# *Impact of climate change on lower trophic levels in polar and sub-polar seas*

(Phytoplankton production in the Bering Sea and Arctic Ocean: A satellite remote sensing study)

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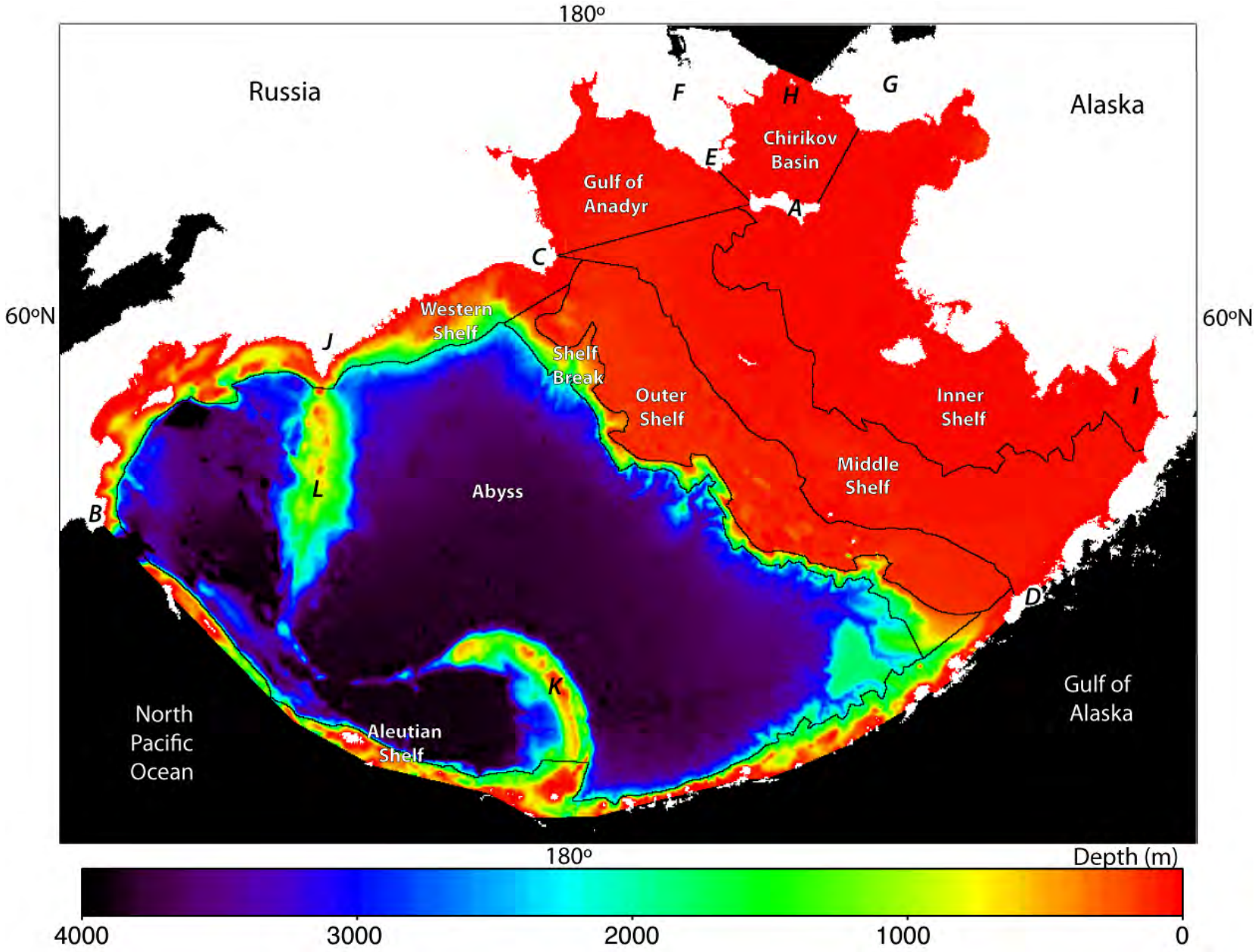
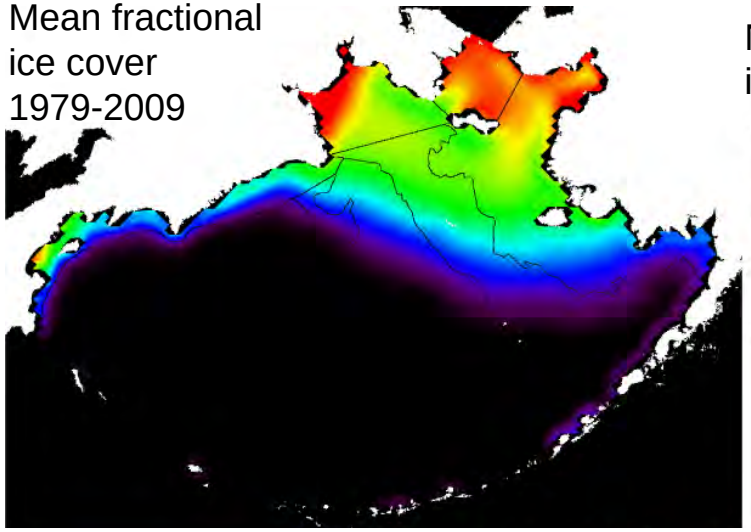
*Stanford University*

# Bering Sea

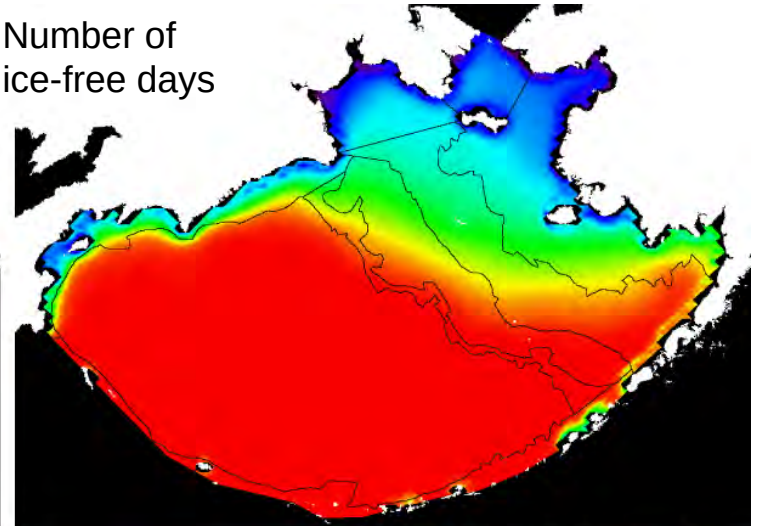

180°
Russia
Alaska
F
H
G
E
Chirikov
Basin
Gulf of
Anadyr
A
C
60°N
60°N
Western
Shelf
J
Shelf
Break
Outer
Shelf
Inner
Shelf
I
Middle
Shelf
L
Abyss
B
D
K
North
Pacific
Ocean
Aleutian
Shelf
Gulf of
Alaska
180°
Depth (m)
4000
3000
2000
1000
0

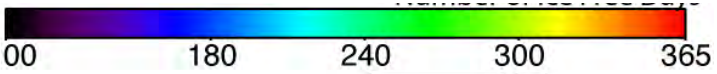
# Bering Sea

Mean fractional ice cover 1979-2009

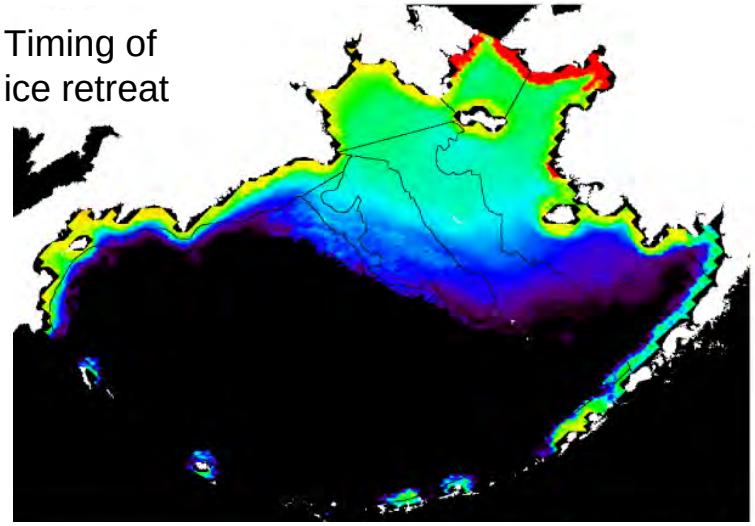



Number of ice-free days

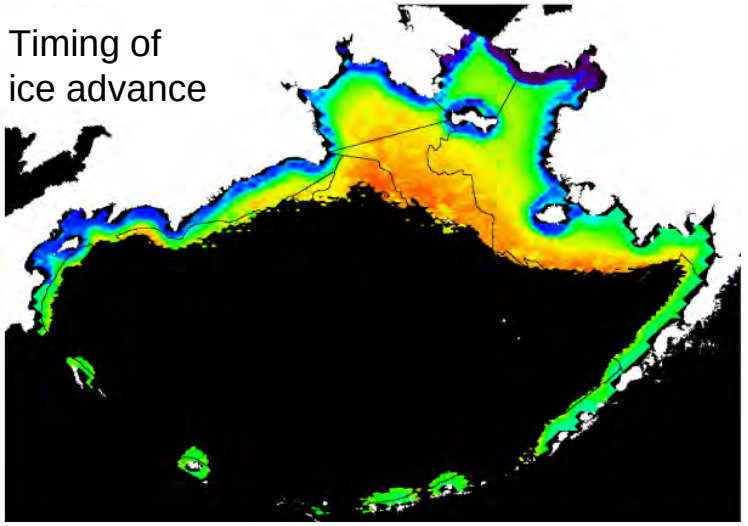




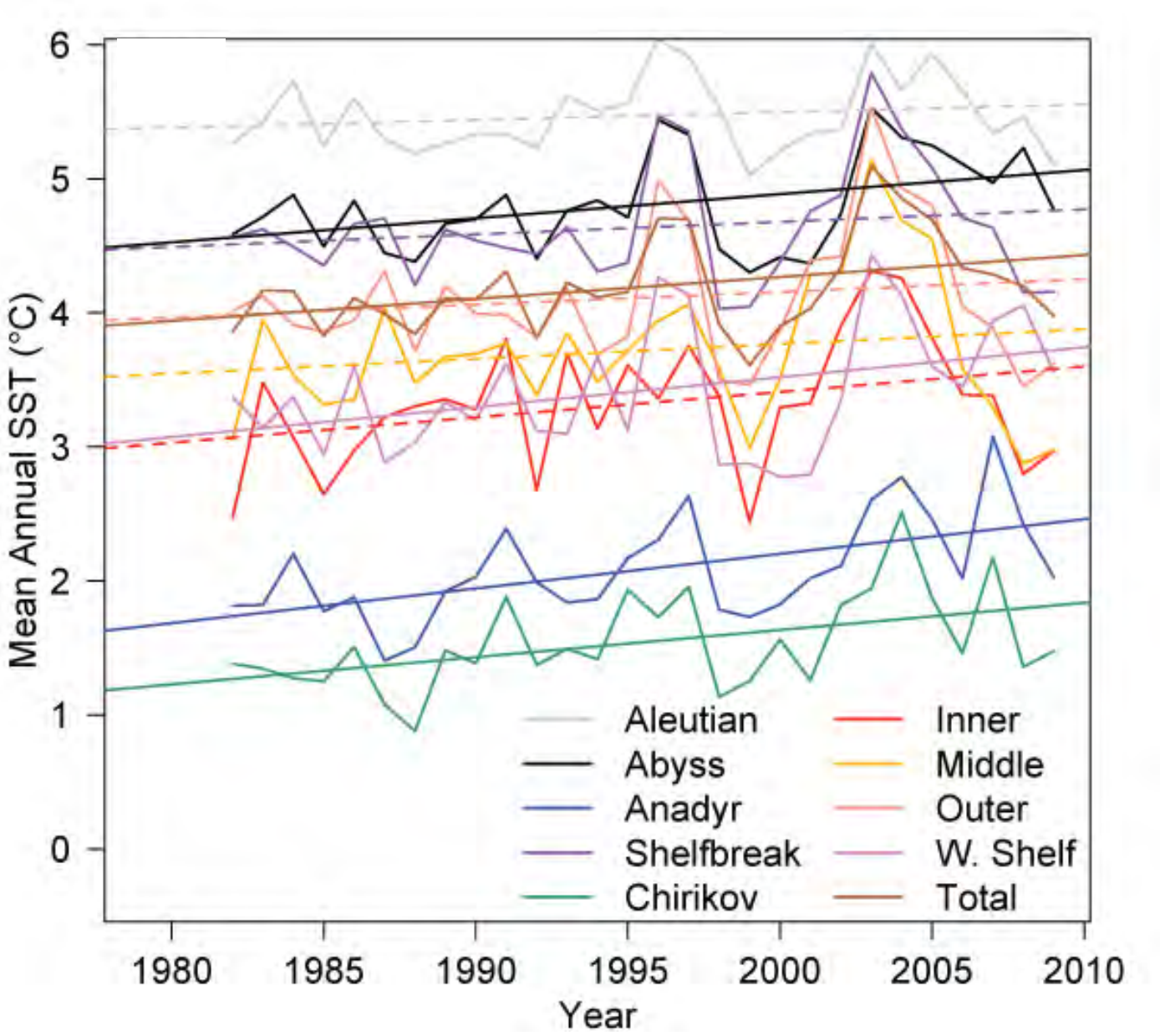

Timing of ice retreat



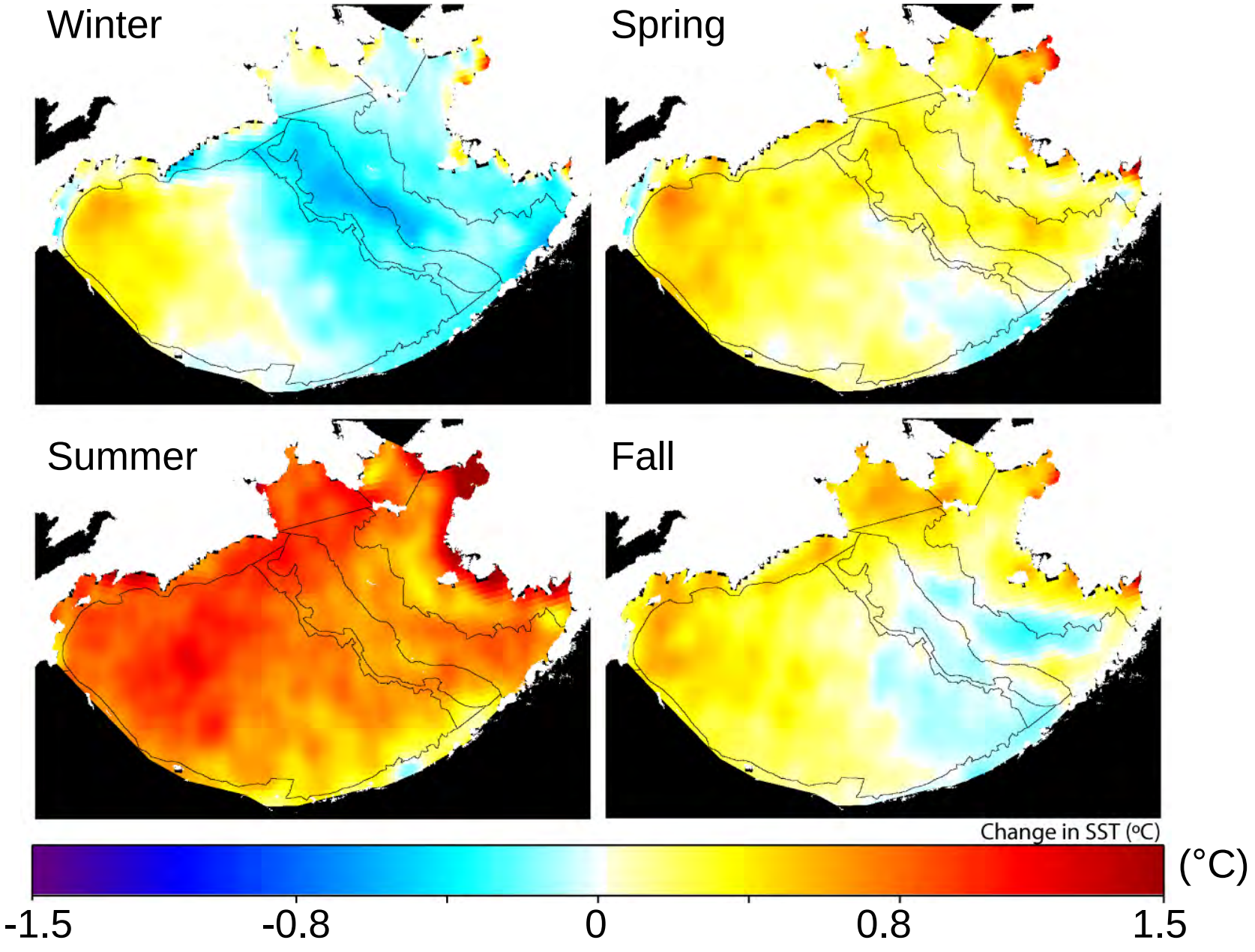

Timing of ice advance



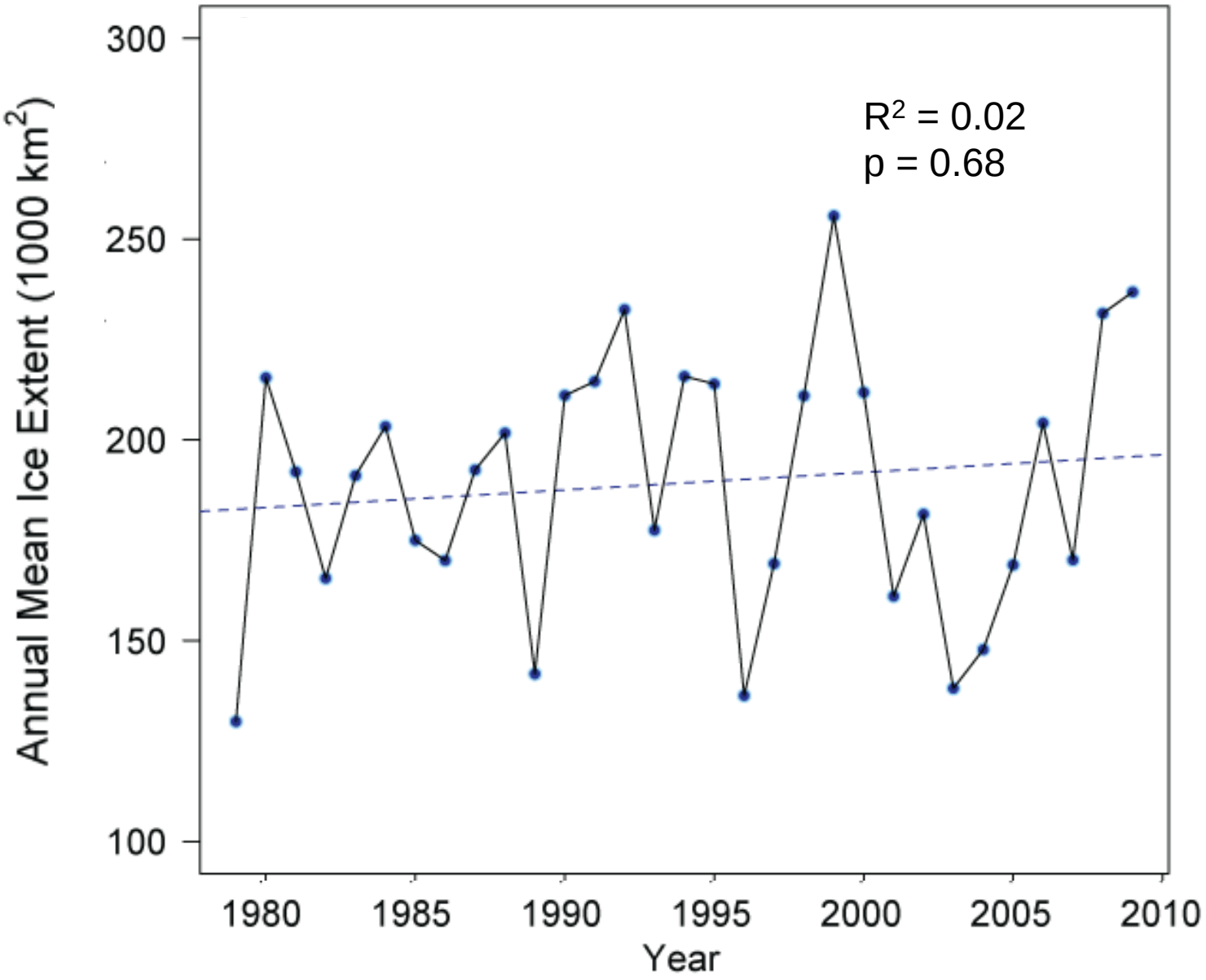
# Bering Sea


Mean Annual SST (°C)
6
5
4
3
2
1
0
1980
1985
1990
1995
2000
2005
2010
Year
Aleutian
Abyss
Anadyr
Shelfbreak
Chirikov
Inner
Middle
Outer
W. Shelf
Total

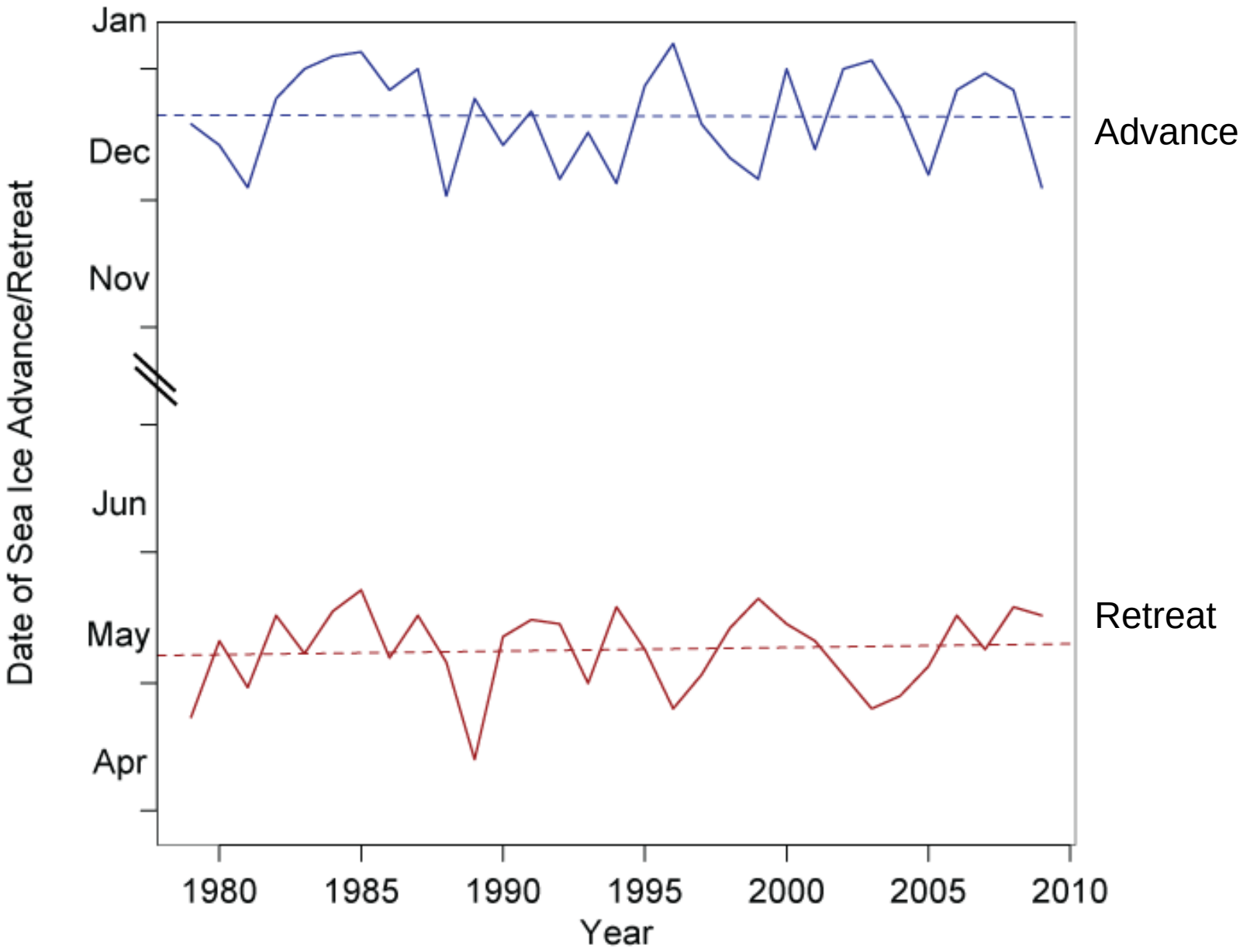
# Bering Sea - Change in SST, 1982-2009



# Bering Sea

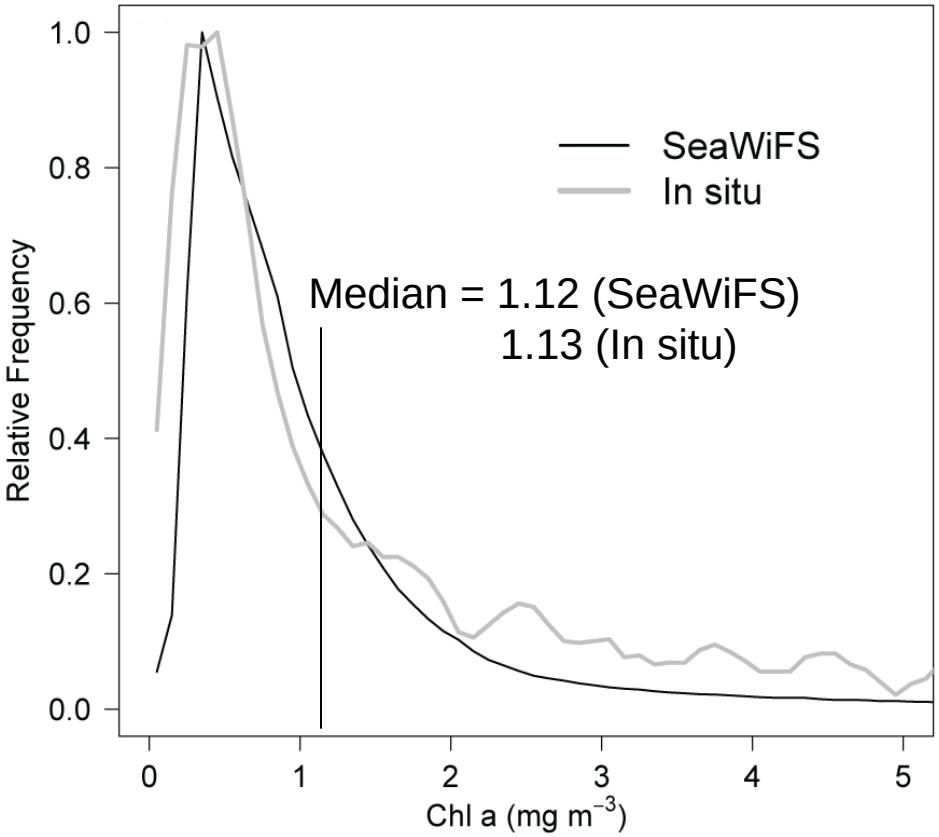

Annual Mean Ice Extent (1000 km$^2$)
300
250
200
150
100
1980
1985
1990
1995
2000
2005
2010
Year
$R^2$ = 0.02
p = 0.68

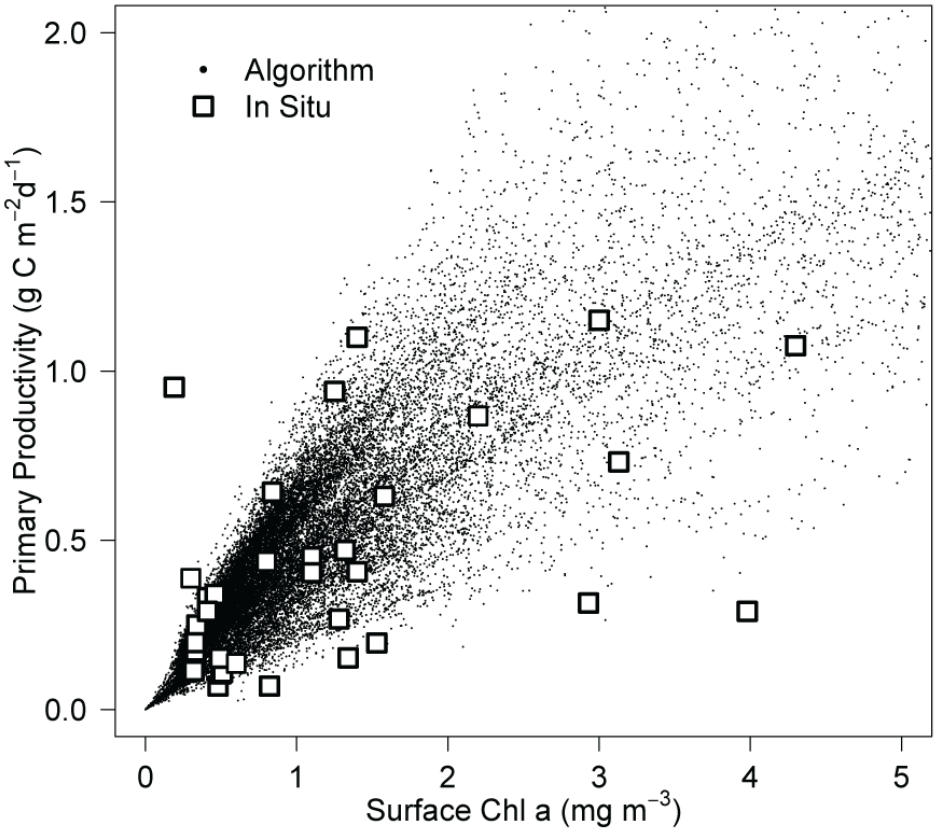
# Bering Sea


Jan
Dec
Nov
Jun
May
Apr
Date of Sea Ice Advance/Retreat
1980
1985
1990
1995
2000
2005
2010
Year
Advance
Retreat


Has primary production in the Bering Sea changed in the last decade?
To address this question, we used a satellite-based approach

# Bering Sea

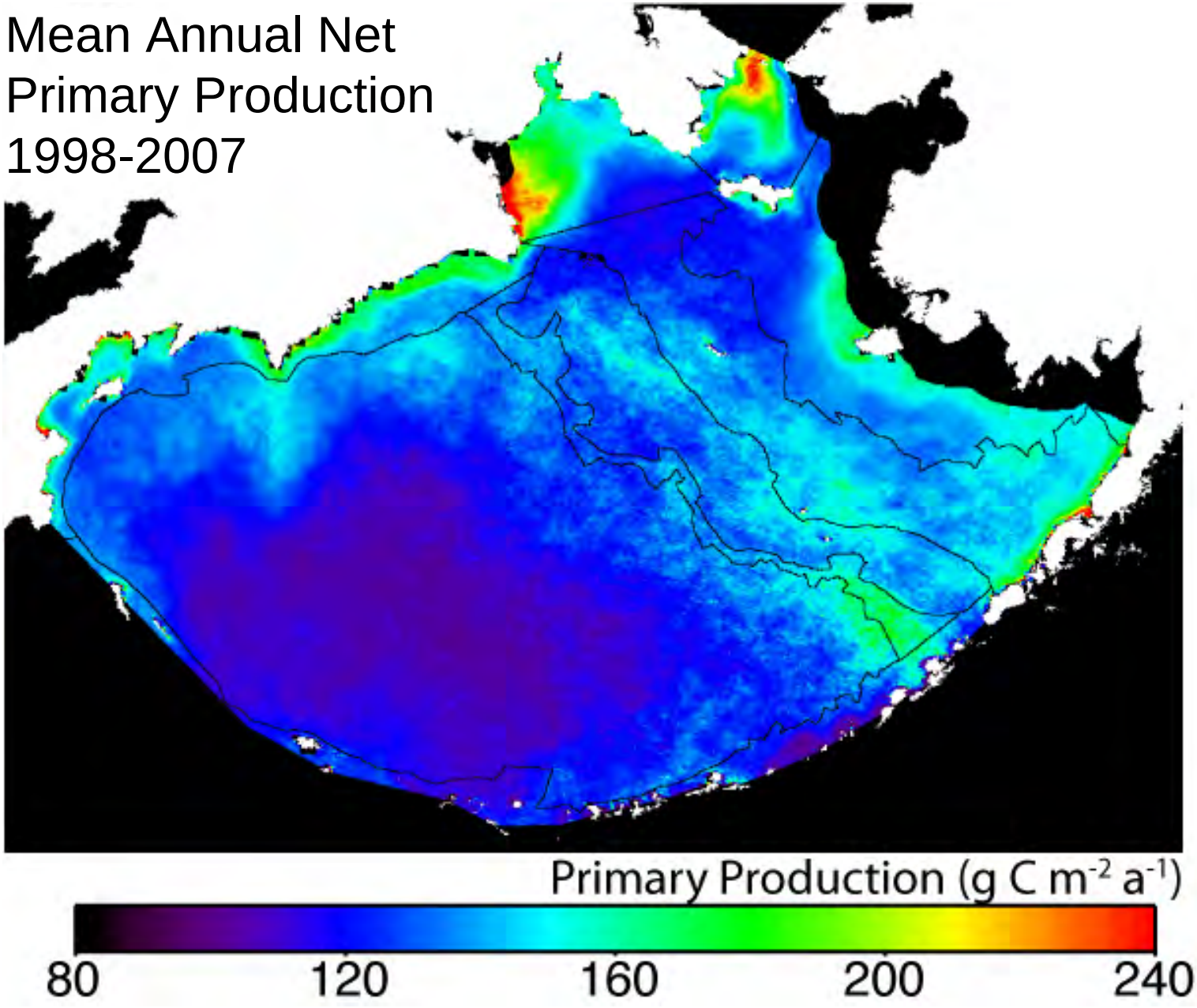


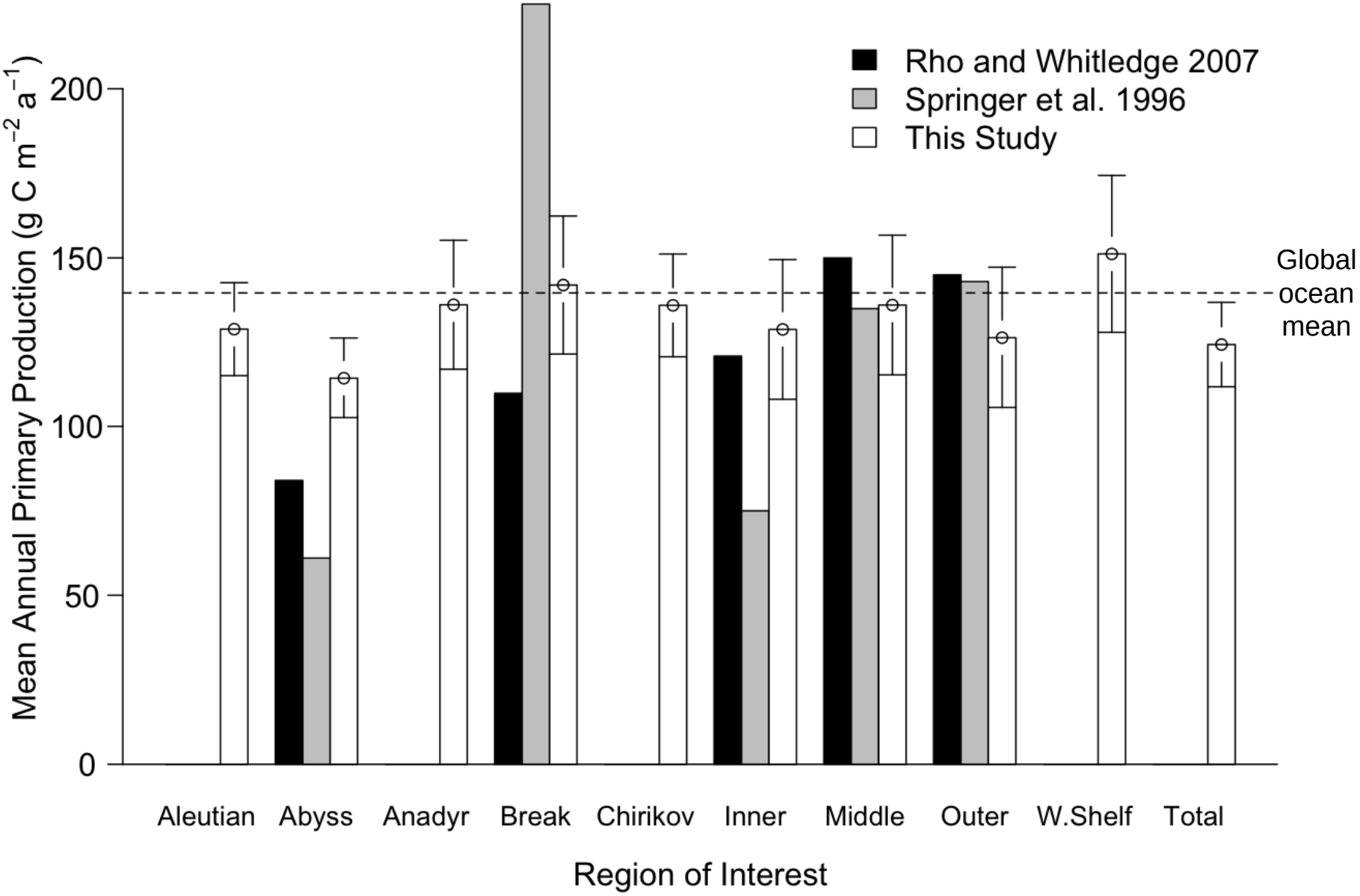

- Based on remotely sensed Chl *a*, SST, and sea ice
- Primary production algorithm modified from Southern Ocean (Arrigo et al. 2008, Brown et al. JGR, in press)
- Forced with winds, cloud cover, and solar radiation

# Bering Sea

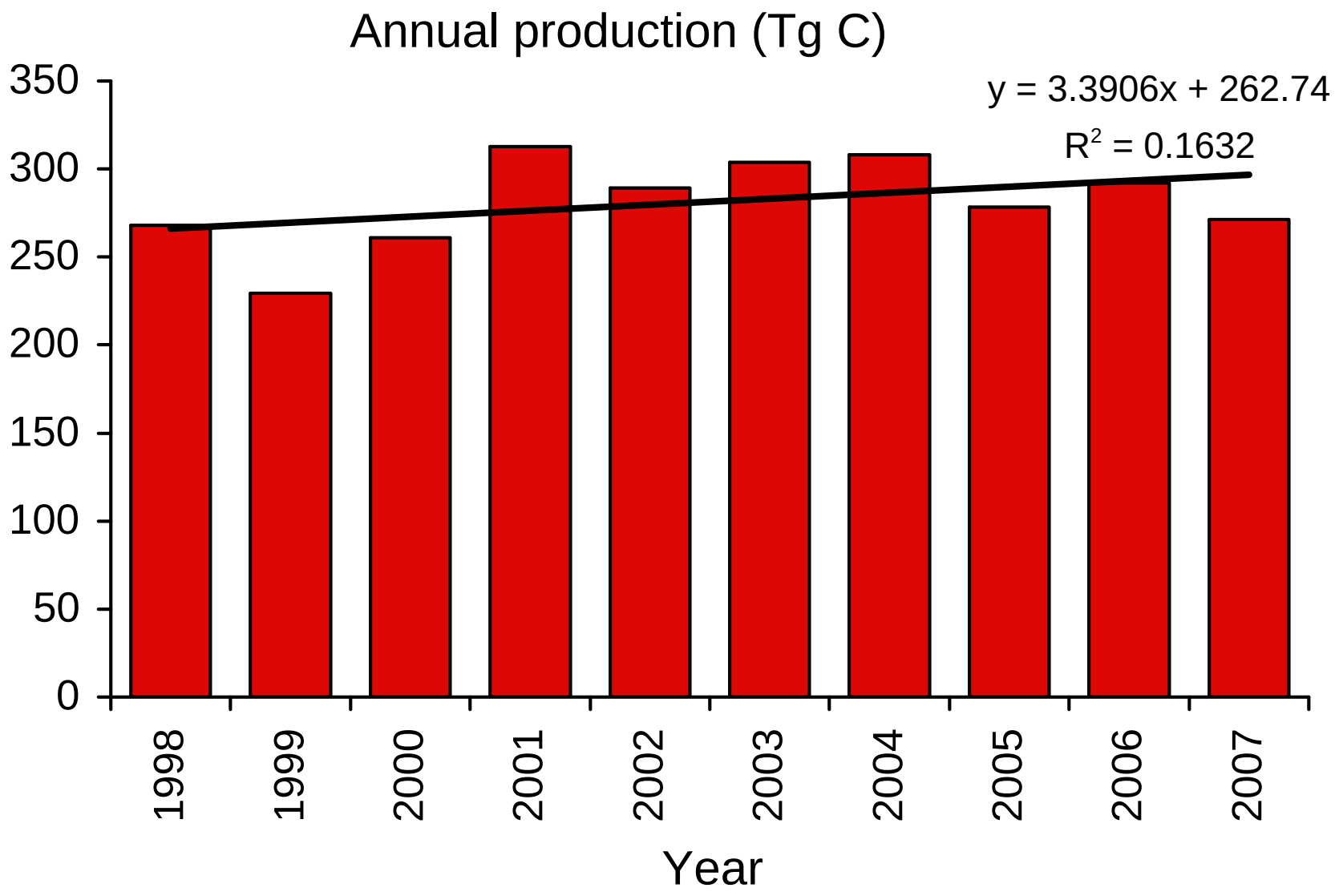
Mean Annual Net
Primary Production
1998-2007



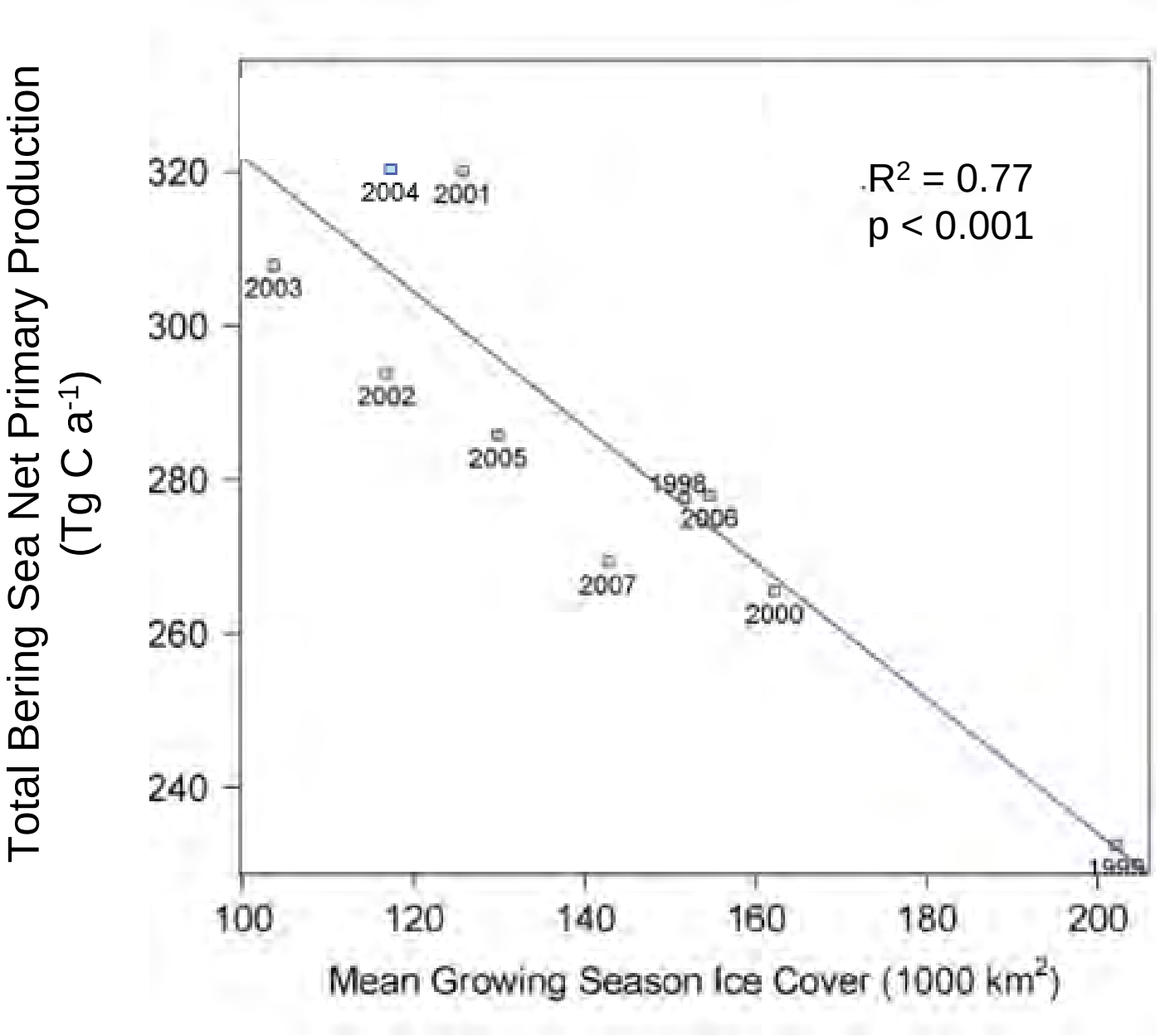
# Bering Sea


Rho and Whitledge 2007
Springer et al. 1996
This Study
Mean Annual Primary Production (g C m$^{-2}$ a$^{-1}$)
200
150
100
50
0
Global ocean mean
Aleutian
Abyss
Anadyr
Break
Chirikov
Inner
Middle
Outer
W.Shelf
Total
Region of Interest

# Bering Sea

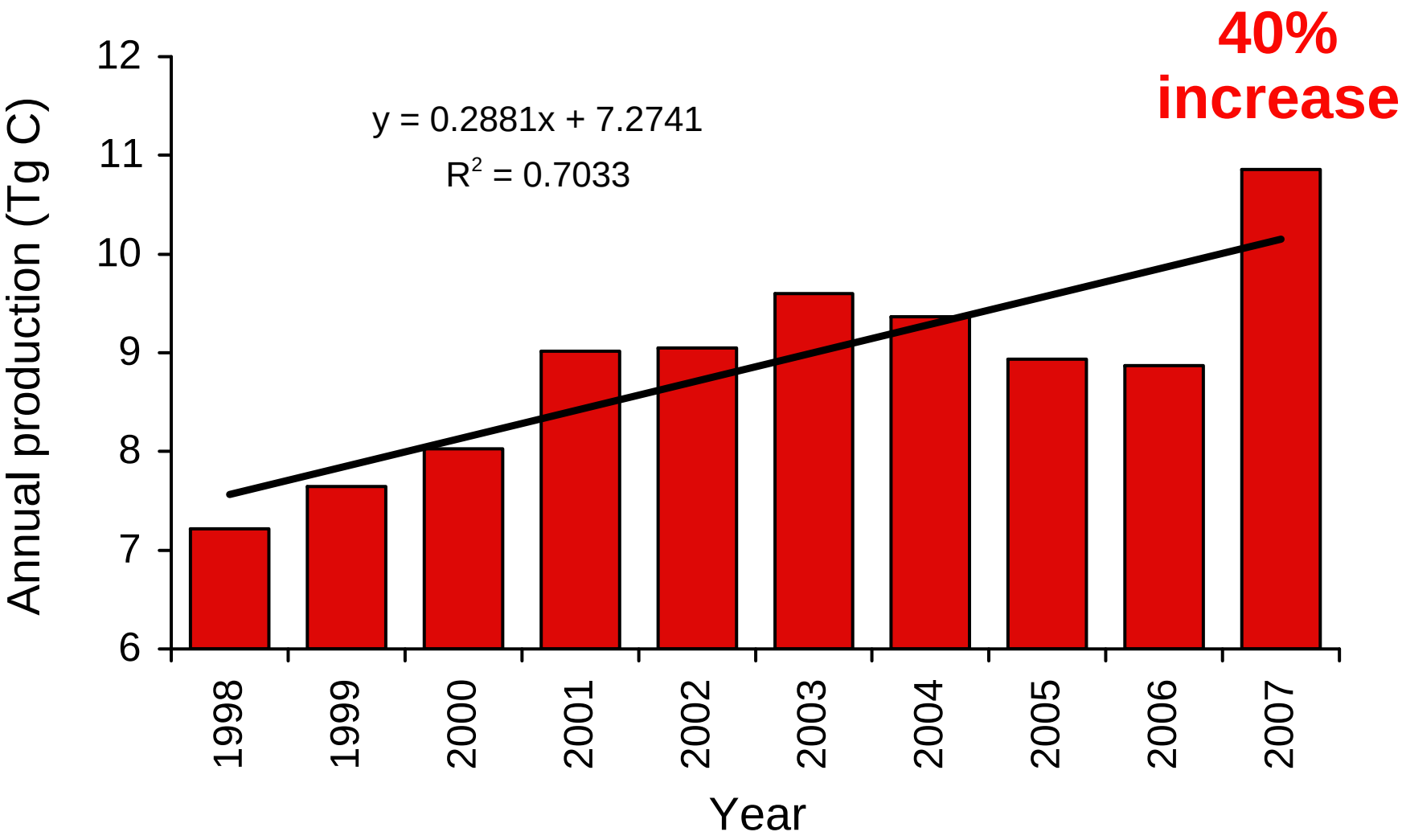

Annual production (Tg C)
y = 3.3906x + 262.74
R2 = 0.1632
350
300
250
200
150
100
50
0
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year

# Bering Sea


Total Bering Sea Net Primary Production
(Tg C a-1)
320
300
280
260
240
2004
2001
2003
2002
2005
1998
2006
2007
2000
1999
$R^2$ = 0.77
p < 0.001
100
120
140
160
180
200
Mean Growing Season Ice Cover (1000 km2)

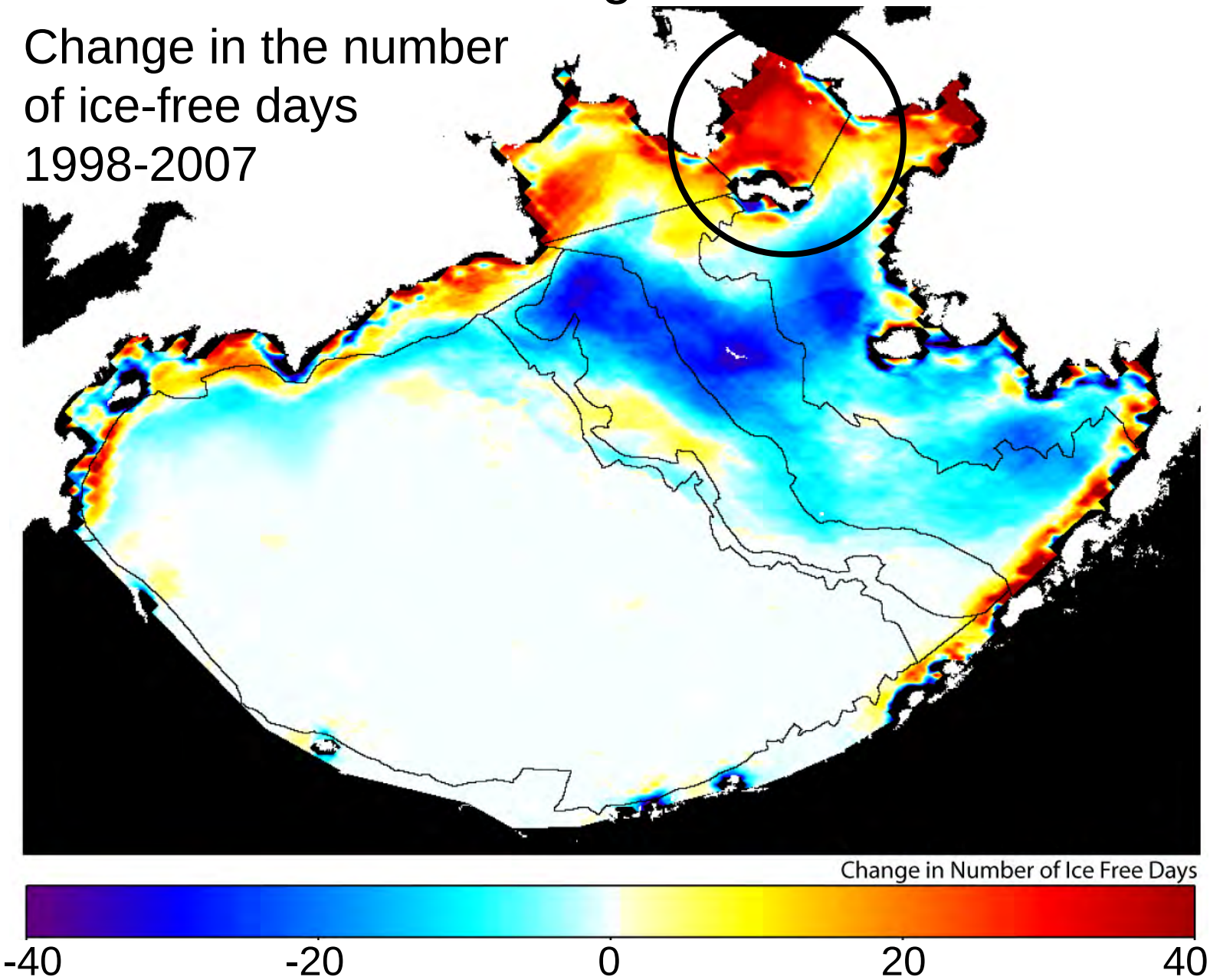

Has primary production changed significantly anywhere in the Bering Sea between 1998 and 2007?

# Bering Sea


40% increase
y = 0.2881x + 7.2741
R2 = 0.7033
Annual production (Tg C)
12
11
10
9
8
7
6
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year

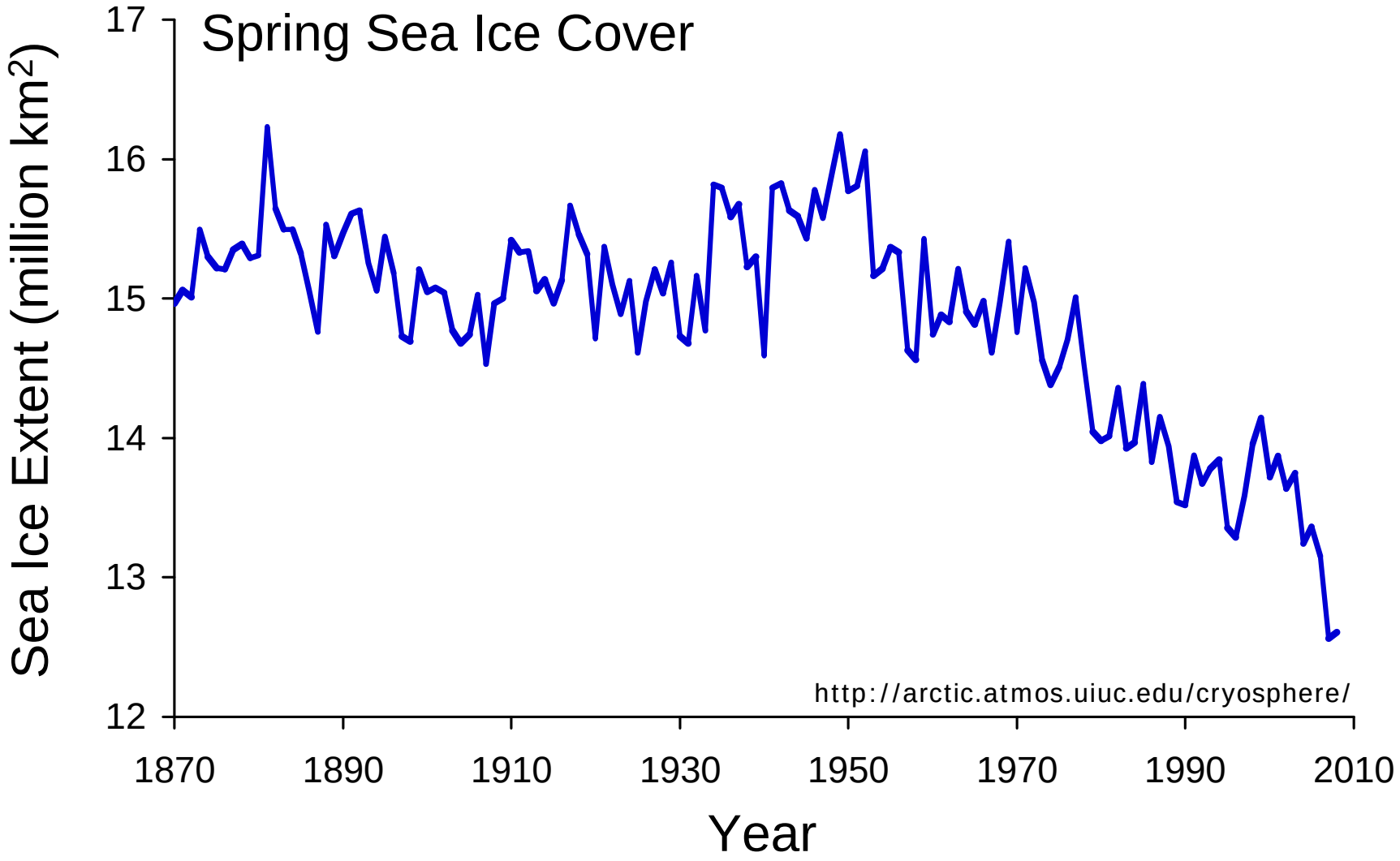
# Bering Sea

Change in the number
of ice-free days
1998-2007



# The Arctic Ocean

# Arctic Ocean

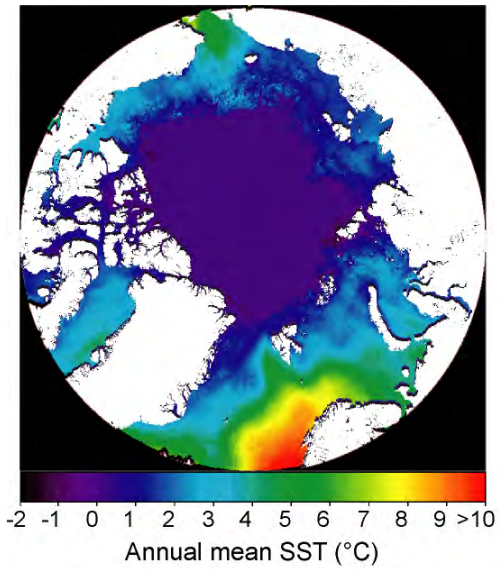


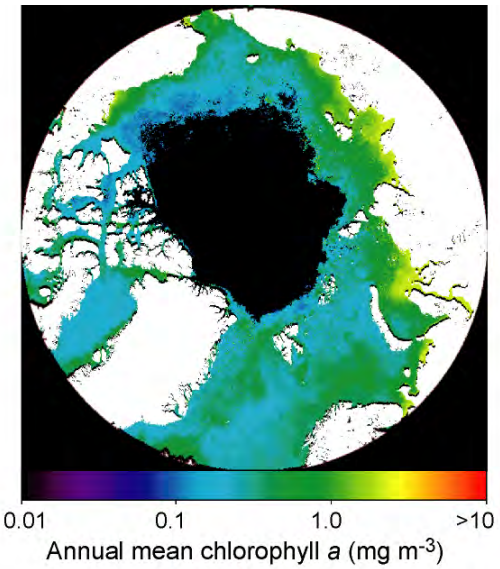

Given ongoing changes in sea ice in the Arctic Ocean…
How has primary production changed in recent years?

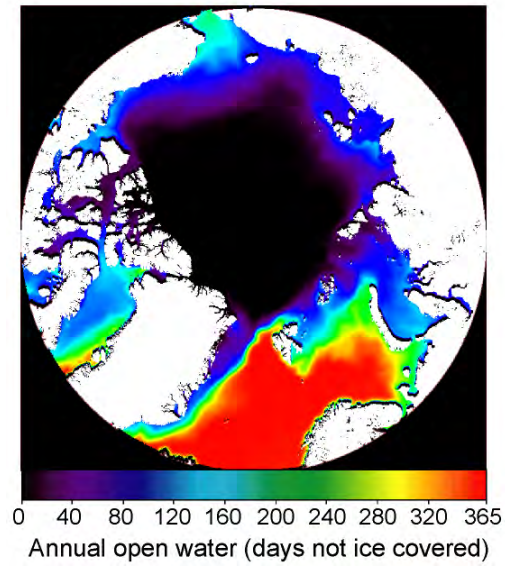
# Arctic Ocean

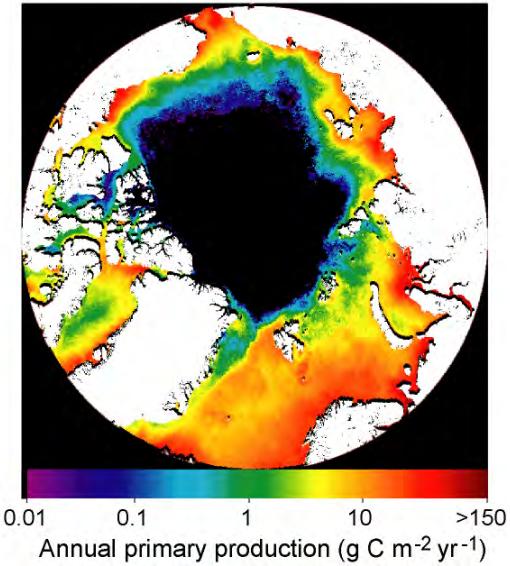
How primary production was calculated

- Algorithm modified from Southern Ocean (Arrigo et al. 2008, Pabi et al. 2008)
- Based on remotely sensed SST, Chl *a*, and sea ice
- Forced with winds, cloud cover, and solar radiation



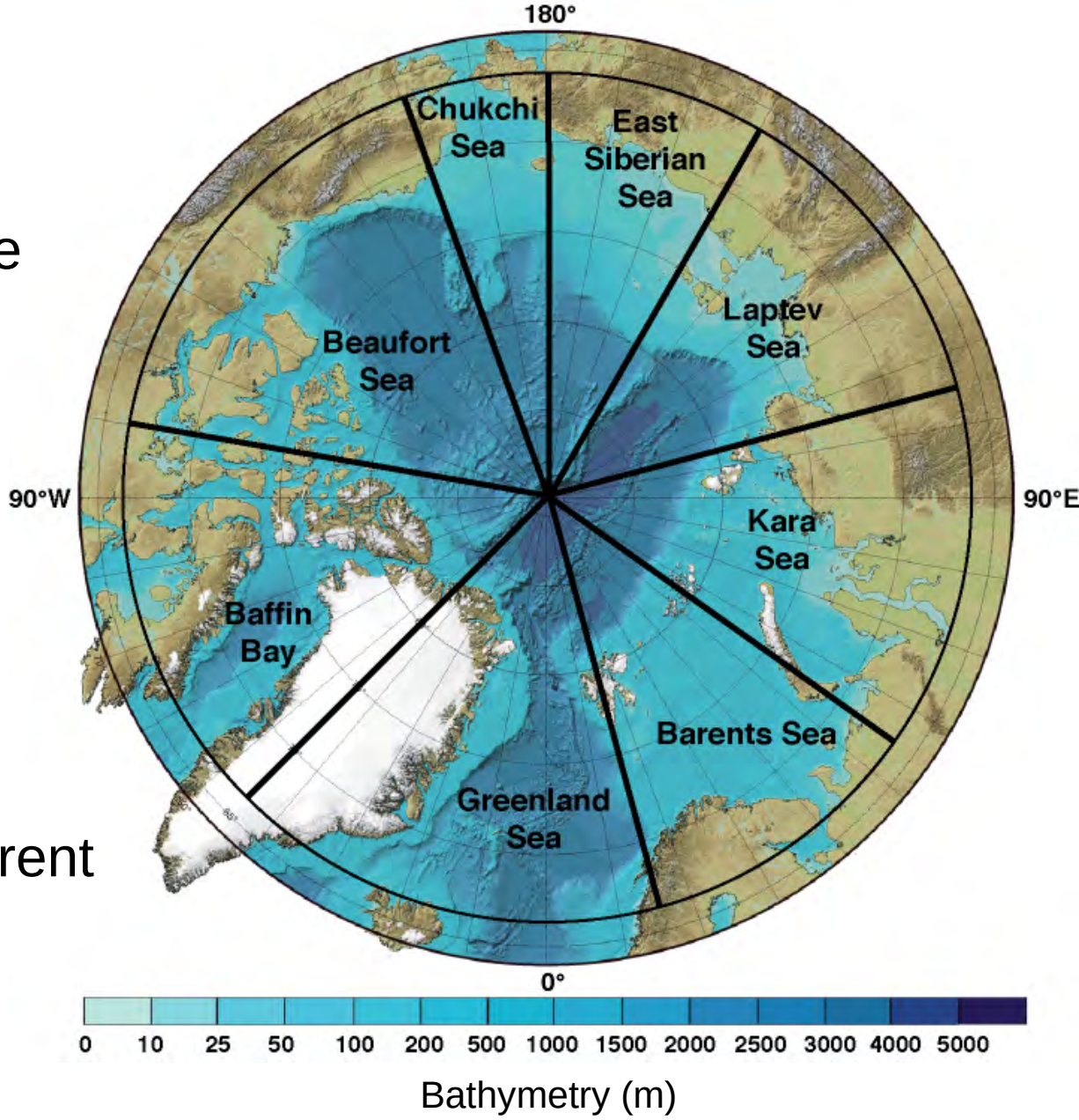



# Arctic Ocean

- Quantified primary production over entire Arctic Ocean

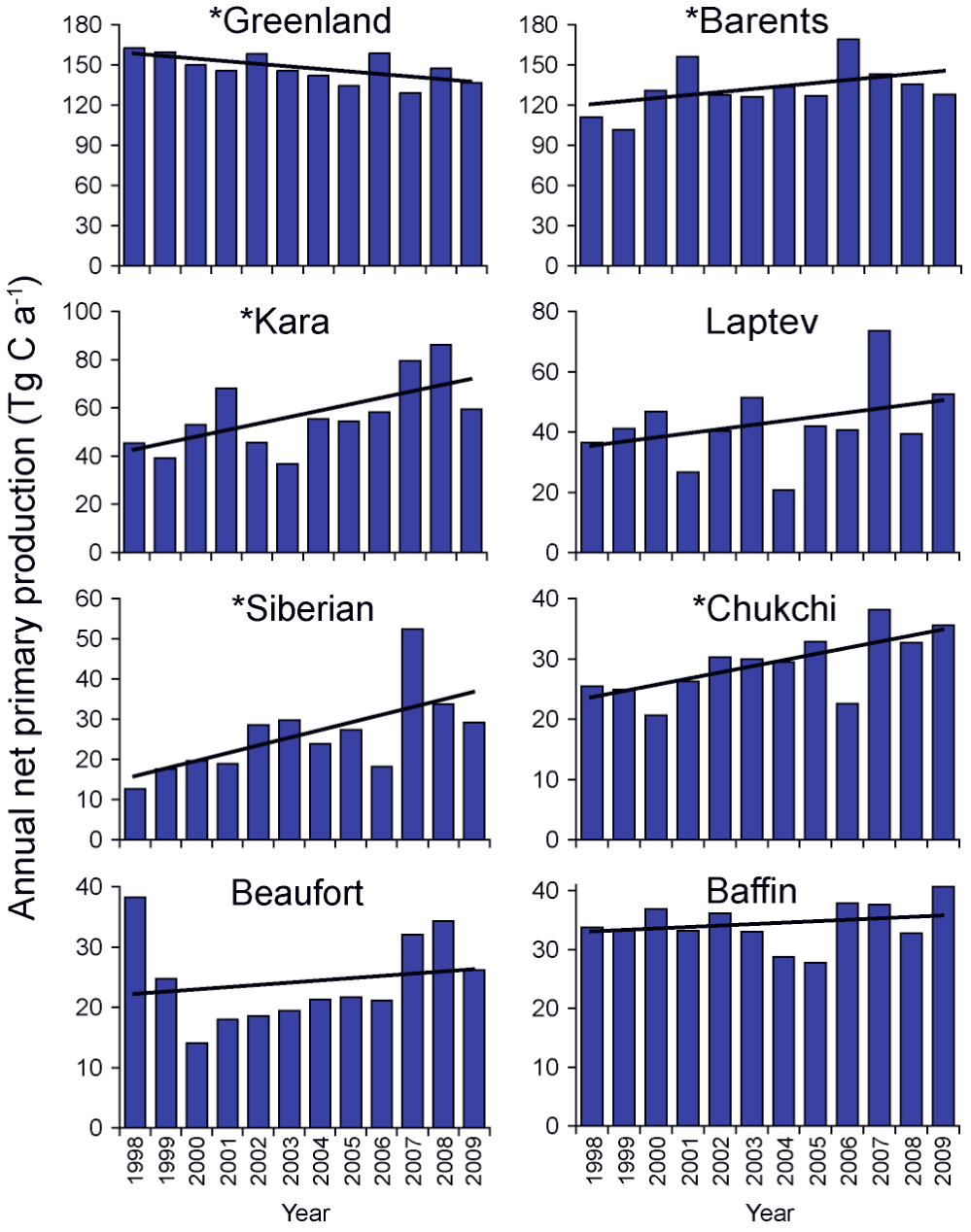
- Also analyzed 8 different geographic sectors



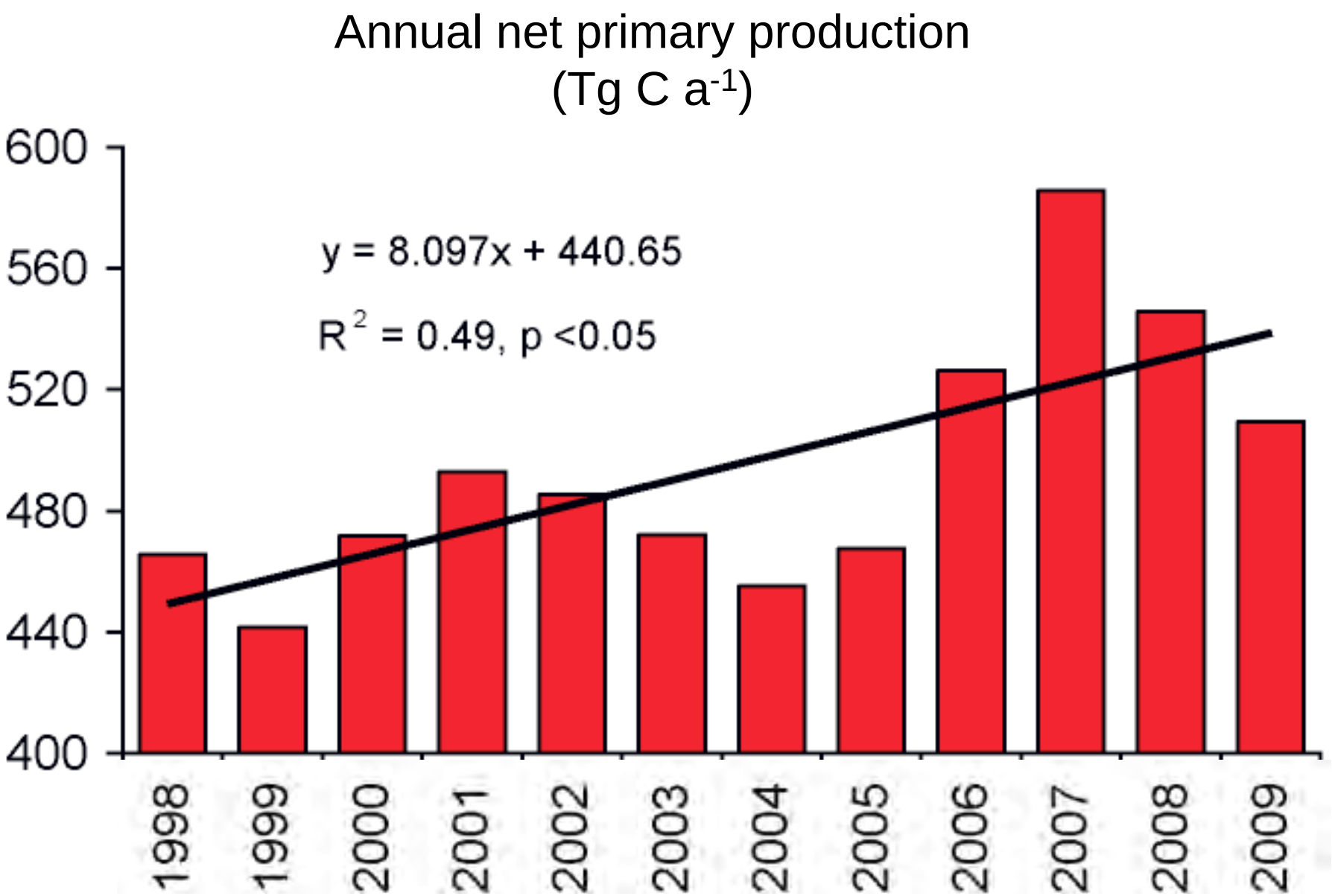
# Changes in Regional Primary Production

- Small but significant decrease in the Greenland -2%

- Significant increases in the:
  - Barents 23%
  - Kara 76%
  - Siberian 131%
  - Chukchi 48%

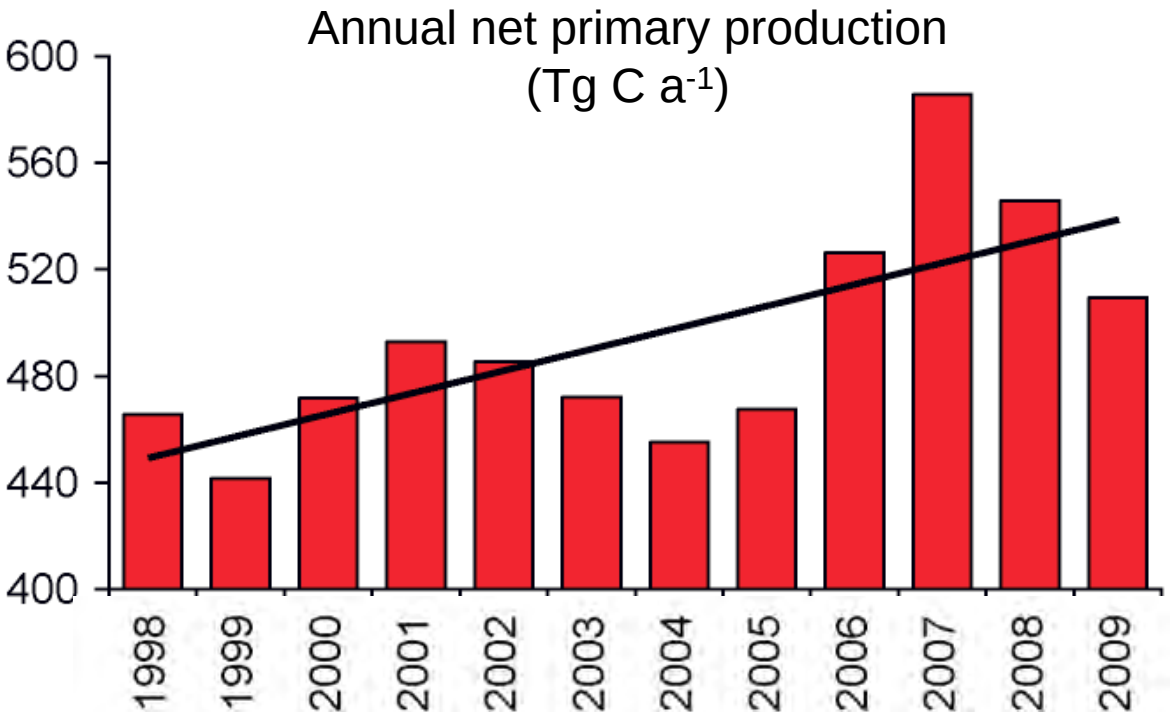


# Changes in Arctic Primary Productivity

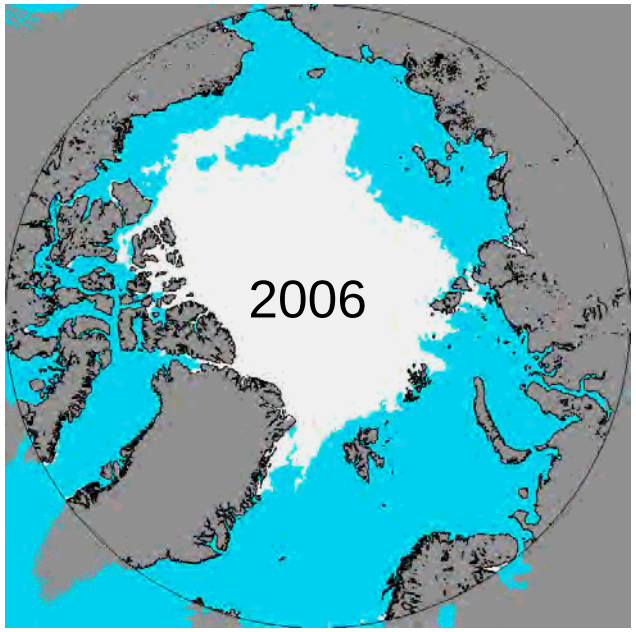


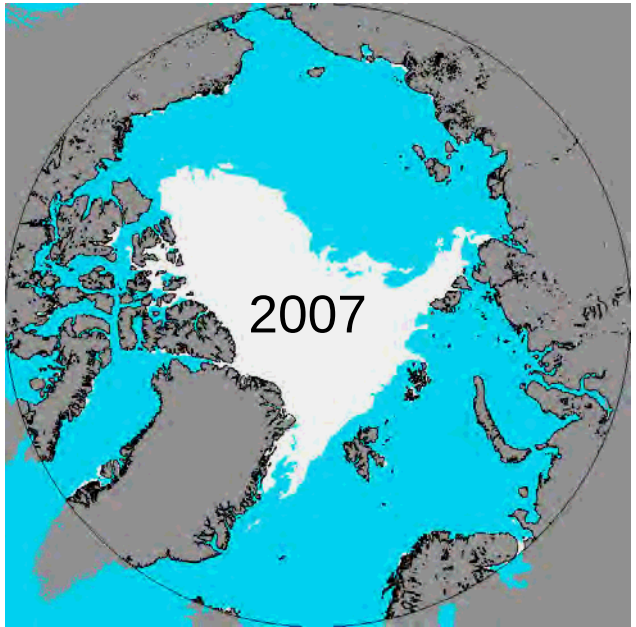
# Changes in Arctic Primary Productivity

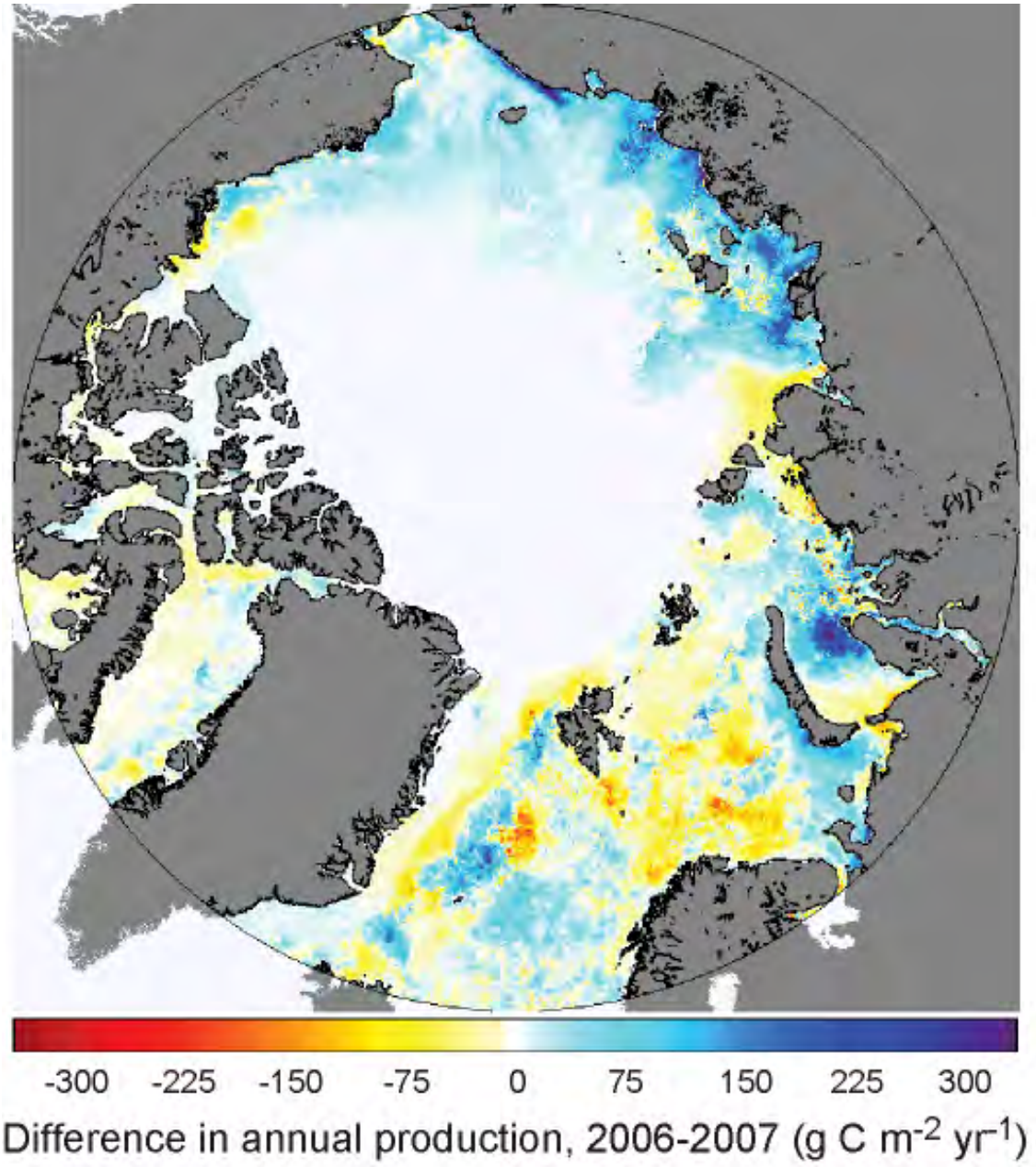
- Annual primary production increased by 97 Tg C over 12 year period
- A 20% increase
- Unexpected given presumed nutrient limitation
- Largest increases on continental shelf



# Changes in Arctic Primary Productivity

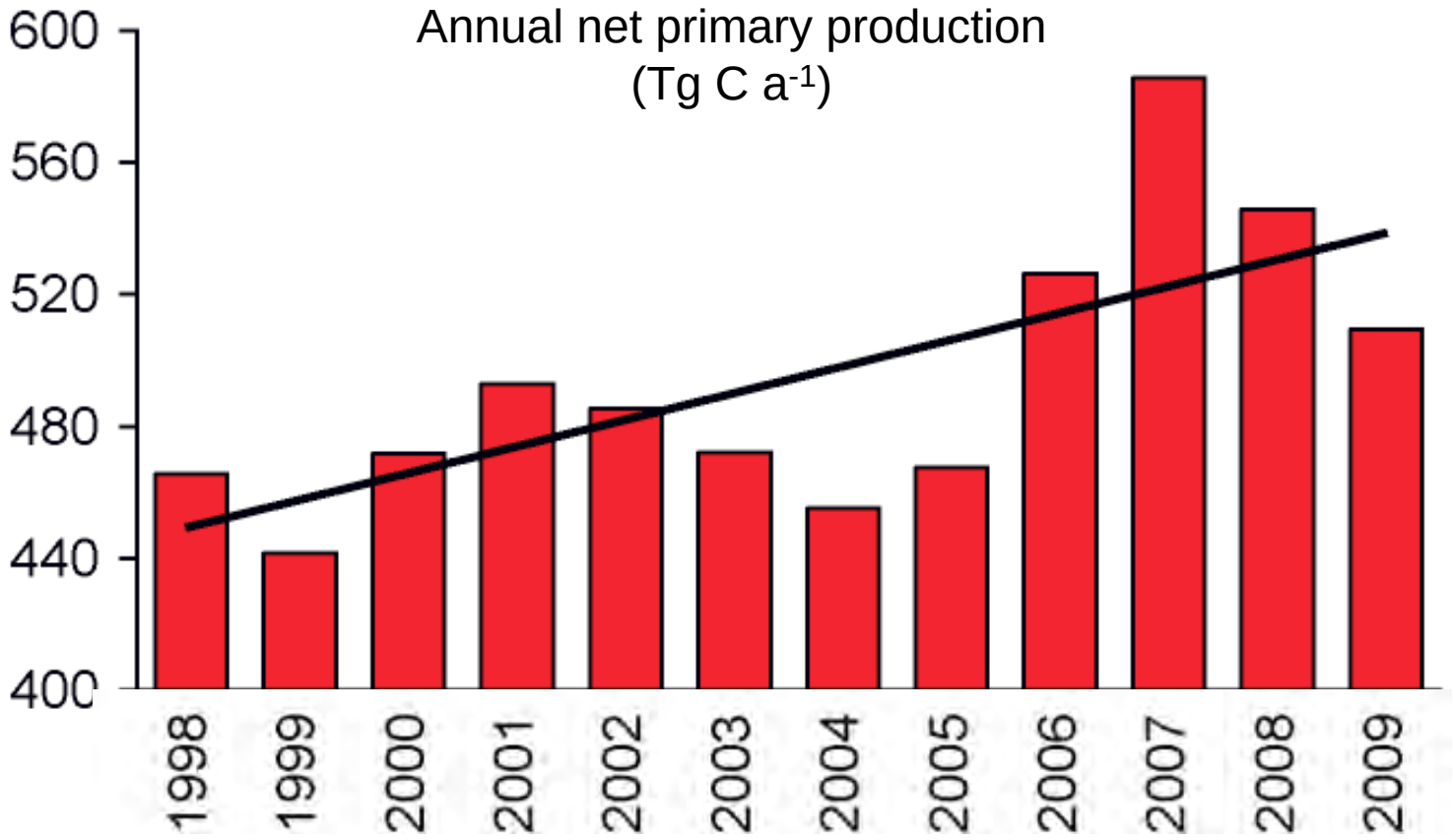


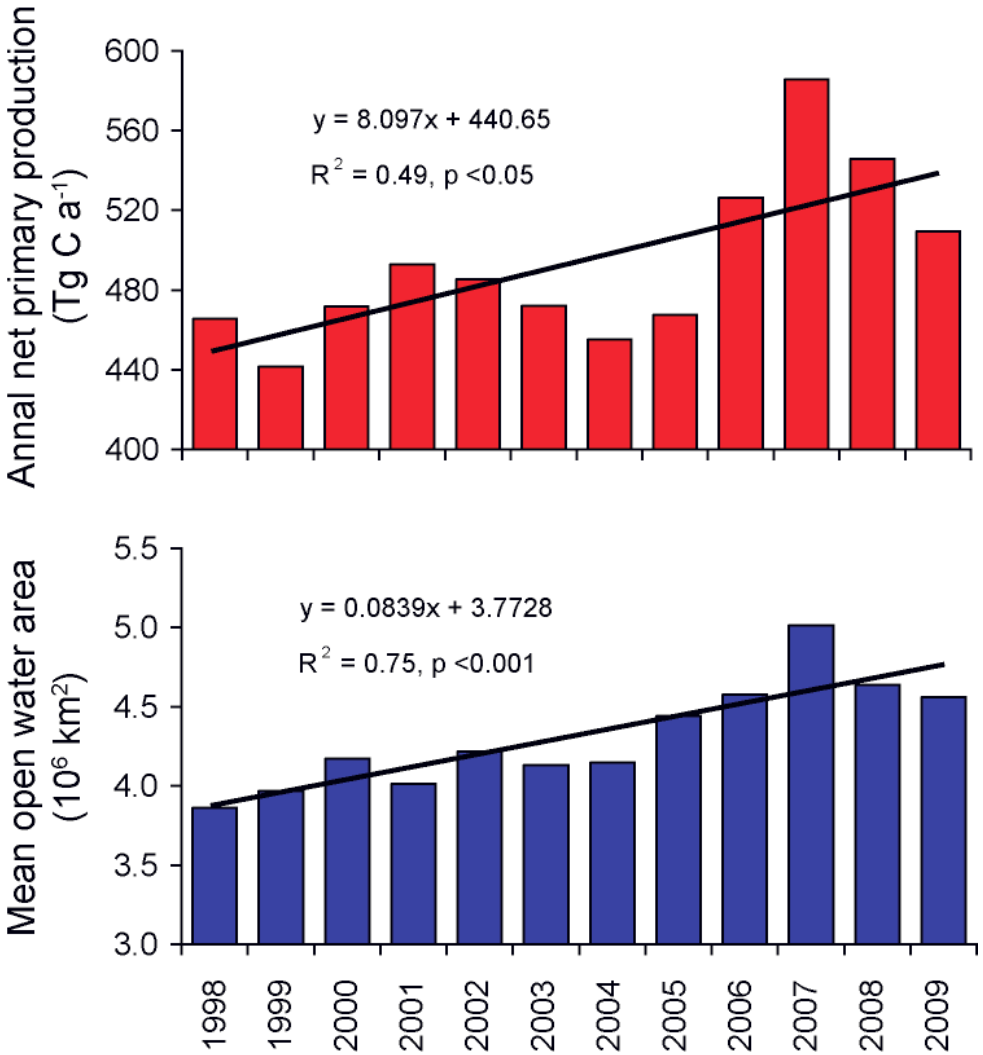



# Changes in Arctic Primary Productivity

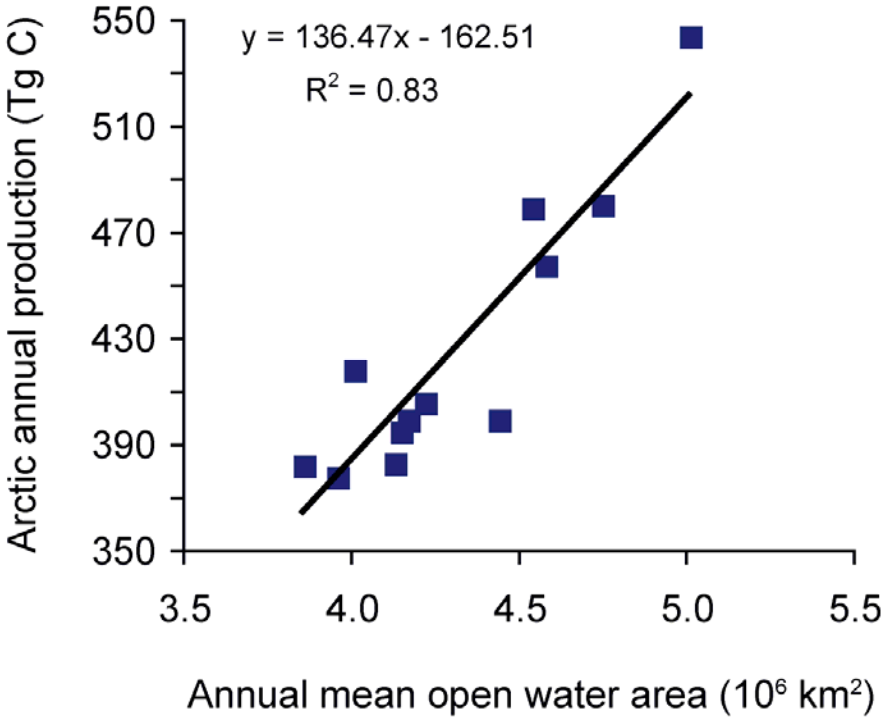
What caused the increase in annual net primary production?



# Changes in Arctic Primary Productivity




Increase in production clearly related to increase in open water area

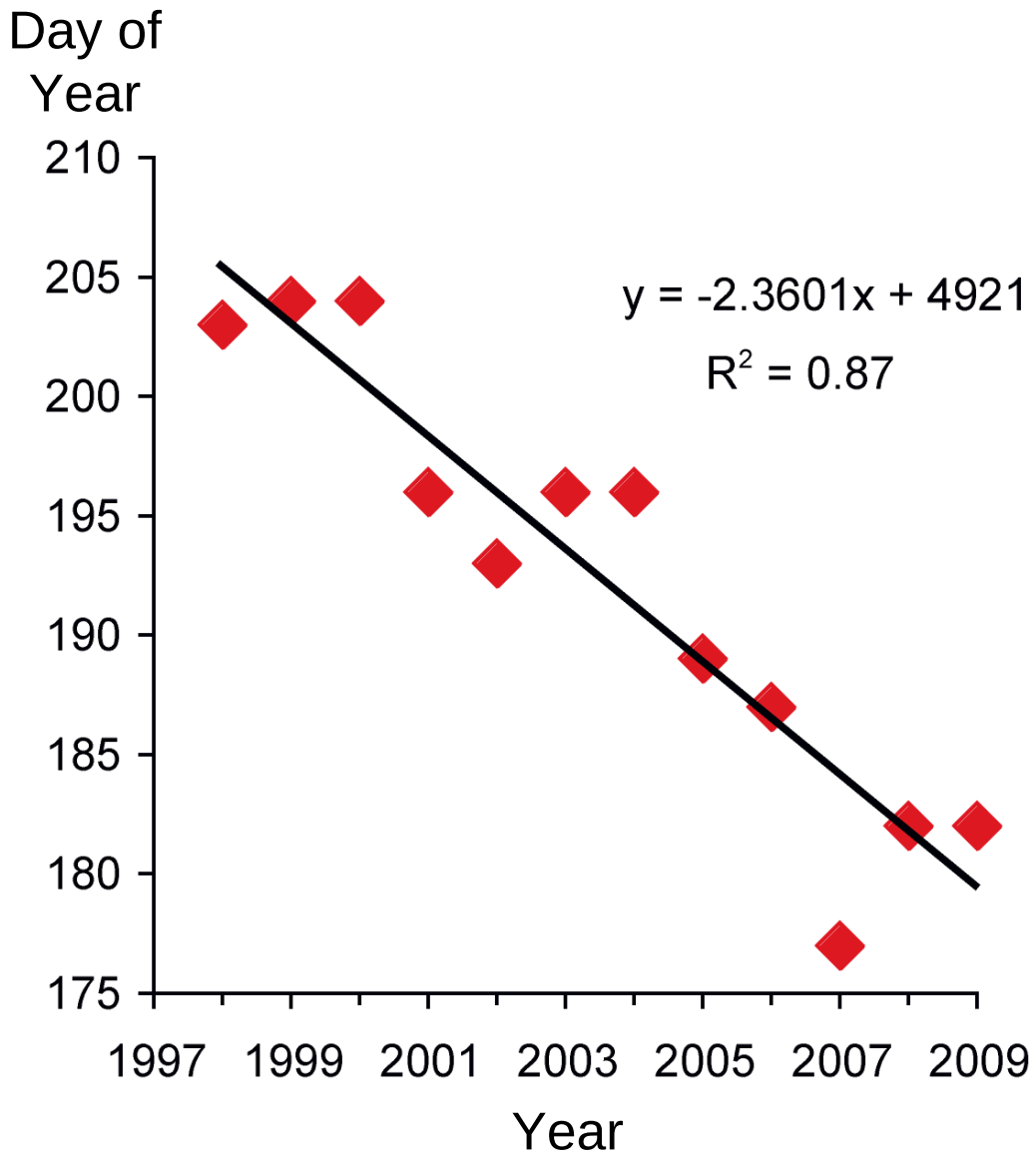


# Changes in Arctic Primary Productivity

What about changes in length of open water season?

Sea ice retreated an average of 2.4 days $yr^{-1}$ earlier over last 12 years

28 days earlier in 2009 than in 1998

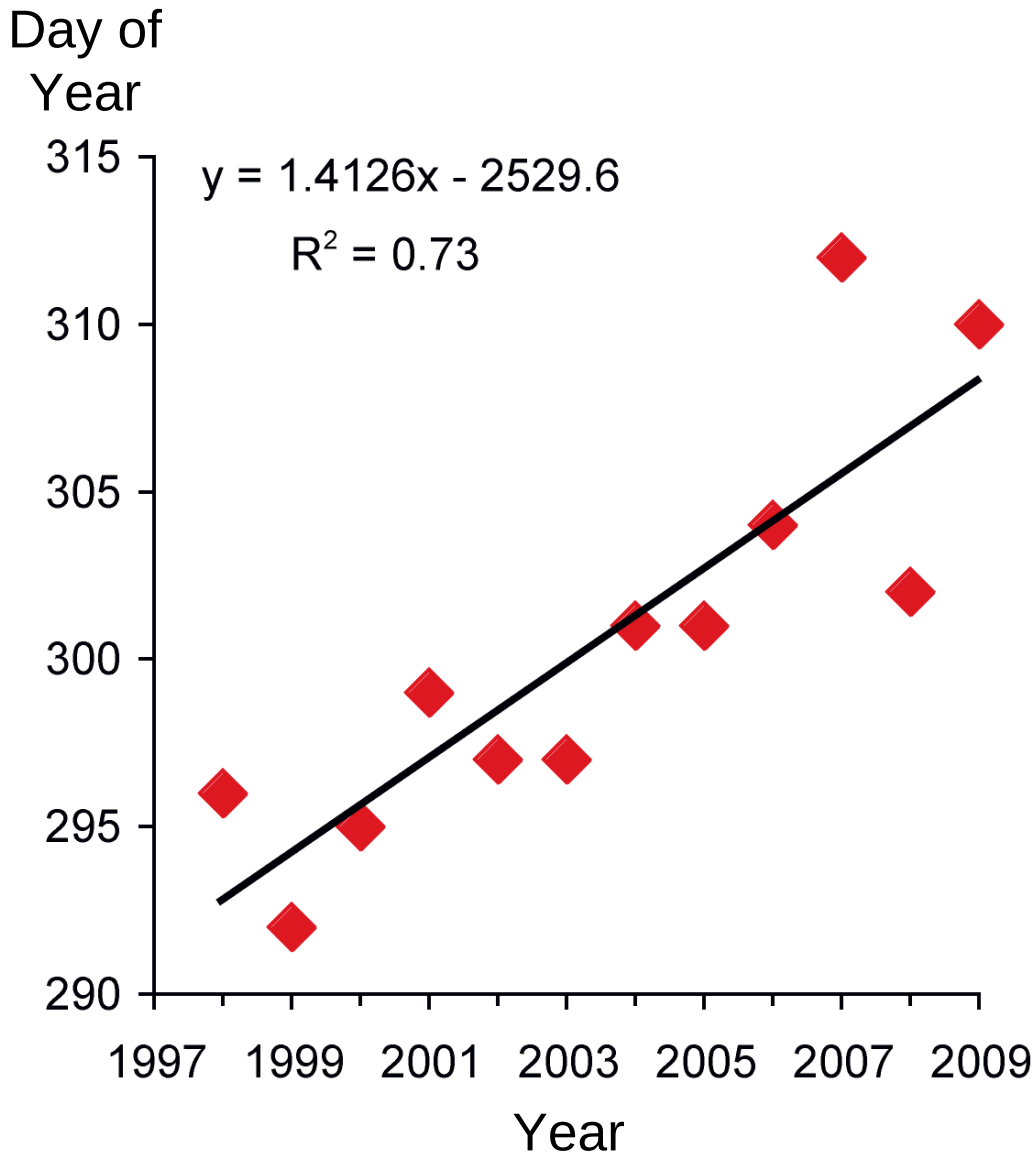


# Changes in Arctic Primary Productivity

What about changes in length of open water season?

Sea ice advanced an average of 1.4 days $yr^{-1}$ later over last 12 years

17 days later in 2009 than in 1998

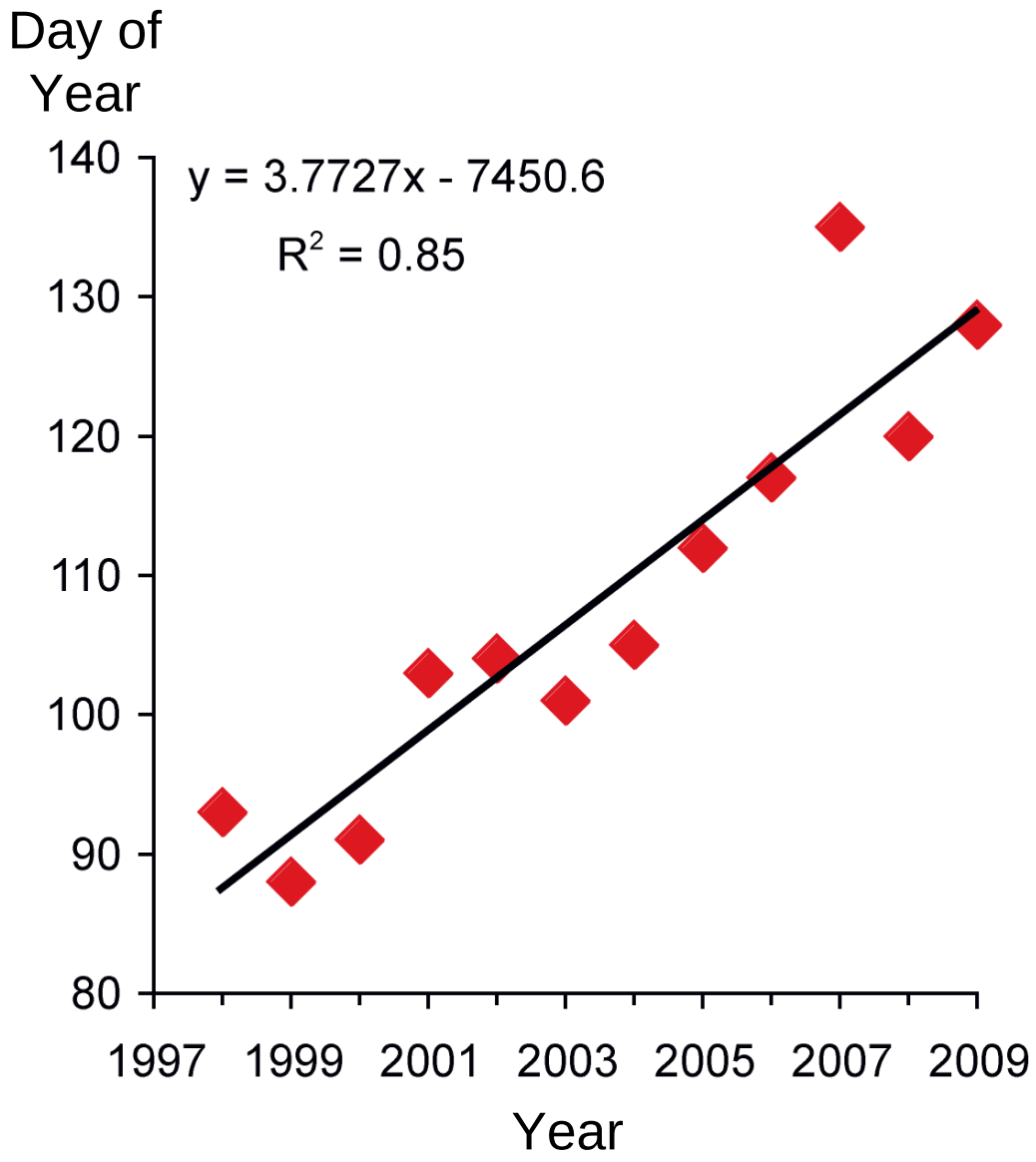


# Changes in Arctic Primary Productivity

What about changes in length of open water season?

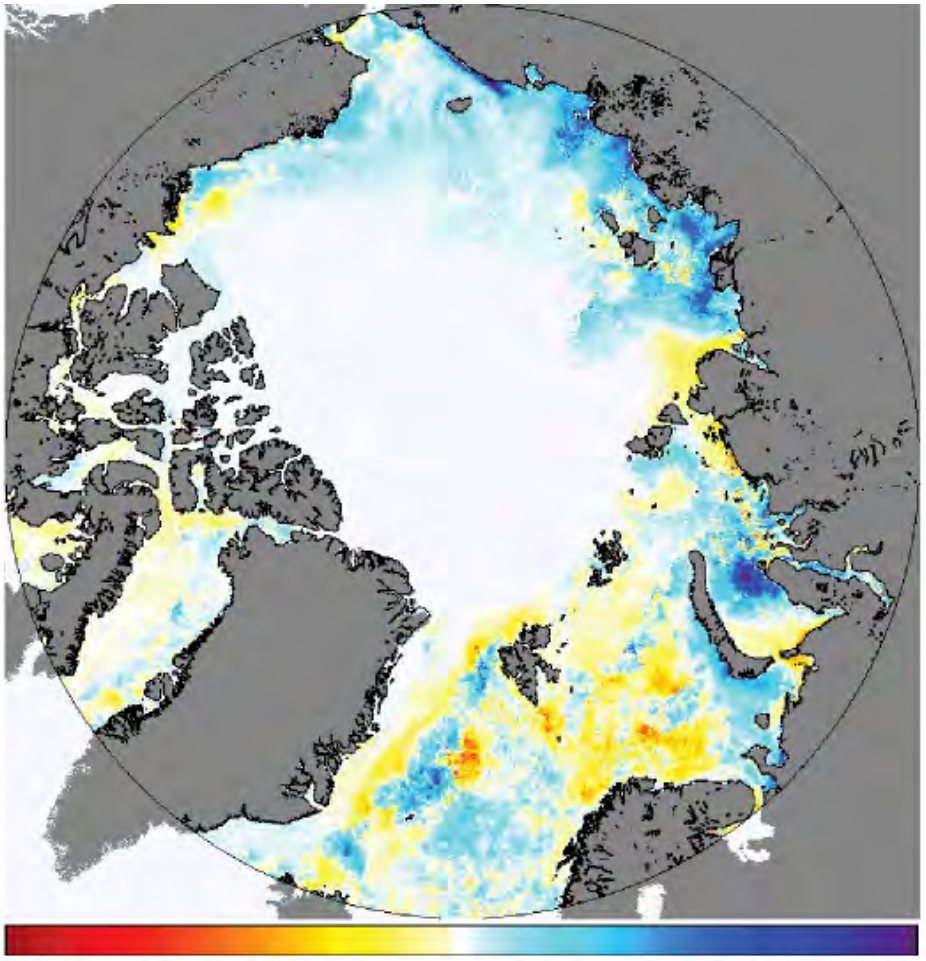
Open water season has lengthened by an average of 3.8 days $yr^{-1}$ over last 12 years

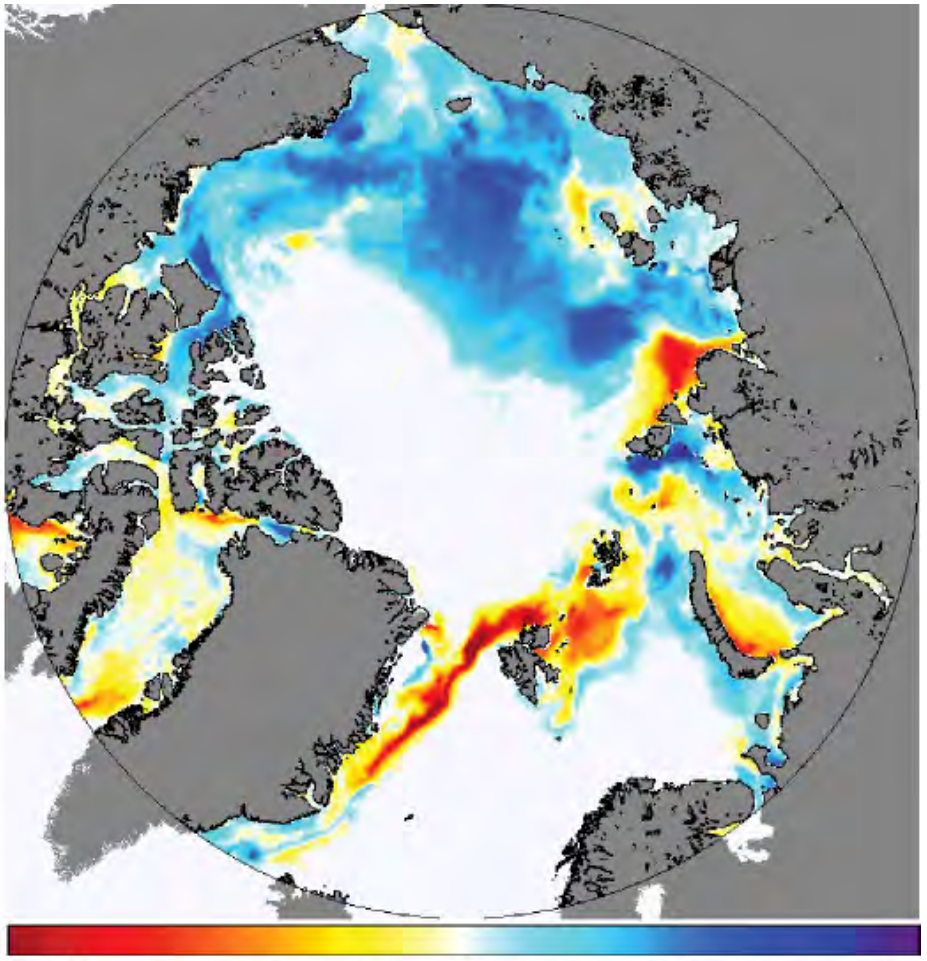
45 days longer in 2009 than in 1998



# Changes in Arctic Primary Productivity

- 70% of increase in primary production between 2006 and 2007 related to longer growing season

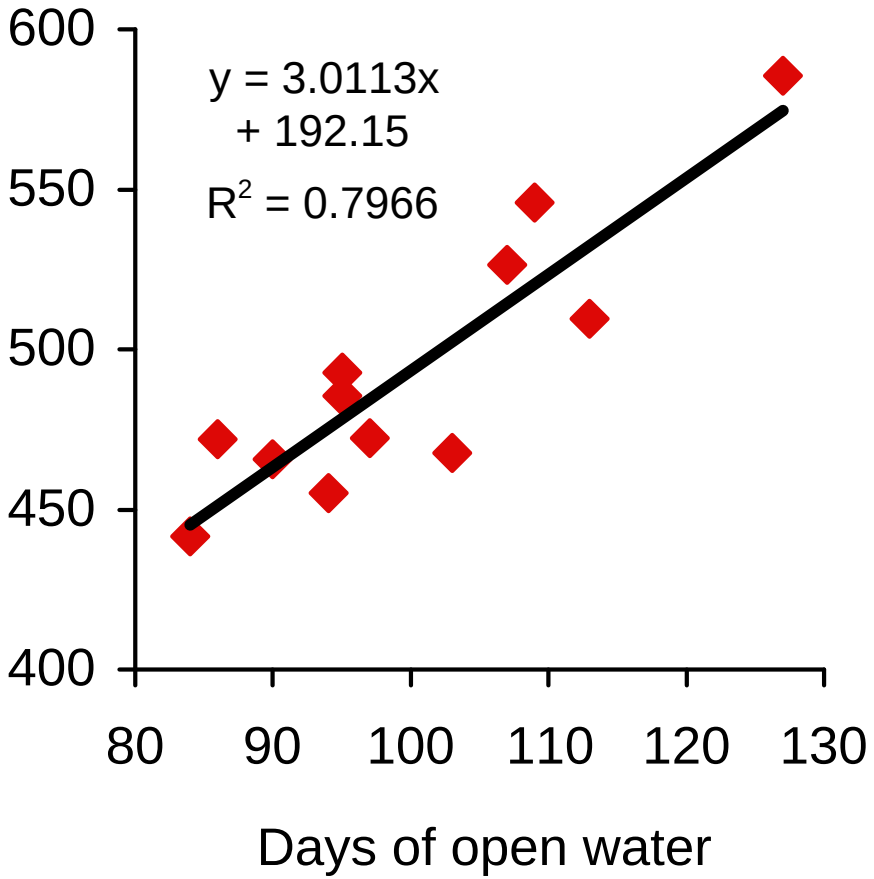


# Changes in Arctic Primary Productivity

Does the positive relationship between annual primary production and length of open water season hold for all years?

YES



# The Future?

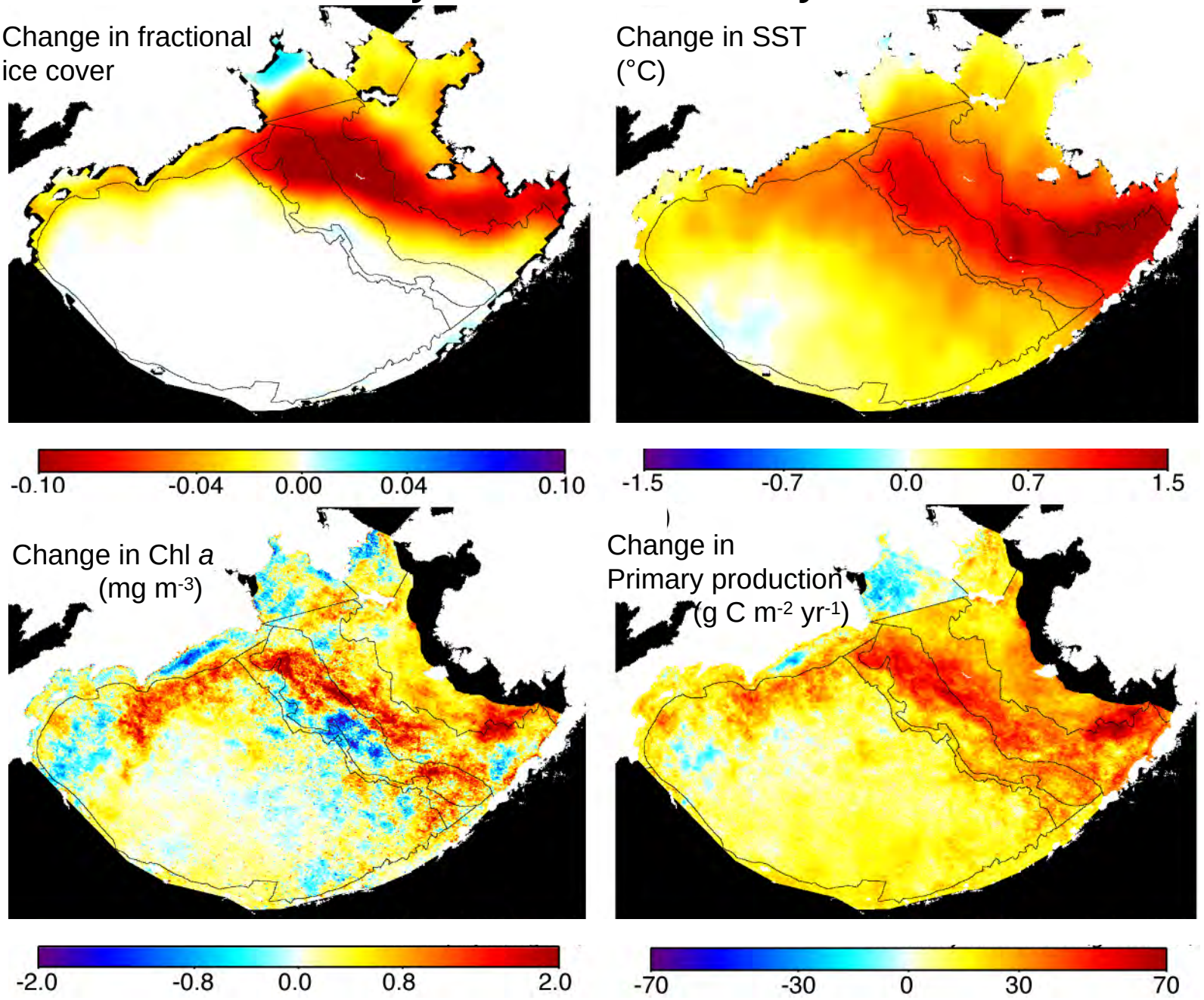
# The Future?

The Bering Sea

Use differences between cold years and warm years as a guide…

Although future changes are likely to be more extreme than recent ones…

# Warm years minus Cold years



# The Future?

The Bering Sea

Using differences between cold years and warm years as a guide…

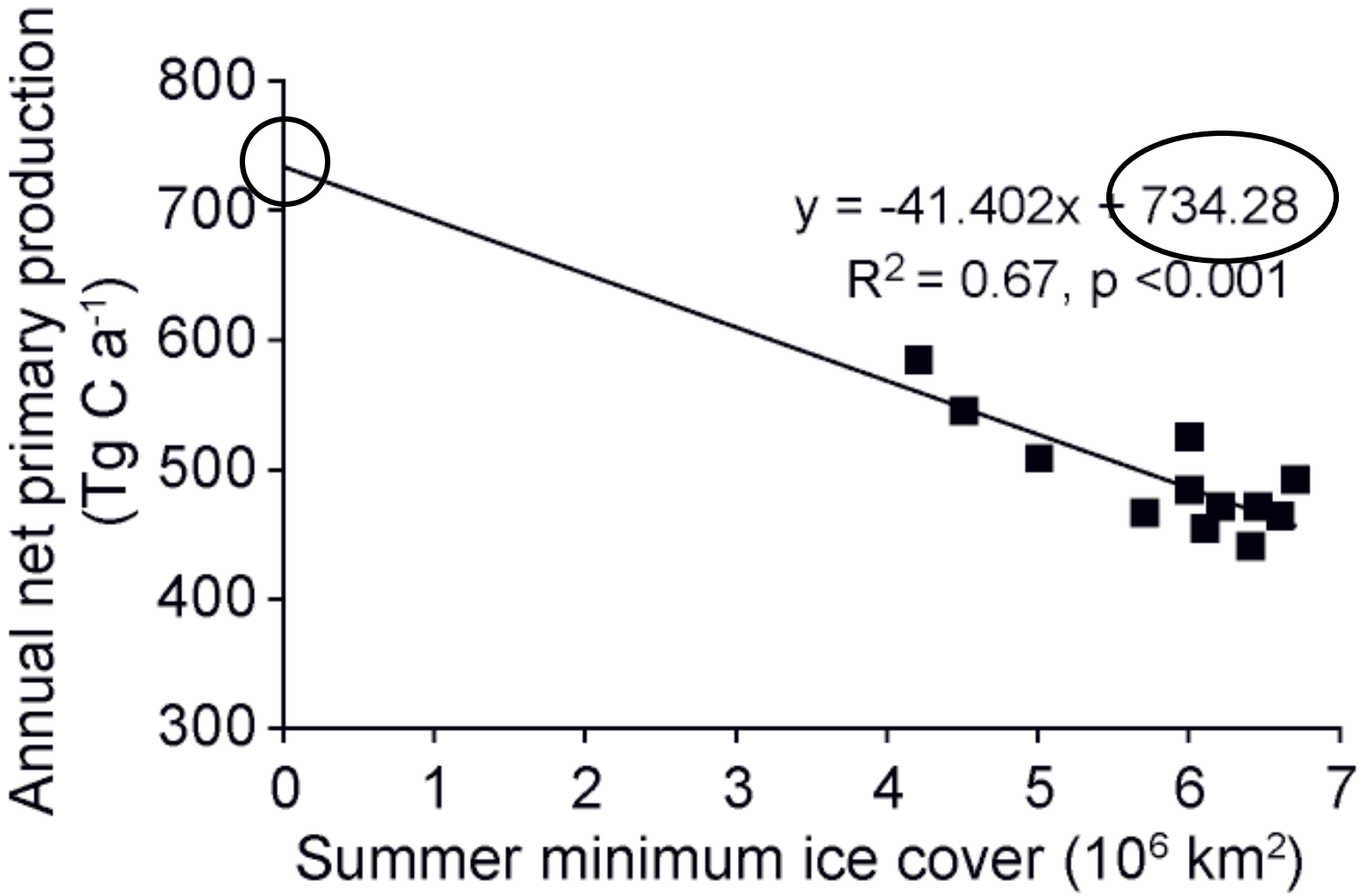
Primary production in the Bering Sea is ~30% higher in warm years than in cold years

# The Future?

The Arctic Ocean

Extrapolate from recent trajectories in ice extent and primary production

# The Future?


Annual net primary production
(Tg C a-1)
800
700
600
500
400
300
0
1
2
3
4
5
6
7
Summer minimum ice cover (10^6 km^2)
y = -41.402x + 734.28
R^2 = 0.67, p <0.001

# The Future?

The Arctic Ocean

Continued loss of summer sea ice could result in a further 30% increase in annual primary production

But is this increased level of production sustainable?

# Conclusions

- In the Bering Sea, SST has warmed over last 30 yrs but there has been no change in sea ice cover or primary production
- Exception is the “Arctic-like” Chirikov Basin where annual primary production increased 40% from 1998 to 2007
- In the future, a warmer more ice-free Bering Sea is likely to be more productive than today
- In the Arctic, changes in sea ice extent and duration have driven a 20% increase in production over last 12 years
- With further loss of sea ice, Arctic productivity could increase even more in the future
- Much work to be done before reliable predictions are possible


Thank You!