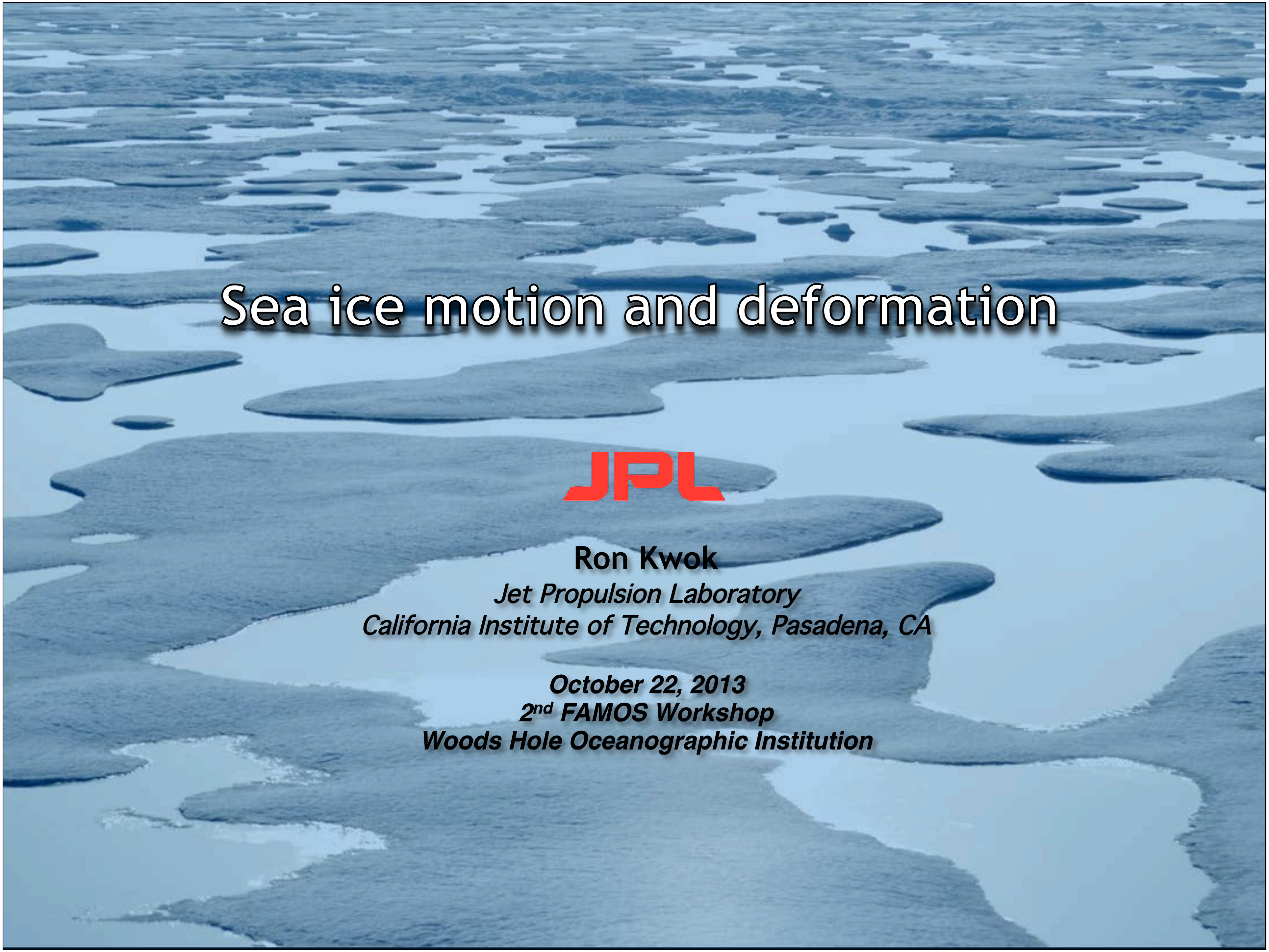


Sea ice motion and deformation

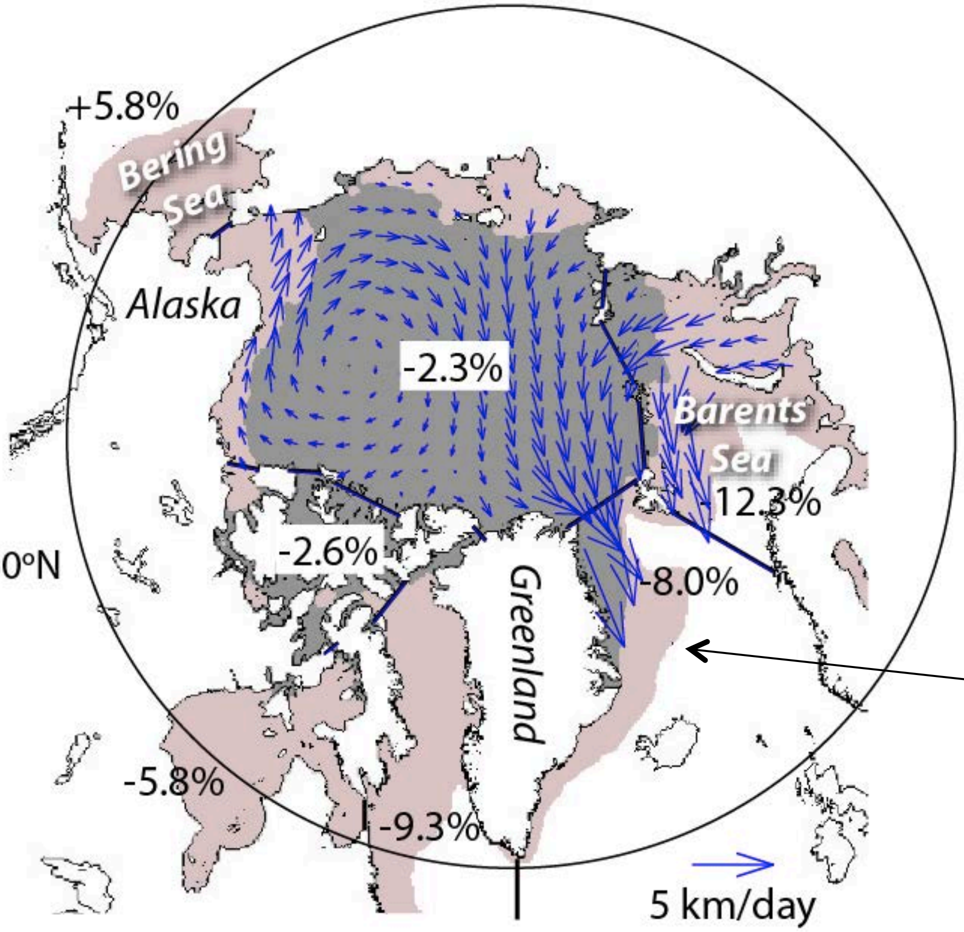
Ron Kwok

Jet Propulsion Laboratory
California Institute of Technology, Pasadena, CA

October 22, 2013
2nd FAMOS Workshop
Woods Hole Oceanographic Institution

Arctic Ocean sea ice cover

1979-2012



Maximum extent

- **Why does it move?**
- **How does it moves? What are the consequences of ice motion?**

Arctic Ocean Sea Ice

QuikScat Ice Cover (Nov)

- Overview
    - Large-scale motion
    - Small-scale motion
- Recent results
- Thoughts about the future

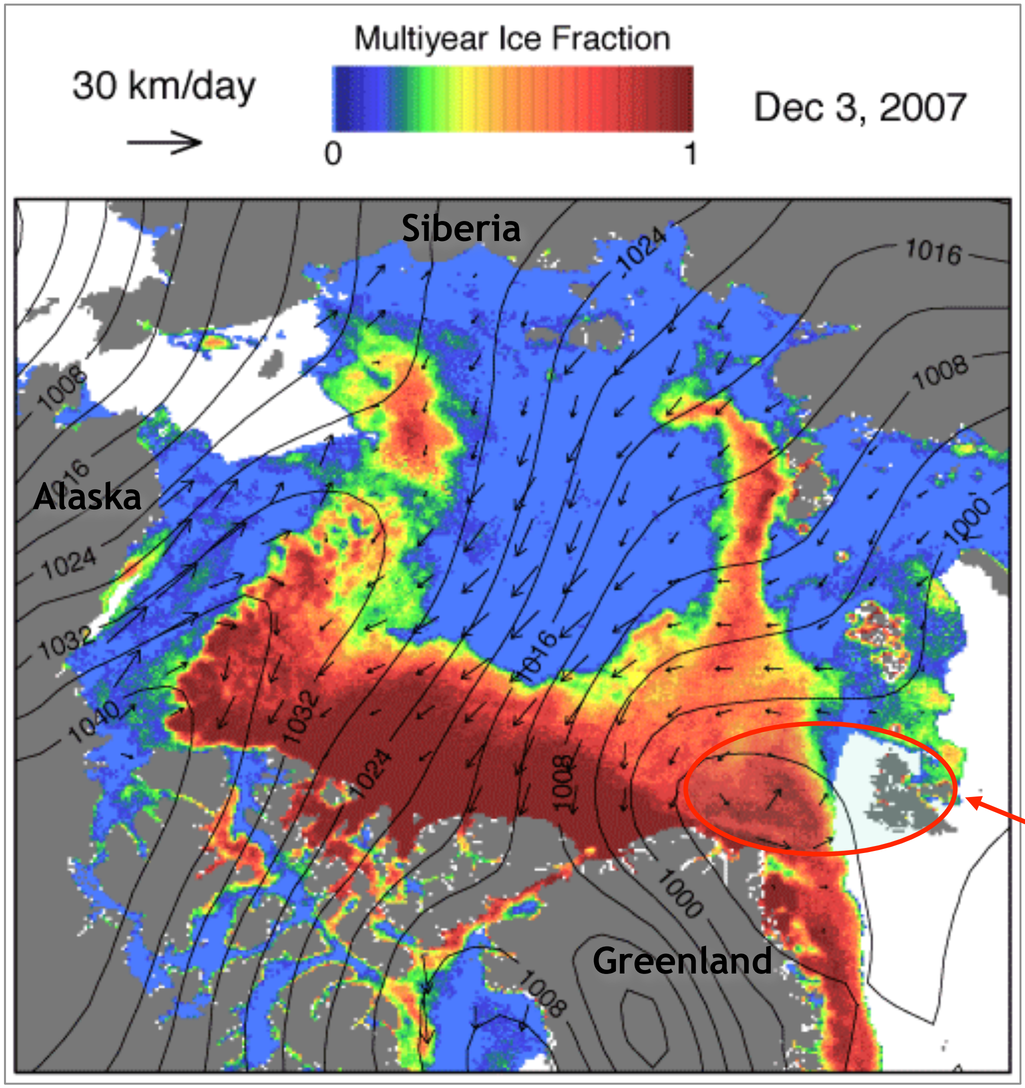
Observations of ice motion

- *Buoy drift/trajectories (since mid-to-late 70s from the Arctic buoy program)*
  - *Argos location (Uncertainty: ~300 m)*
  - *GPS (uncertainty: ~10^1 m)*
  - *Density: typically ~10^2 km, hourly samples*

- *Satellite fields (tracking features in sequence of images)*
  - *Passive microwave (uncertainty: km)*
    - *Routine retrievals since late 90s*
  - *Synthetic Aperture Radar data (uncertainty: 10s of meters)*
    - *Routine retrievals since early 2000*
  - *Time sampling: hours to several days*

Daily Sea Ice Motion (Dec 03 - Feb 15)

- *Red -old ice*
- *Blue - seasonal ice*



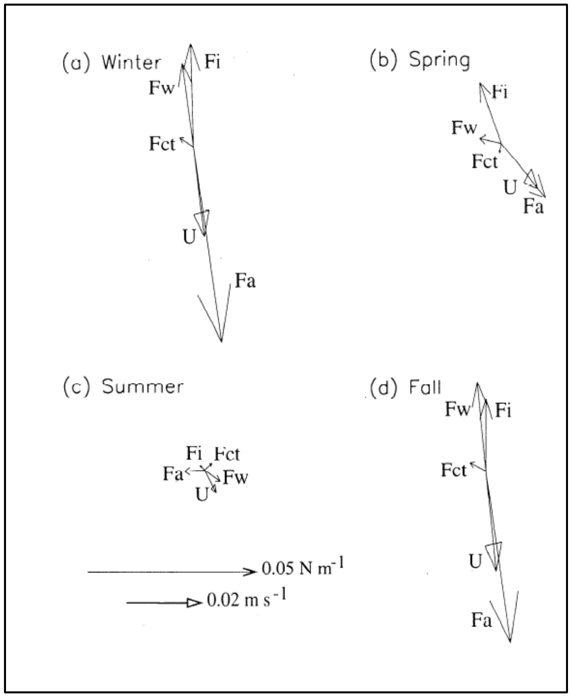
Fram Strait

LARGE-SCALE ICE DRIFT

Dynamics: Why sea ice moves

Force Balance:

$$\rho h \frac{\partial U}{\partial t} = \overset{\text{Air}}{F_a} + \overset{\text{water}}{F_w} + \overset{\text{ice}}{F_i} + \overset{\text{Coriolis}}{F_c} + \overset{\text{tilt}}{F_t}$$



Seasonal variability of each term in a model (Steele et al., 1997)

Focus is on how it moves: Kinematics

Relationship between ice drift and wind:

Sea Ice Motion in Response to Geostrophic Winds

A. S. THORNDIKE AND R. COLONY 1982

Polar Science Center, University of Washington, Seattle 98105

$$u = AG + c$$

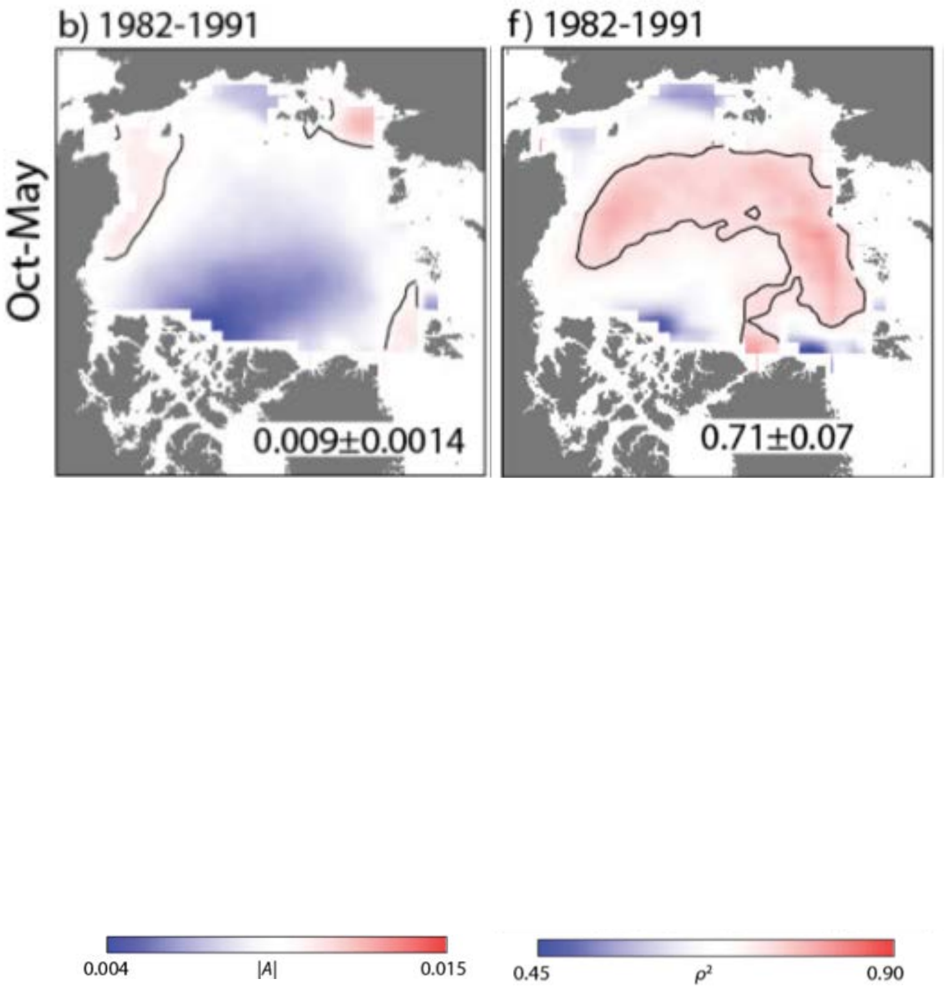
Vector quantities
u = ice motion (buoy drift)
A = scaling factor
G = Geostrophic wind
C = ocean current

$$A = \begin{cases} 0.0077\, e^{-i5^\circ} & \text{winter, spring} \\ 0.0105\, e^{-i18^\circ} & \text{summer} \\ 0.0080\, e^{-i6^\circ} & \text{fall} \end{cases}$$

Away from the coast (~400 km), more than 70% of the variance in ice motion in central Arctic can be explained by geostrophic wind at daily time scales.

Scale factor, Squared Correlation (from satellite ice motion)

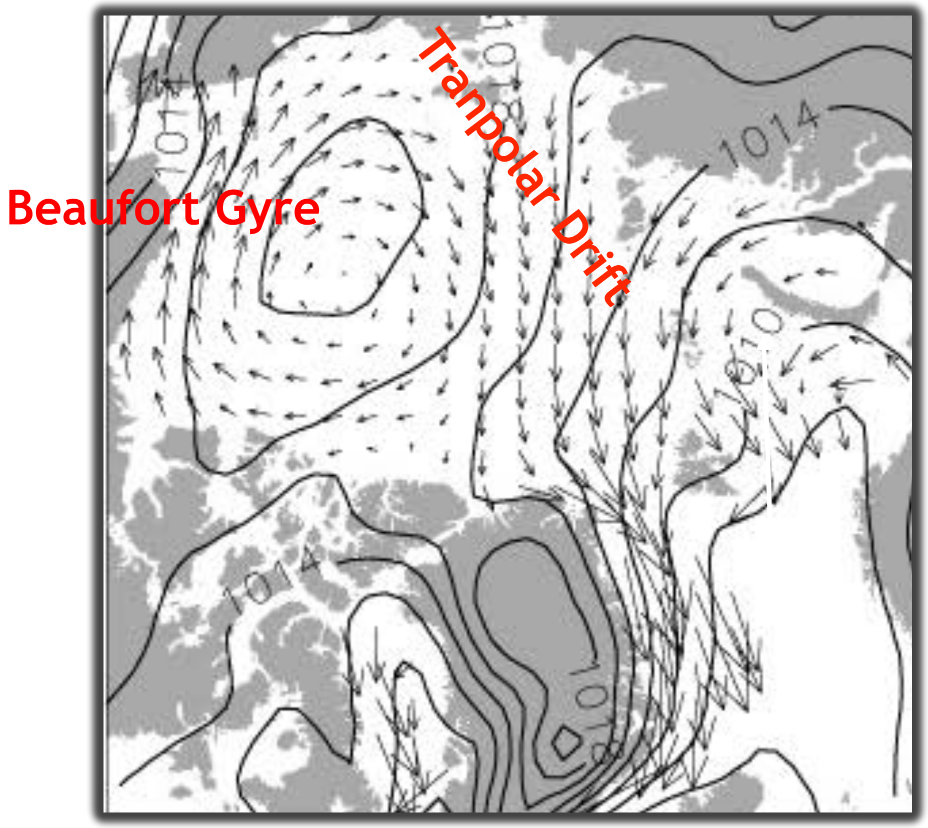
A ρ^2



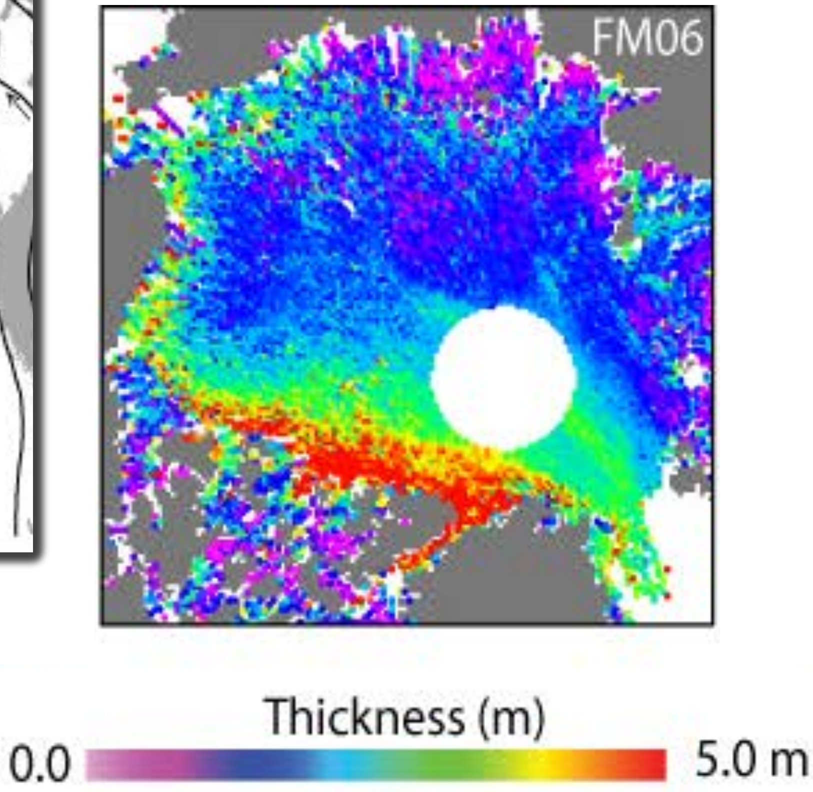
Isopleth: 0.01 0.75

Kwok et al., 2013

Ice Motion

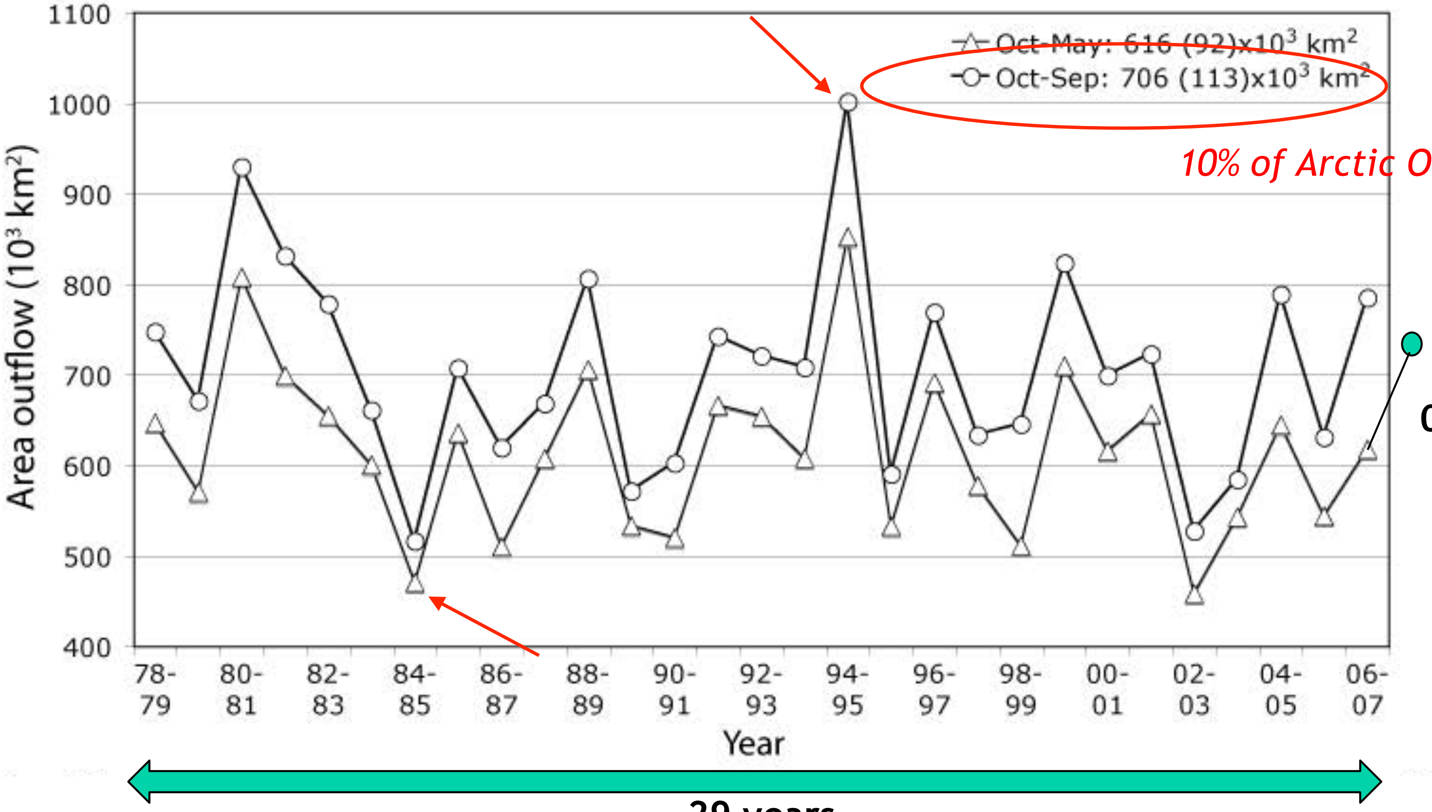


- *Circulation pattern*
  - *Thickness pattern*
  - *Regional Mass balance*
- *Ice Export*
  - *Straits and passages*



Fram Strait Area Outflow
Annual and Winter (Oct-May): 1979-2007

Peak (near peak of +NAO index)



10% of Arctic Ocean area

07-08

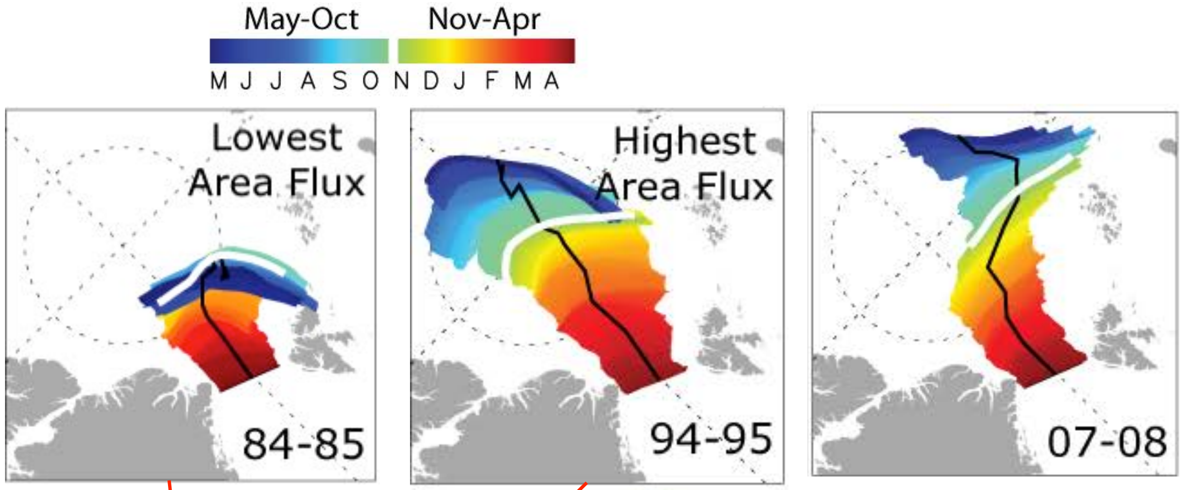
29 years

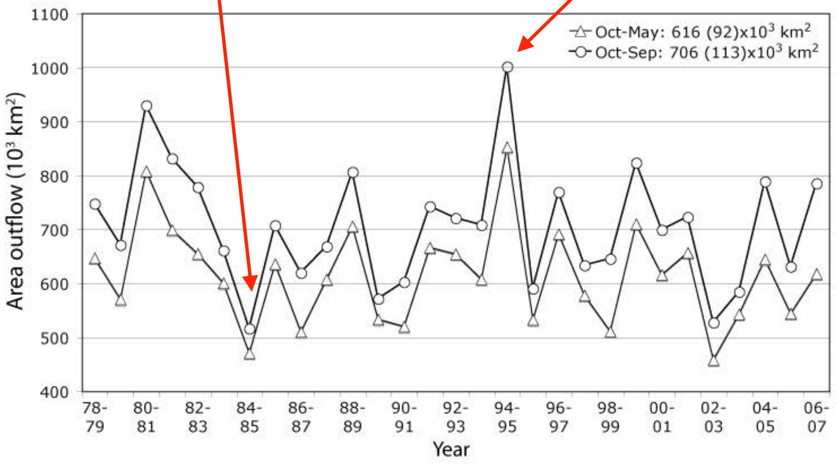
Avg Annual Export: ~2000 km^3

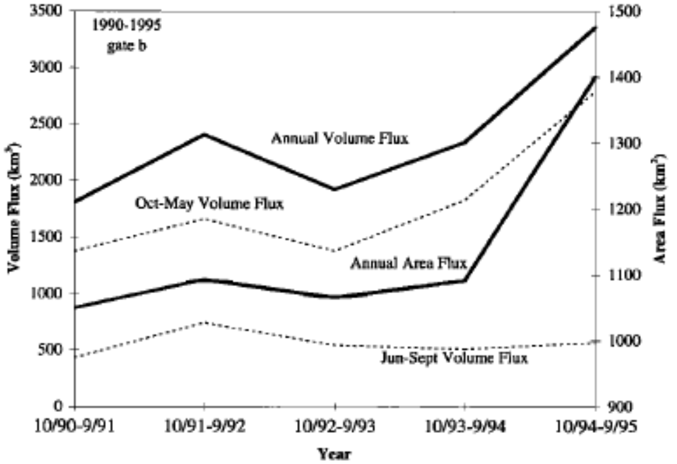
Variability is high!

Kwok and Rothrock [1999] and Kwok [2009]

Source regions of sea ice by backpropagation



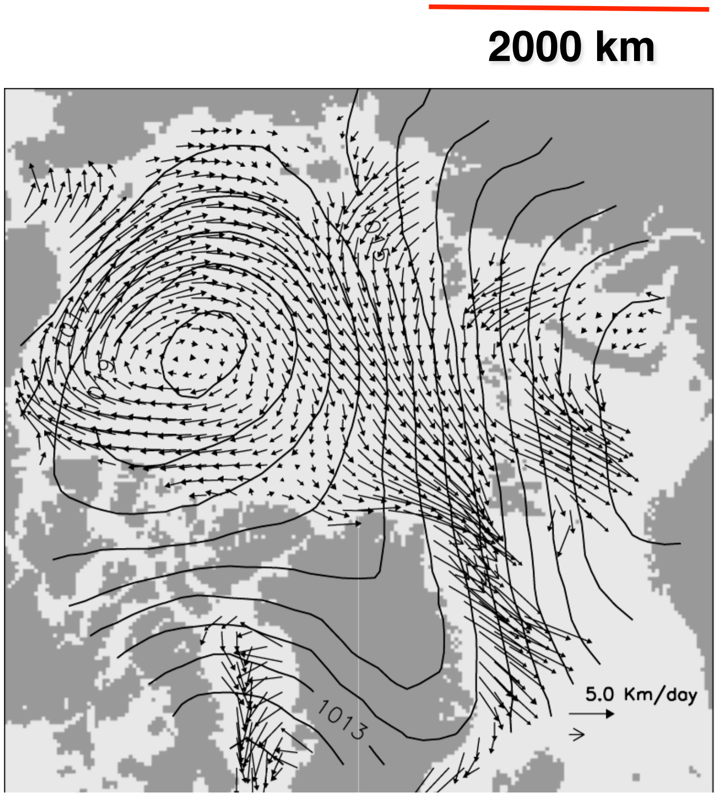


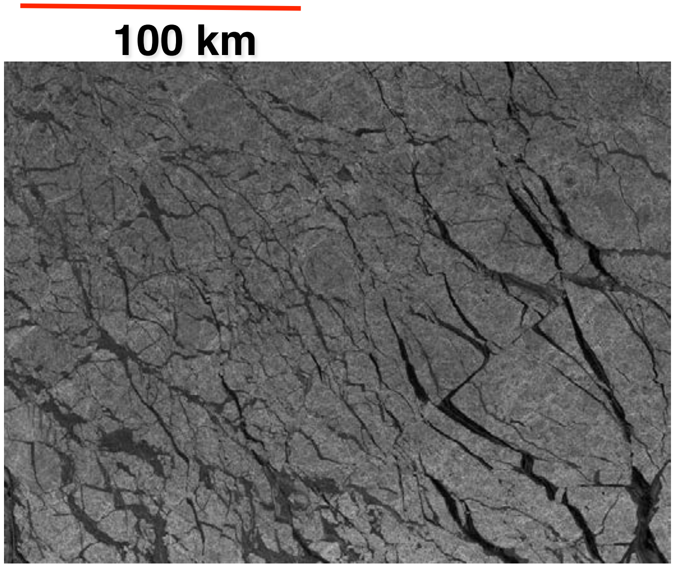


Area swept by the trajectories is correlated to the area flux

SMALL-SCALE ICE DRIFT

Dynamic response of ice
(at smaller length scales)



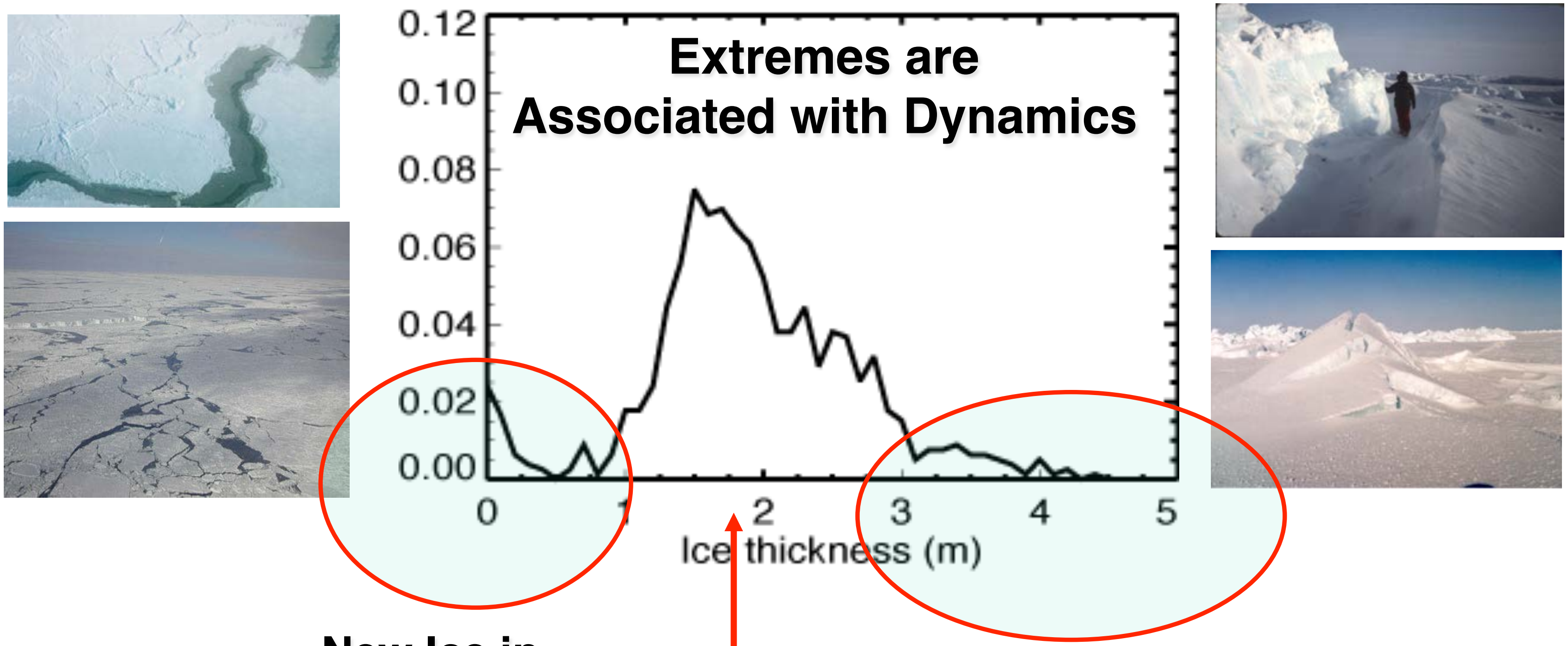


RADARSAT (100 m res)

ICE is a SOLID!
Dynamic response of winter sea ice to gradients in large-scale surface wind stress is often localized along quasi-linear fractures hundreds of kilometers long

Effect on Thickness distribution:
Thermodynamics vs Dynamics

Sample thickness distribution from ICESat: ~100 km transect



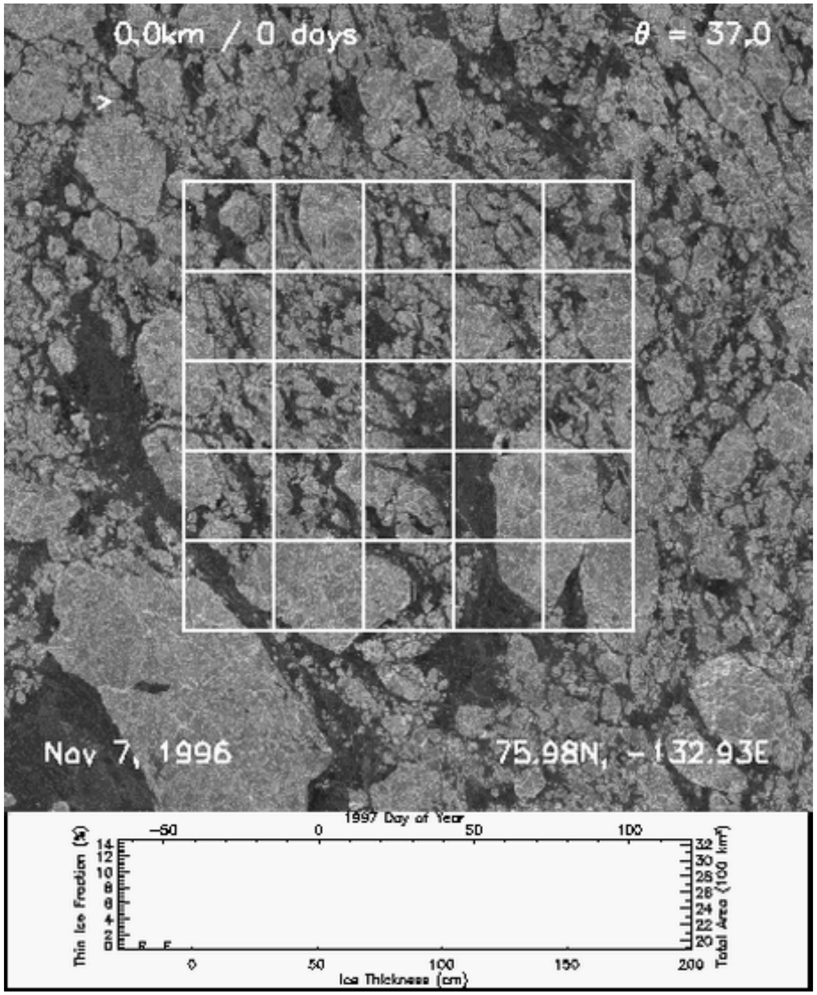
Extremes are Associated with Dynamics

New Ice in fractures

Seasonal Growth

Thick multiyear ice and Ridges

Ice Deformation from RADARSAT



5 km grid

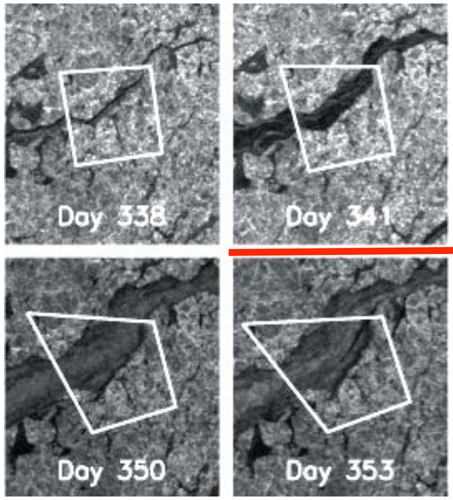
Div - ice prod
Conv- ridging

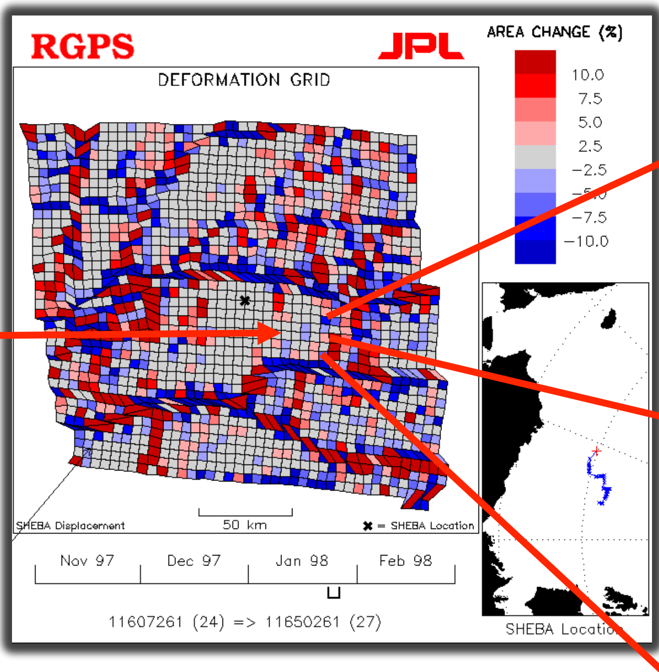
Resolution ~ 150 m

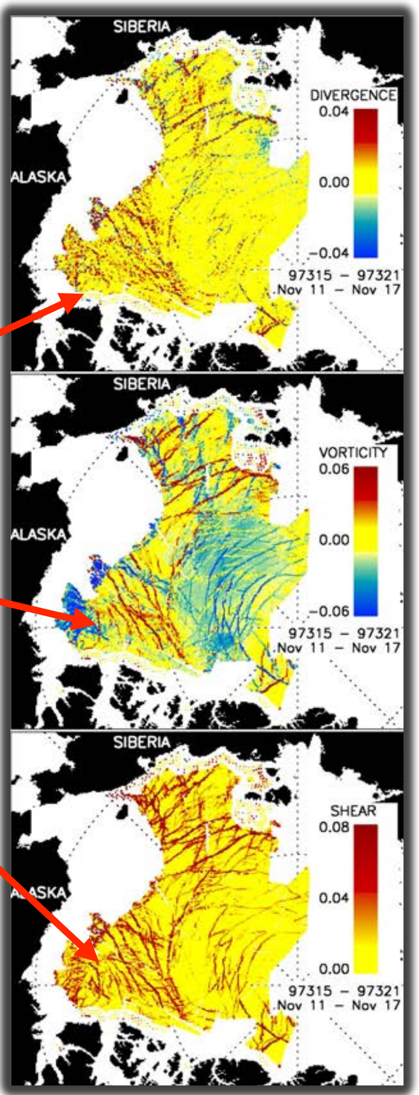
← Ice production

Satellite mapping of time-varying fractures in the ice cover

Grid resolution: 10 by 10 km





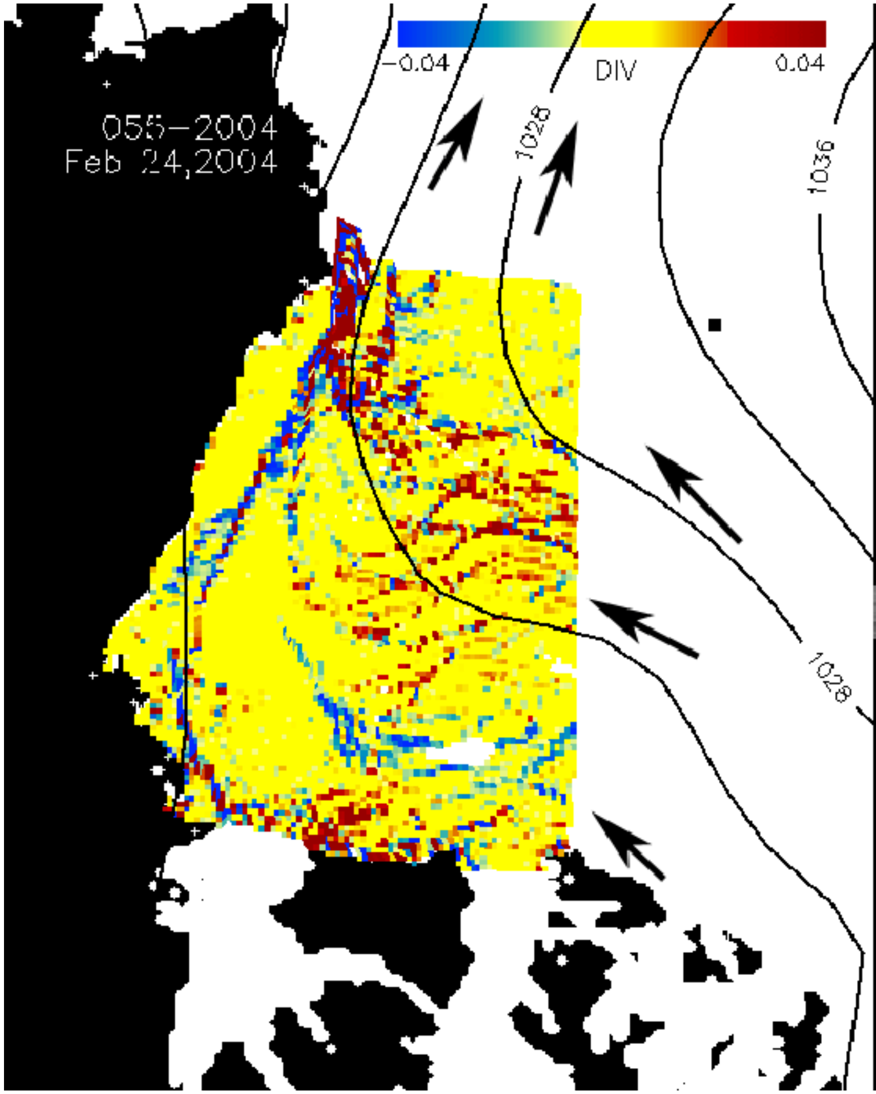


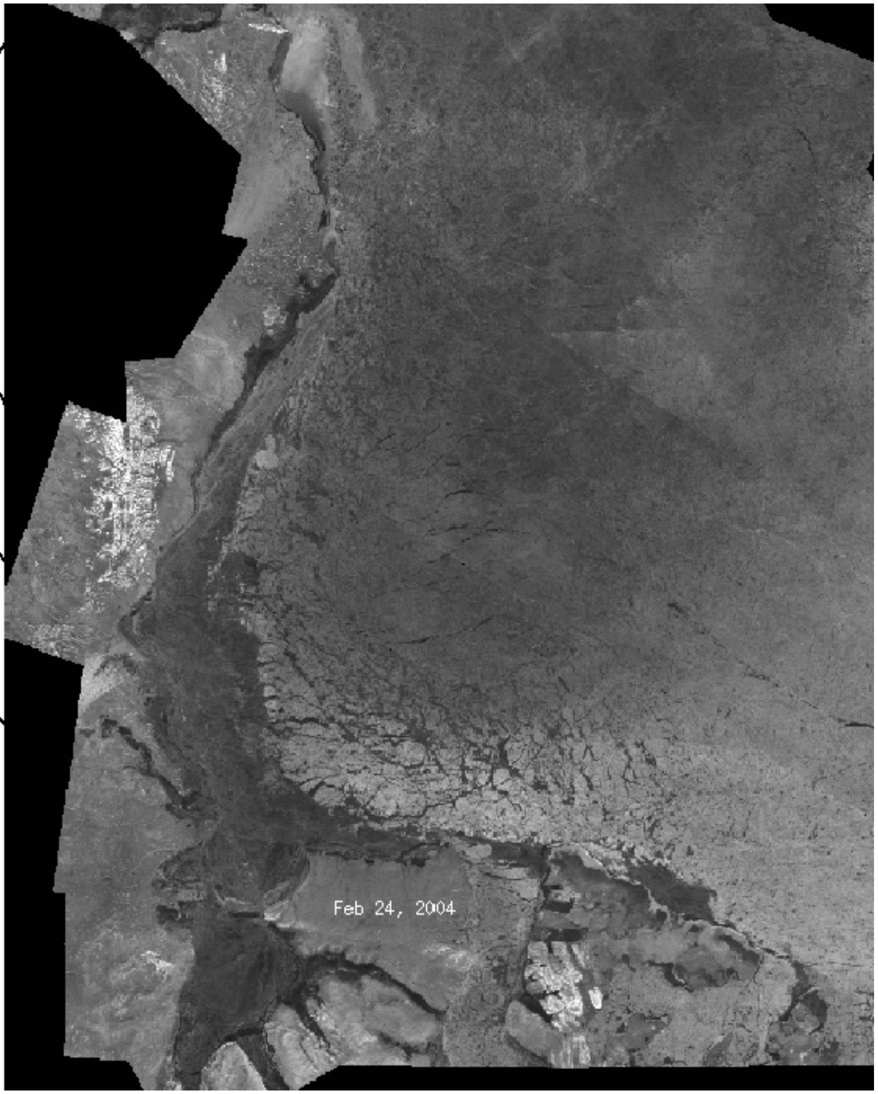
10^1 km

10^2 km

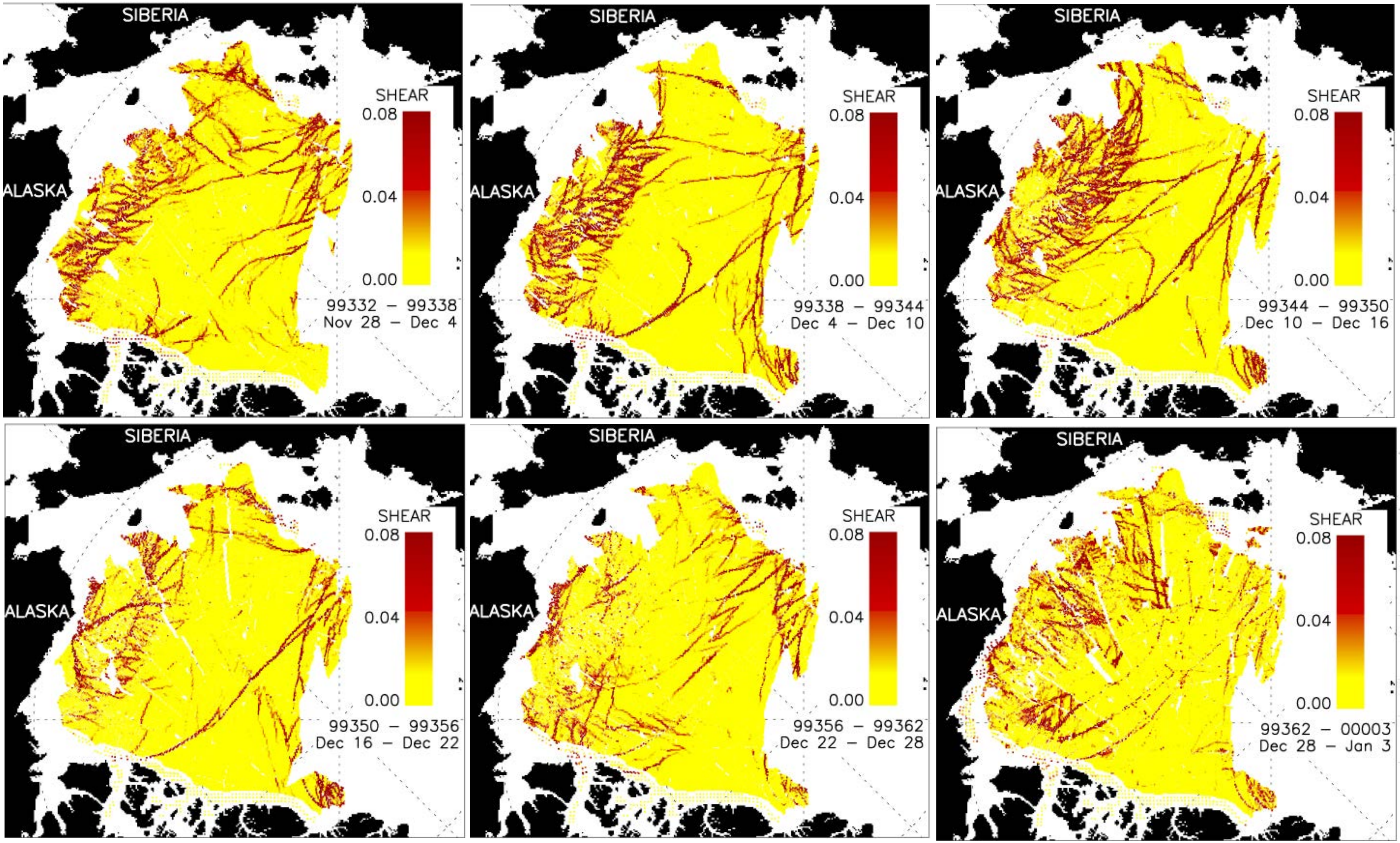
10^3 km

Time-varying deformation - Beaufort Sea (Divergence)



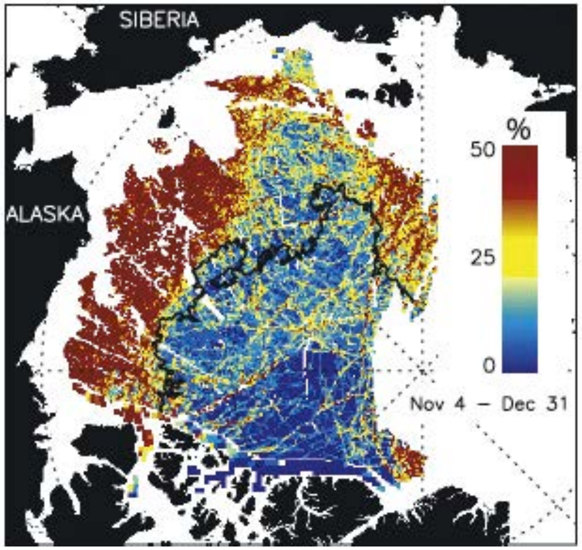


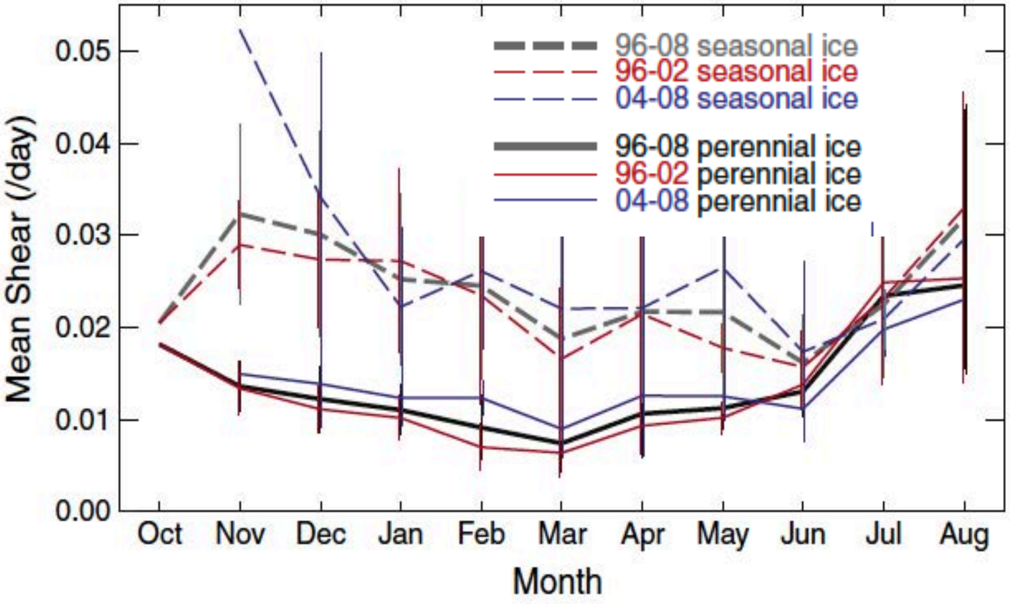
Shear patterns – density, orientation, persistence



Ice Deformation
Contrast between seasonal and old ice

1999-2000





- Question: how will increase in drift speed and deformation affect the ocean?

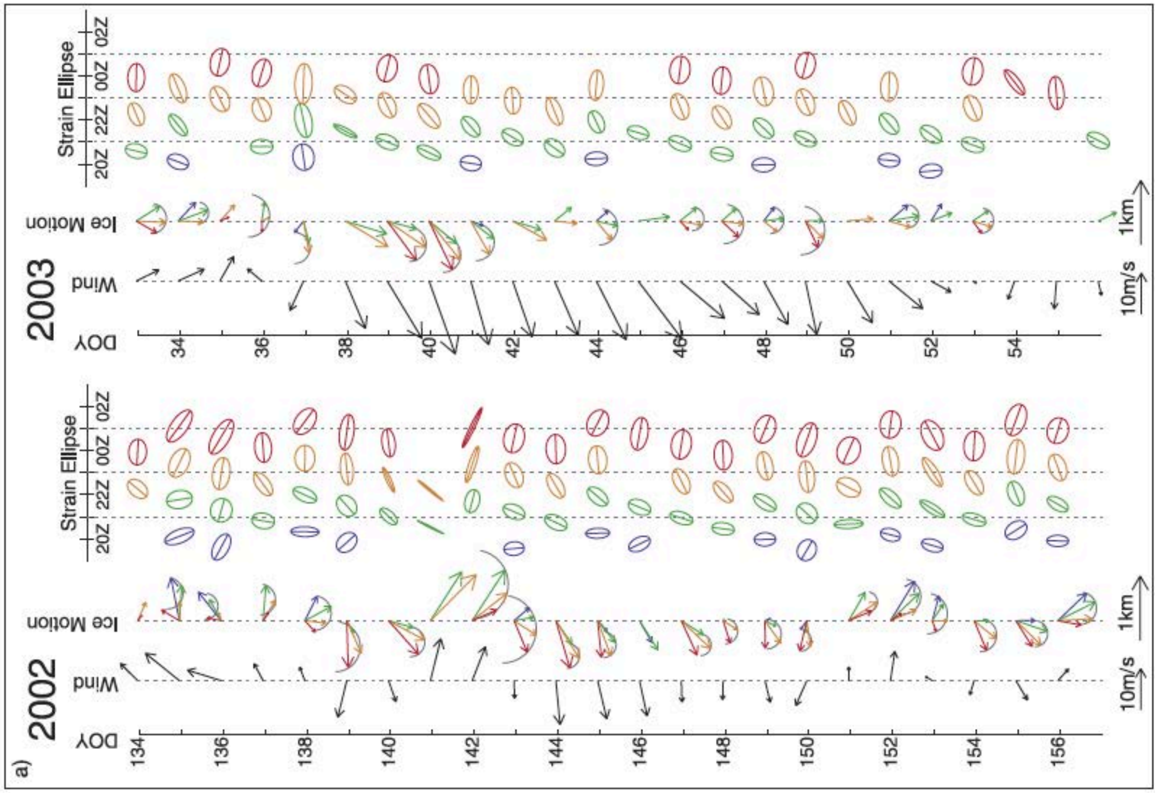
Sub-daily motion and deformation

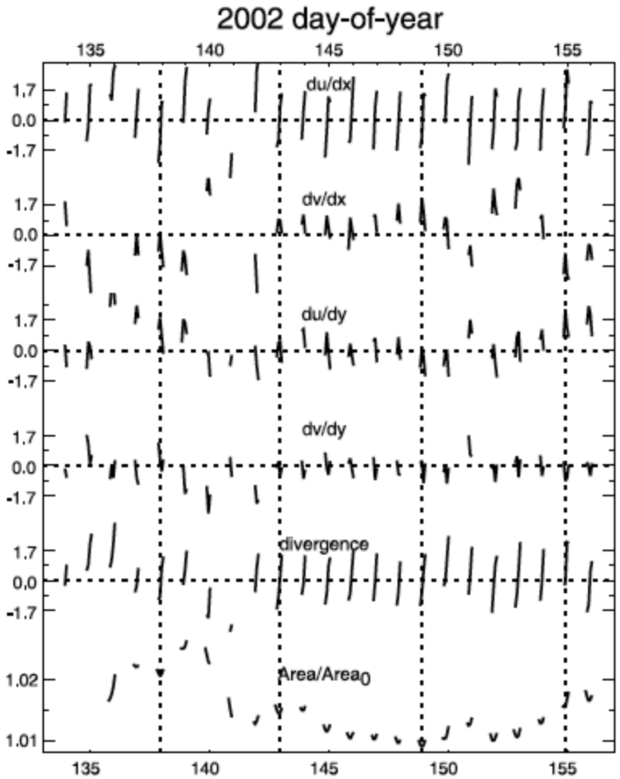
Sub-daily sea ice motion and deformation from RADARSAT observations

Ron Kwok and Glenn F. Cunningham
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

William D. Hibler III
IARC/Frontier, University of Alaska, Fairbanks, Alaska, USA

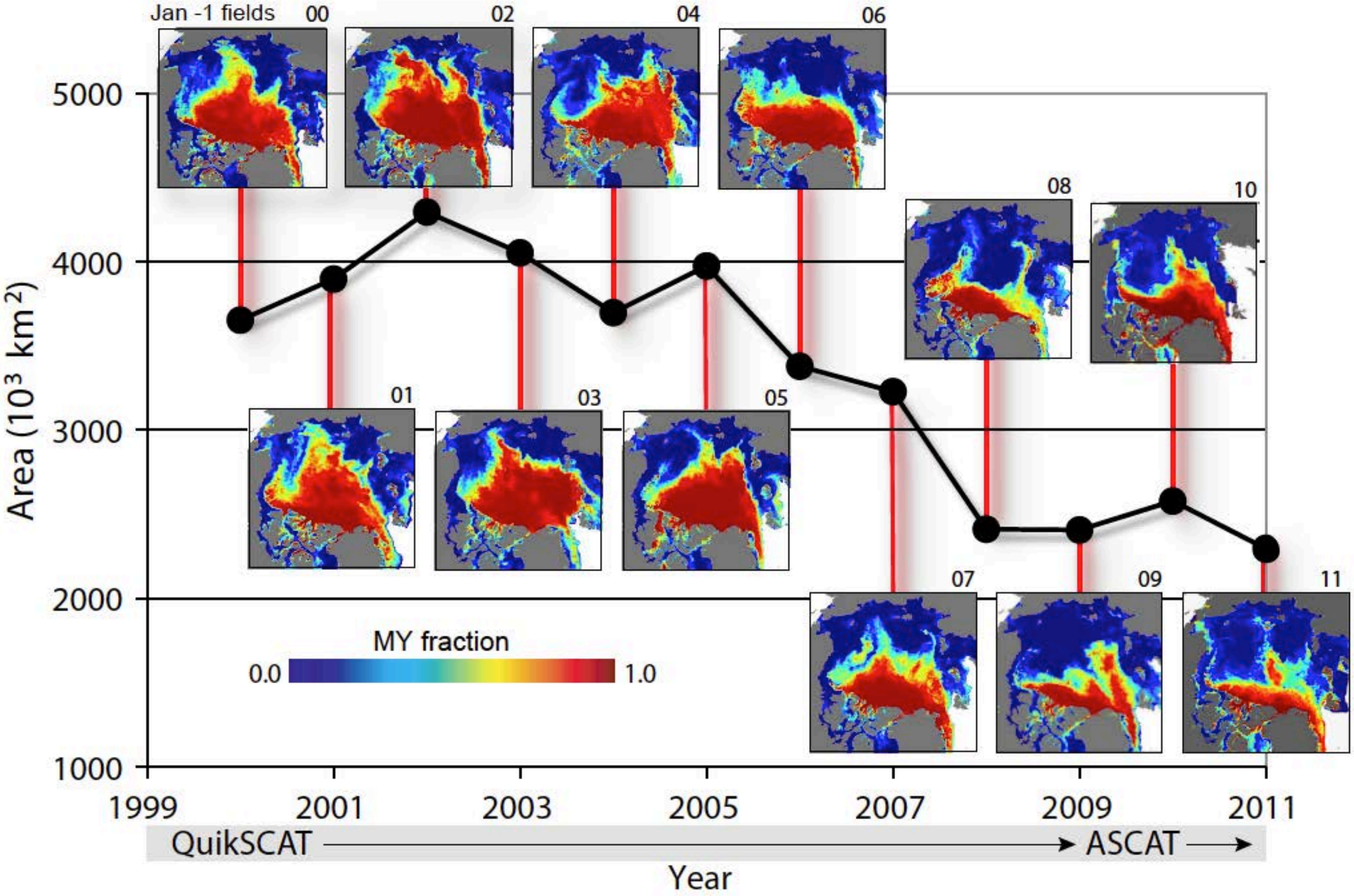
Received 26 September 2003; revised 21 October 2003; accepted 28 October 2003; published 11 December 2003.



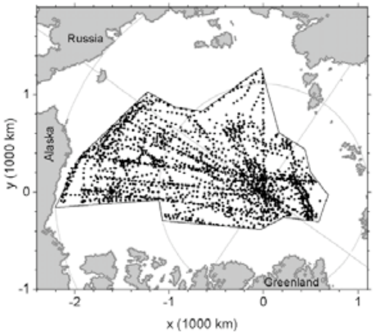


RECENT RESULTS

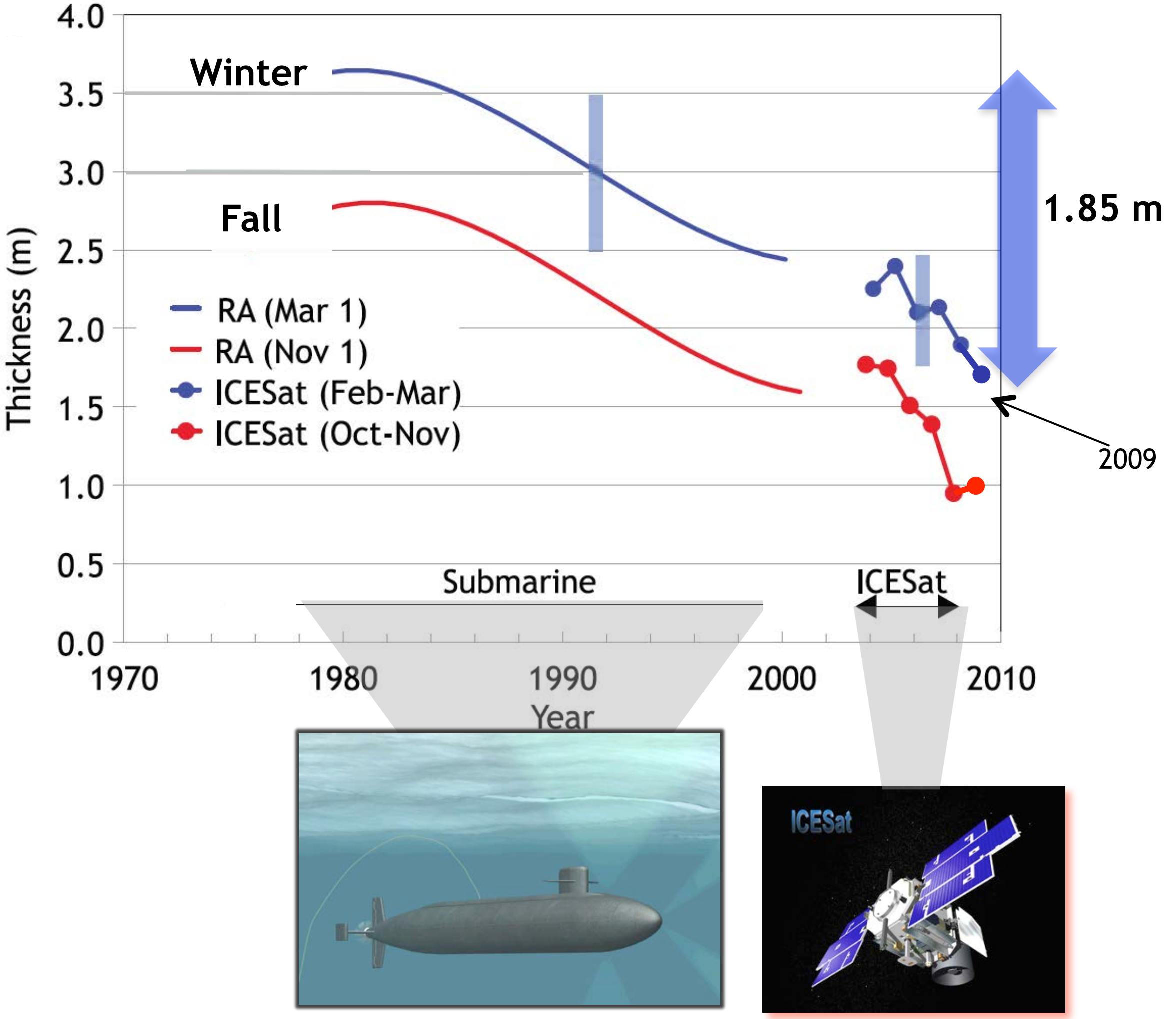
Decline in multiyear ice coverage



Decline in sea ice thickness from submarine and ICESat records: 1978 - 2009



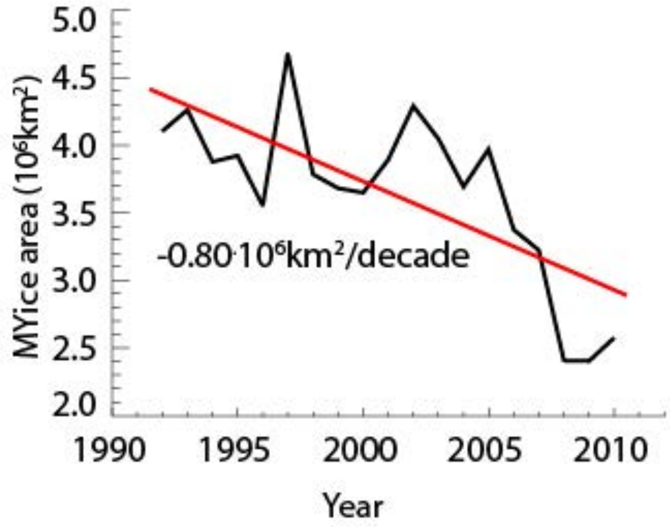
Note: Submarine estimates based on regression of available ice draft from US Navy submarines



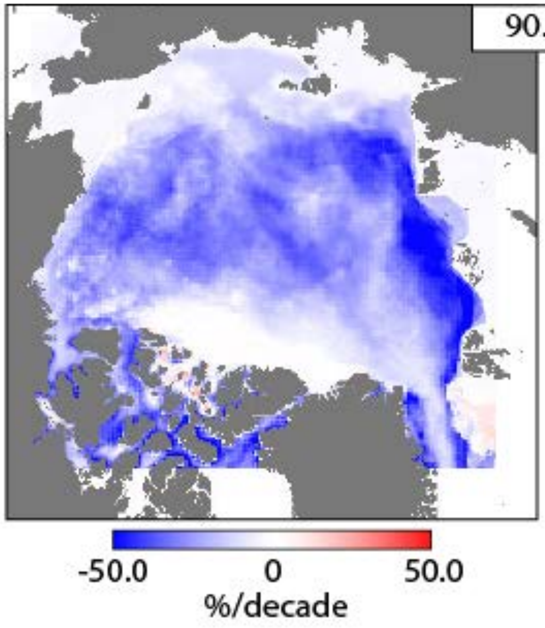
(Kwok and Rothrock, 2009)

Satellite Ice Drift and MY ice coverage
1992-2010

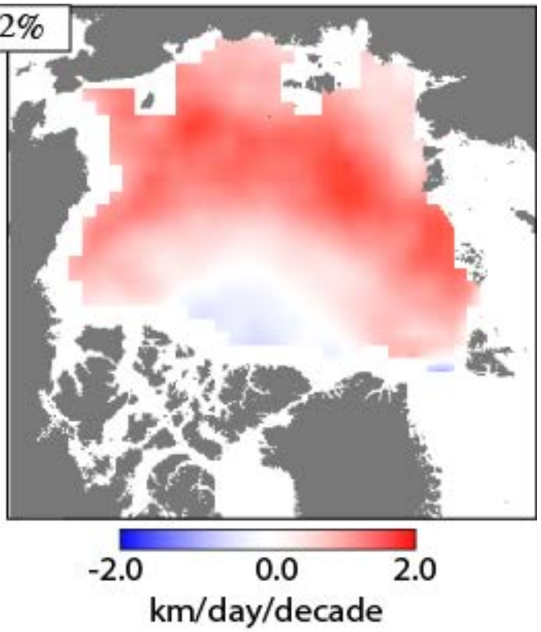
MY ice coverage trend



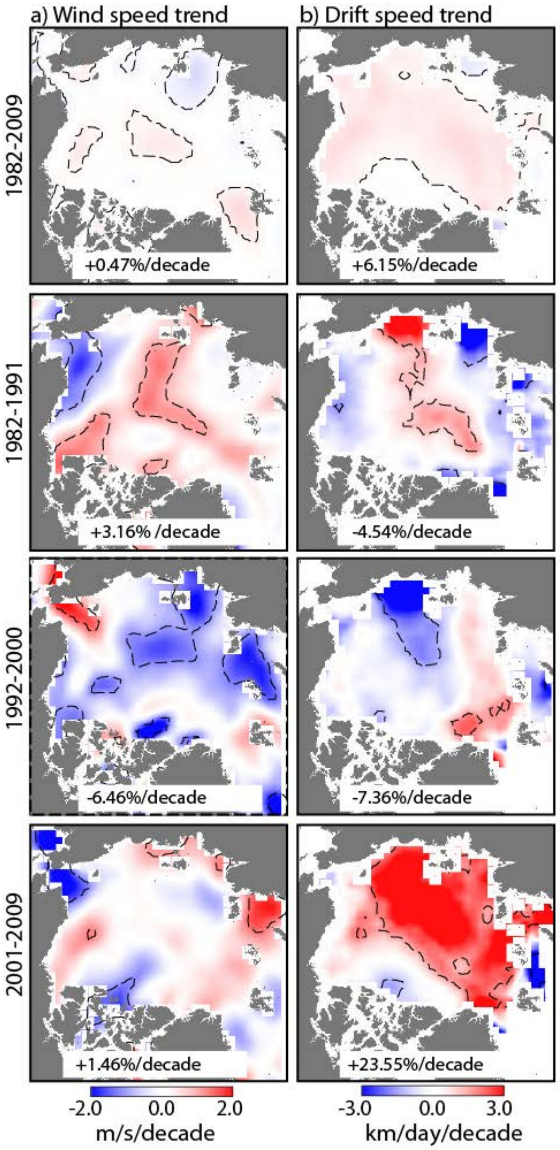
MY ice coverage trend

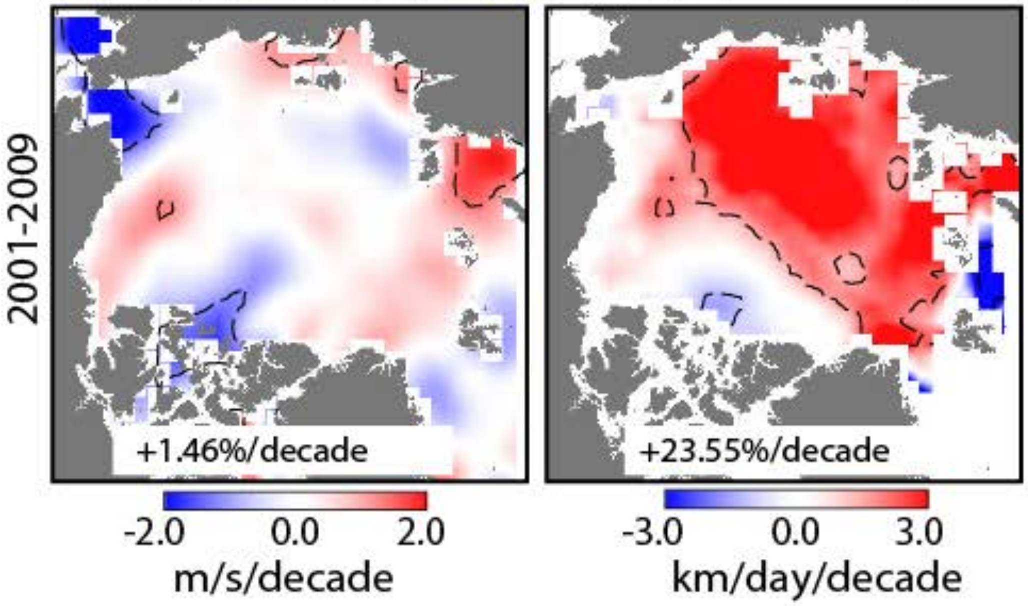


Trend in drift speed

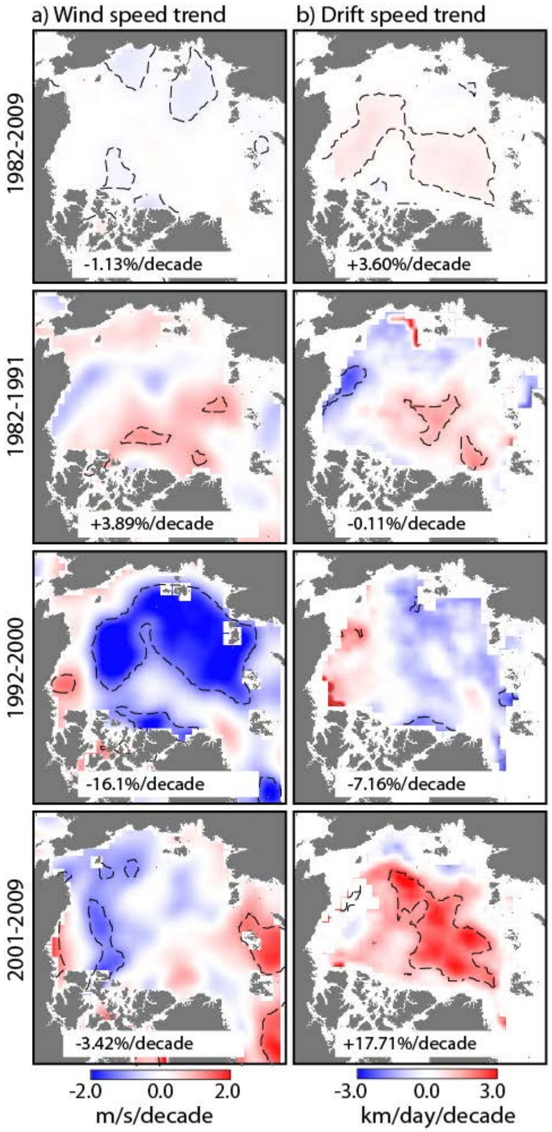


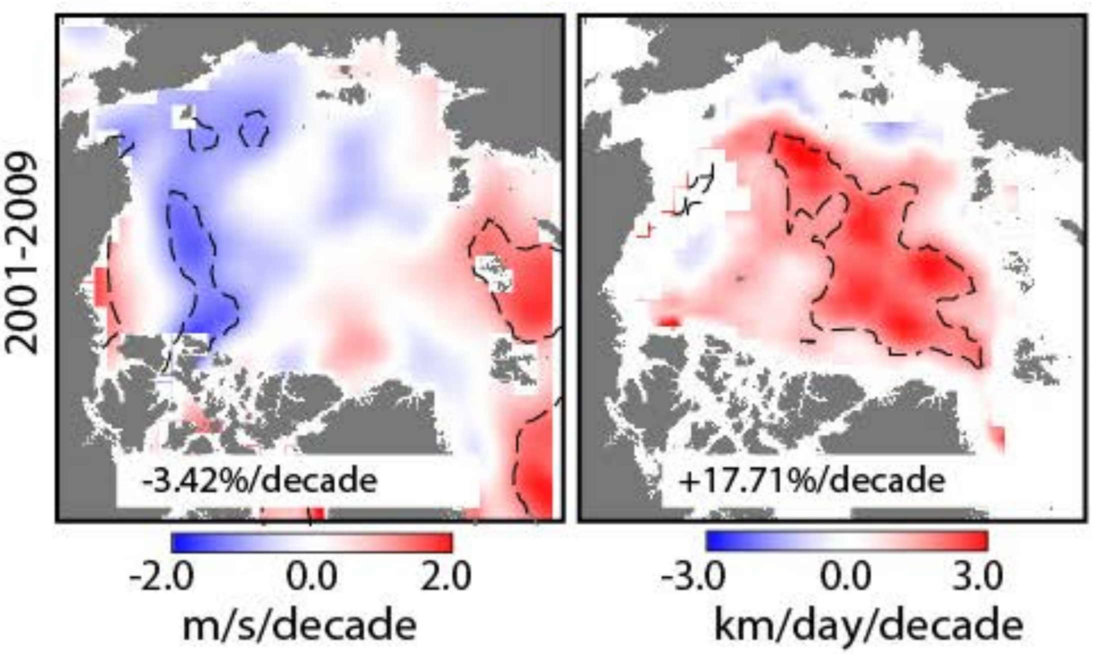
Changes in Drift Speed - Winter



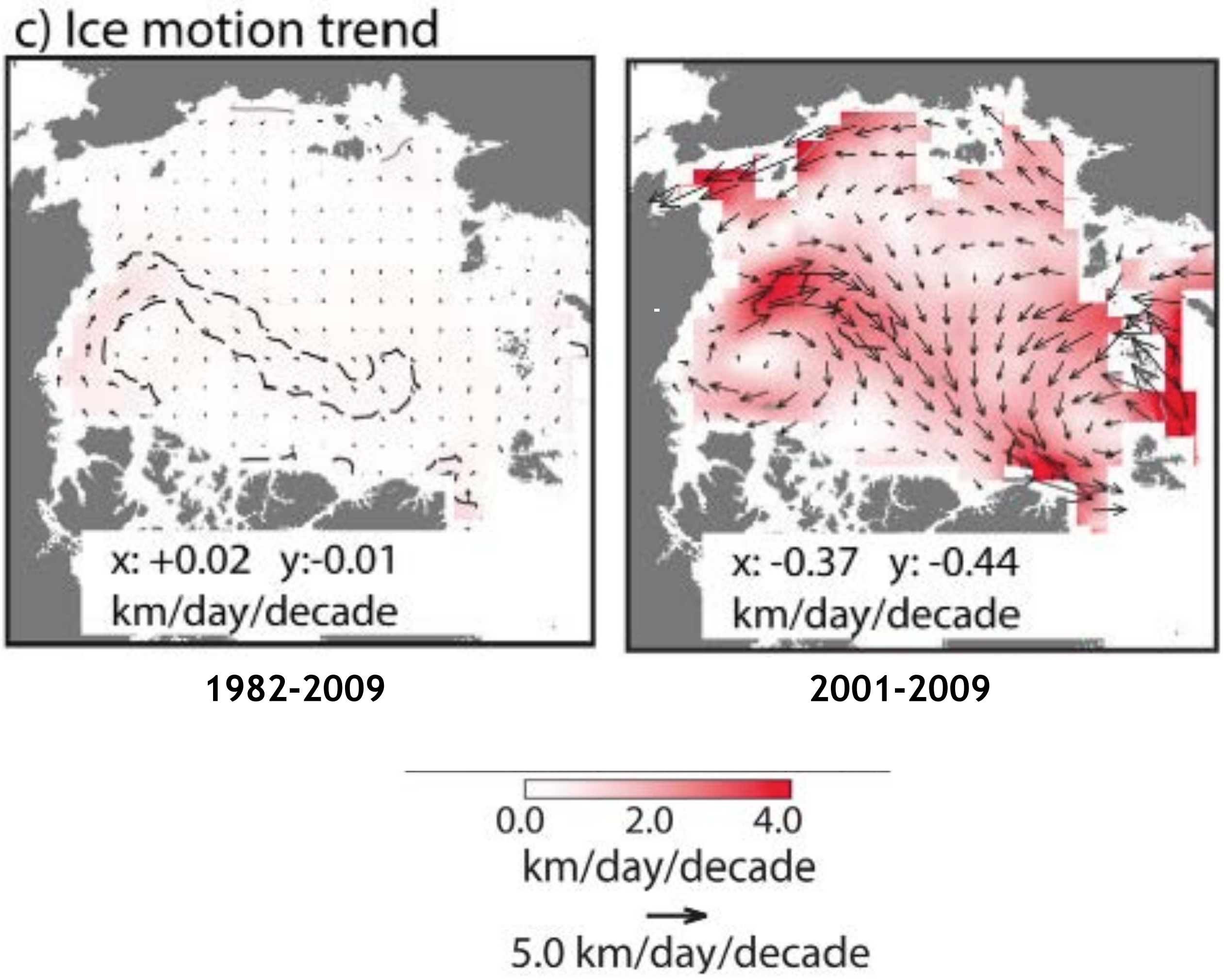


Changes in Drift Speed - Summer





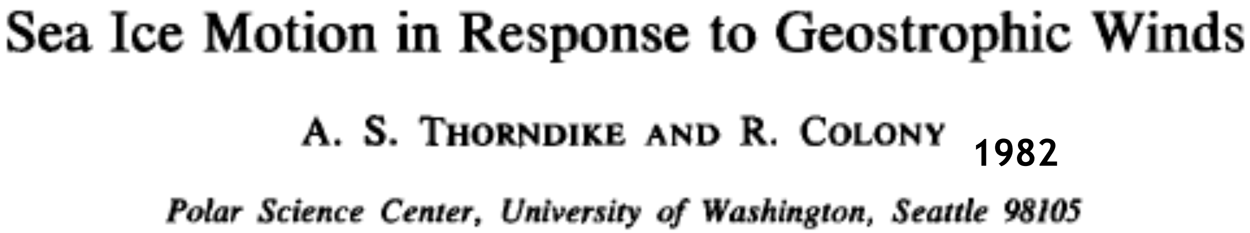
Vector Trend



1982-2009

2001-2009

Relationship between wind and ice drift: Has it changed?



Sea Ice Motion in Response to Geostrophic Winds

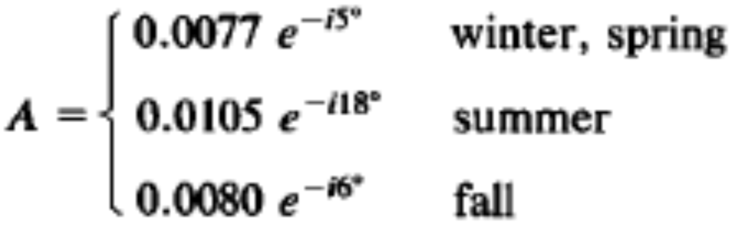
A. S. THORNDIKE AND R. COLONY

Polar Science Center, University of Washington, Seattle 98105

1982

$$\mathbf{u} = A\mathbf{G} + \mathbf{c}$$

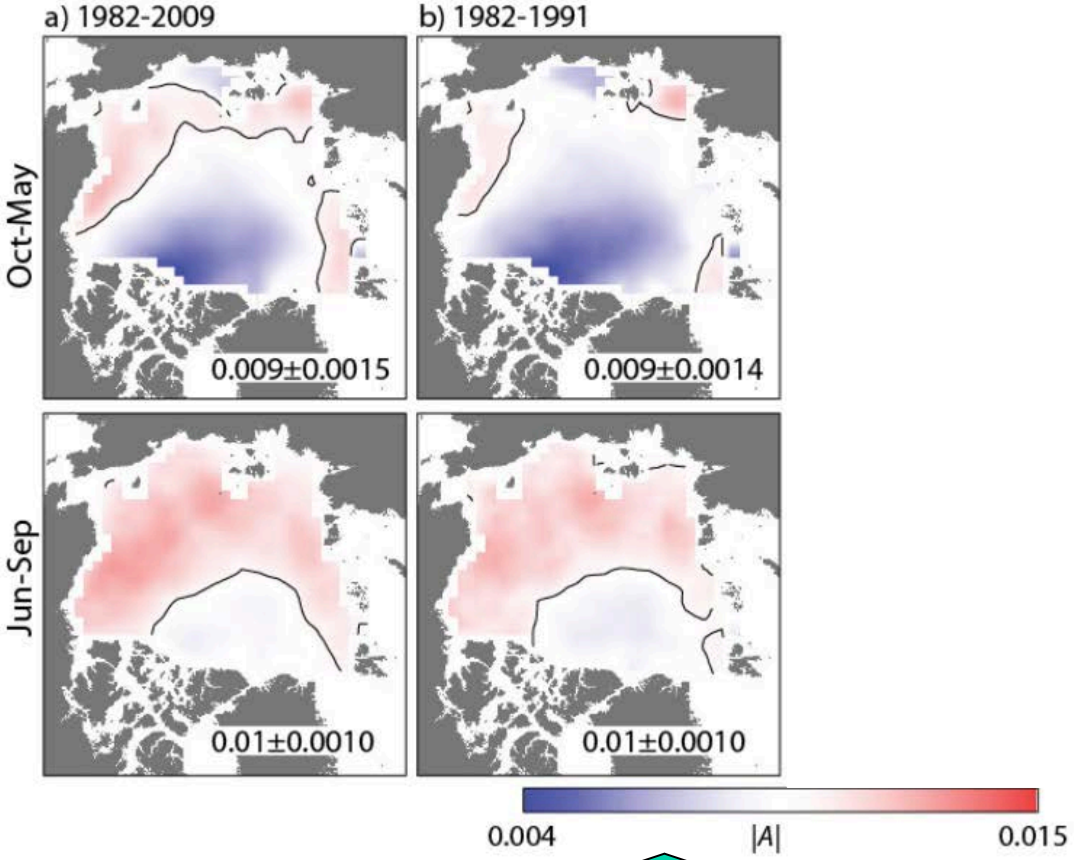
Vector quantities
u = ice motion (buoy drift)
A = scaling factor
G = Geostrophic wind
C = ocean current



$$A = \begin{cases} 0.0077\, e^{-i5^\circ} & \text{winter, spring} \\ 0.0105\, e^{-i18^\circ} & \text{summer} \\ 0.0080\, e^{-i6^\circ} & \text{fall} \end{cases}$$

Away from the coast (~400 km), more than 70% of the variance in ice motion in central Arctic can be explained by geostrophic wind at daily time scales.

Scale Factor A in (u =AG + c)

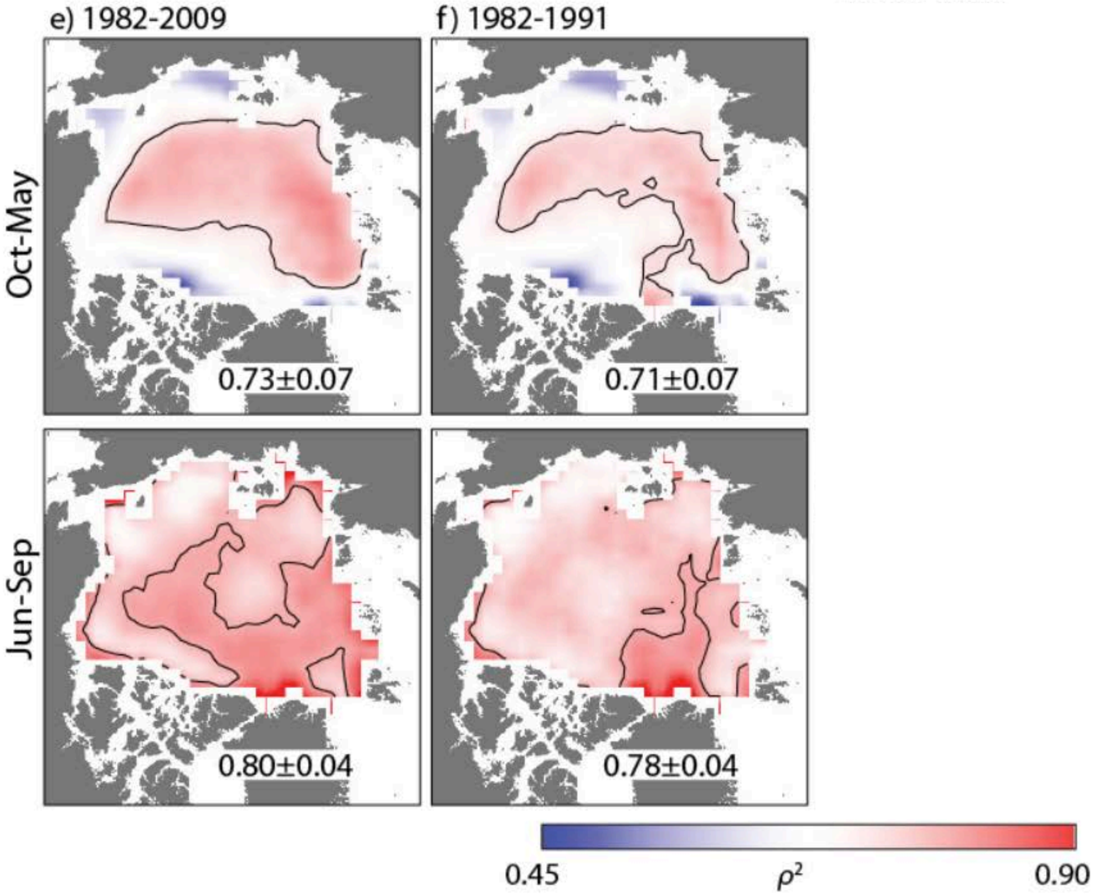


Isopleth: 0.01

$$A = \begin{cases} 0.0077\, e^{-i5^\circ} & \text{winter, spring} \\ 0.0105\, e^{-i18^\circ} & \text{summer} \\ 0.0080\, e^{-i6^\circ} & \text{fall} \end{cases}$$

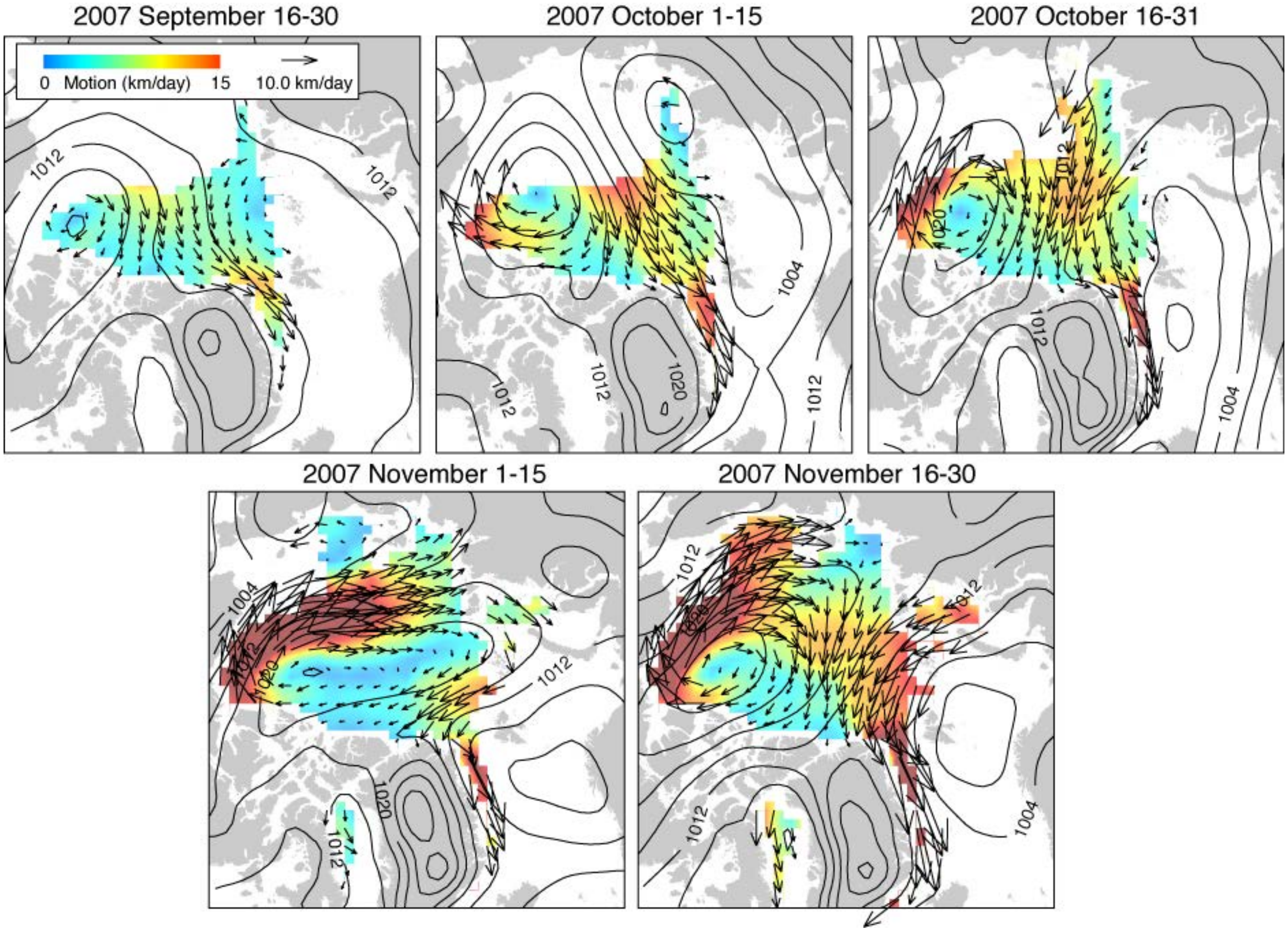
(Thorndike and Colony, 1982)

Squared Correlation Field

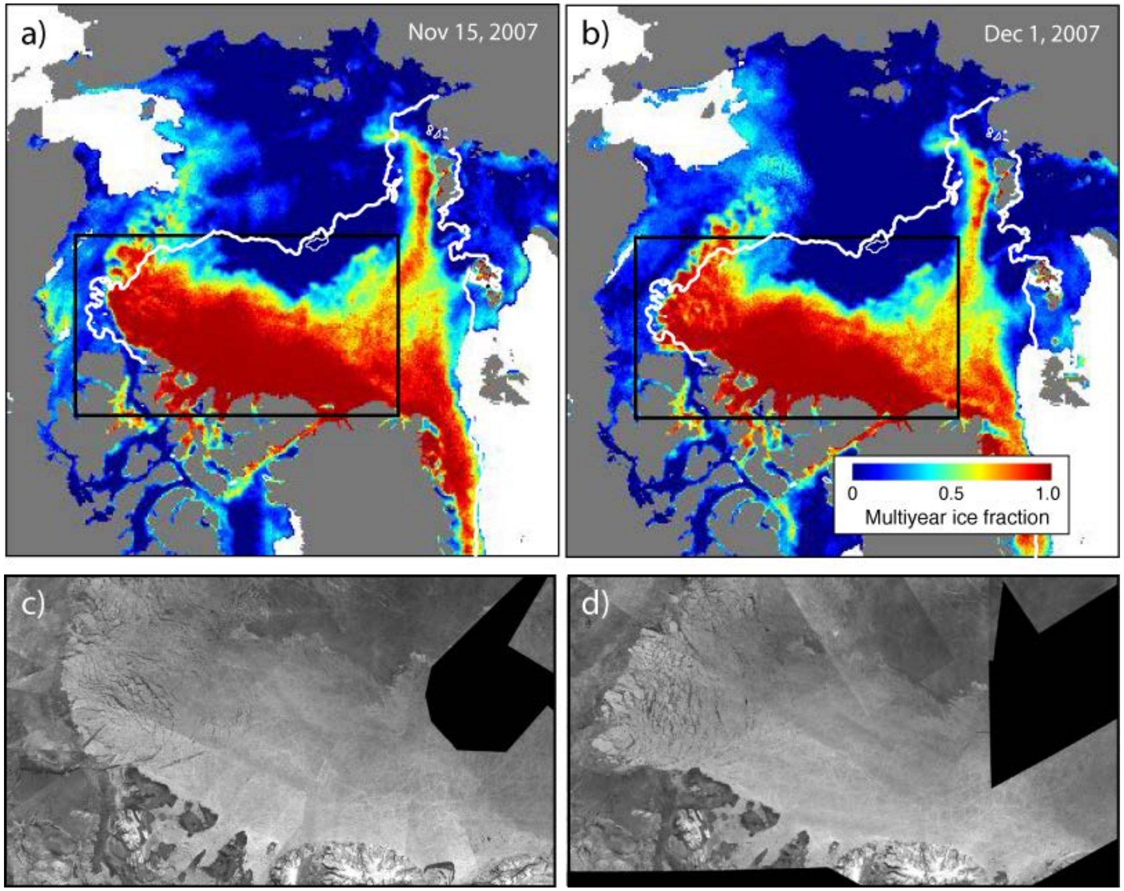


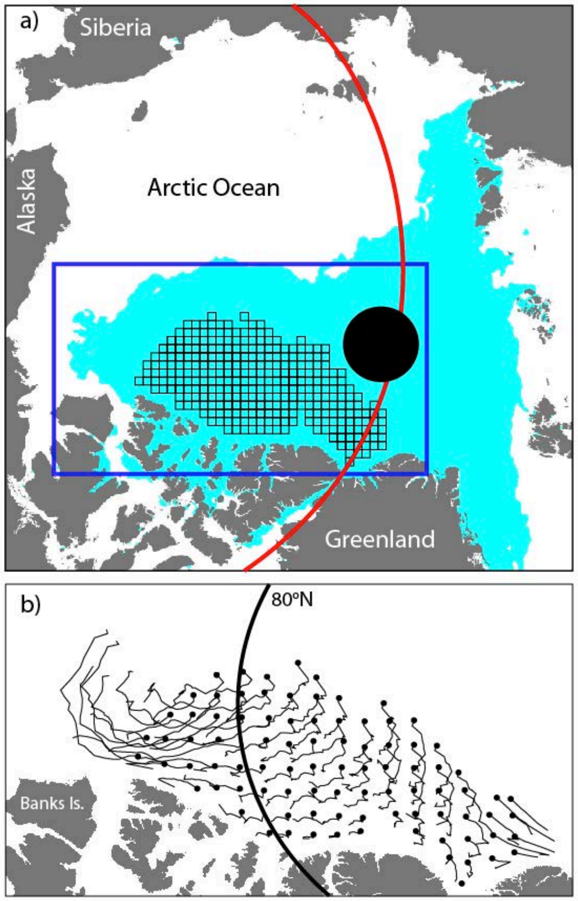
Isopleth: 0.75

Ice Motion in Sept - Nov 2007 after record minimum

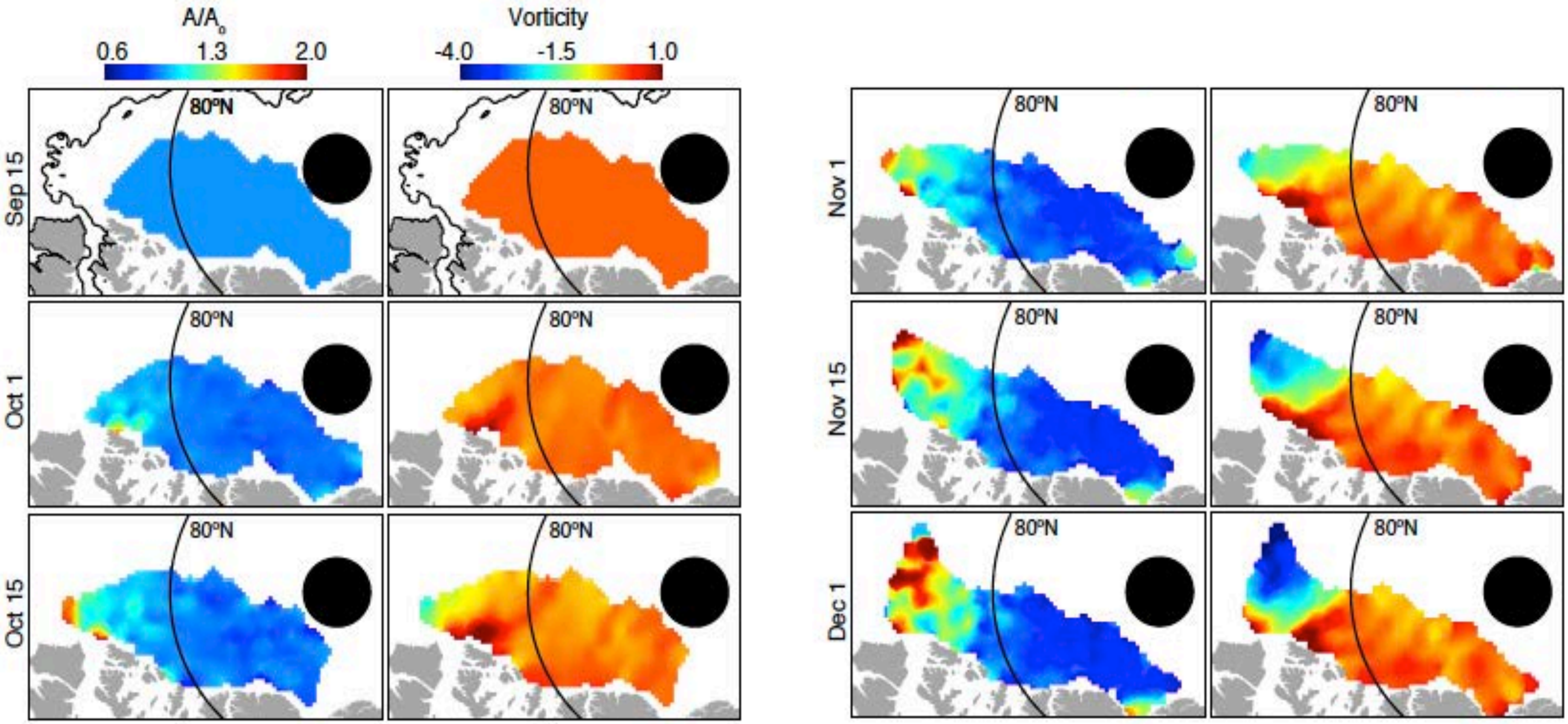


Large convergence north of coast of Ellesmere and Greenland





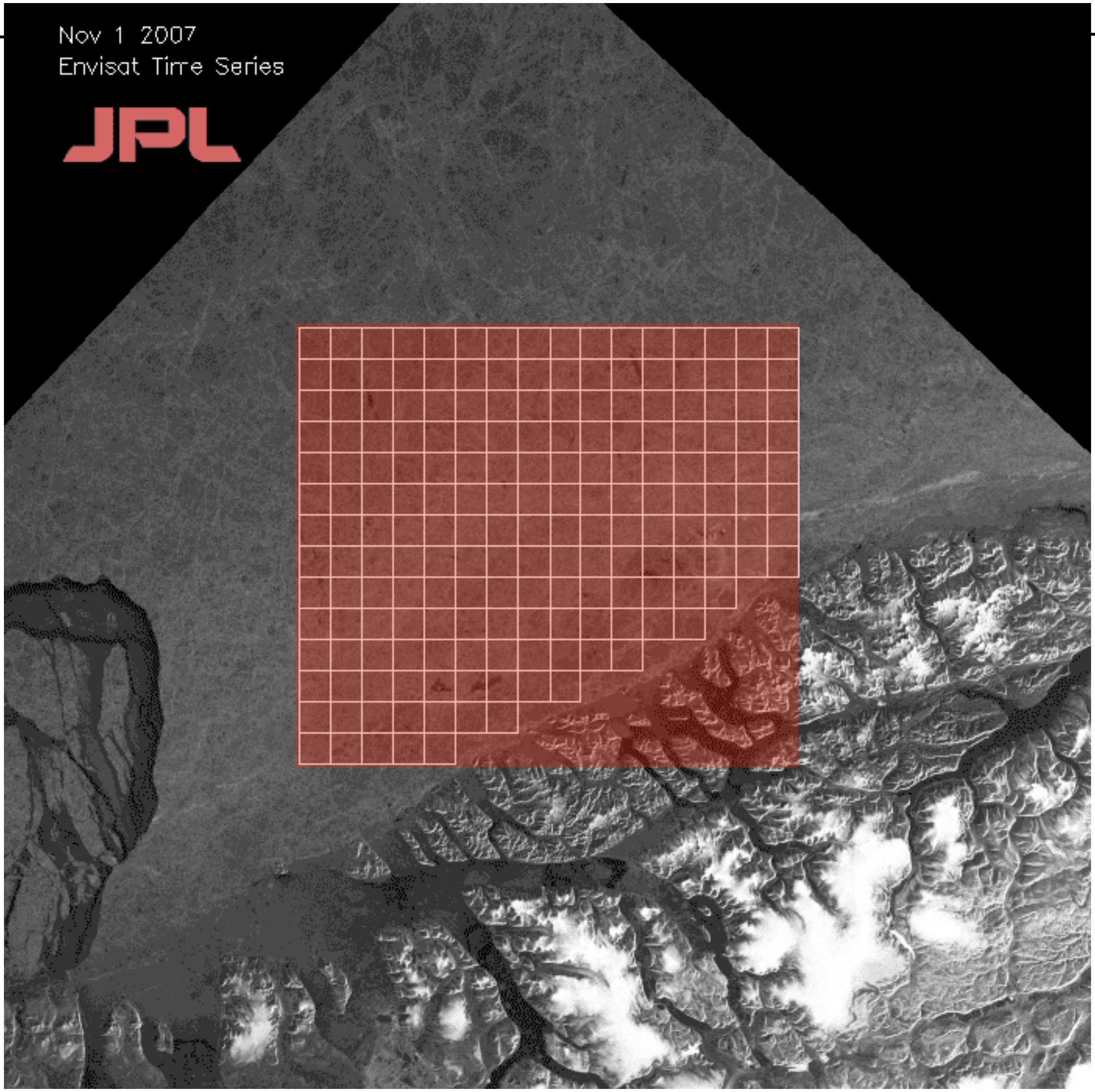
Convergence and divergence between Sep and Dec



25% increase

13% decrease

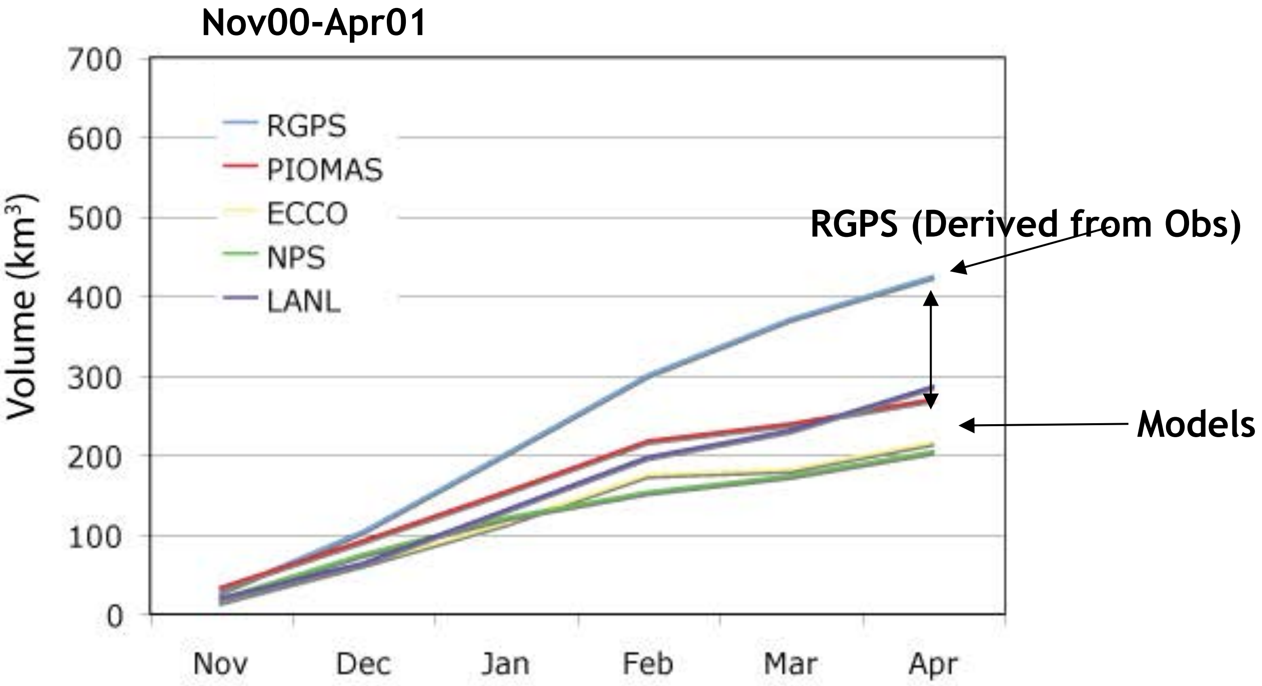
Northeast Lincoln Sea (Nov 1 – Jan 2)



5 km cells

THOUGHTS ABOUT THE FUTURE

Model vs RGPS ice production

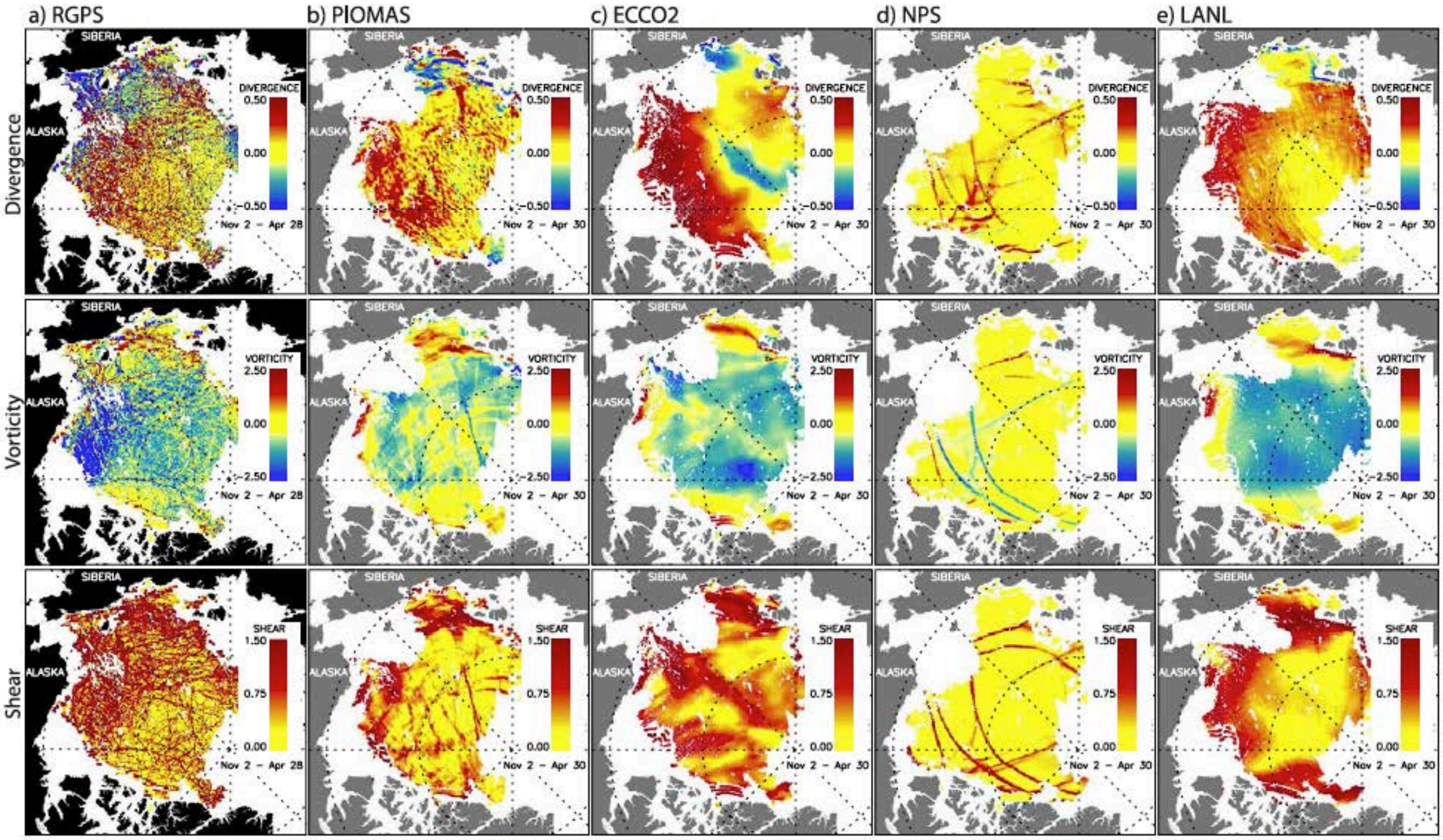


RGPS (Derived from Obs)

Models

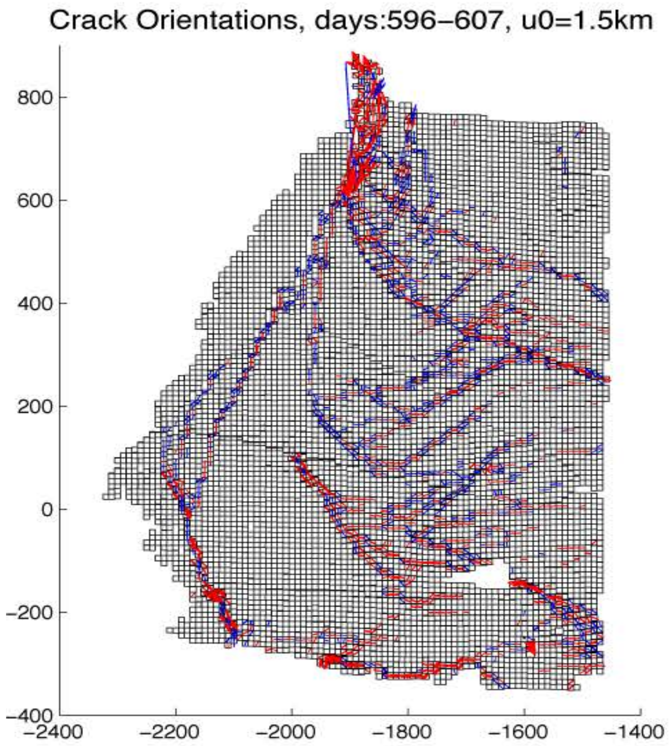
Model simulations produce less ice because deformation is poorly simulated – comparison is over limited domain

Deformation in models

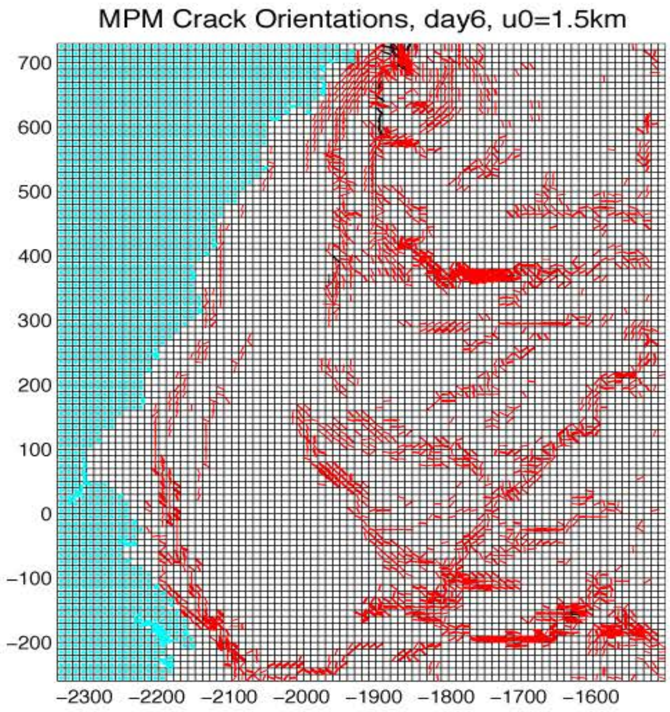


Kwok et al., 2008

Elastic Decohesion



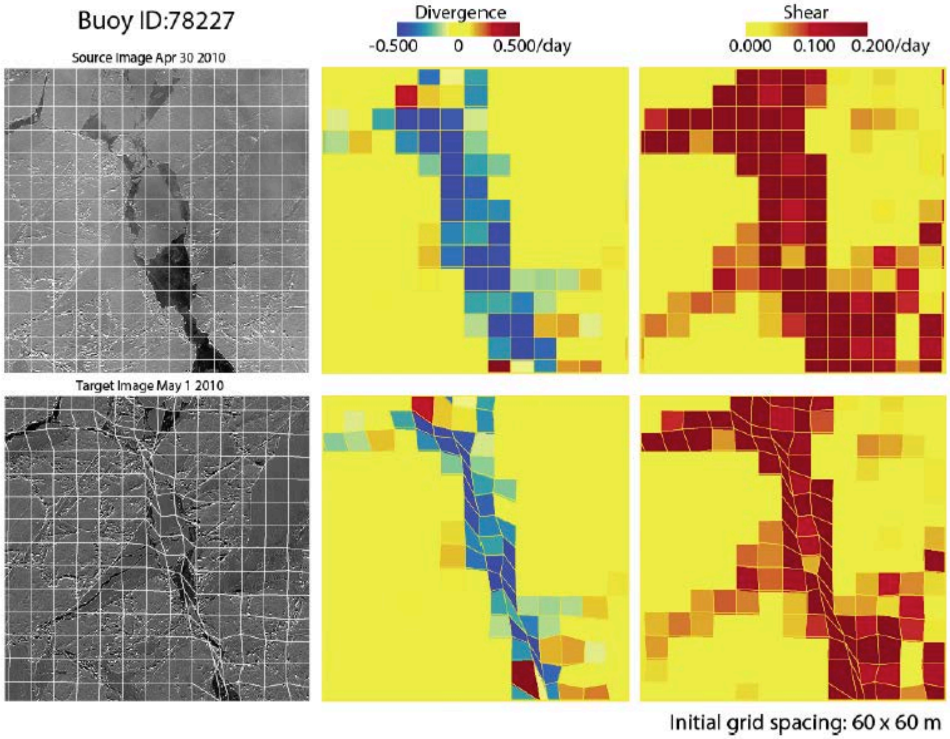
Kinematics



Start day 54, BCs & injection & initialization

Sulsky, Schreyer, Coon and Kwok

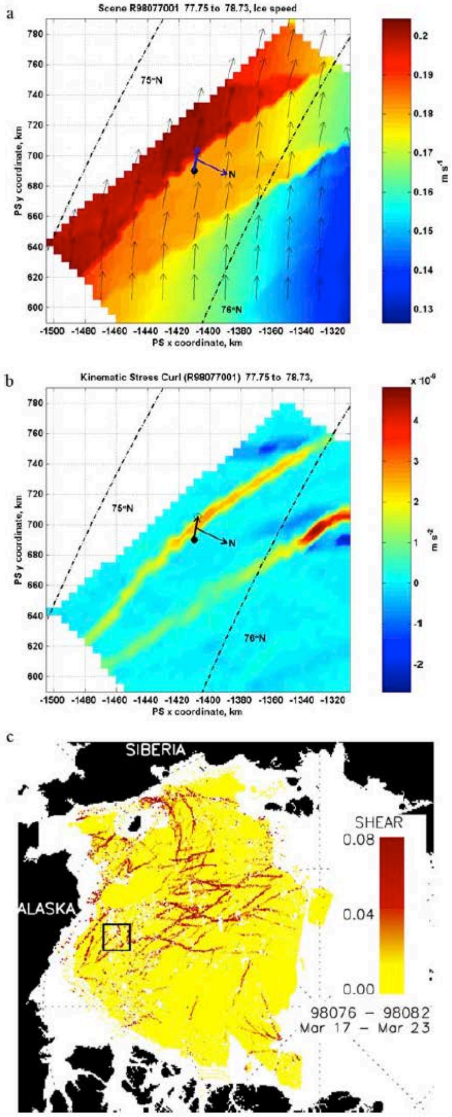
Ridging/rafting (mechanical redistribution)



- Much less effort has focused on how ice is redistributed among thickness categories by mechanical processes such as rafting and pressure ridging
- Current ridging schemes used in coupled ice/ocean models are largely heuristic and are difficult to verify empirically

Upwelling of Arctic Pycnocline associated with shear motion of ice (SHEBA)

Kinematic stress curl
From satellite ice drift



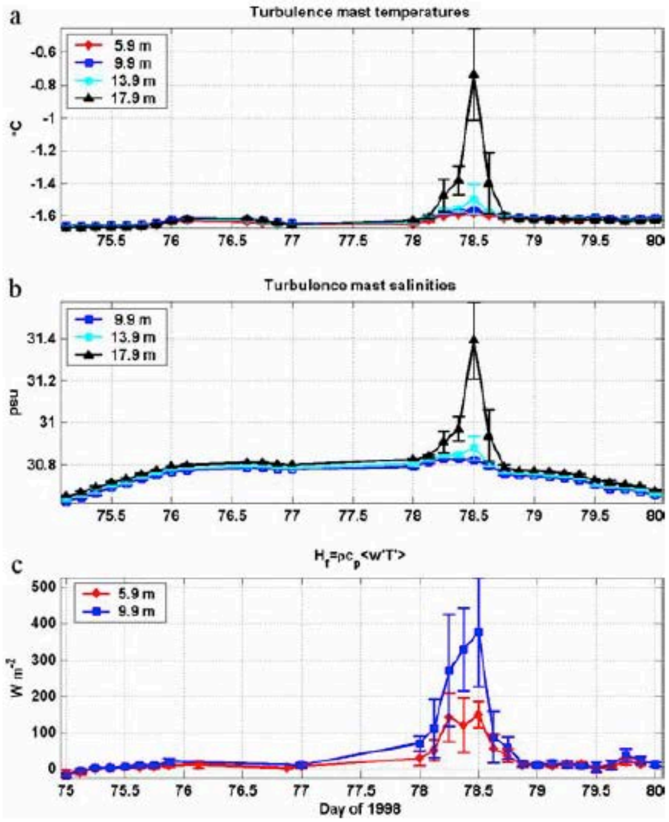


Figure 1. (a) Temperature (3-h averages) at fixed levels on the SHEBA turbulence mast. Error bars are twice the sample standard deviation. (b) Salinity. Conductivity measurements at 5.9 m were made with an open electrode microstructure instrument (c) Turbulent heat flux from the covariance of temperature deviations and vertical velocity. Error bars are twice the standard deviation of the 15-min turbulence realizations in each 3-h average. On day 78, clusters at 13.9 and 17.9 m were in the pycnocline where turbulence statistics were contaminated by internal waves.

McPhee et al. 2005

- *Broad survey*
- *Changes in ice motion and circulation*
- *Some topics of interest*
  - *Sub-daily deformation (tides and inertial motion)*
  - *Ocean response to changes in ice motion*
  - *Modeling fractures and redistribution*

QUESTIONS?