PICES/CLIVER Workshop
October 23-24, 2004

Temporal and spatial variability of phytoplankton biomass and productivity in the Bering Sea in relation to climate variability

Sei-ichi Saitoh, Takahiro Iida and Kohei Mizobata

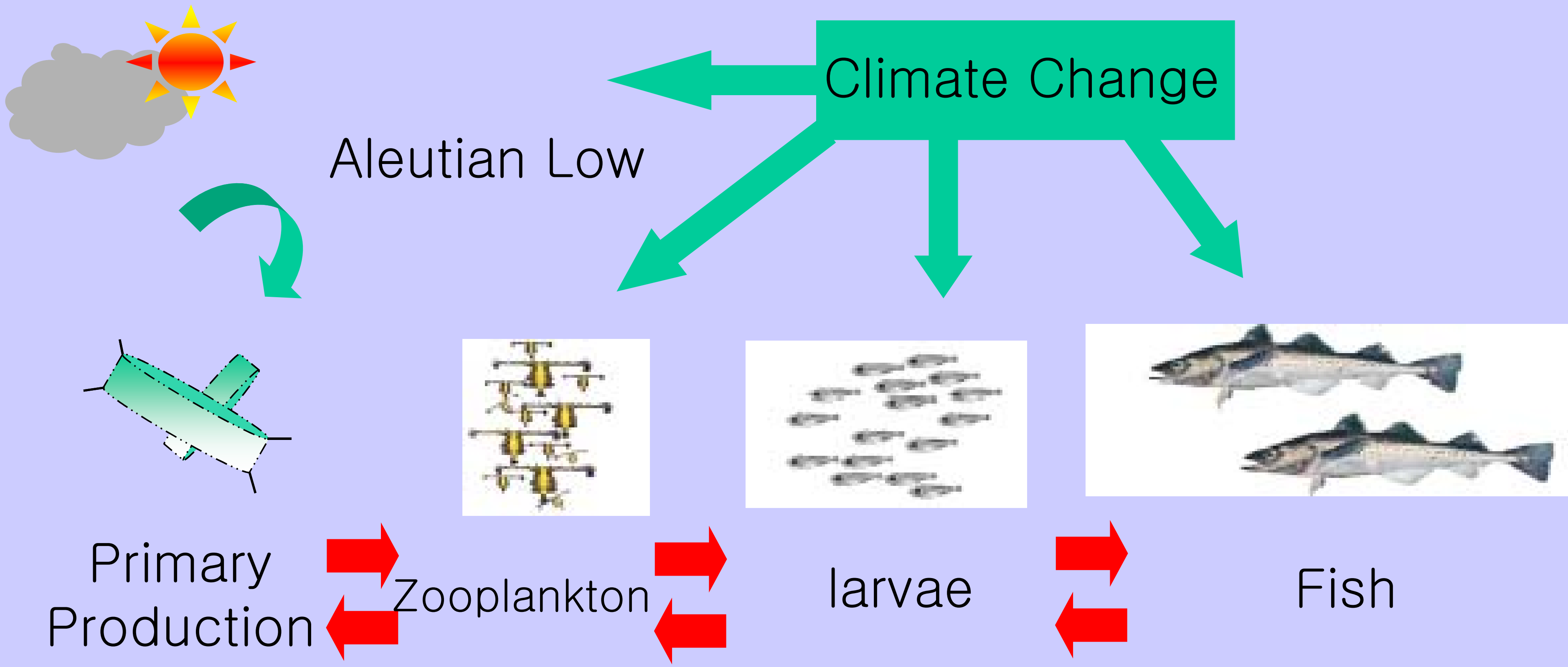
Graduate School of Fisheries Sciences

Hokkaido University

Outline

- Key Question
- Background and Motivations
- Objectives
- Satellite Data and Methods
- Results and Discussion
  - Phytoplankton Biomass
  - Primary Production+Eddy Modeling
- Conclusions
- Future Works

Key Question



How will climate change affect the ecosystem of the Bering Sea ?

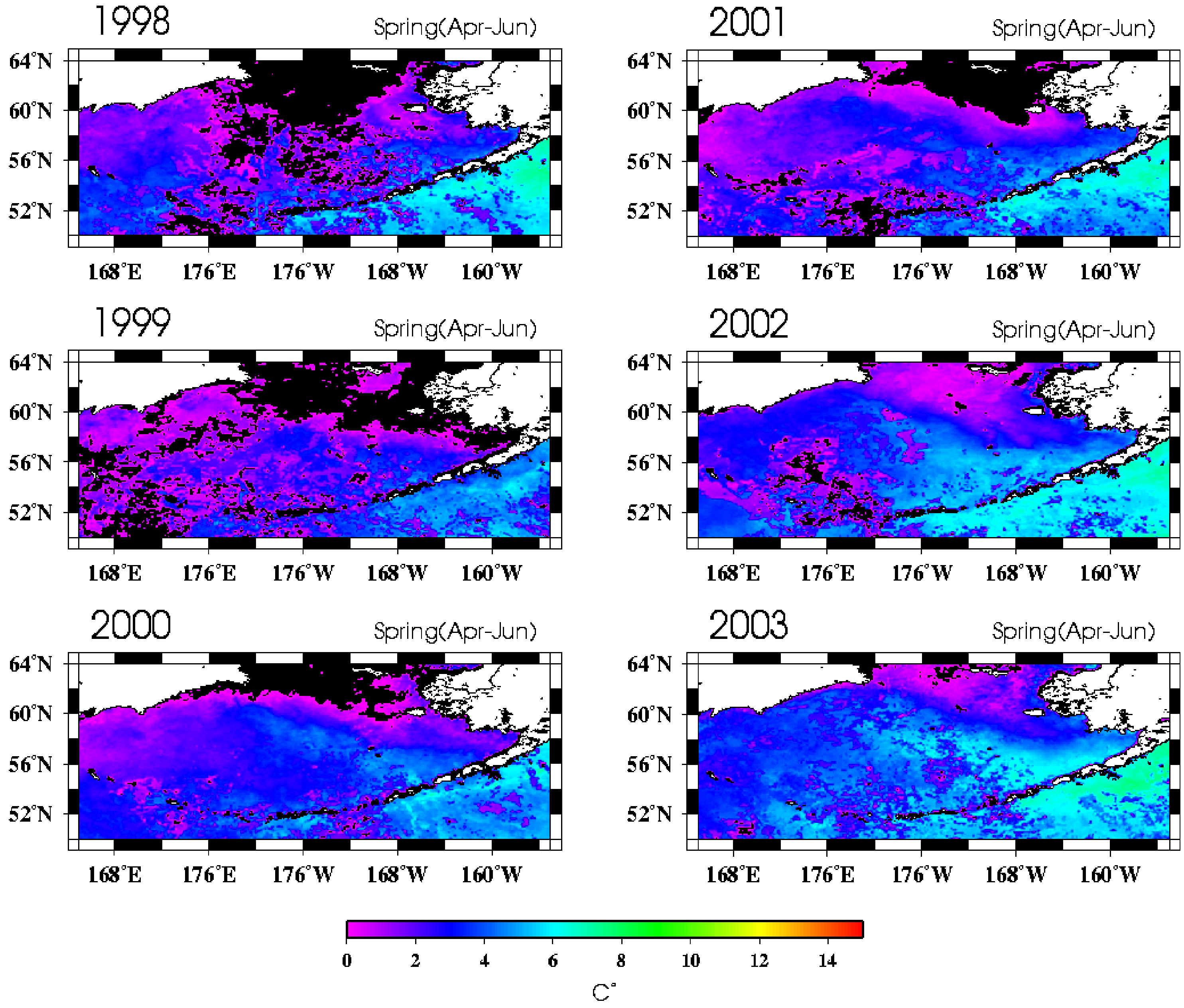
Another Questions (Overland, 2004)

The Bering Sea switched from long-term (170 yrs) stable cold Arctic system to sub-arctic system?

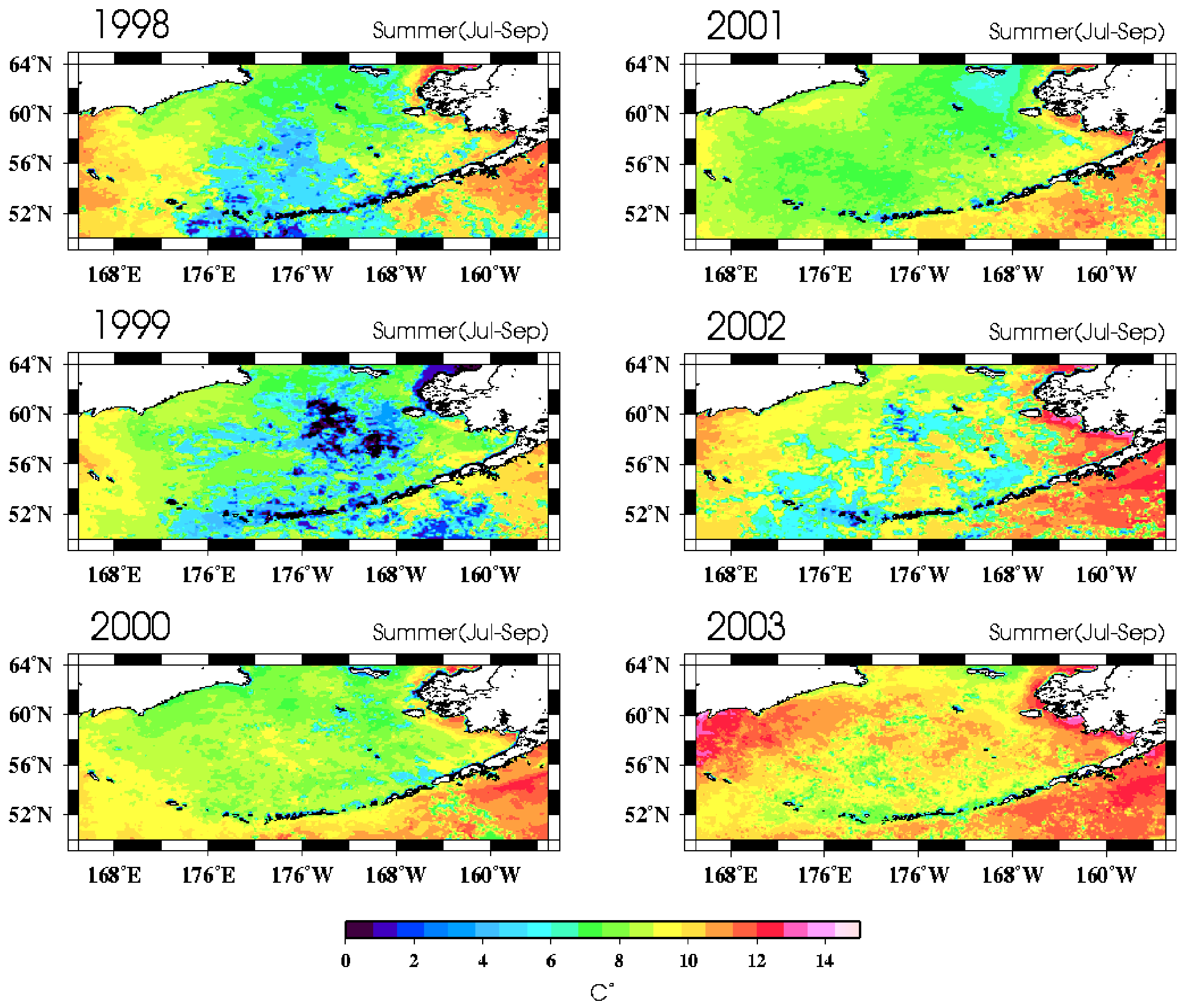
The Bering Sea stuck in "warm phase" due to Arctic climate change ?

(Evidence: persistent warm and ice-free conditions over the previous 4 years)

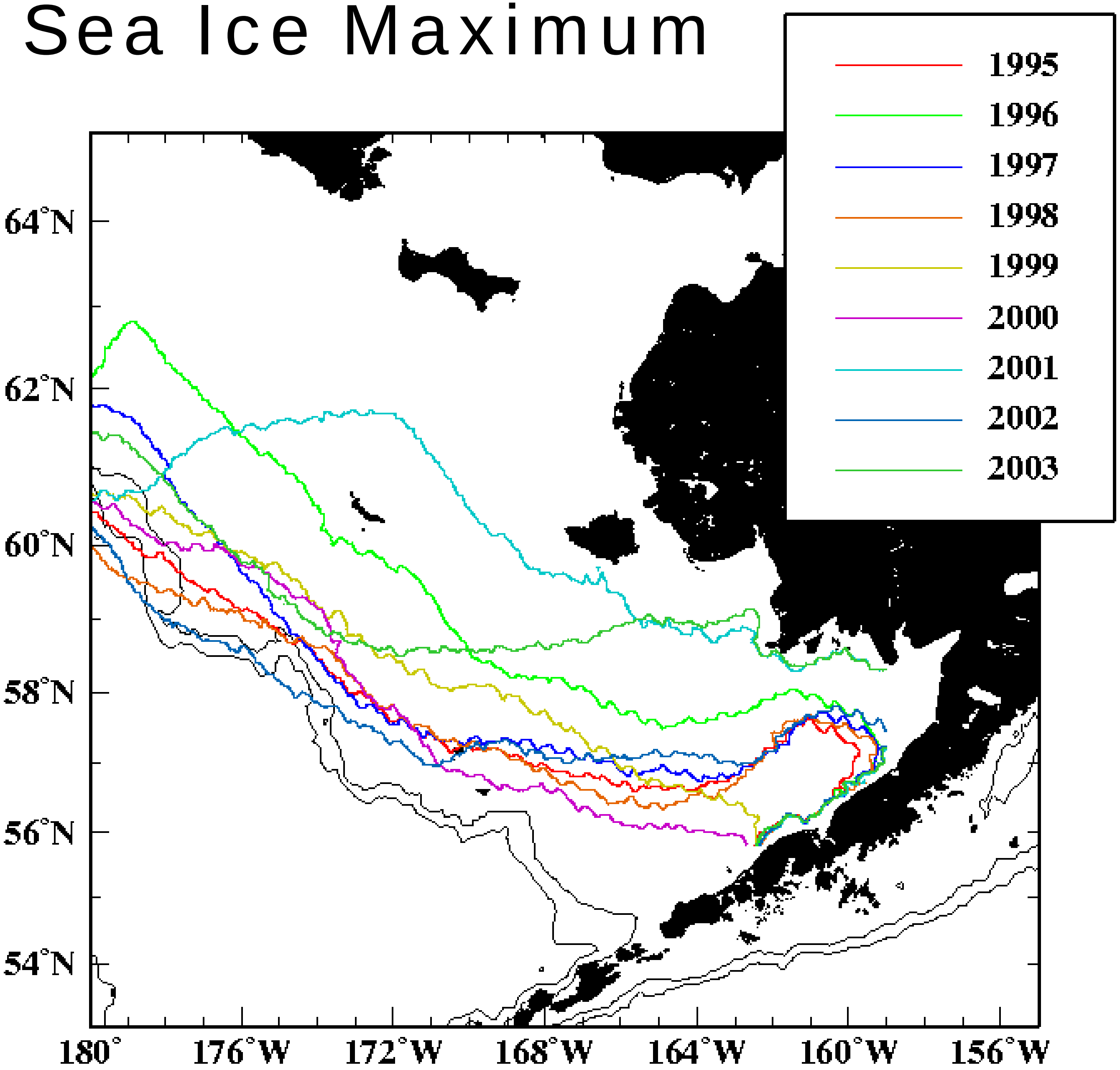
SST - Spring(April-June)



SST - Summer(July-Sep.)

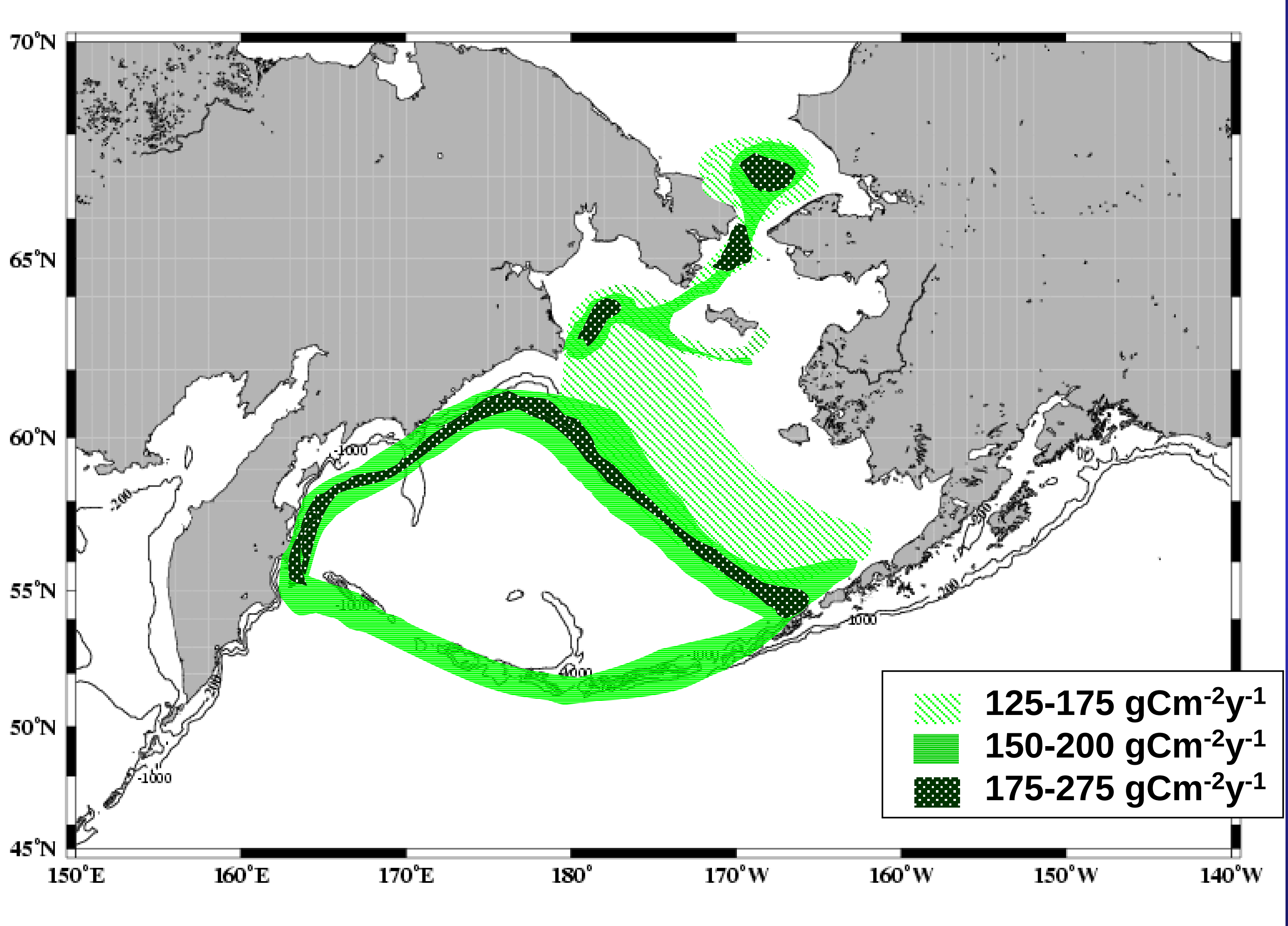


Sea Ice Maximum



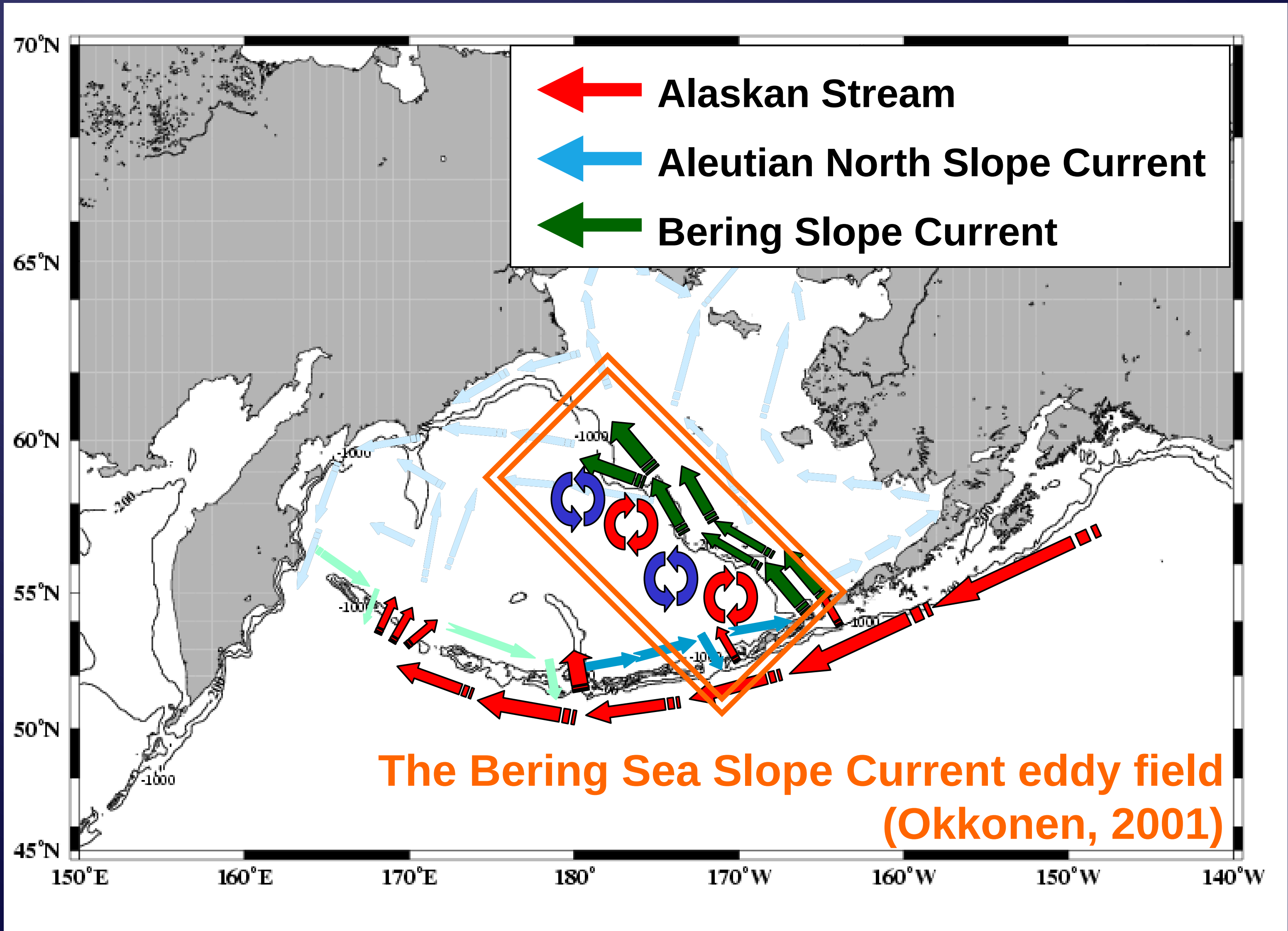
Background

High Productivity Region → The Bering Sea Green Belt



Springer et al.,1996

Background



Alaskan Stream
Aleutian North Slope Current
Bering Slope Current
70°N
65°N
60°N
55°N
50°N
45°N
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
The Bering Sea Slope Current eddy field
(Okkonen, 2001)

Background

1. **Shelf-Slope exchange**
   Stabeno et al., 1999

2. **Nutrient supply & high chl-*a* concentration**
   Sapozhnikov, V.V., 1993
   Mizobata et al., 2002

3. **Positive correlation of Walleye pollock larvae & Bering Sea eddies**
   Schumacher and Stabeno, 1994
   Napp et al., 2000

4. **High Iron & Low Nutrient of Shelf water ⇔ Low Iron & High Nutrient of Basin water**
   McRoy et al., 2001

5. **East-West Seesaw pattern of phytoplankton biomass**
   Saitoh et al., 2002

Past Study

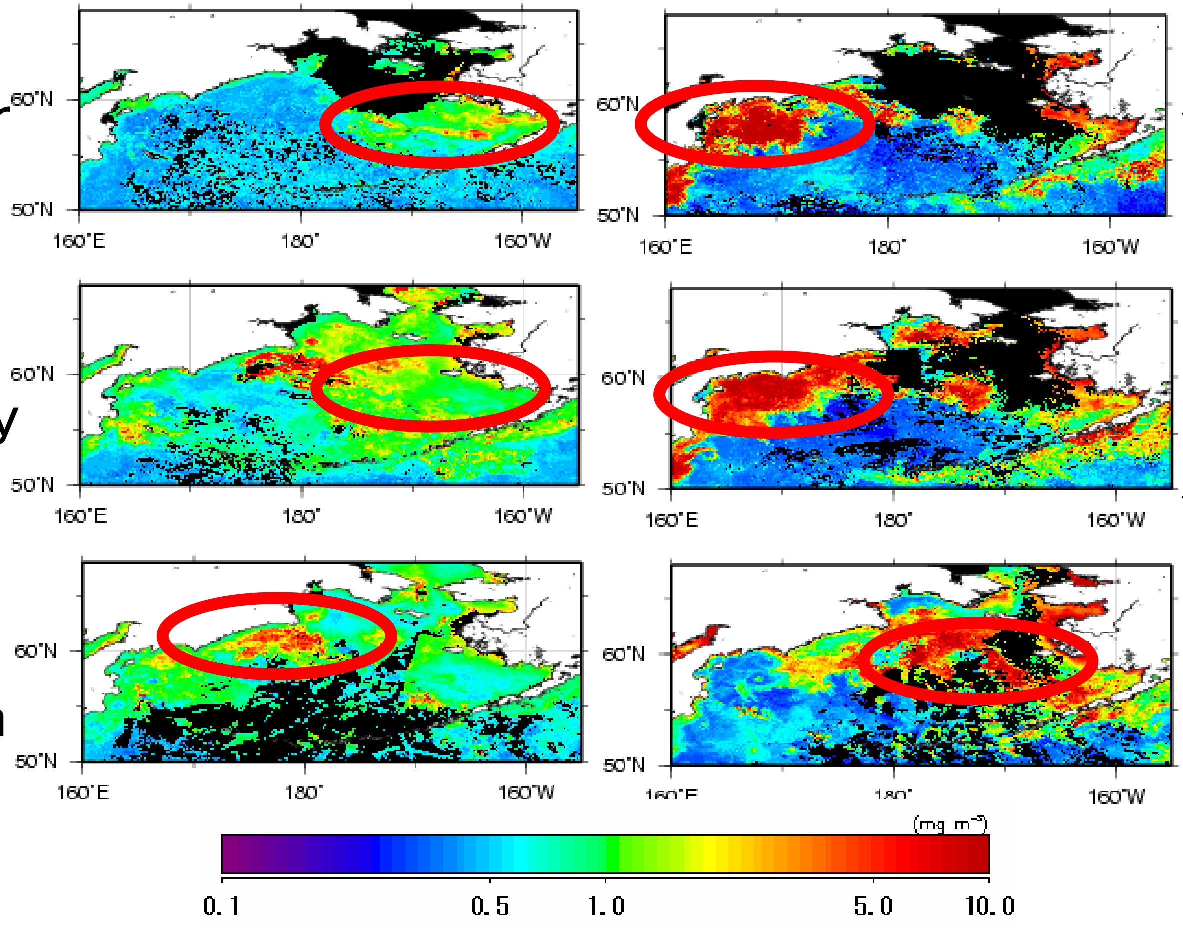
Description of spring bloom in 1997 and 1998

1997 1998

Apr

May

Jun



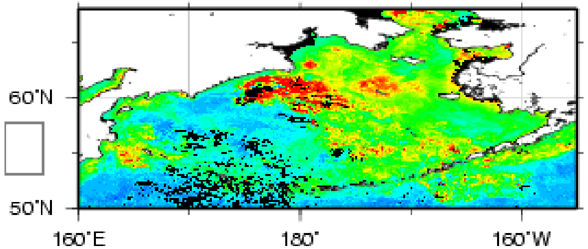
Spring bloom in 1997
→started from East then occurred in west

Spring bloom in 1998
→started from West then occurred in west

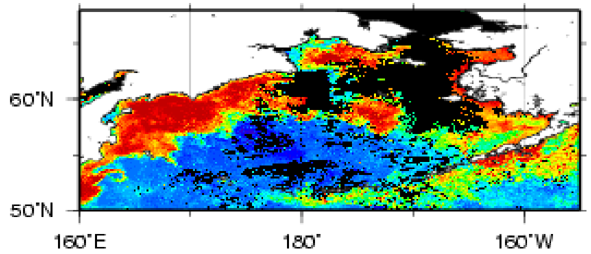
Saitoh et al. (2002)

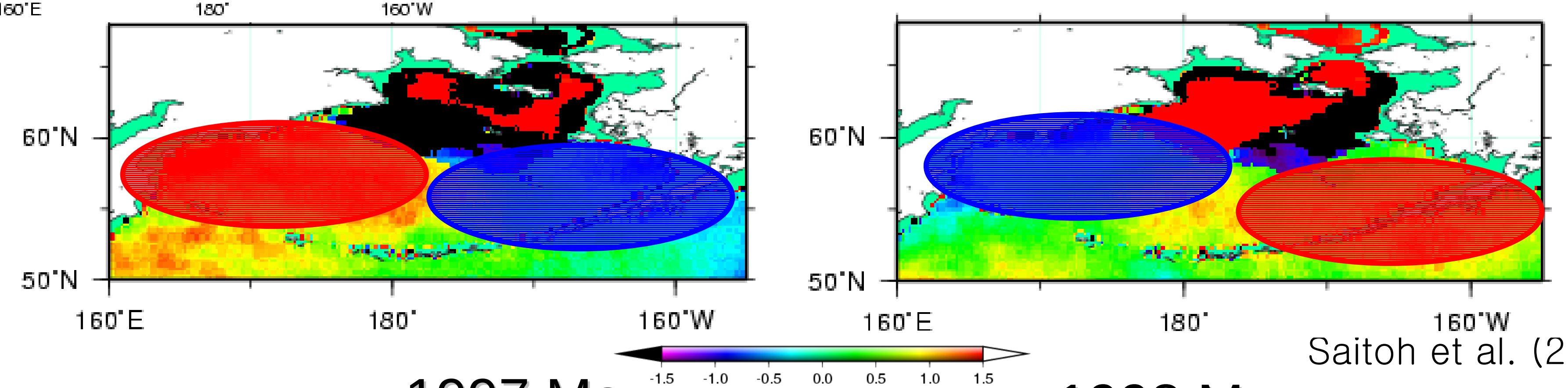
Past Study

Description of spring bloom in 1997 and 1998



Sea surface wind anomaly

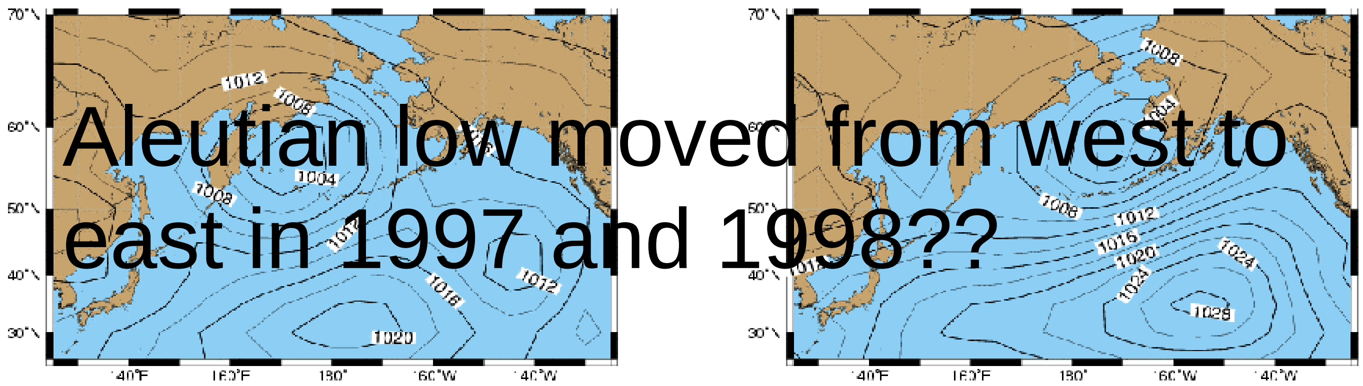




Saitoh et al. (2002)

1997 May

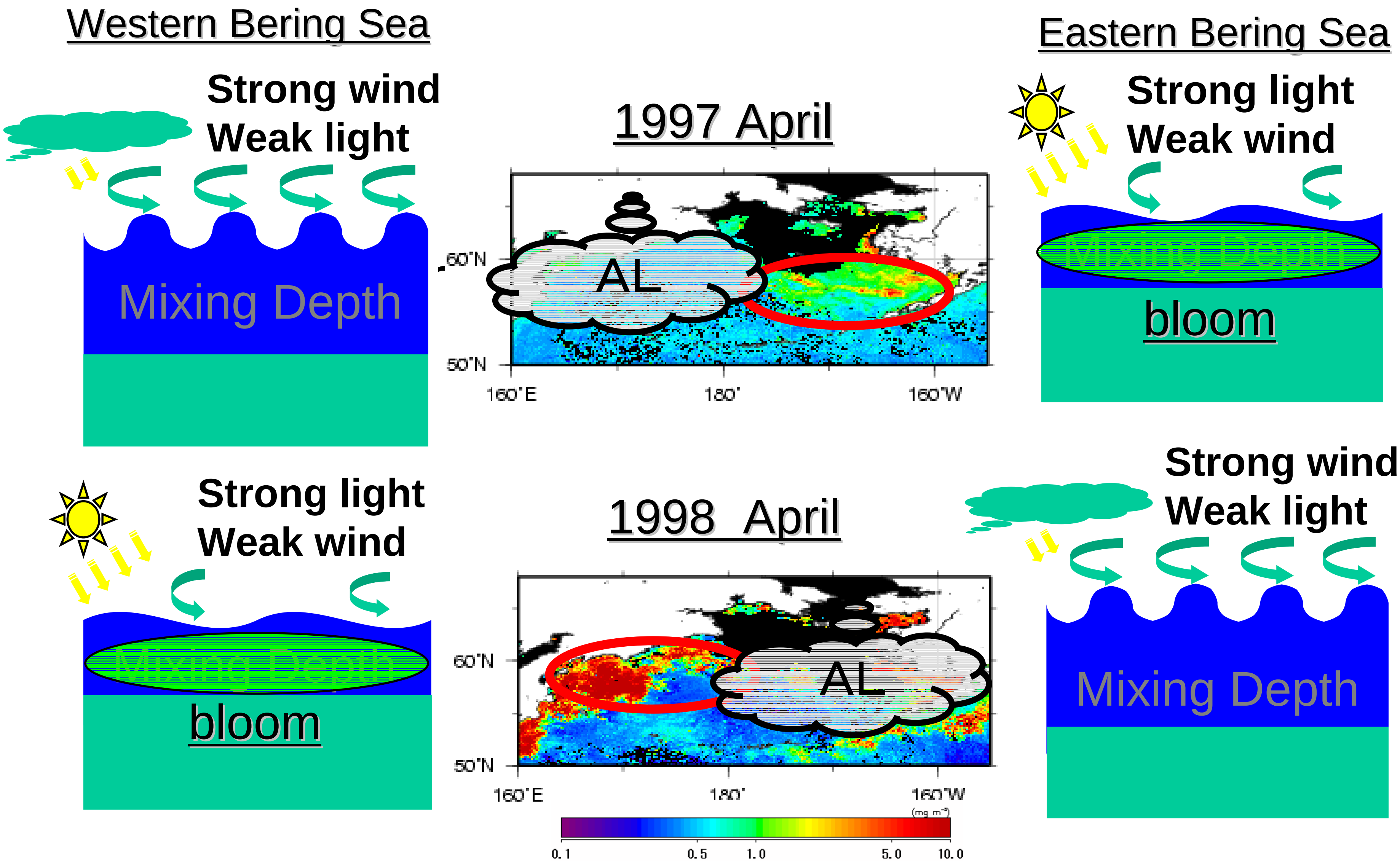
1998 May



Aleutian low moved from west to east in 1997 and 1998??

Hypothesis

Forcing to spring bloom interannual variability in the Bering Sea



Final Goal

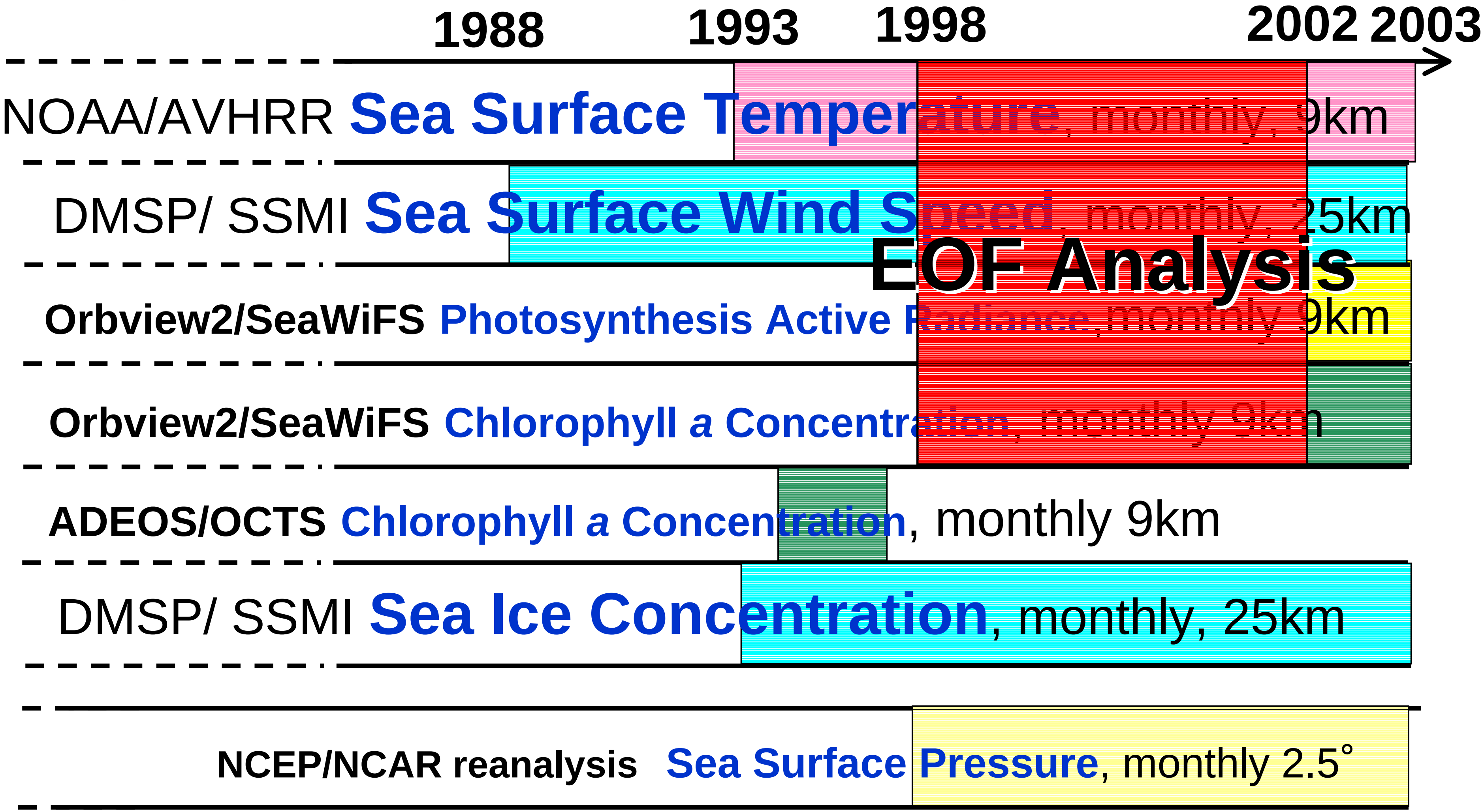
To clarify the quantitative relationship between climate change and phytoplankton variability.

Objectives

- To provide a quantification of the synoptic phytoplankton biomass variability using EOF analysis.
- To clarify the quantitative relationship between phytoplankton biomass and productivity variability and ocean environment (SST, sea wind, light strength etc.).

Material and Methods

Data period



Material and Methods

- Description of phytoplankton seasonal and interannual variability
- Statistical analysis of remotely sensed chlorophyll a concentration

  a） Development of data interpolation

  b） Analysis of temporal and spatial modulation of chl-a using Empirical Orthogonal Function (EOF) analysis
- Analysis of physical parameters by satellite datasets

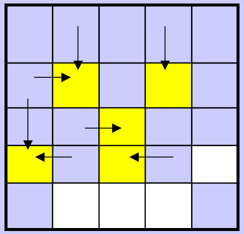
  a) EOF analysis of sea surface temperature (SST), sea surface wind (SSW) and Photosynthetically active radiation (PAR)

  b) To examine correlation coefficient between chl-a EOF and physical parameter EOF

Material and Methods

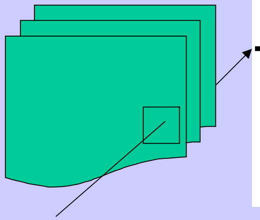
Interpolation

1st Step



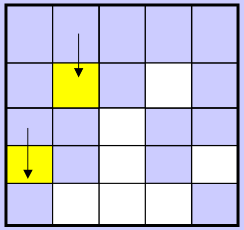
Nearest neighbor
5x5 pix.

2nd Step



Temporal interpolation.
5x5 pix.

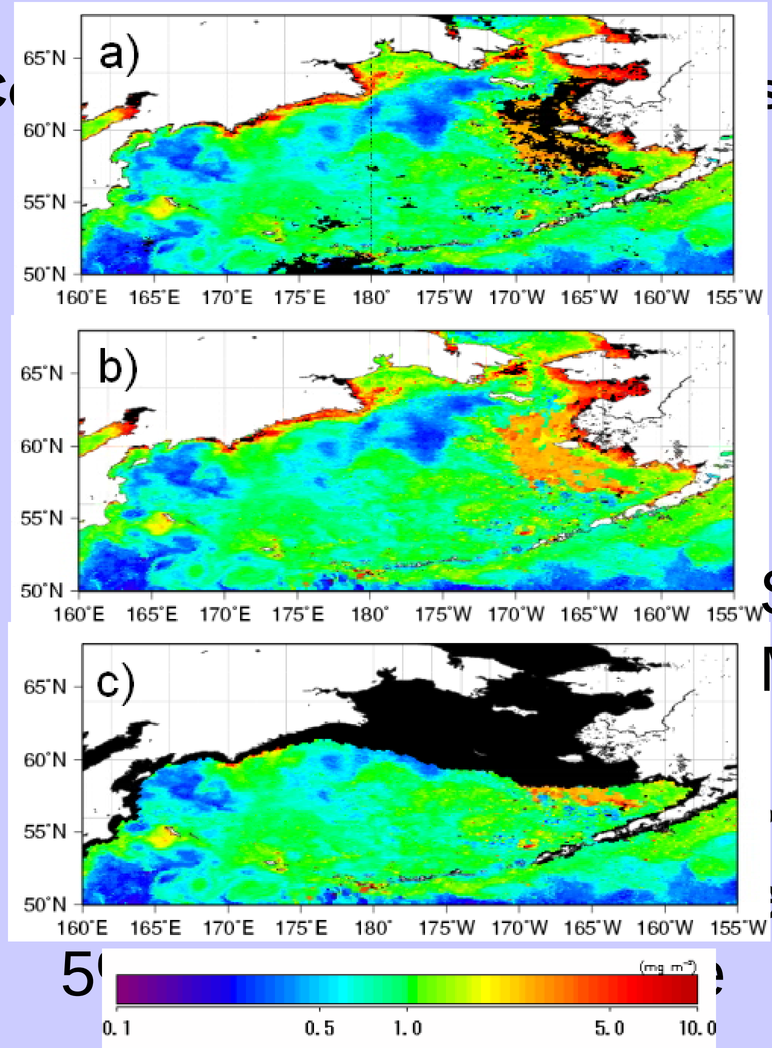
3rd Step



Nearest neighbor
10x10 pix.

1998 August L3SMI chl-*a*

C... st pixel



SSMI
Maxice
... e at
5... e

Modeling of primary production

VGPM Model (Behrenfeld and Falkowski, 1997)

Satellite data : SST PAR Chl-a

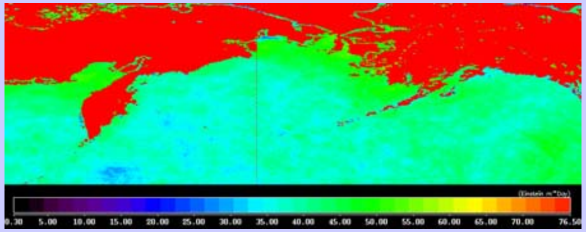
$$PP_{eu}=0.66125*PB_{opt}*[Eo/Eo+4.1]*Zeu*Csat*Dirr$$

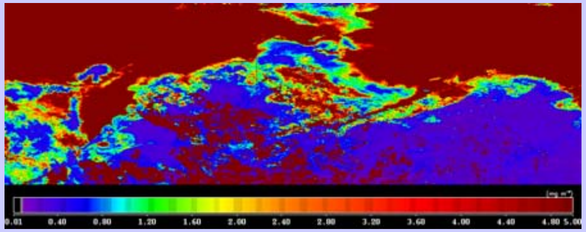
PP_{eu} : Daily C fixation integrated from the surface to Zeu ($mgCm^{-2}$)
PB_{opt} : Maximum C fixation rate within a water column ($mgC(mgChl^{-1})h^{-1}$)
Eo : Sea surface daily PAR (Photosynthtically Available irradiance) mol quanta m^{-2}
Z_{eu} : Physical depth receiving 1% of Eo (m)
C_{sat} : Surface Chl-a concentration derived by satellite mgm^{-3}
Dirr : Photoperiod, decimal hours

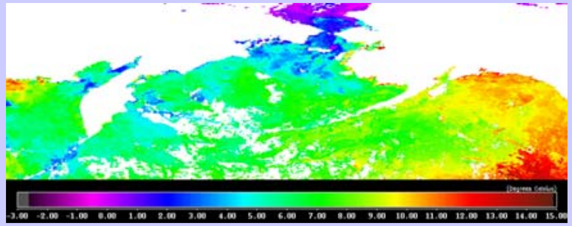
$$PB_{opt} = a*T^7+bT^6+cT^5+dT^4+eT^3+fT^2+gT+h$$

T: Sea Surface Temperature

PAR image | **Chlorophyll a image** | **SST image**



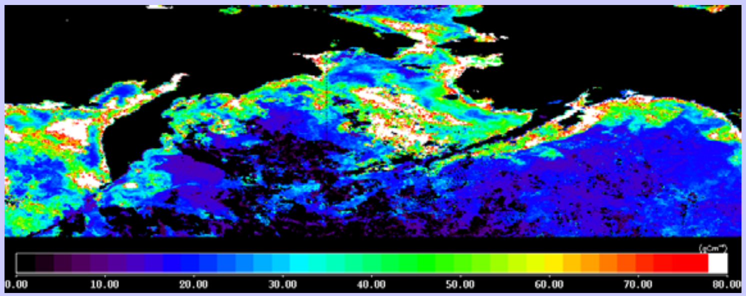




SeaWiFS → **Eo: PAR**

SeaWiFS → $\mathbf{Z_{eu}}$

AVHRR → $\mathbf{PB_{opt}}$

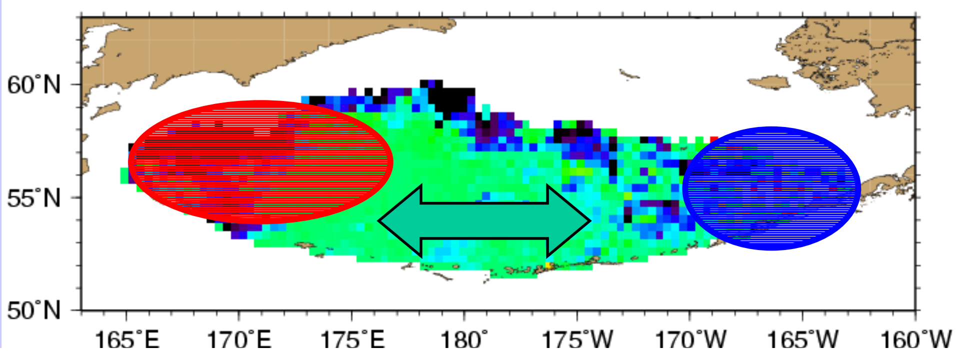


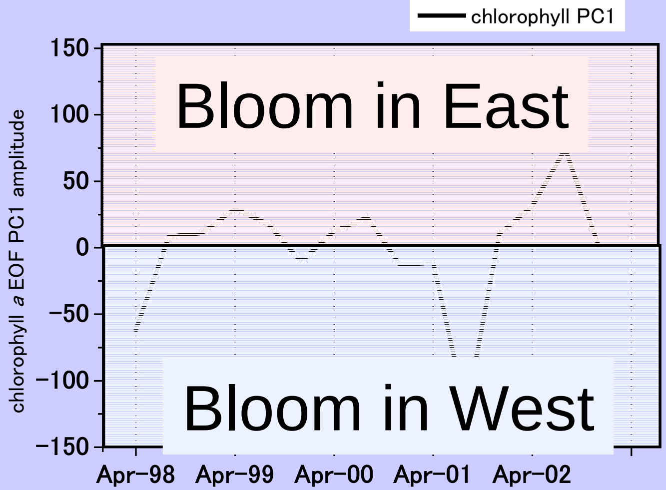
Primary Production Map (PPeu)

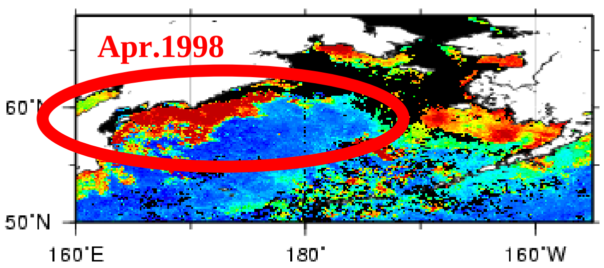
Phytoplankton biomass

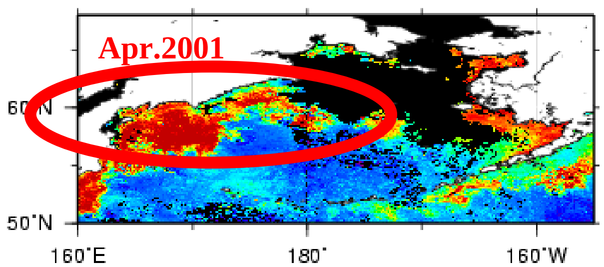
Spring data EOF analysis

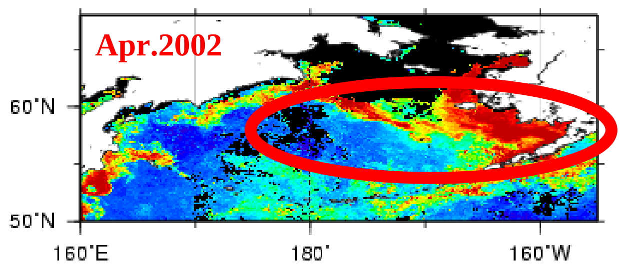
EOF 1st mode **Variance = 23.0**









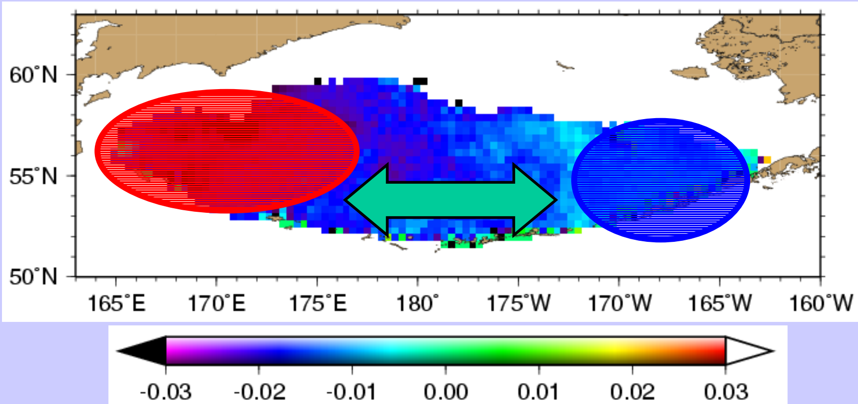


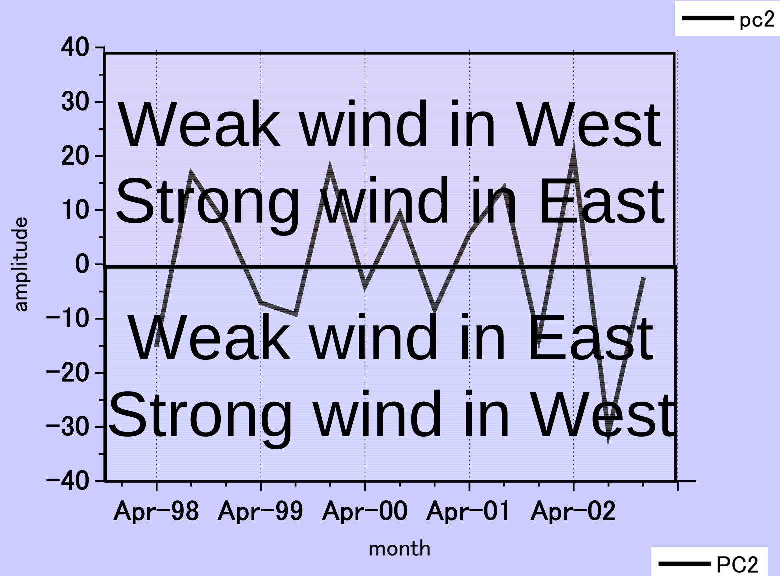
month

EOF1 + EOF2 = 36.4

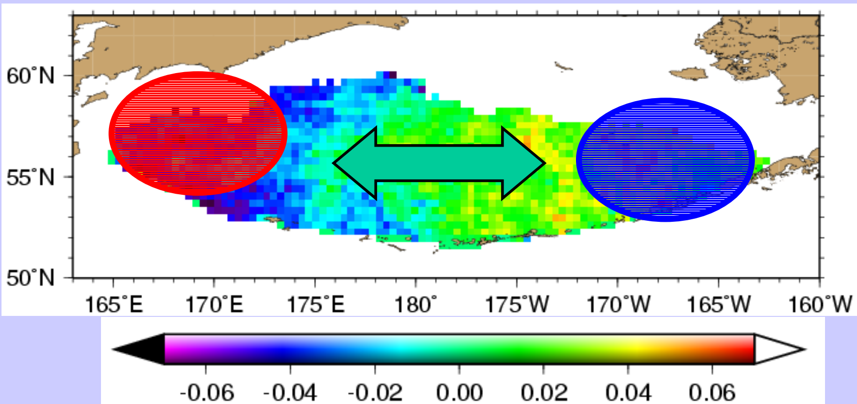
Phytoplankton biomass

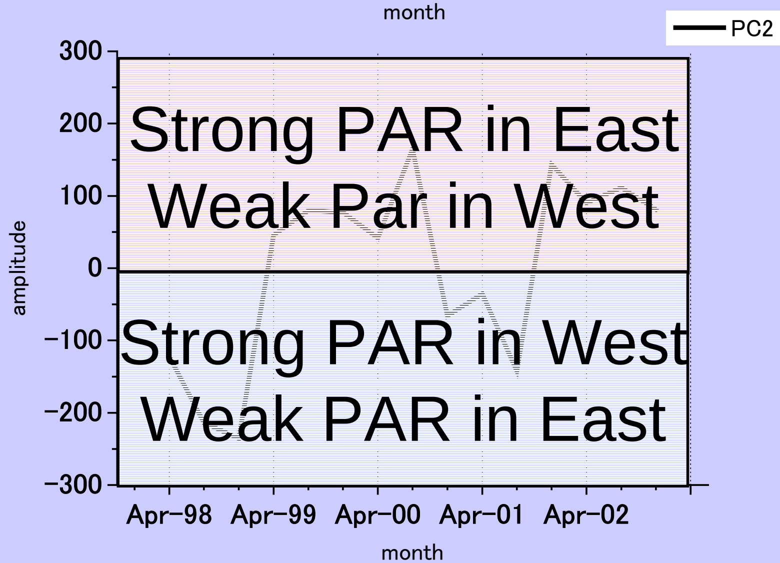
Wind speed EOF2 **Variance = 10.9**



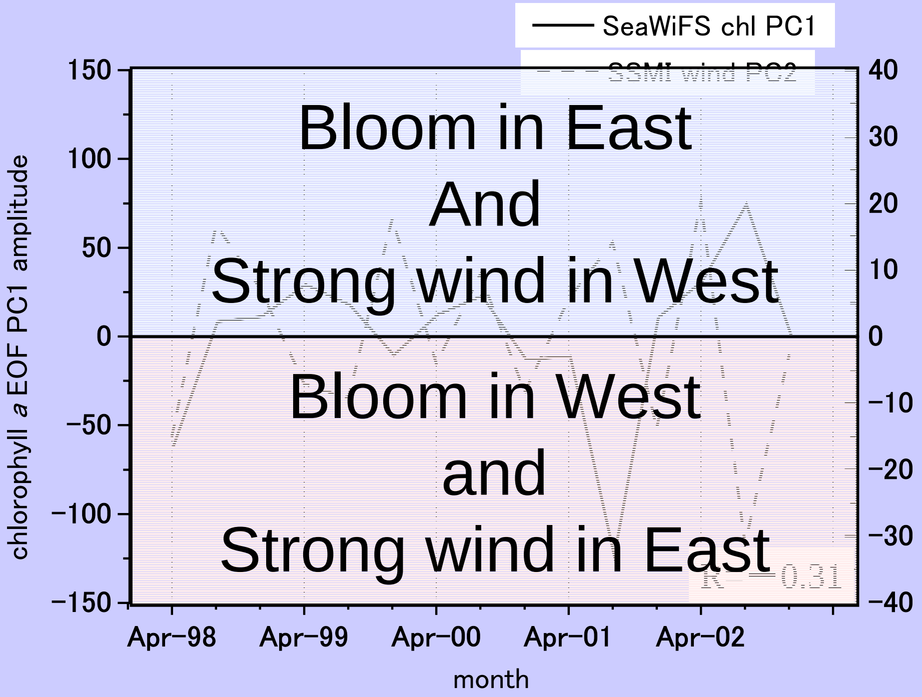


PAR EOF2 **Variance = 13.4**



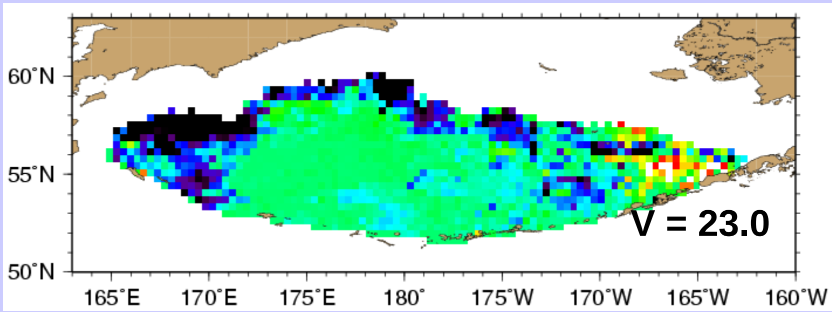


Phytoplankton biomass

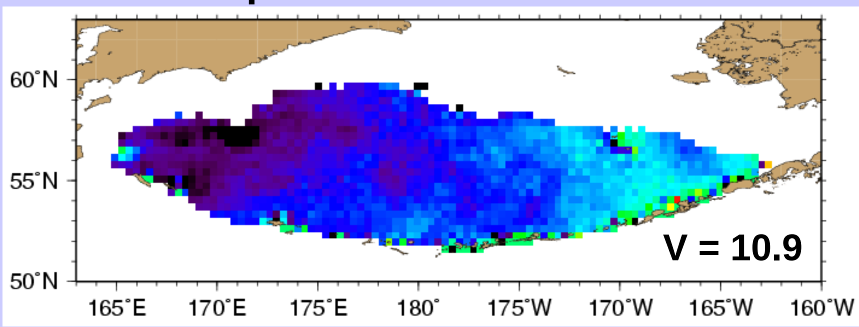


Negative correlation R=－0.31

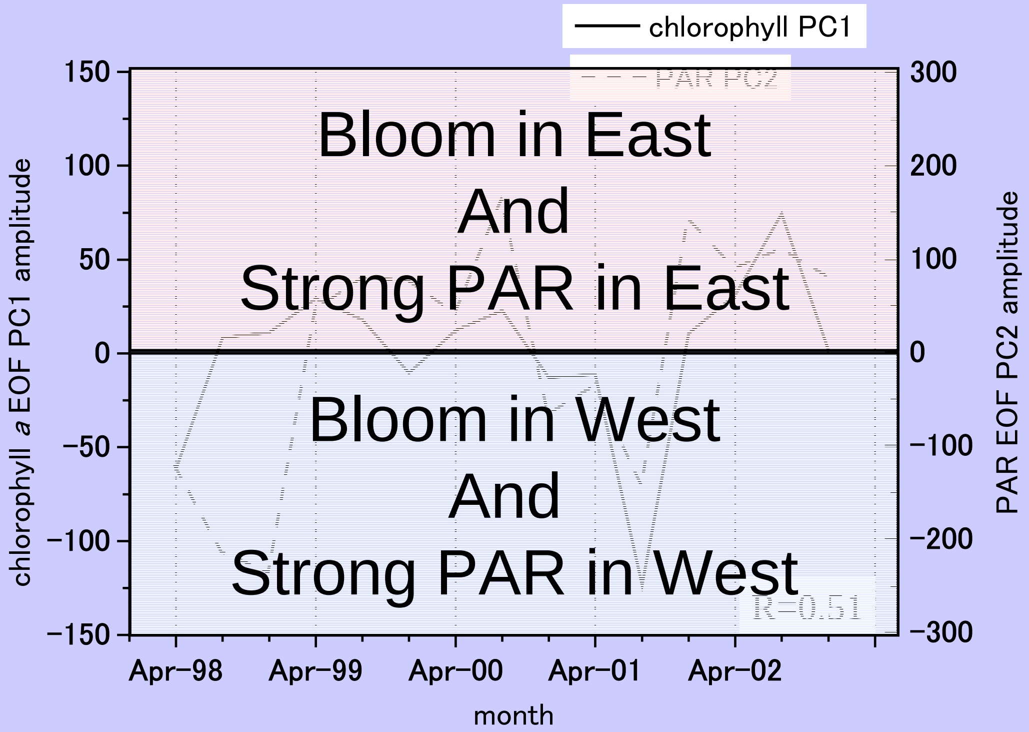
Chlorophyll a EOF1



Wind speed EOF2

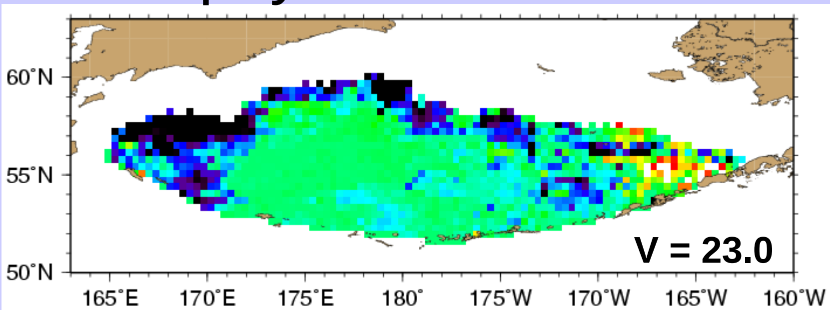


Phytoplankton biomass

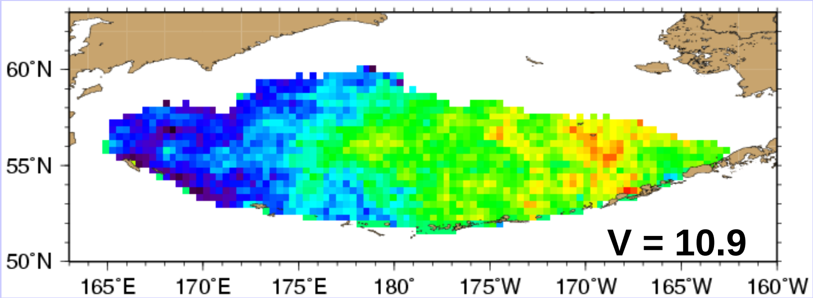


Positive correlation R=0.51

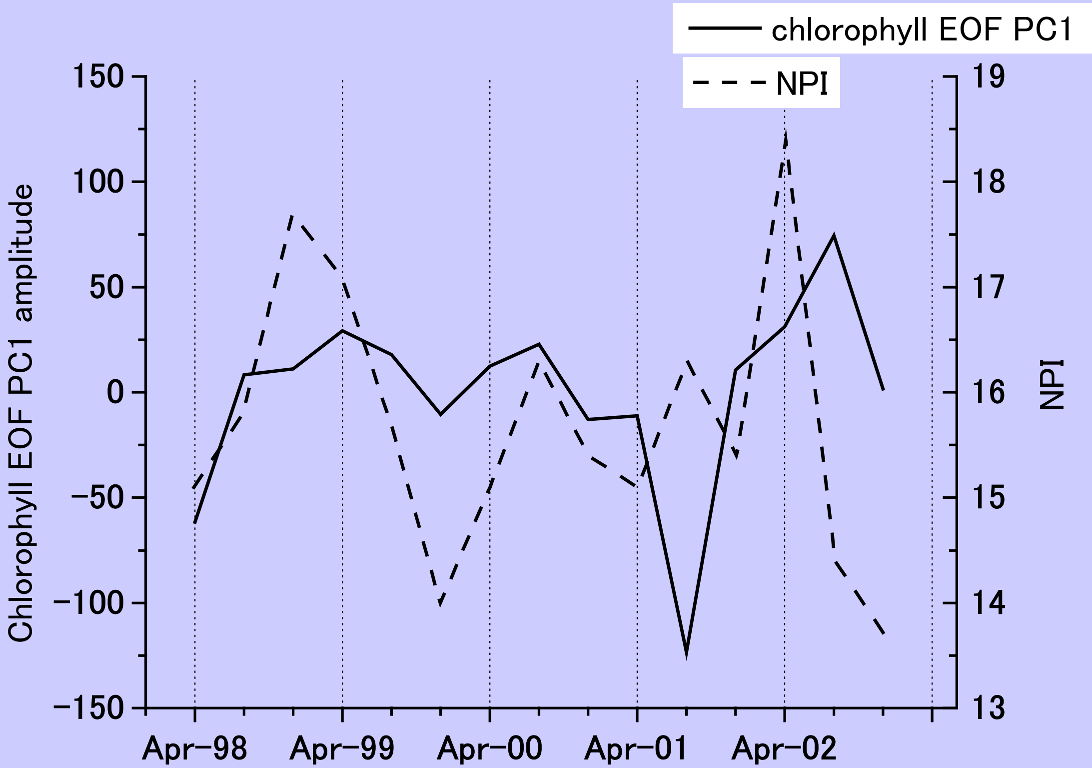
Chlorophyll a EOF1

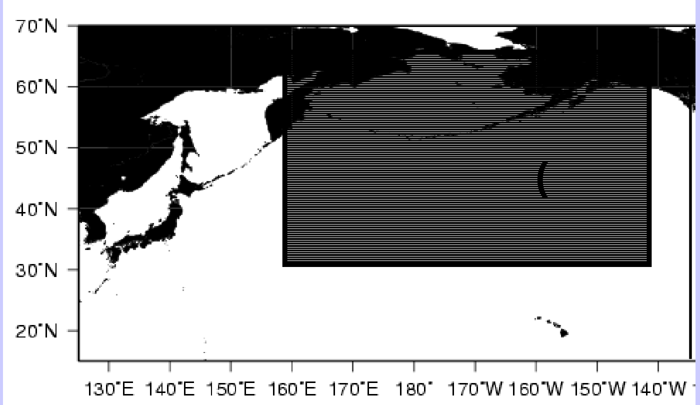


PAR EOF 2



Phytoplankton biomass



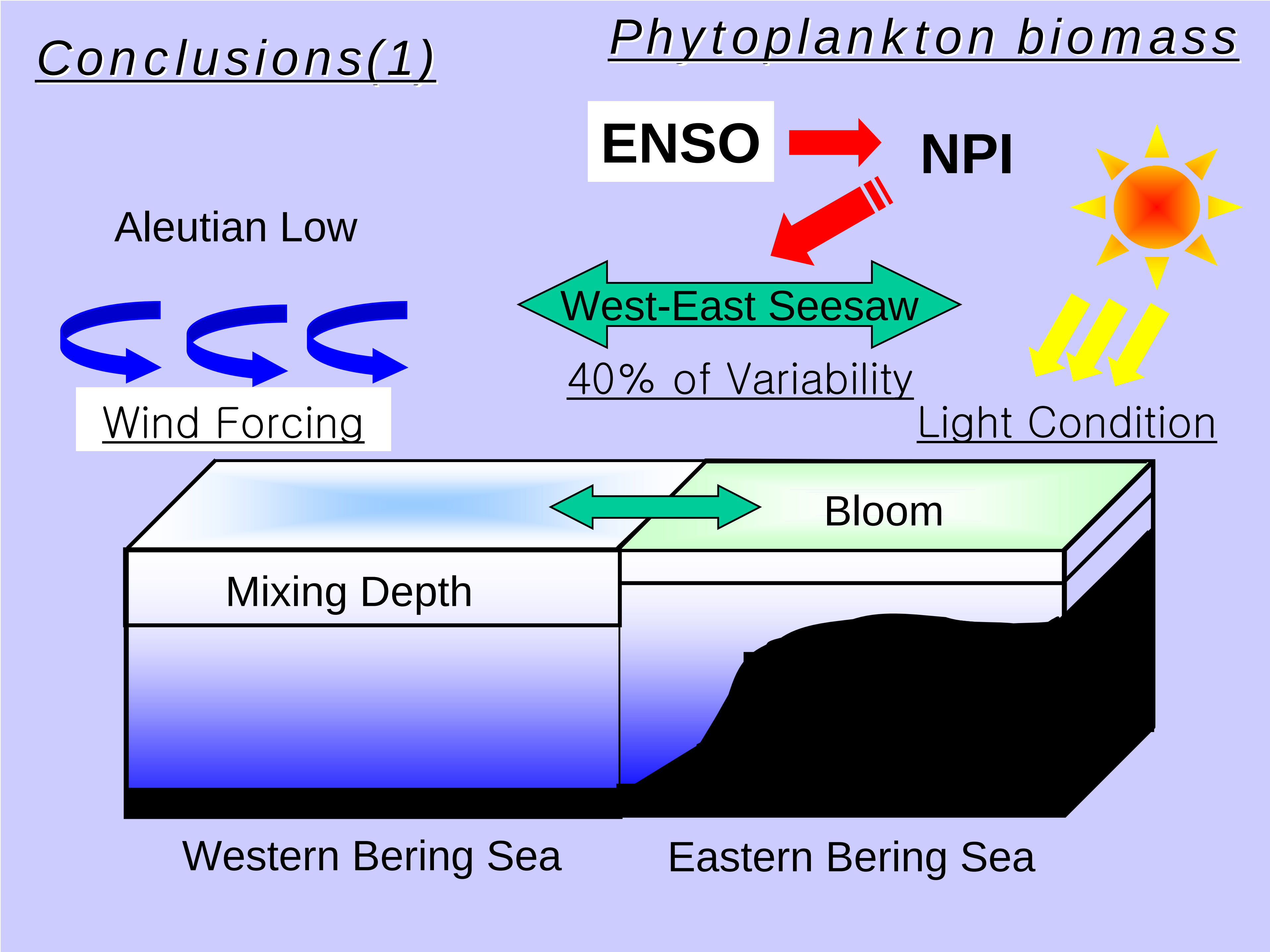


NPI : 1000 - Mean SLP

NPI (PNAI)

→correspond with Teleconnection pattern of El Niño, La Niña

Being Sea phytoplankton is affected by ENSO event through Atmospheric tele-connection


Conclusions(1)
Phytoplankton biomass
ENSO
NPI
Aleutian Low
West-East Seesaw
40% of Variability
Wind Forcing
Light Condition
Bloom
Mixing Depth
Western Bering Sea
Eastern Bering Sea

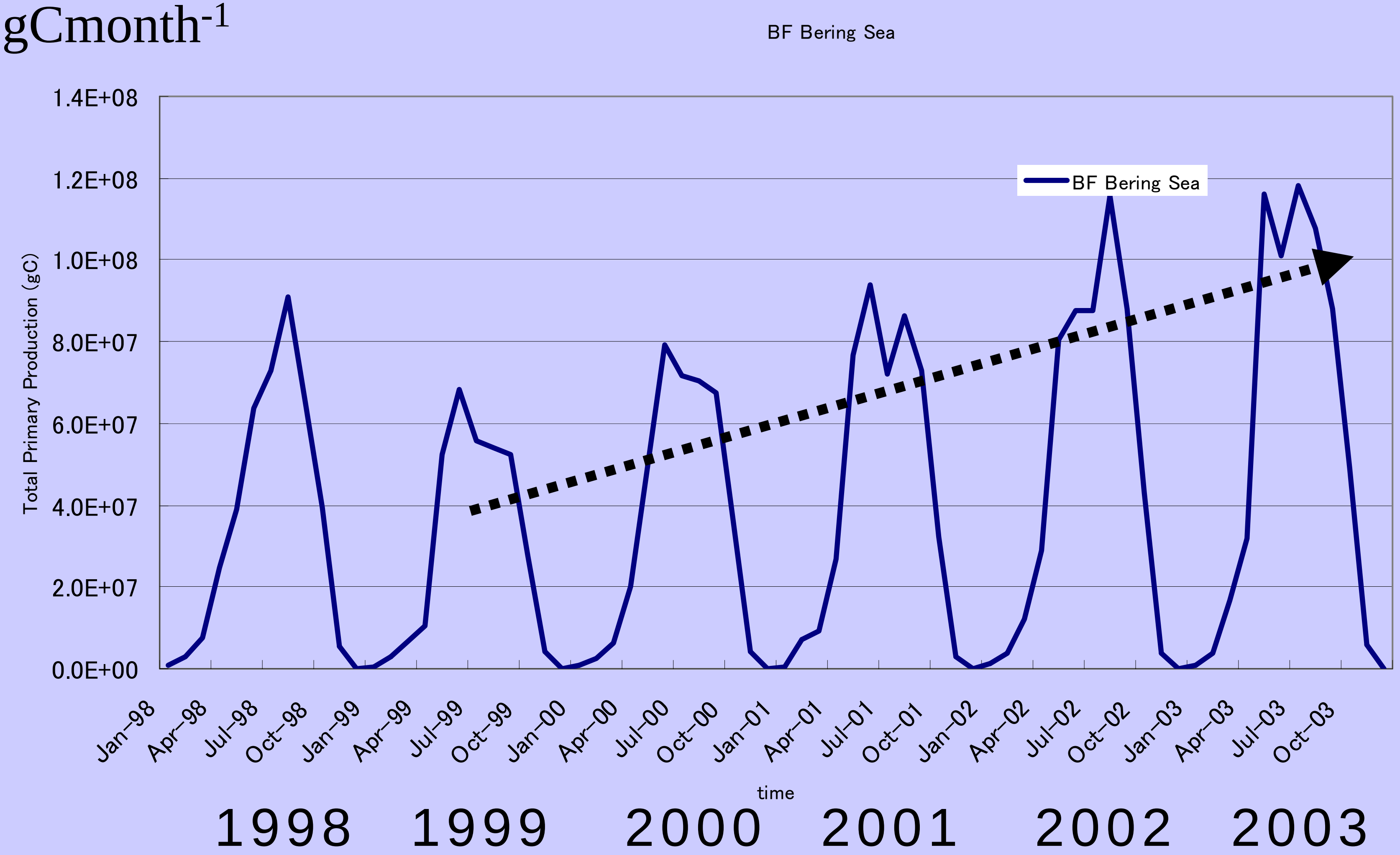
Conclusion(1) Phytoplankton biomss

We described quantitative spring phytoplankton bloom interannual variability in the Bering Sea. Dominant mode of interannual variability was east-west pattern, it was about 40% total spring phytoplankton variability.

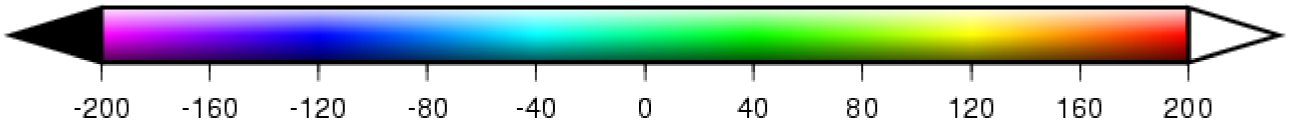
The pattern due to changes wind and light east-west variability related to Aleutian low position. El nino and La nina phenomena related to changing Aleutian low position, it might be influence to the Bering Sea ecosystems.

Primary Production

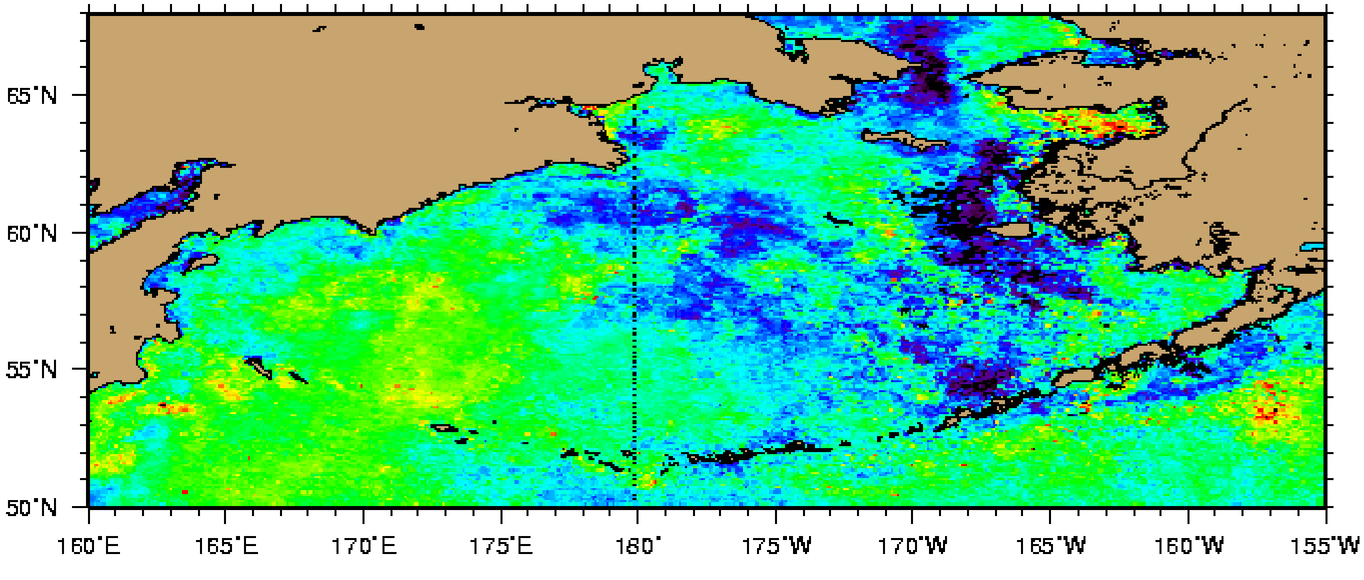
gCmonth^{-1}



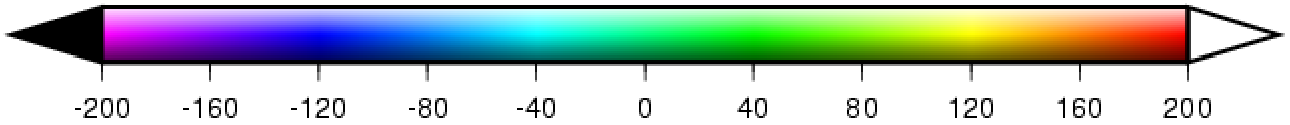
Primary Production



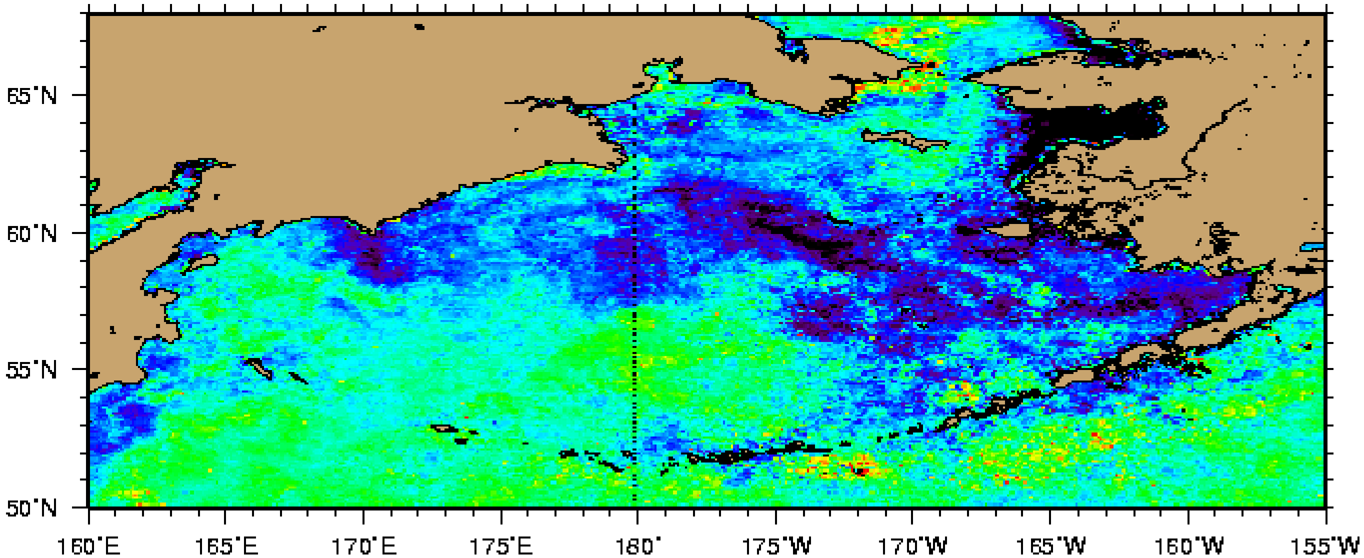
PP anomaly in 1998



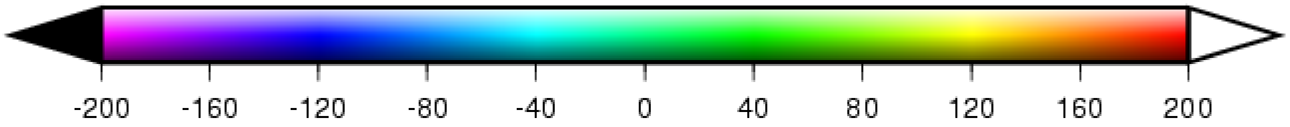
Primary Production



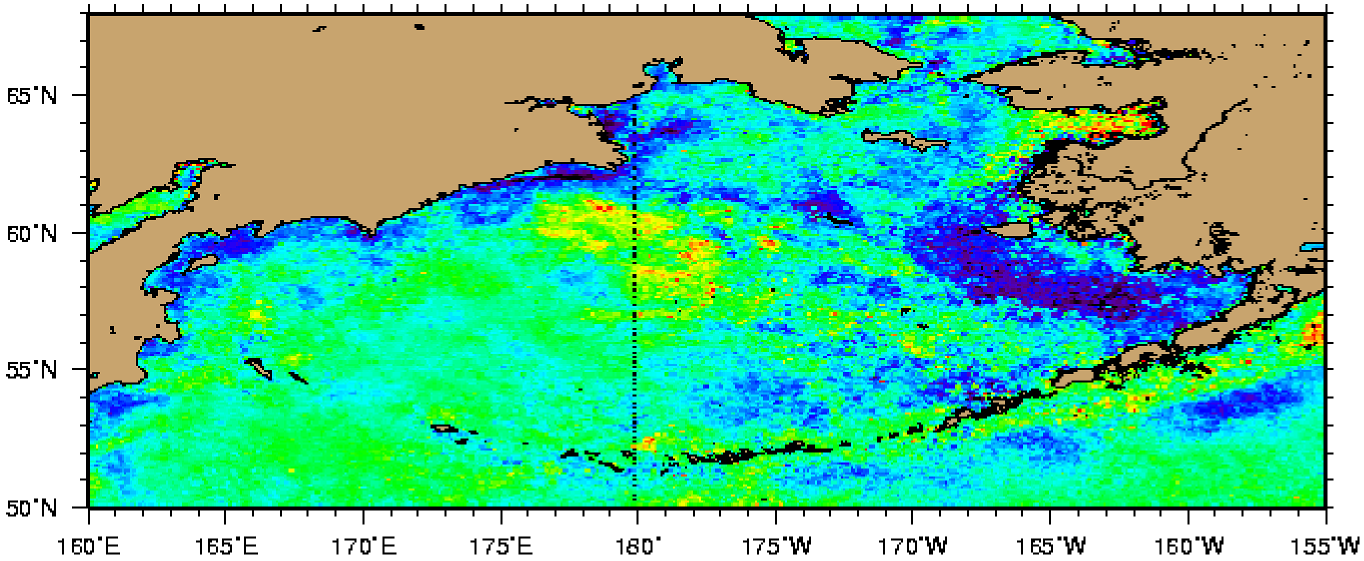
PP anomaly in 1999



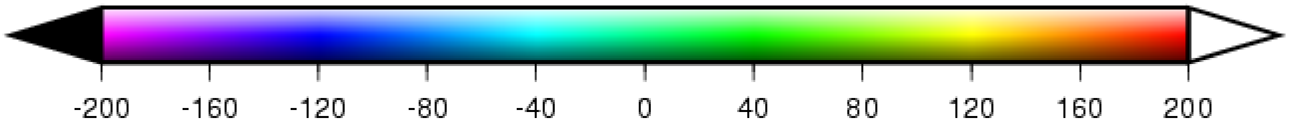
Primary Production



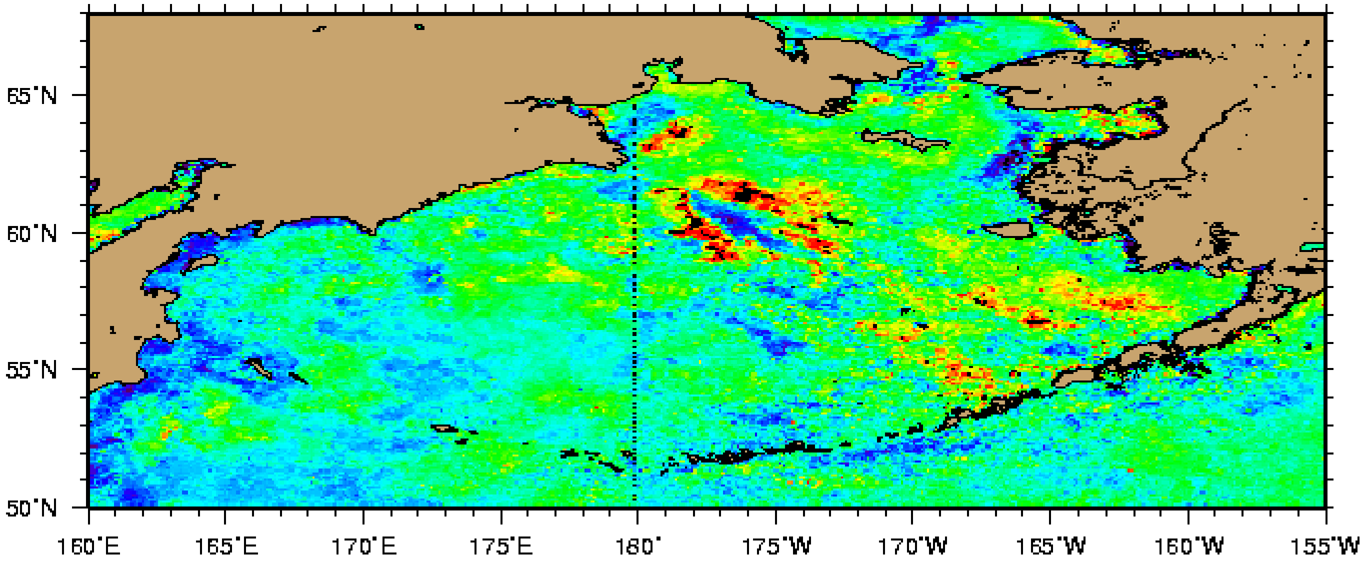
PP anomaly in 2000



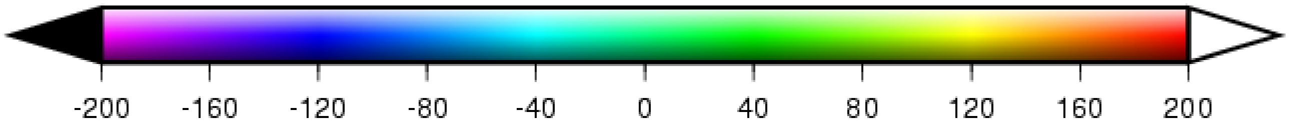
Primary Production



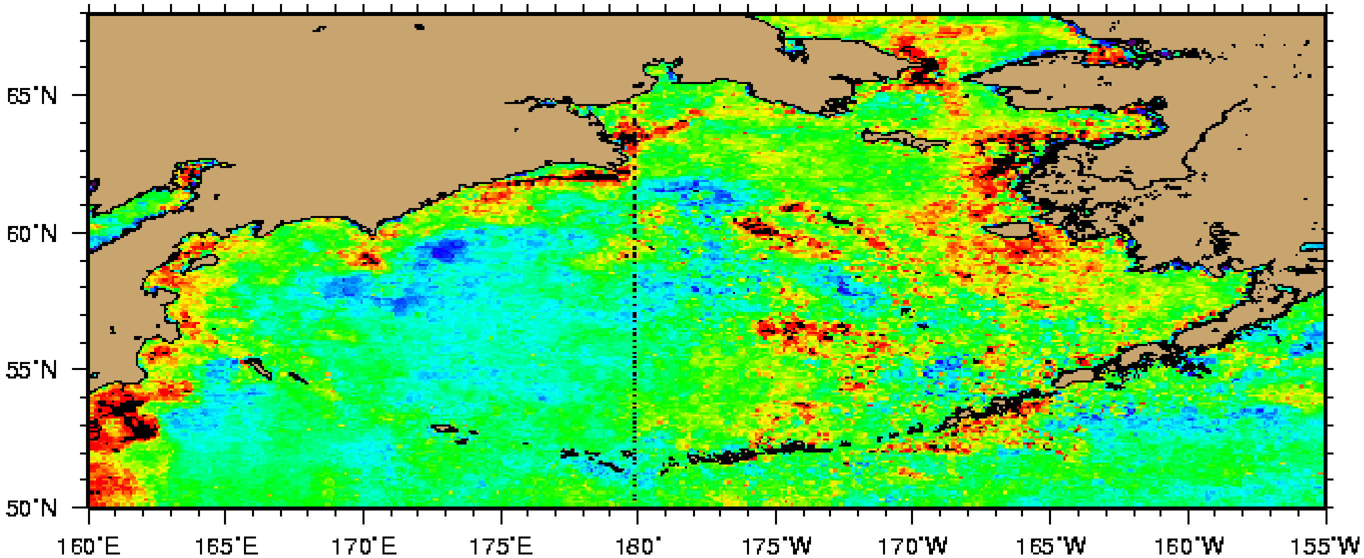
PP anomaly in 2001



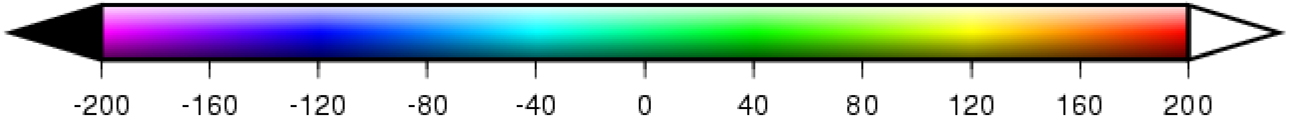
Primary Production



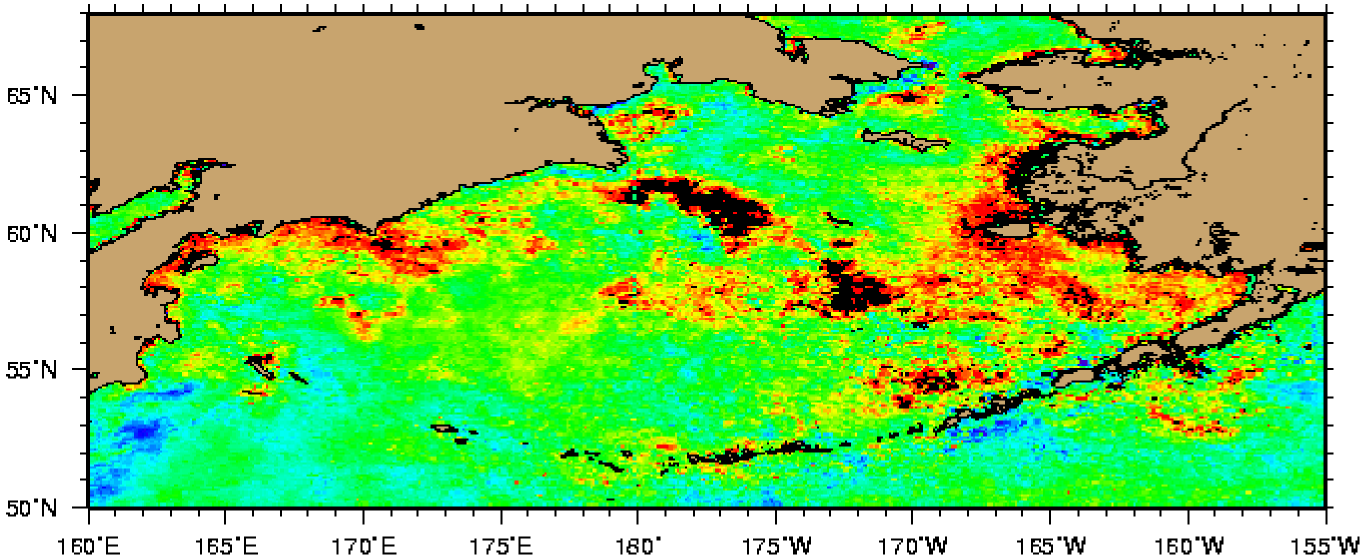
PP anomaly in 2002



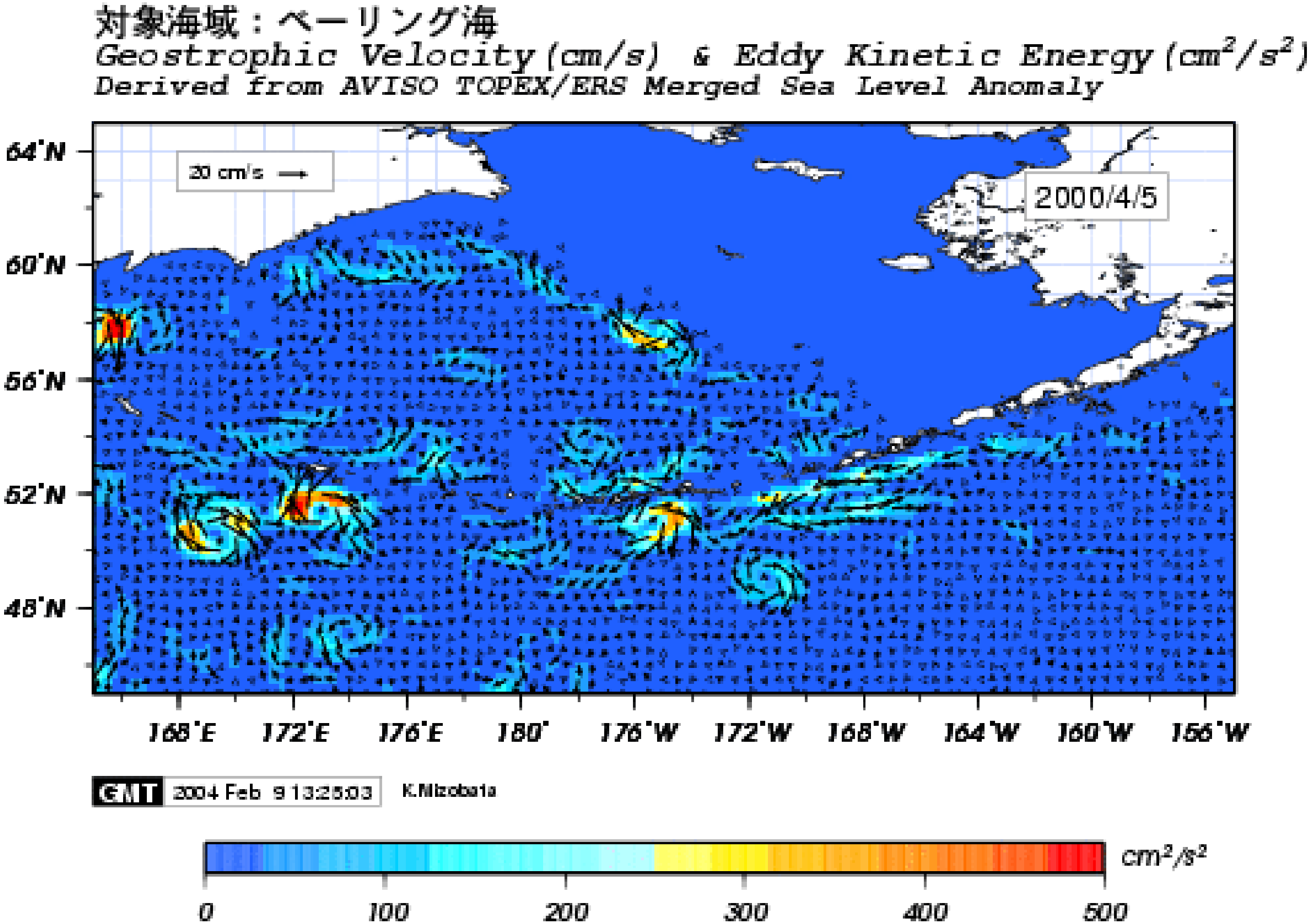
Primary Production



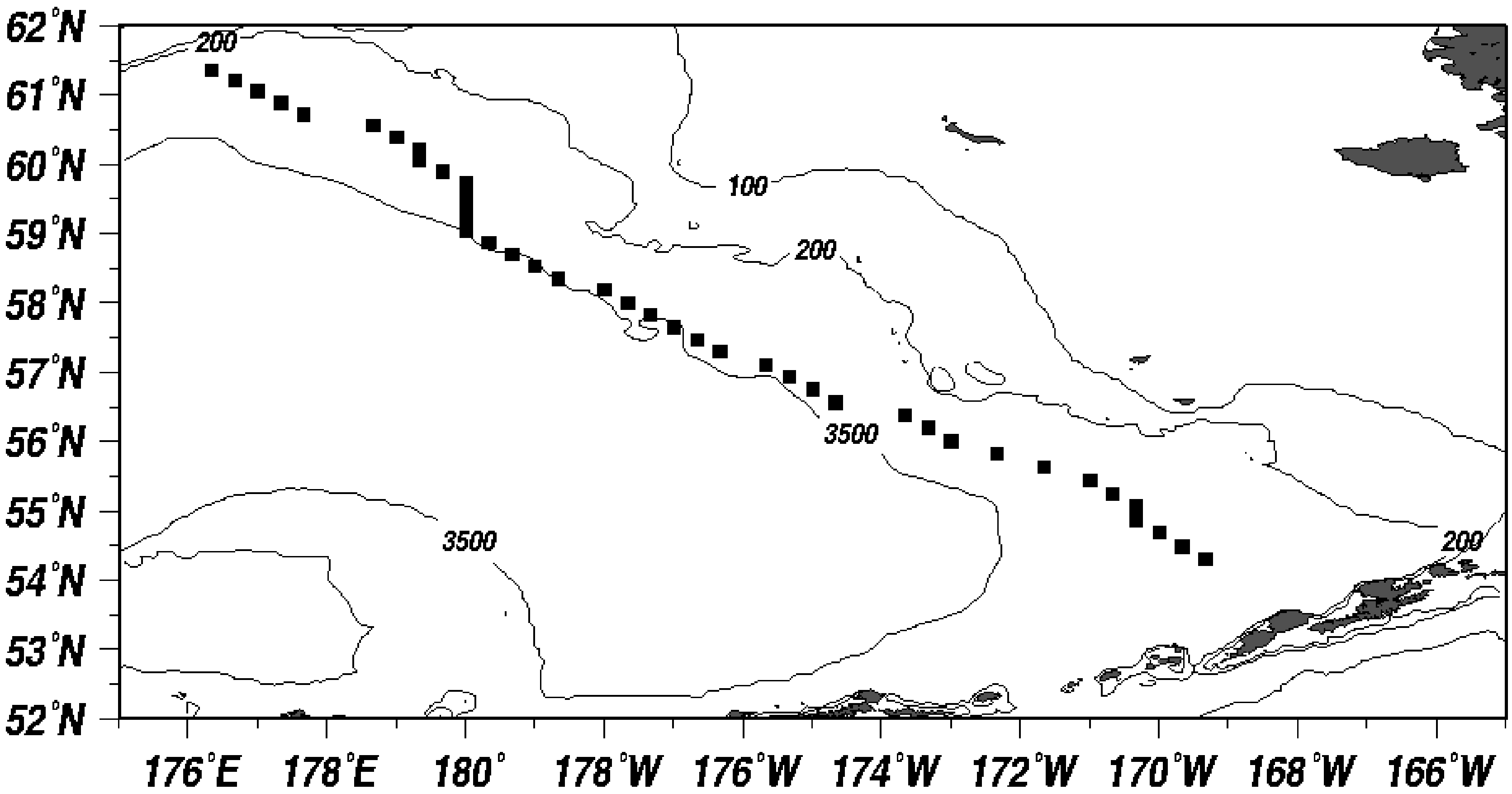
PP anomaly in 2003



Eddy Kinetic Energy in the Bering Sea (2000)

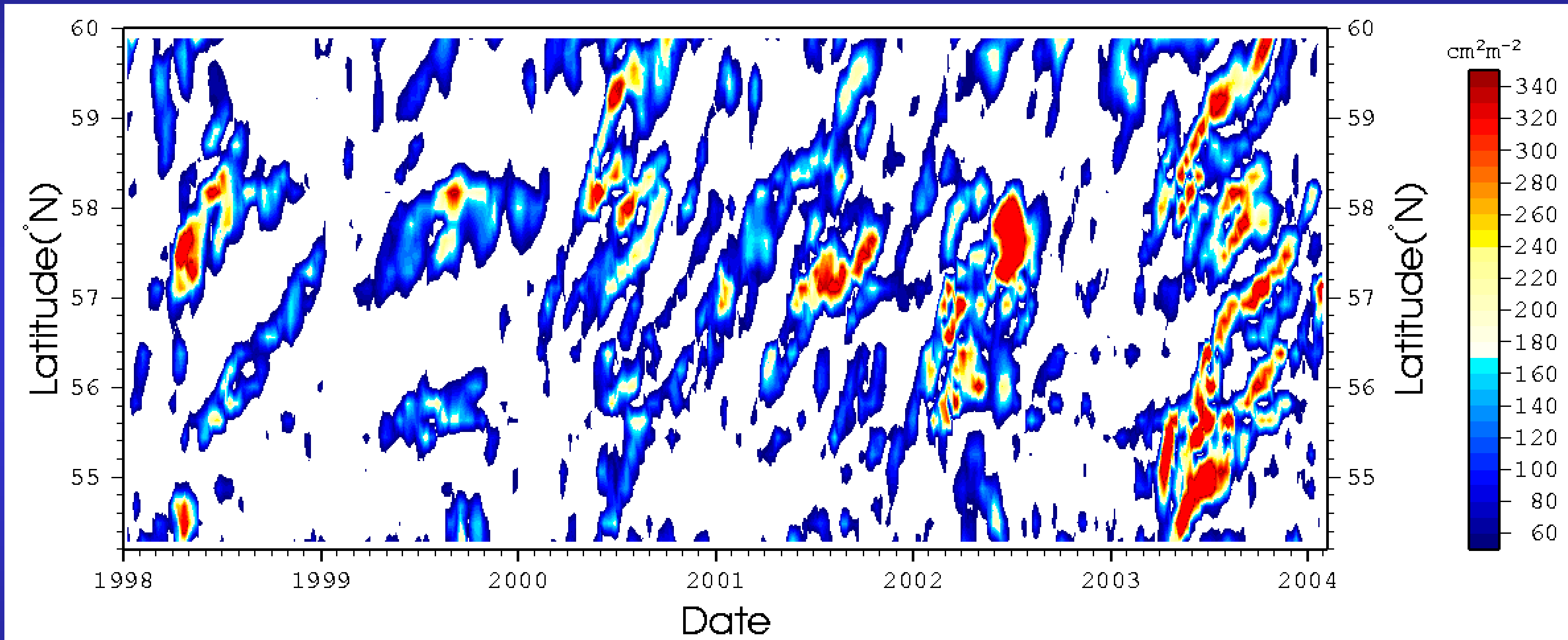


AVISO TOPEX/ERS Merged SSH anomaly



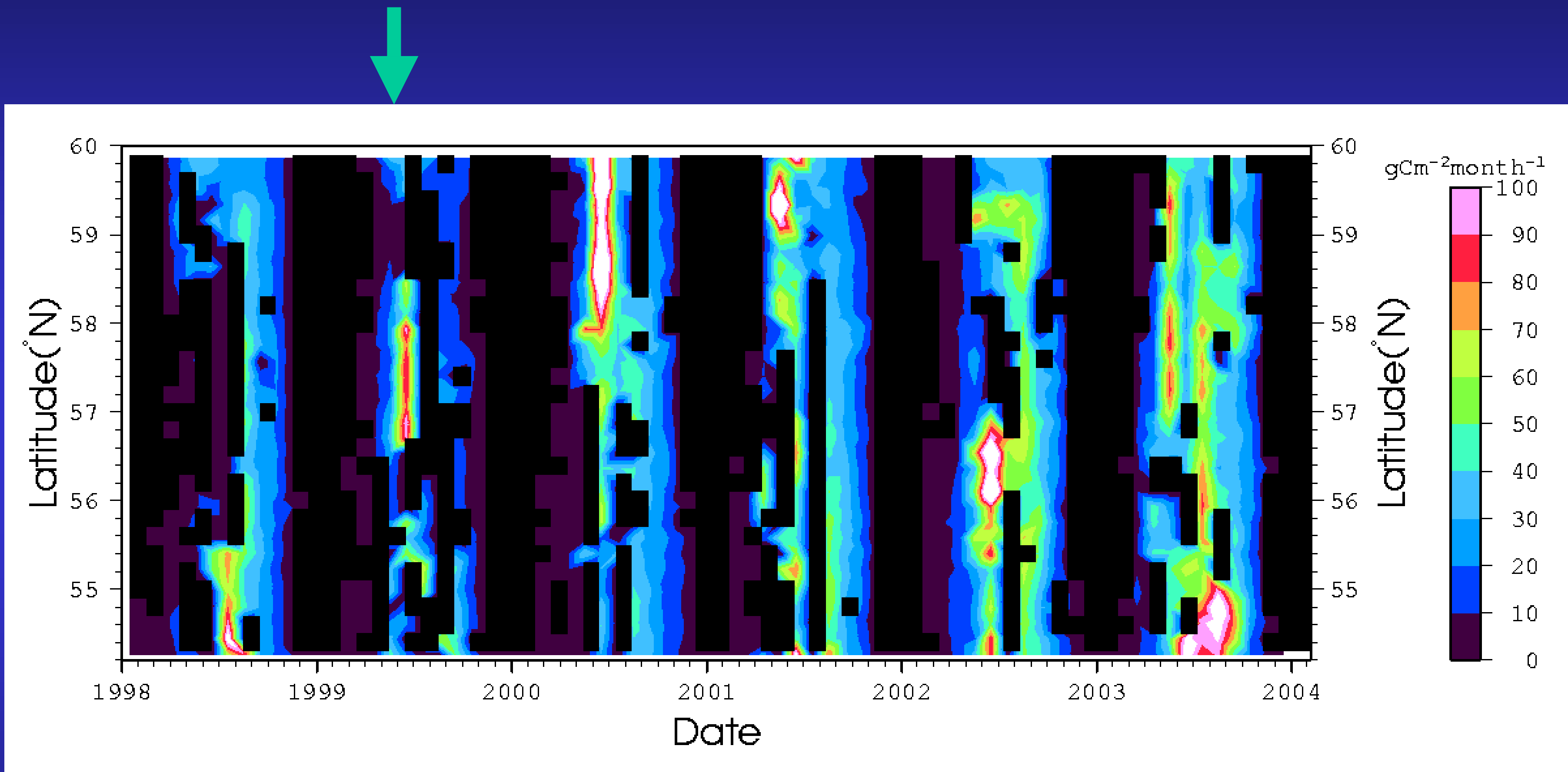
Eddy Kinetic Energy (1998-2003)

1999



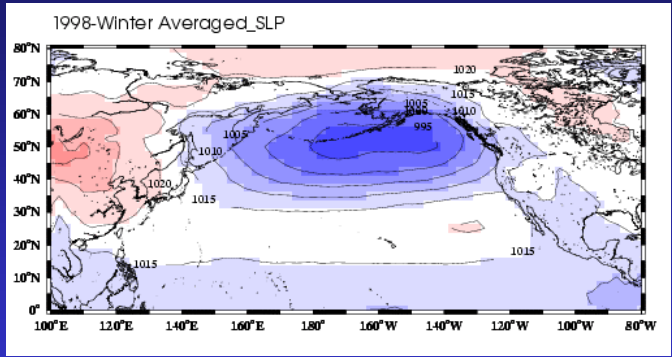
Primary Production(1998-2003)

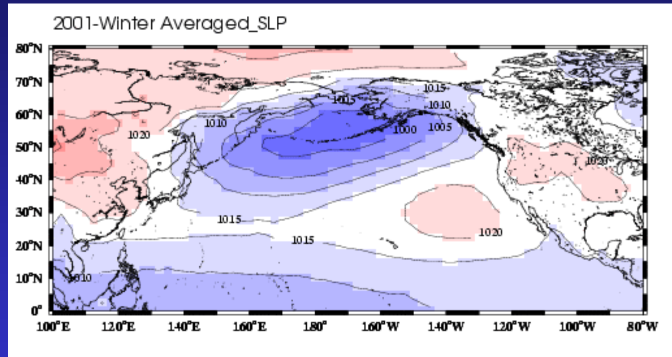
1999 (Behrenfeld & Falkowski model)



Winter-averaged SLP

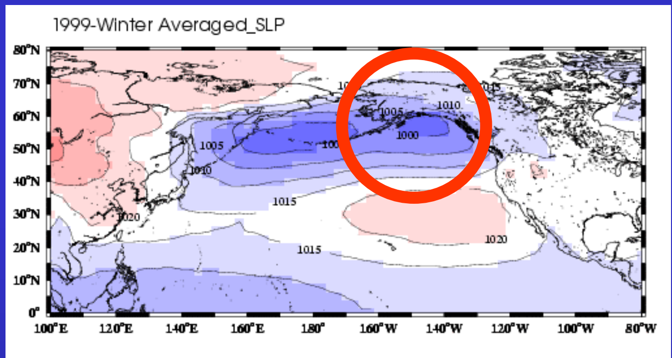
1998

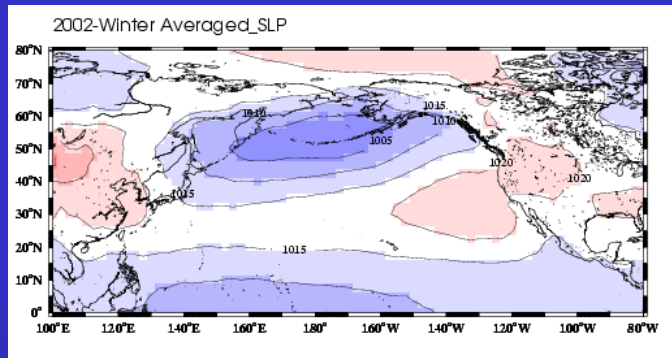




2001

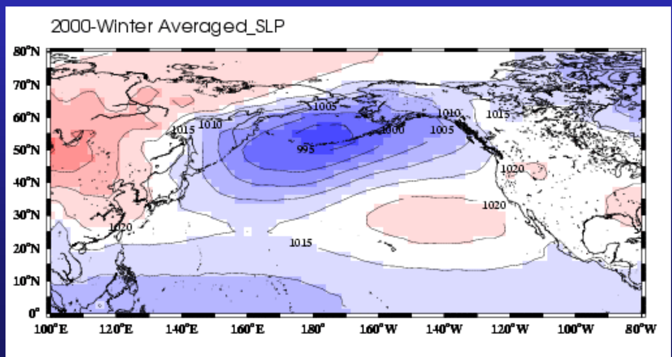
1999

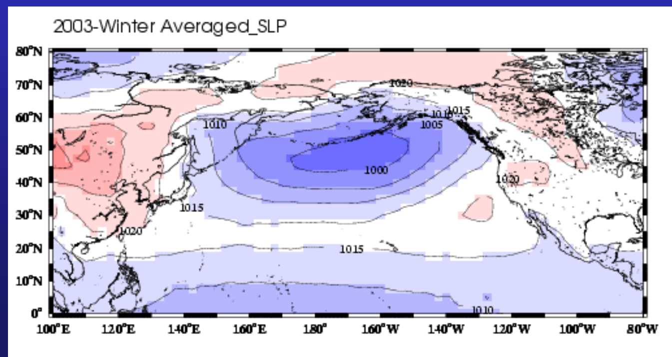




2002

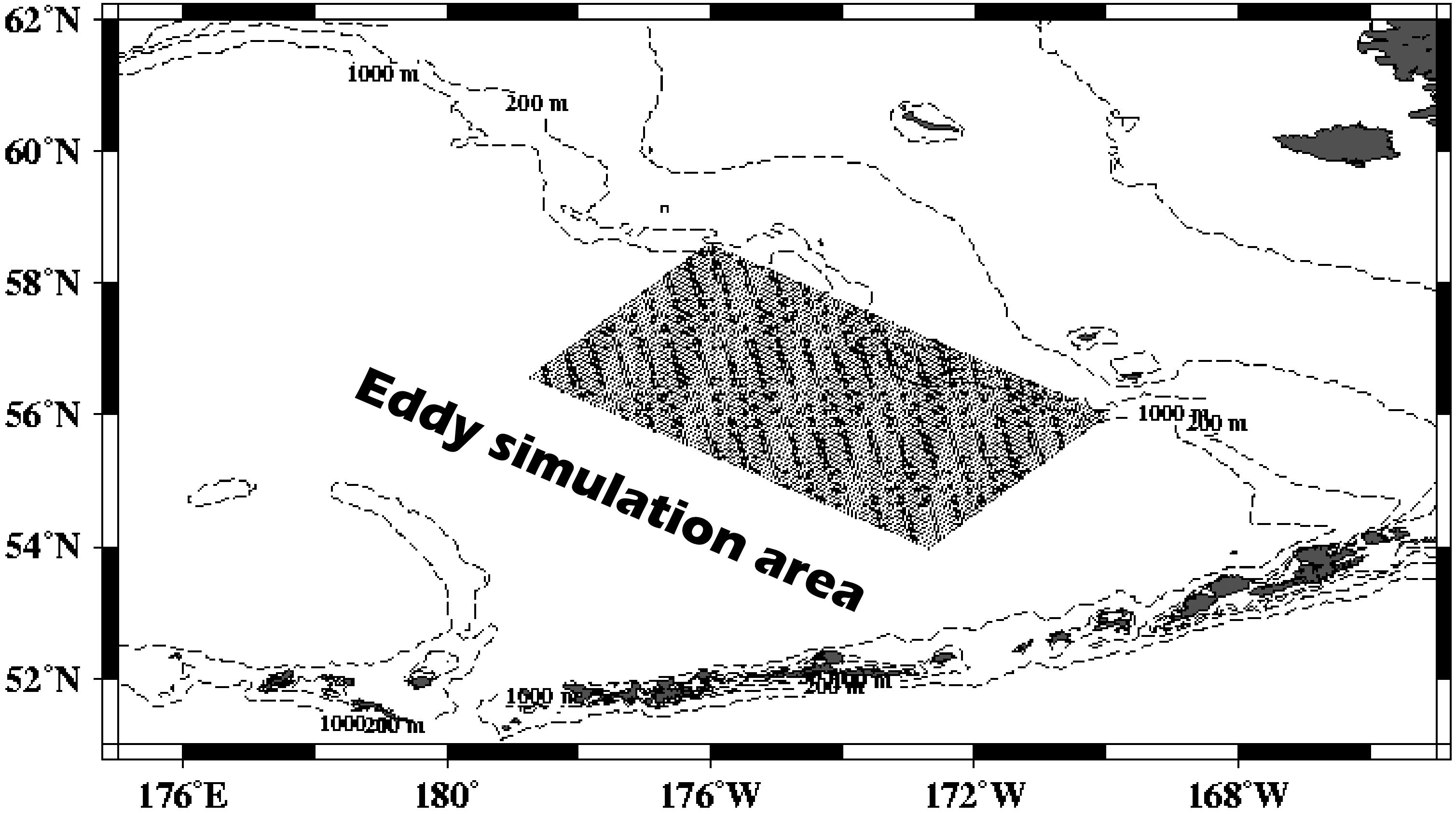
2000





2003

Modeling Study of Eddies

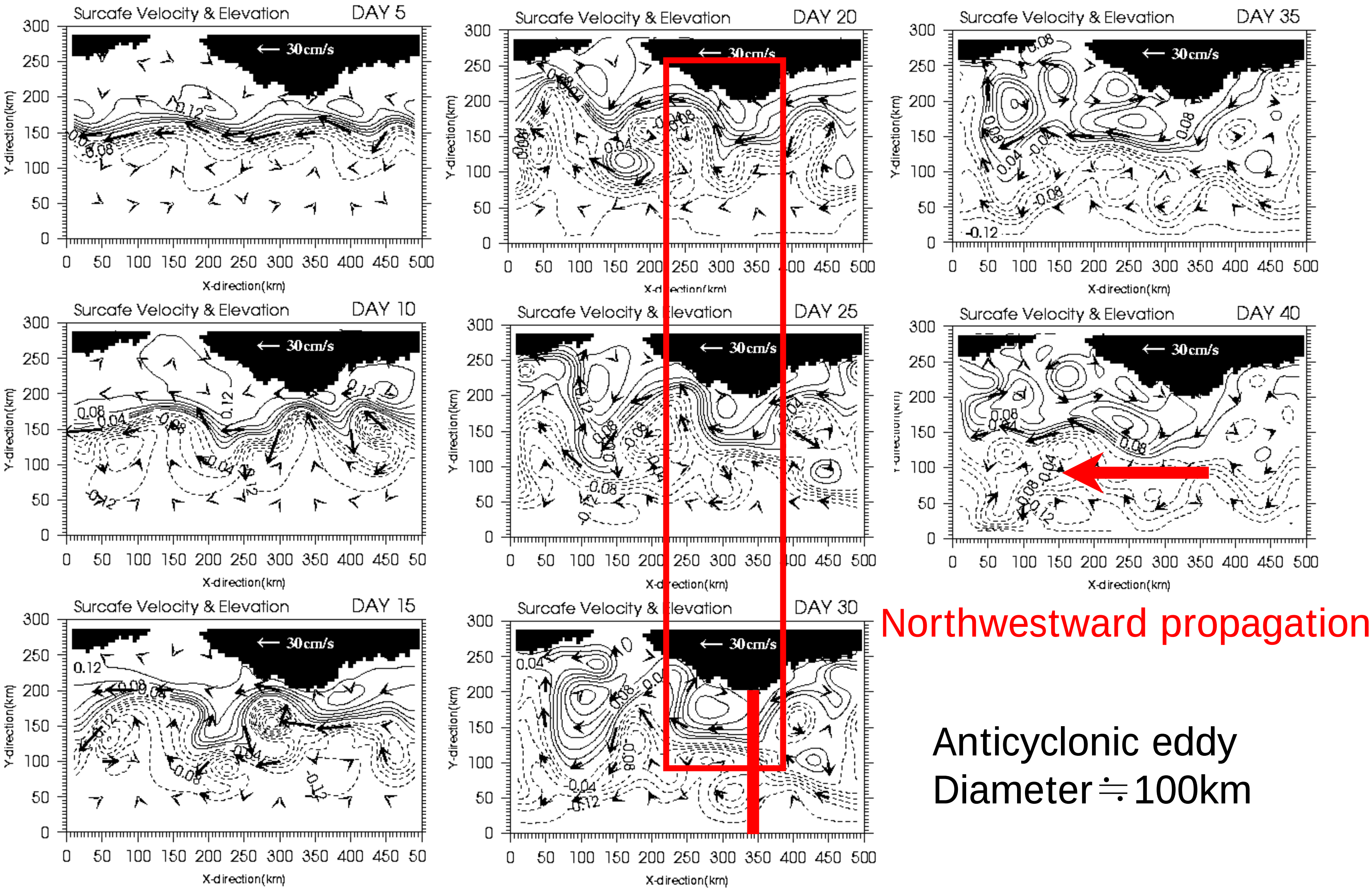


ECOM-si (Estuarine, Coastal and Ocean Model with semi-implicit; Wang and Ikeda, 1997)

Spatial resolution=5km 21layers

Results

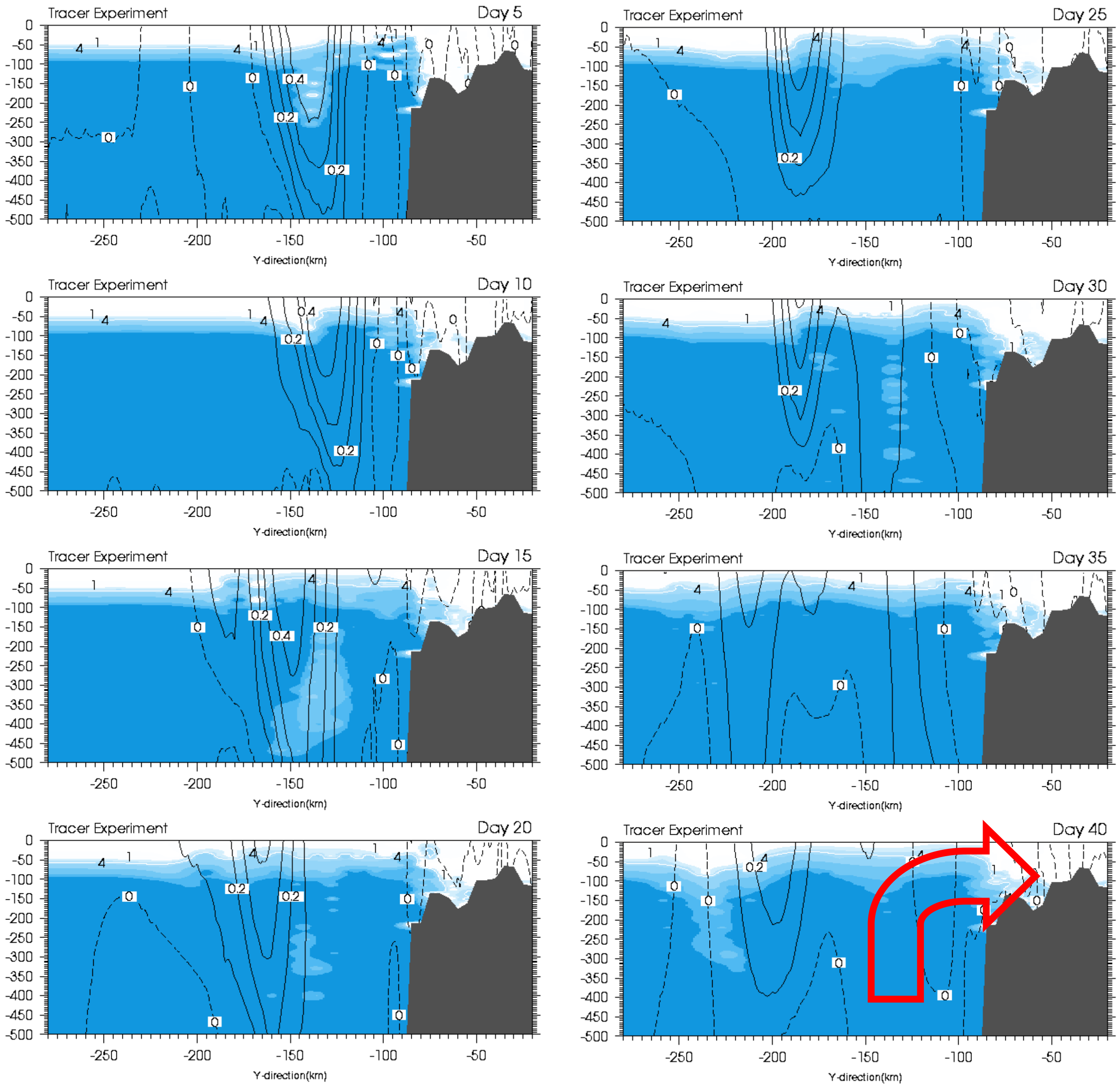
Jet Flow with perturbation off 50km from shelf break



Anticyclonic eddy
Diameter≒100km

Results

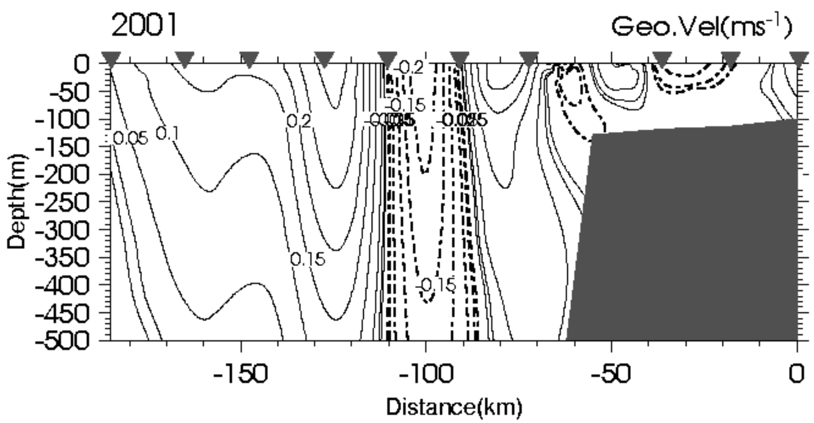
Tracer experiments for Basin nutrient-rich water distribution

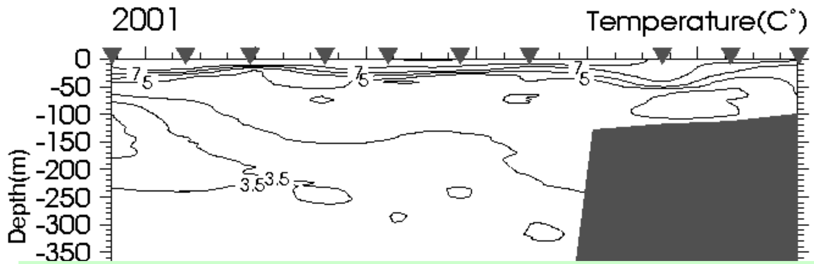


Tracer (Nutrients)
➔transported to shelf region when eddy was developed

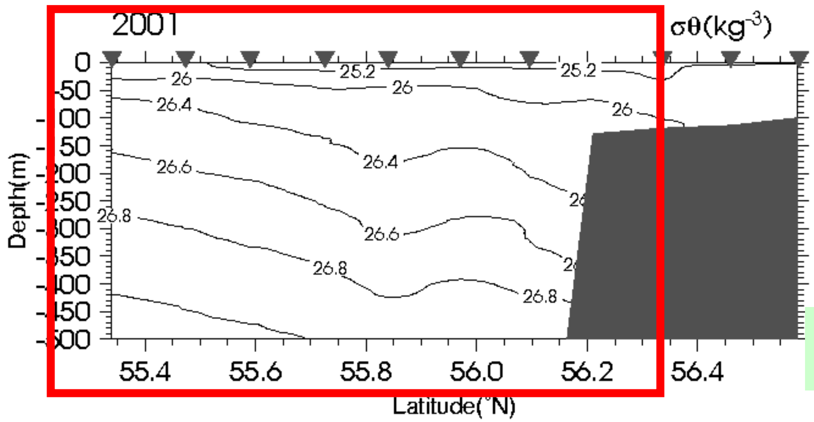
➔corresponded with in-situ observation

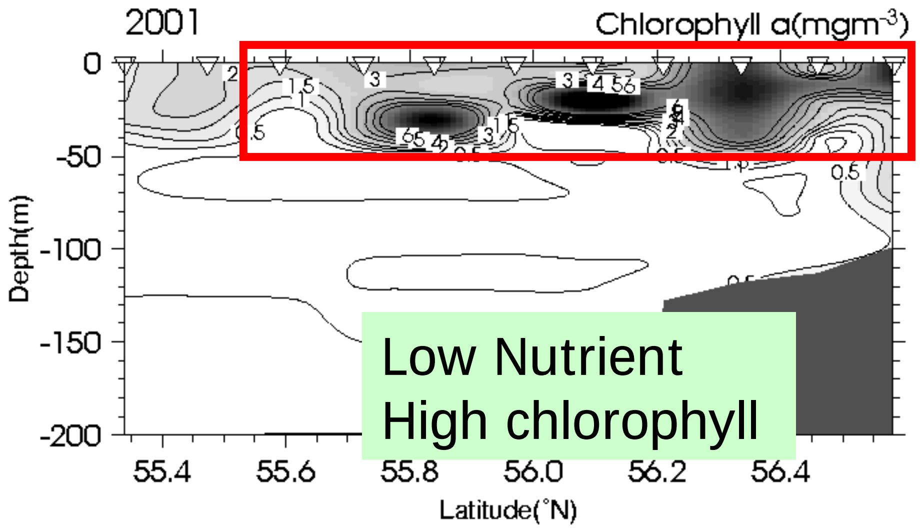
Results



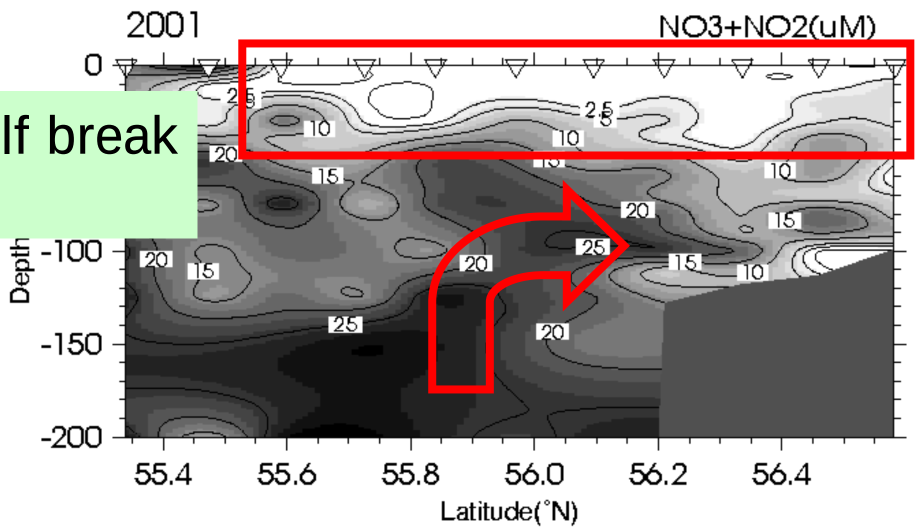


Isopycnals has inverse slope of shelf break
➔ eddy tend to be developed





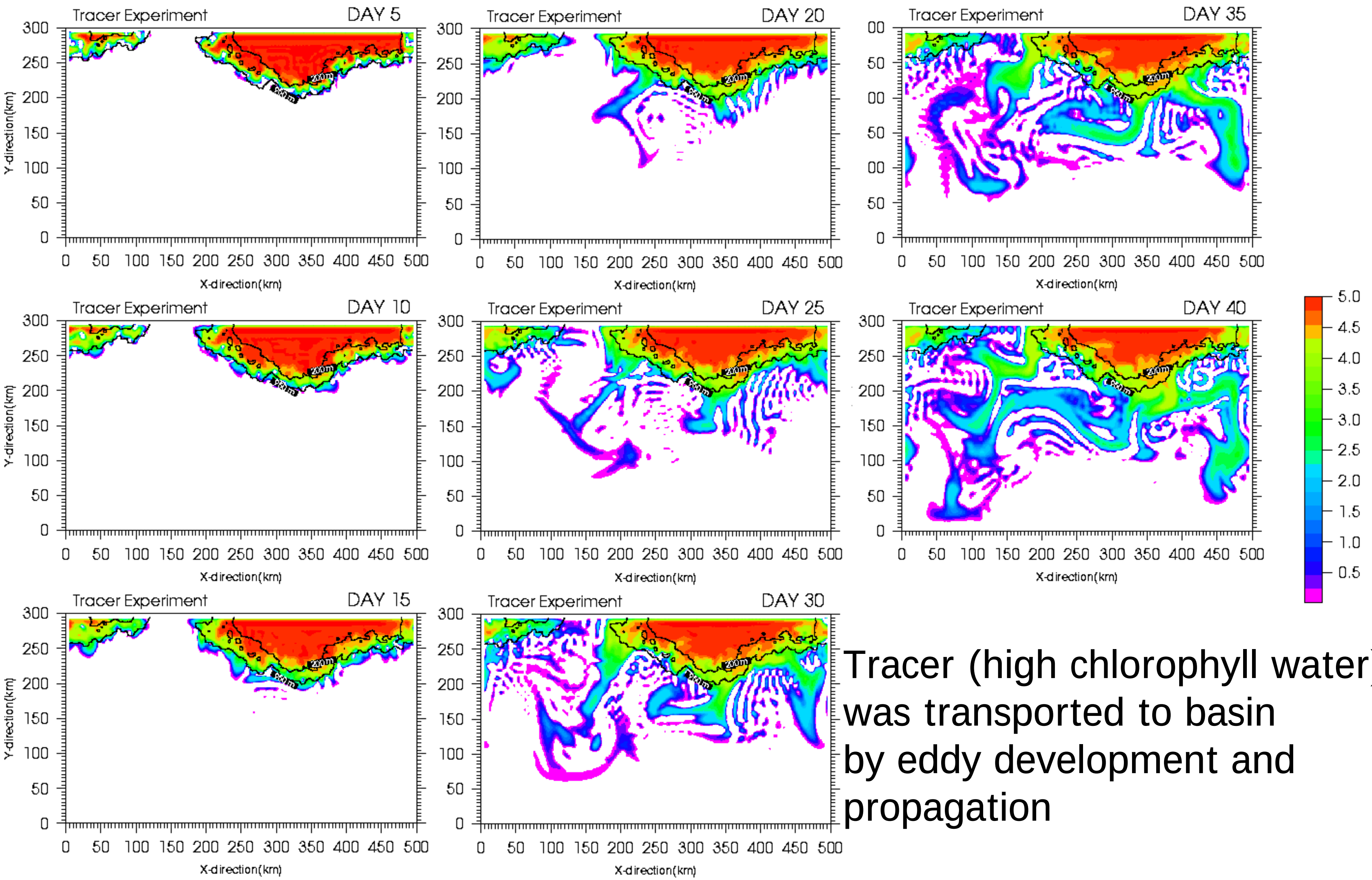
Low Nutrient
High chlorophyll



High nutrient distributed from basin to shelf

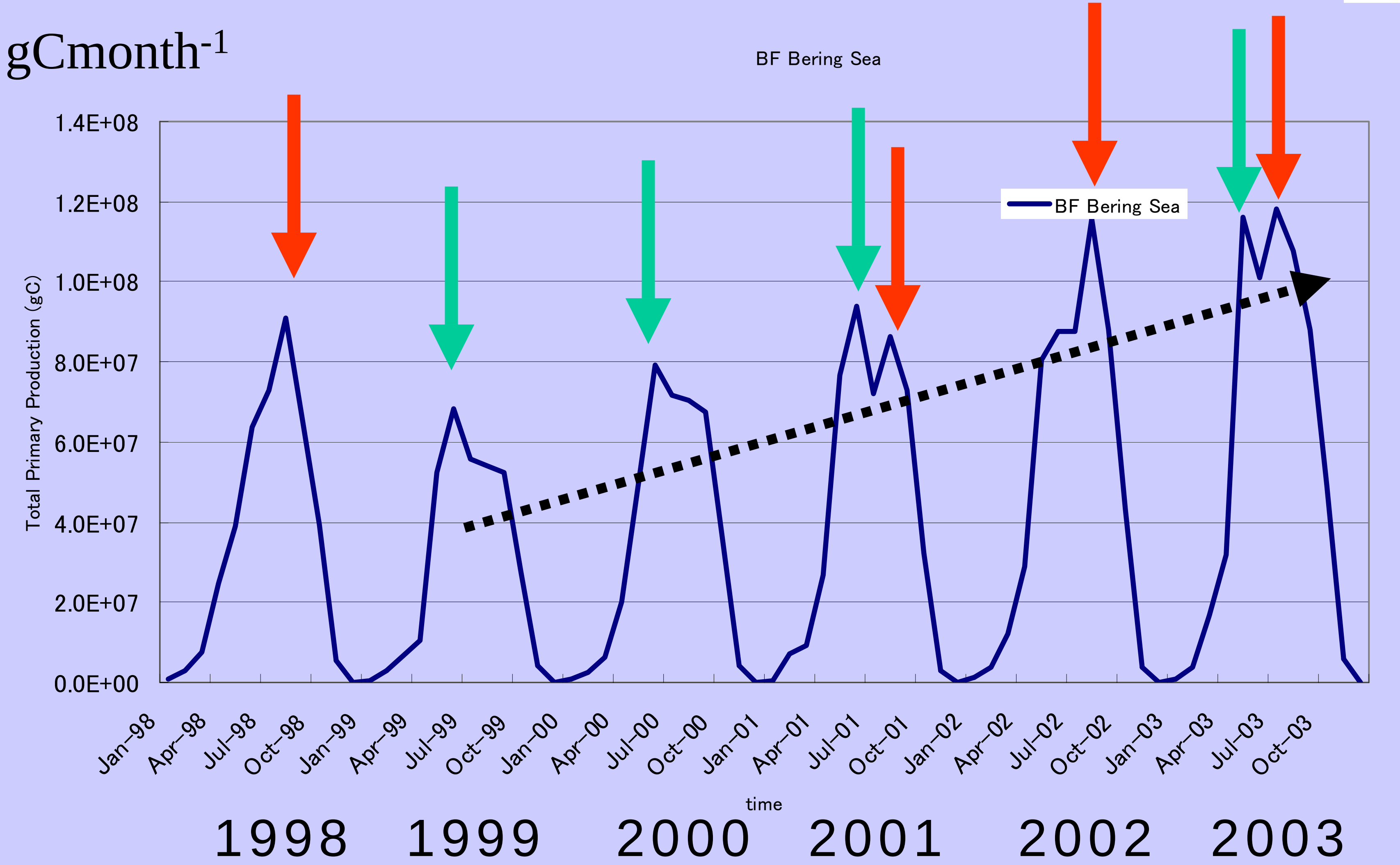
Results

Tracer experiments for Shelfbreak high productive water distribution

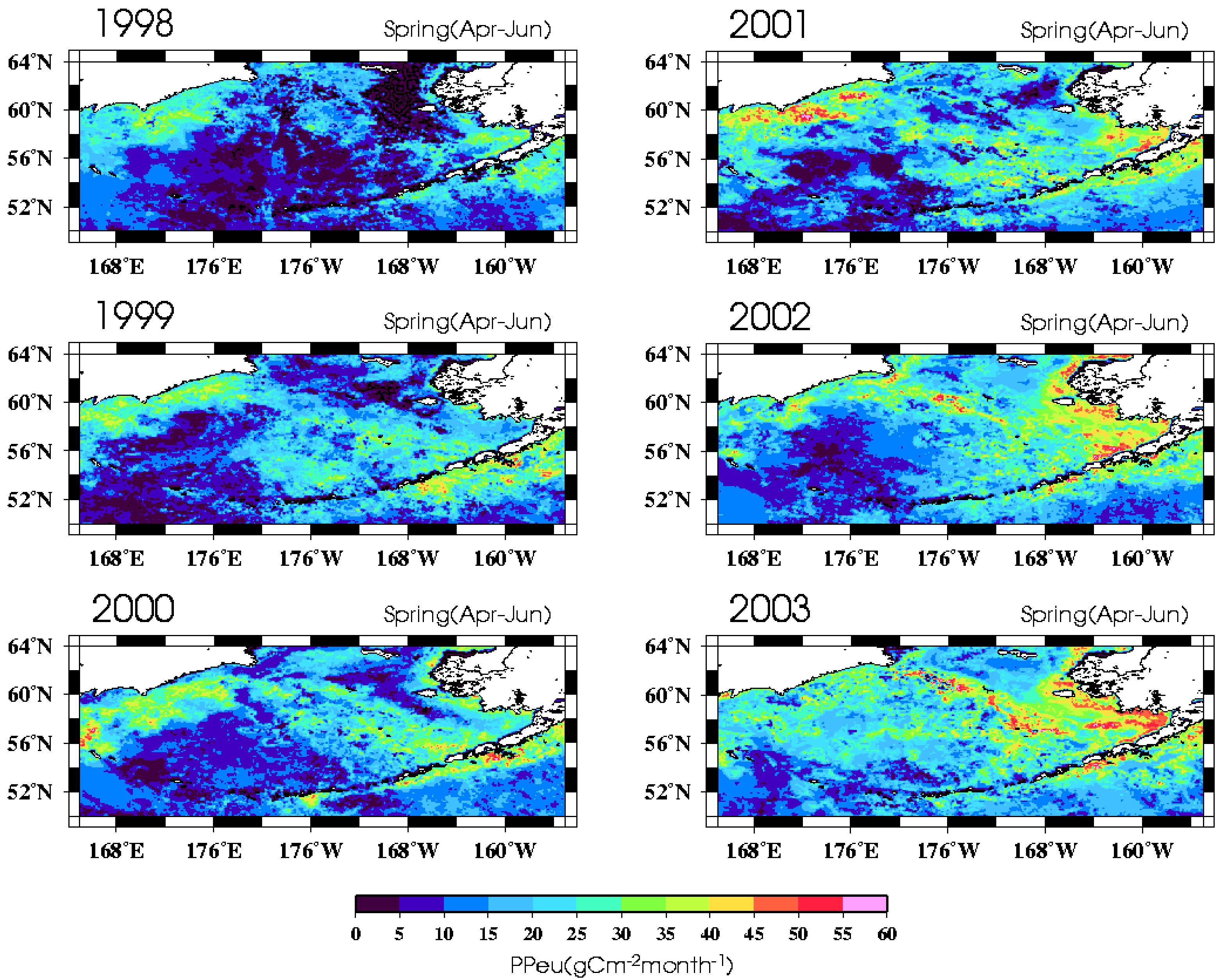


Tracer (high chlorophyll water) was transported to basin by eddy development and propagation

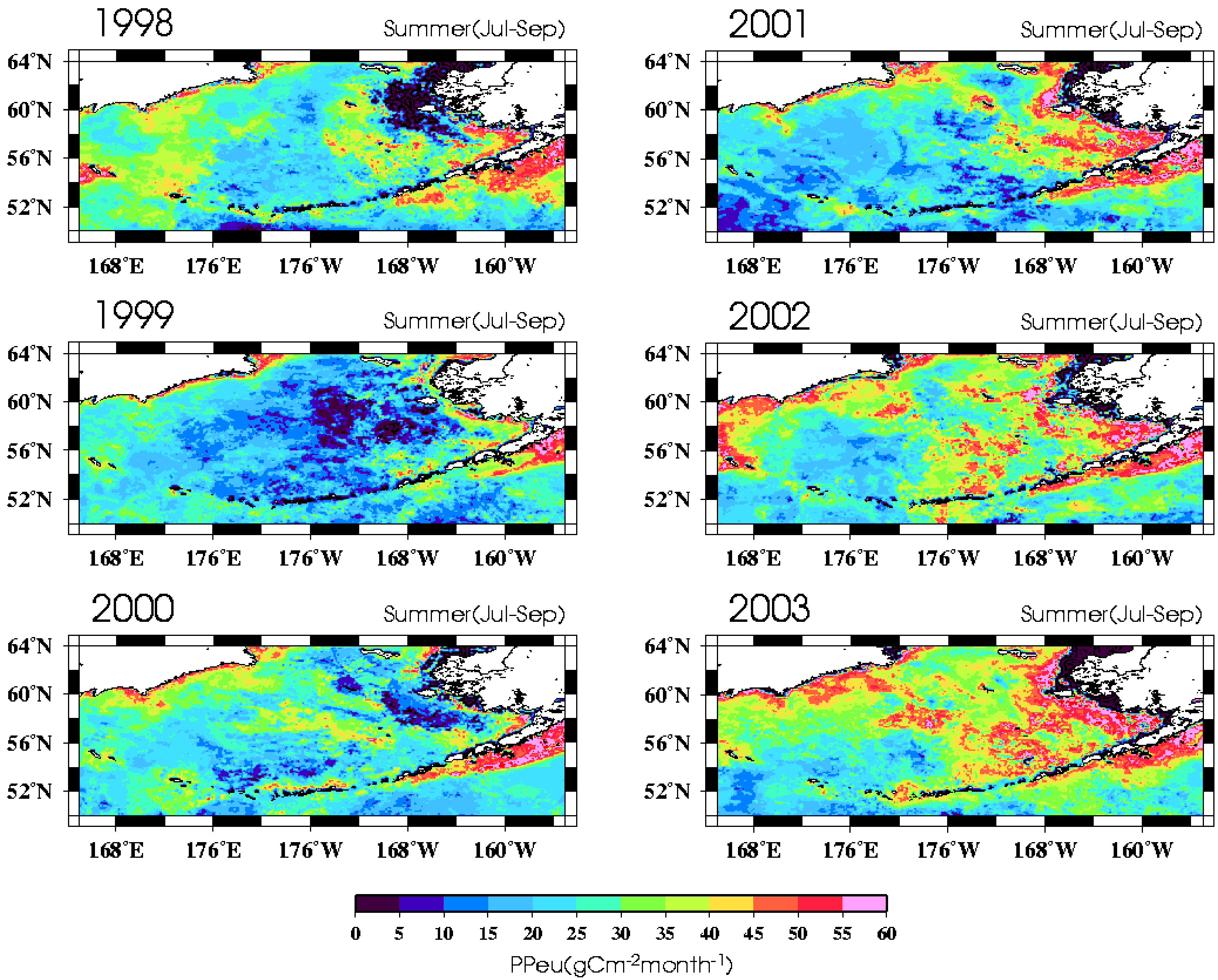
Primary Production



Primary Production - Spring(April-June)



Primary Production - Summer(July-Sep.)

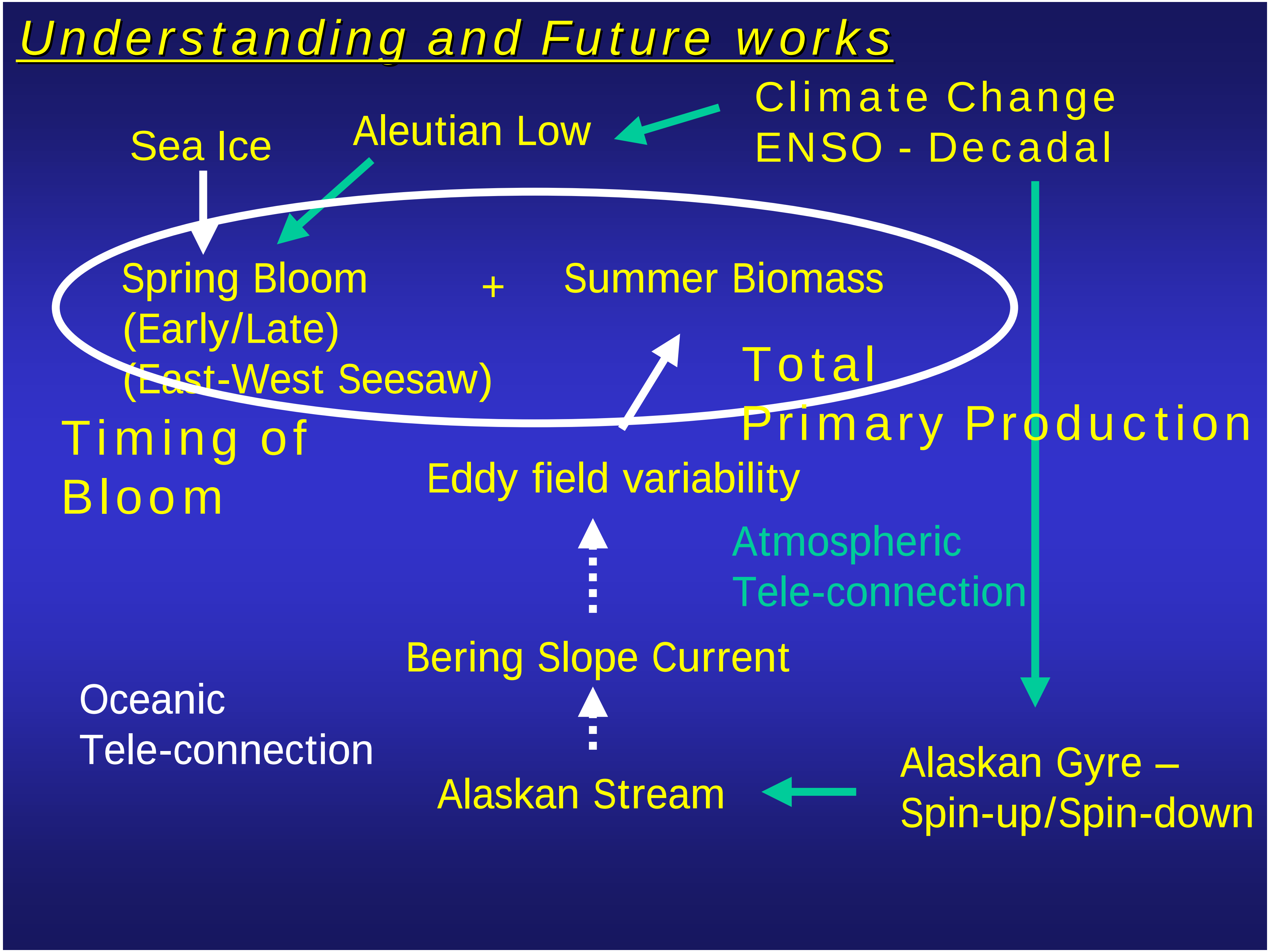


Conclusion(2) Primary Production

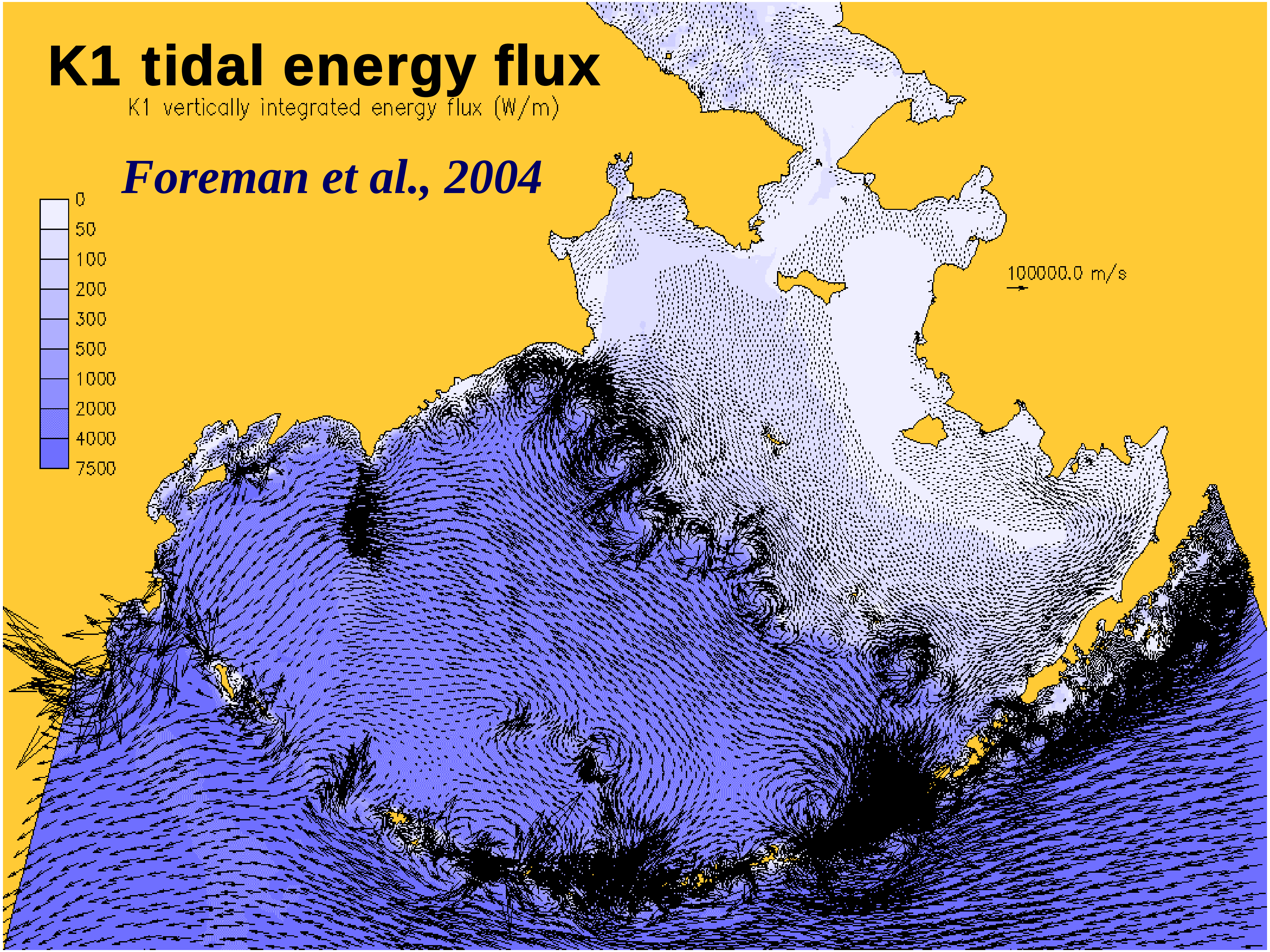
We found the increasing trend of primary production since 1999. Summer primary production maintains the increasing trend.

Minimum year of total primary production is 1999 and eddy kinetic energy was also lowest in 1999.

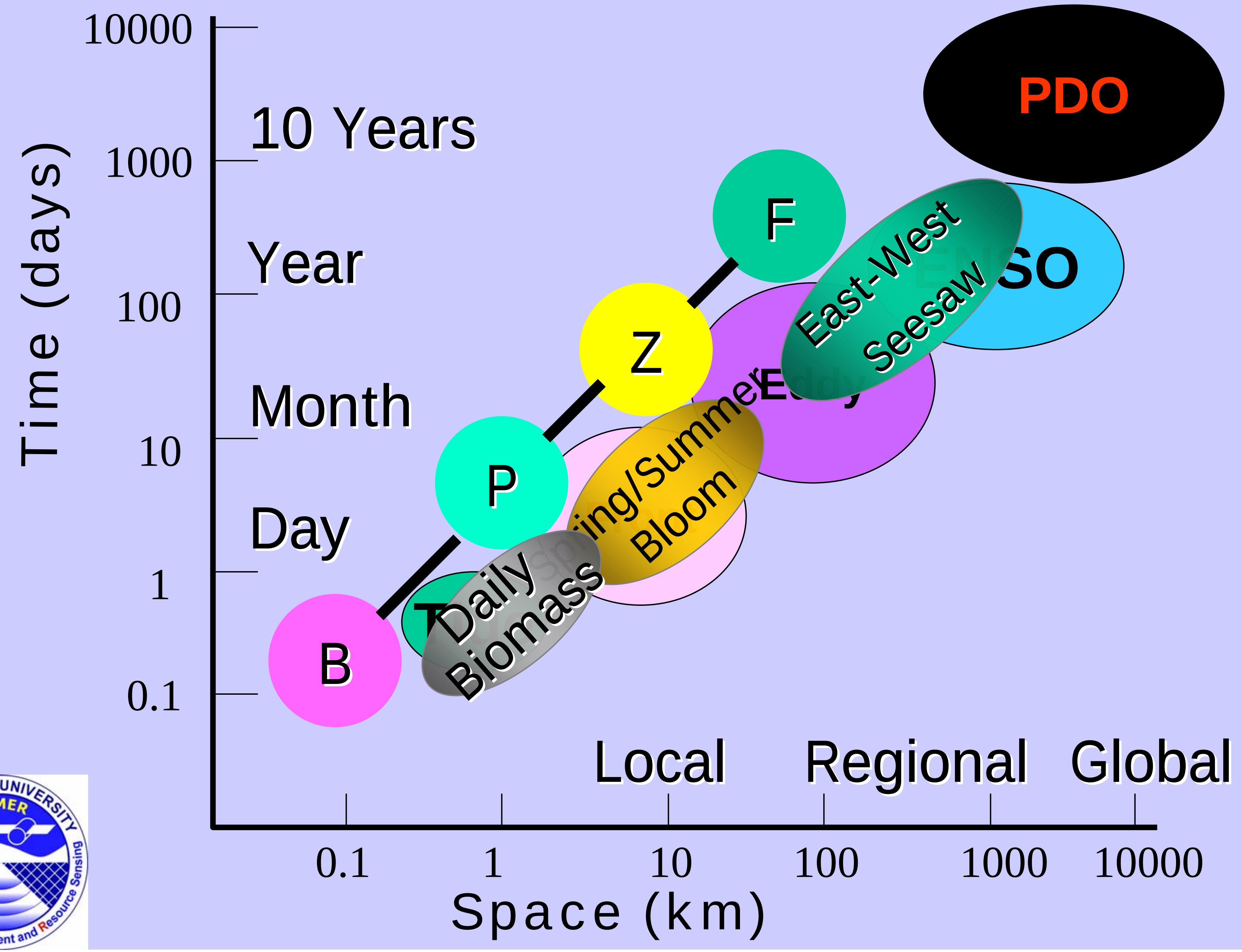
From eddy modeling study, instability of Bering Slope Current is important to generate eddies along shelf edge in the Bering Sea and eddies contribute enhancement of phytoplankton biomass.


Understanding and Future works
Climate Change
ENSO - Decadal
Sea Ice
Aleutian Low
Spring Bloom
(Early/Late)
(East-West Seesaw)
+
Summer Biomass
Total
Primary Production
Timing of
Bloom
Eddy field variability
Atmospheric
Tele-connection
Bering Slope Current
Oceanic
Tele-connection
Alaskan Stream
Alaskan Gyre –
Spin-up/Spin-down

K1 tidal energy flux



Foreman et al., 2004



Time (days)
10000
1000
100
10
1
0.1
10 Years
Year
Month
Day
PDO
F
East-West
Seesaw
Z
P
Bloom
Daily
Biomass
B
Local
Regional
Global
0.1
1
10
100
1000
10000
Space (km)

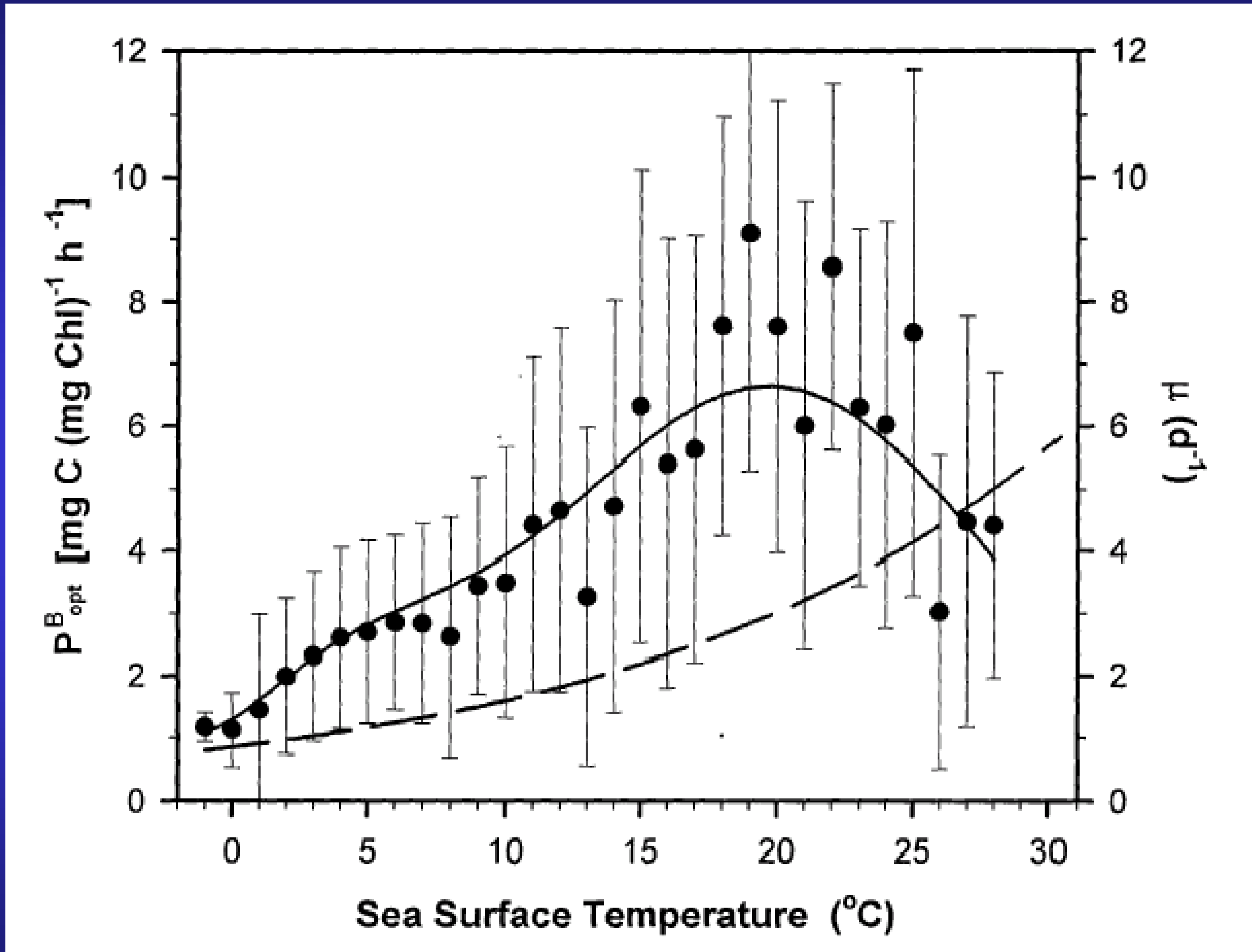
- Acknowledgement -

A part of this study is supported
by the Japan Aerospace Exploration Agency (JAXA)
through the program of Arctic Research projects
using IARC (International Arctic Research Center)-JAXA
Information System (INIS).

Did Sea Lion know climate change?

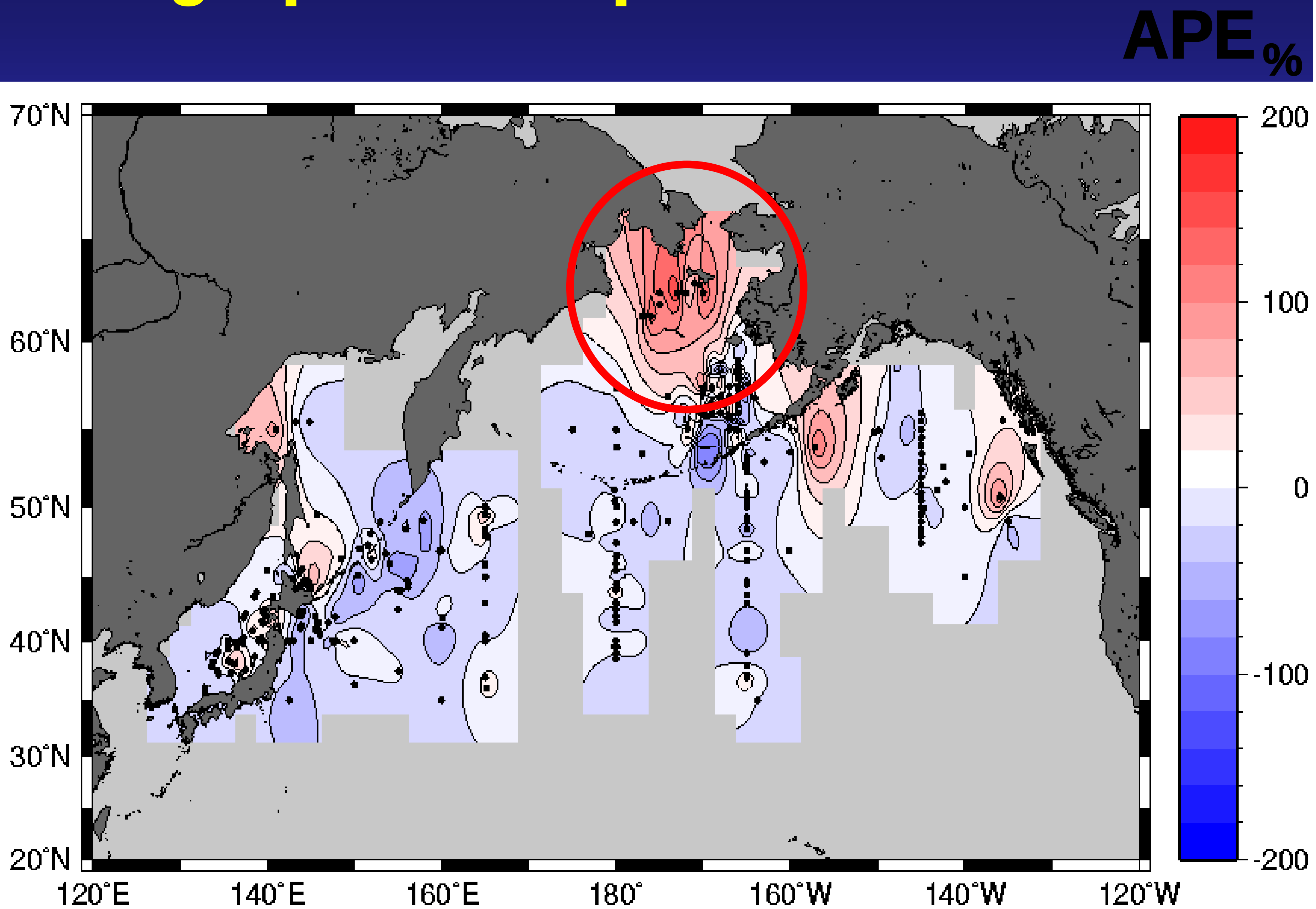
Photo by Sei-ichi Saitoh
Baby Island, Aleutian Islands
in Summer, 1975

VGPM Model (Behrenfeld and Falkowski, 1997)

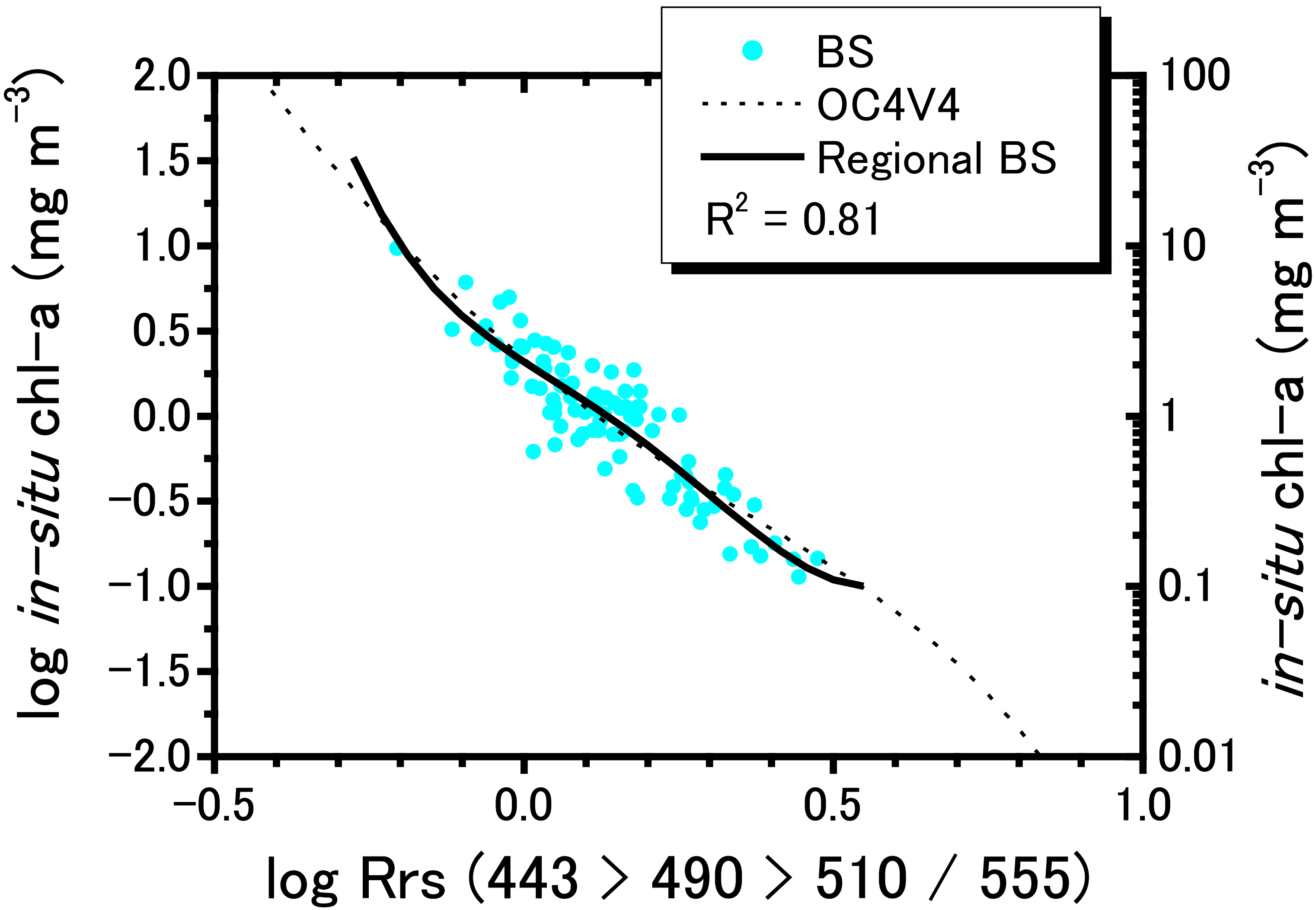


$$P^B_{opt} = a*T^7+bT^6+cT^5+dT^4+eT^3+fT^2+gT+h$$

Geographical map of APE for OC4V4



Regional algorithm for Bering Sea



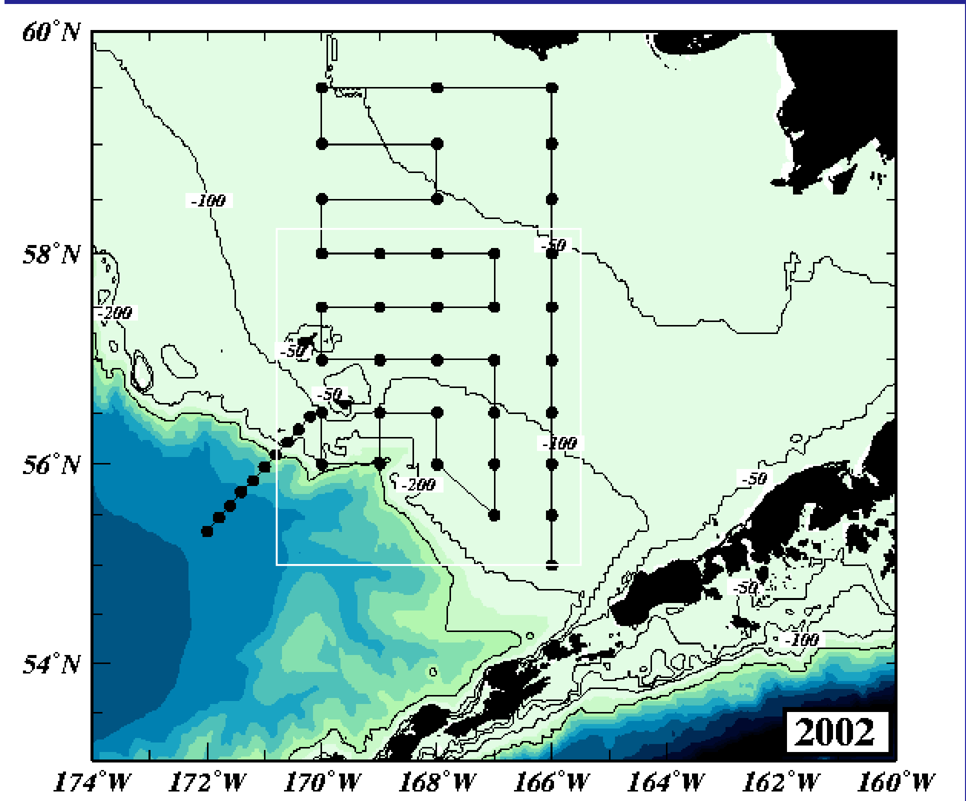
OC4V4 VS. Regional Bering Sea

$$Chl\text{-}a = 10^{\wedge}(a0 + a1*R + a2*R^2 + a3*R^3 + a4*R^4\ )$$

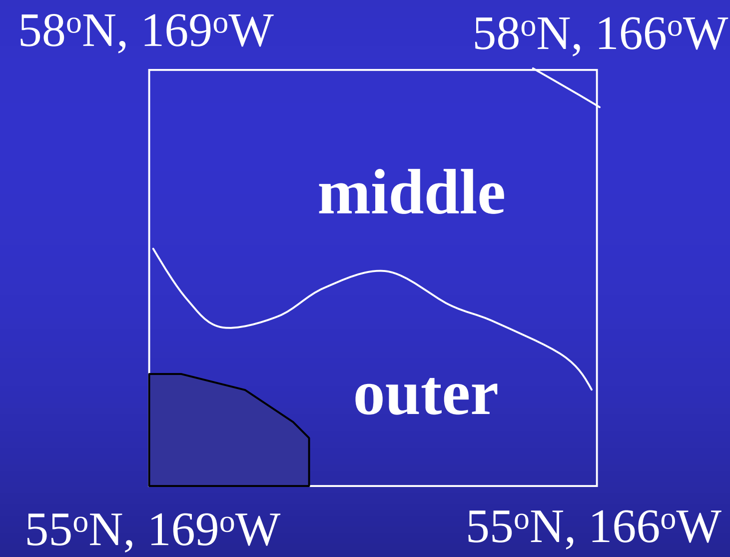
R=log10(Rrs(443)>Rrs(490)>Rrs(510)/Rrs(555

Algorithm	Coefficients (a)	$APE_{\%}$ at BS	RMSE at BS
OC4-V4	a=[0.336, –3.067, 1.930, 0.649, –1.532]	20.03	0.035
Regional_BS	a=[0.317, –2.376, 1.708, -14.33, 20.35]	8.30	0.029

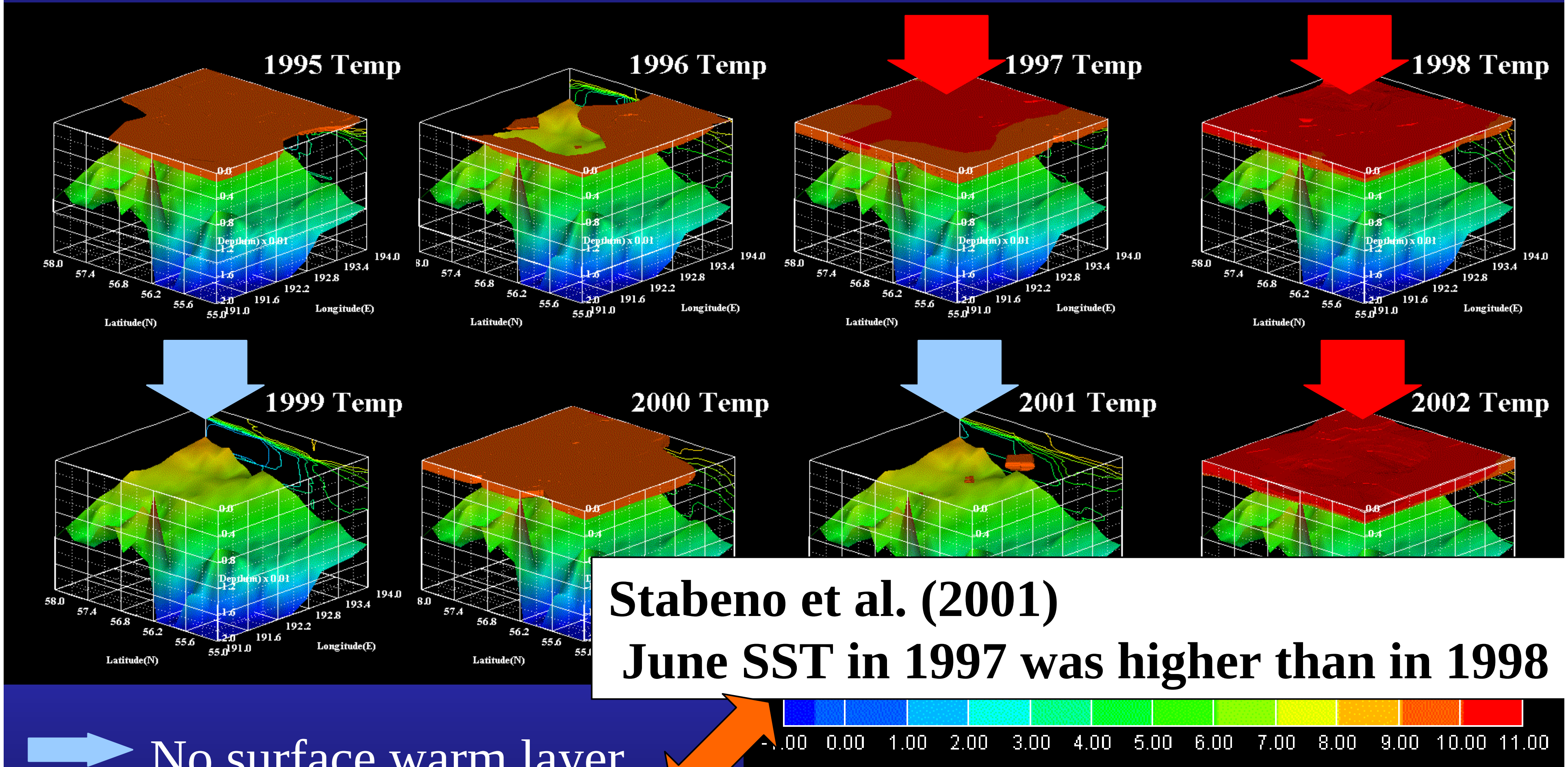
Hydrographic stations by Oshoro-maru 1995-2002



Observation Grid have covered middle-outer shelf simultaneously



Changes in the volume of Surface Warm Layer (>9ºC)

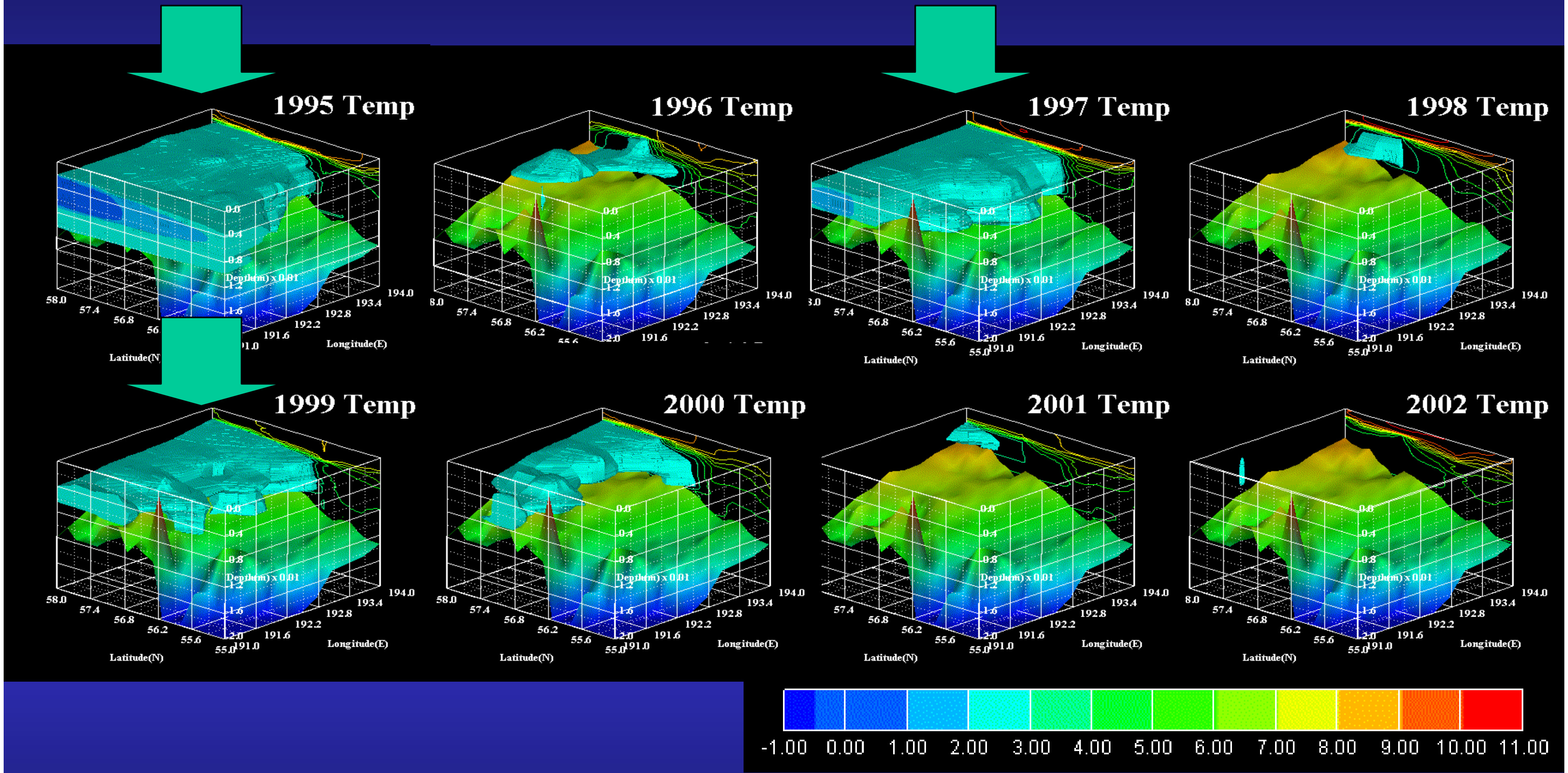


Stabeno et al. (2001)
June SST in 1997 was higher than in 1998

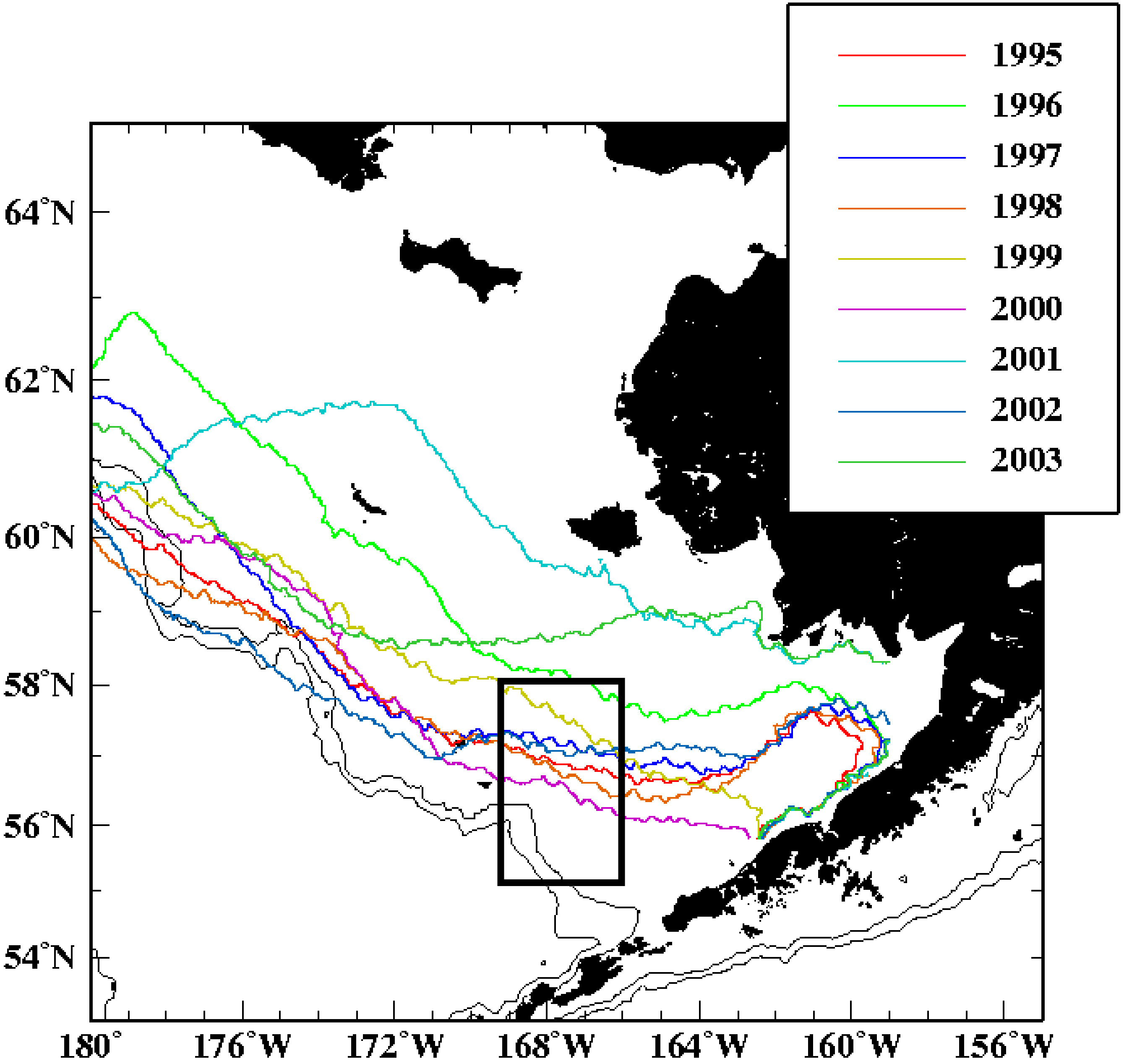
- No surface warm layer
- 98' SST warmer than 97' SST

97/98/02 SSTs are related to El Ñino events?

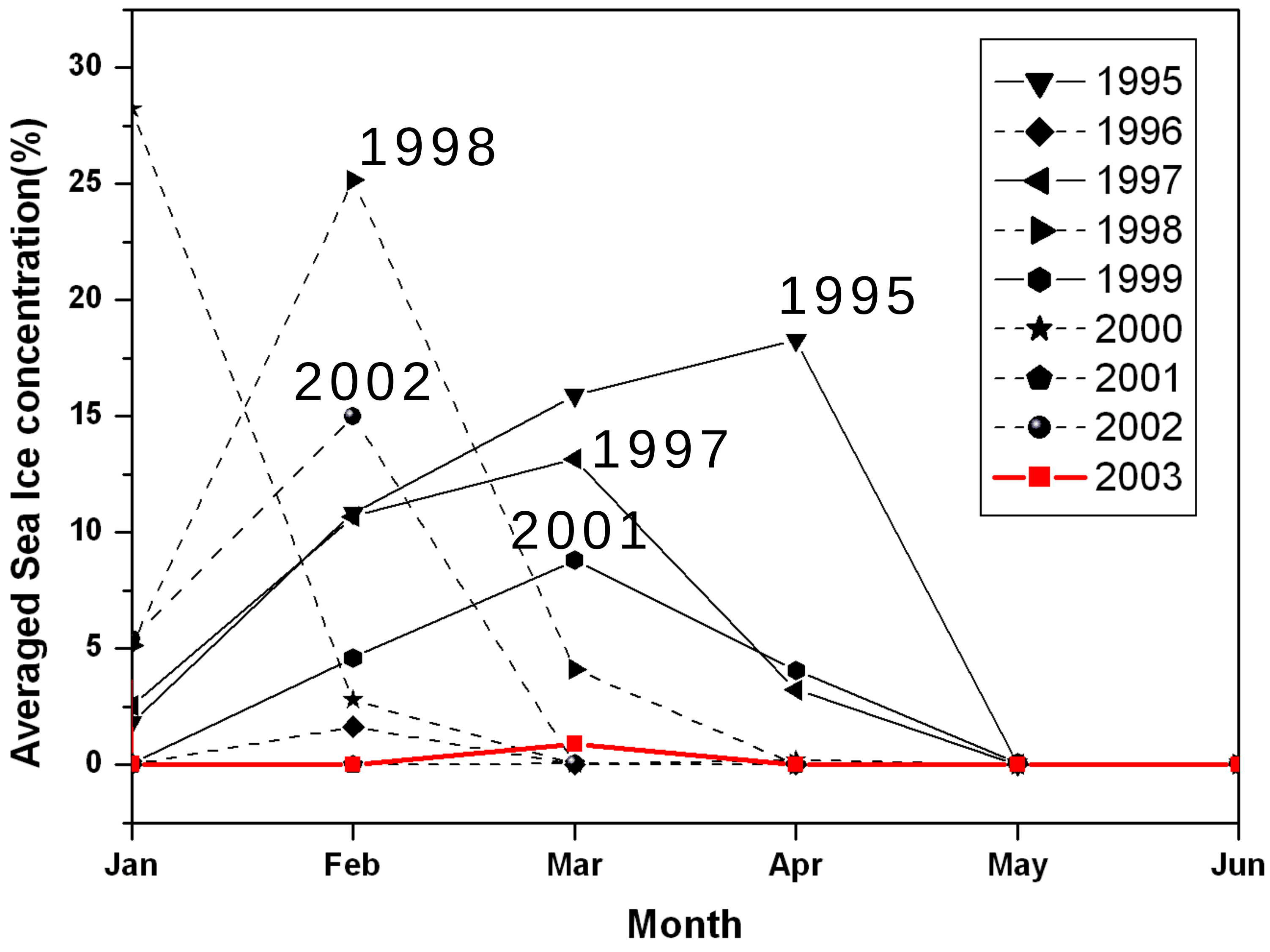
Changes in the volume of Cold bottom water(<3ºC)



In 1995, 1997 and 1999, 2000
large amount of cold bottom waters were found over the shelf.



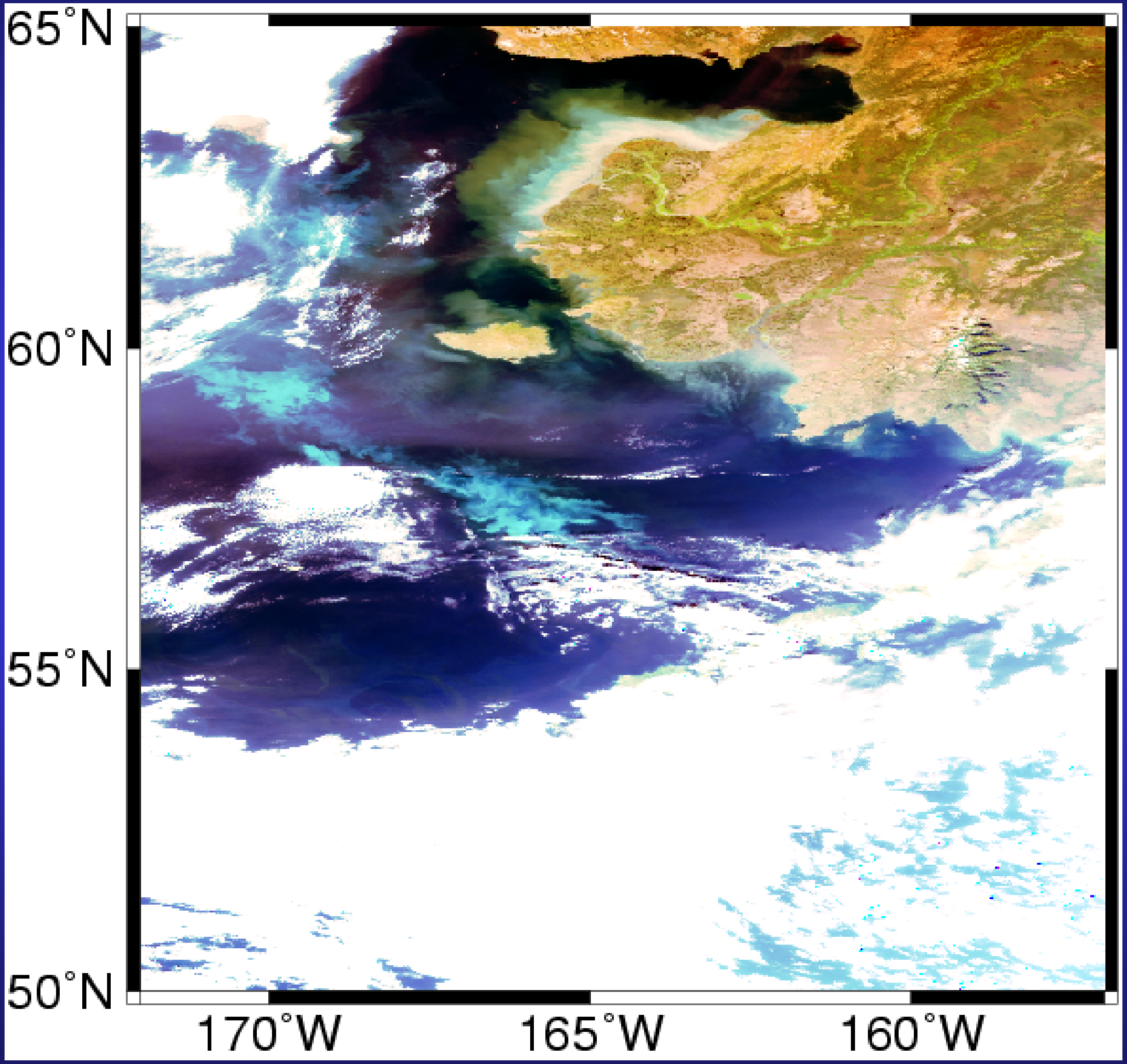
1995
1996
1997
1998
1999
2000
2001
2002
2003
64°N
62°N
60°N
58°N
56°N
54°N
180°
176°W
172°W
168°W
164°W
160°W
156°W



Averaged Sea Ice concentration(%)
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Month
1998
1995
2002
1997
2001
1995
1996
1997
1998
1999
2000
2001
2002
2003

18 September 2003

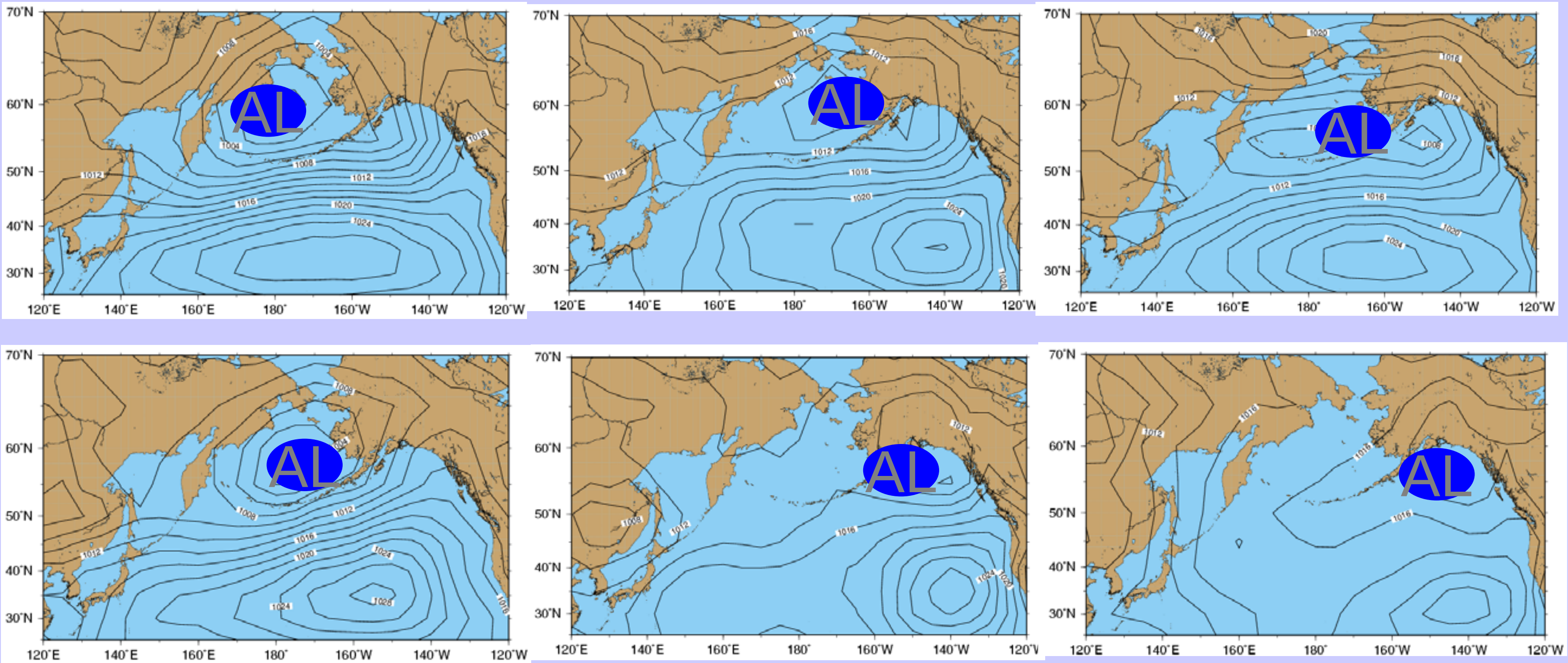
Bering Sea SeaWiFS false color image



1998 | 1999 | 2000

Apr.

May



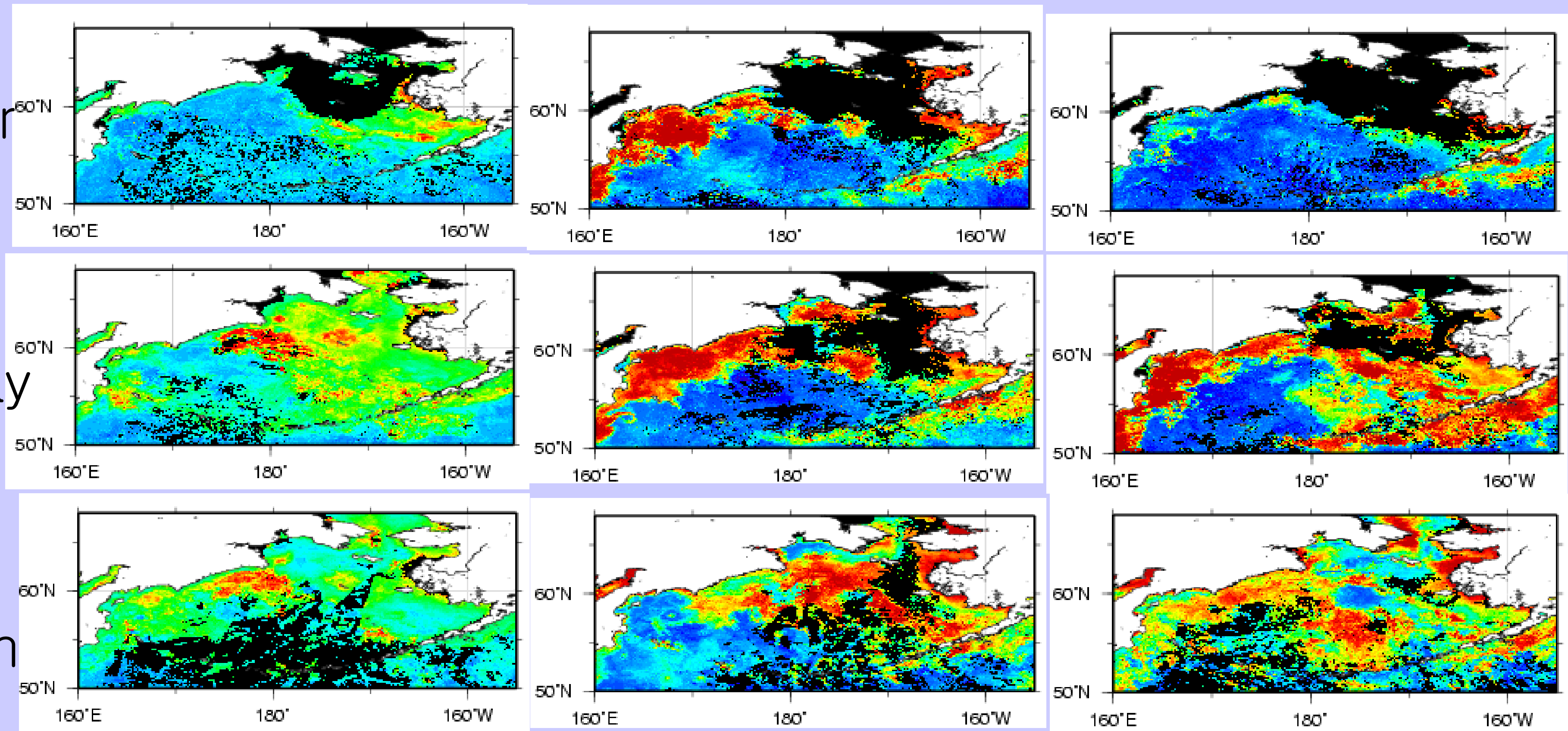
West Pattern | East pattern | East pattern

1997 1998

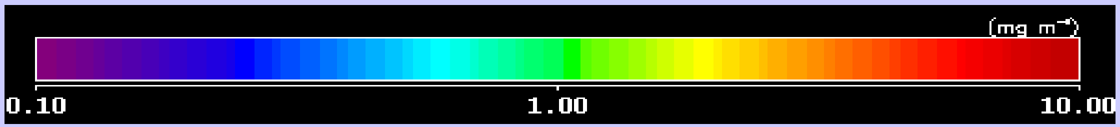
Apr

May

Jun



OC4 ver4 algorism

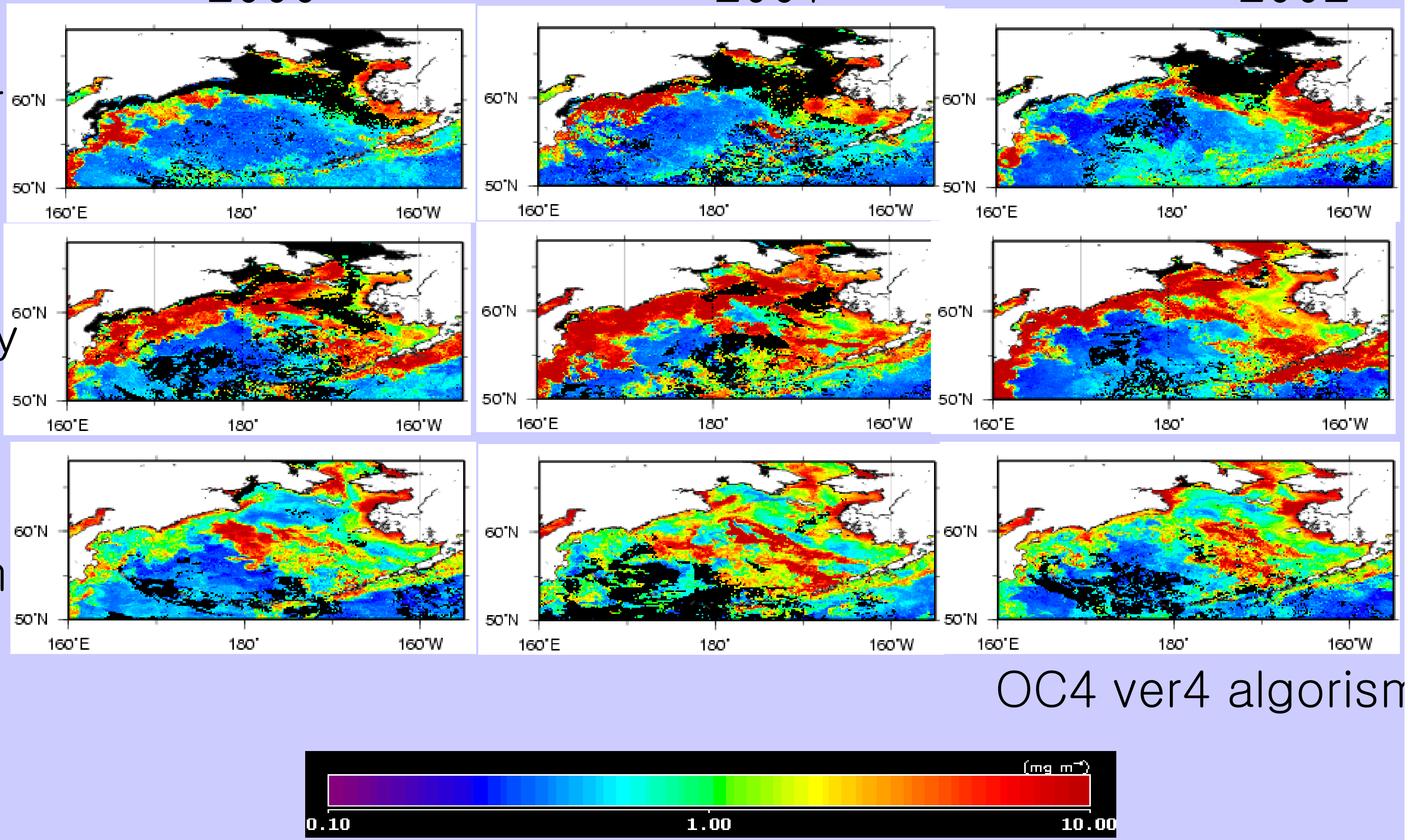


2000 2001 2002

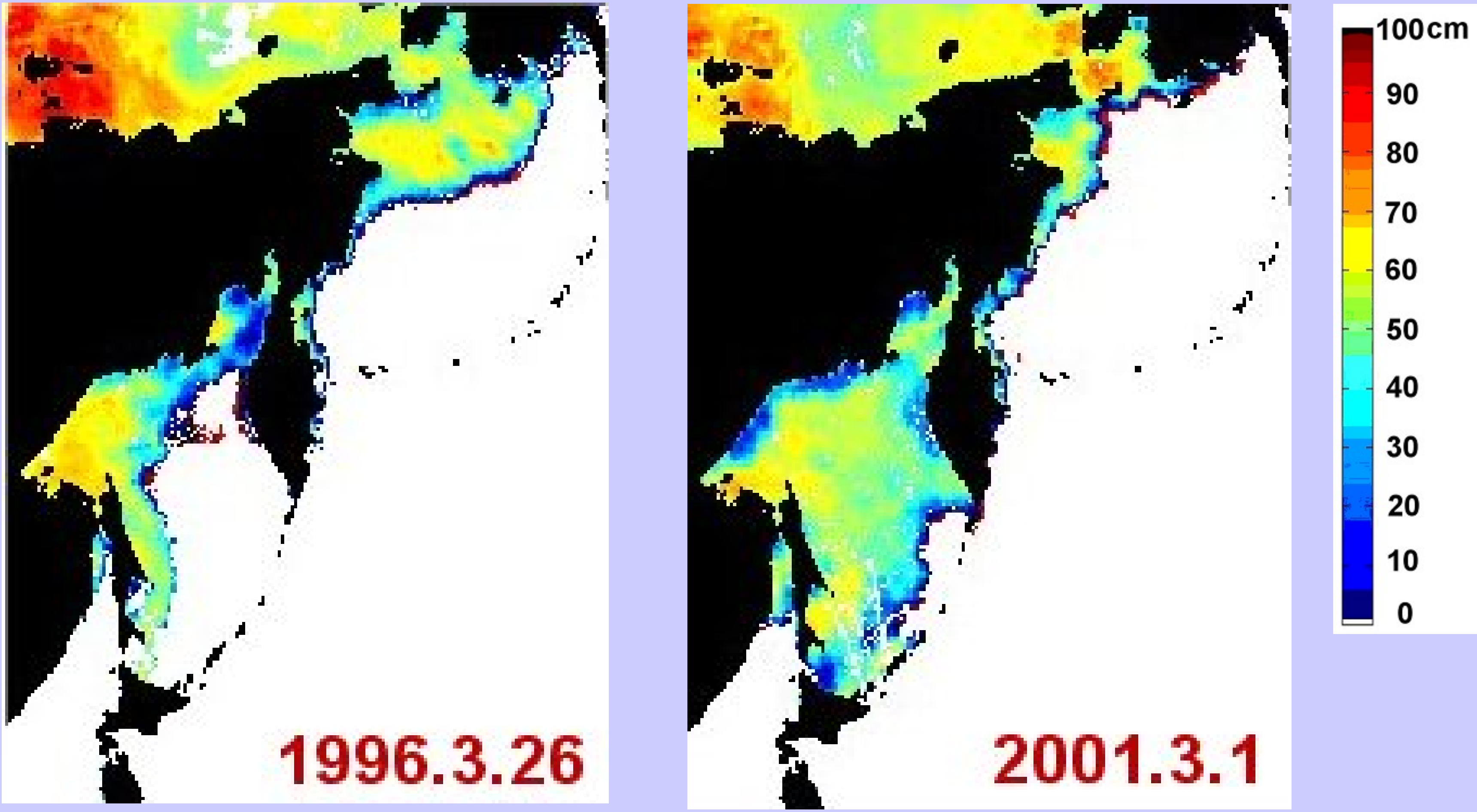
Apr

May

Jun



OC4 ver4 algorism



Okhotsk < Bering

Okhotsk > Bering

1st Announcement International GLOBEC Symposium

Climate Variability and Sub-Arctic Marine Ecosystems

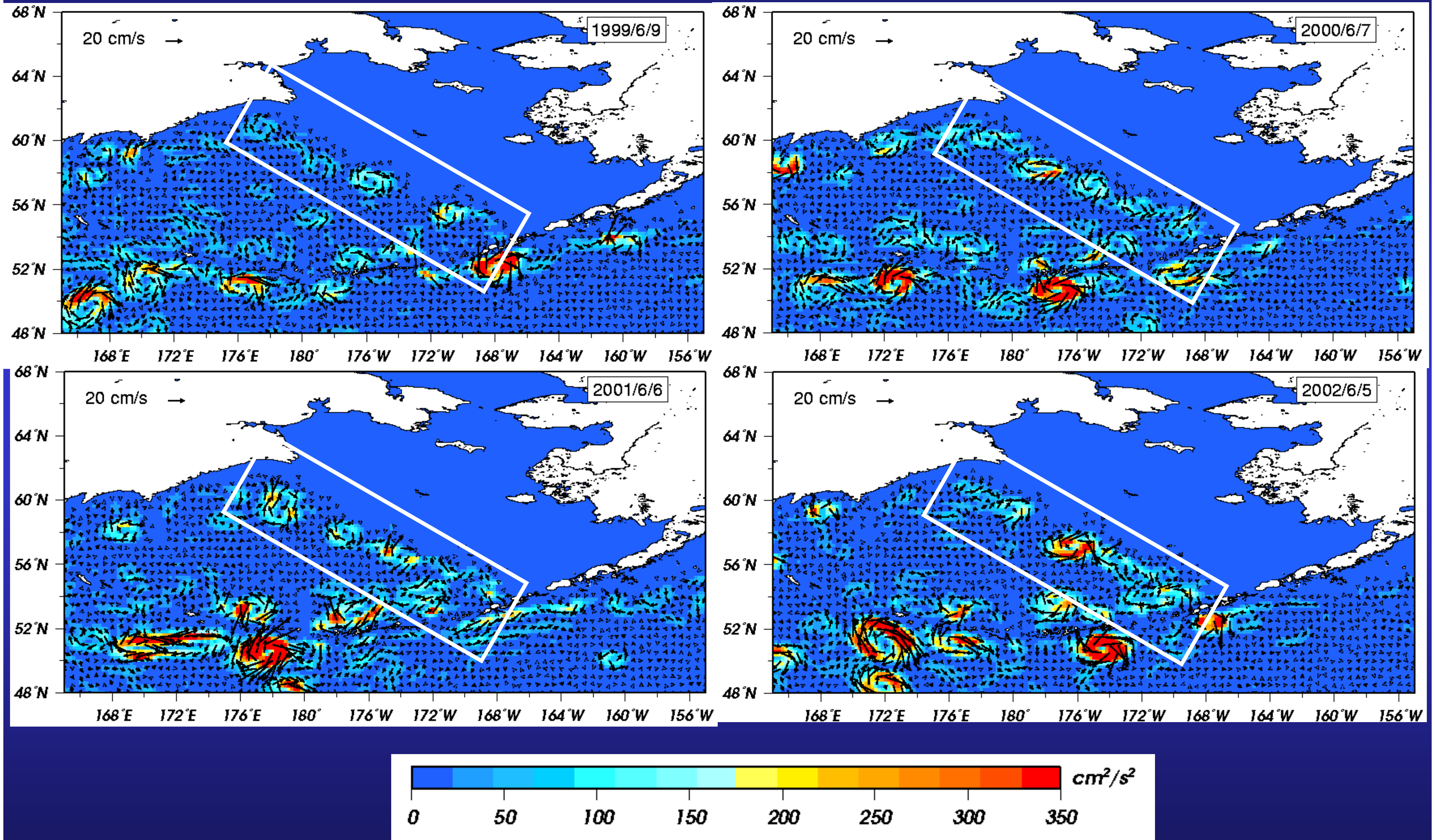
Victoria, B.C., Canada, May 16-20, 2005

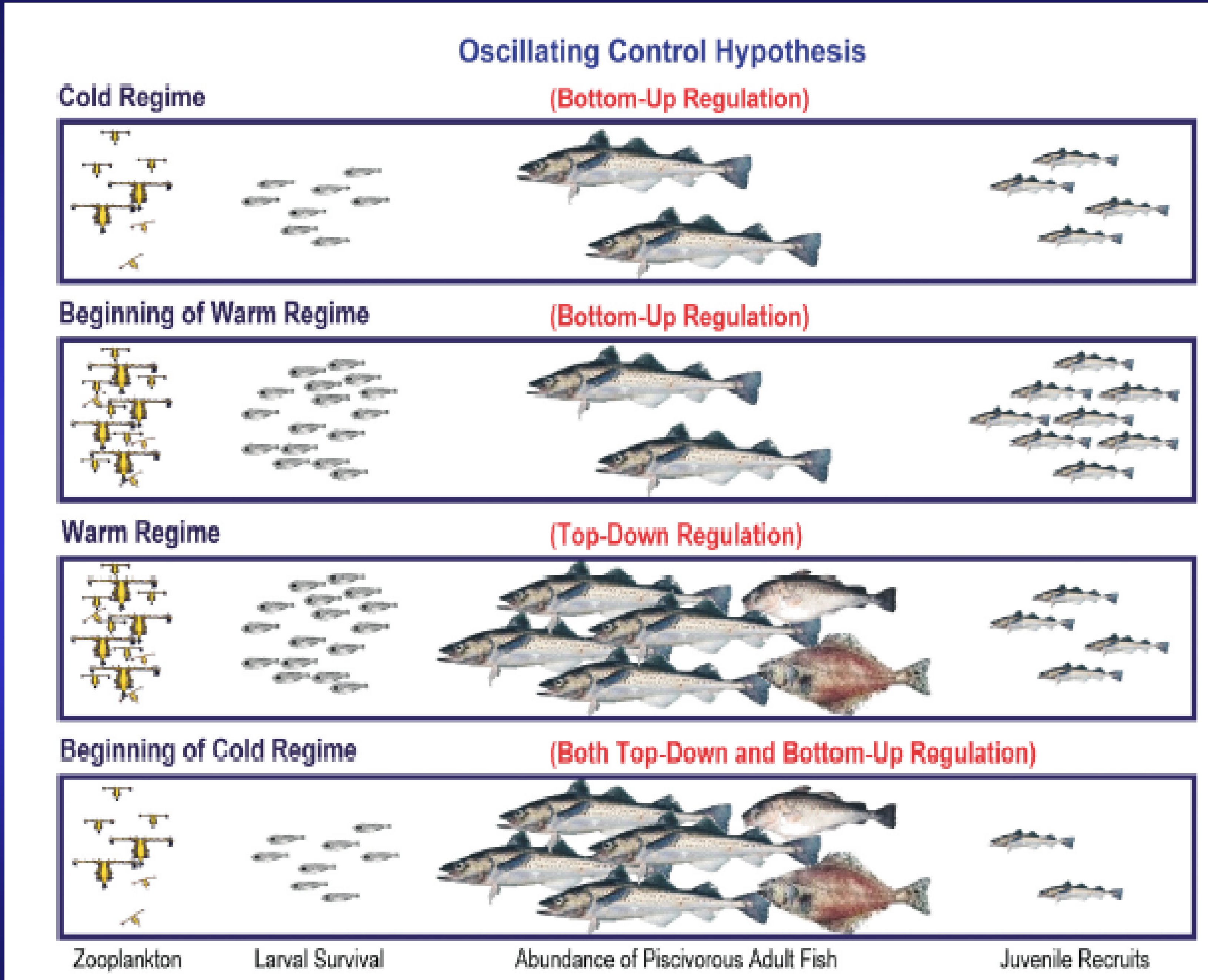
Including
Oyashio region

Ecosystem Study of Sub-Arctic Seas

http://www.pml.ac.uk/globec/Structure/RegProgs/symposium/announcement.htm

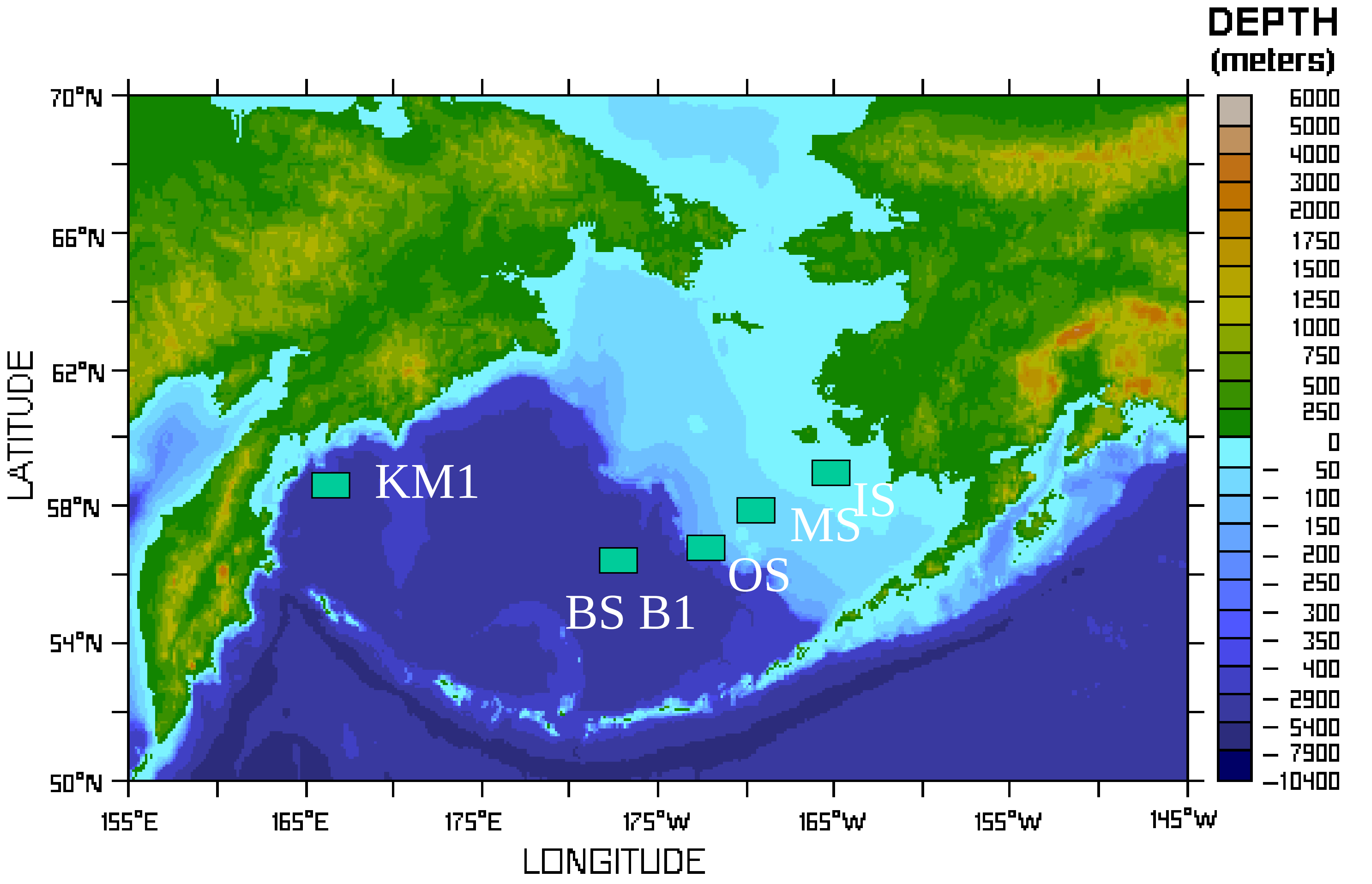
Altimeter-derived BSC eddy field in the summer from 1999 to 2002

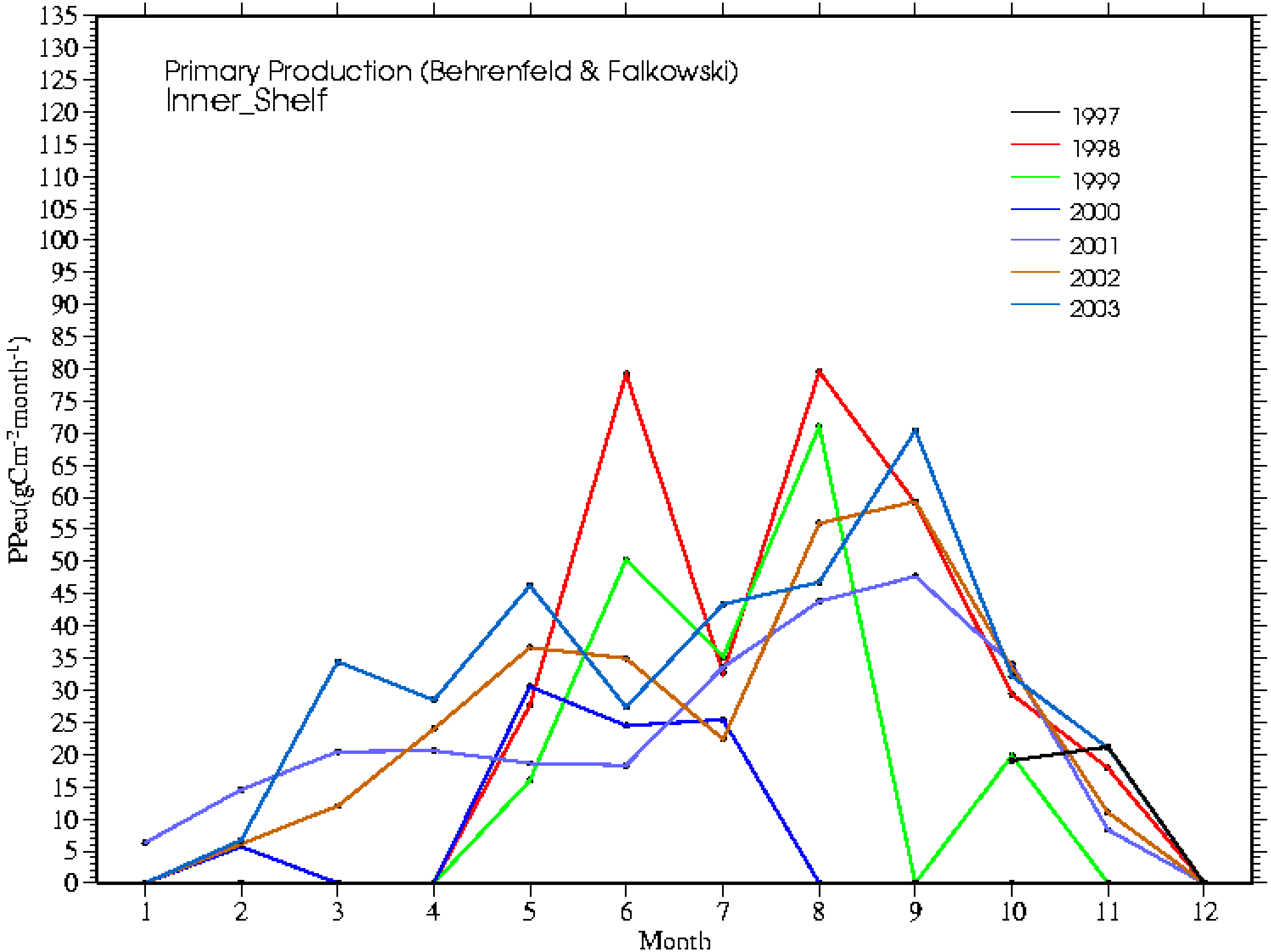




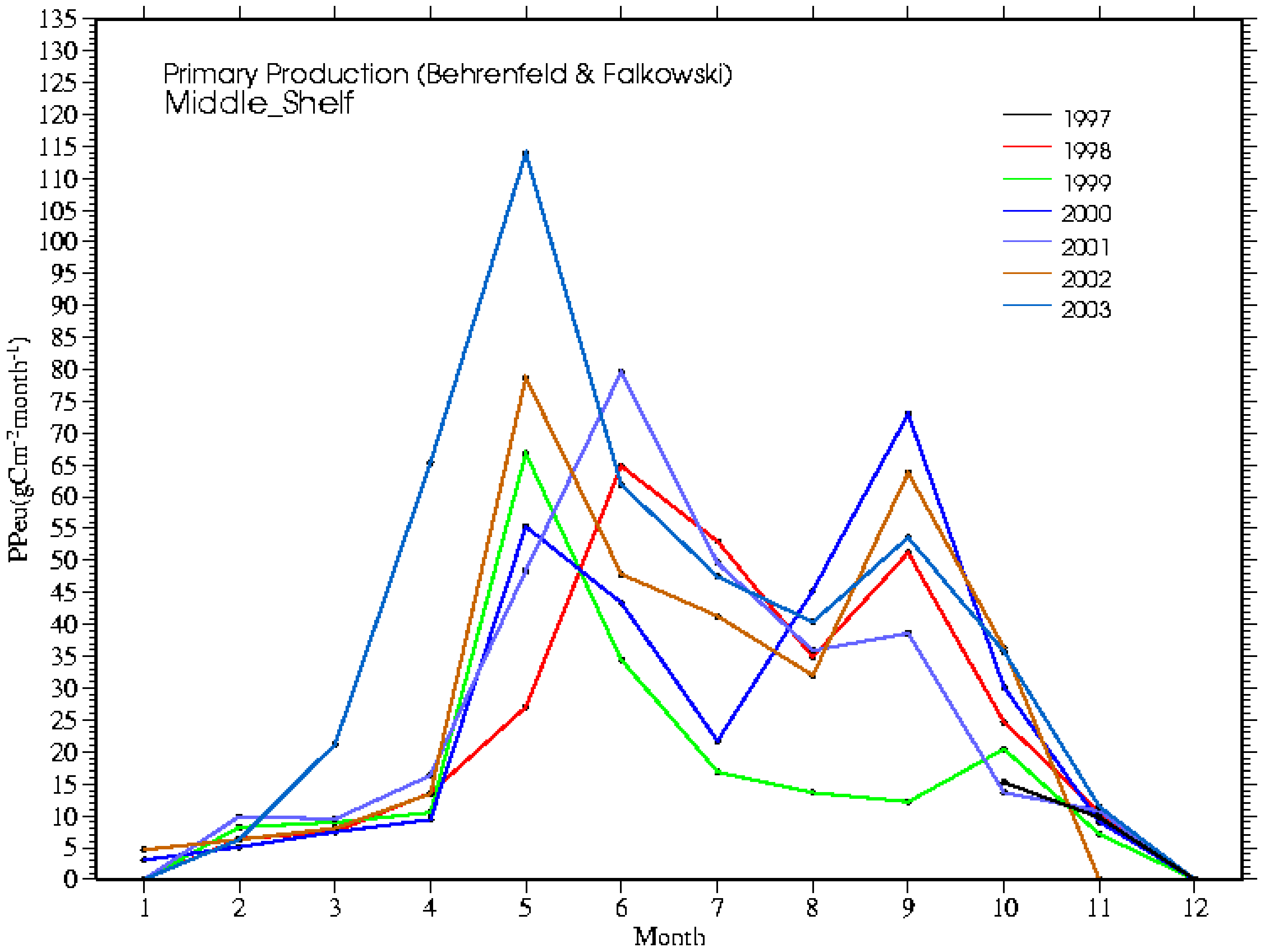
Hunt et al., 2002

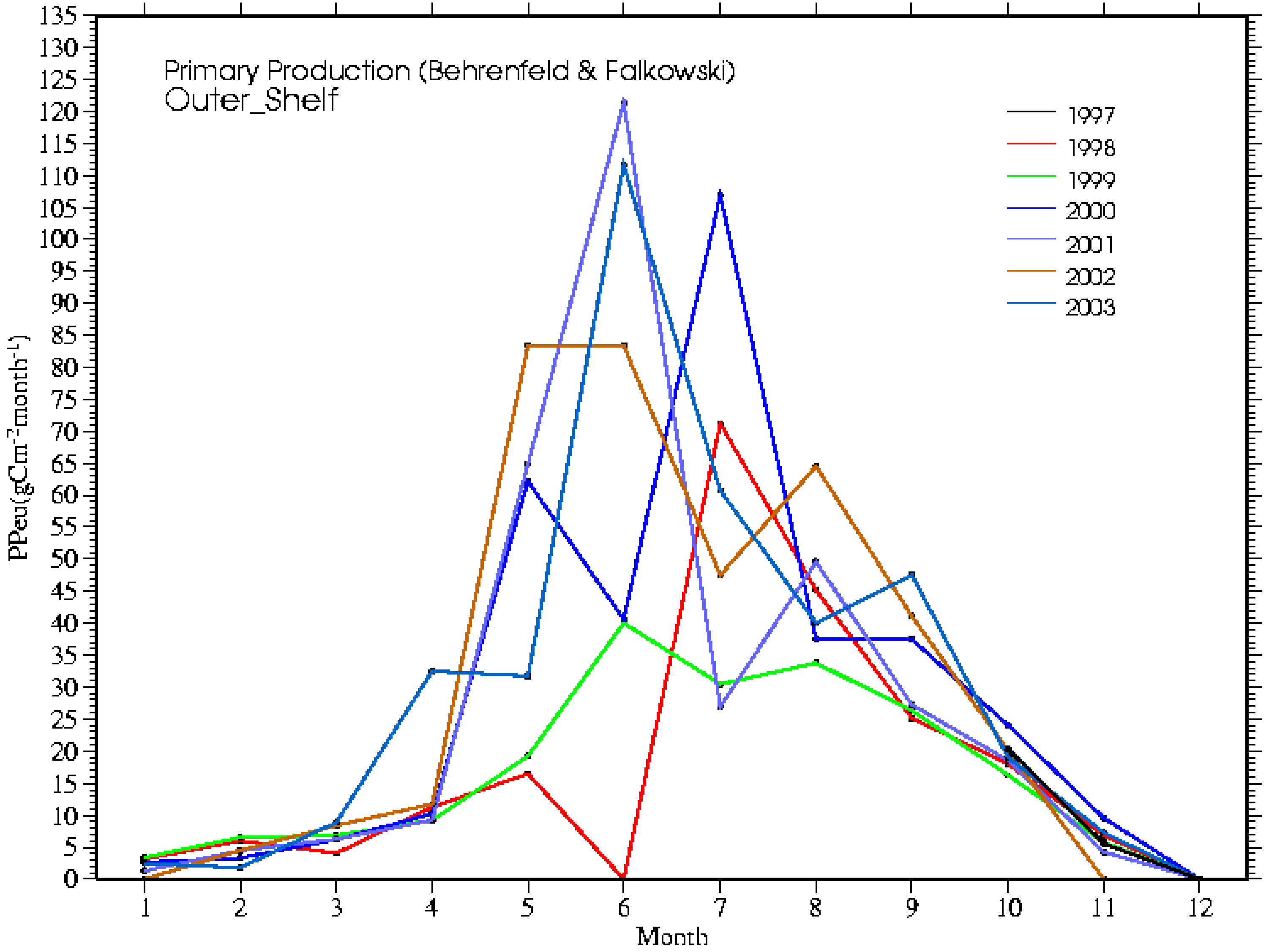
Primary Production



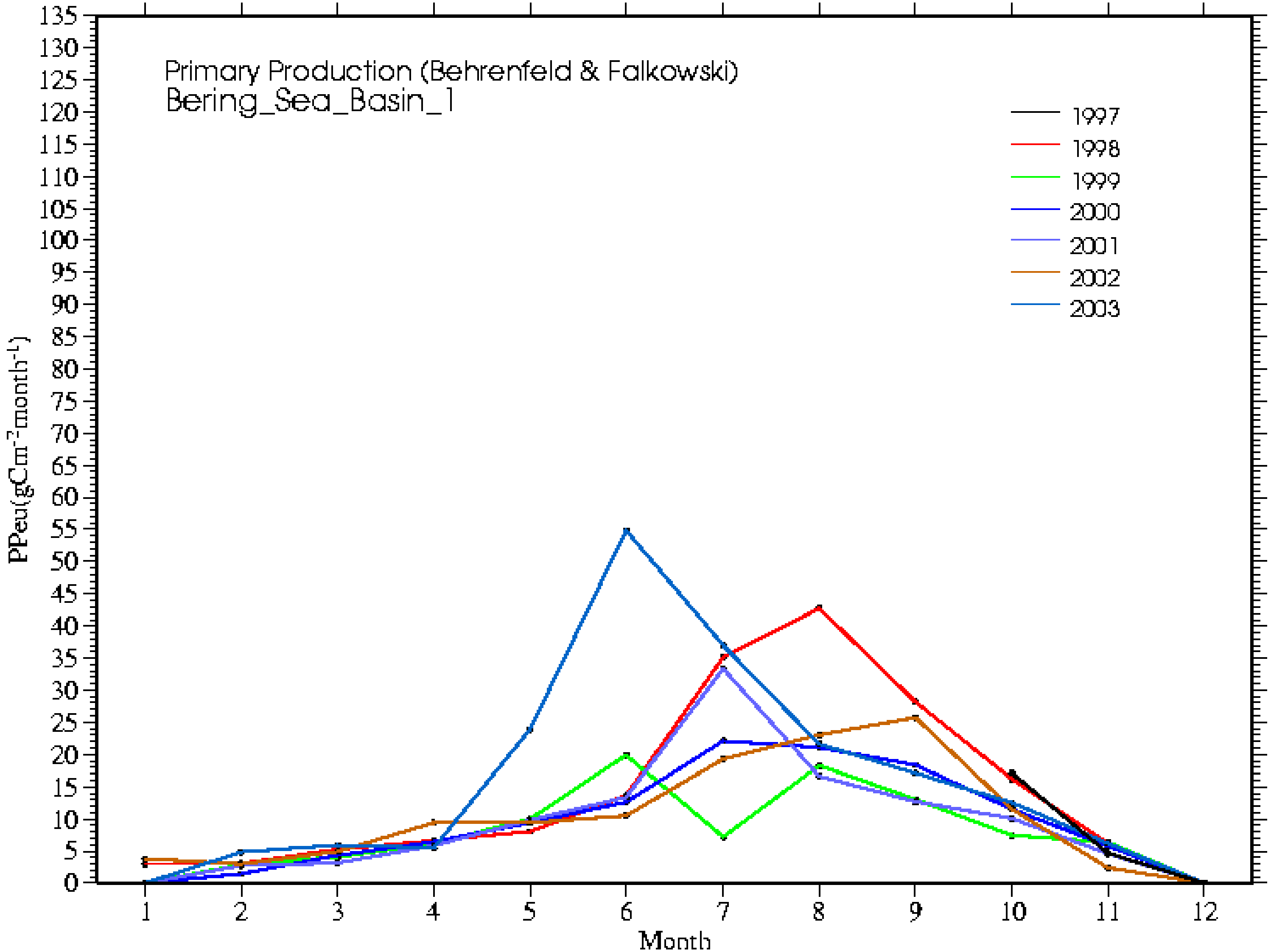


Primary Production (Behrenfeld & Falkowski)
Inner_Shelf
1997
1998
1999
2000
2001
2002
2003
PPeu(gCm-2month-1)
Month
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
1
2
3
4
5
6
7
8
9
10
11
12

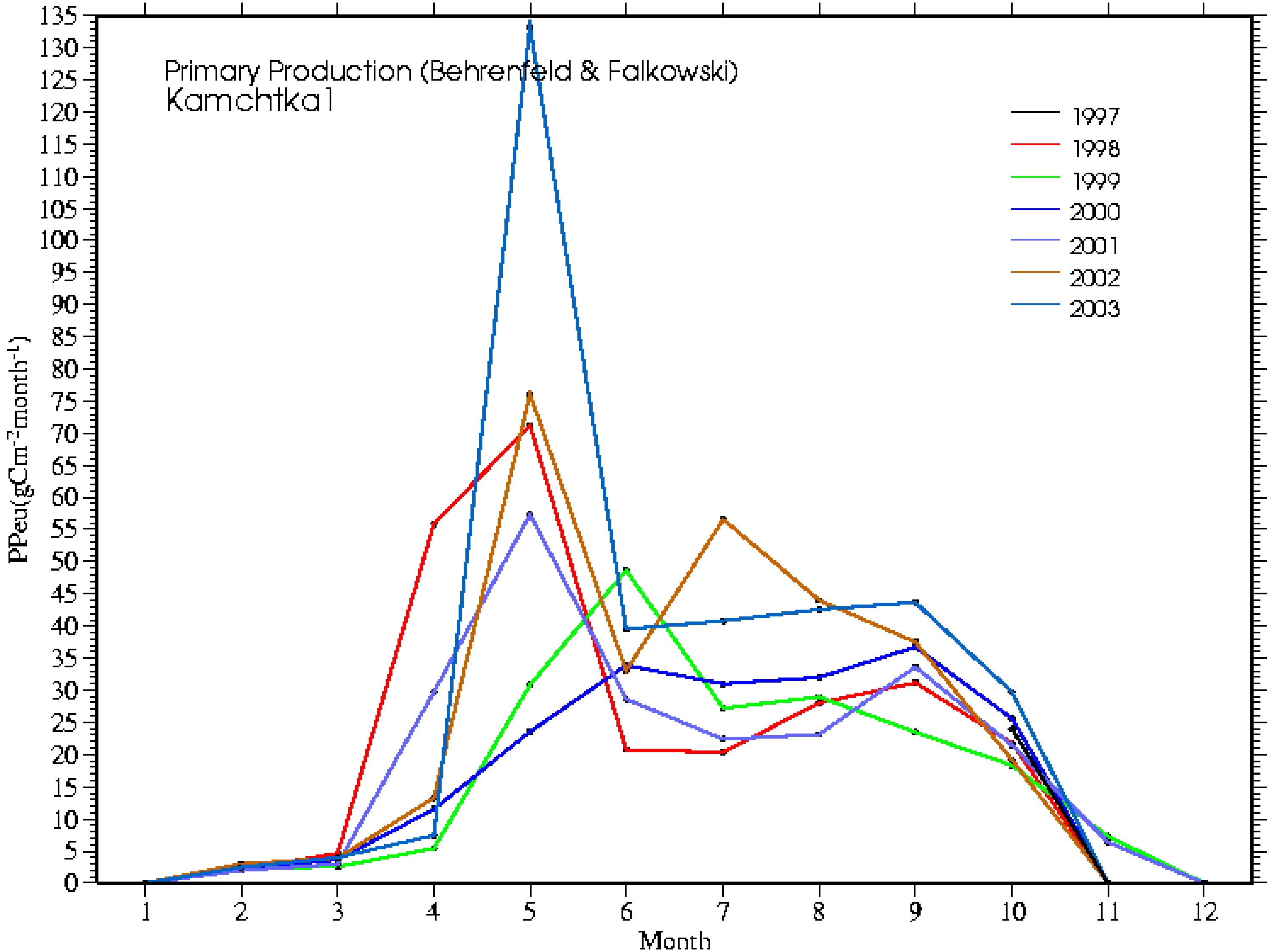

Primary Production (Behrenfeld & Falkowski)
Middle_Shelf
1997
1998
1999
2000
2001
2002
2003
PPeu(gCm-2month-1)
Month
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
1
2
3
4
5
6
7
8
9
10
11
12



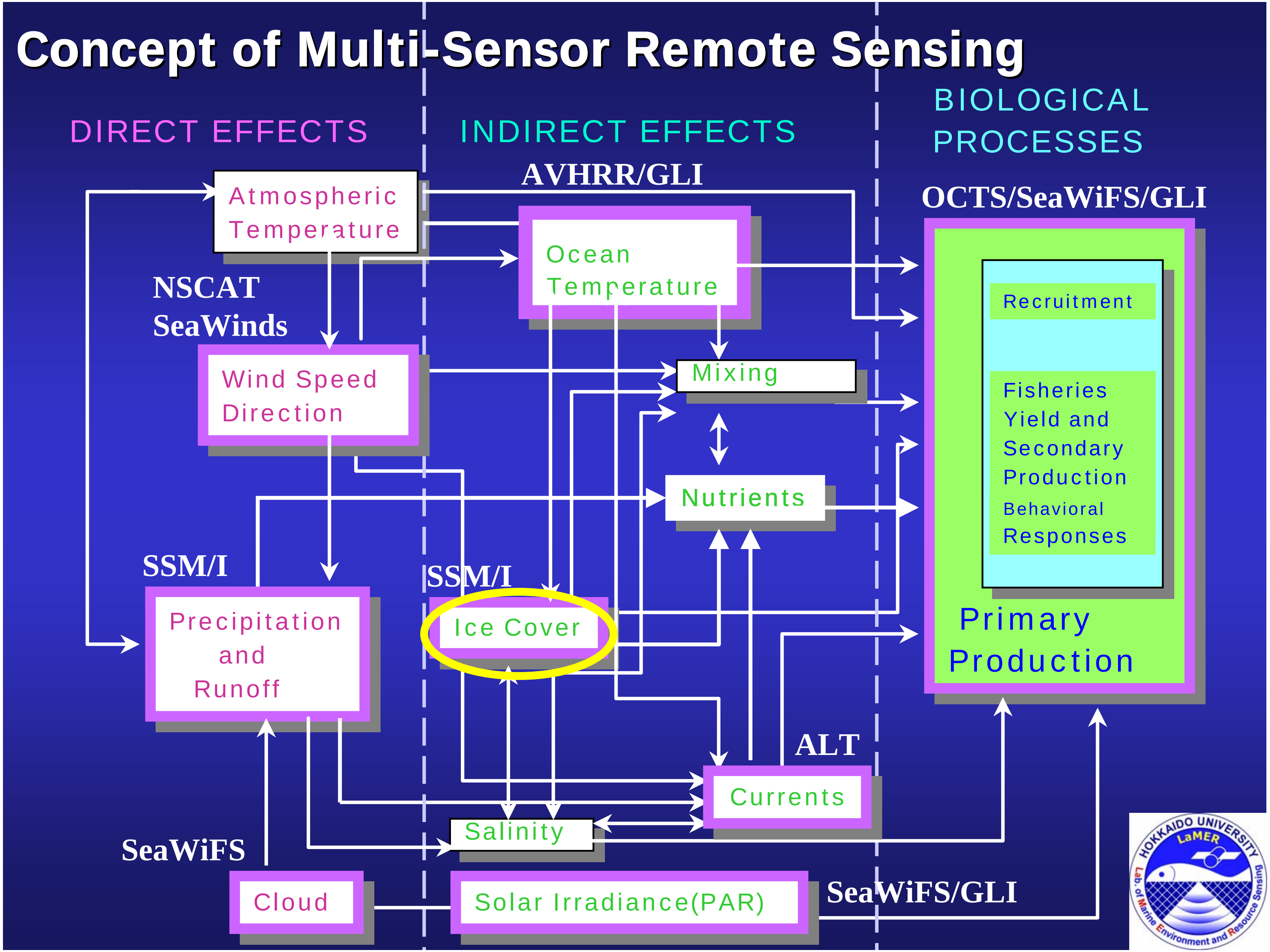
Primary Production (Behrenfeld & Falkowski)
Outer_Shelf
1997
1998
1999
2000
2001
2002
2003
PPeu(gCm-2month-1)
Month



Primary Production (Behrenfeld & Falkowski)
Bering_Sea_Basin_1
1997
1998
1999
2000
2001
2002
2003
PPeu(gCm-2month-1)
Month
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
1
2
3
4
5
6
7
8
9
10
11
12



Primary Production (Behrenfeld & Falkowski)
Kamchtka1
1997
1998
1999
2000
2001
2002
2003
PPeu(gCm-2month-1)
Month
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
1
2
3
4
5
6
7
8
9
10
11
12


Concept of Multi-Sensor Remote Sensing
DIRECT EFFECTS
INDIRECT EFFECTS
BIOLOGICAL PROCESSES
AVHRR/GLI
OCTS/SeaWiFS/GLI
Atmospheric Temperature
Ocean Temperature
NSCAT SeaWinds
Wind Speed Direction
Mixing
Recruitment
Fisheries Yield and Secondary Production
Behavioral Responses
Nutrients
SSM/I
Precipitation and Runoff
SSM/I
Ice Cover
Primary Production
ALT
Currents
Salinity
SeaWiFS
Cloud
Solar Irradiance(PAR)
SeaWiFS/GLI
HOKKAIDO UNIVERSITY
LaMER
Lab. of Marine Environment and Resource Sensing