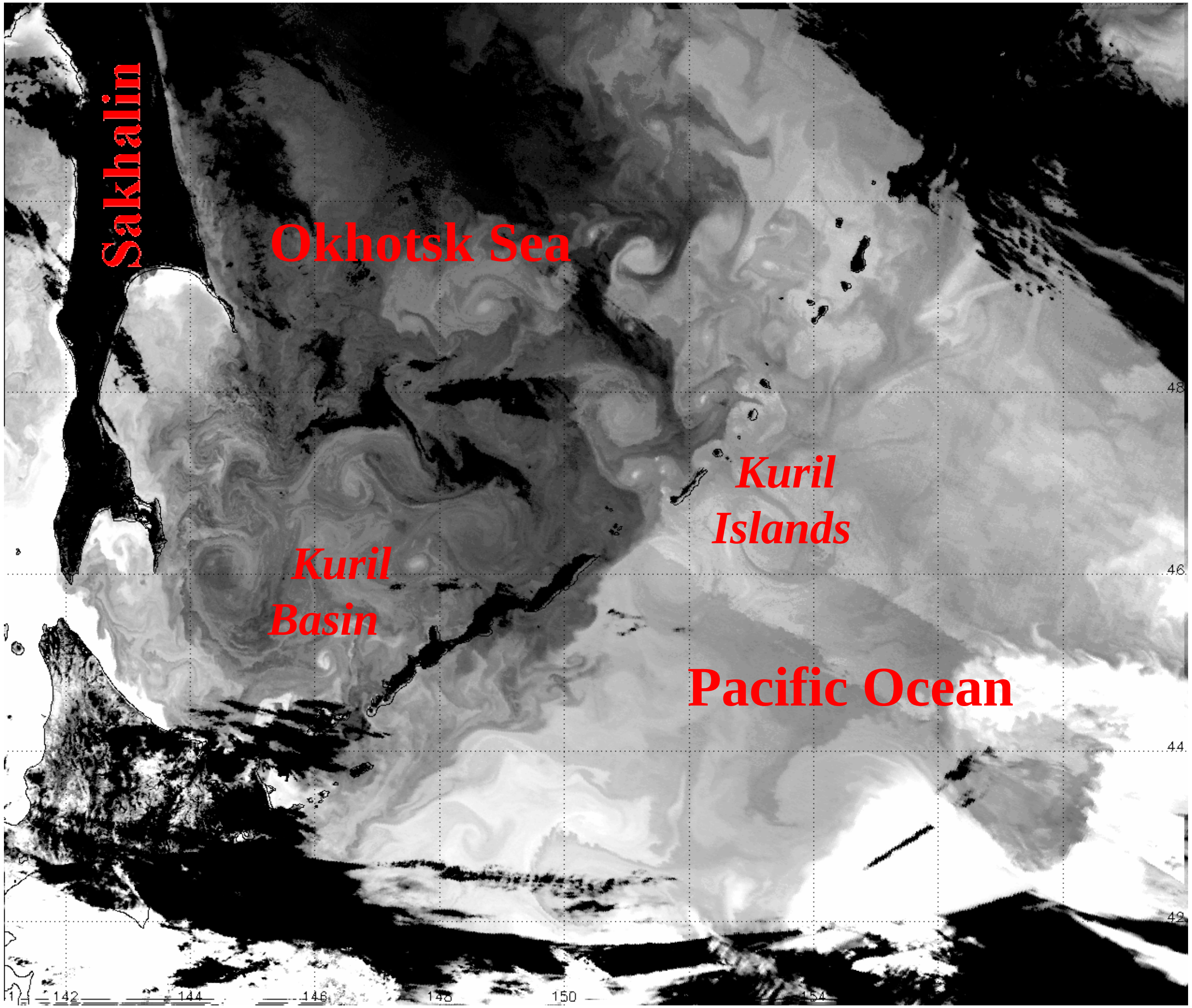
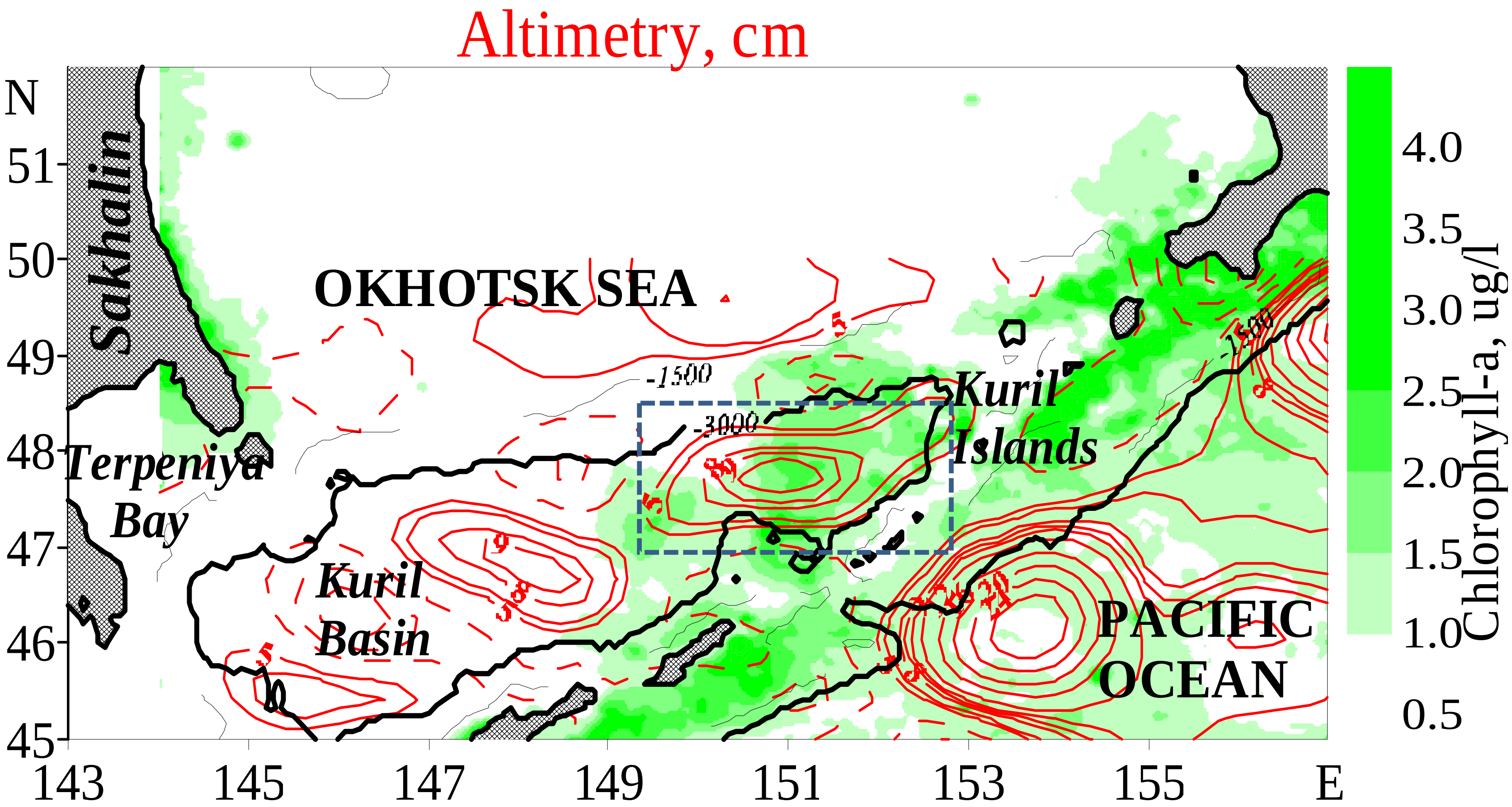
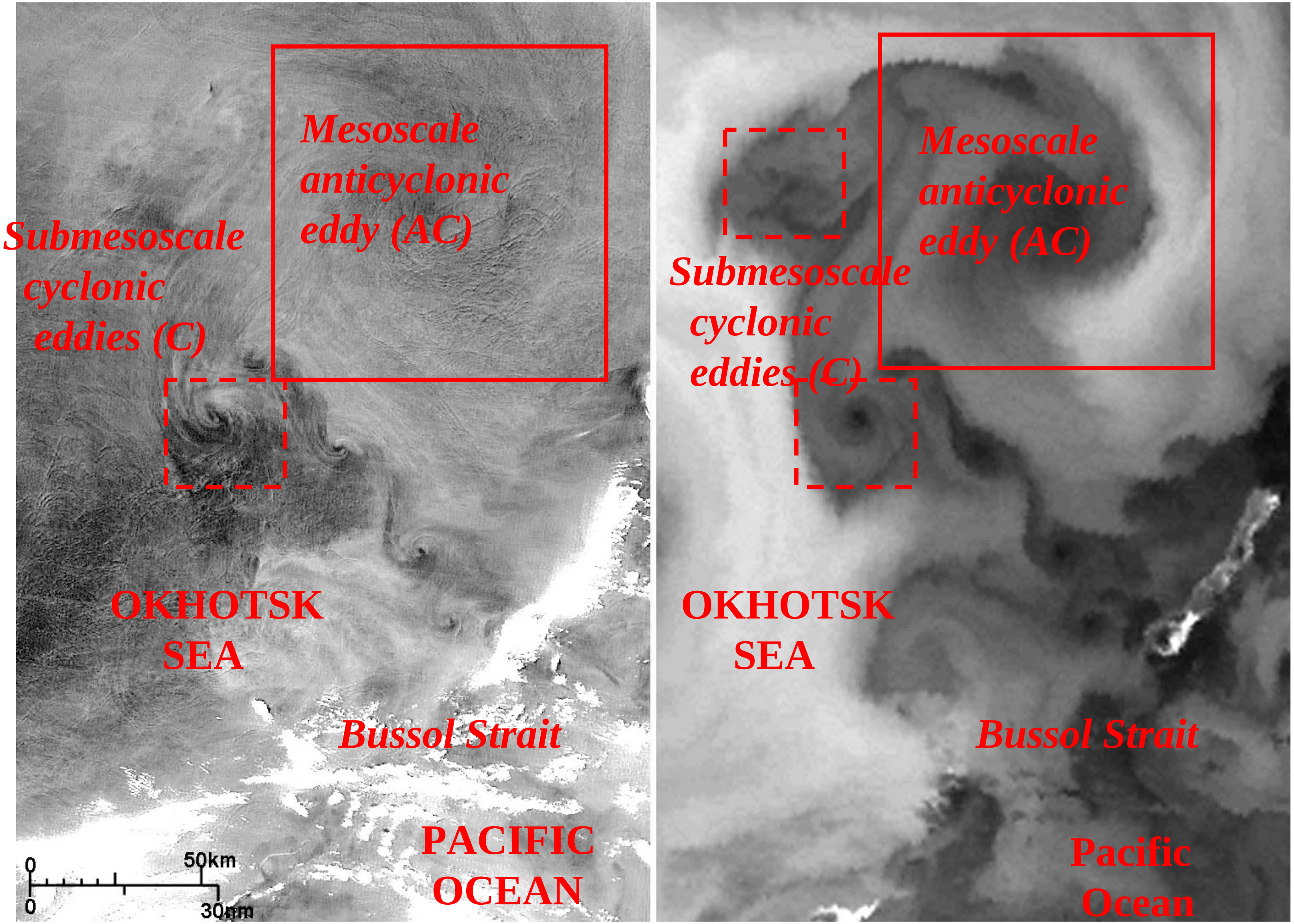
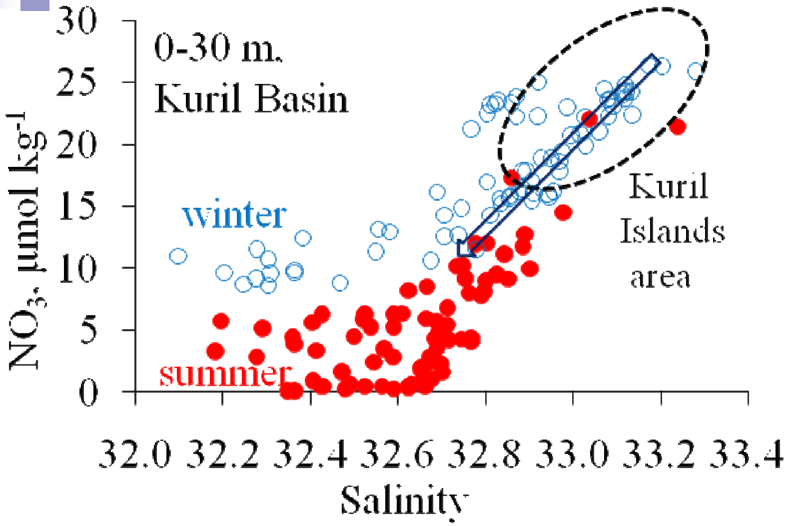
In the post-spring-bloom period (July-September), the high primary production values in the Okhotsk Sea are commonly confined to dynamically active zone, where nutrients are supplied to the upper mixed layer. Strong tidal mixing in the Kuril straits area augment nutrients in the euphotic zone, and submesoscale and mesoscale eddies transport high-nutrient coastal waters into pelagic part of the Okhotsk Sea. We demonstrate that mesoscale eddies originating in the Kuril Basin are related to the baroclinic waves coming from the Pacific Ocean into the Okhotsk Sea through the Kuril Straits. There is a strong relationship between the wind stress curl in the northern North Pacific in winter and the eddy dynamics in the Okhotsk Sea. Increased wind stress curl results in enhanced mesoscale eddy activity and high chlorophyll concentration in the Okhotsk Sea in late summer and fall with 1- year lag.

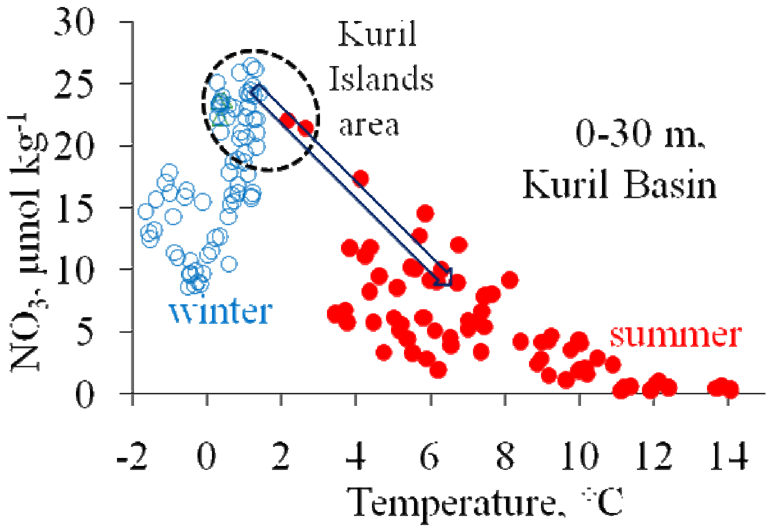
MODIS (Terra, Aqua)

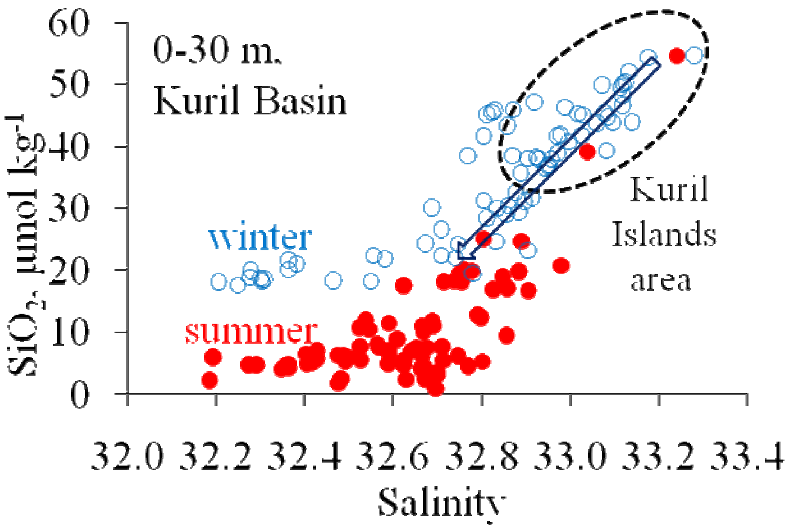


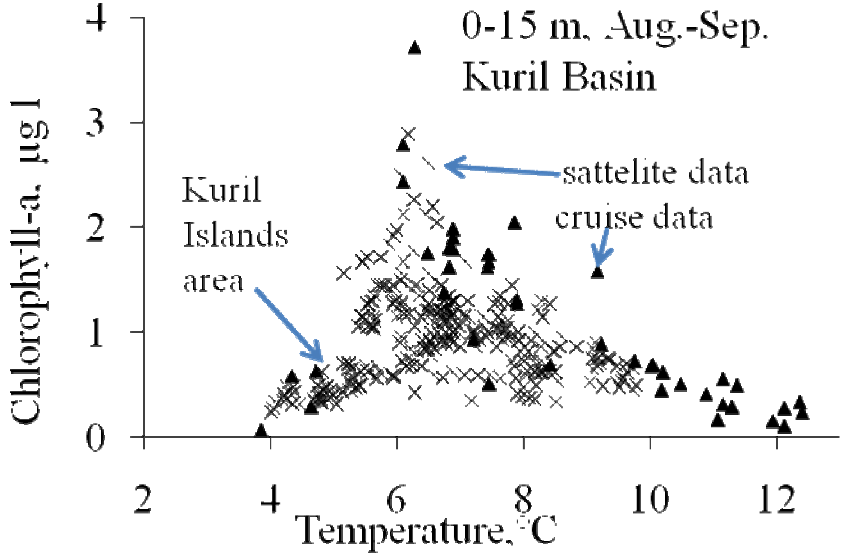

Altimetry, cm
N
51
50
49
48
47
46
45
143
145
147
149
151
153
155
E
Sakhalin
OKHOTSK SEA
Terpeniya
Bay
Kuril
Basin
Kuril
Islands
PACIFIC
OCEAN
-1500
-3000
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Chlorophyll-a, ug/l


Mesoscale anticyclonic eddy (AC)
Submesoscale cyclonic eddies (C)
OKHOTSK SEA
Bussol Strait
PACIFIC OCEAN
0 50km
0 30nm
Mesoscale anticyclonic eddy (AC)
Submesoscale cyclonic eddies (C)
OKHOTSK SEA
Bussol Strait
Pacific Ocean


0-30 m.
Kuril Basin
winter
summer
Kuril
Islands
area
NO3, μmol kg-1
0
5
10
15
20
25
30
32.0 32.2 32.4 32.6 32.8 33.0 33.2 33.4
Salinity

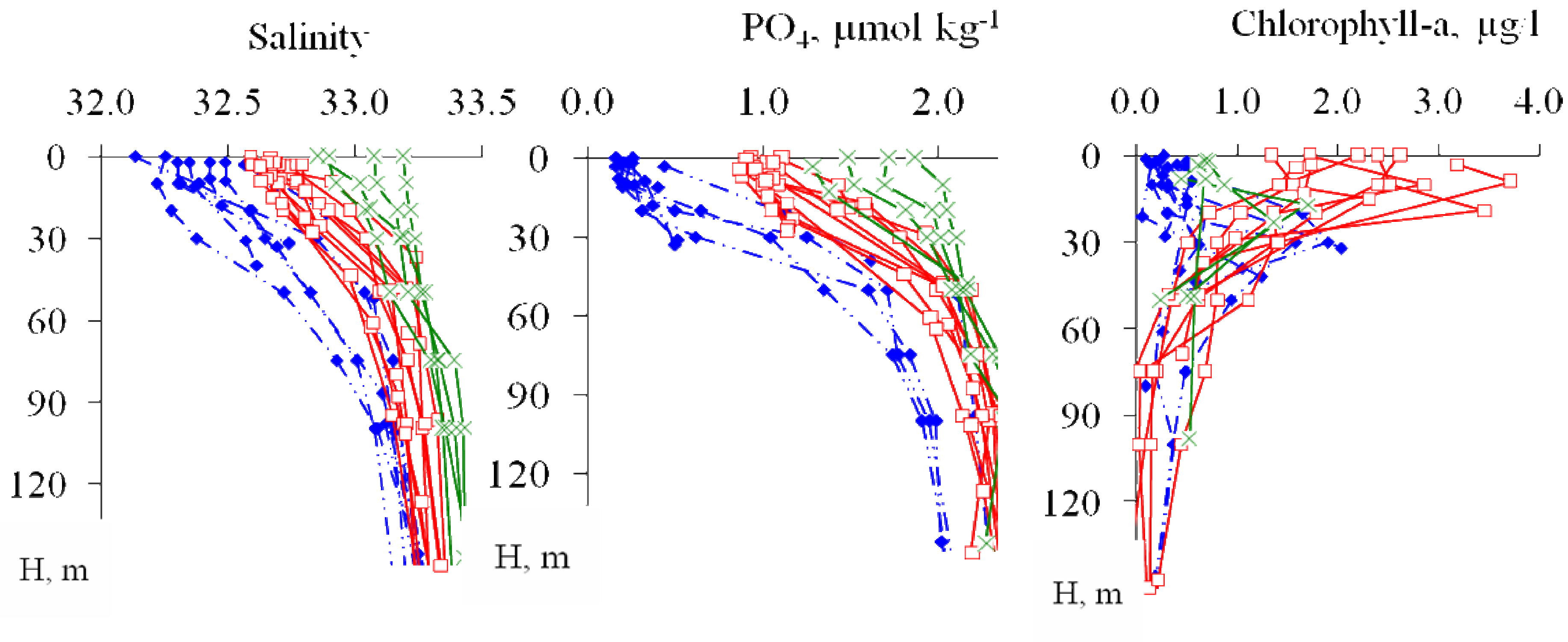

Kuril
Islands
area
0-30 m.
Kuril Basin
winter
summer
NO3, μmol kg-1
0
5
10
15
20
25
30
-2 0 2 4 6 8 10 12 14
Temperature, °C

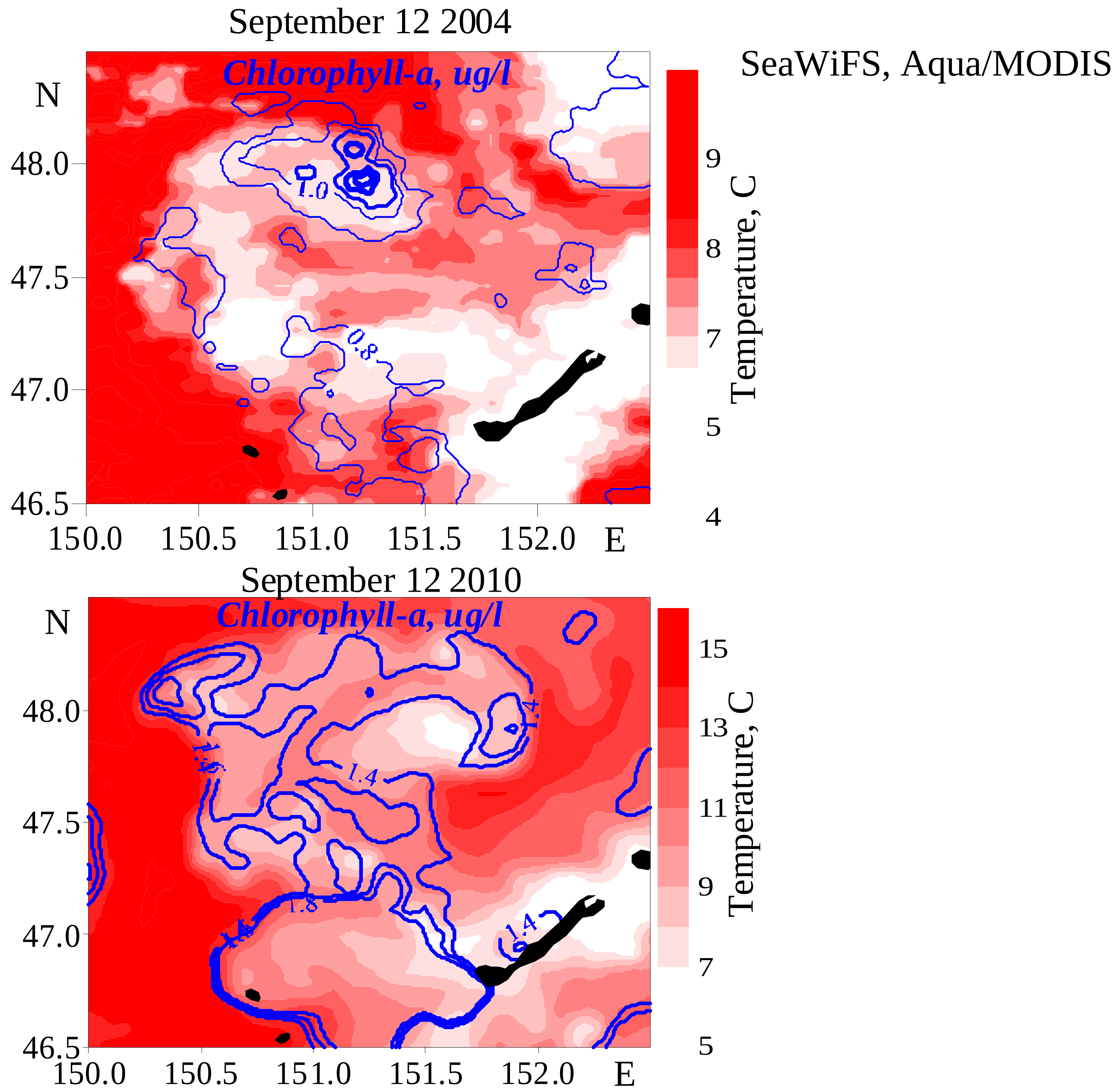

0-30 m.
Kuril Basin
winter
summer
Kuril
Islands
area
SiO2, μmol kg-1
0
10
20
30
40
50
60
32.0 32.2 32.4 32.6 32.8 33.0 33.2 33.4
Salinity

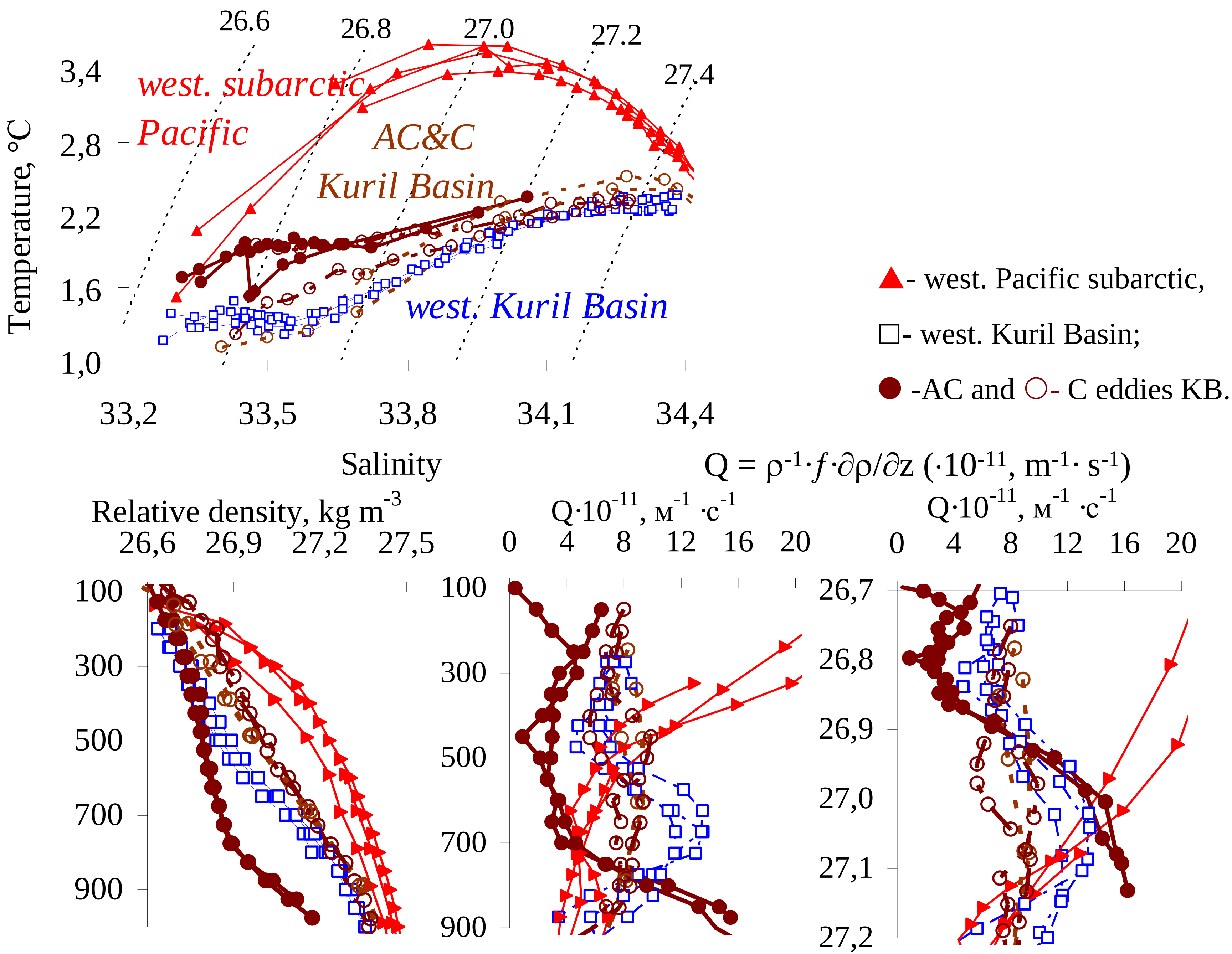

0-15 m. Aug.-Sep.
Kuril Basin
sattelite data
cruise data
Kuril
Islands
area
Chlorophyll-a, μg l
0
1
2
3
4
2 4 6 8 10 12
Temperature, °C

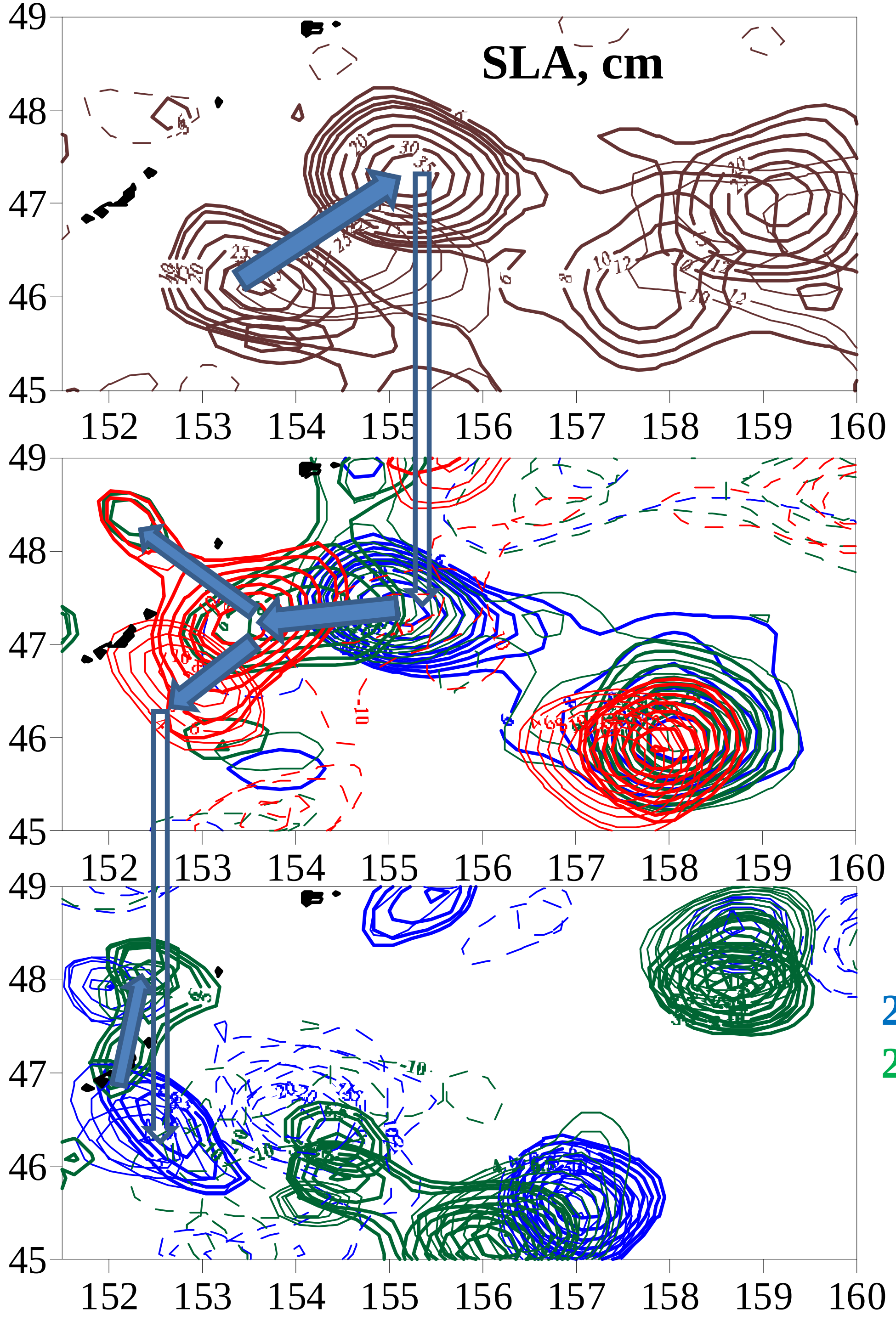
Kuril Basin, August-September

◆- western Kuril Basin, ✕ - Kuril Straits area, ■ - AC & C.




September 12 2004
Chlorophyll-a, ug/l
SeaWiFS, Aqua/MODIS
N
48.0
47.5
47.0
46.5
150.0
150.5
151.0
151.5
152.0
E
1.0
0.8
9
8
7
5
4
Temperature, C
September 12 2010
Chlorophyll-a, ug/l
N
48.0
47.5
47.0
46.5
150.0
150.5
151.0
151.5
152.0
E
1.4
1.6
1.8
15
13
11
9
7
5
Temperature, C


26.6
26.8
27.0
27.2
27.4
west. subarctic
Pacific
AC&C
Kuril Basin
west. Kuril Basin
Temperature, °C
3,4
2,8
2,2
1,6
1,0
33,2
33,5
33,8
34,1
34,4
Salinity
▲- west. Pacific subarctic,
□- west. Kuril Basin;
● -AC and ○- C eddies KB.
Q = ρ-1·f·∂ρ/∂z (·10-11, m-1· s-1)
Relative density, kg m-3
26,6
26,9
27,2
27,5
100
300
500
700
900
Q·10-11, м-1 ·c-1
0
4
8
12
16
20
100
300
500
700
900
Q·10-11, м-1 ·c-1
0
4
8
12
16
20
26,7
26,8
26,9
27,0
27,1
27,2



2003.83-2003.98

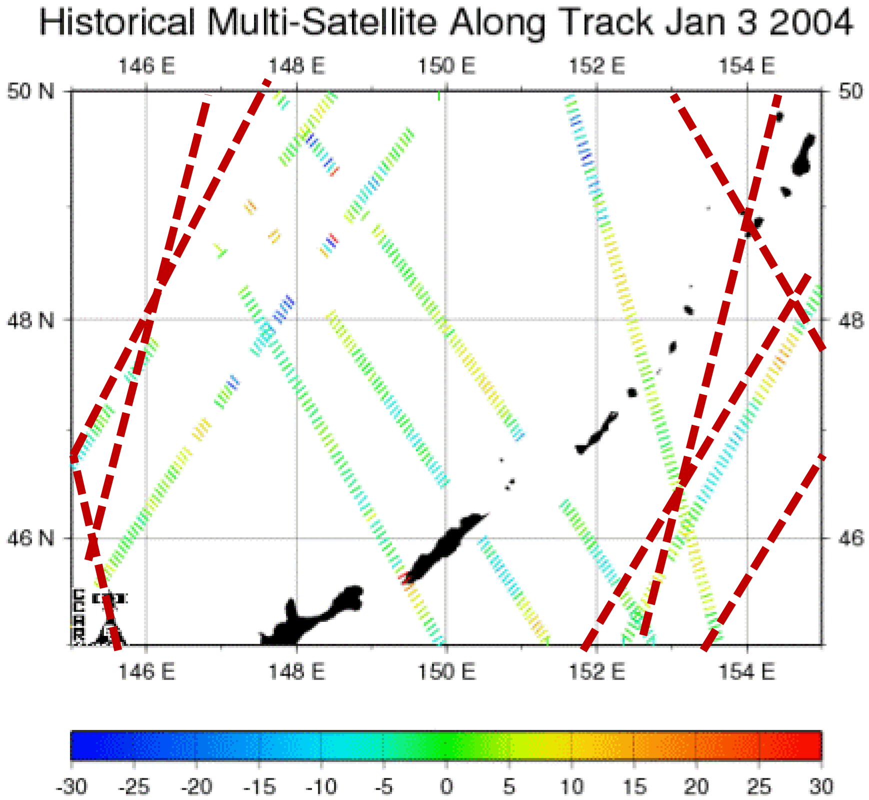
SLA (merged),
weeekly,
1/3° x 1/3°

2004.00,
2004.02-2004.04,
2004.06-2004.09

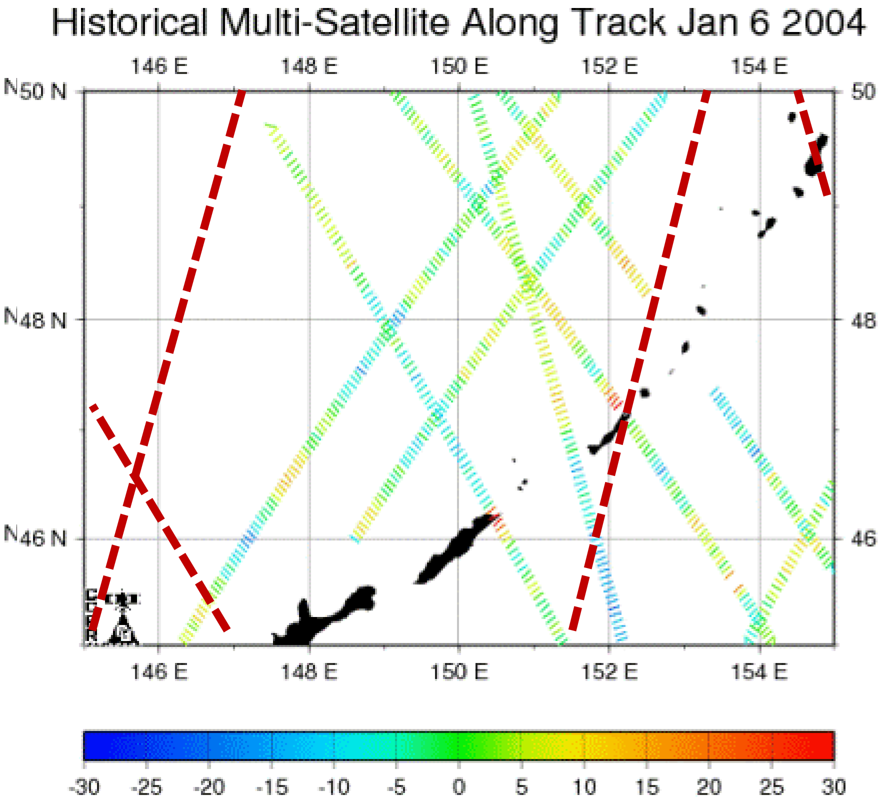
2004.13-2004.17,
2004.21-2004.29

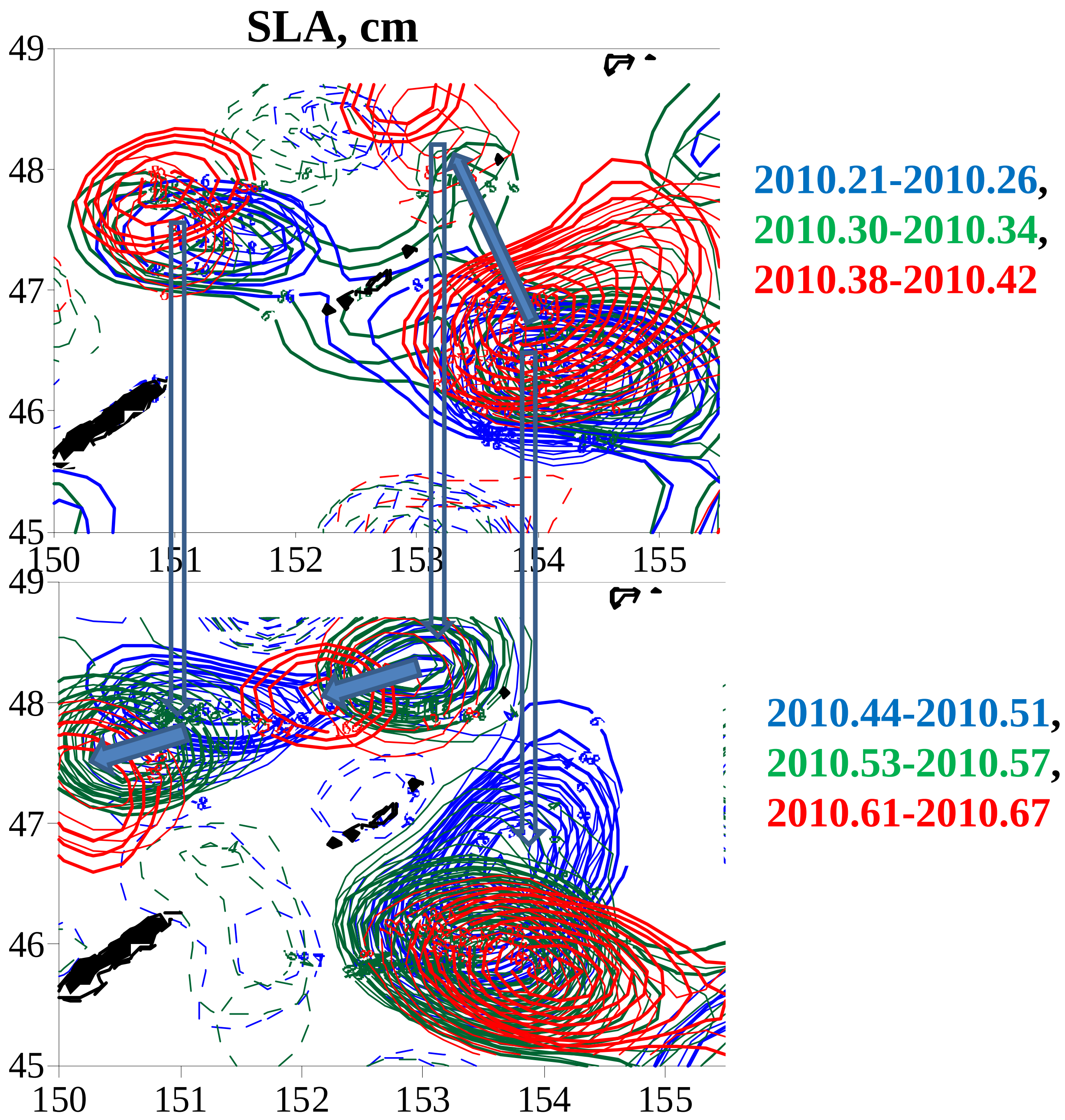
Multi-Satellite tracks Jan 01-07 2004

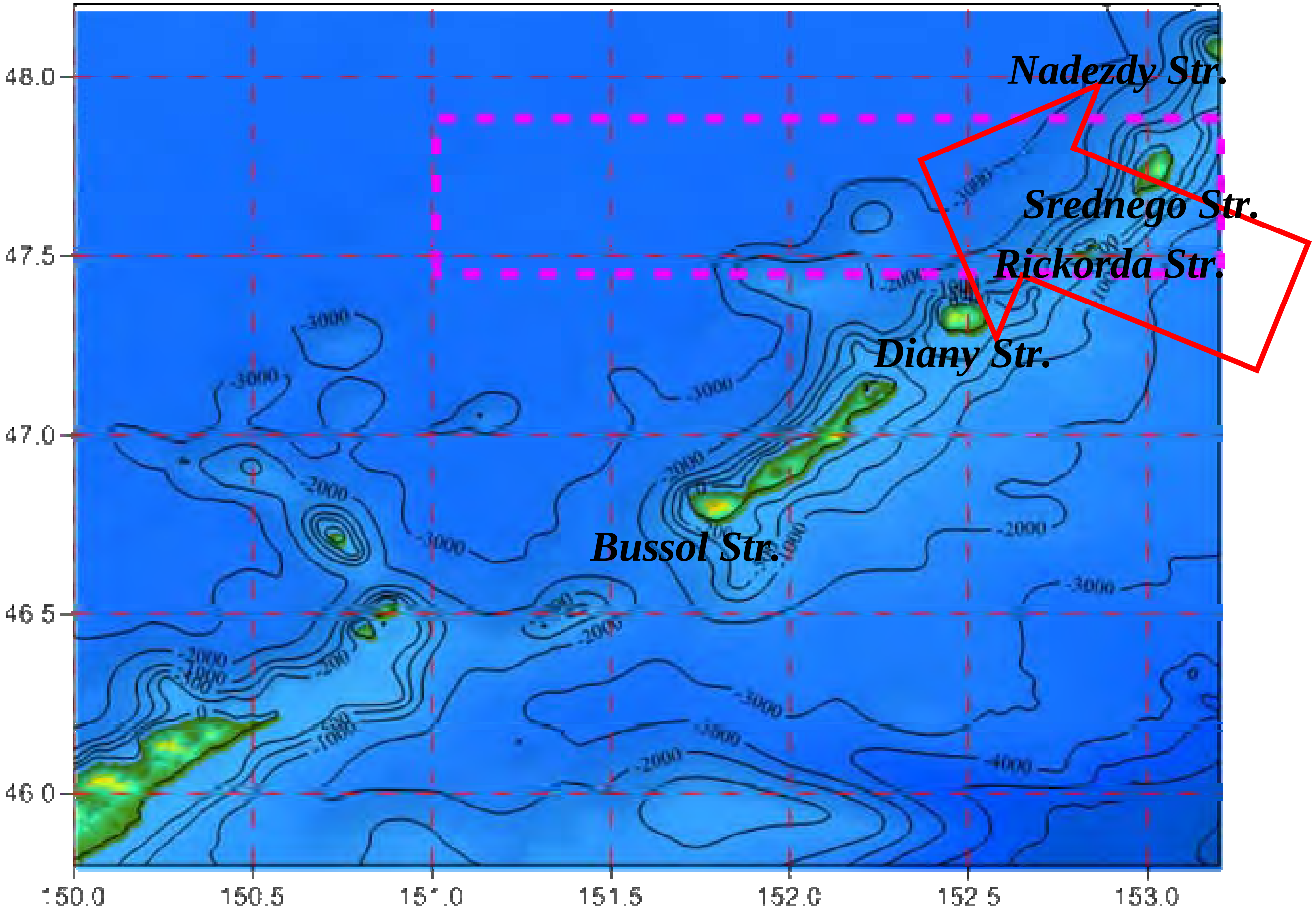
Jan 01-03 2004



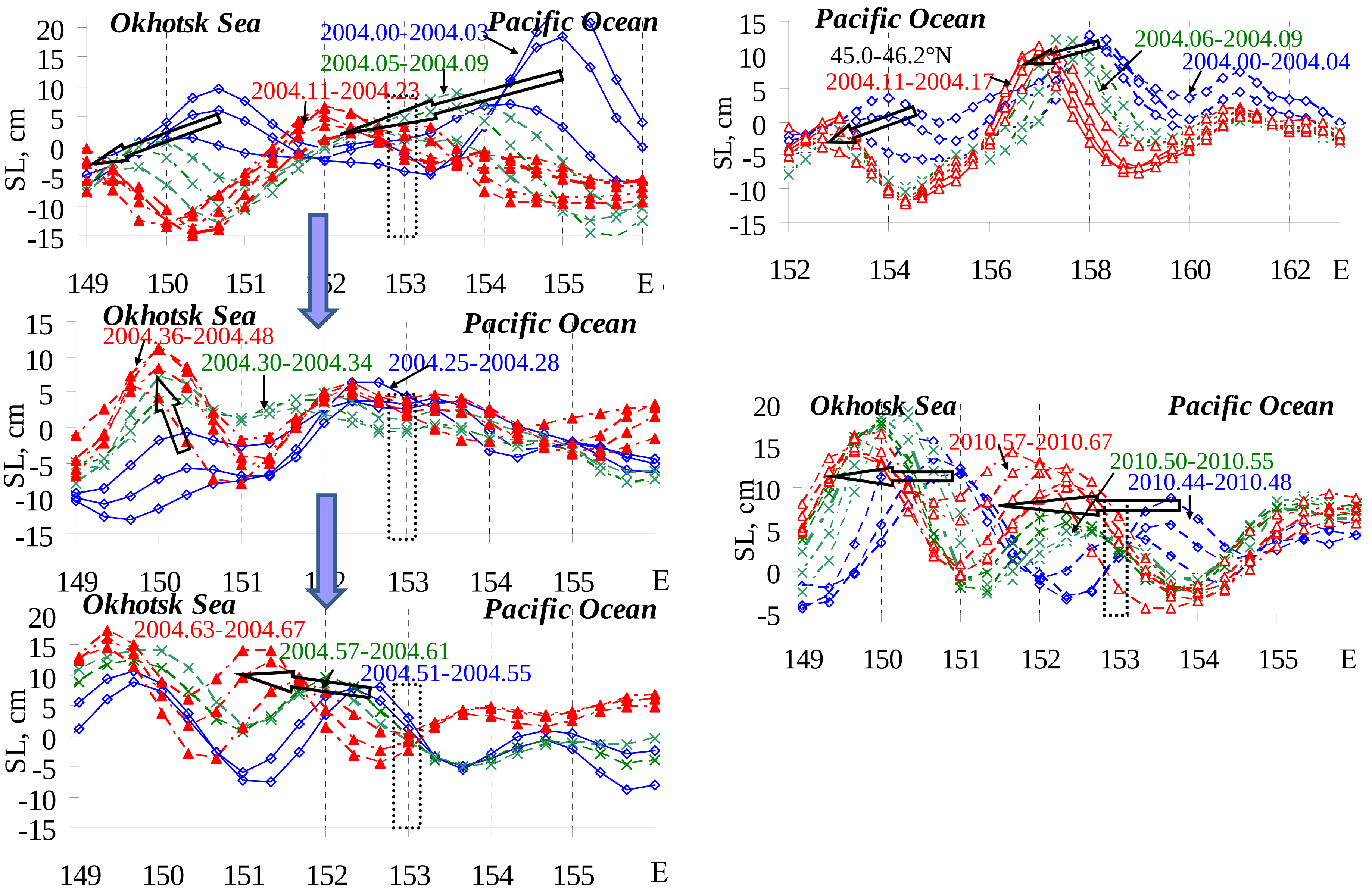
Jan 04-07 2004



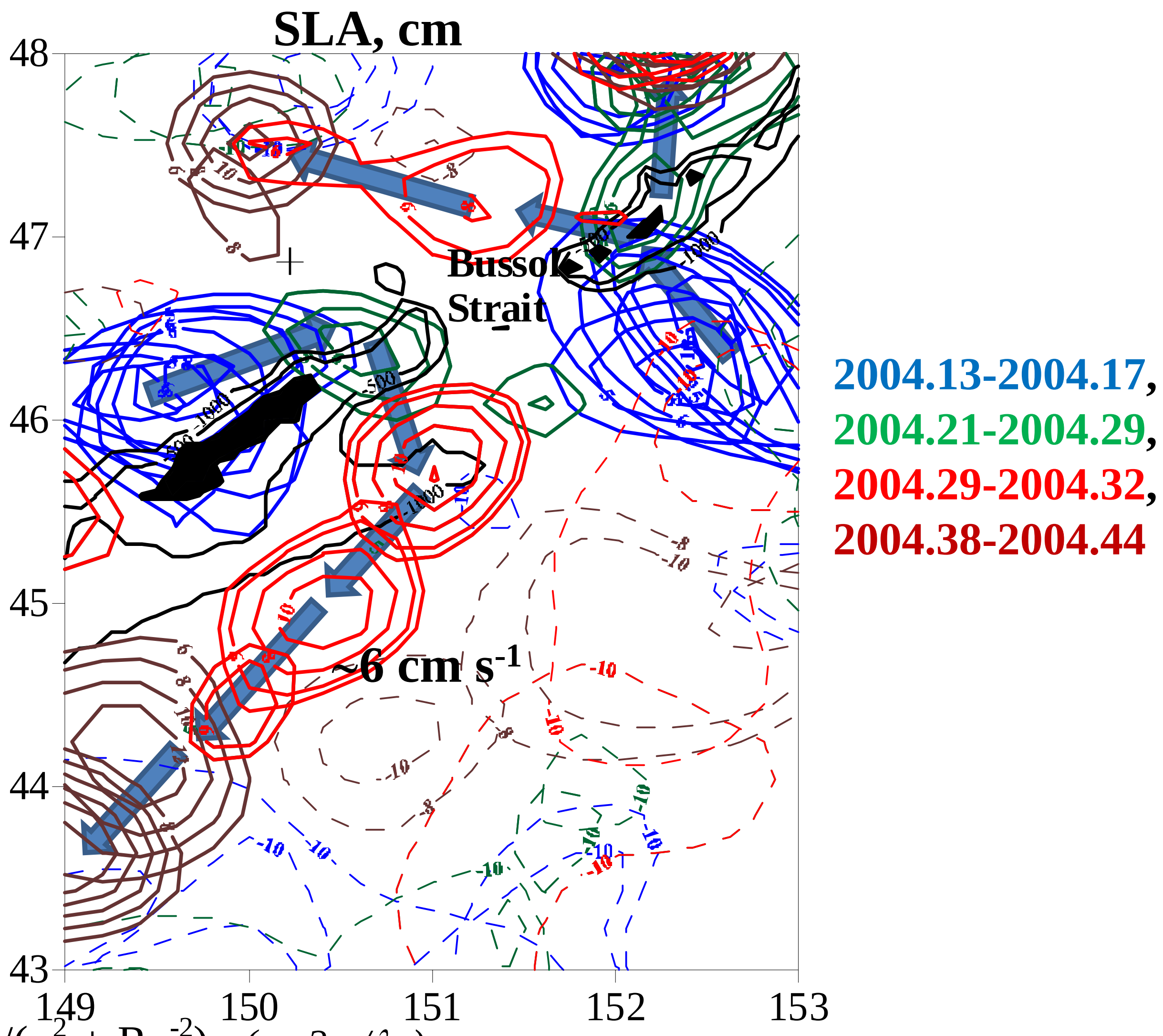

SLA, cm
49
48
47
46
45
150
151
152
153
154
155
2010.21-2010.26,
2010.30-2010.34,
2010.38-2010.42
2010.44-2010.51,
2010.53-2010.57,
2010.61-2010.67



Nadezdy Str.
Srednego Str.
Rickorda Str.
Diany Str.
Bussol Str.
48.0
47.5
47.0
46.5
46.0
150.0
150.5
151.0
151.5
152.0
152.5
153.0



Okhotsk Sea
Pacific Ocean
2004.00-2004.03
2004.05-2004.09
2004.11-2004.23
SL, cm
149 150 151 152 153 154 155 E
Okhotsk Sea
Pacific Ocean
2004.36-2004.48
2004.30-2004.34
2004.25-2004.28
SL, cm
149 150 151 152 153 154 155 E
Okhotsk Sea
Pacific Ocean
2004.63-2004.67
2004.57-2004.61
2004.51-2004.55
SL, cm
149 150 151 152 153 154 155 E
Pacific Ocean
45.0-46.2°N
2004.11-2004.17
2004.06-2004.09
2004.00-2004.04
SL, cm
152 154 156 158 160 162 E
Okhotsk Sea
Pacific Ocean
2010.57-2010.67
2010.50-2010.55
2010.44-2010.48
SL, cm
149 150 151 152 153 154 155 E



$c = \sigma/\kappa = -\beta/(\kappa^2 + R_D^{-2})$, $(\kappa = 2\pi/\lambda x)$

$c_{barotrop.} = 1.6\text{-}3.6$ cm s^{-1}, $(R_D = \sqrt{gh}\cdot f^{1}$, $\lambda x = 2\text{-}3\cdot 10^5$ $m)$

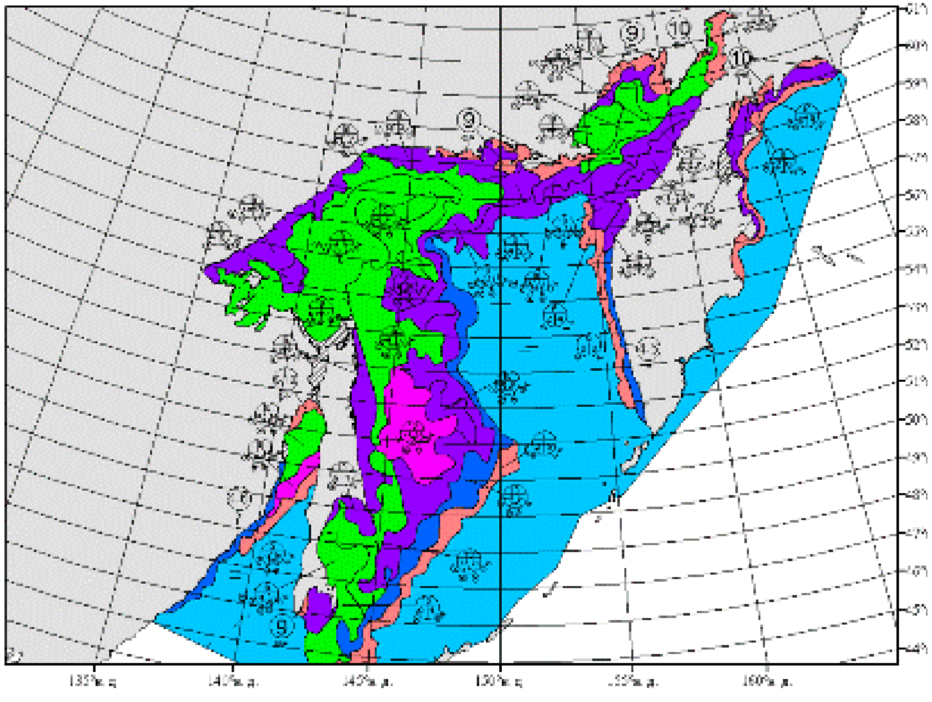
$c_{baroclin.} = 0.3\text{-}0.8$ cm s^{-1} $(R_D = \sqrt{g'he}\cdot f^{1}$, $\Delta\rho\cdot\rho^{-1} = 10^{-3}$, $h_e = 200\text{-}500$ $m)$

$c = \sigma/\kappa = fH^{-1}\partial H/\partial y/(\kappa^2 + R_D^{-2})$, $H^{-1}\partial H/\partial y = 2\text{-}5\cdot 10^{-5}$ m, $\lambda x = 3\cdot 10^5$ m,

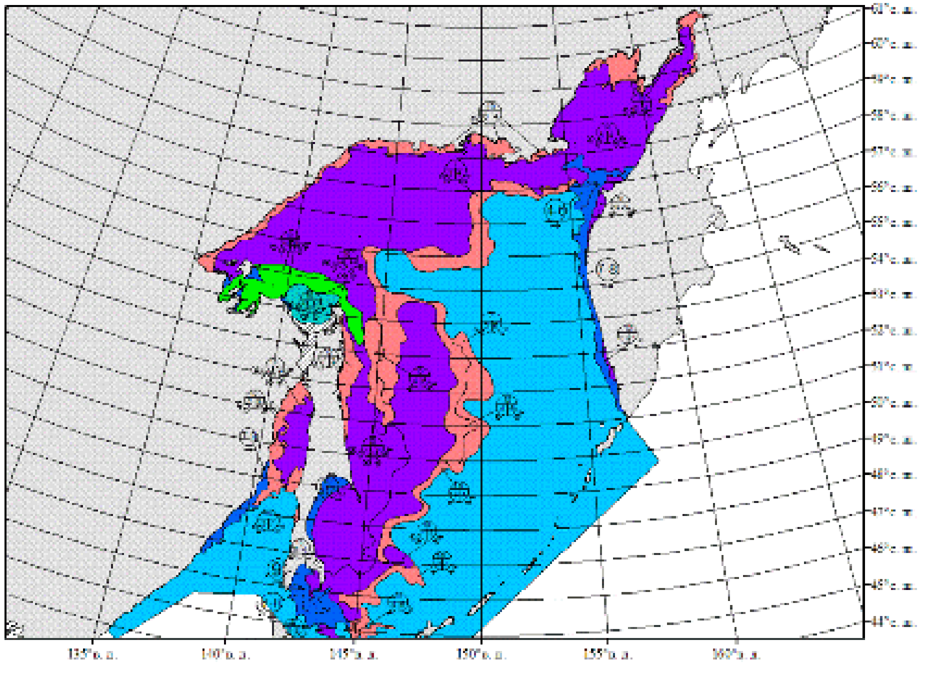
$R_D = 1.4\text{-}2.2\cdot 10^4$ m, $c_{barot.} = 5$–10 m s^{-1}, $c_{barocl.} = 0.4$–2.5 m s^{-1}

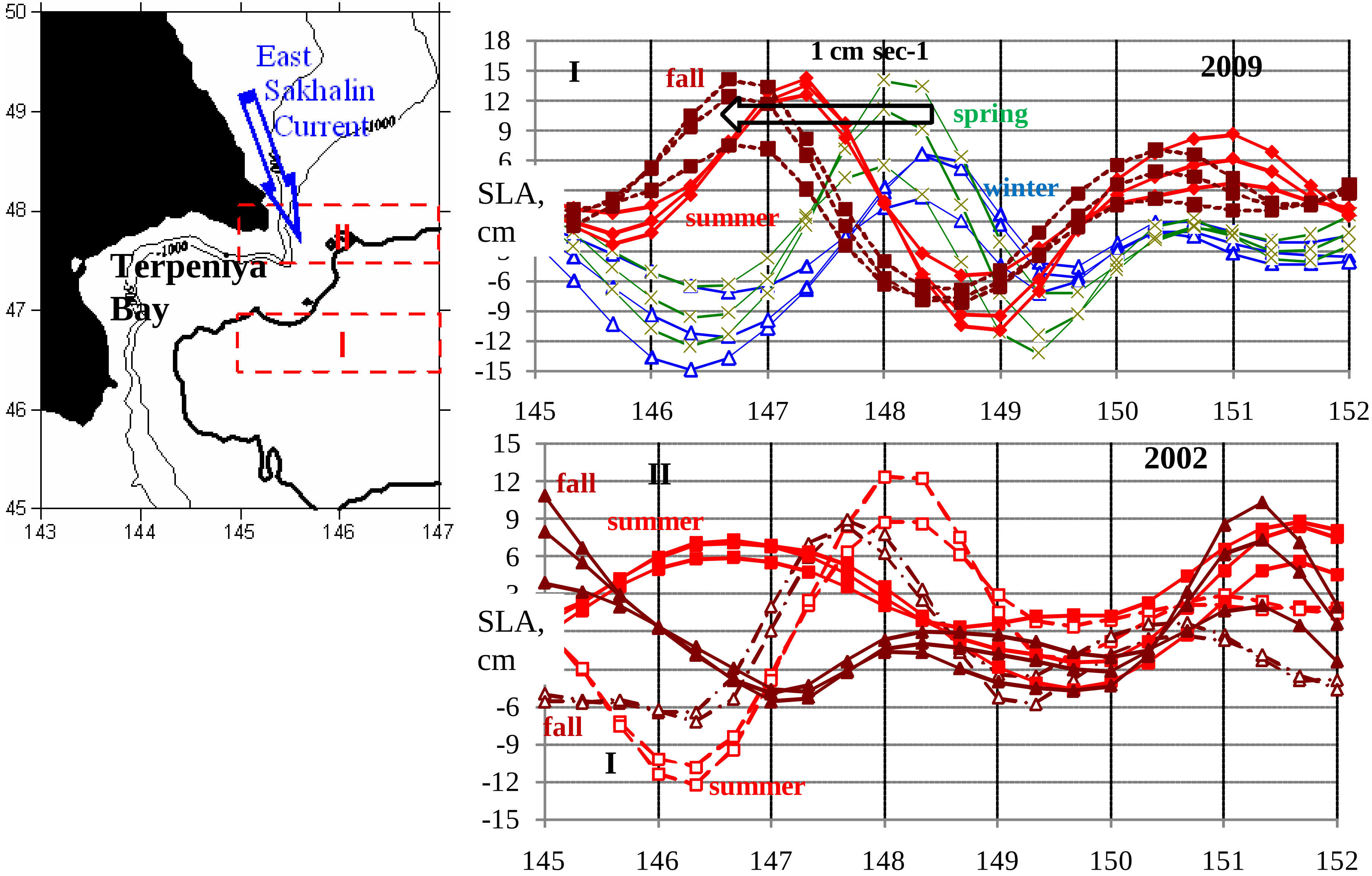
Ice extent

March 2004



March 2010



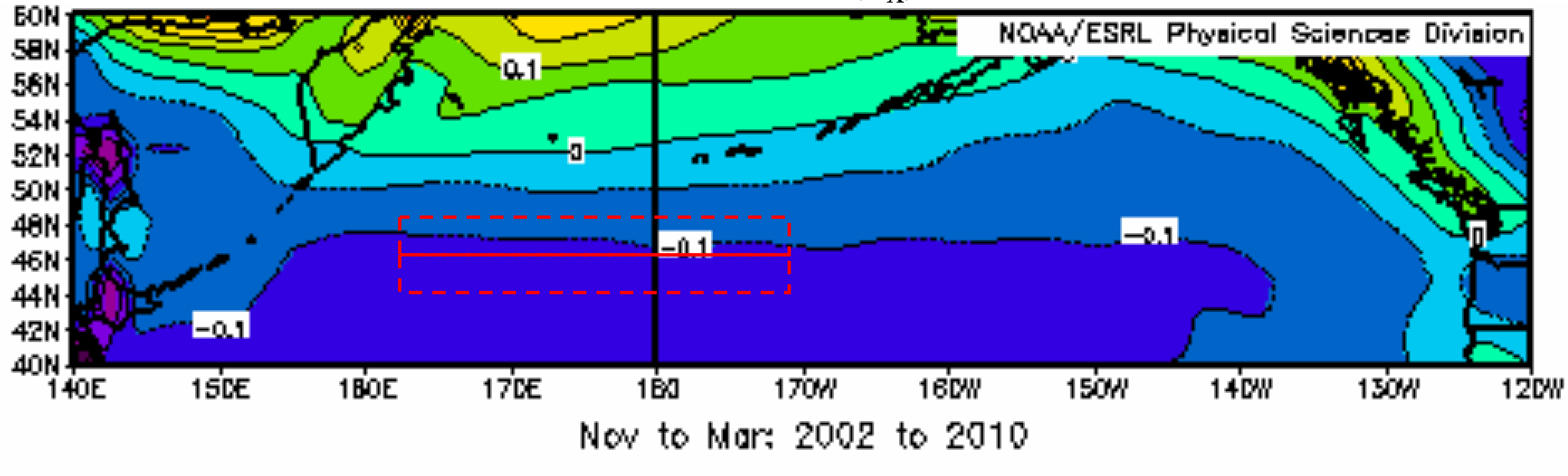


$$c = \sigma/\kappa = -\beta/(\kappa^2 + R_D^{-2}), \quad (\kappa = 2\pi/\lambda x)$$

$$c_{barotrop.} = 1.6\text{-}3.6 \text{ cm s}^{-1}, \ (R_D = \sqrt{gh} \cdot f^{-1}, \ \lambda x = 2\text{-}3 \cdot 10^5 \ m)$$

$$c_{baroclin.} = 0.3\text{-}0.8 \text{ cm s}^{-1} \ (R_D = \sqrt{g'he} \cdot f^{-1}, \ \Delta\rho \cdot \rho^{-1} = 10^{-3}, \ h_e = 200\text{ -}500 \ m)$$

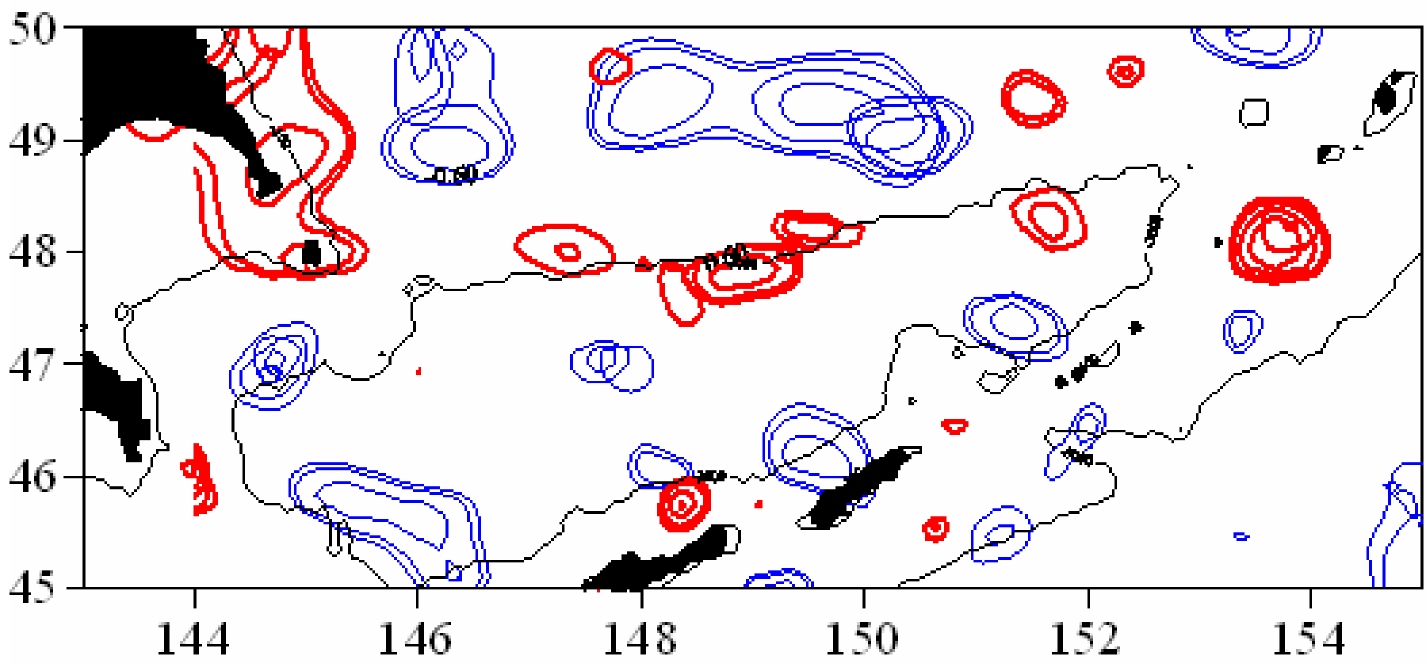
Zonal wind stress (τ_x), N m^{-2}

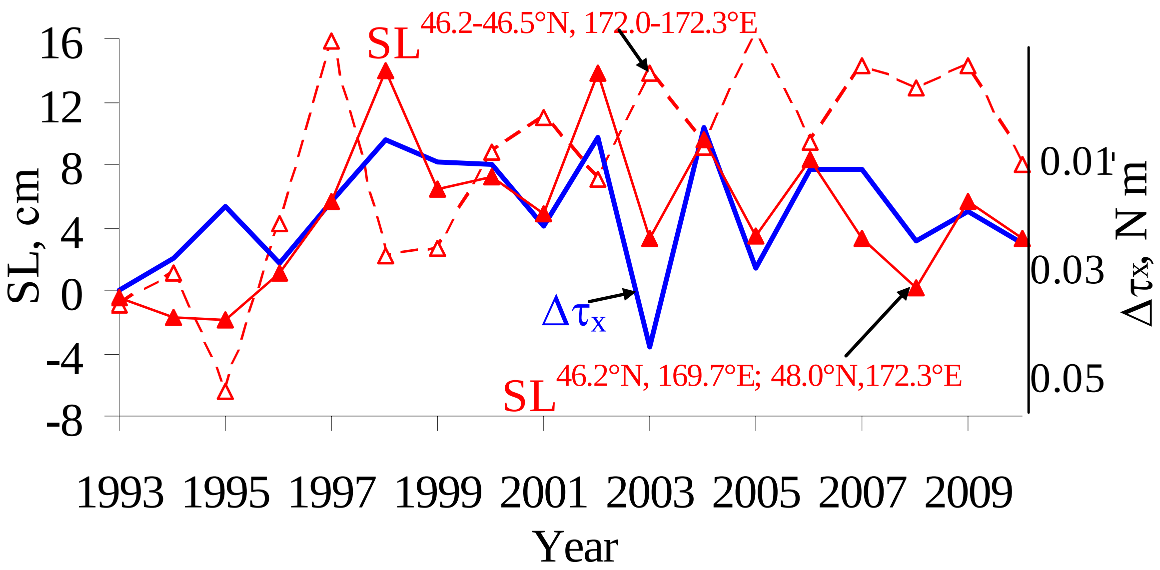


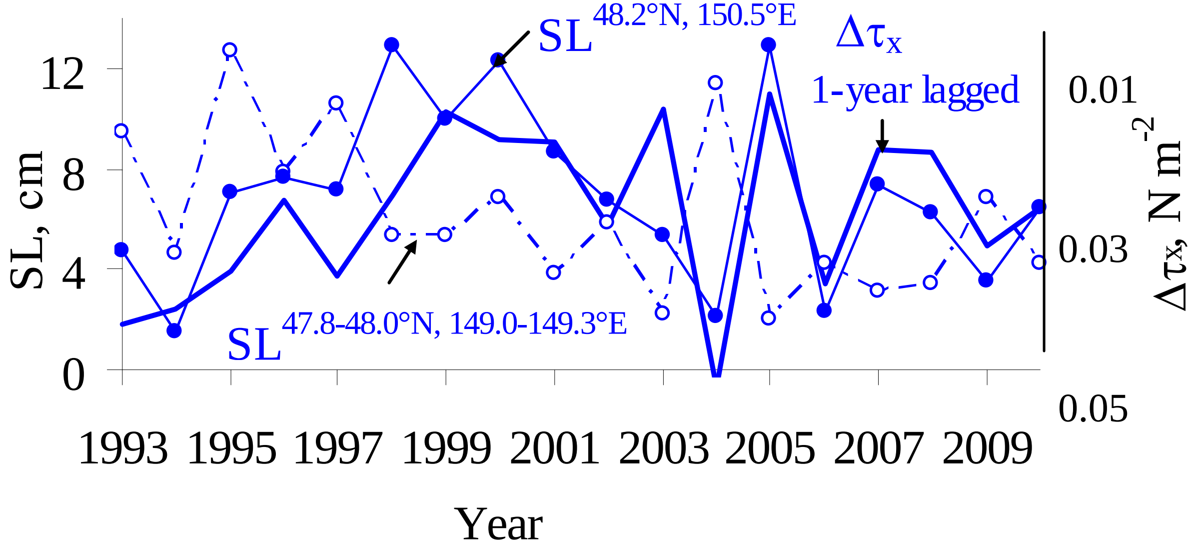
$$\Delta\tau_x = \tau_x^{\text{46-48°N,165°E-170°W}} - \tau_x^{\text{44-46°N,165°E-170°W}}$$

Correlation between ($\tau_x^{46-48°N,165°E-170°W} - \tau_x^{44-46°N,165°E-170°W}$) (November – March, 1-year lagged) and SL (monthly averaged, July, August, September)

r= 0.6-0.8, **r= -0.6 - -0.9**





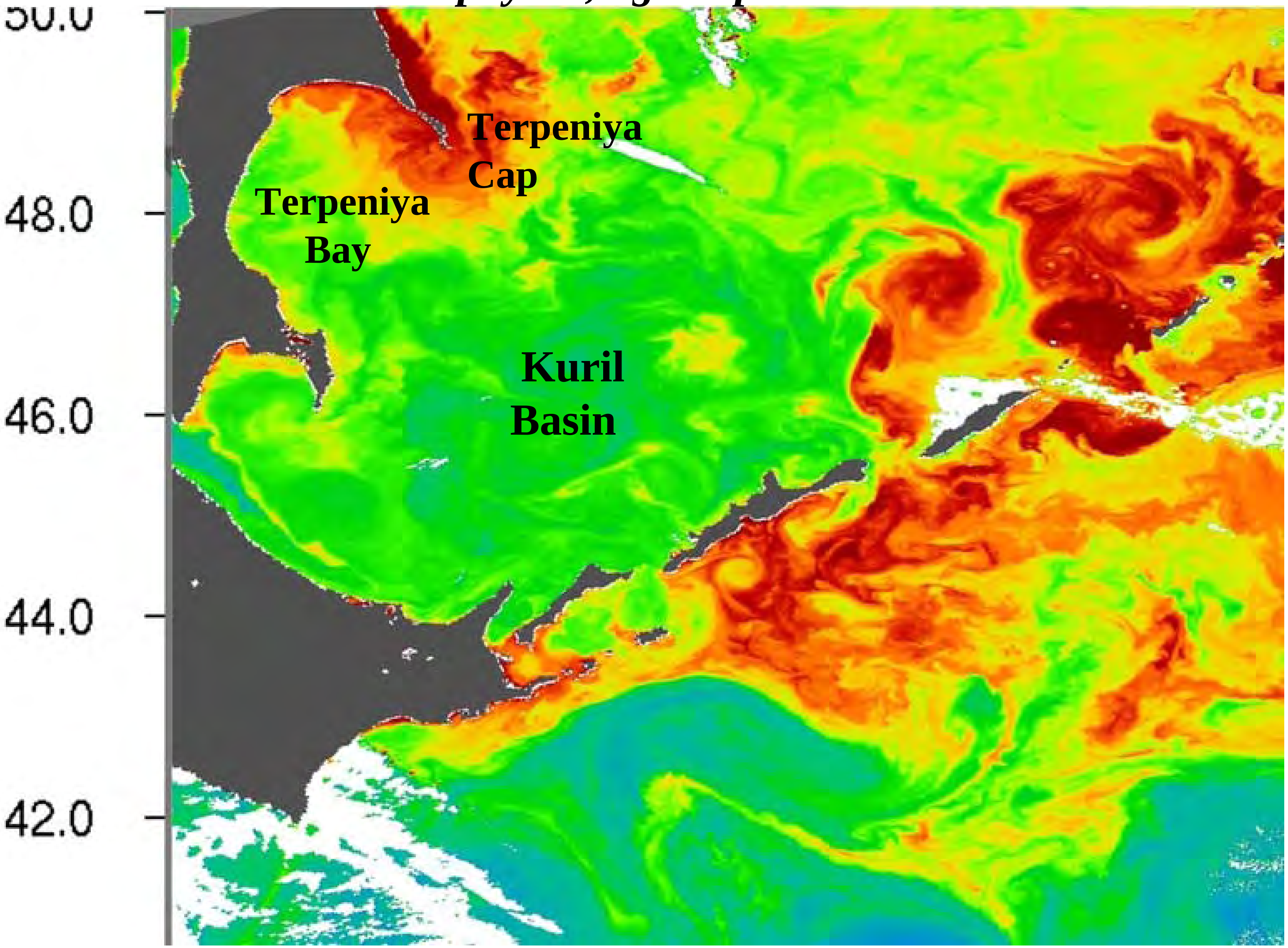


$\mathbf{\Delta SL} \sim -h_e \cdot f/(\rho \cdot \beta \cdot g \cdot h_1^2) \cdot \nabla\tau(\sim\Delta\tau_{\mathbf{x}}/\Delta y) \cdot \Delta x,$

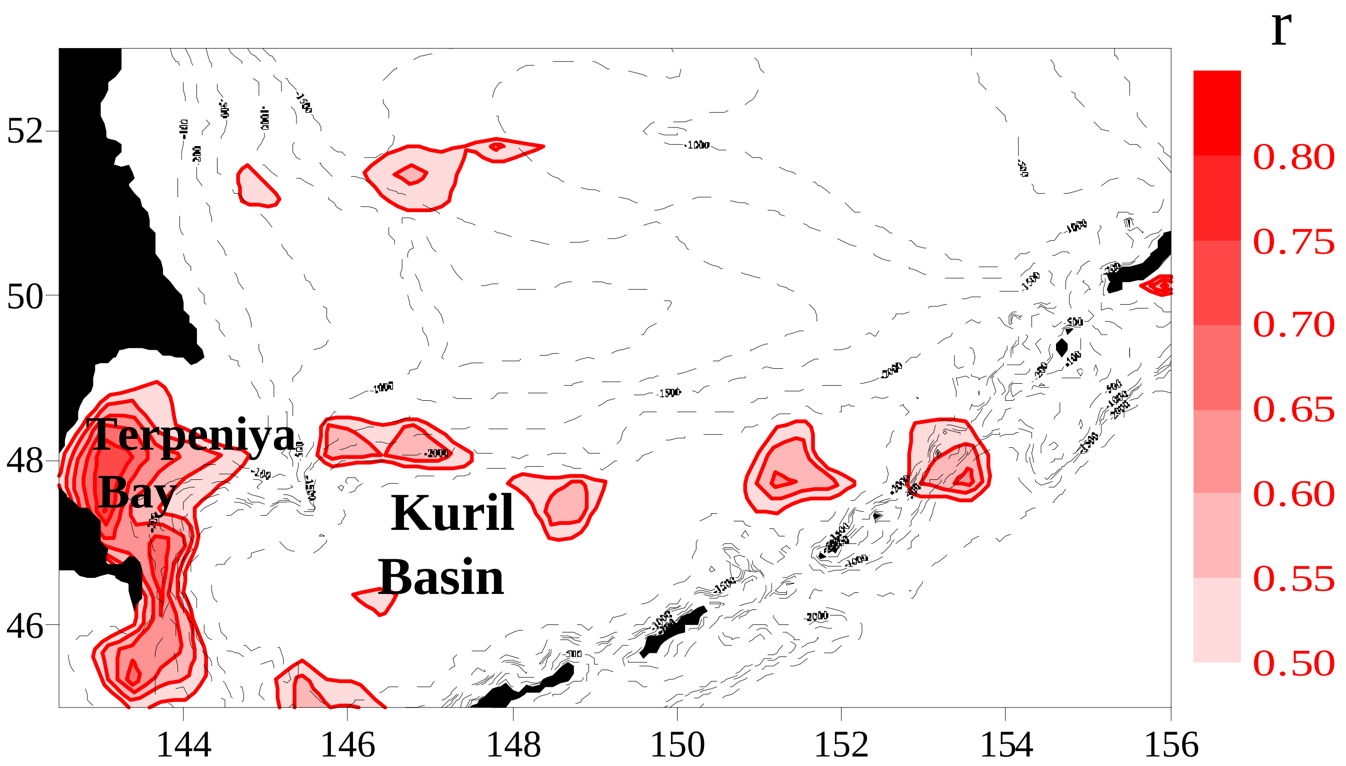
$\Delta\tau_{\mathbf{x}} = \tau_x^{46\text{-}48°N,\ 165°E\text{-}170°W} - \tau_x^{44\text{-}46°N,\ 165°E\text{-}170°W} = 0.04\ N\ m^{-2}$, $\Delta x = 225$ km

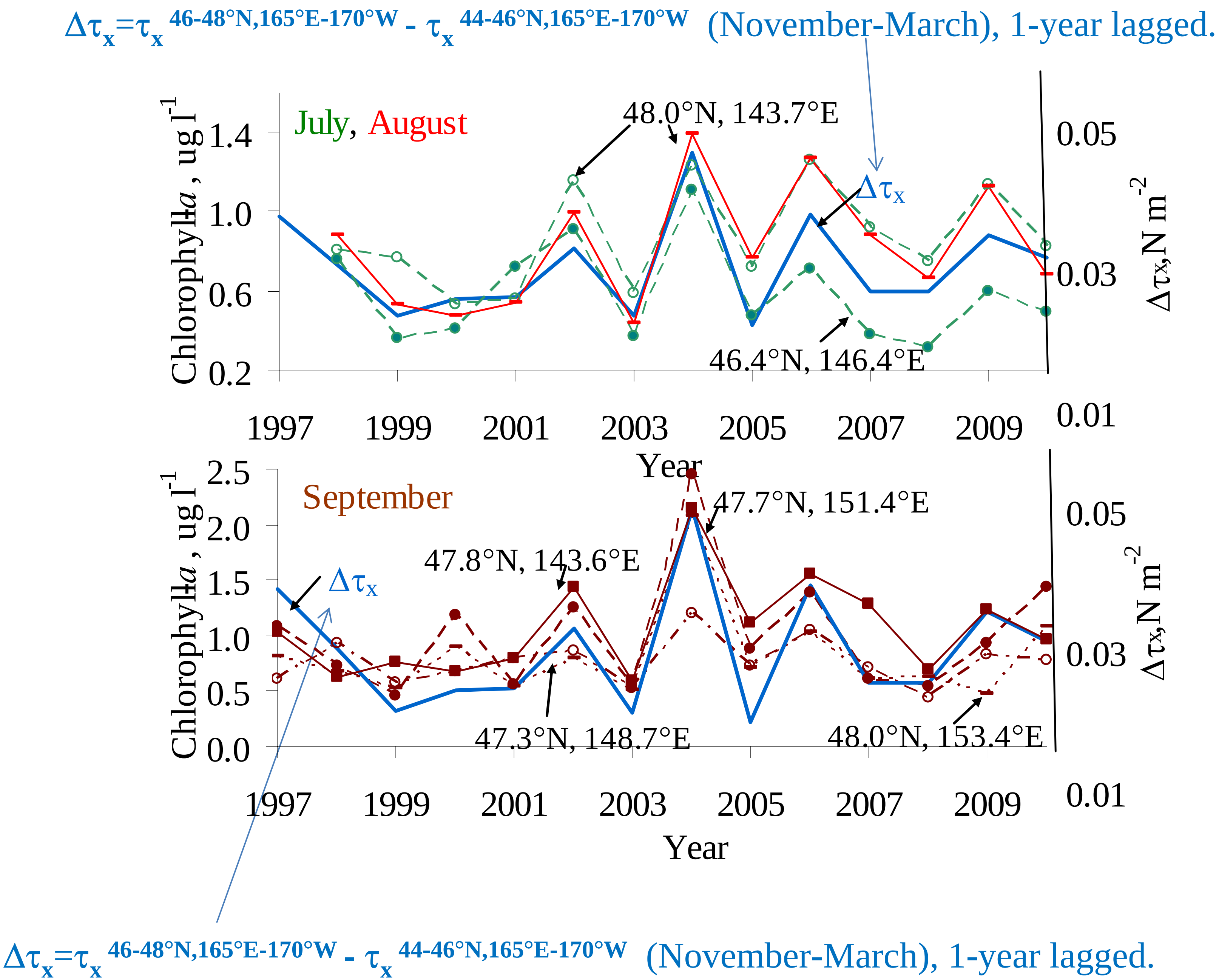
(c~ 1-2 см сек$^{-1}$, November-March), $h_1 = 200$ m, $\mathbf{\Delta SL} \sim 12$ cm.

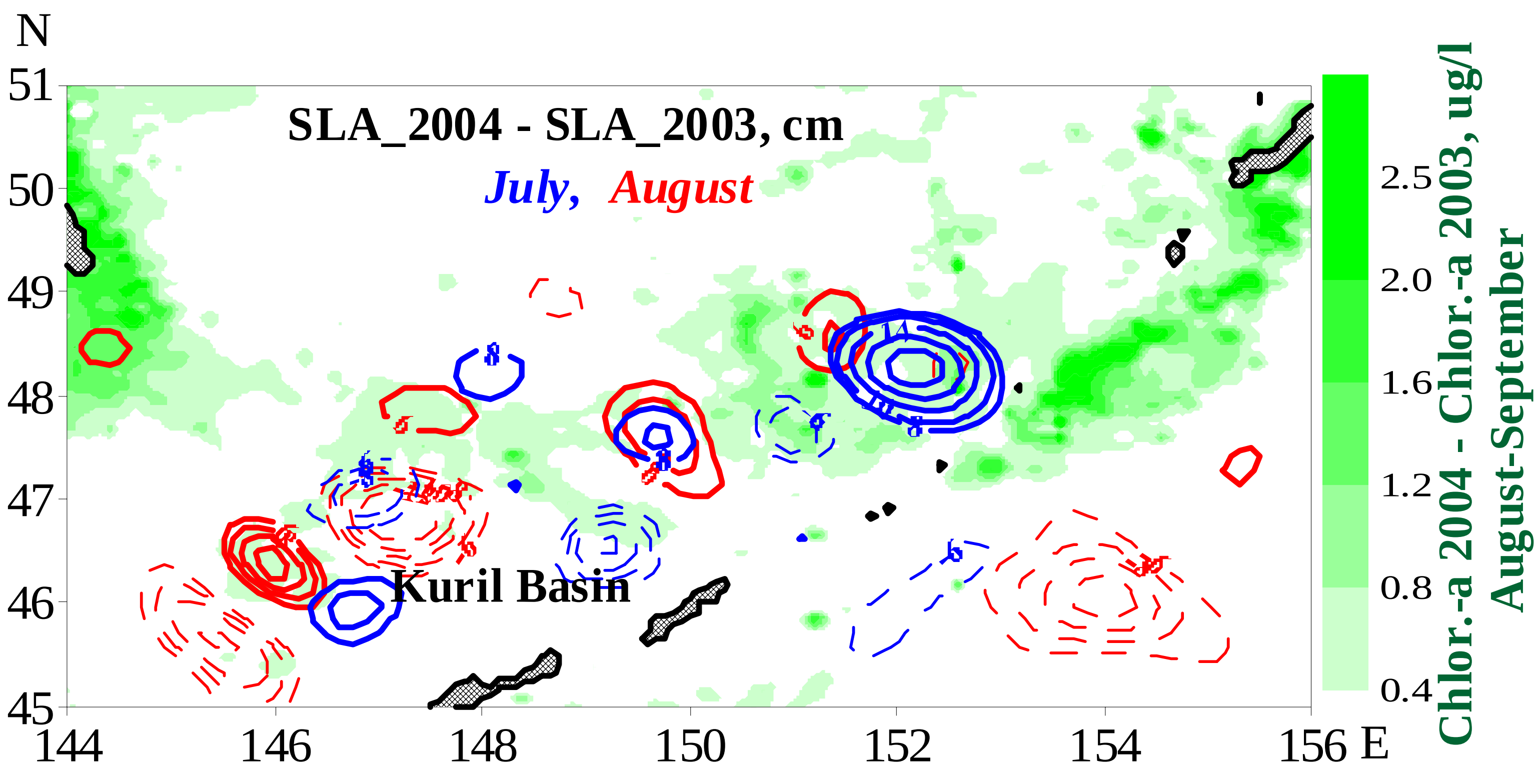
Chlorophyll-a, ug/l September 09 2010

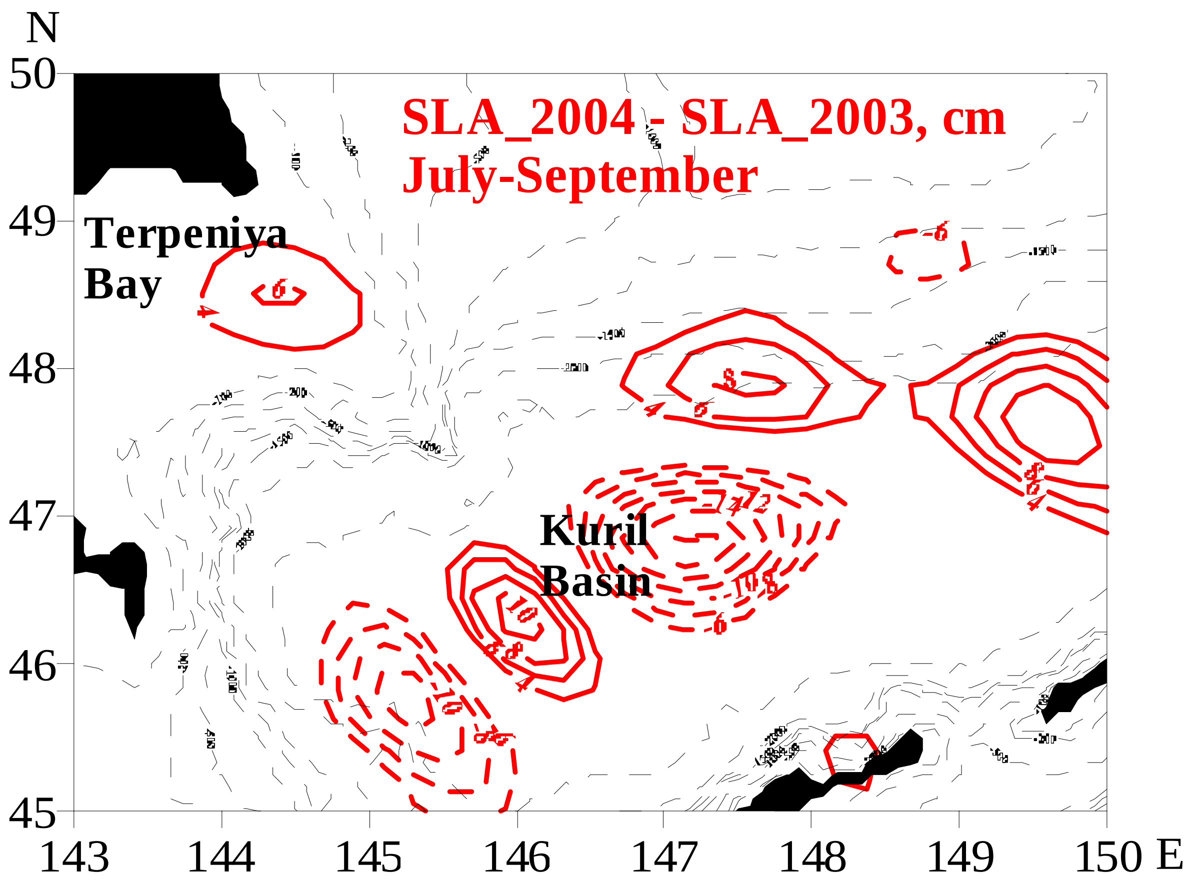


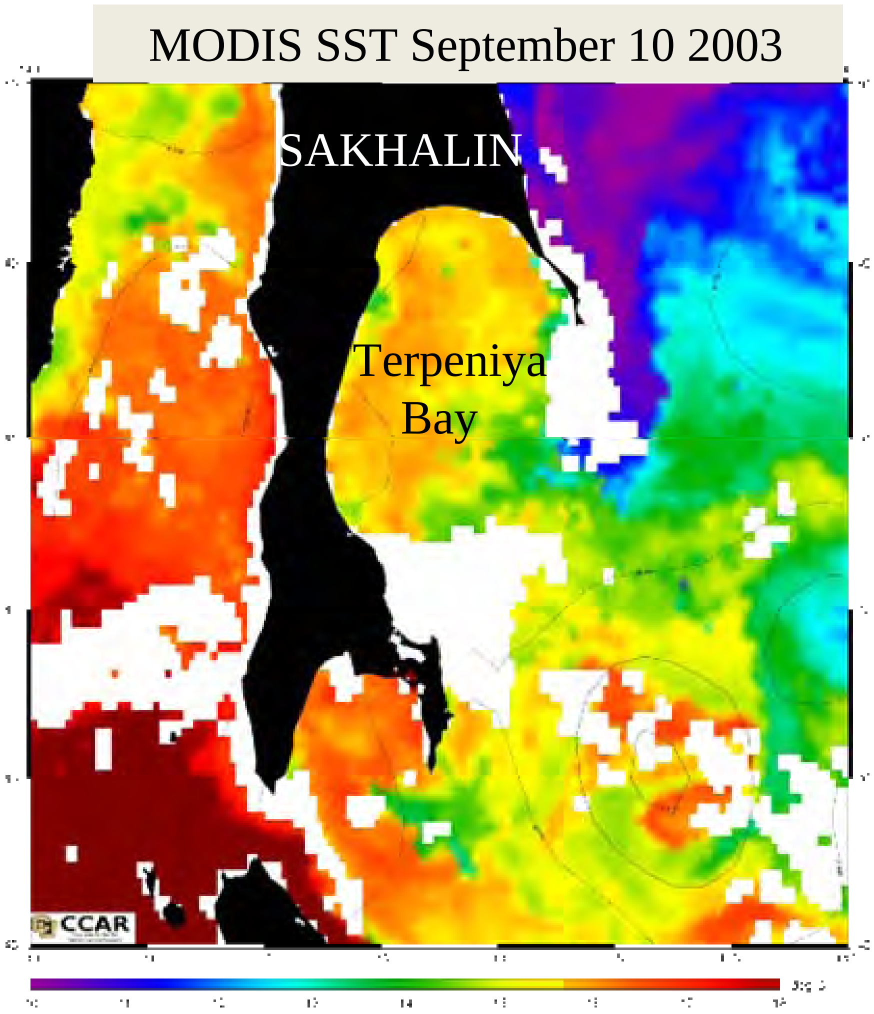
Correlation between ($\tau_x^{\,46\text{-}48°N,165°E\text{-}170°W} - \tau_x^{\,44\text{-}46°N,165°E\text{-}170°W}$) (November-March, 1-year lagged) and satellite chlorophyll-*a* concentration (August-September, 1997-2010)

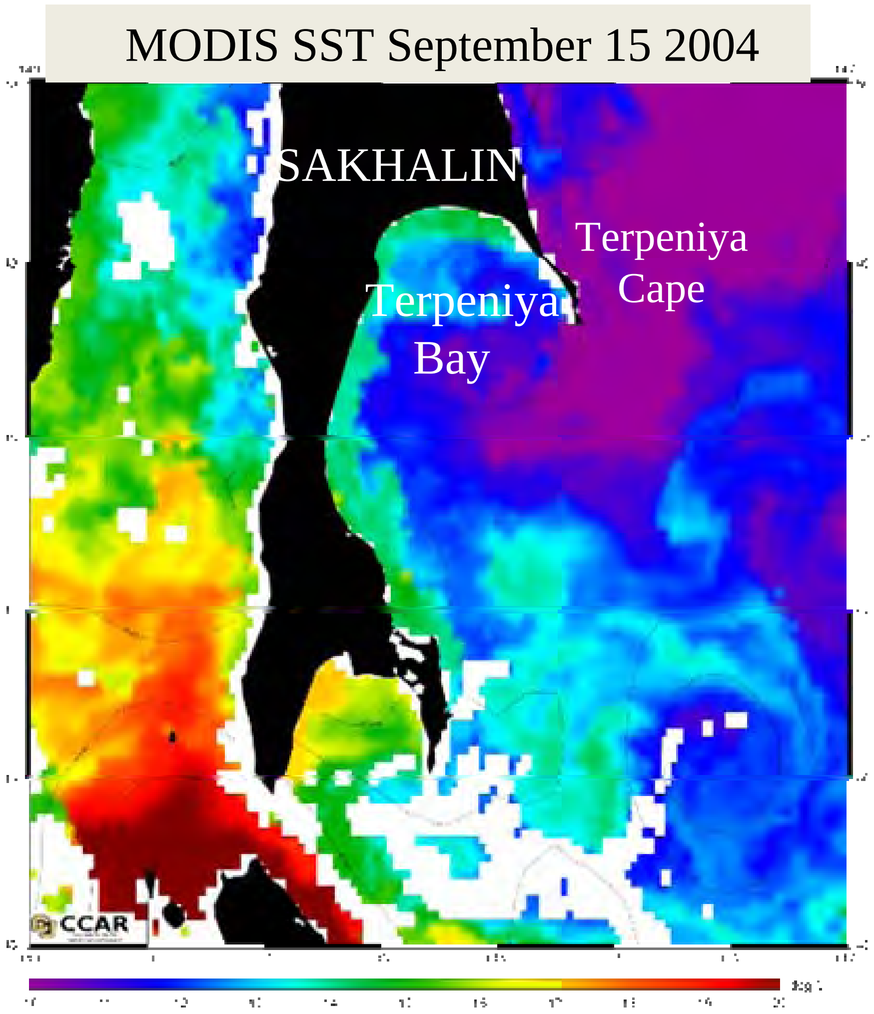



Δτx=τx 46-48°N,165°E-170°W - τx 44-46°N,165°E-170°W (November-March), 1-year lagged.
July, August
48.0°N, 143.7°E
Δτx
46.4°N, 146.4°E
Chlorophyll a , ug l-1
1.4
1.0
0.6
0.2
0.05
0.03
0.01
Δτx,N m-2
1997
1999
2001
2003
2005
2007
2009
Year
September
47.7°N, 151.4°E
47.8°N, 143.6°E
Δτx
47.3°N, 148.7°E
48.0°N, 153.4°E
Chlorophyll a , ug l-1
2.5
2.0
1.5
1.0
0.5
0.0
0.05
0.03
0.01
Δτx,N m-2
1997
1999
2001
2003
2005
2007
2009
Year
Δτx=τx 46-48°N,165°E-170°W - τx 44-46°N,165°E-170°W (November-March), 1-year lagged.

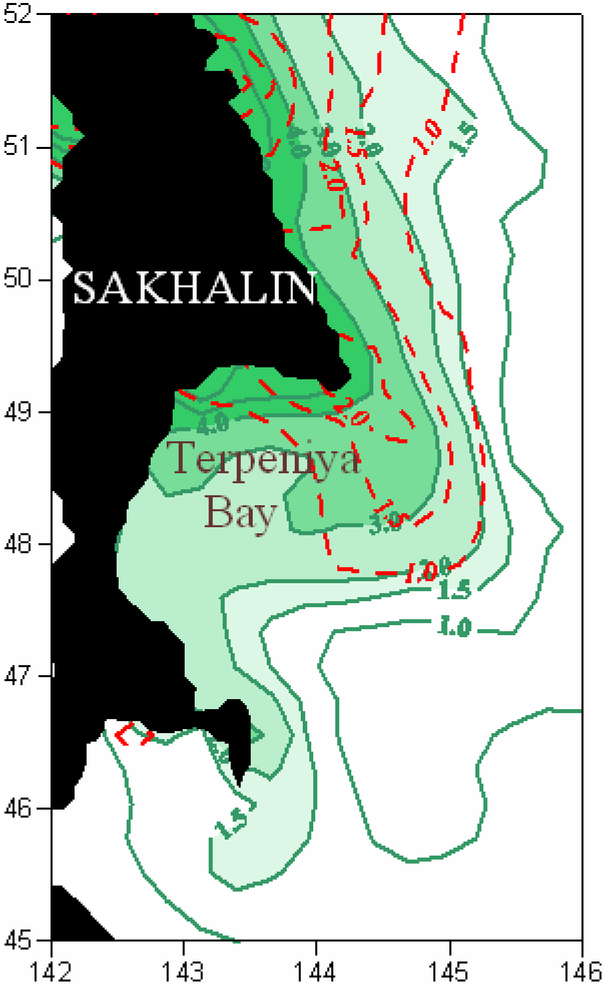

SLA_2004 - SLA_2003, cm
July, August
Kuril Basin
N
51
50
49
48
47
46
45
144
146
148
150
152
154
156 E
Chlor.-a 2004 - Chlor.-a 2003, ug/l
August-September
2.5
2.0
1.6
1.2
0.8
0.4


SLA_2004 - SLA_2003, cm
July-September
Terpeniya
Bay
Kuril
Basin
N
50
49
48
47
46
45
143
144
145
146
147
148
149
150 E

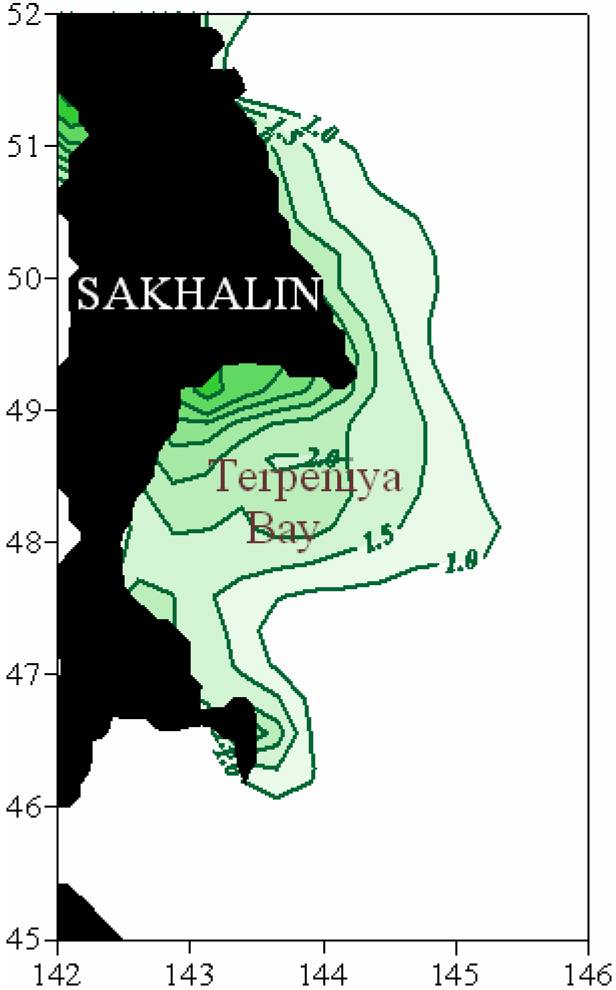

MODIS SST September 10 2003
SAKHALIN
Terpeniya
Bay
CCAR


MODIS SST September 15 2004
SAKHALIN
Terpeniya
Cape
Terpeniya
Bay
CCAR

Chlorophyll-*a*, ug/l
September 2003; September 2004



C *Chlorophyll September 2004 –*
C *Chlorophyll September 2003*, ug/l



Summary

- The mesoscale eddies originating in the Kuril Basin are related to the baroclinic waves coming from the Pacific Ocean into the Okhotsk Sea through the Kuril Straits.
- There is a strong relationship between the wind stress curl in the northern North Pacific in winter and the eddy dynamics in the Okhotsk Sea.
- Increased wind stress curl results in enhanced mesoscale eddy activity and high chlorophyll concentration in the Okhotsk Sea in late summer and fall with 1- year lag.