

Sea ice decline in the Arctic: an ocean mechanism

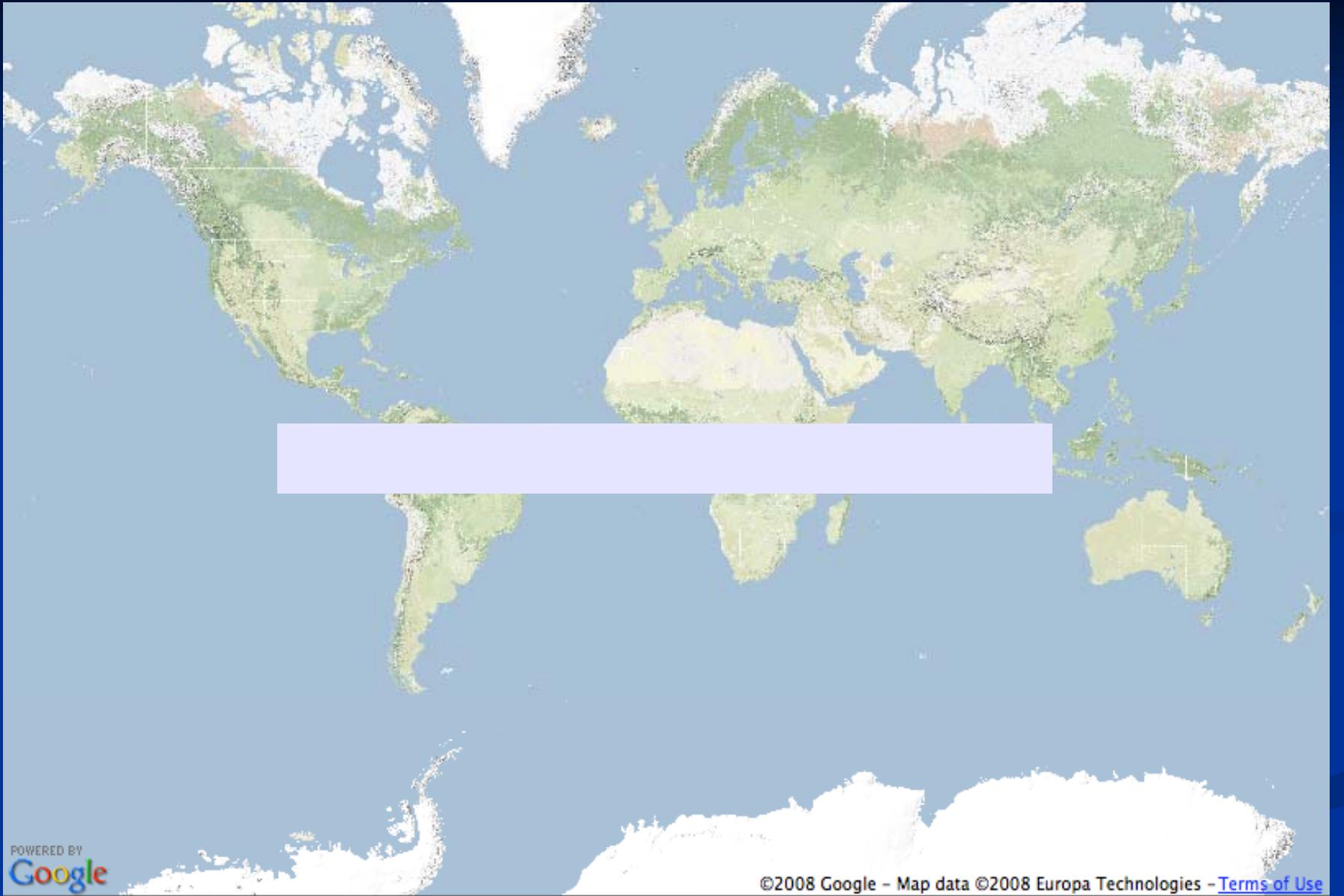
Bruno Tremblay

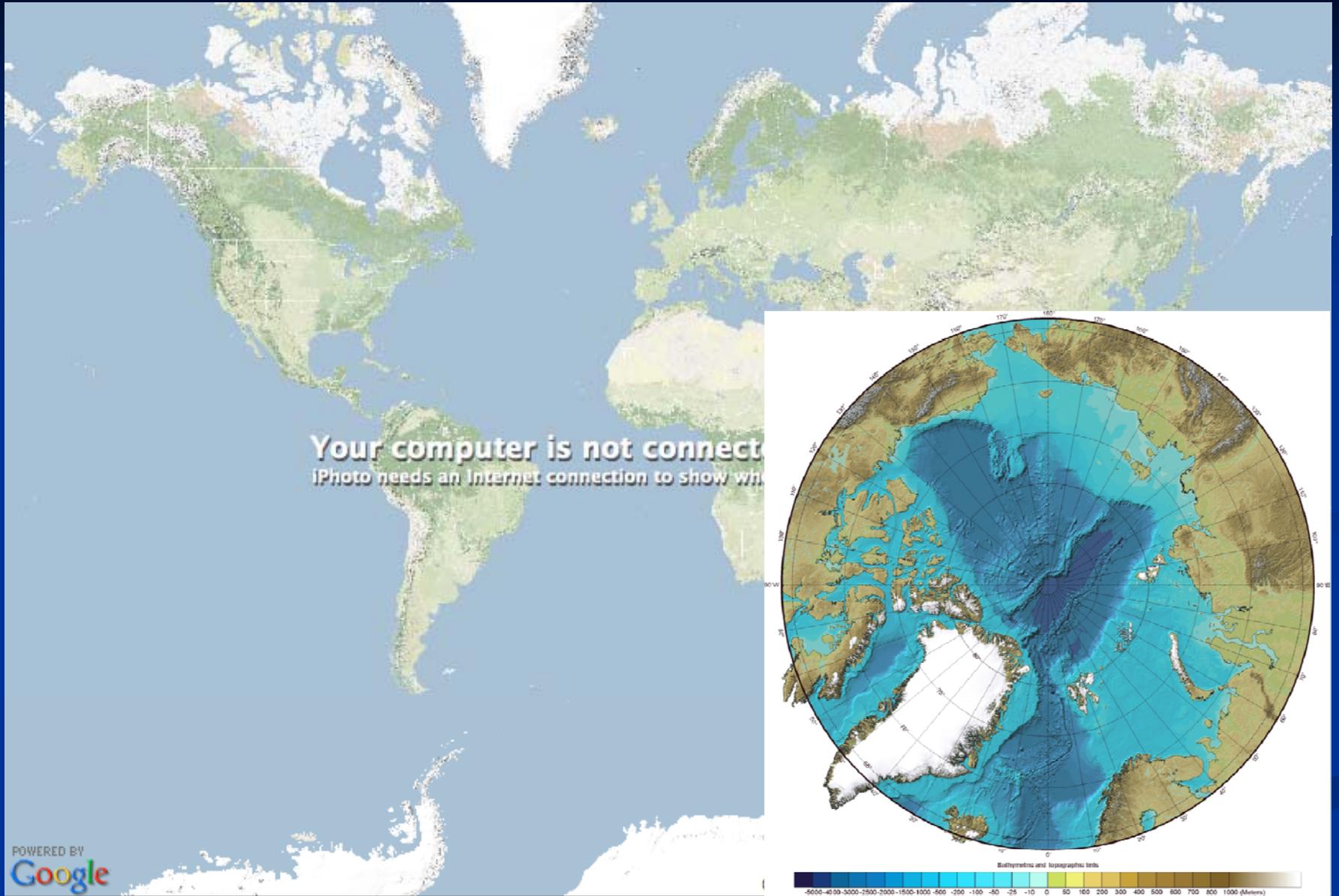
McGill University

bruno.tremblay@mcgill.ca

Collaborators: Alexander Slavin, Louis Renaud-Desjardins, David Straub

Funded by : Ouranos



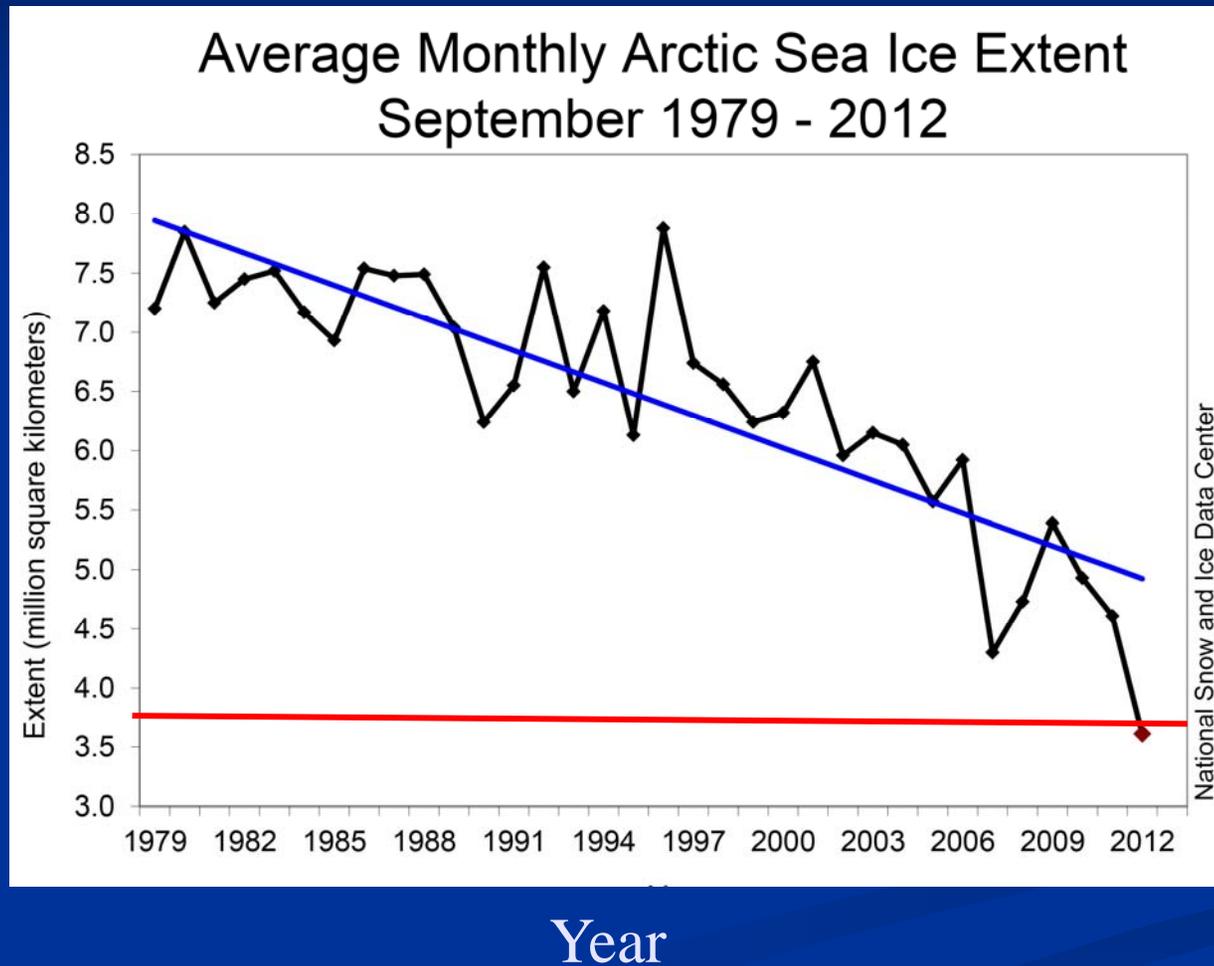


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Minimum Arctic Sea Ice Extent

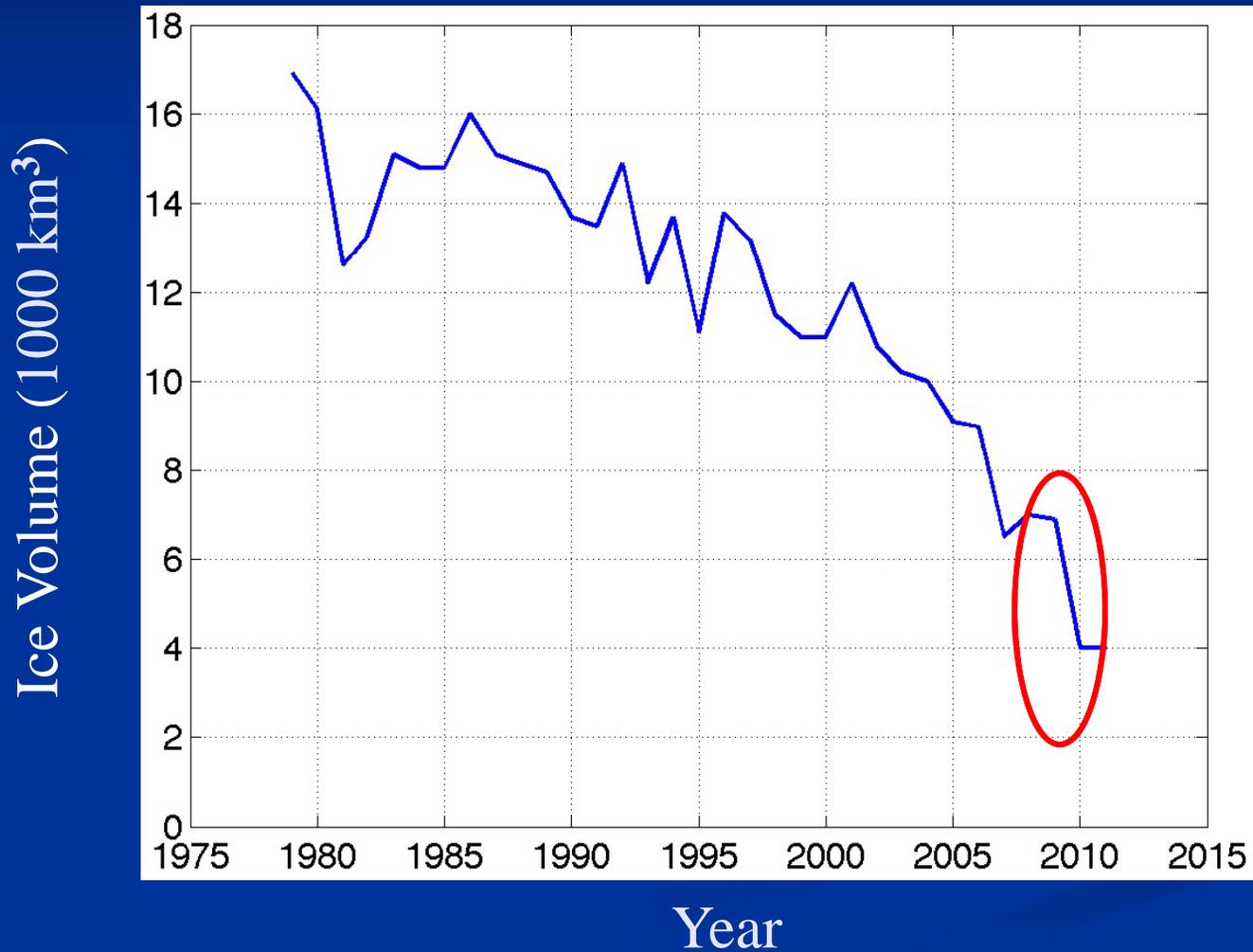
Ice Extent (million km²)



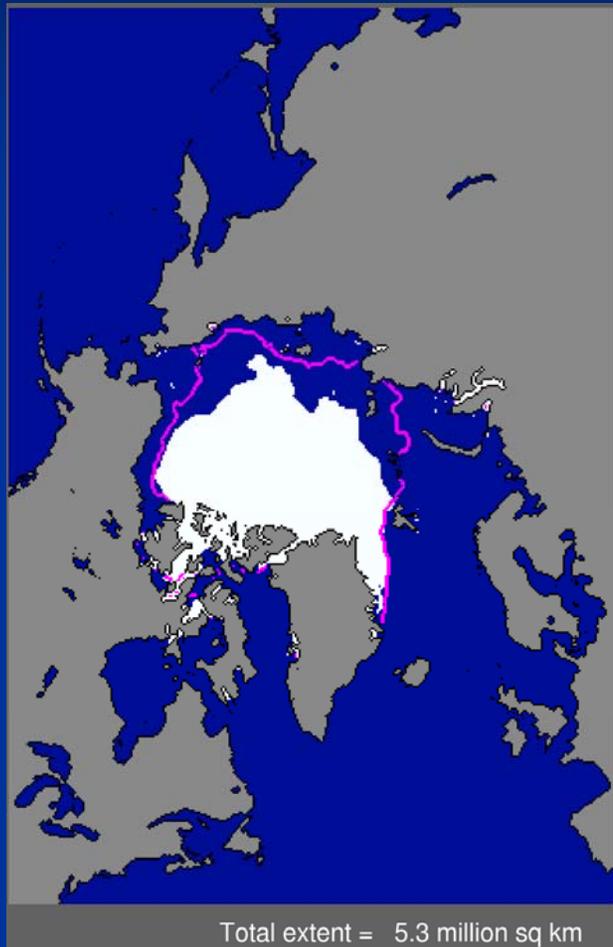
NSIDC, 2012

Minimum Arctic Sea Ice Volume

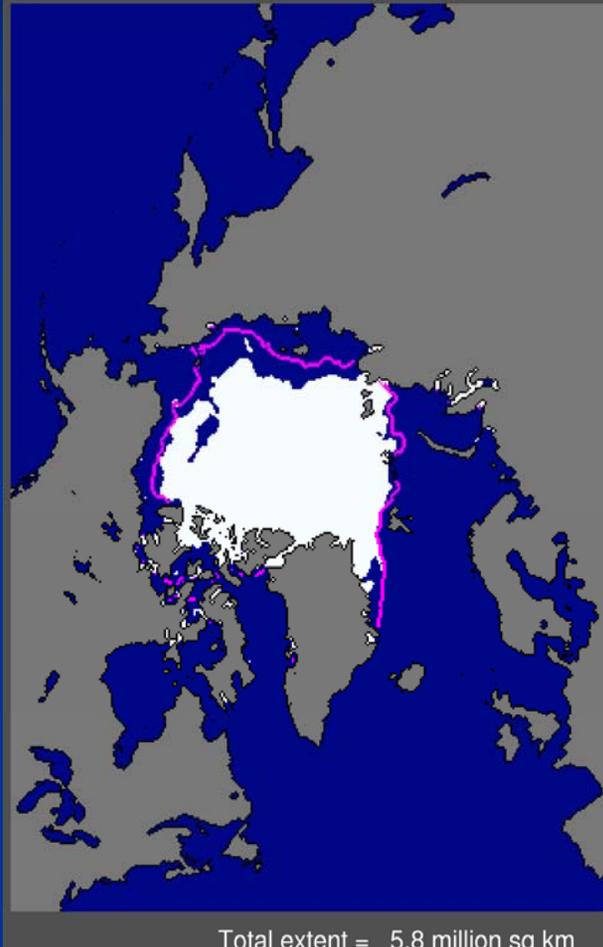
PIOMAS



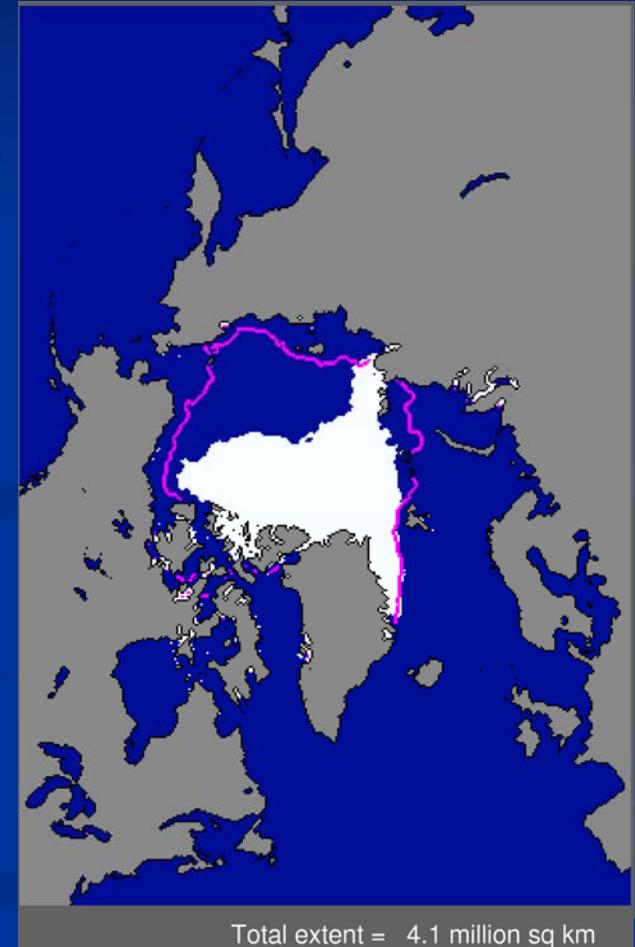
Minimum Sea Ice Extent



2005

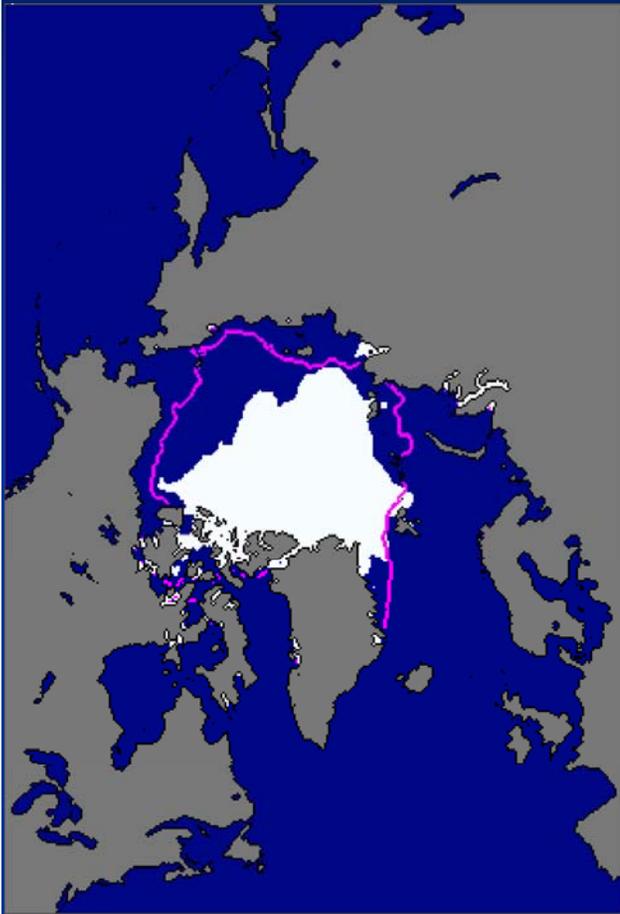


2006



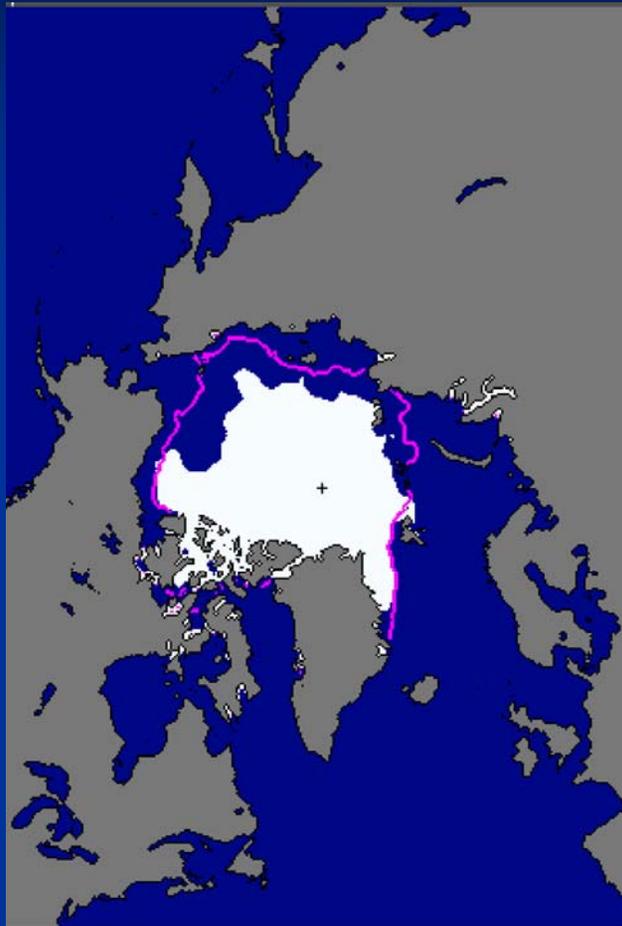
2007

Minimum Sea Ice Extent



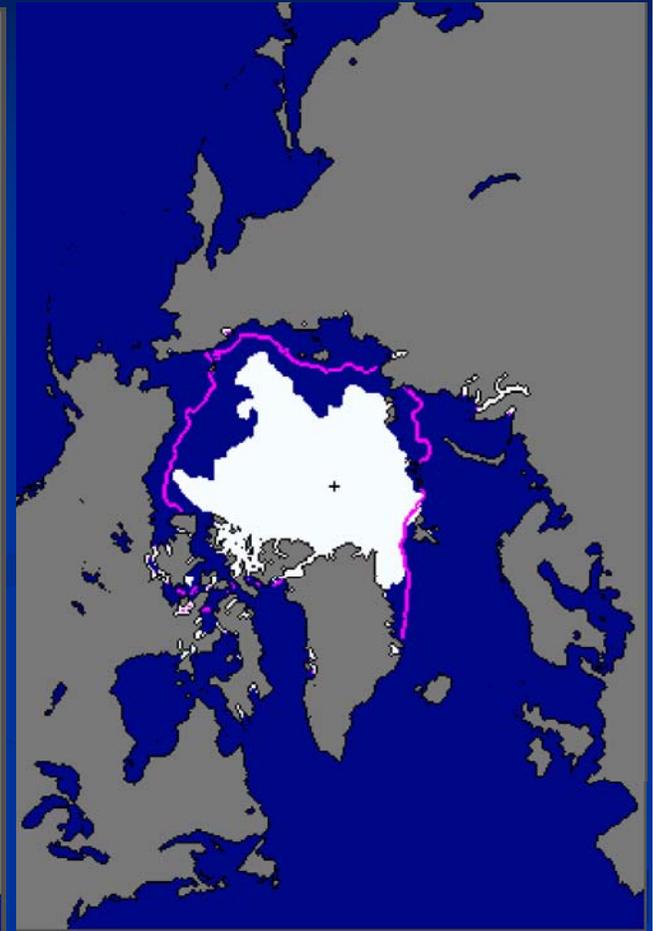
Total extent = 4.7 million sq km

2008



Total extent = 5.4 million sq km

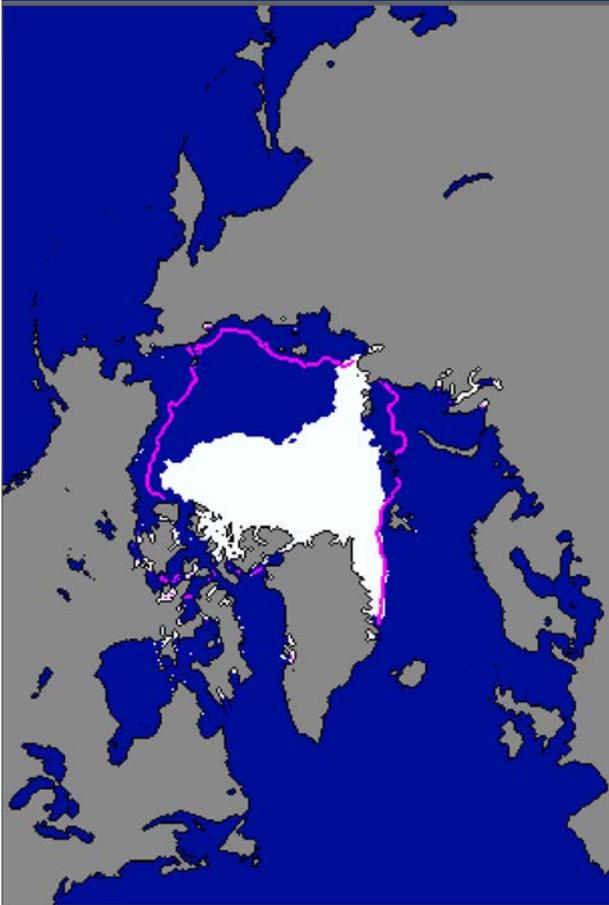
2009



Total extent = 4.9 million sq km

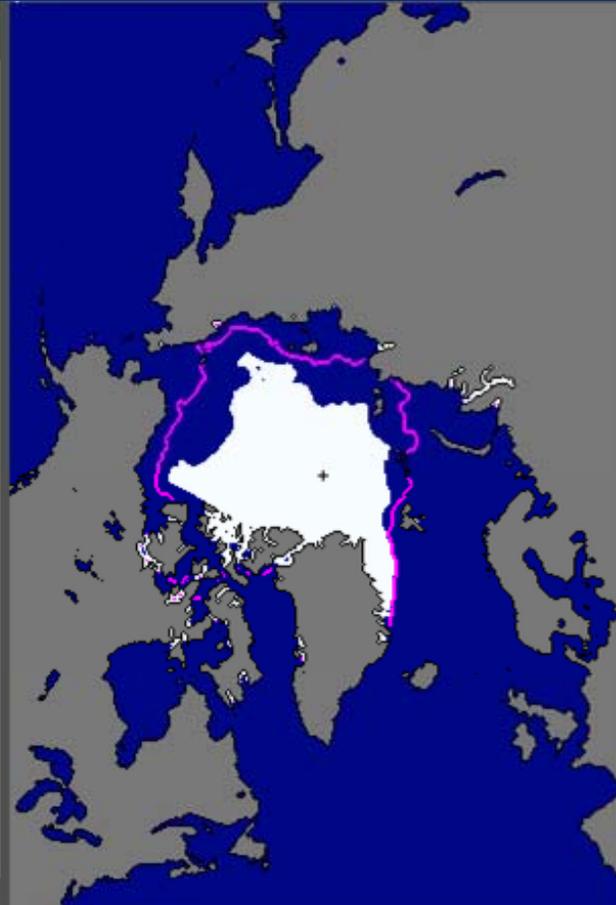
2010

Minimum Sea Ice Extent



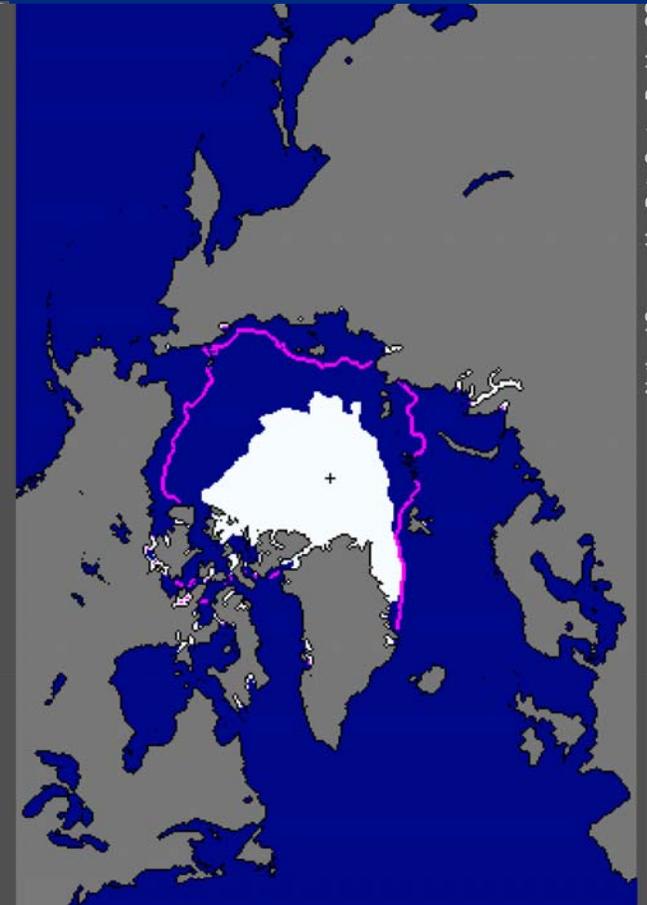
Total extent = 4.1 million sq km

2007



Total extent = 4.6 million sq km

2011



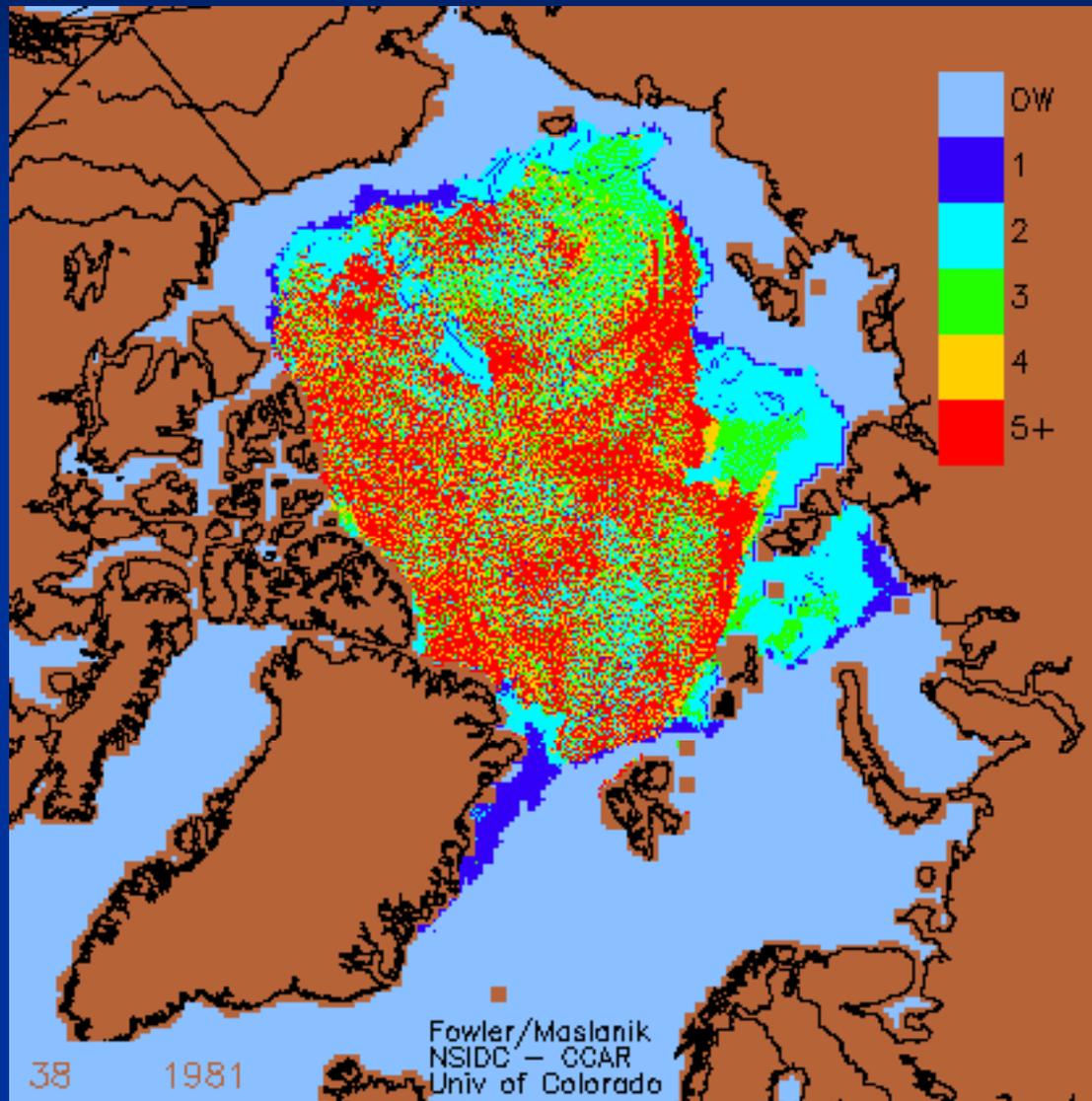
Total extent = 3.6 million sq km

2012

Mean Sea Ice Circulation



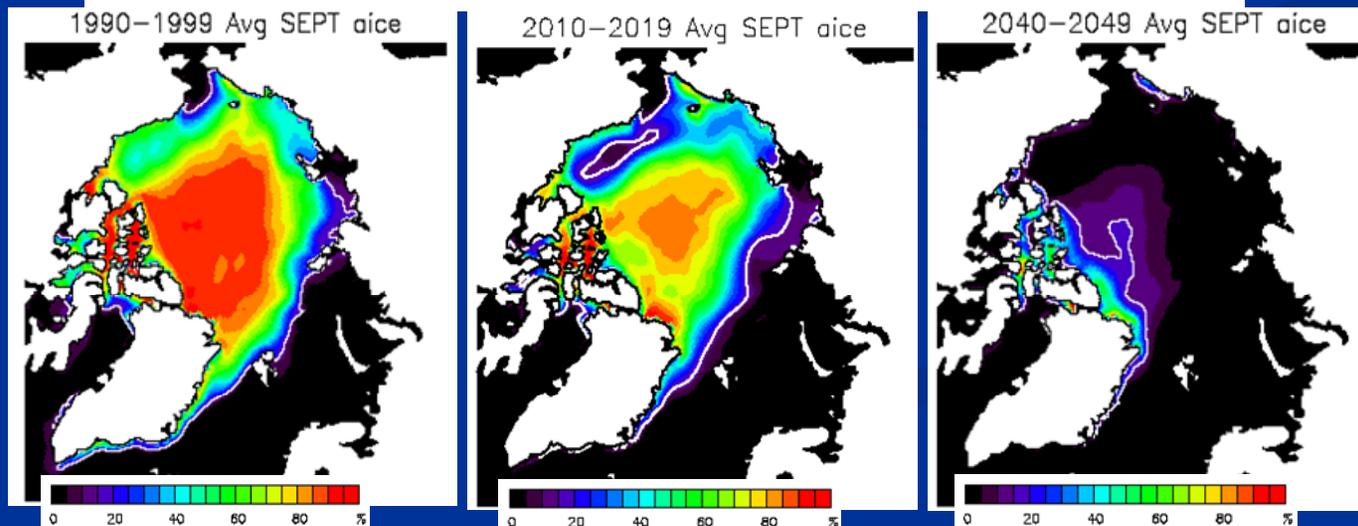
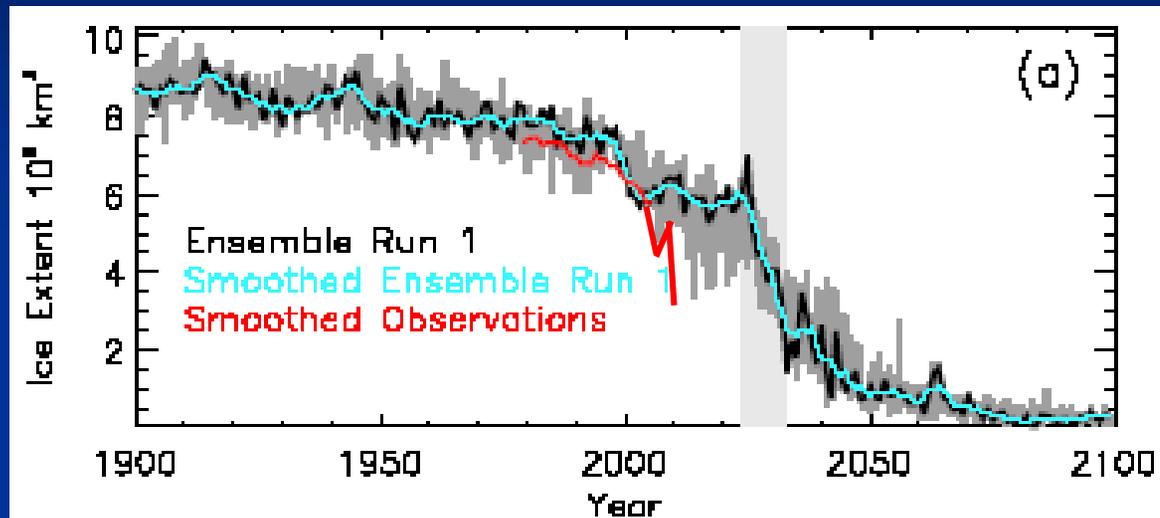
Ice Age Animation



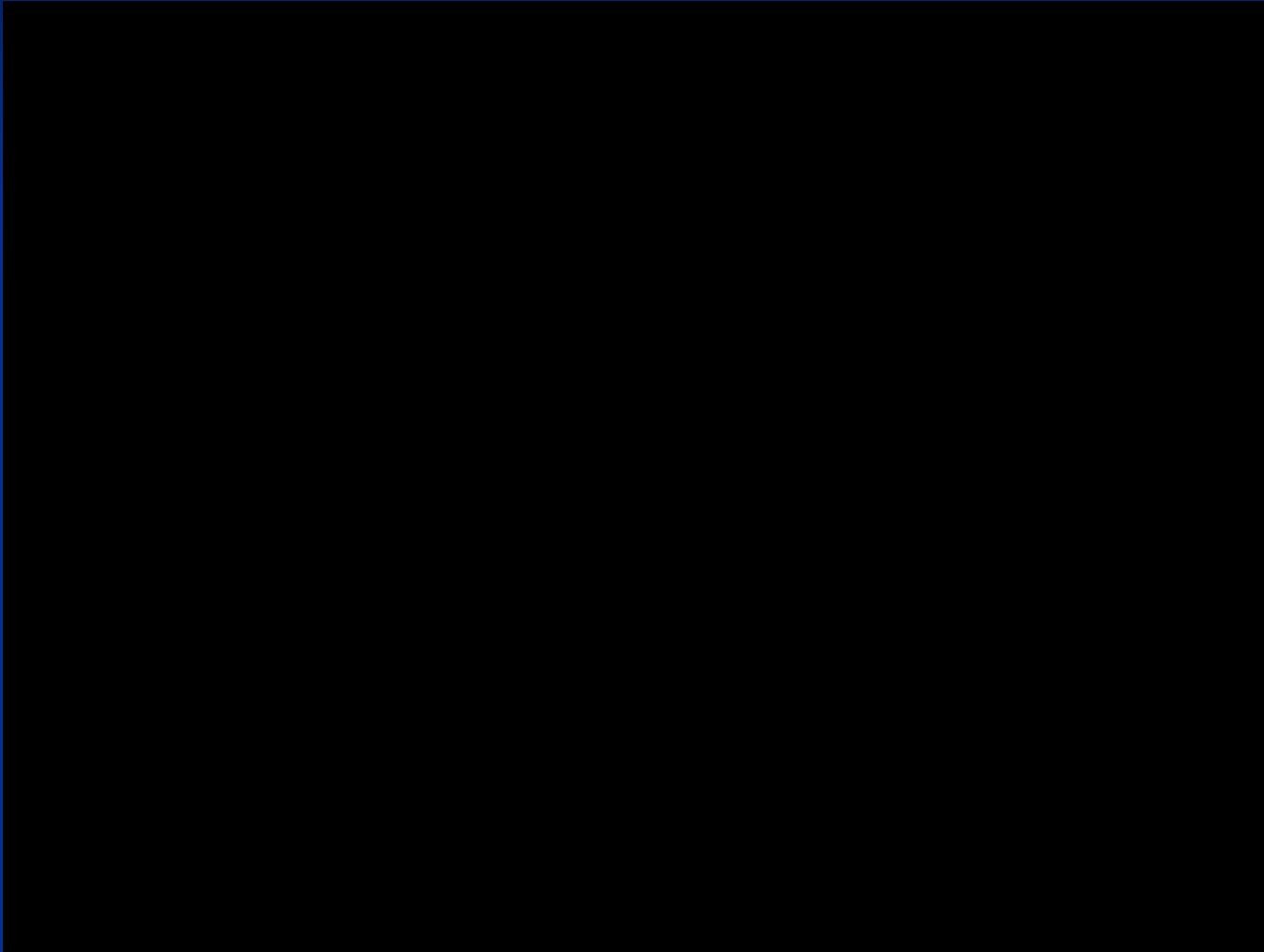
Chuck Fowler, CSU

Simulated Sea Ice Extent

Community Climate System Model – Version 3

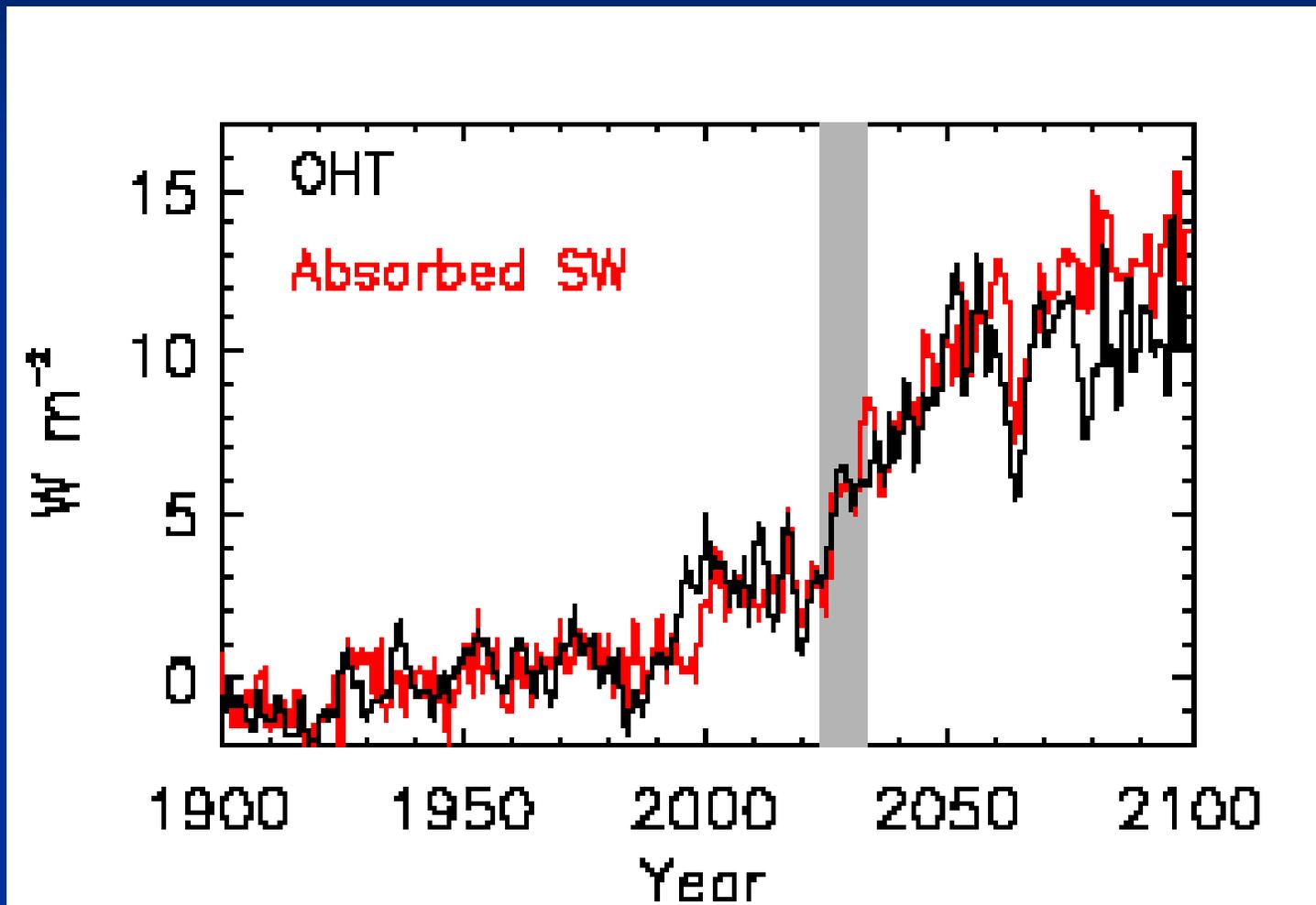


Minimum Ice Extent Animation

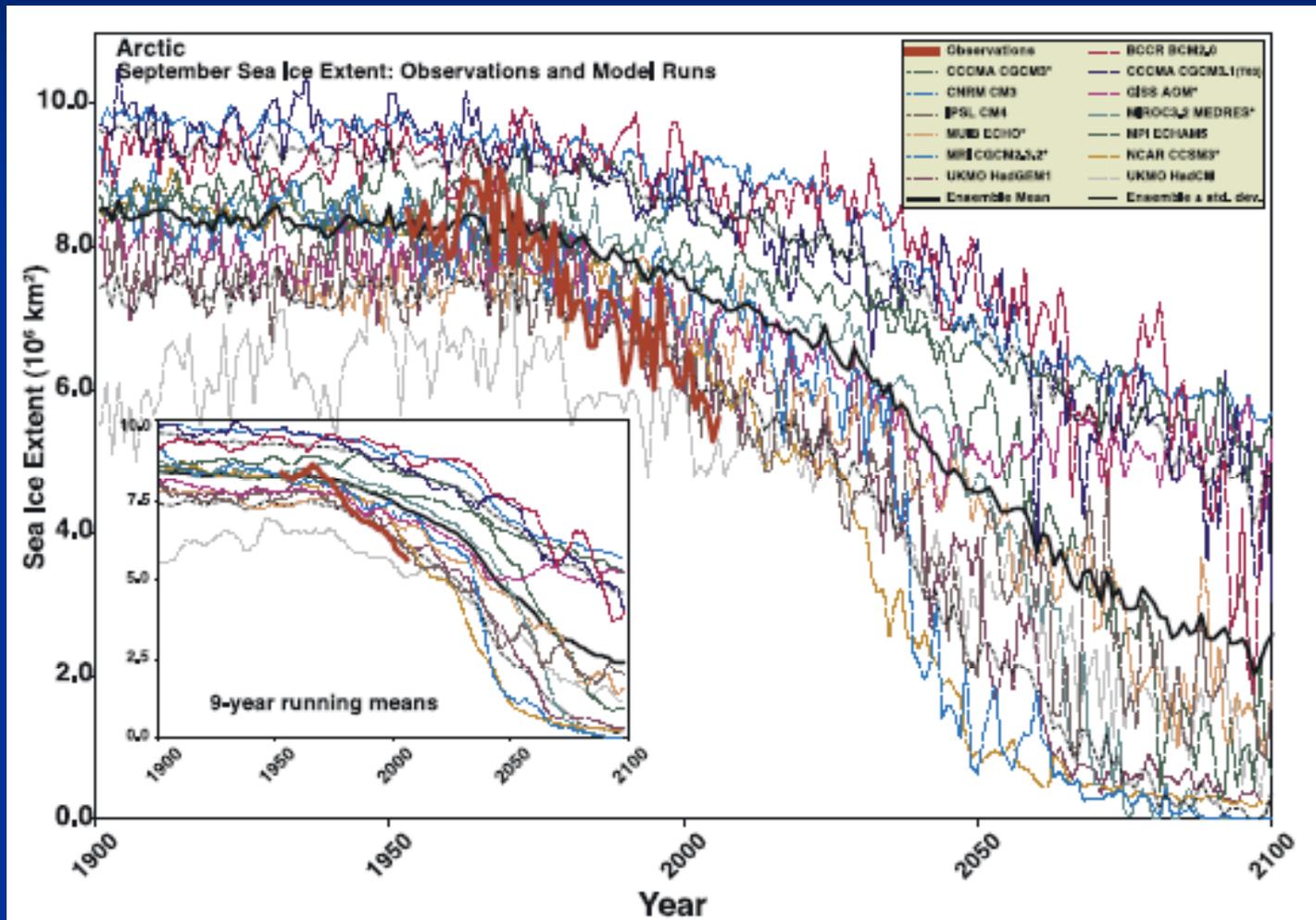


Holland Bitz Tremblay, 2006

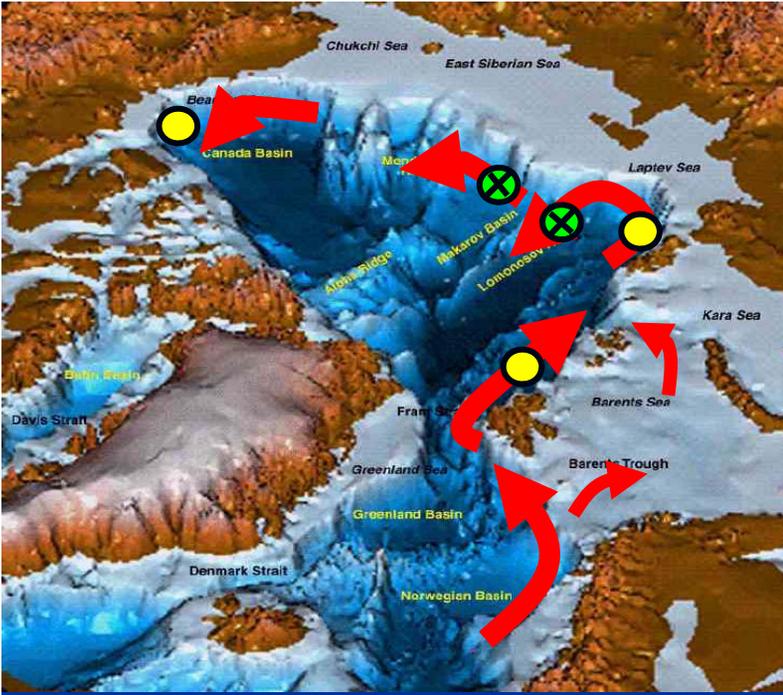
Atmosphere Feedback



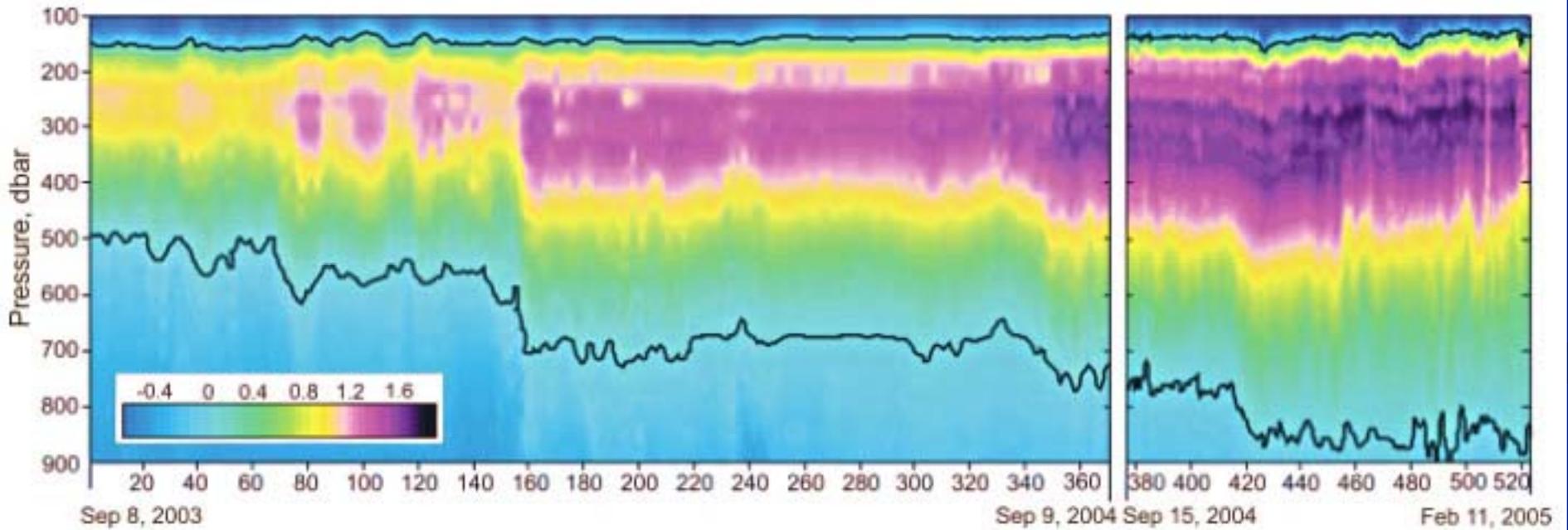
All models underestimate the present sea ice extent decline



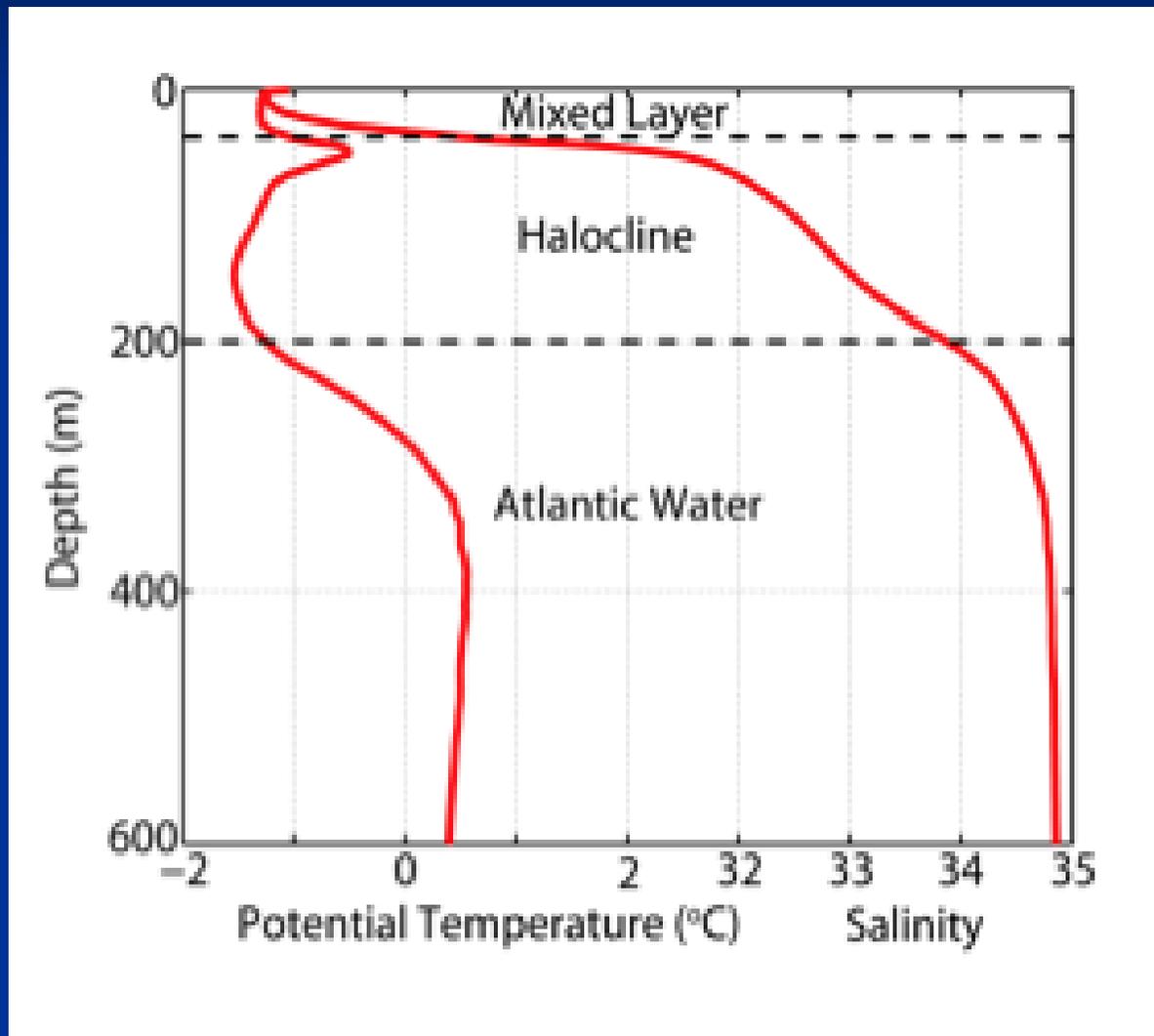
Stroeve et al 2007



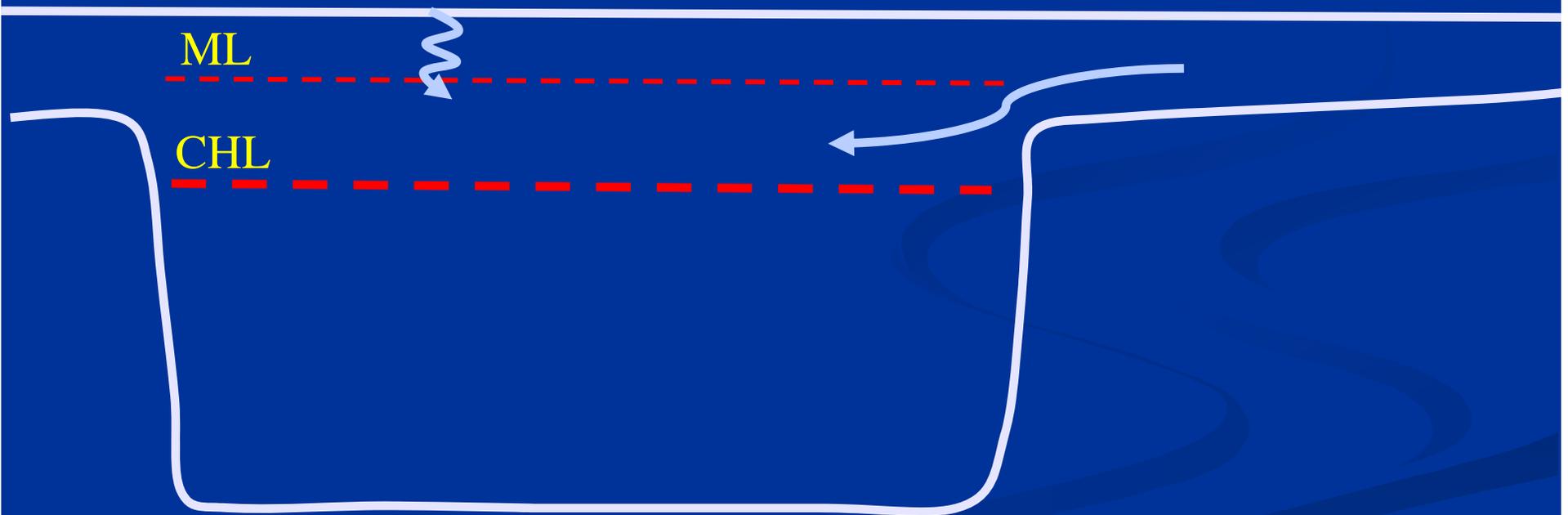
Atlantic Layer Temperature NABOS



Cold Halocline Layer

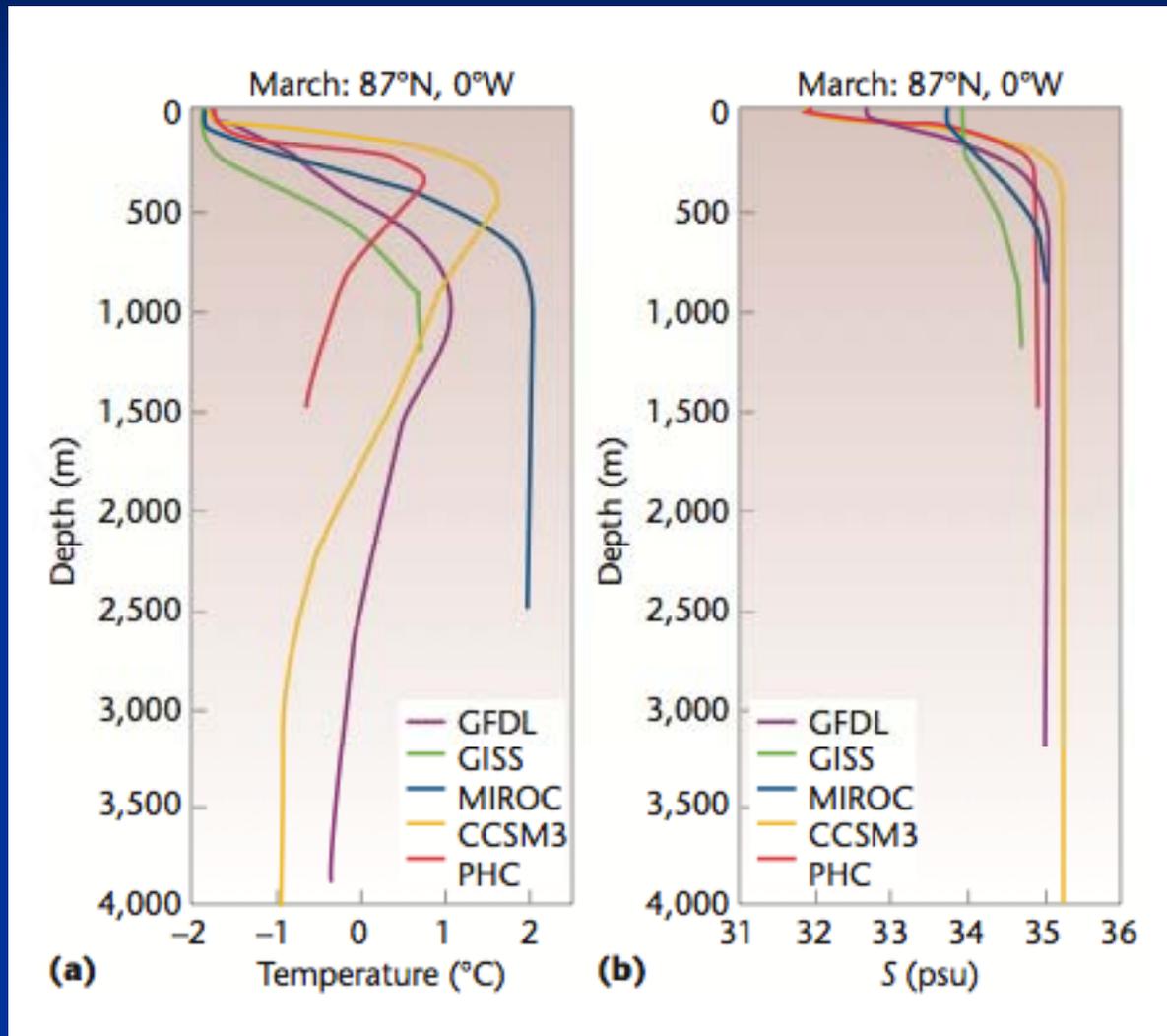


Cold Halocline Formation



Aagaard and Carmack
Rudel et al

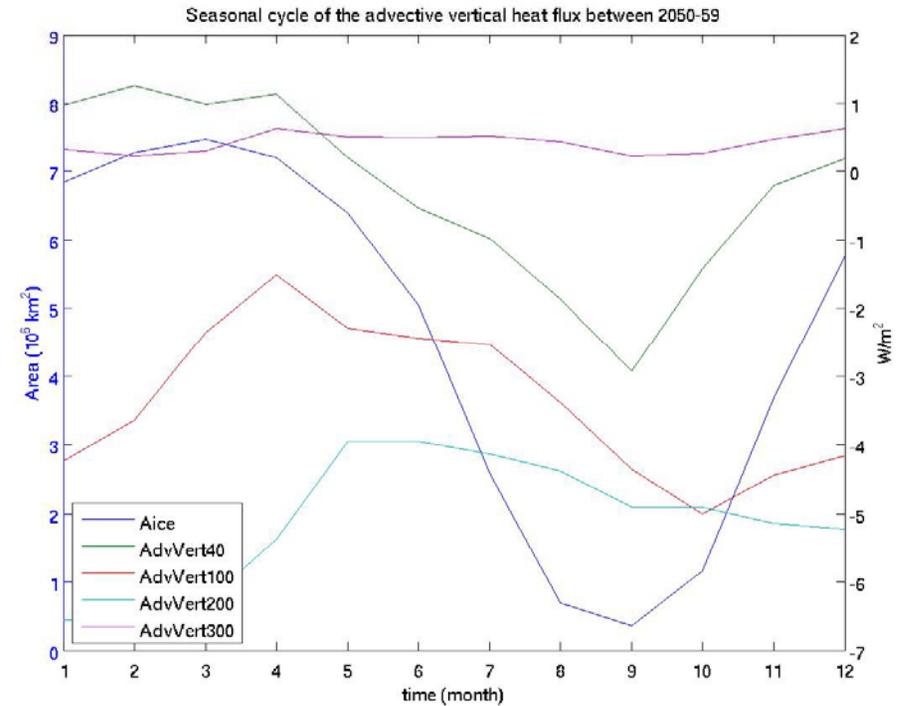
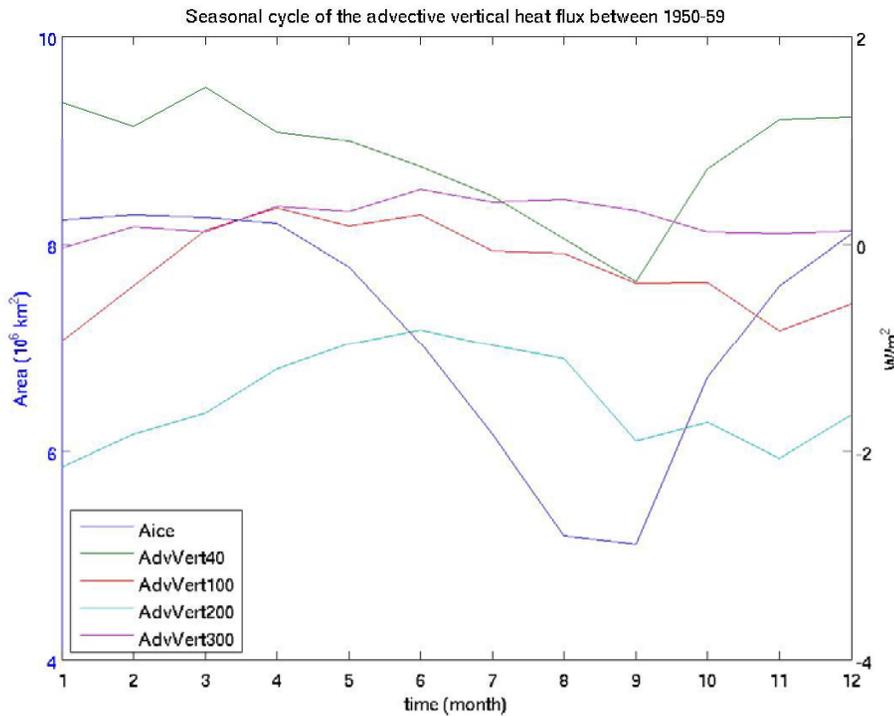
CCSM3 vs Obs



Advective Flux Seasonal Cycle

1950-1959

2050-2059



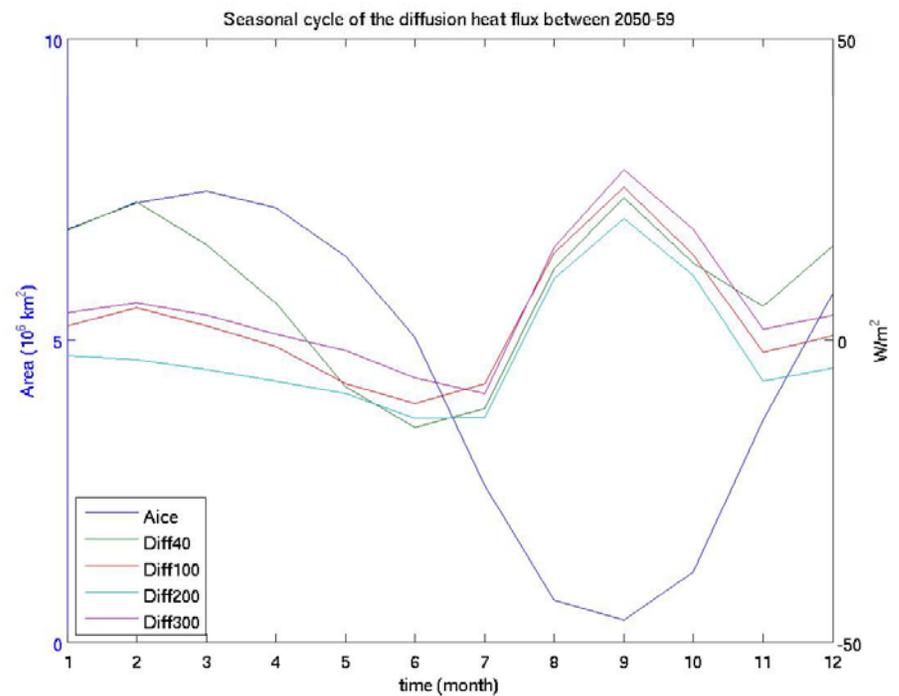
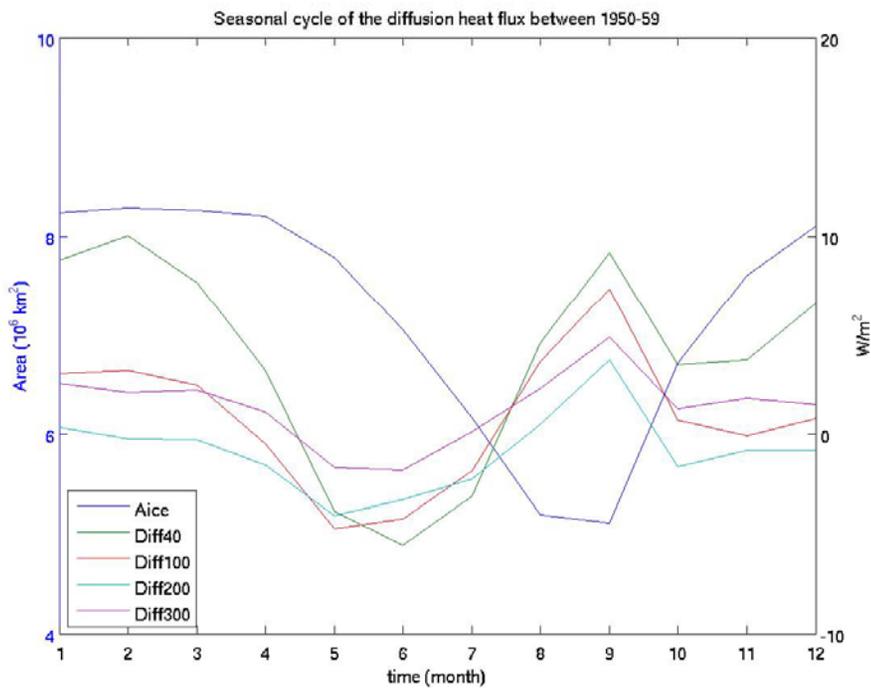
CCSM3

Diffusive Flux

Seasonal Cycle

1950-1959

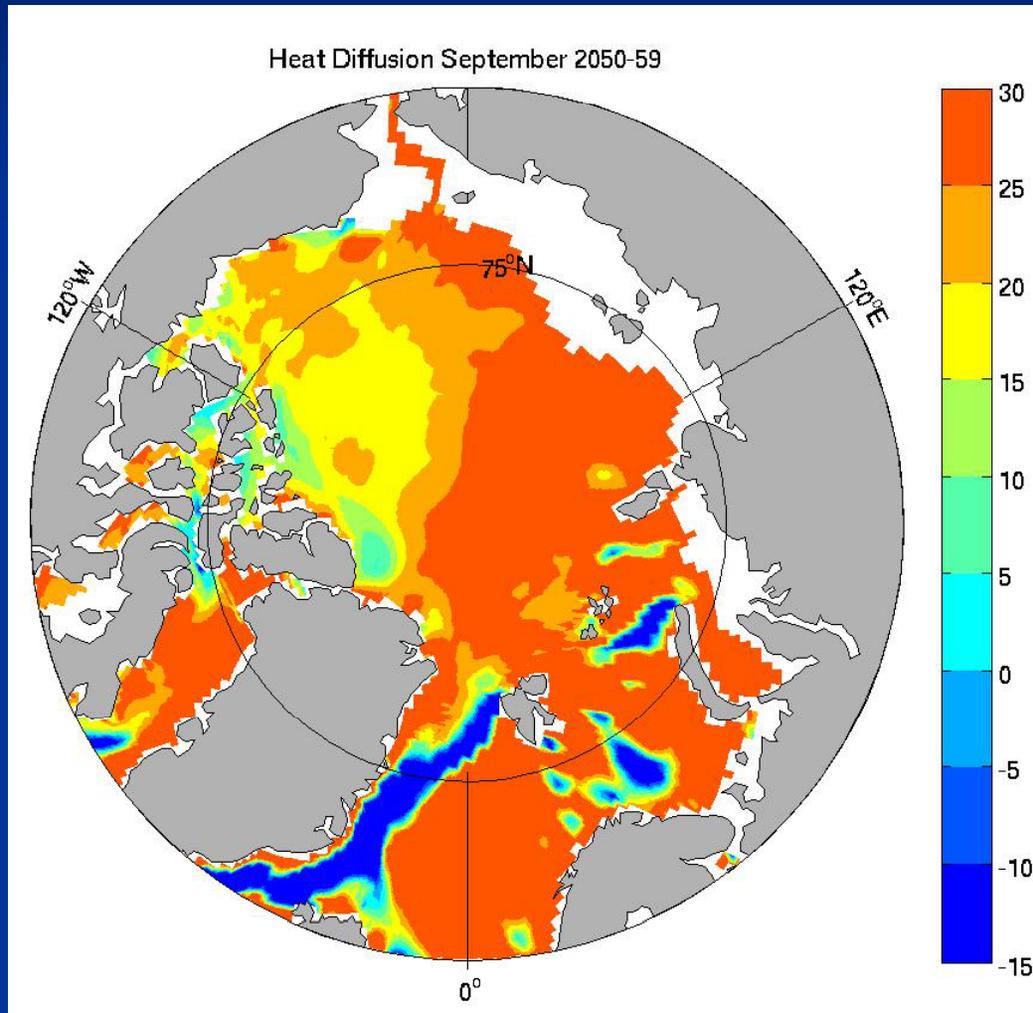
2050-2059



CCSM3

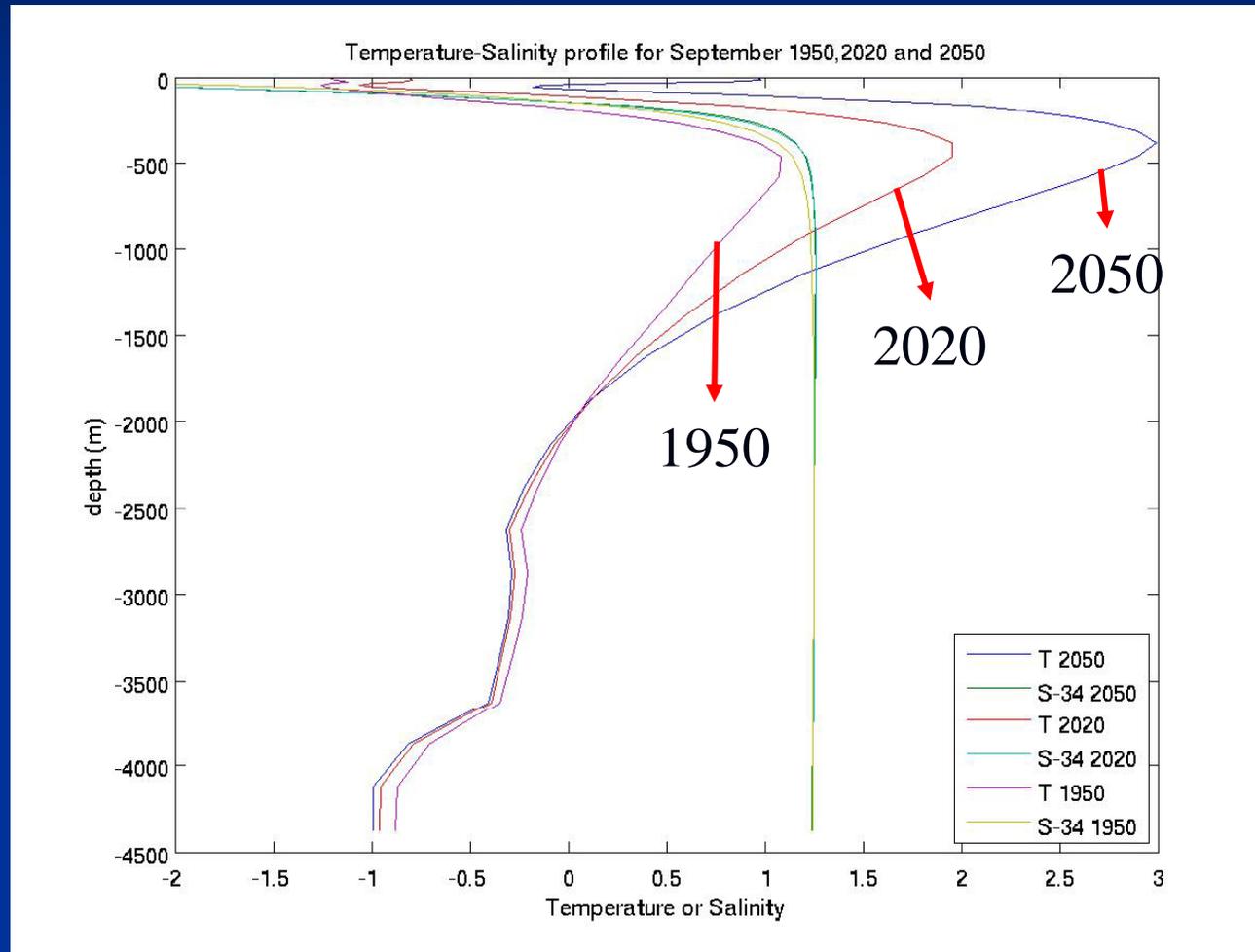
September Diffusive Flux

@40 m



T-S vertical profiles

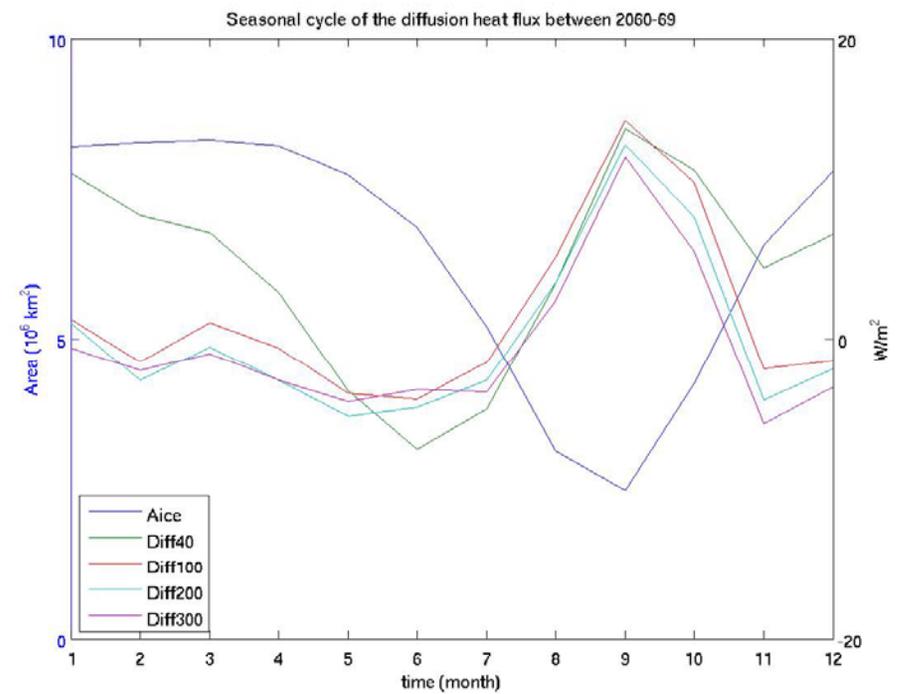
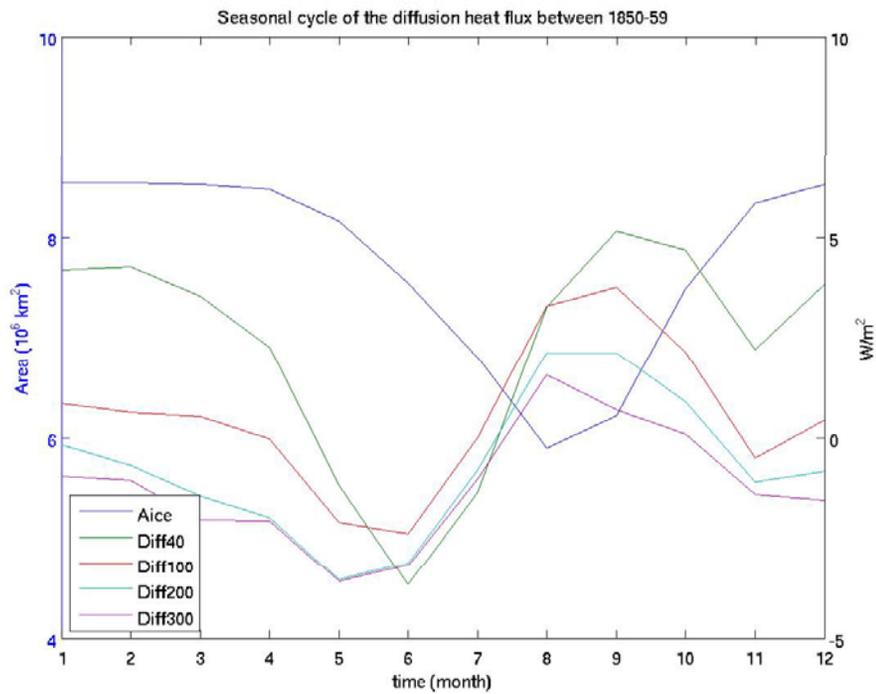
September



Diffusive Flux Seasonal Cycle

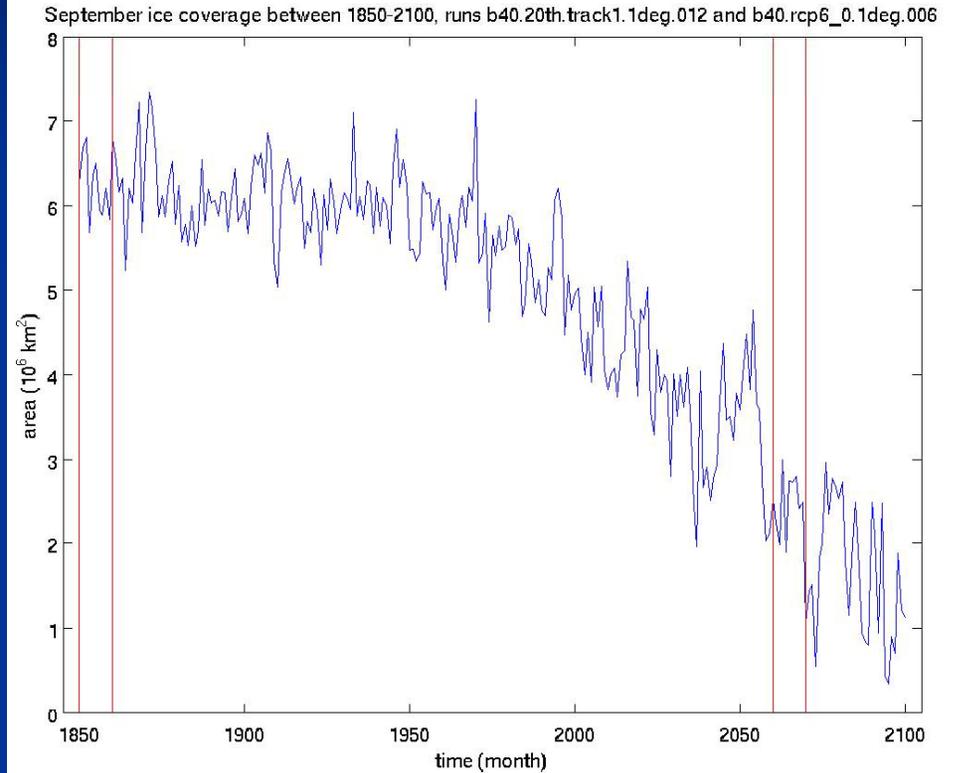
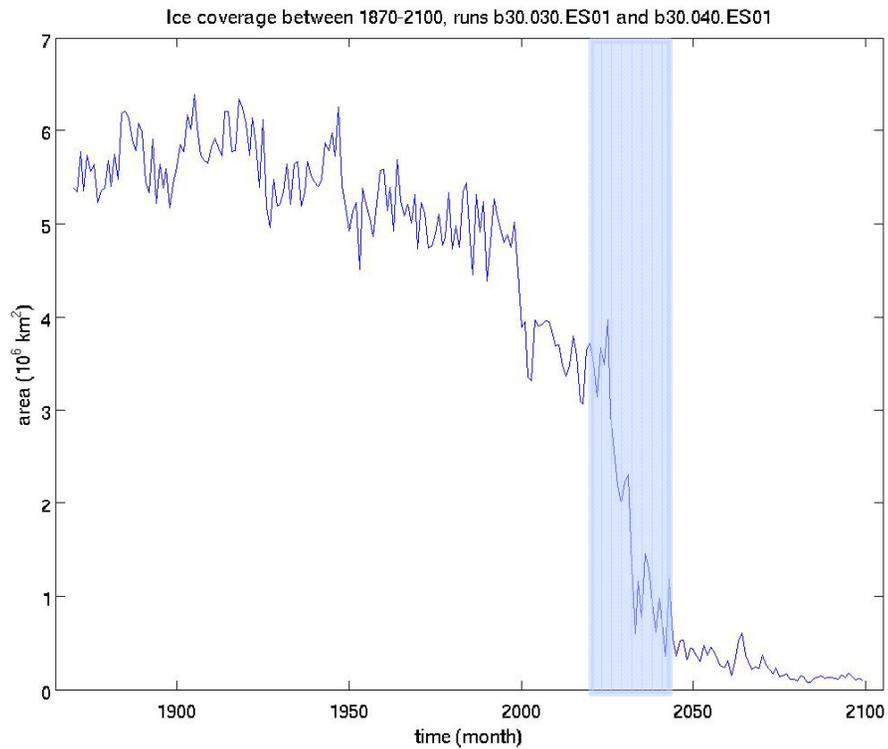
1850-1859

2060-2069



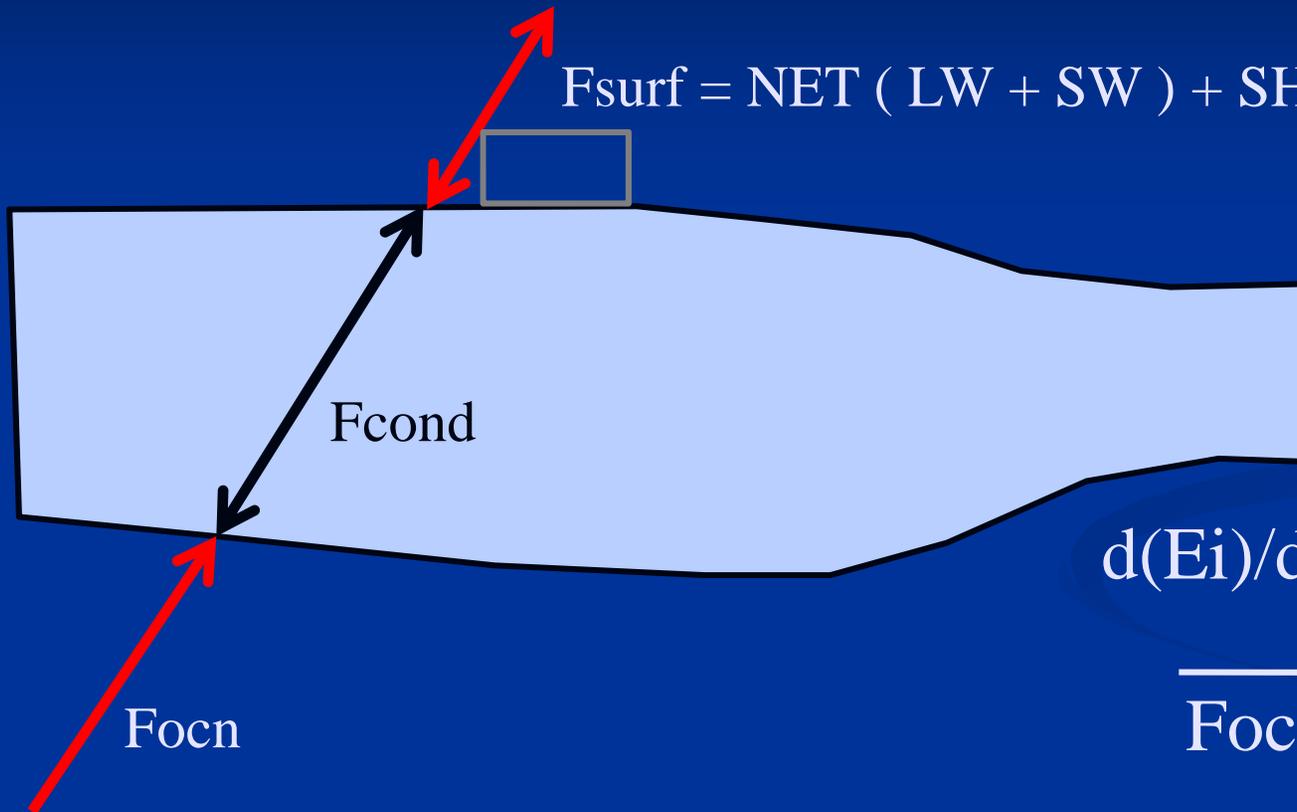
CCSM4

Sea Ice Extent



CCSM4

Vertical Ocean Heat Fluxes



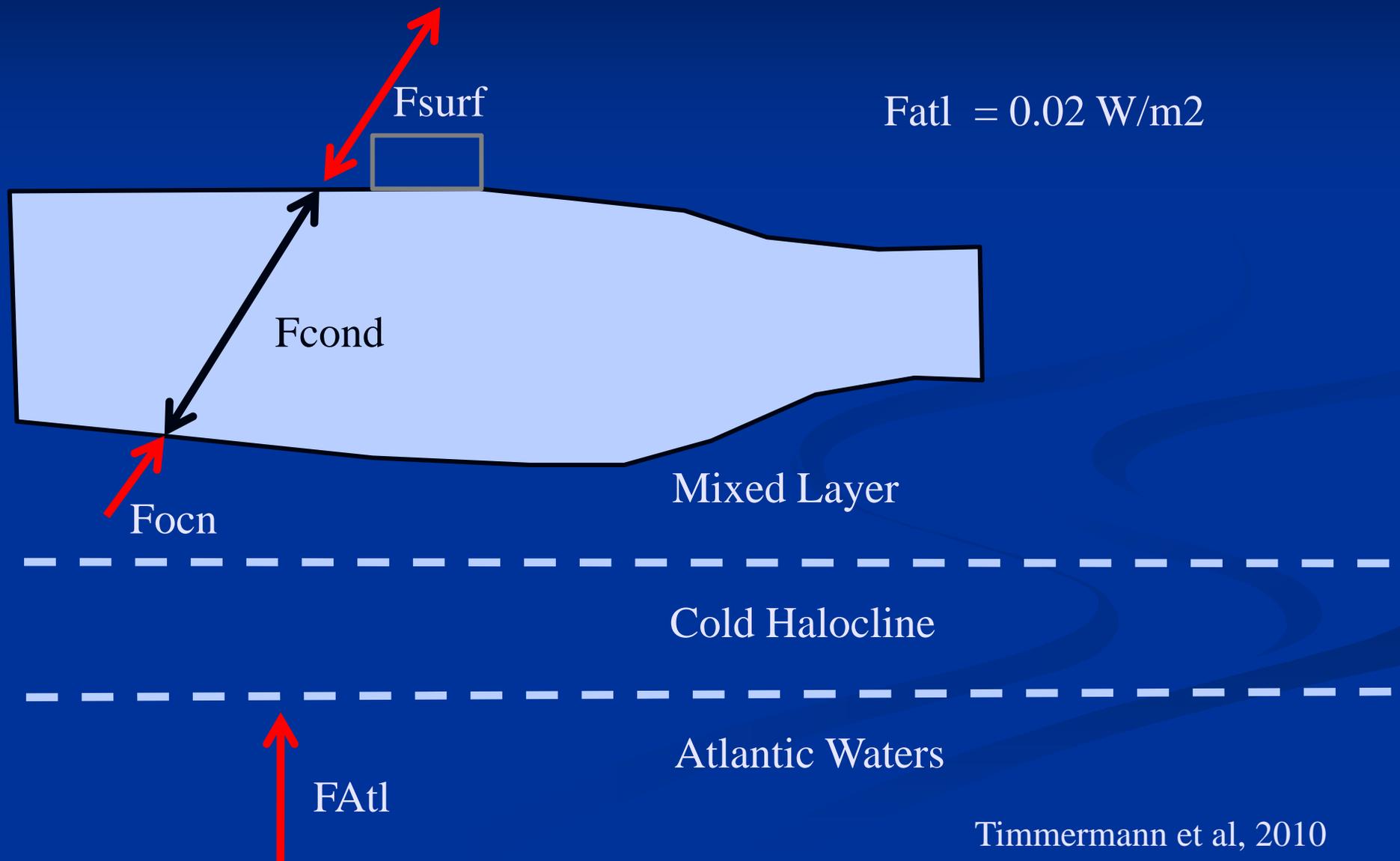
$$F_{surf} = NET (LW + SW) + SH + LH$$

$$\frac{d(E_i)/dt = F_{ocn} + F_{surf}$$

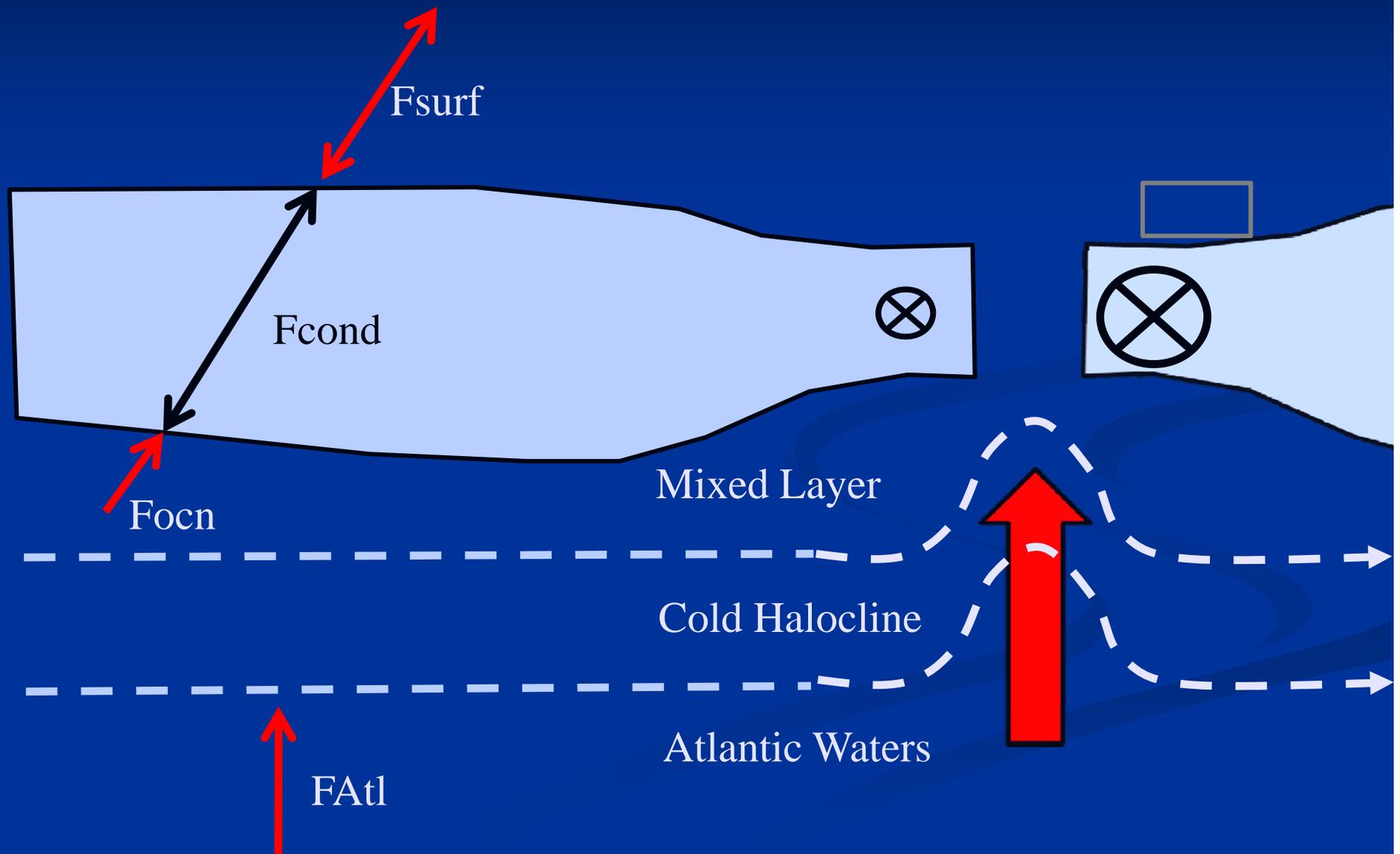
$$\overline{F_{ocn}} = 2 - 3 \text{ W/m}^2$$

$$F_{ocn} = 2 - 40 \text{ W/m}^2$$

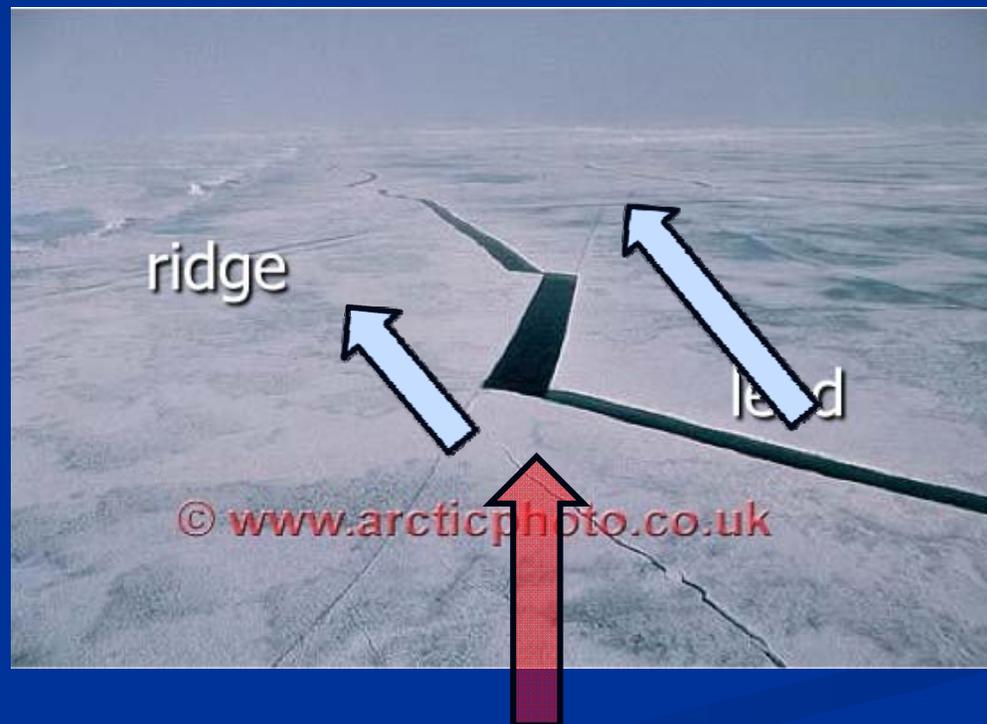
Vertical Ocean Heat Fluxes



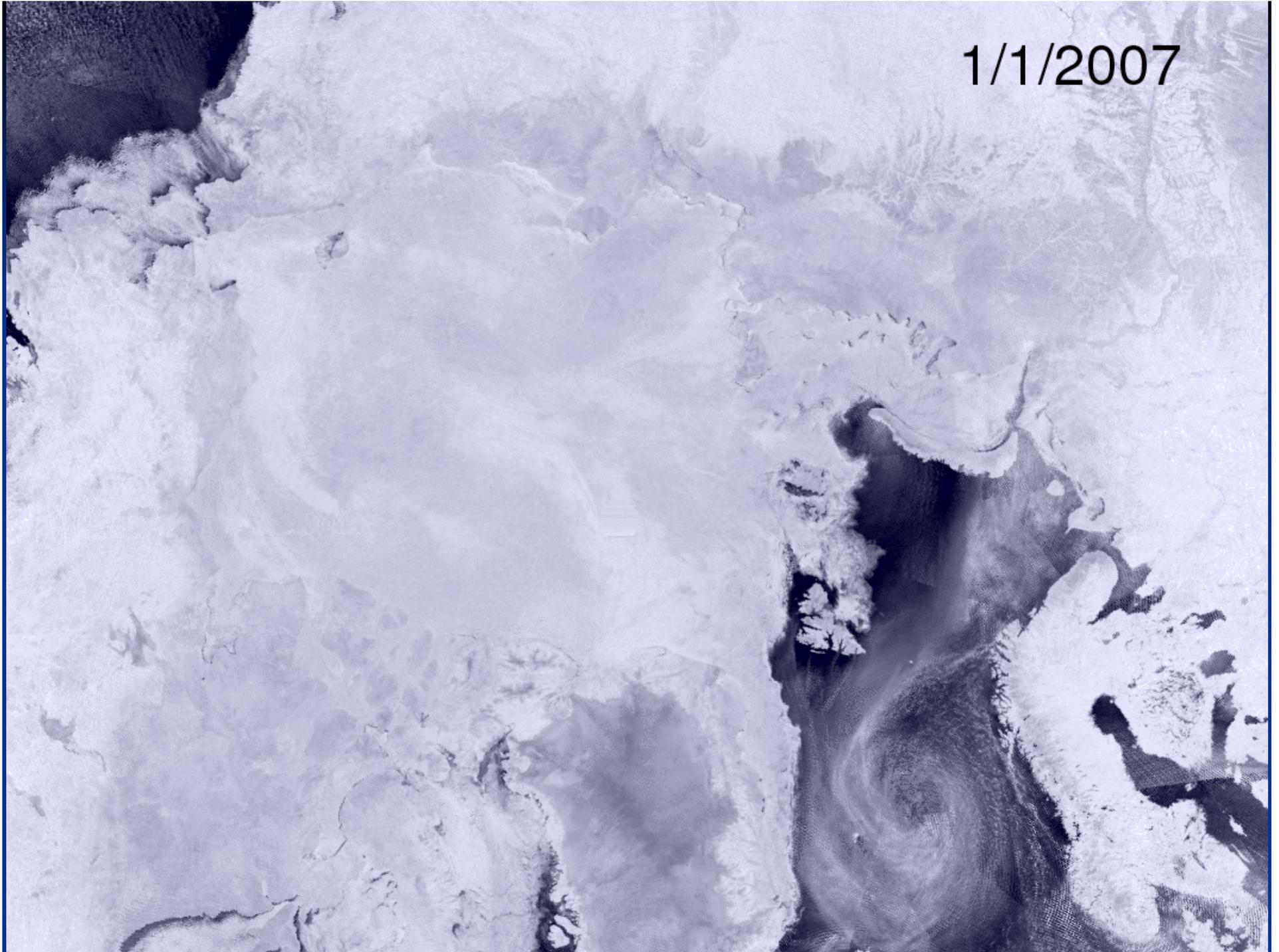
Vertical Ocean Heat Fluxes



Shear, Divergence and Upwelling

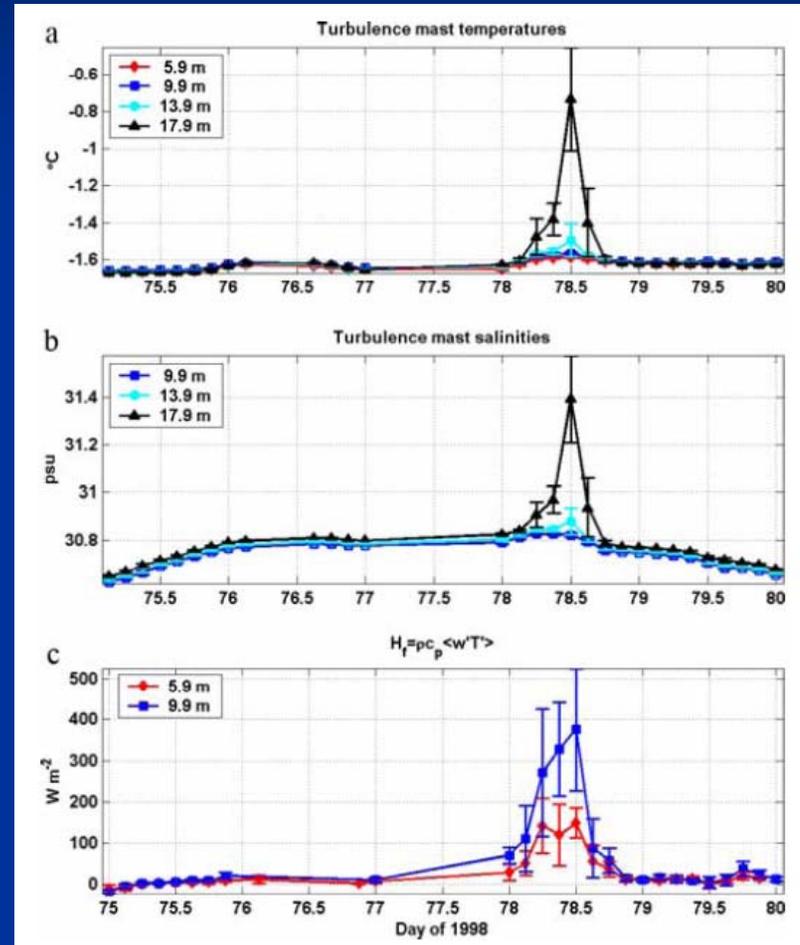
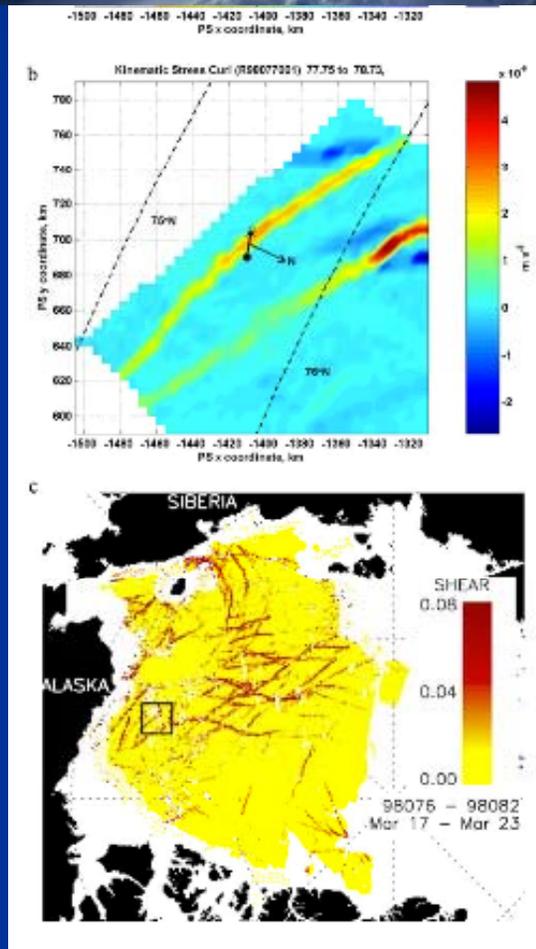


1/1/2007





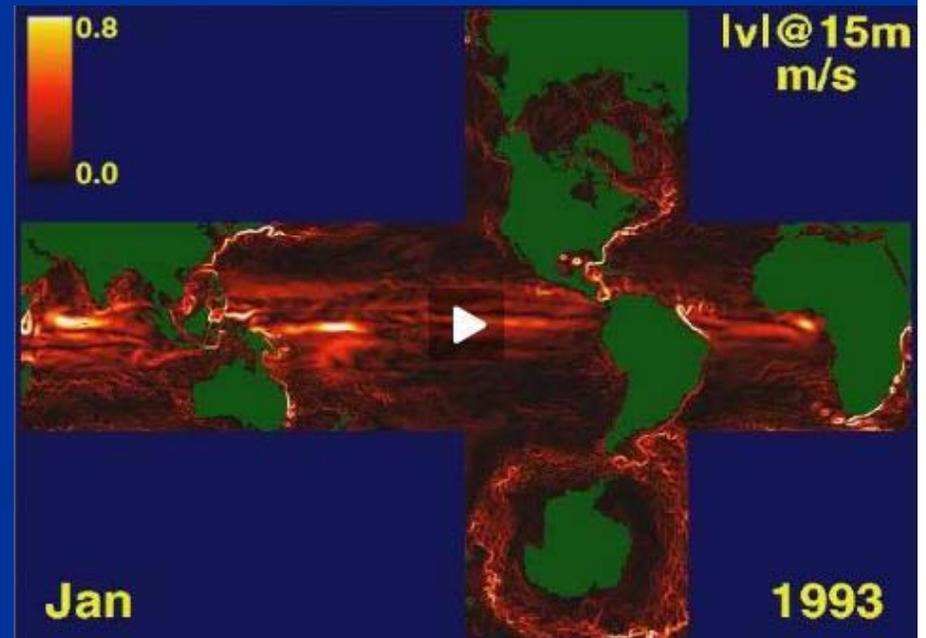
Vertical Ocean Heat flux



McPhee et al, GRL, 2005

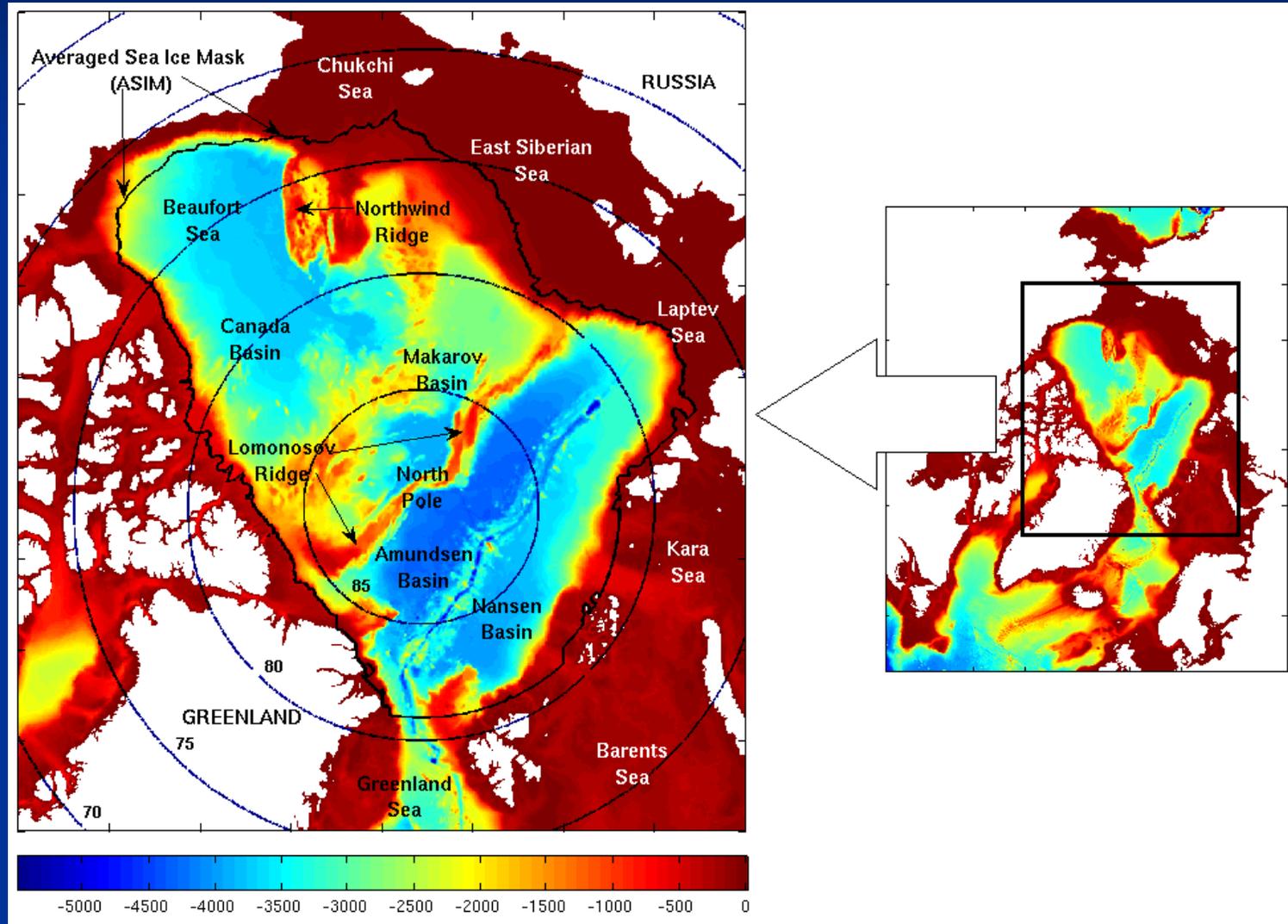
MITgcm

- Cube-Sphere – avoid convergence of the meridian at the pole
- Global and Regional version of the model
- 4 km resolution
- 50 vertical levels with 10m layers near surface
- VP sea ice model of Hibler (1979)

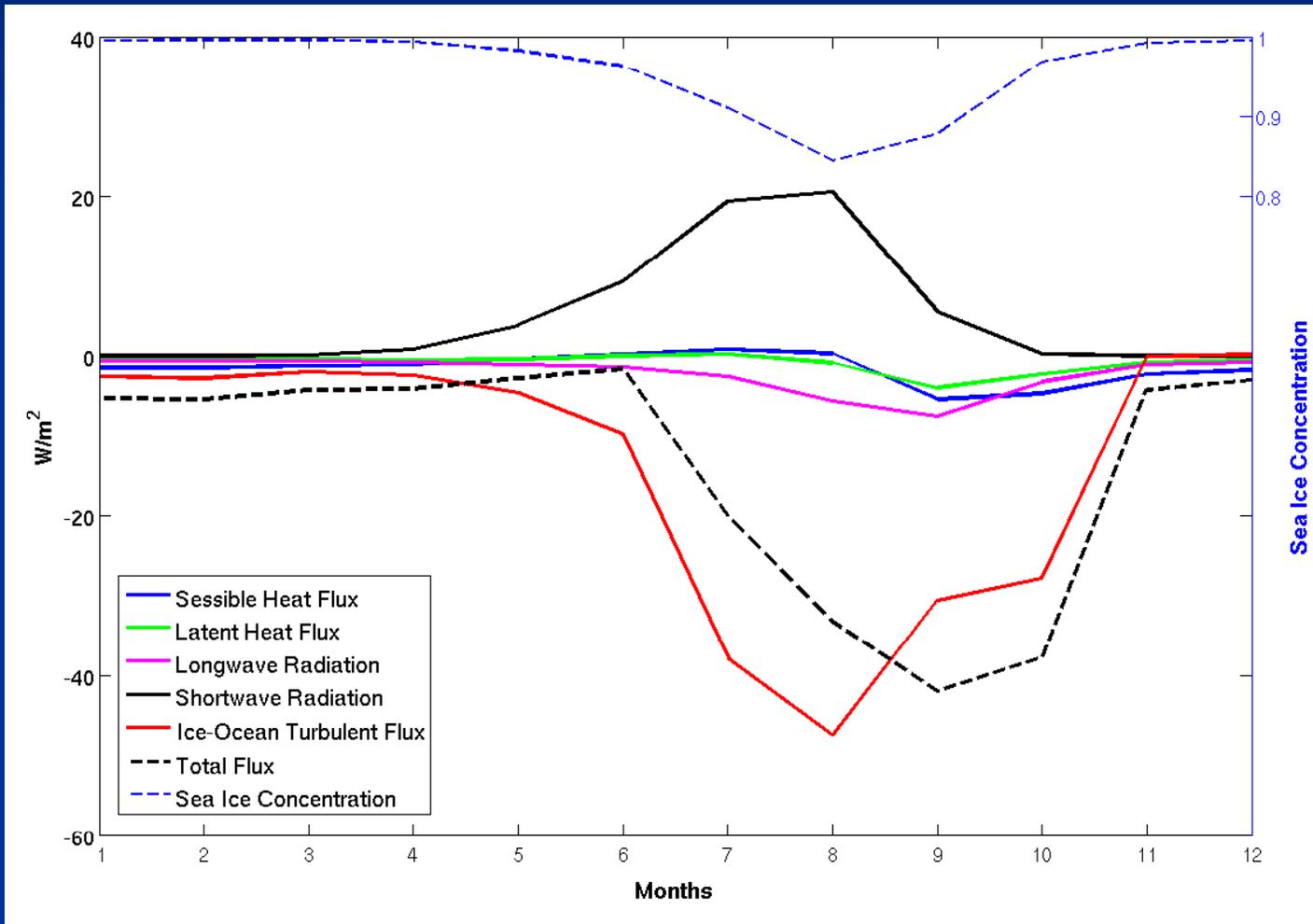


Model Domain

Bathymetry

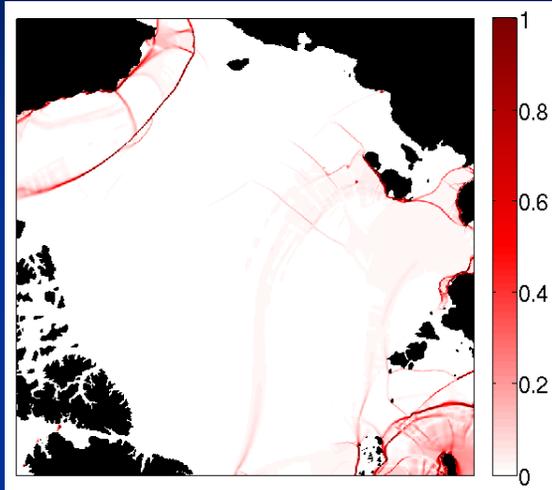


Vertical Heat Fluxes



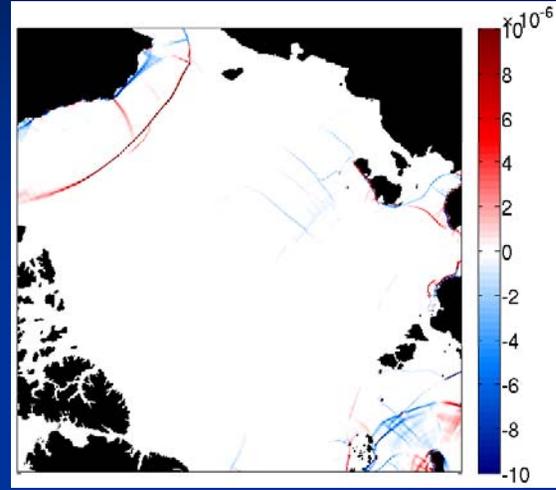
January 5

Shear



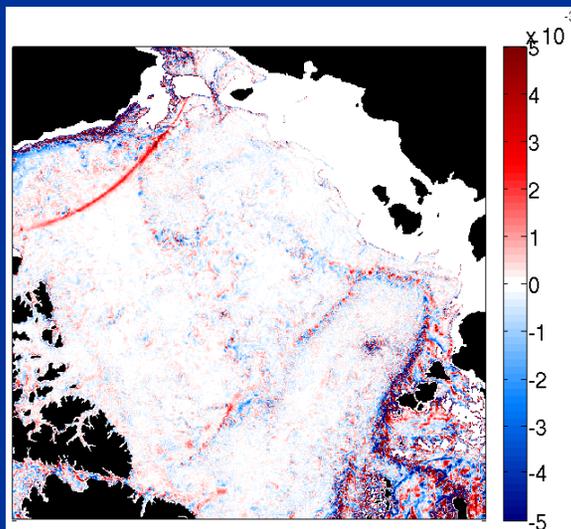
Curl

+



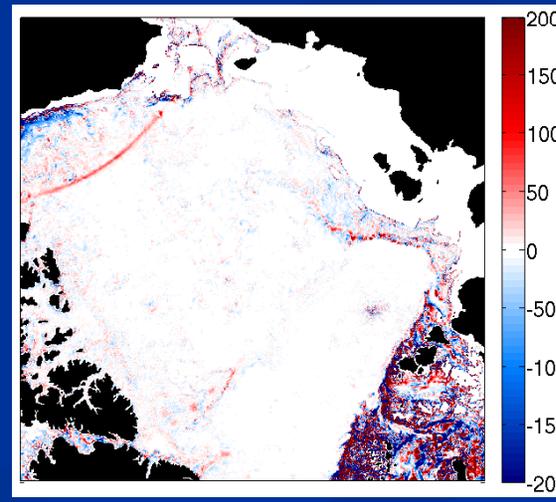
W

+



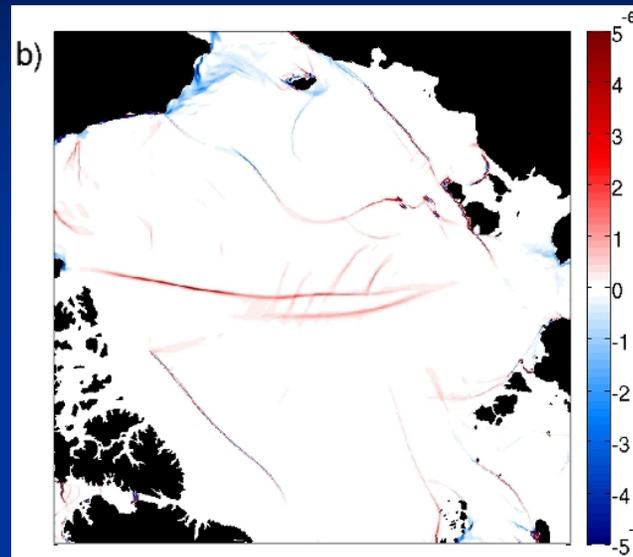
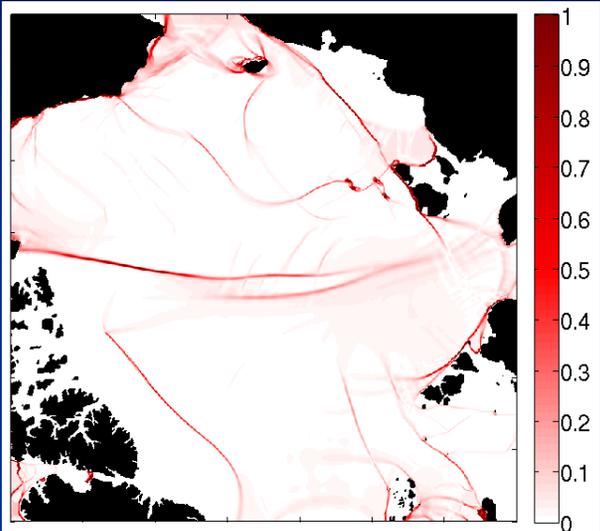
Focn

+



January 7

Shear

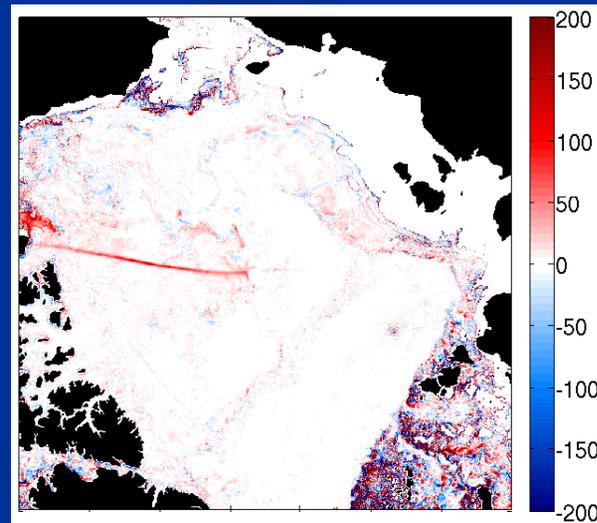
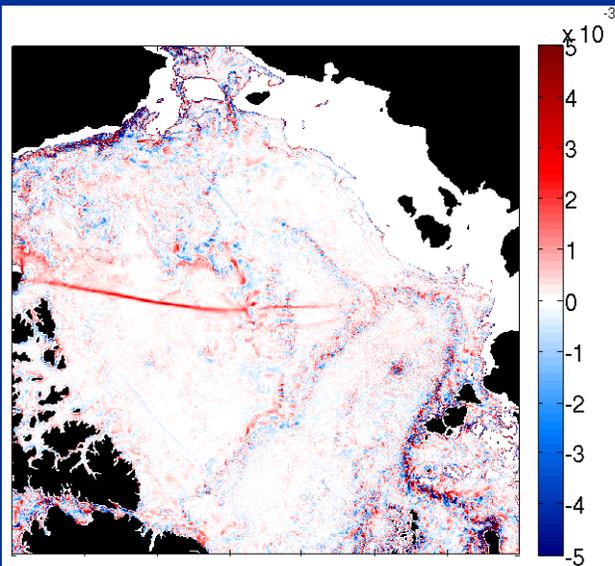


Curl

+

w

+



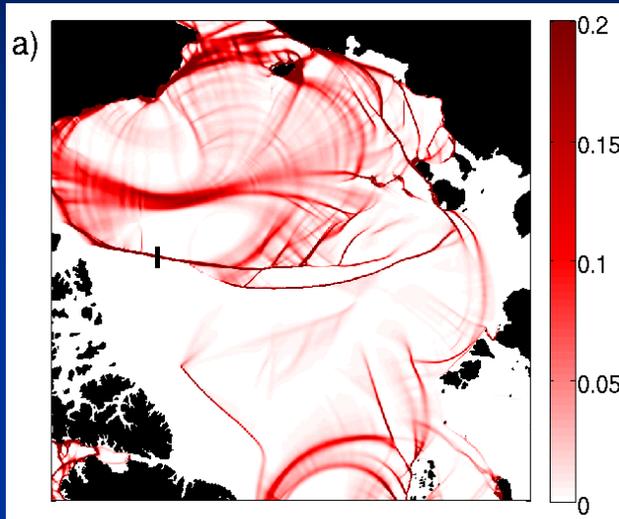
Focn

+

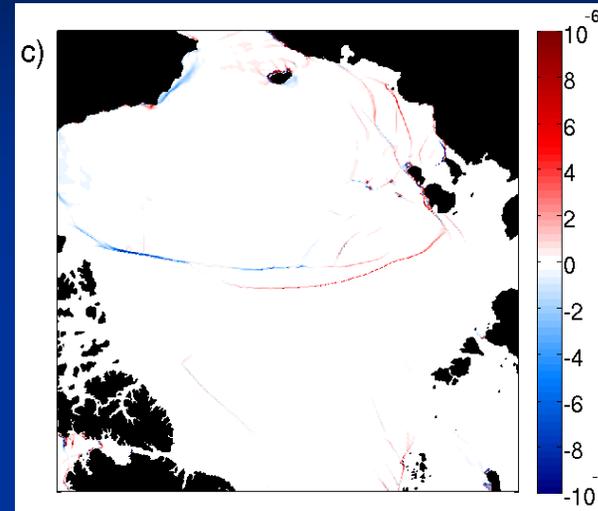
Slavin et al, in prep

January 8

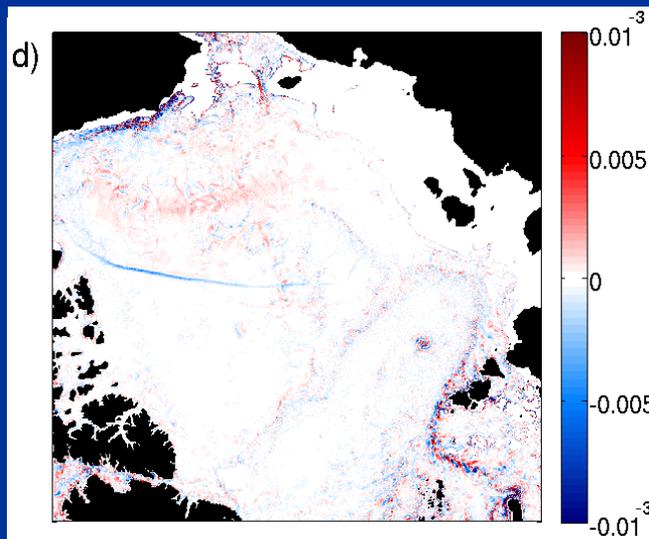
Shear



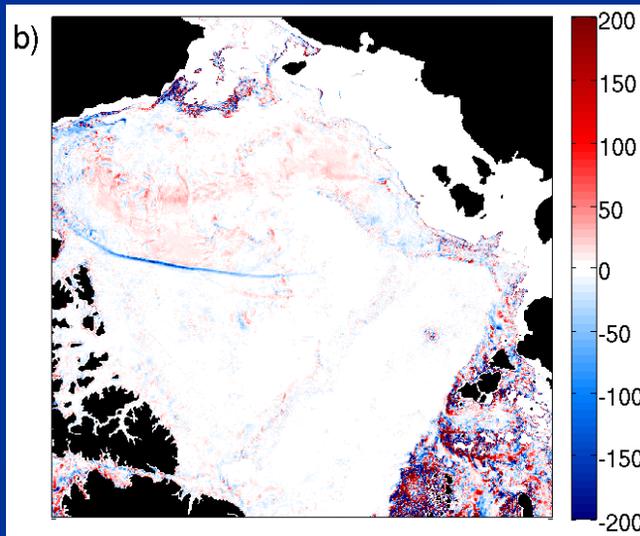
Curl



W



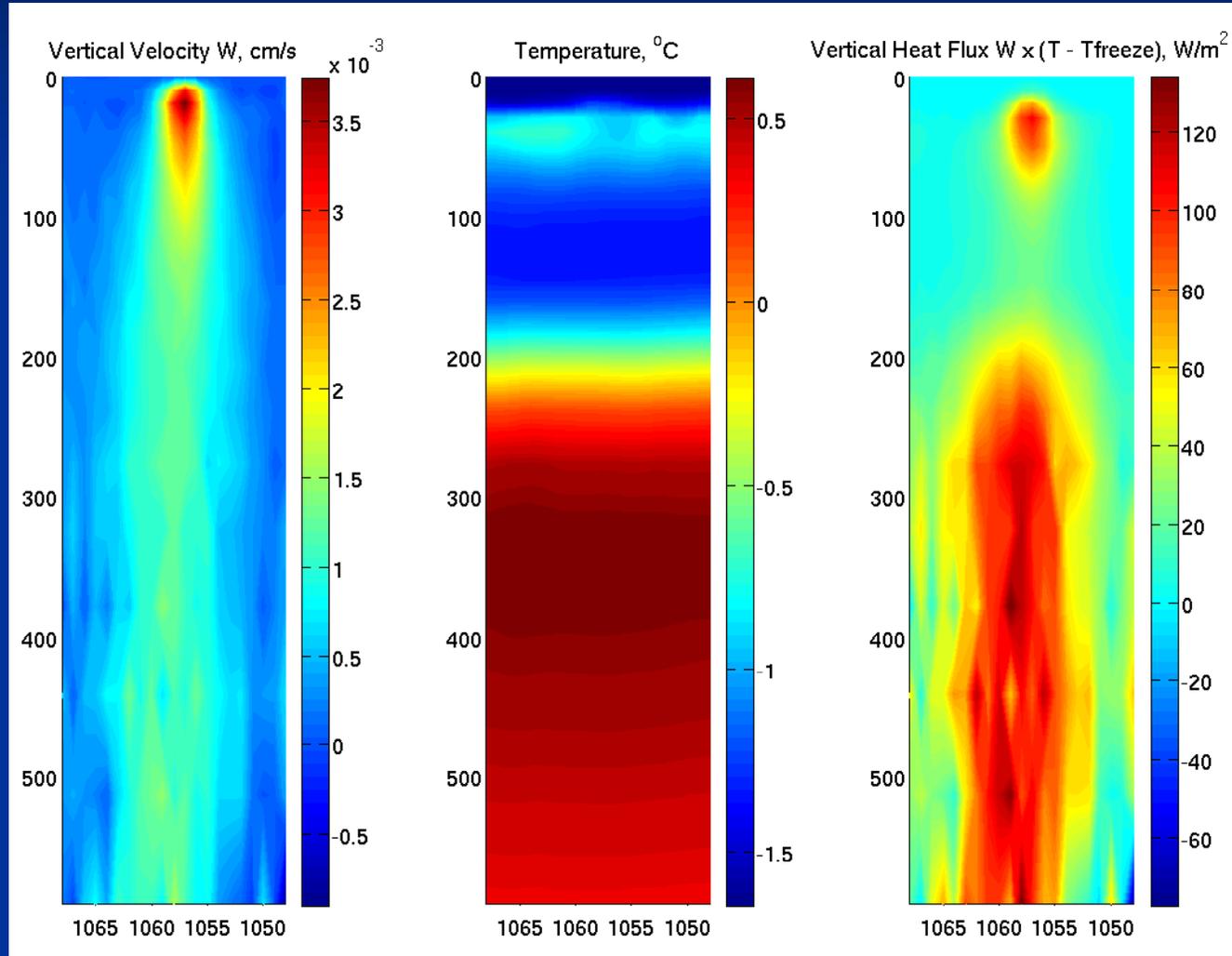
Focn



Vertical Cross Section

~10m/3day

Across Lead

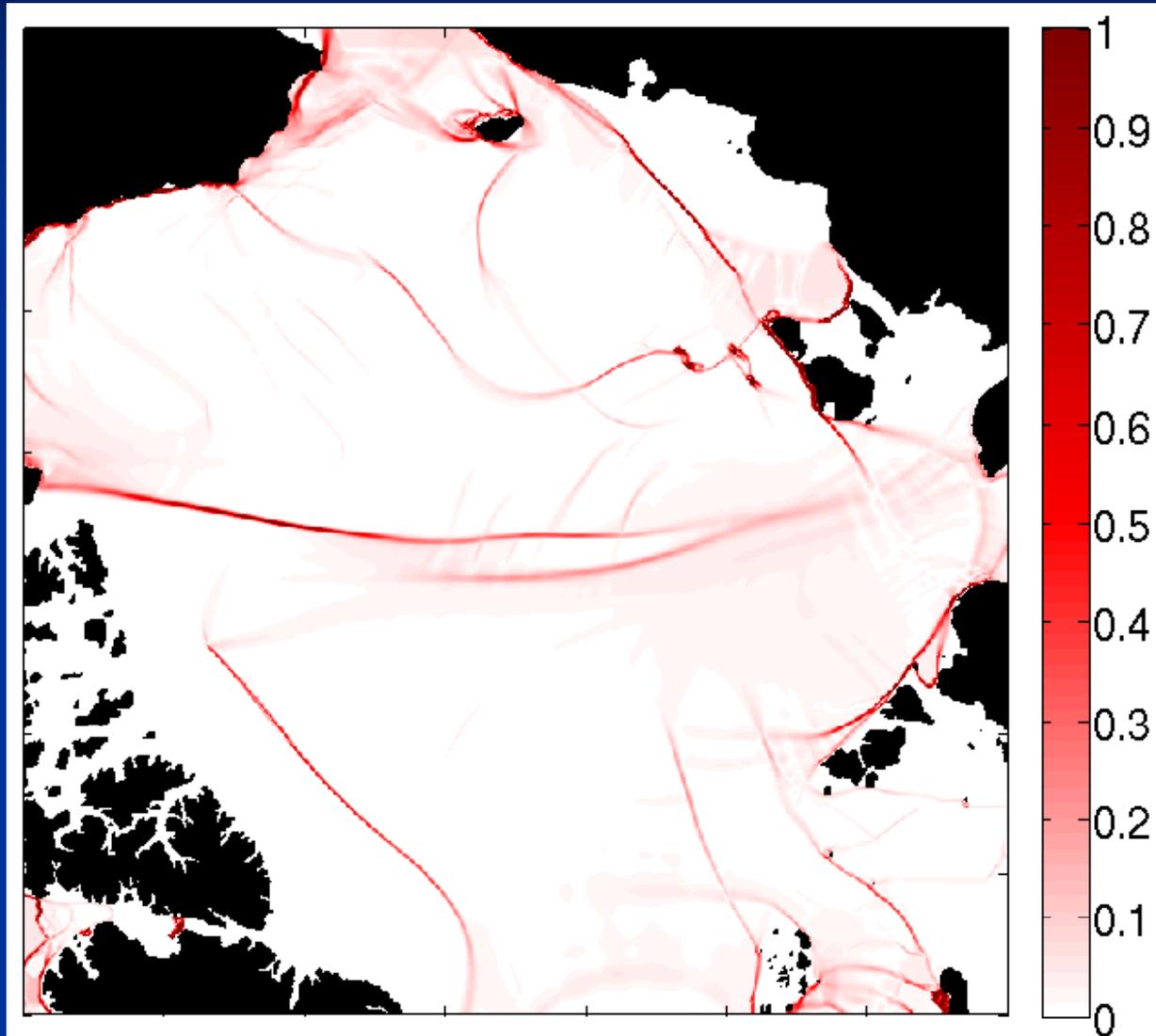


W

T

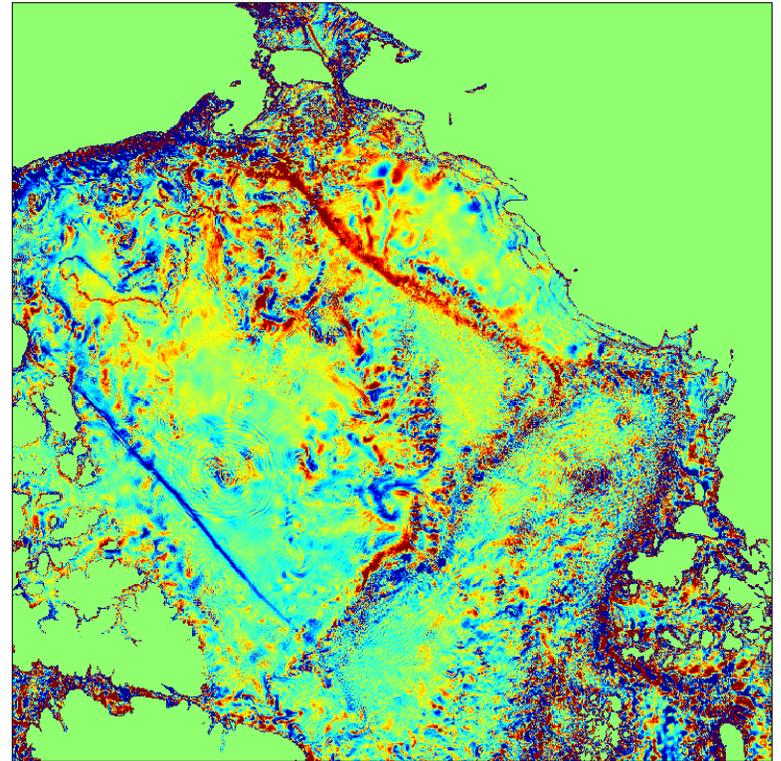
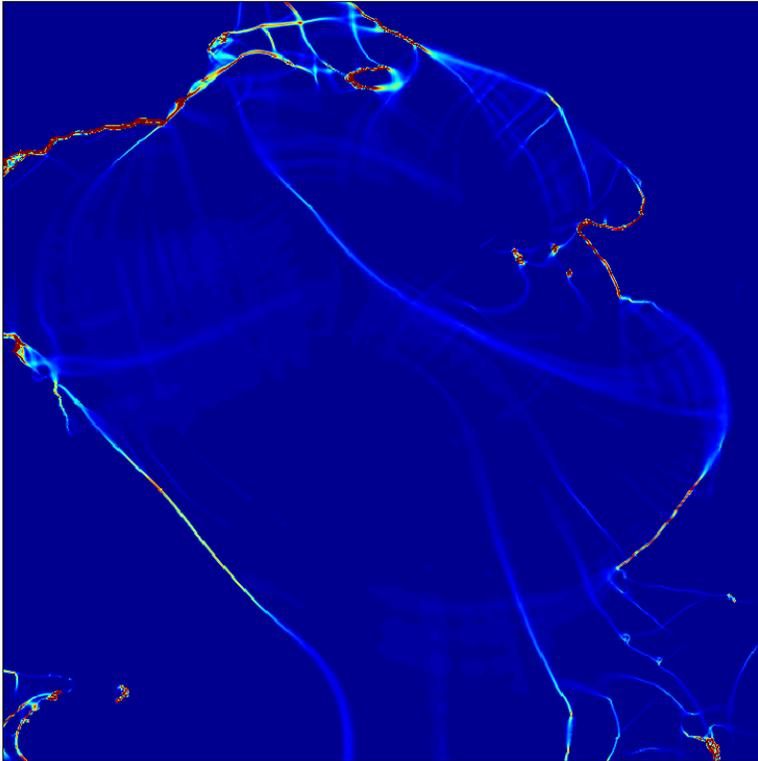
$W \times (T - T_{\text{ref}})$

Shear Strain Rate

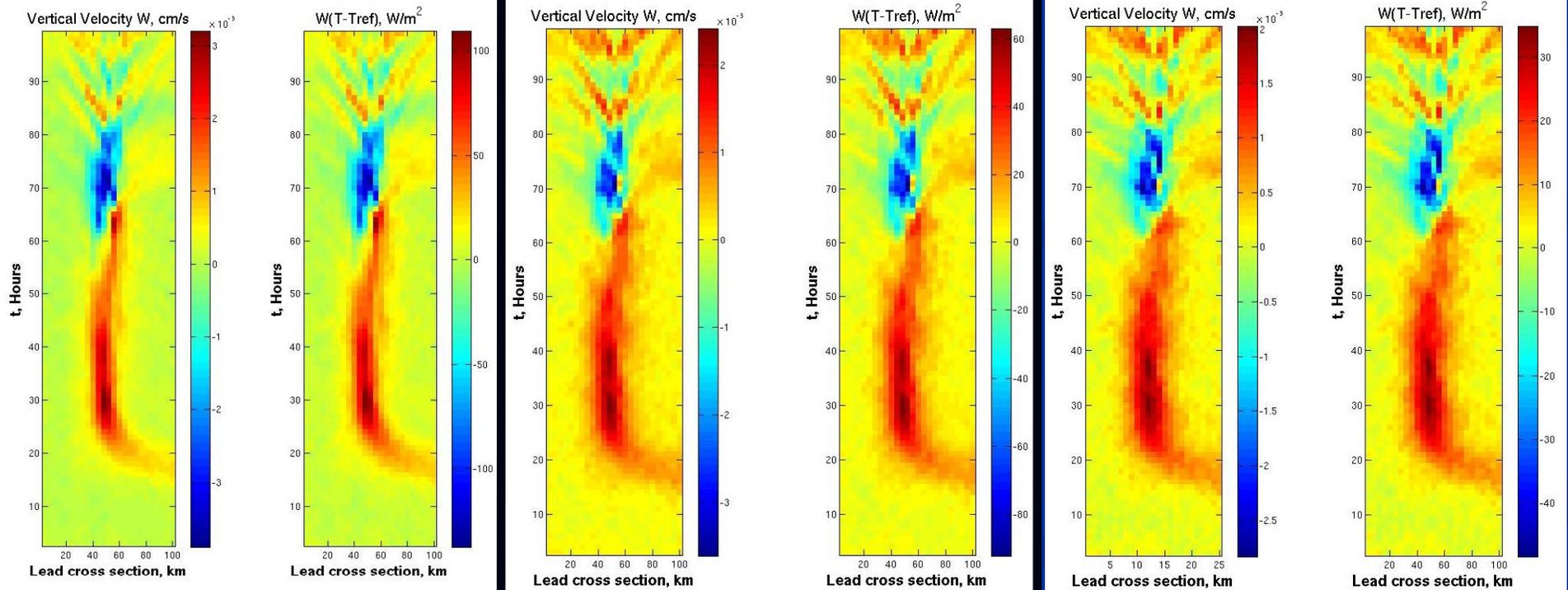


Shear Strain

Vertical Velocity – 40m



Hovmuller Diagram

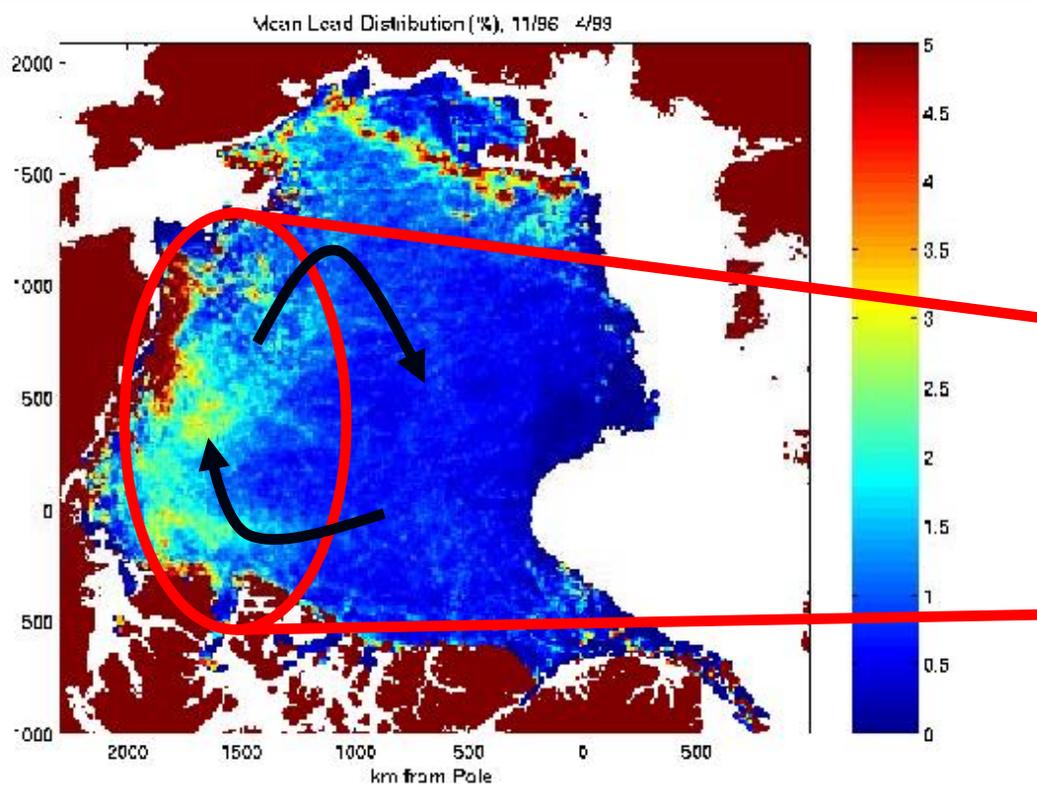


40 m

70 m

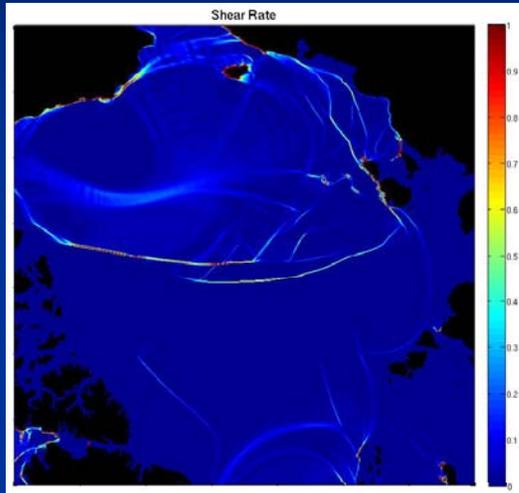
100 m

Lead Activity Distribution



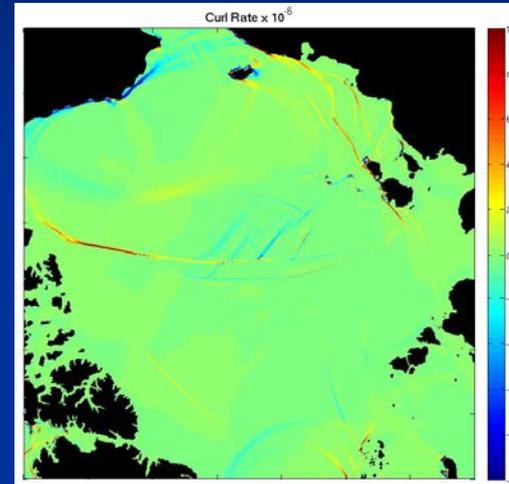
January 9

Shear



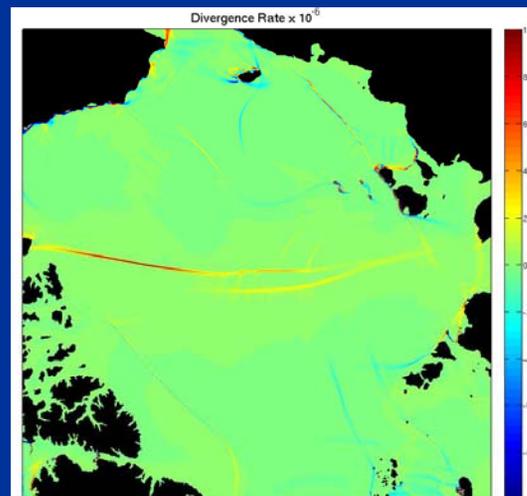
Curl

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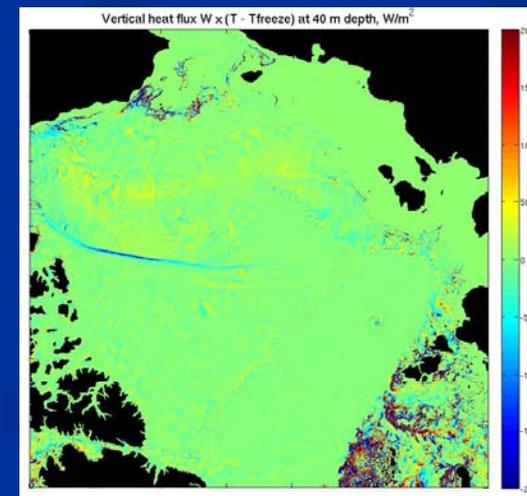
Div

+

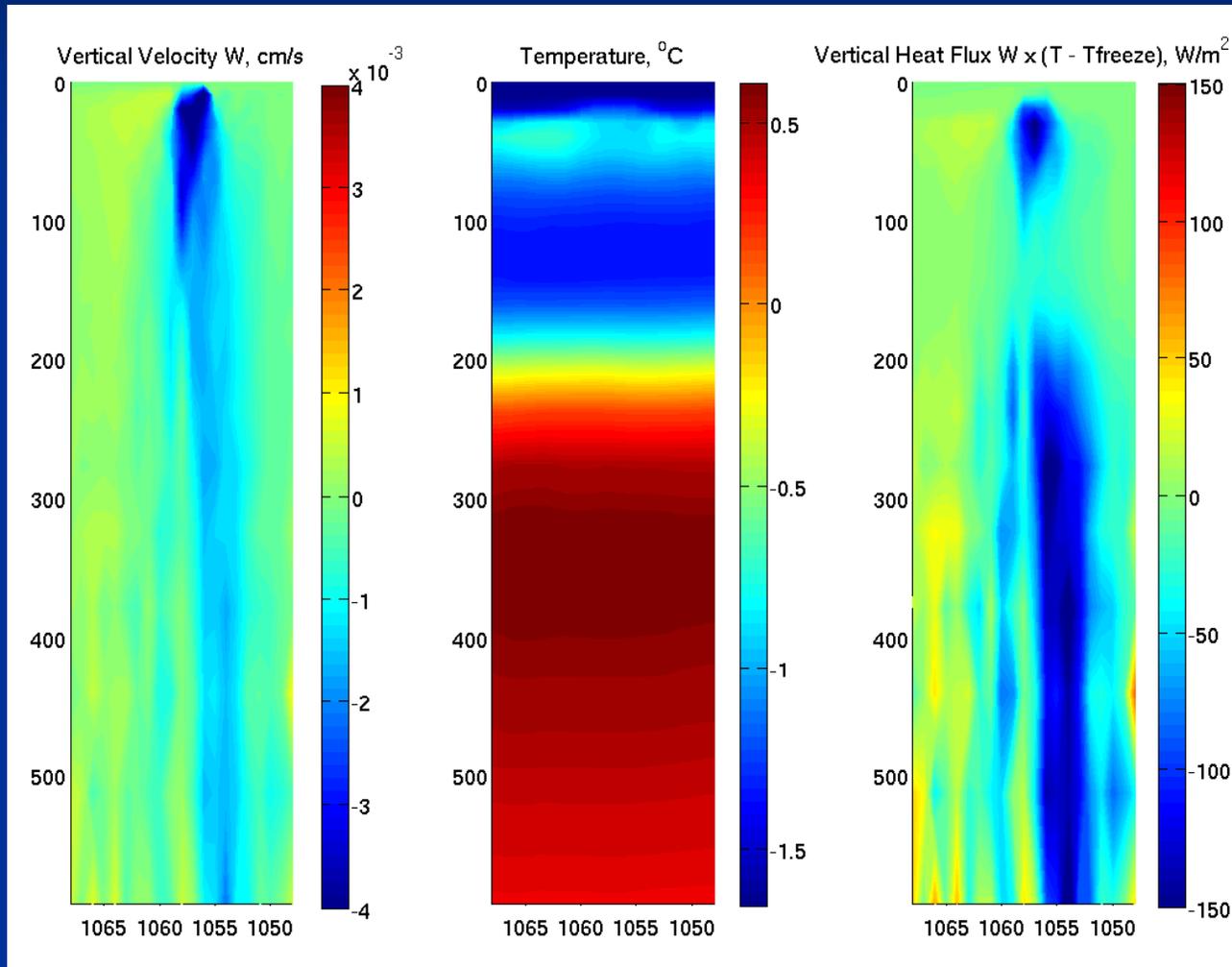


Focn

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Vertical Cross Section Across Lead



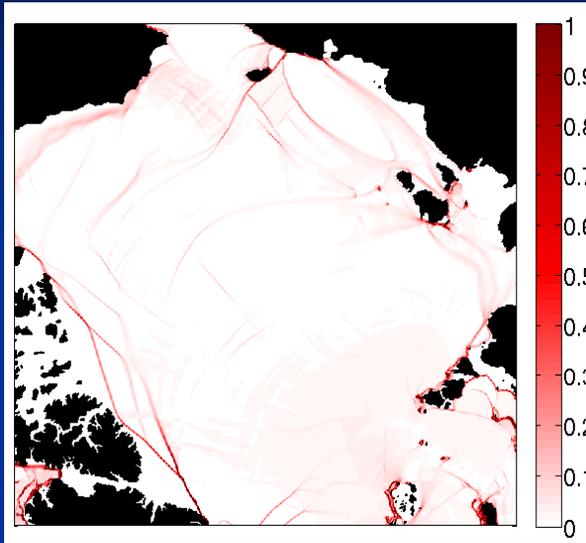
W

T

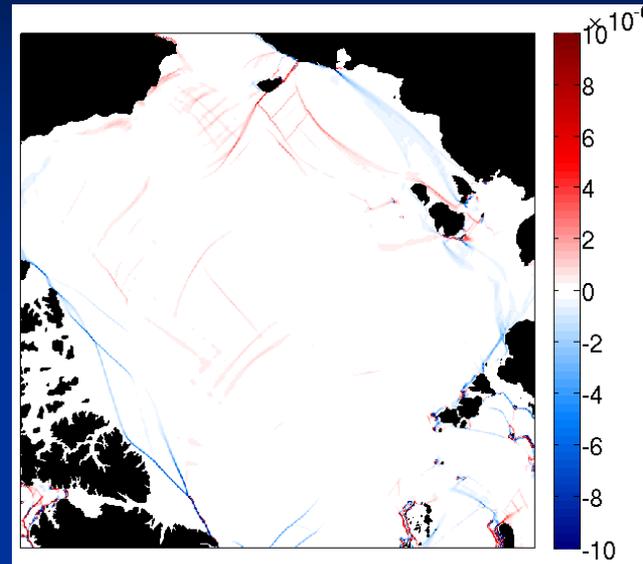
$W \times (T - T_{\text{ref}})$

January 25

Shear

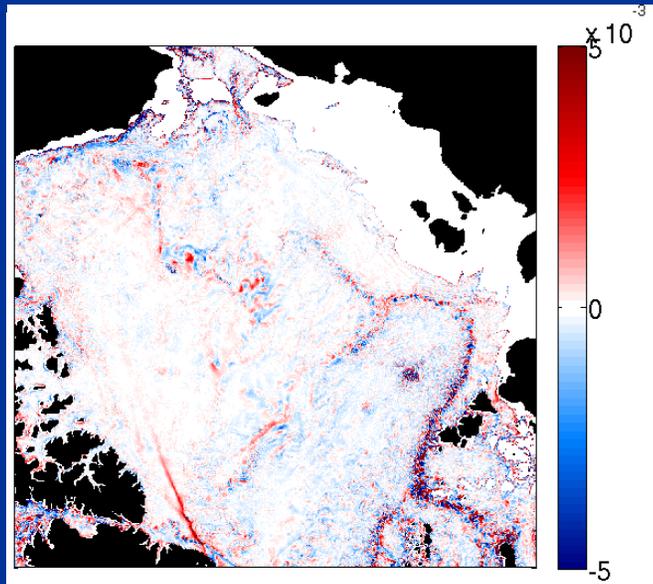


Curl

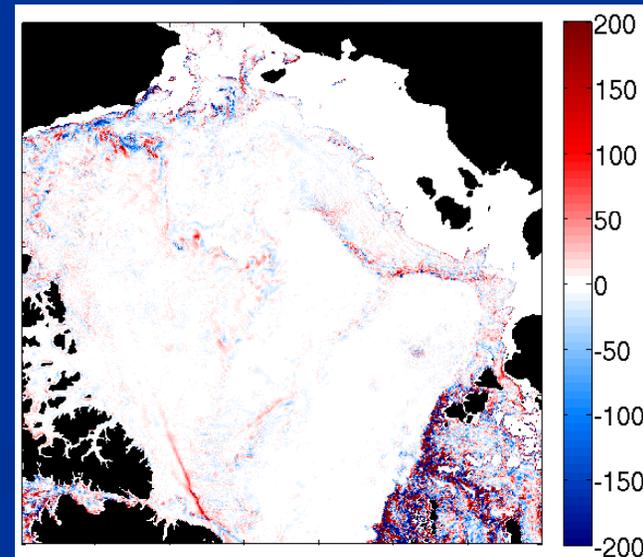


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Div

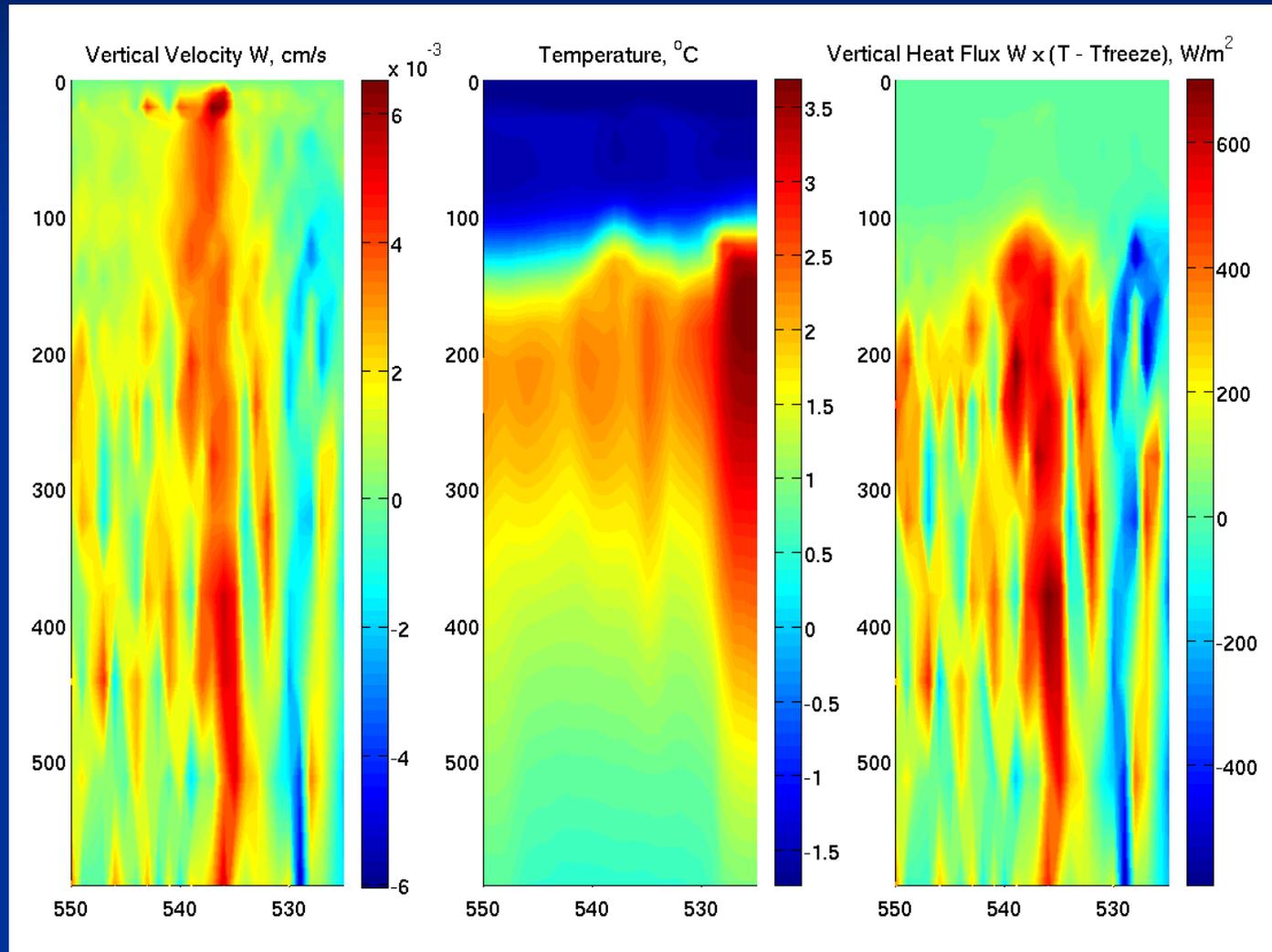


Focn



+

Vertical Cross Section Across Lead



W

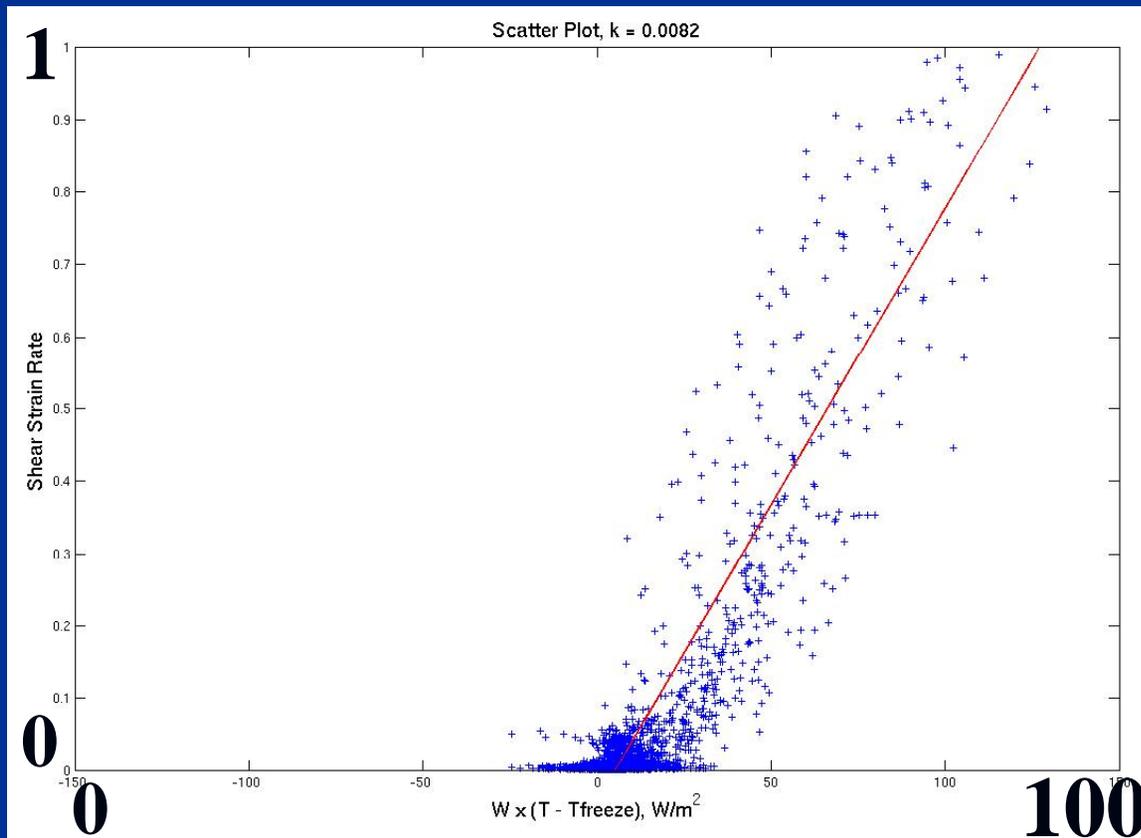
T

$W \times (T - T_{\text{ref}})$

Shear strain rate - Focn

$$\text{Focn} = 100 * \text{shear strain rate}$$

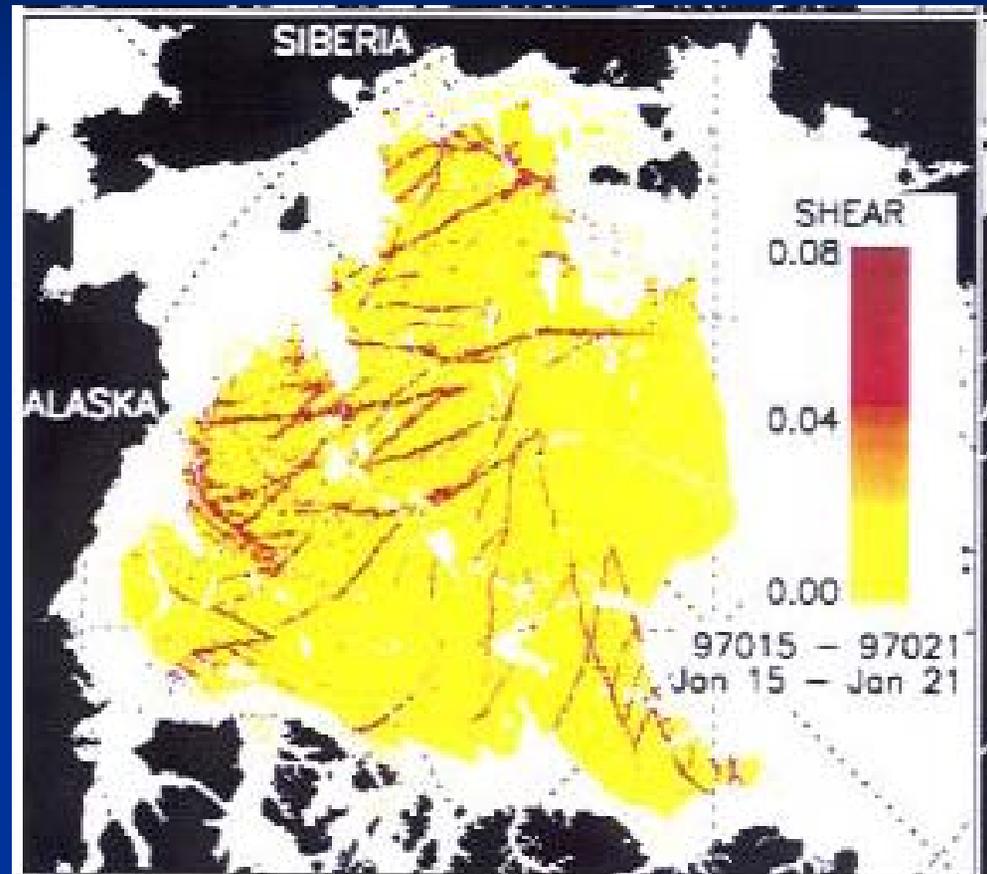
Shear strain rate (per day)



Vertical Ocean Heat Flux (W/m²)

Sea ice deformation

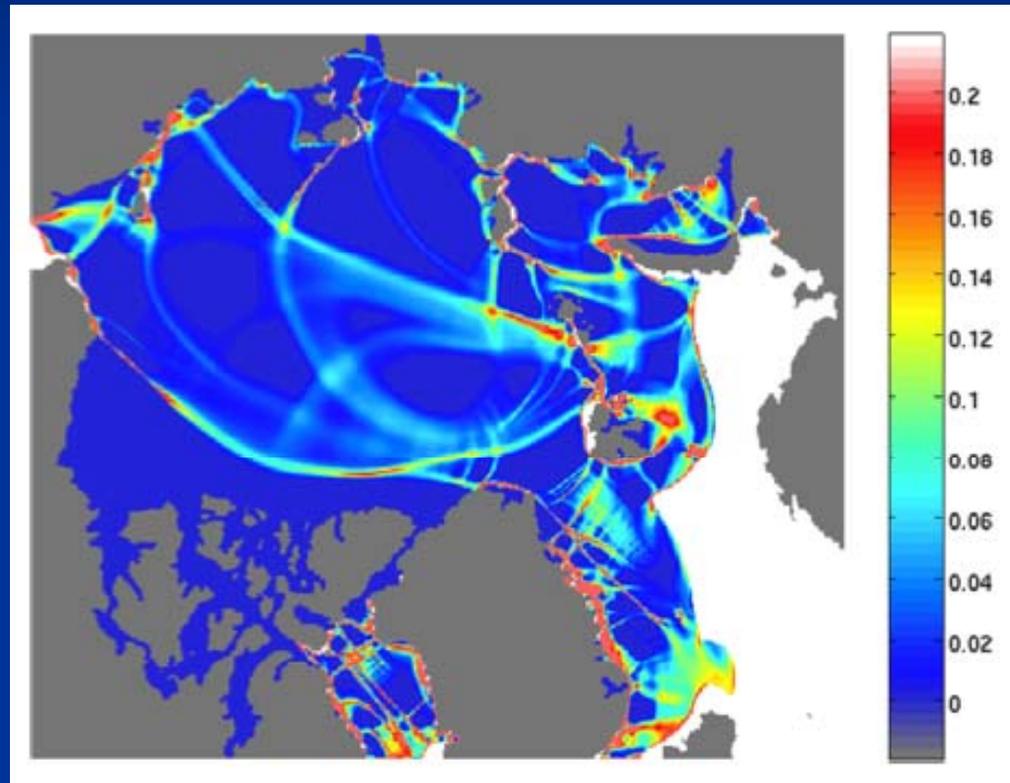
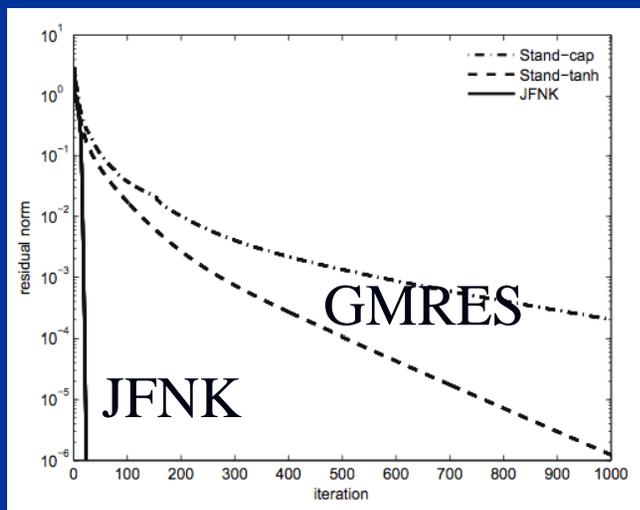
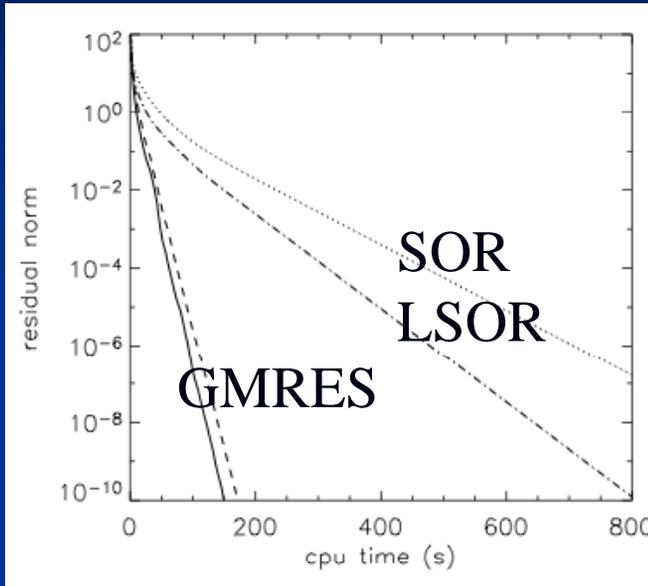
Focn ~ 3-4 W/m²
OR
~ 20 cm



shear

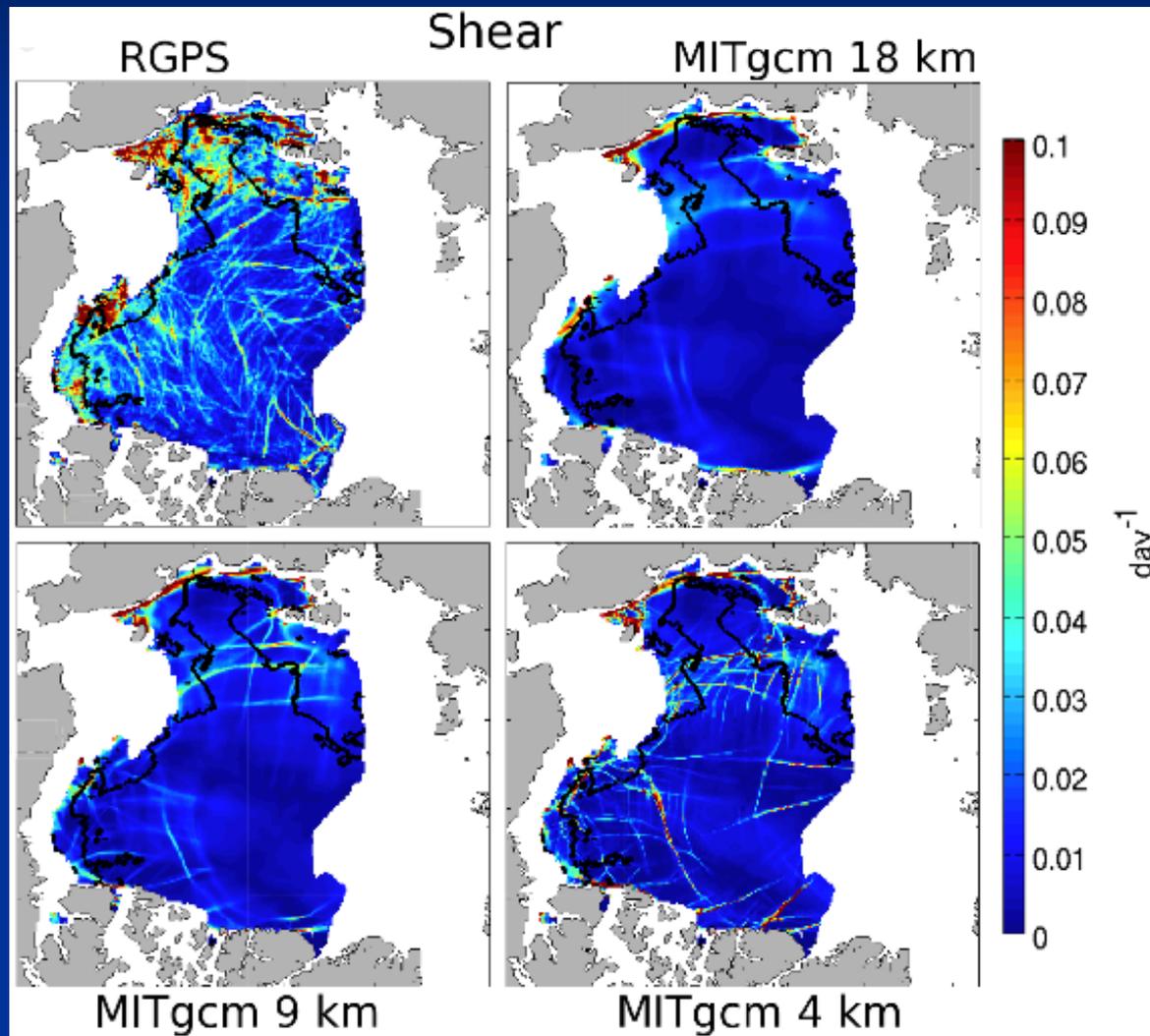
RGPS data, Kwok

Jacobian Free Newton Krylov-JFNK solver



Lemieux et al, 2008, 2009; Lemieux Tremblay, 2010

RGPS – Model Comparison

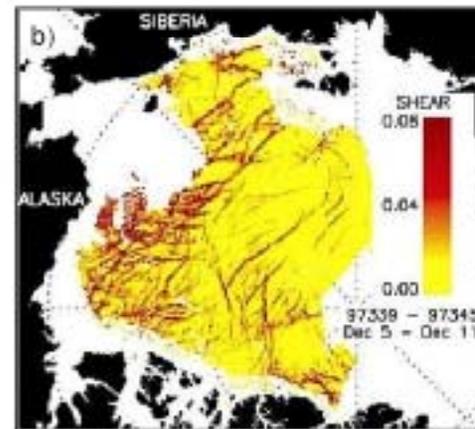
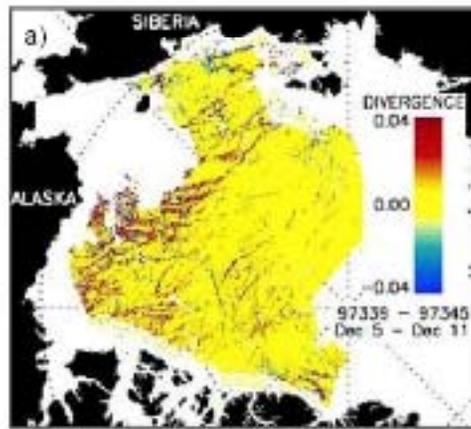


Coulombic Yield Curve

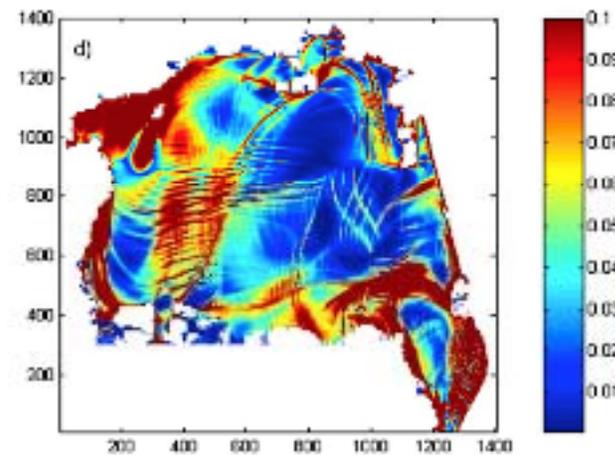
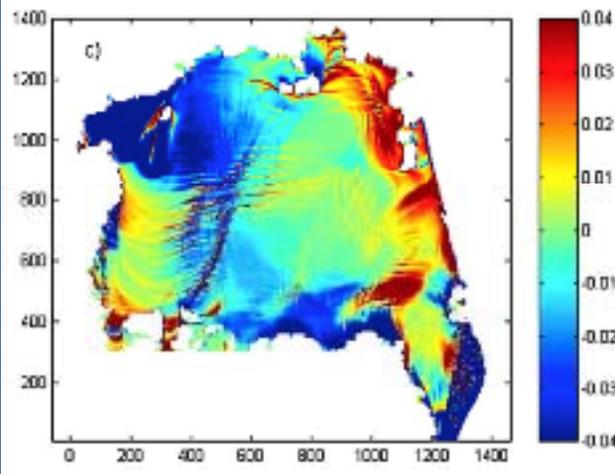
Divergence

Shear

Obs



Model



Ellipse

Coulombic

Wang and Wang, 2009

Conclusions

CCSM3 and CCMS4

- Rapid sea ice decline in the CCSM3 model are triggered by pulses of Atlantic waters - and make their way up to the surface through increased diffusive heat flux ($\sim 25\text{W}/\text{m}^2$)
- CCSM4 model does not simulate “rapid” sea ice decline in the future – and vertical diffusive heat fluxes are more modest.

Conclusions

MITgcm

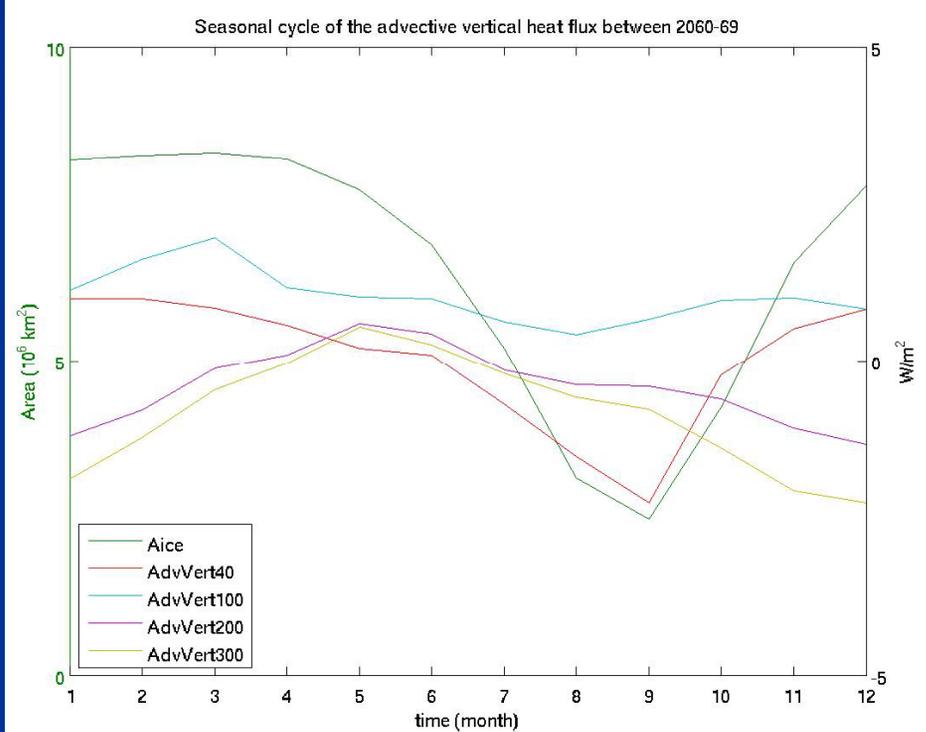
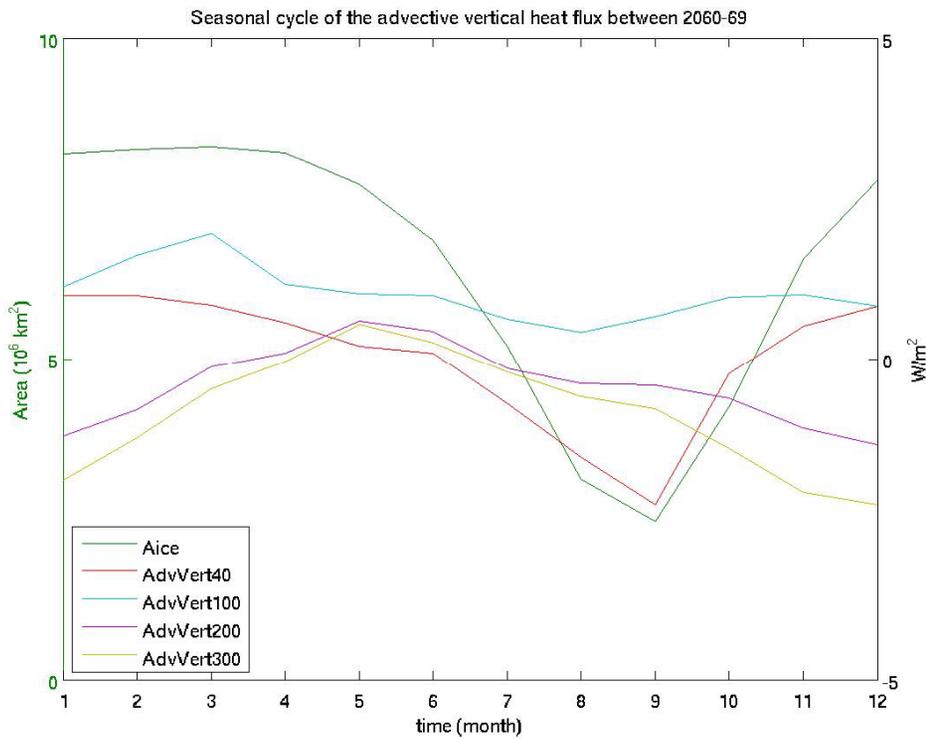
- Discontinuities in ice-ocean stress across sea-ice lead can lead to significant vertical ocean heat fluxes up to 2 orders of magnitude larger than over stable sea ice
- Anomalous upwelling velocities of up to 4 m/day extending through the CHL and into the Atlantic layer.
- Mechanism for upwelling is Ekman pumping

Advective Flux

Seasonale Cycle

1850-1859

2060-2069



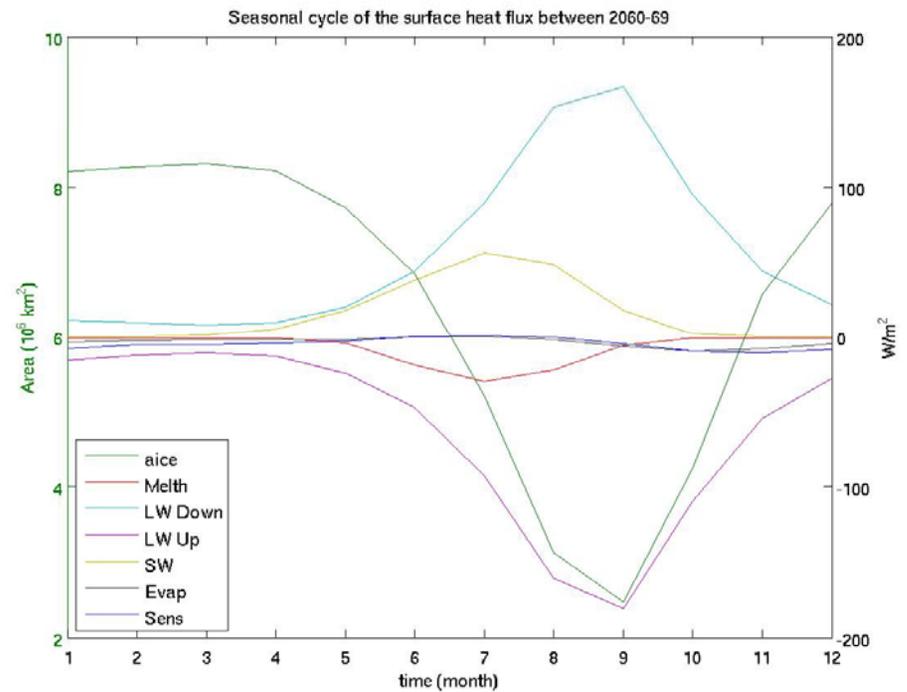
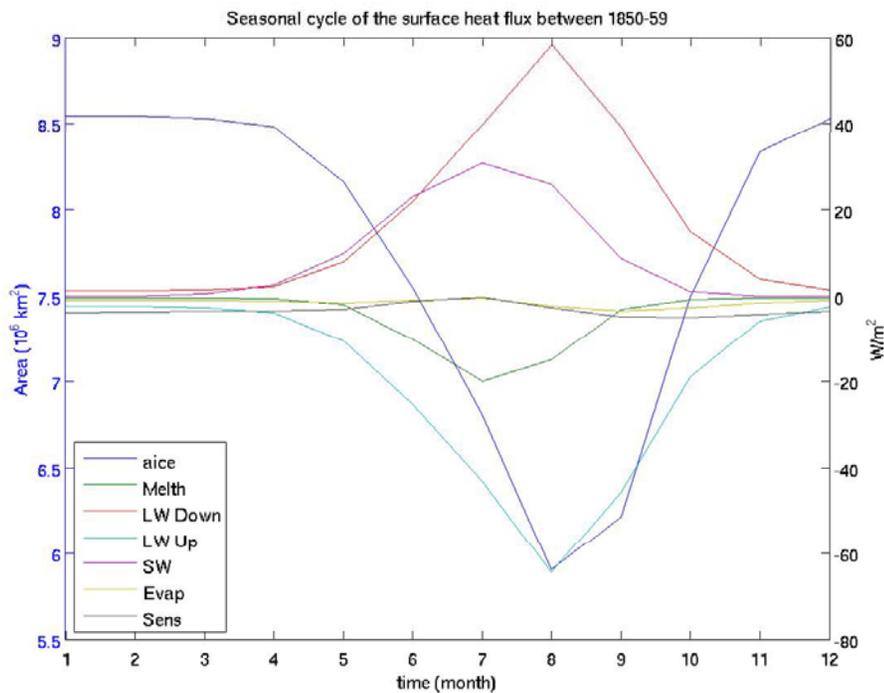
CCSM4

Surface Fluxes

Seasonal Cycle

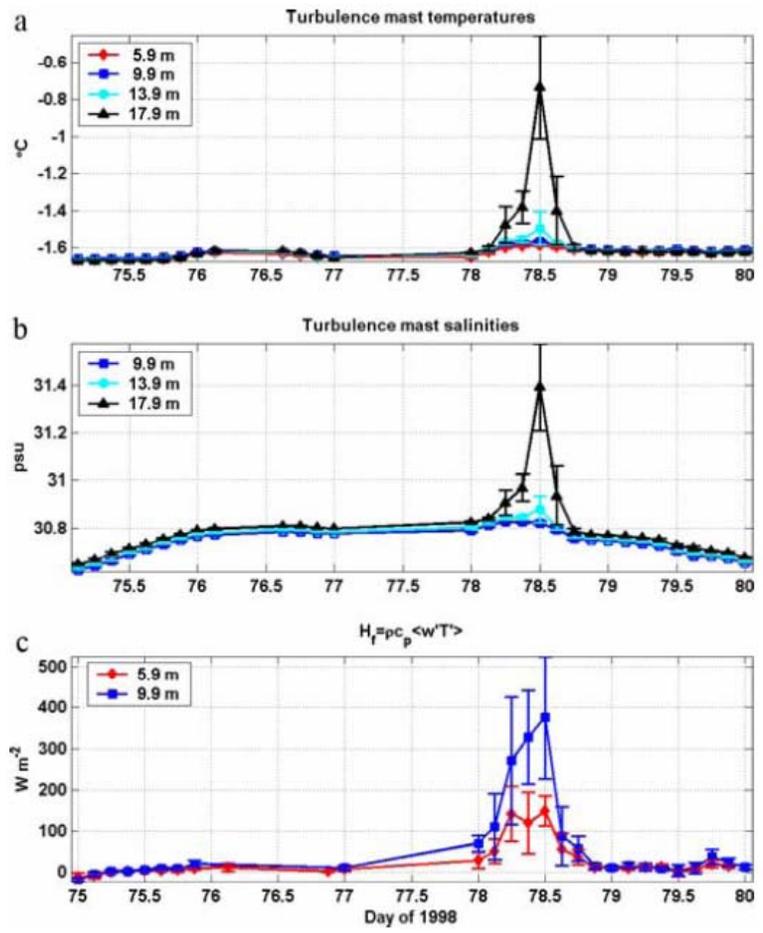
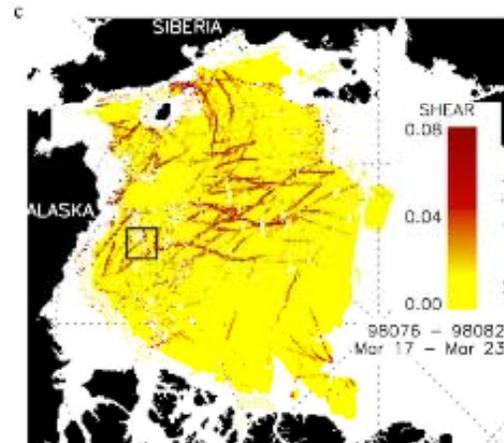
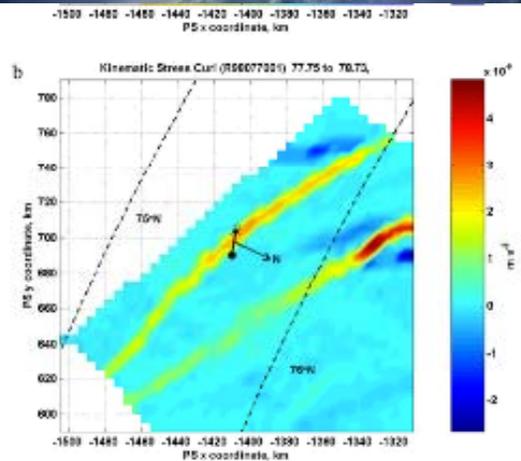
1850-1859

2060-2069



CCSM4

Vertical Ocean Heat flux

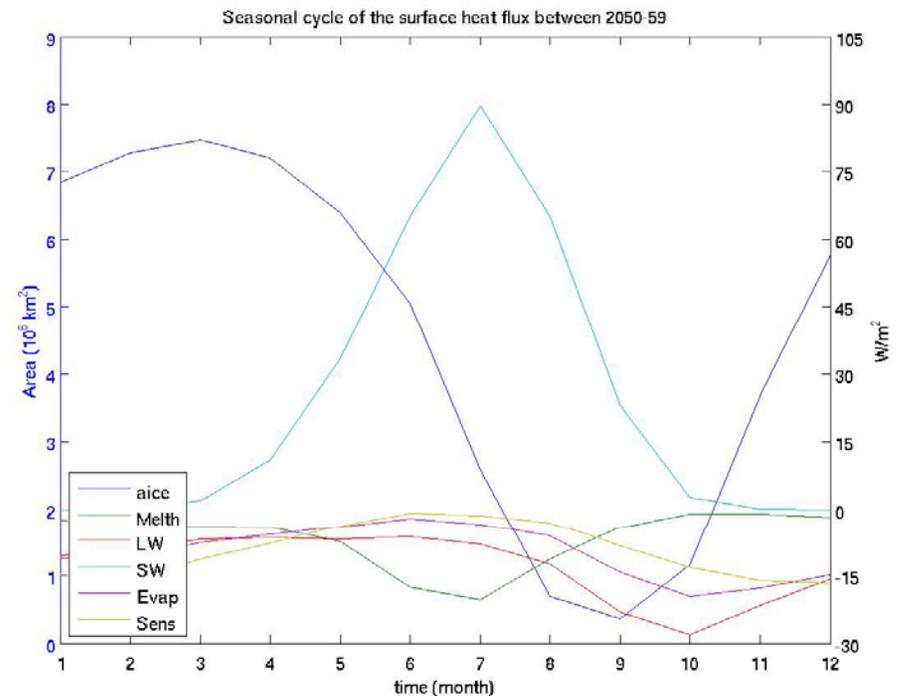
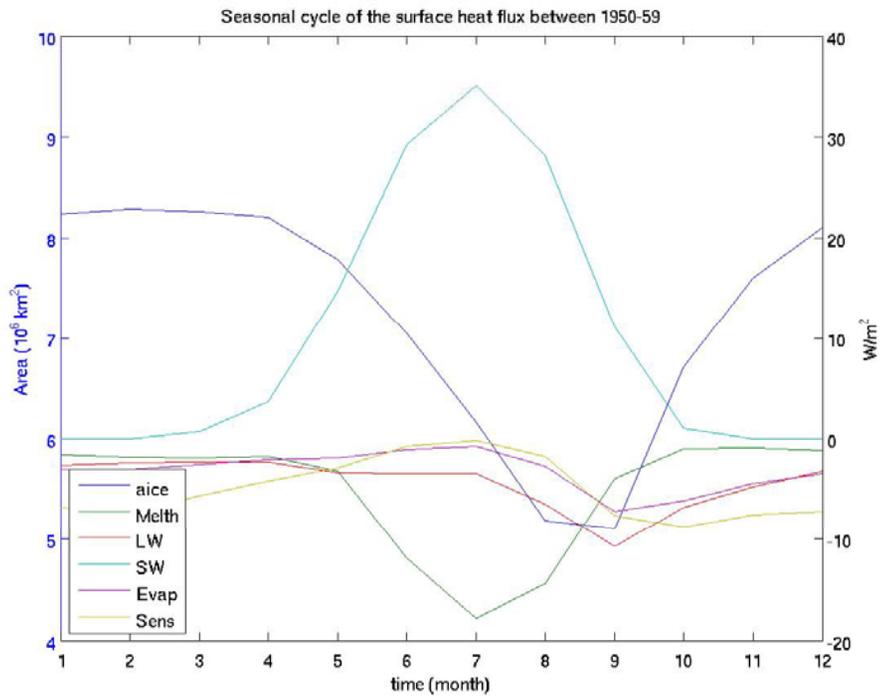


Surface Fluxes

Seasonal Cycle

1950-1959

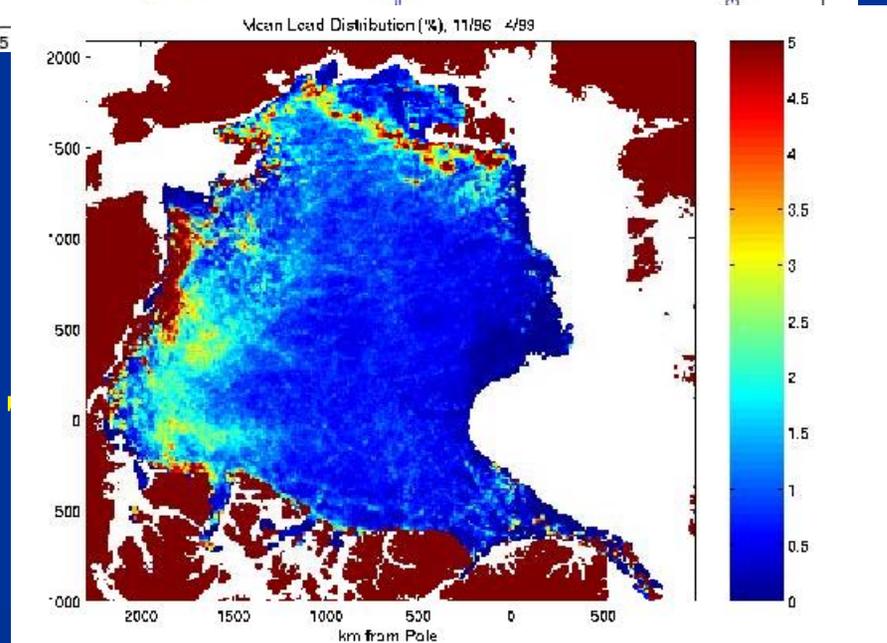
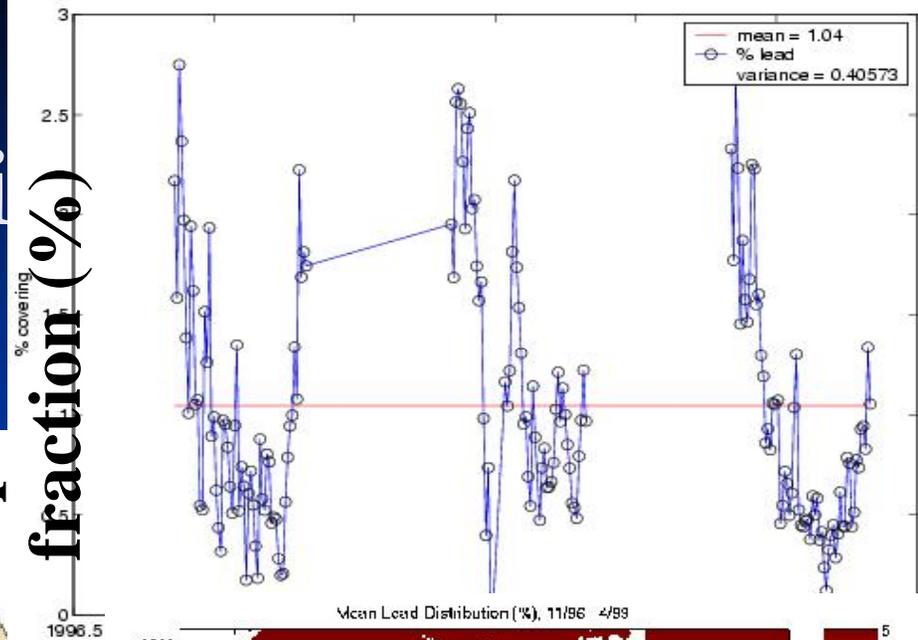
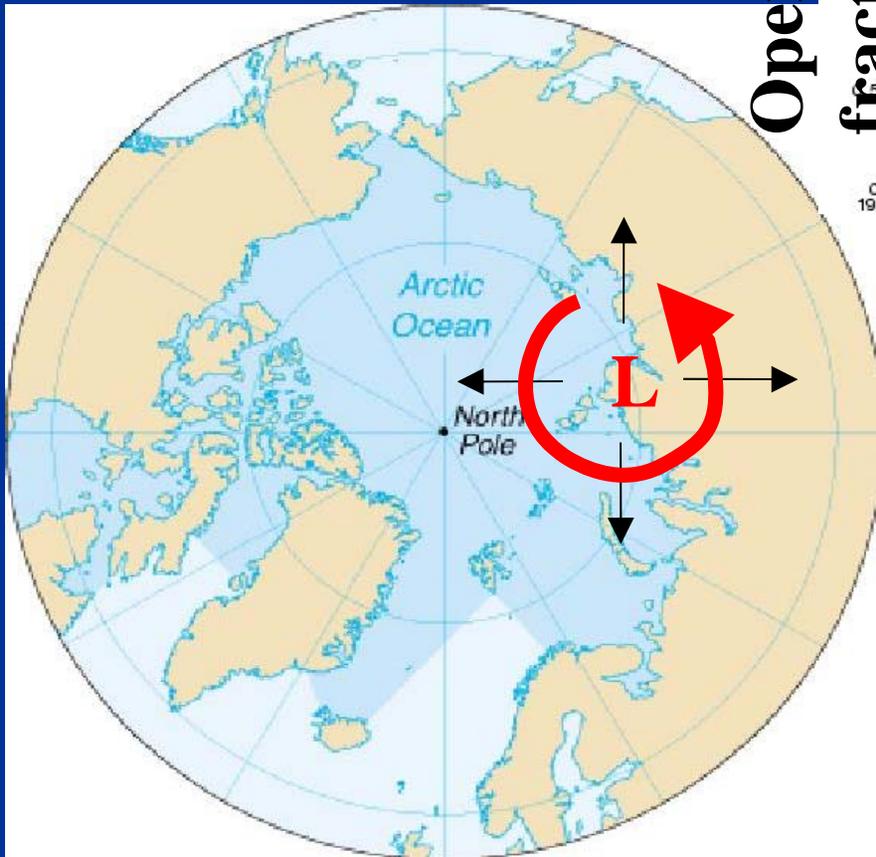
2050-2059



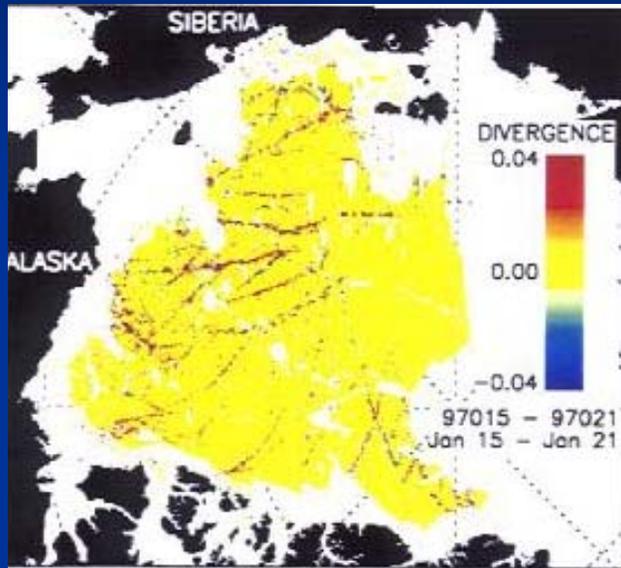
CCSM3

Dynamics

Open water fraction (%)

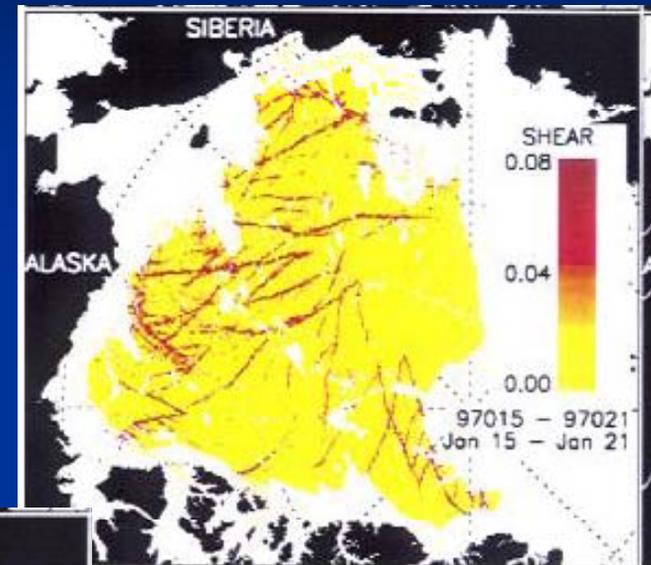


Sea ice deformation

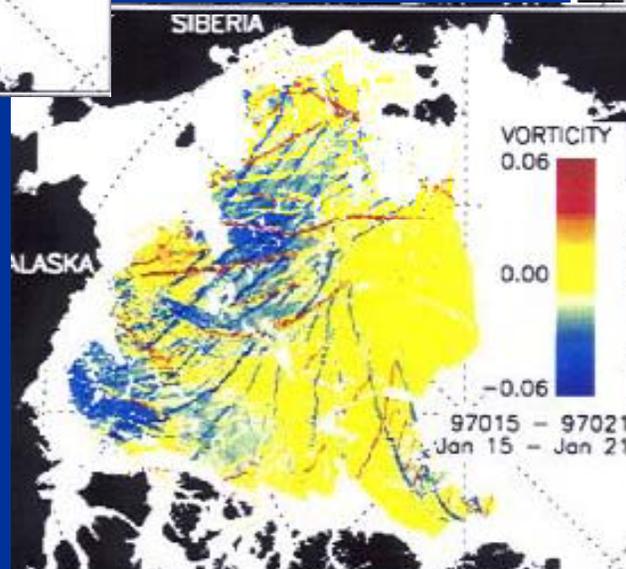


divergence

vorticity



shear

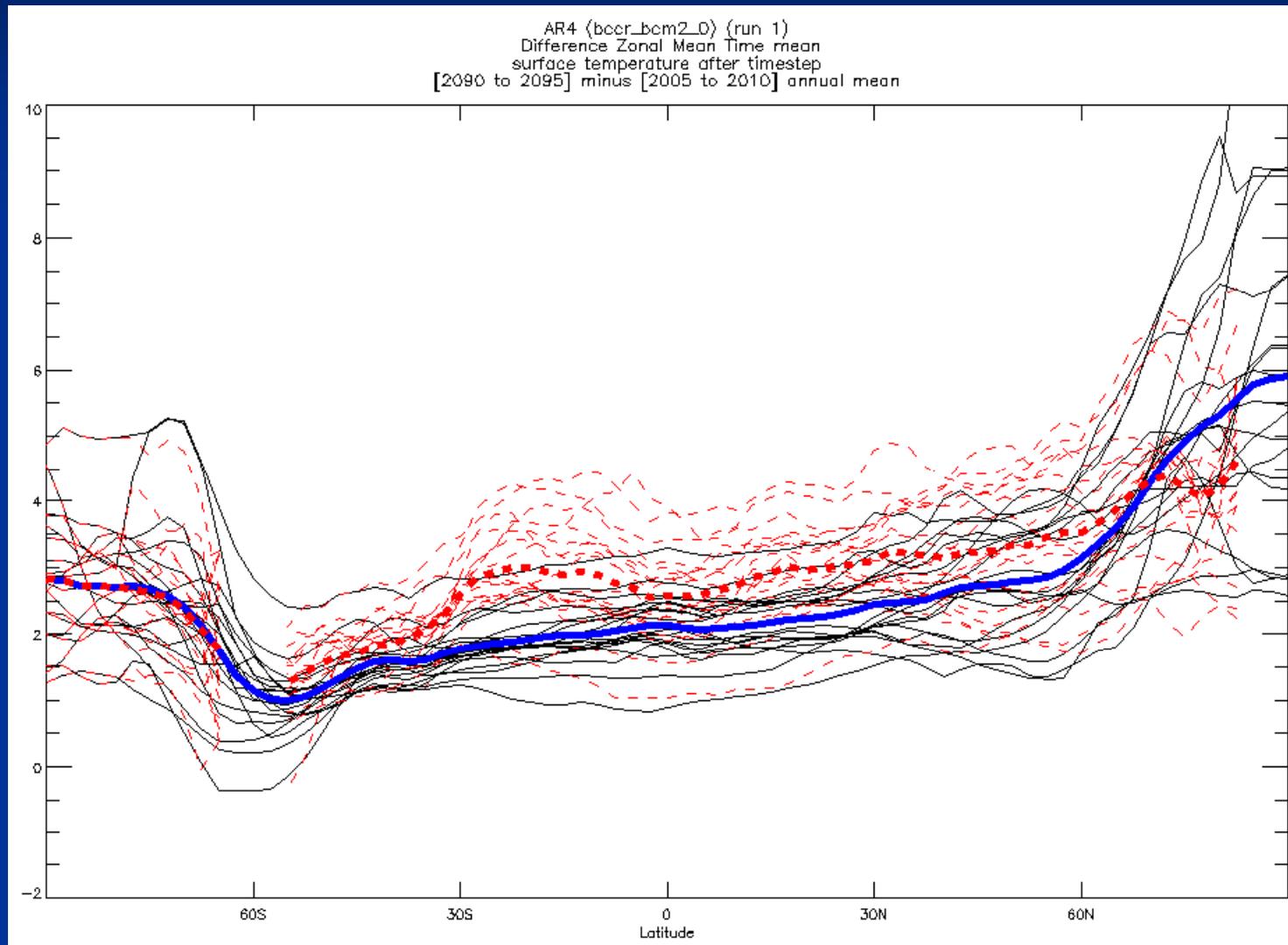


RGPS data, Kwok

Sea Ice Ridge



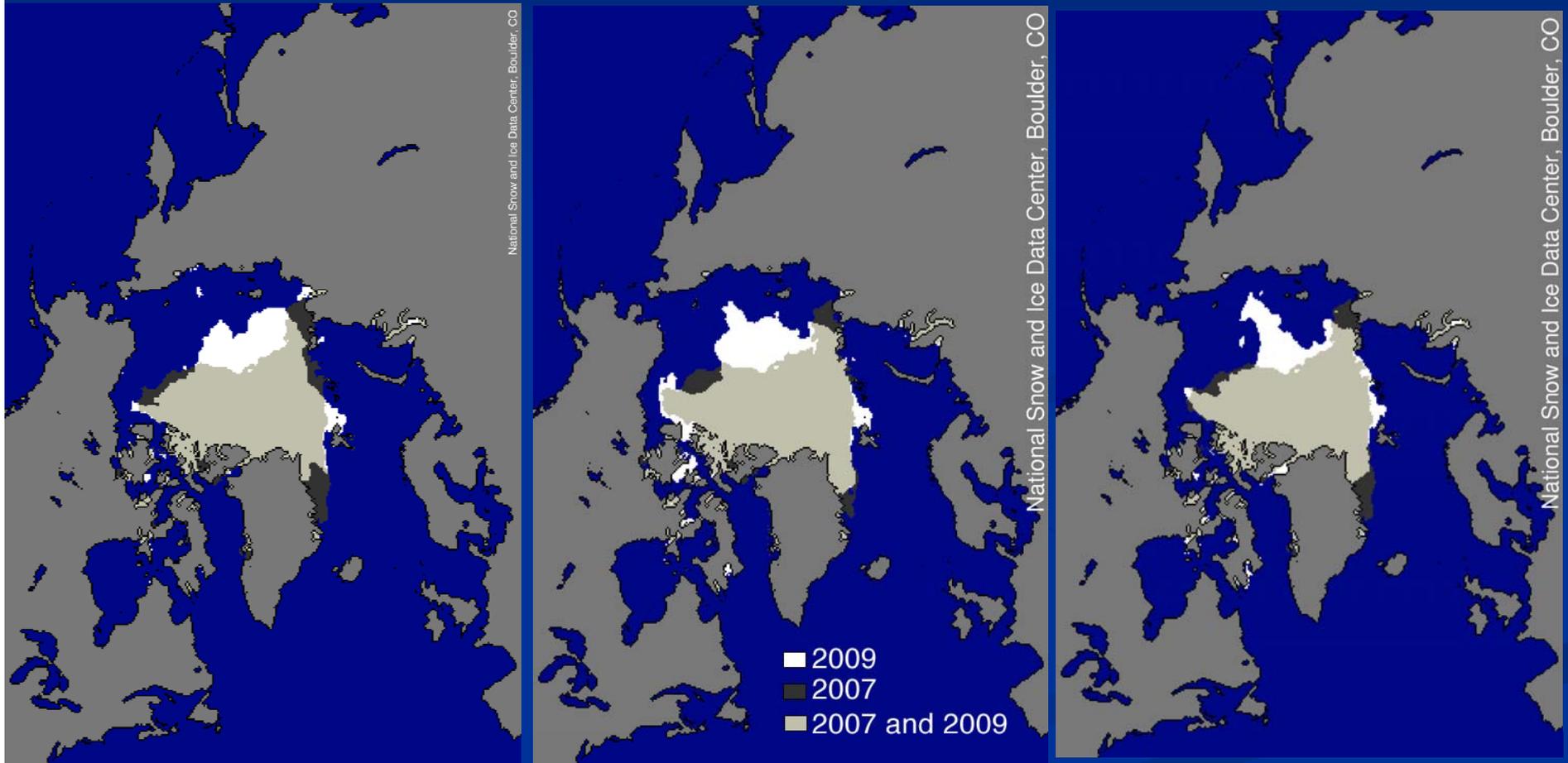
Polar Amplification



Vertical Ocean Heat Fluxes

- Constant throughout the year at $\sim 2 \text{ W/m}^2$ (Maykut Untersteiner, 1971; Untersteiner, 1964)
- Seasonally varying between 0 and $40\text{-}60 \text{ W/m}^2$, (Maykut McPhee, 1995)
- High in localized region $\sim 400 \text{ W/m}^2$ (McPhee et al, 2005)
- 0.5 W/m^2 increase in ocean heat flux Eurasian basin (from obs + 1D model); Polyakov et al, 2010.
- 0.05 to 0.3 W/m^2 in Canada Basin by double-diffusive (staircase) fluxes.
- Important upwelling vertical heat fluxes locally and at specific time (Yang 2006).

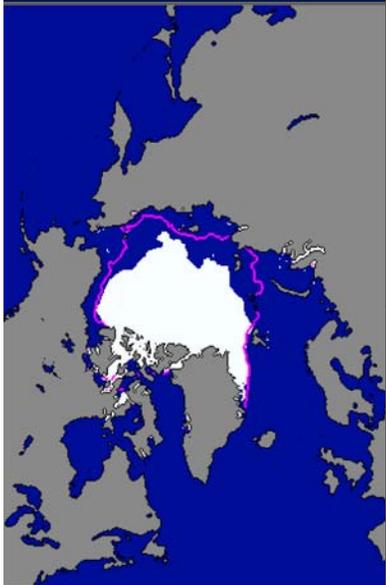
Minimum Sea Ice Extent



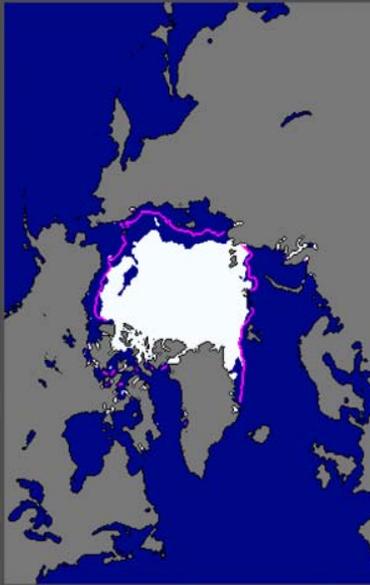
2008

2009

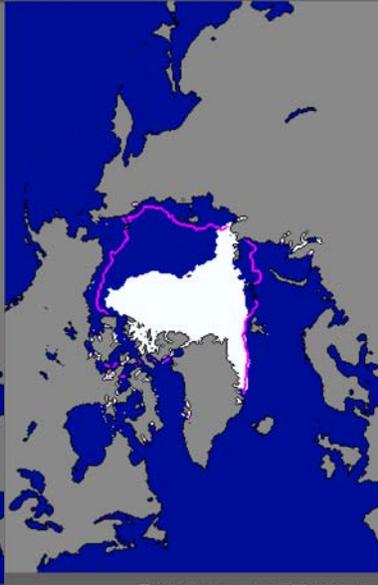
2010



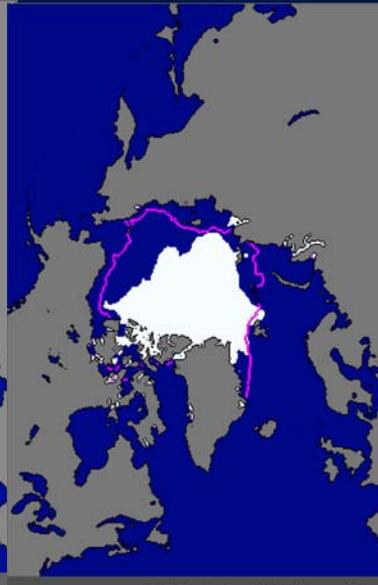
Total extent = 5.3 million sq km



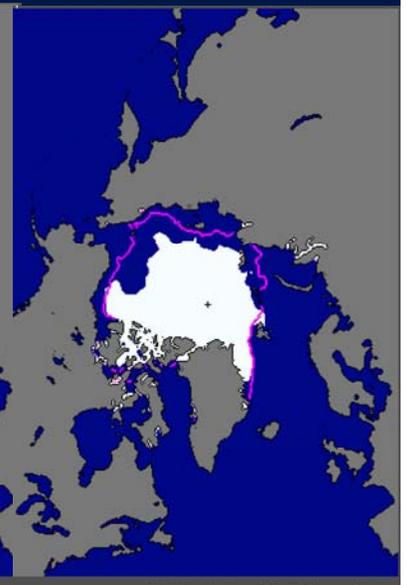
Total extent = 5.8 million sq km



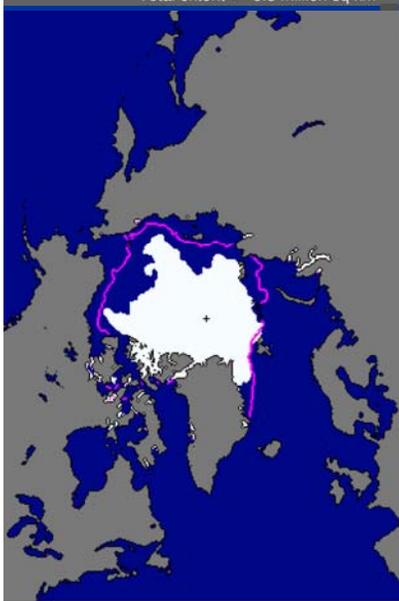
Total extent = 4.1 million sq km



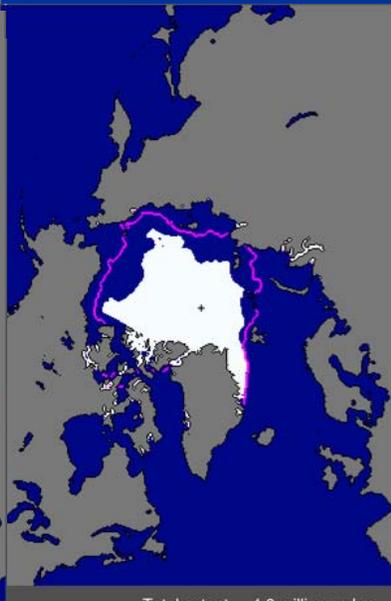
Total extent = 4.7 million sq km



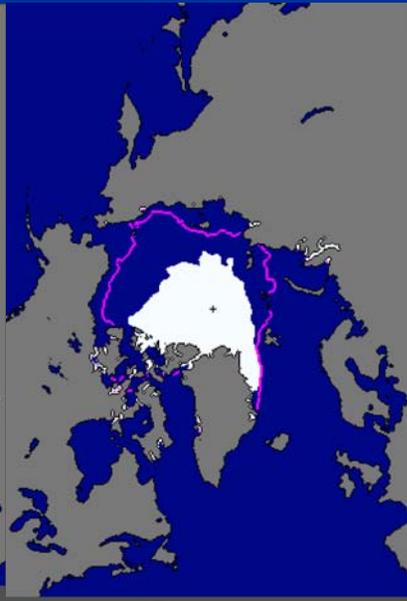
Total extent = 5.4 million sq km



Total extent = 4.9 million sq km



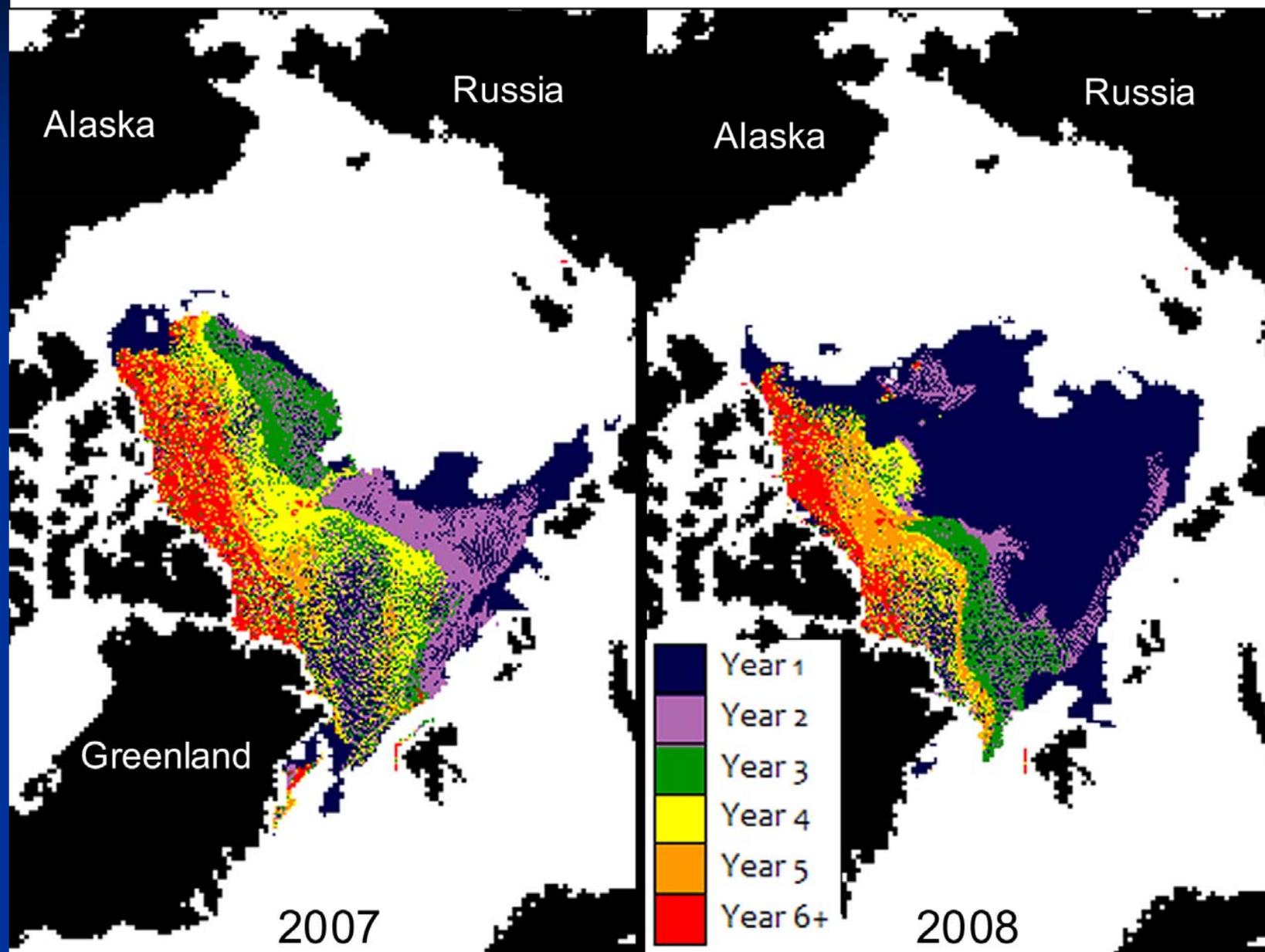
Total extent = 4.6 million sq km



Total extent = 3.6 million sq km



Ice age at the end of the 2007 and 2008 melt seasons



Ocean Positive Feedback

