Sea Ice Motion:
Physics and Observations

JPL

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Topics

- Kinematics: How does the ice move?
- Sea ice motion
  - Large Scale: Regional and basin scale mass balance
  - Small Scale: deformation and thickness distribution
- Observations
- Results and Challenges

Ice Motion in the Arctic Basin

Data from the
International Arctic Buoy Programme (IABP)
1979 - 1998

The IABP is funded by its Participants
from 31 Institutions from 10 different countries.

For more information on the IABP,
please visit their web page.
http://IABP.apl.washington.edu.

Untersteiner, Colony, Rigor

Arctic Ocean Sea Ice

QuikScat Ice Cover (Nov)

Some relevant facts:

Arctic Ocean coverage:
Max: ~8 x 10^6 km^2
Min: 4-5 x 10^6 km^2

Mean winter Ice Thickness: ~2.5-3 m

Winter Snow Thickness ~10-30 cm

Total Winter Volume: ~15,000 km^3
(~70% is in deformed ice, Melling and Riedel, 1995)

Ice Export: ~10% of Volume and Area annually (2000 km^3) – freshwater/heat

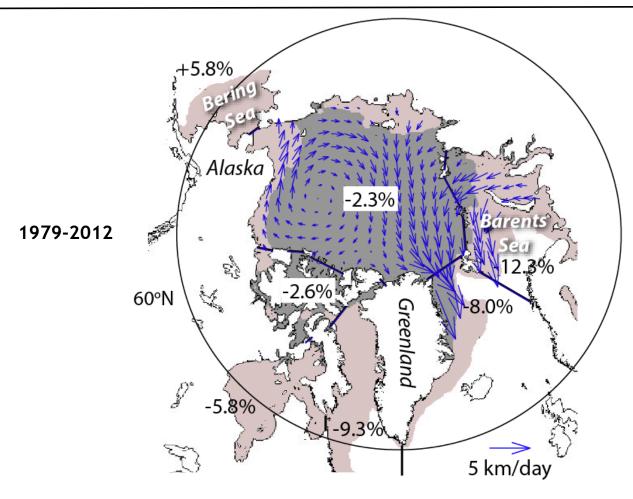**Albedo**:0.8 (snow covered ice); 0.2 (leads)

Ice Salinity: 0 -3 psu (old ice)
            3-10 psu (first-year ice)

Multiyear ice: survived one summer's melt (generally thicker; residence time < 5 yrs but decreasing)

1979-2012

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

$$\rho h \frac{\partial U}{\partial t} = F_a + F_w + F_i + F_c + F_t$$

Air   water   ice   Coriolis   tilt

Coriolis and tilt

$$rh\frac{\P u_i}{\P t} = t_i^a + t_i^w + \frac{\P S_{ij}}{\P x_j} + C_i + rgh\frac{\P H}{\P x_i}$$

Air

Water

Ice:
Internal ice stress
Hibler's VP formulation

$$\tau_a = \rho_a C_d^a |V_{air} - V_{ice}|(V_{air} - V_{ice})$$

$$\tau_w = -\rho_w C_d^w |V_{water} - V_{ice}|(V_{water} - V_{ice})$$

Force Balance:

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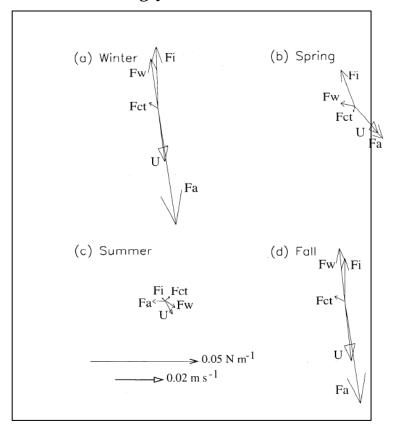
$$\rho h \frac{\partial U}{\partial t} = F_a + F_w + F_i + F_c + F_t$$

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

LARGE-SCALE ICE DRIFT (~10^2 KM)

Ice Motion: 0-40 km/day:
wind-driven at short time
scales; ~1-3% of geostrophic
wind

Beaufort Gyre:
Time to make 1 circuit: 5yrs
Time for ice to grow thick

Transpolar Drift Stream:
Time to traverse: 2-3 yrs

Significant ice area/vol
exported through the Fram
Strait
(Why is it important?)

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.

SMALL-SCALE KINEMATICS (~10 M)
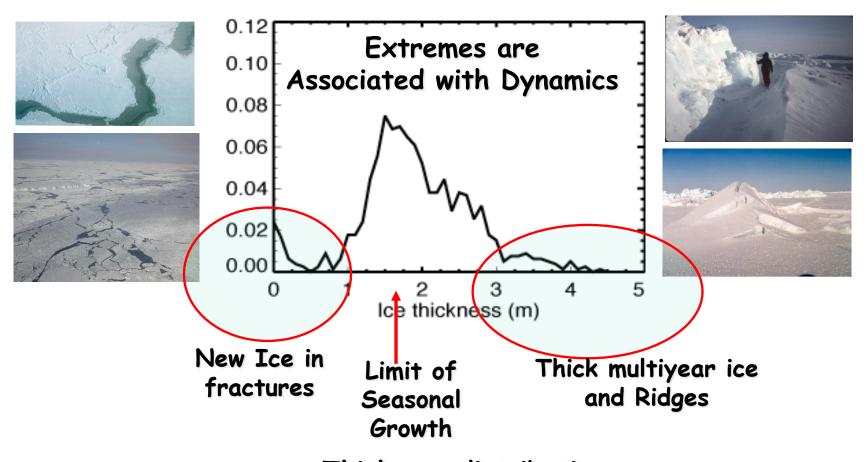
Sample thickness distribution: ~100 km transect

Extremes are
Associated with Dynamics

New Ice in
fractures

Limit of
Seasonal
Growth

Thick multiyear ice
and Ridges

Thickness distribution:
Variability due to Thermodynamics and Dynamics
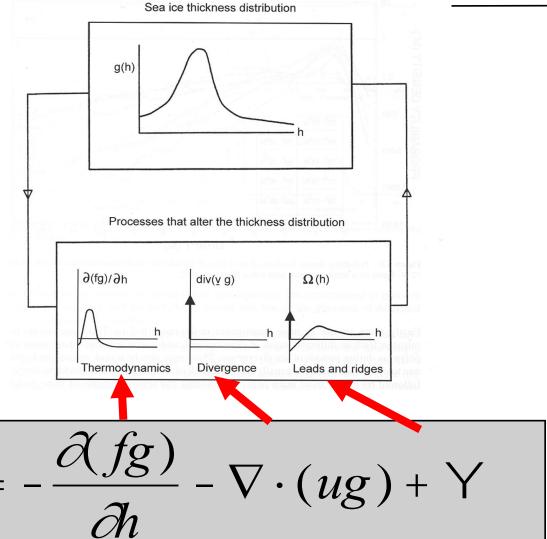
A Framework for understanding the ice thickness distribution g(h)

$$\frac{\partial g}{\partial t} = -\frac{\partial (fg)}{\partial h} - \nabla \cdot (ug) + Y$$

2000 km

100 km
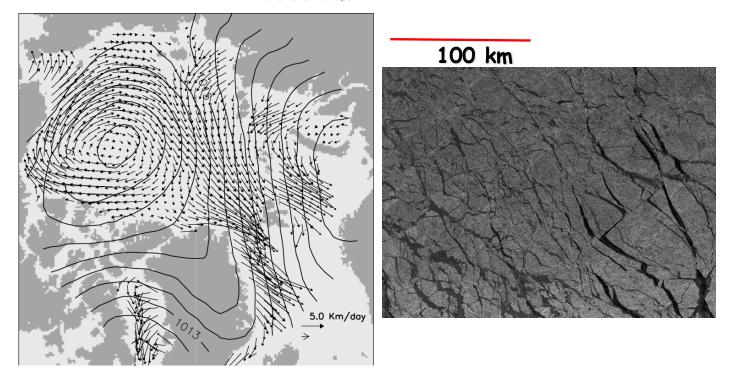
ICE is a SOLID!
All large scale 'gradients' are concentrated in cracks and fractures
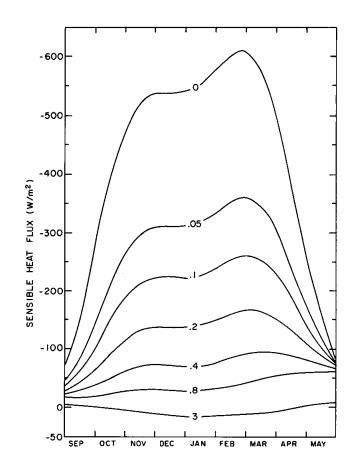
Why are cracks important?
Strong discontinuities in the displacement field
Heat flux and ice growth
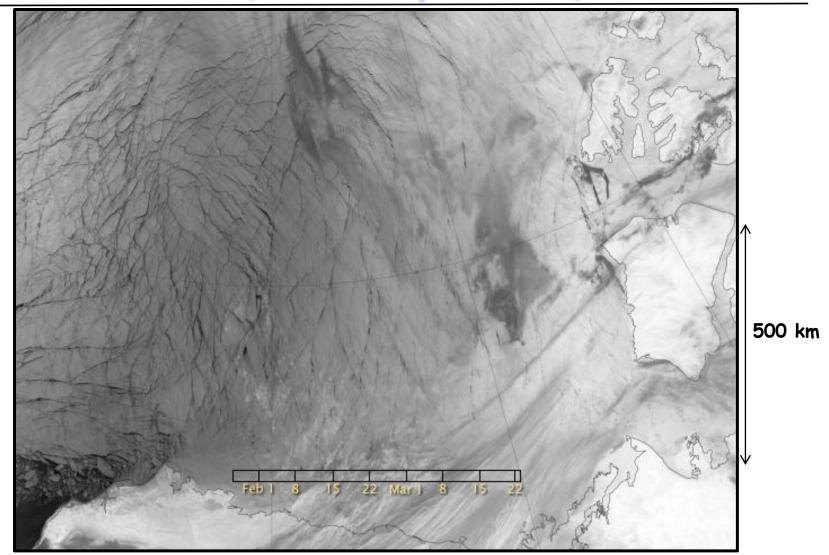
Seasonal variation in sensible heat flux as a function of ice thickness (m)

(after Maykut, 1978)

500 km

5 km grid

Div - ice prod
Conv- ridging
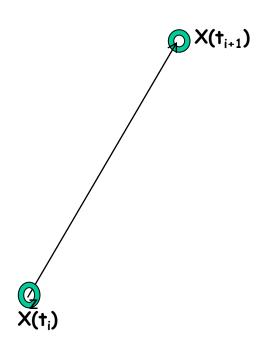
← **Ice production**

OBSERVATIONS OF ICE DRIFT (NO CLEAR PARTITION IN SCALE)

$X(t_{i+1})$

$X(t_i)$

Displacement:

$$u = \left[x(t_{i+1}) - x(t_i)\right]\big|_{x=\text{constant}}$$

Average velocity:

$$v = \frac{u}{T} \qquad T = t_{i+1} - t_i$$

$$\rho(m, n, \theta) = \frac{\displaystyle\sum_{i=1}^{N}\sum_{j=1}^{N} I_1(i, j; \theta) I_2(i - m, j - n) - \overline{I_1 I_2}}{\sigma_1 \sigma_2}$$

Images I_1 and I_2 separated by Δt

Uncertainties in displacement:

$$u = (x_B + \varepsilon_{gB}) - (x_A + \varepsilon_{gA}) + \varepsilon_f$$

$$\sigma_u^2 = 2\sigma_g^2 + \sigma_f^2$$

g: geolocation errors
f: tracking errors

Uncertainties in spatial differences (strain):

$$\Delta u = \left[(x_{B2} + \varepsilon_{gB2}) - (x_{A2} + \varepsilon_{gA2}) + \varepsilon_{f2} \right]$$
$$- \left[(x_{B1} + \varepsilon_{gB1}) - (x_{A1} + \varepsilon_{gA1}) + \varepsilon_{f1} \right]$$
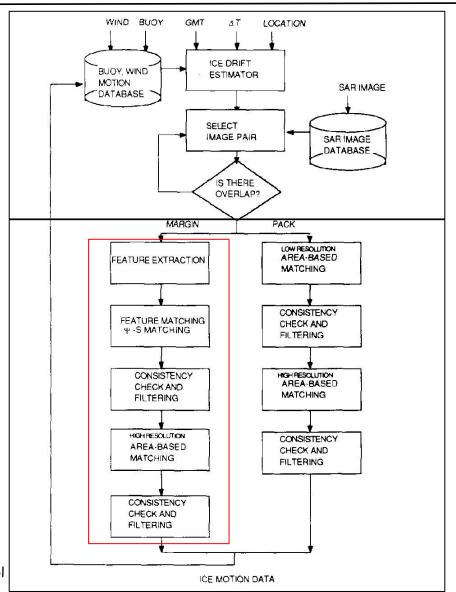
$$\sigma_{\Delta u}^2 = 2\sigma_f^2$$

Assuming geolocation errors (g) are correlated.

Estimation and image selection
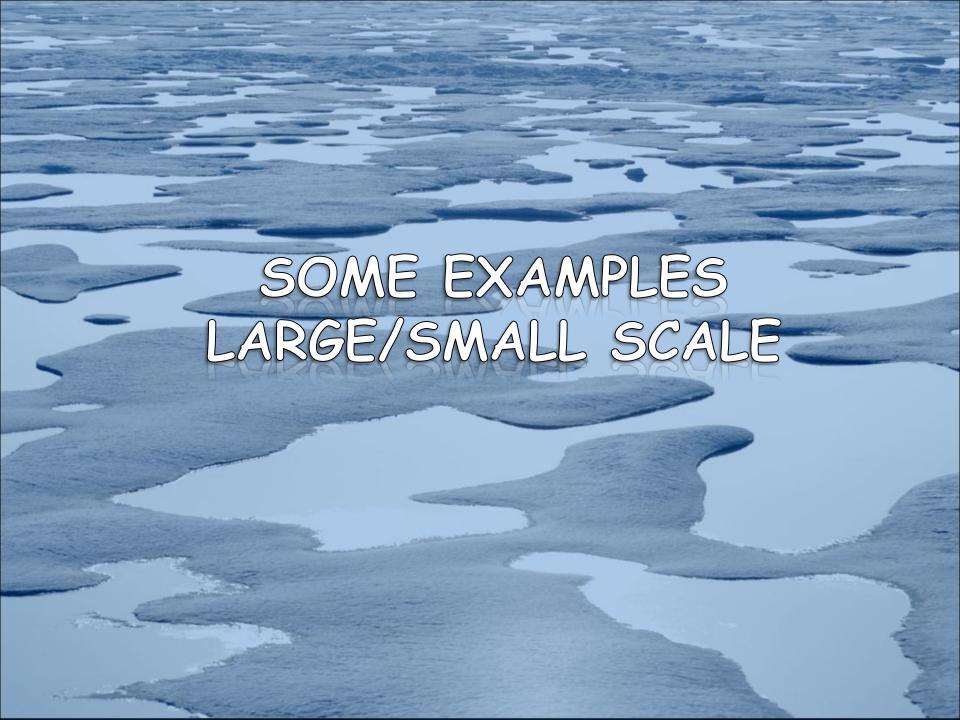
Motion tracking

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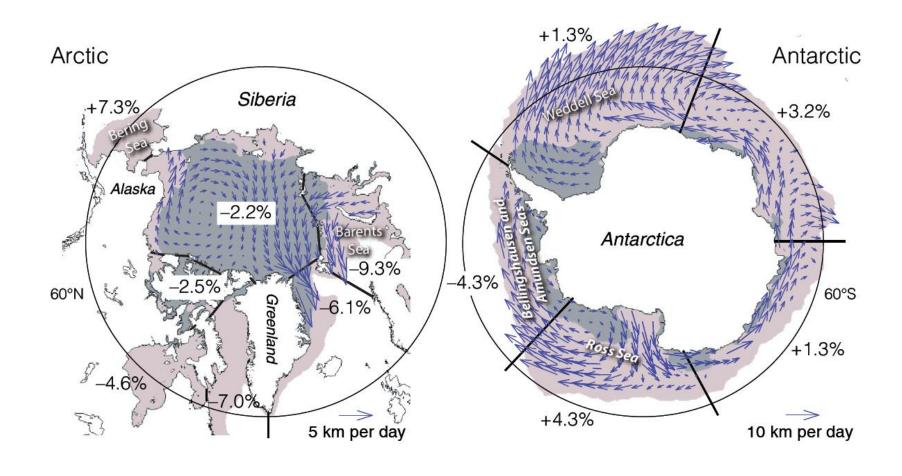
- Buoy drift/trajectories (since mid-to-late 70s from the Arctic buoy program)
    - Argos location (Uncertainty: ~300 m)
    - GPS (uncertainty: ~10^1 m)
    - Density: typically ~10^2 km, hourly samples

- 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

SOME EXAMPLES LARGE/SMALL SCALE

From passive microwave fields (~12.5 km resolution)
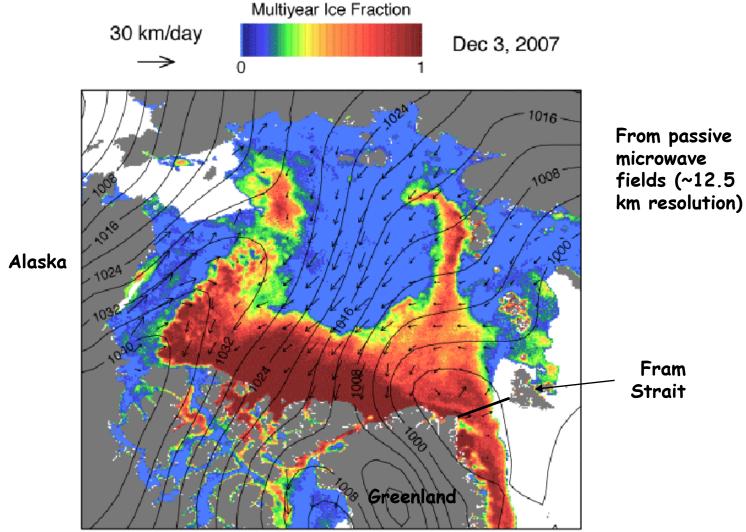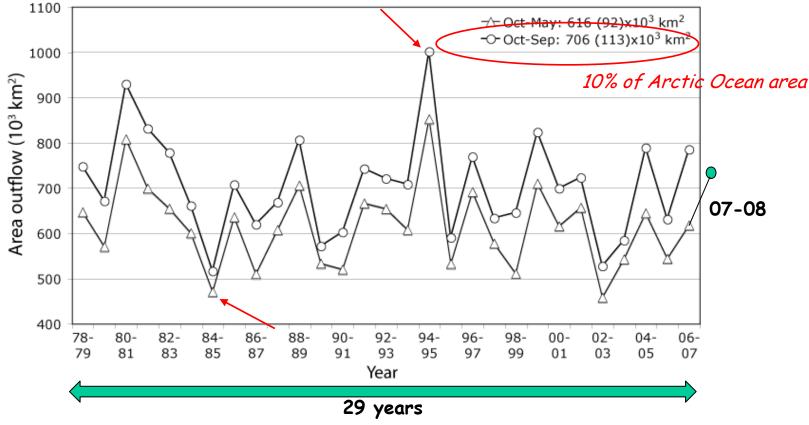
Peak (near peak of +NAO index)

Oct-May: 616 (92)x10^3 km^2
Oct-Sep: 706 (113)x10^3 km^2

10% of Arctic Ocean area

07-08

29 years
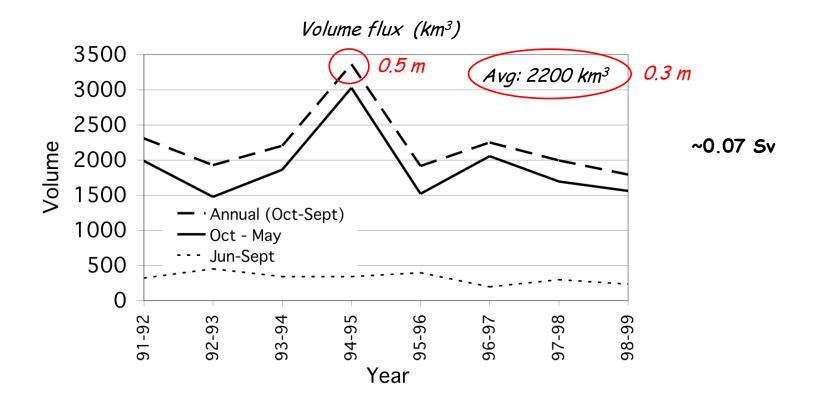
Kwok and Rothrock [1999] and Kwok [2009]

Variability is high!

What about volume flux (freshwater/heat)?

Volume flux (km^3)

0.5 m

Avg: 2200 km^3 0.3 m

~0.07 Sv
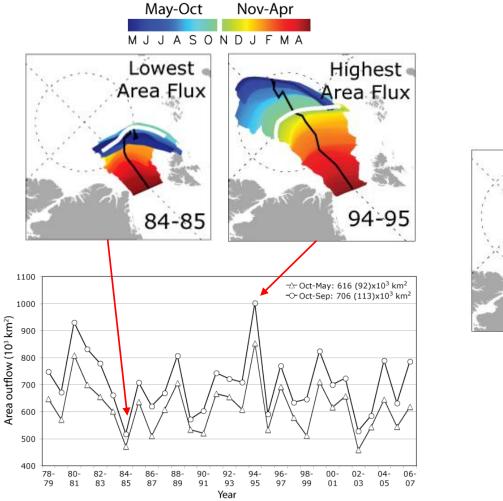
Based on ice draft from NPI and AWI moorings
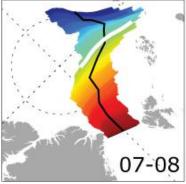
Source regions of sea ice
by backpropagation

Area swept by the trajectories is highly correlated to the area flux
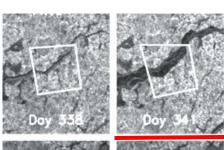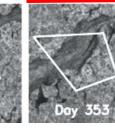
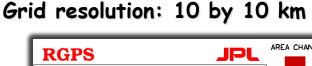# High-res Satellite mapping of time-varying fractures in the ice cover (Radarsat-1, Envisat, Sentinel-1)

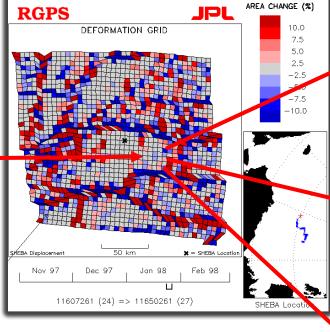**Grid resolution: 10 by 10 km**

SAR imagery 25 m resolution

$$divergence = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y},$$
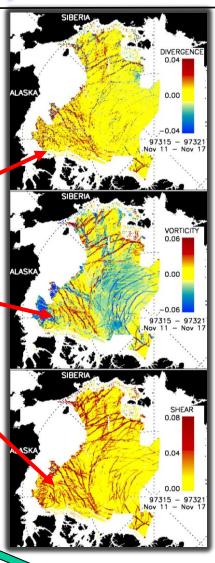
$$shear = \left[\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} \right)^2 \right]^{1/2},$$

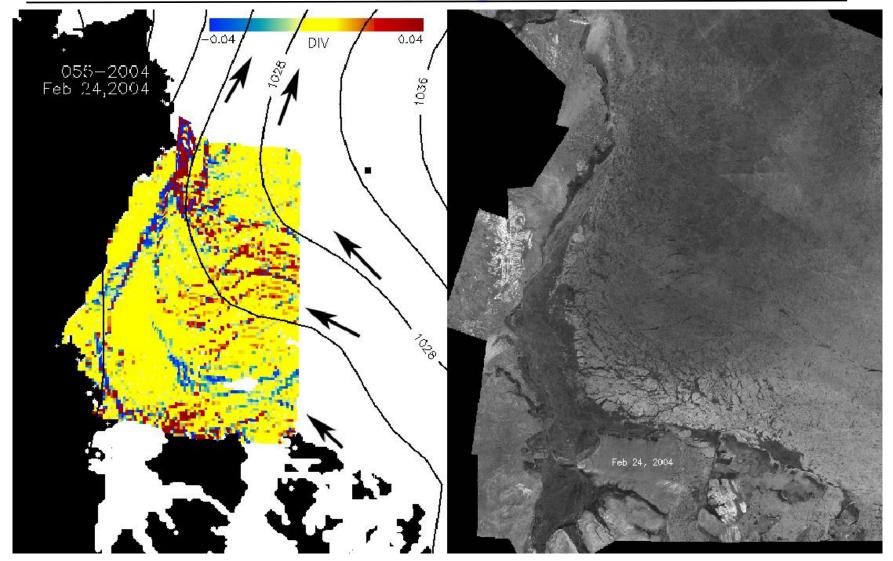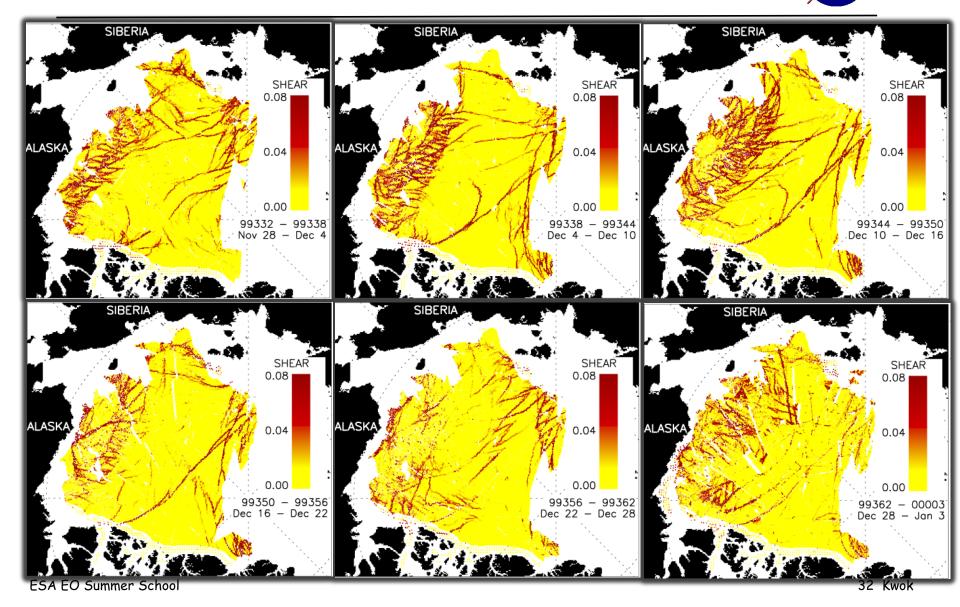$$vorticity = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}.$$

10^1 km

10^2 km

10^3 km

30 Kwok
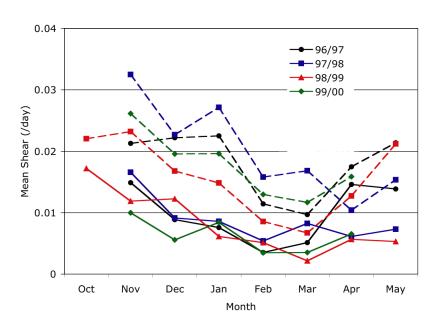
Deformation activity

Shear Deformation

(Kwok, 2005)

------------- **Seasonal ice**

——————— **Multiyear ice**
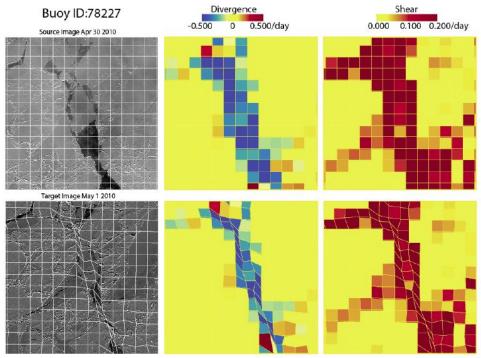
Ridging/rafting
(mechanical redistribution)

Buoy ID:78227
Source Image Apr 30 2010
Target Image May 1 2010

Divergence
-0.500   0   0.500/day

Shear
0.000   0.100   0.200/day
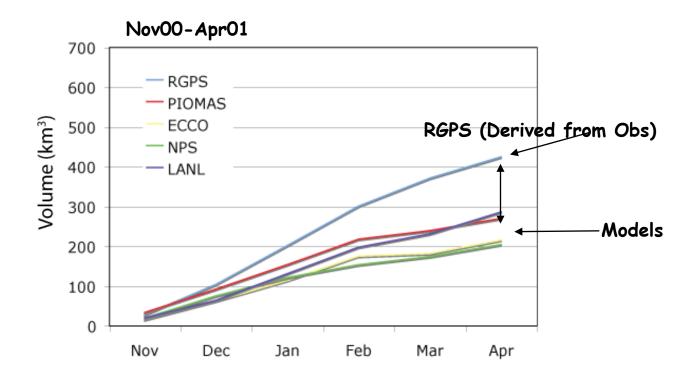
Initial grid spacing: 60 x 60 m

- 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

Nov00-Apr01

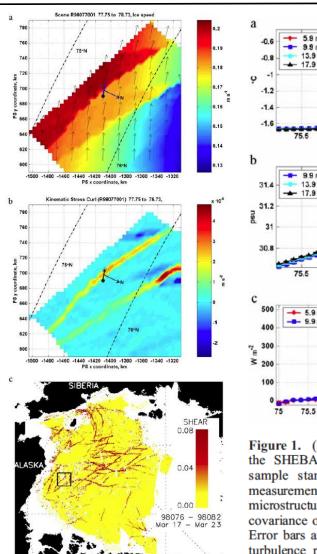Model simulations produce less ice because
deformation is poorly simulated – comparison
is over limited domain

Kinematic stress curl
From satellite ice drift

McPhee et al. 2005

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.
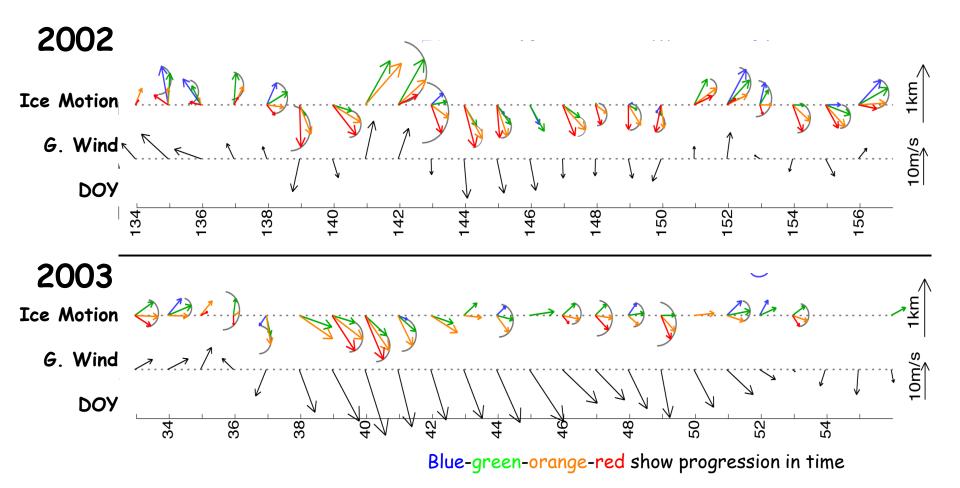
SUB-DAILY ICE MOTION (TIDES, INERTIAL OSCILLATION)

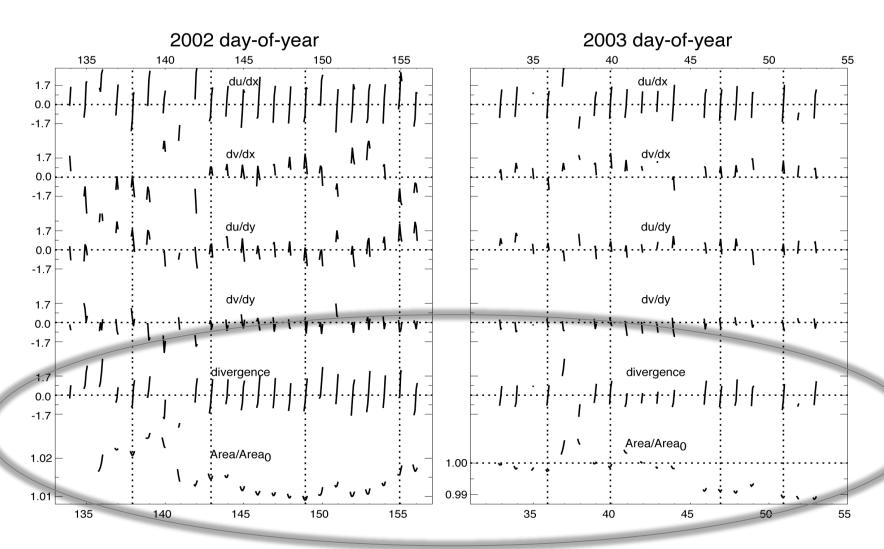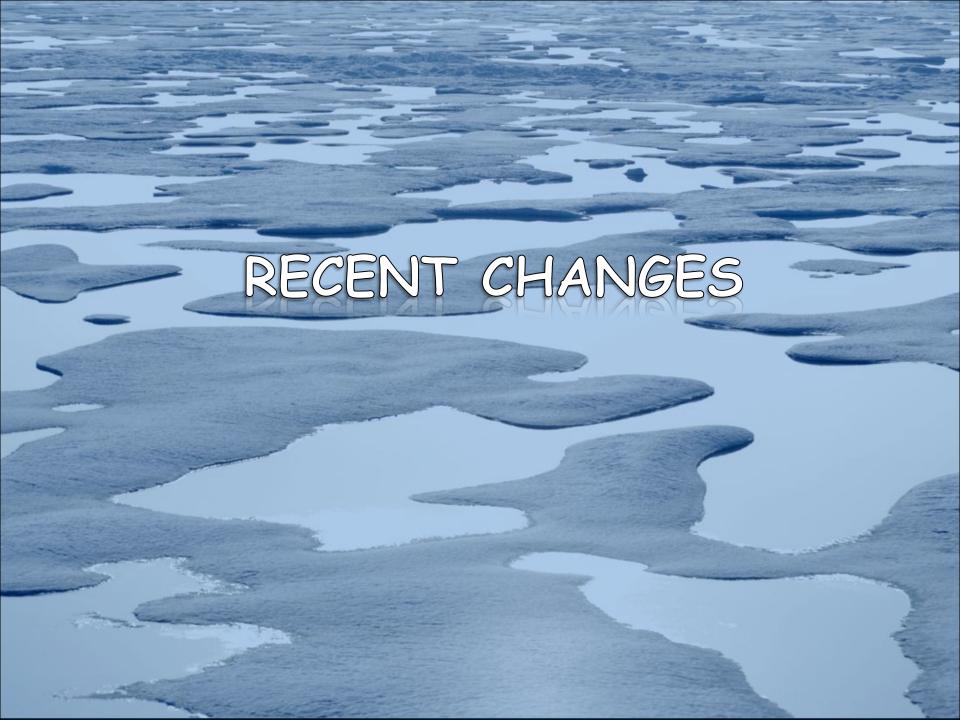Clockwise Rotation of ice motion vectors over 100 minute intervals over a region of relatively thick ice

Blue-green-orange-red show progression in time

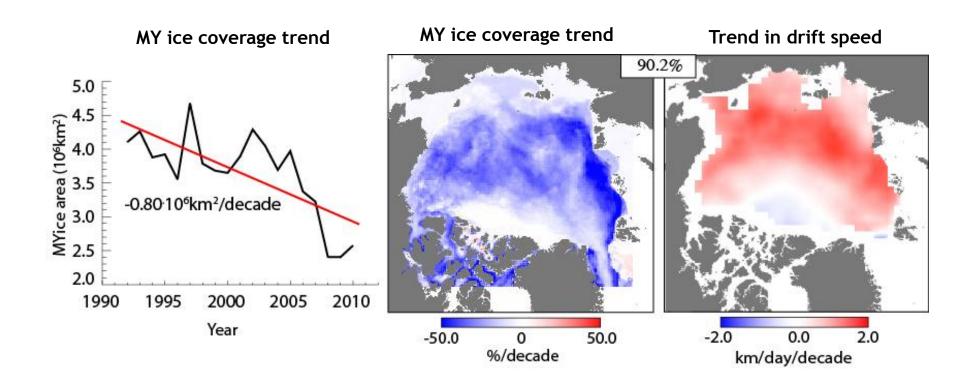Kwok, Cunningham and Hibler (2004)

2002 day-of-year

2003 day-of-year

RECENT CHANGES

Satellite Ice Drift and MY ice coverage 1992-2010

MY ice coverage trend

MY ice coverage trend

Trend in drift speed

c) Ice motion trend

x: +0.02   y:-0.01
km/day/decade

1982-2009

x: -0.37   y: -0.44
km/day/decade

2001-2009

0.0   2.0   4.0
km/day/decade

5.0 km/day/decade

(Kwok, 2011)
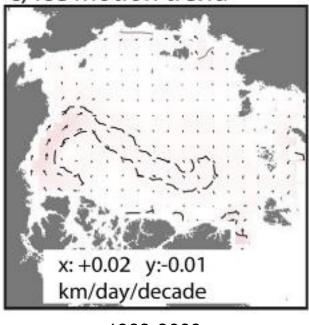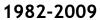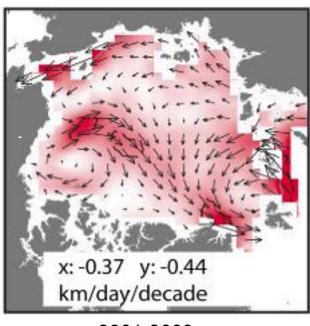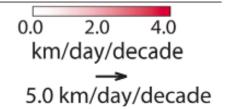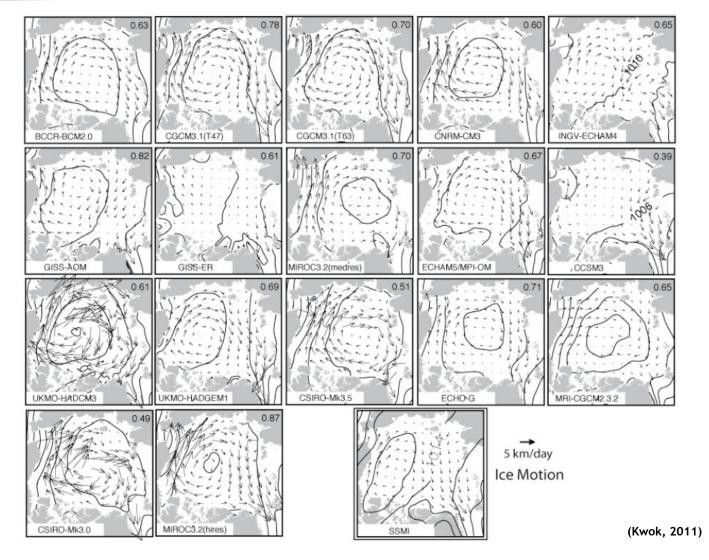
Summary Remarks

- Brief highlights of the role of ice motion in the shaping the character of the Arctic Ocean sea ice cover

- Ice motion is complex and plays a critical role in the time-varying behavior of the ice cover
  - Controls the extremes in the ice thickness distribution

- Very challenging observationally because of space and time scales of variability

- In most models, small-scale ice motion seems to modeled poorly
  - Mechanics and sub-grid scale processes are not represented correctly
    - Need better ice treatment of ice behavior
  - Lack observations of short time scale processes

Questions?

12.02.2004