

Remote Sensing of Arctic Sea Ice

Ron Kwok

Jet Propulsion Laboratory

California Institute of Technology, Pasadena, CA

Summer School – Using Satellites Observations to Advance Climate Models

Keck institute for Space Studies

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Topics



- *What are the important large-scale variables?*
- *How are they measured?*
- *What observations are available for assessing climate models?*
- *How well do climate models simulate these variables?*

Arctic Ocean Sea Ice



Some facts relevant to this talk:

Max winter Arctic Ocean coverage:
 $\sim 7 \times 10^6 \text{ km}^2$

Min Summer coverage:
 $4\text{-}5 \times 10^6 \text{ km}^2$

Mean winter Ice Thickness:
 $\sim 2.5\text{-}3 \text{ m}$

Winter Snow Thickness $\sim 10\text{-}30 \text{ cm}$

Total Winter Volume: $\sim 15,000 \text{ km}^3$
($\sim 70\%$ is in deformed ice
Melling and Riedel, 1995)

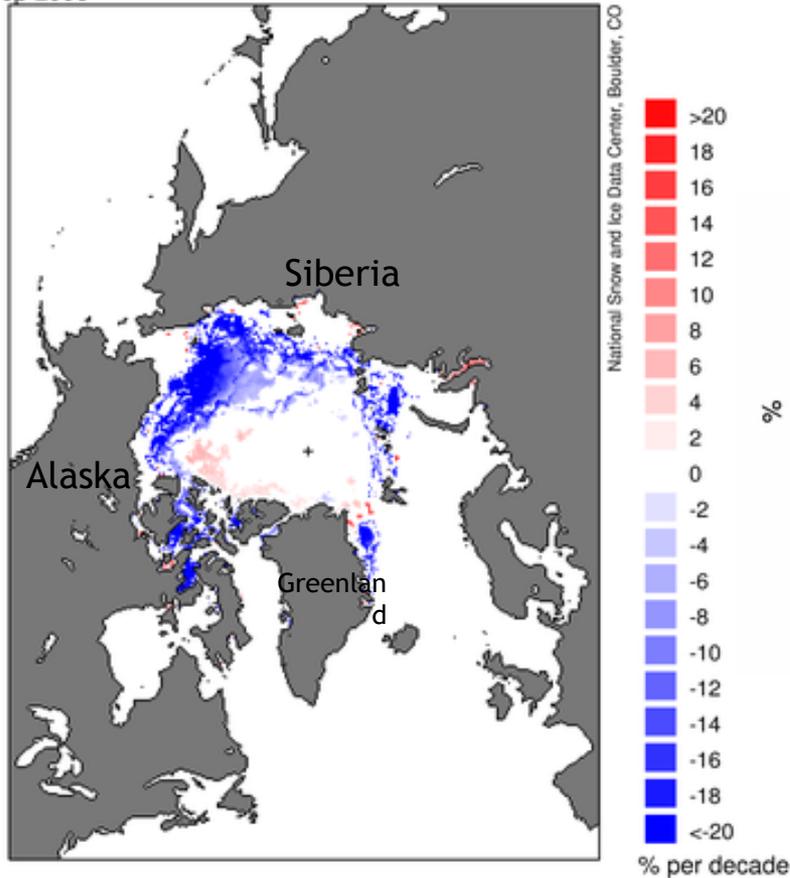
Ice Export: $\sim 10\%$ of Volume
and Area annually

Ice Salinity: 0 -10 psu

Decline in summer sea ice extent over the satellite record (1978-present)

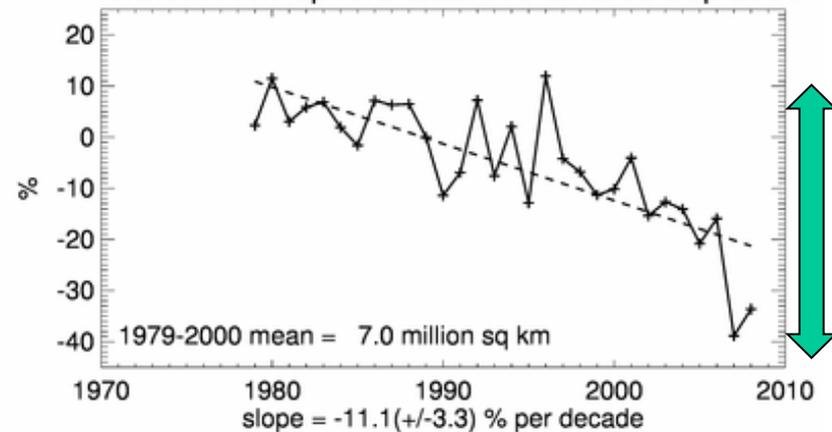


Sea Ice Concentration Trends
Sep 2008

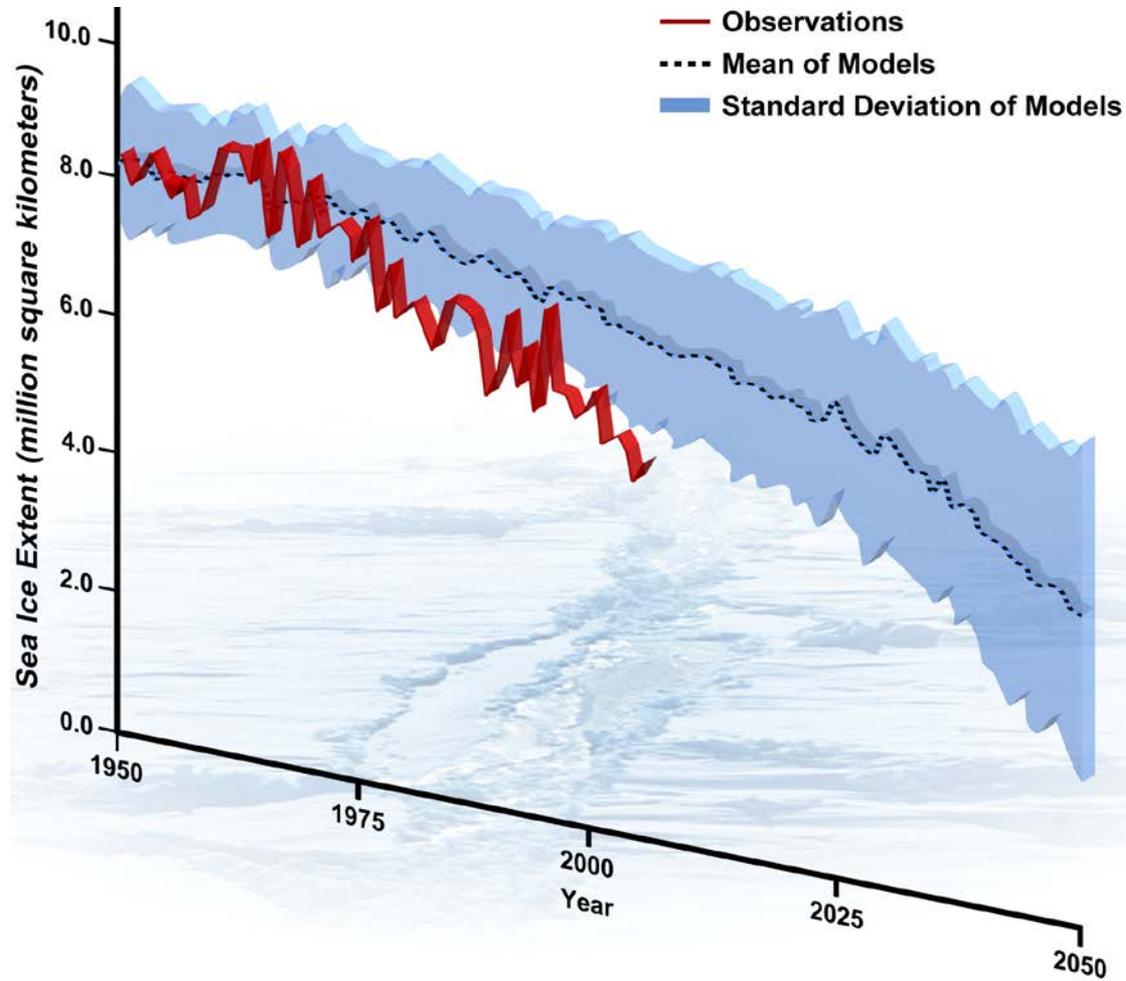


NSIDC

Northern Hemisphere Extent Anomalies Sep 2008



Arctic summer ice extent: Observations and Model Projections



Annual Sea Ice Mass Balance: Dynamics and Thermodynamics



$$\Delta = \text{Ice Export} + \text{Ice Growth} + \text{Ice Melt}$$

Thickness
Ice Motion

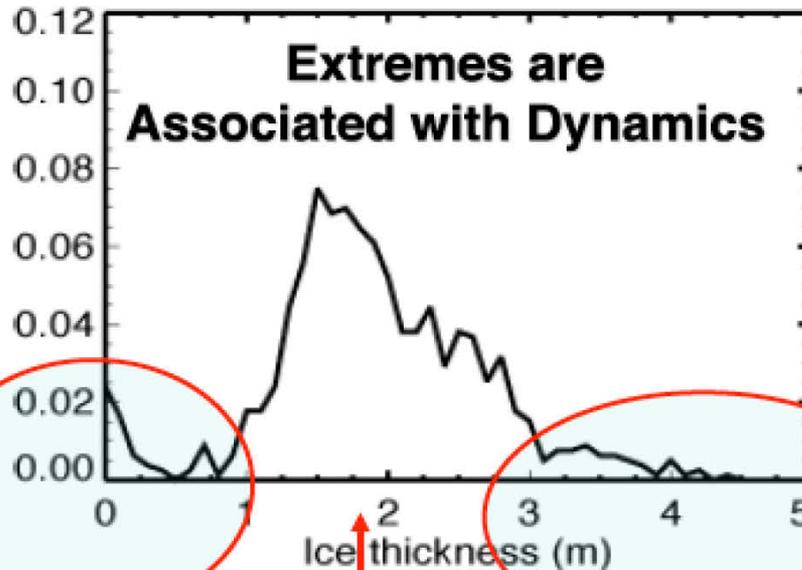
Thickness

Thickness

Ice thickness distribution: Interplay of Dynamics and Thermodynamics



Sample thickness distribution: ~100 km transect



New Ice in fractures

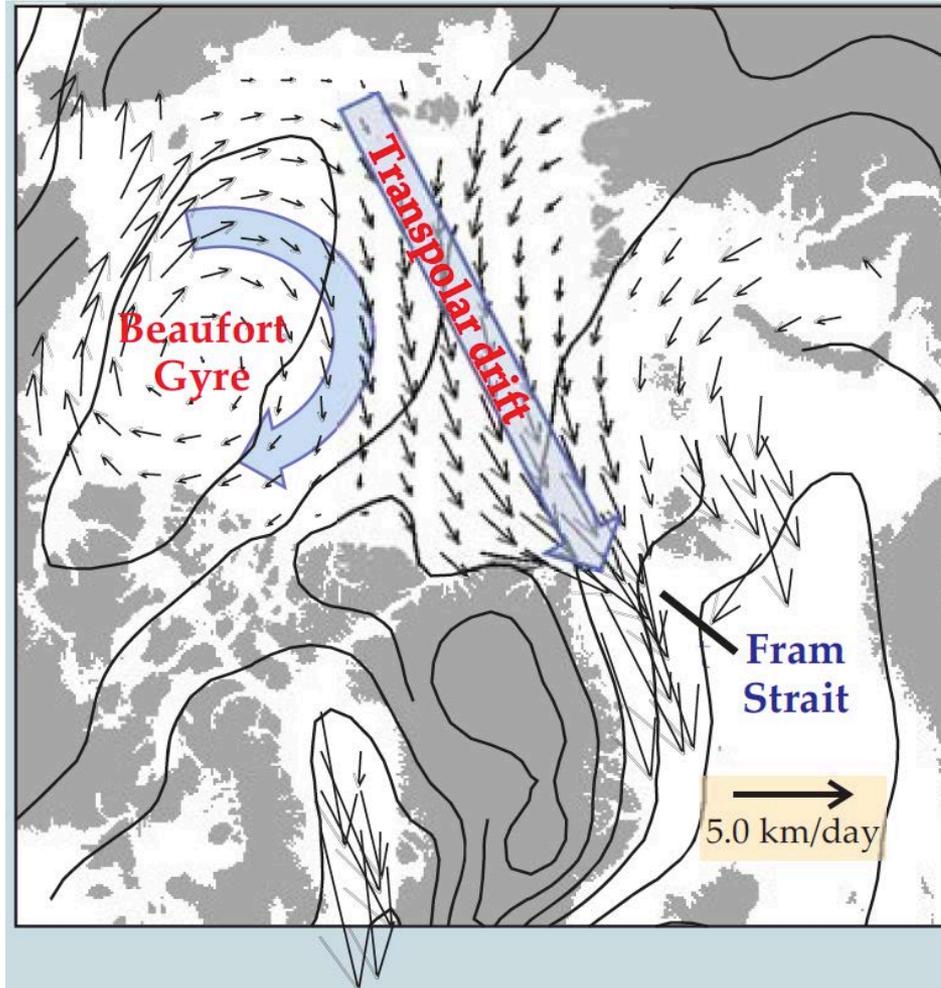
Limit of Seasonal Growth

Thick multiyear ice and Ridges (ice floes pushed together)



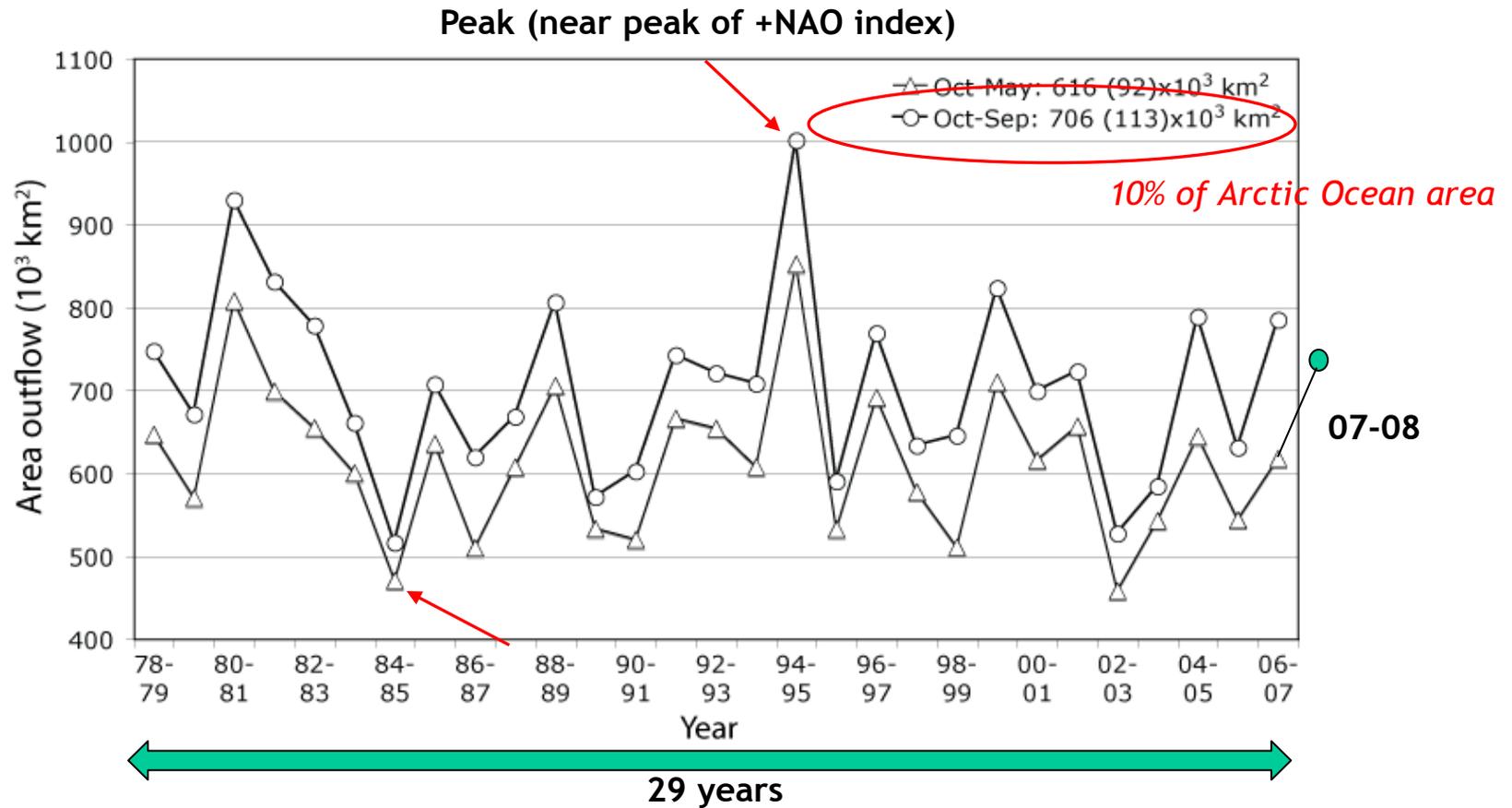
Ice Motion

Large Scale Mean Field of Ice Motion



- *Ice Export*
- *Circulation pattern*
 - *Regional Mass balance*

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



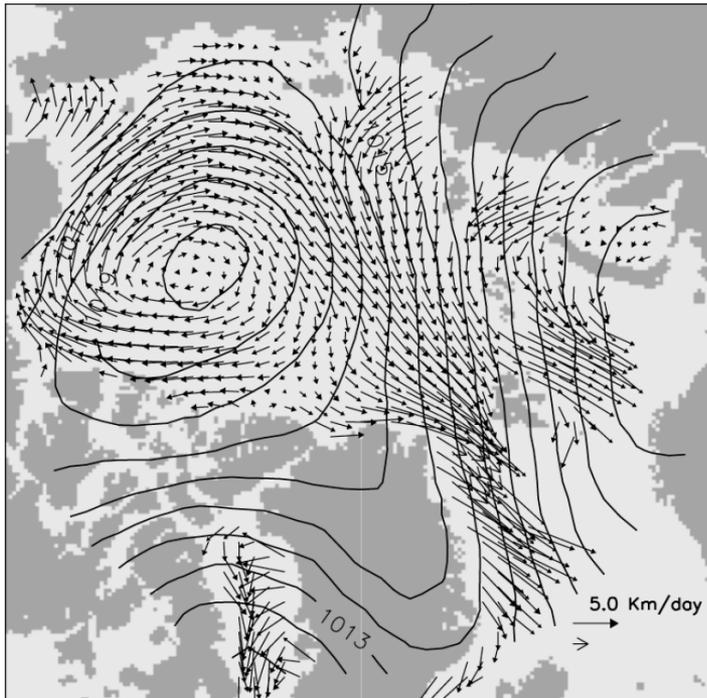
Kwok and Rothrock [1999] and Kwok [2009]

Variability is high!

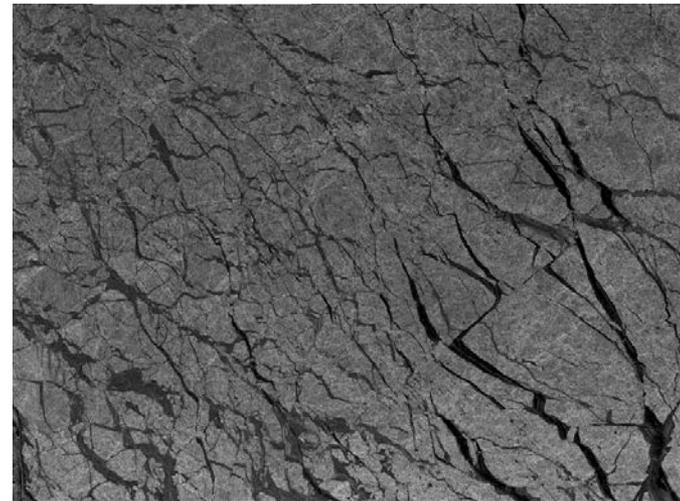


Ice Drift (Different length scales)

2000 km



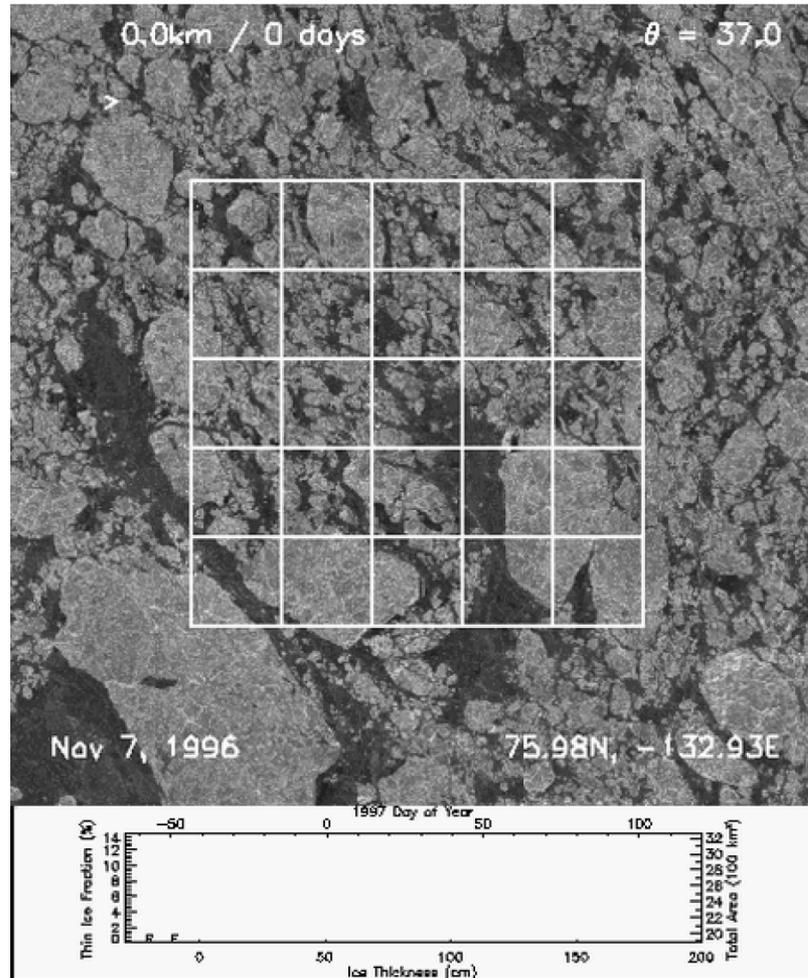
100 km



ICE is a SOLID!

All large scale 'gradients' are concentrated along cracks and fractures

Ice Deformation from Synthetic Aperture Radar



5 km grid

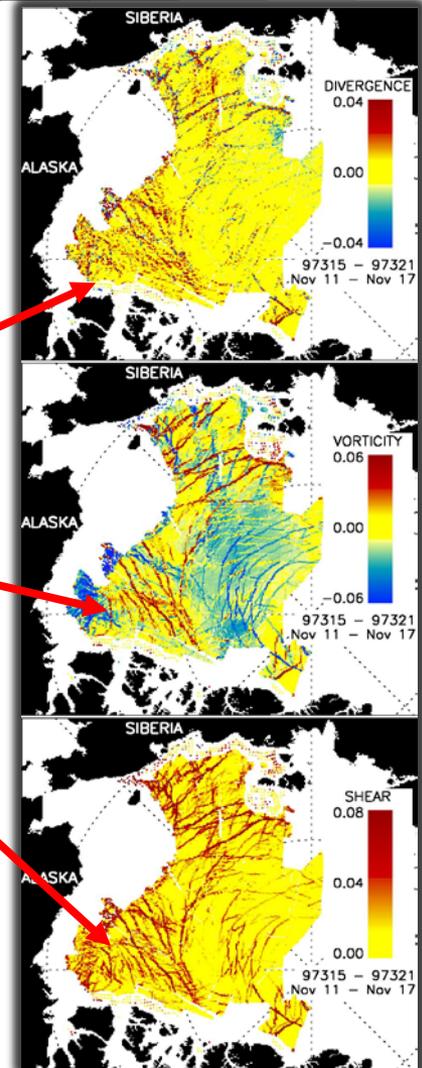
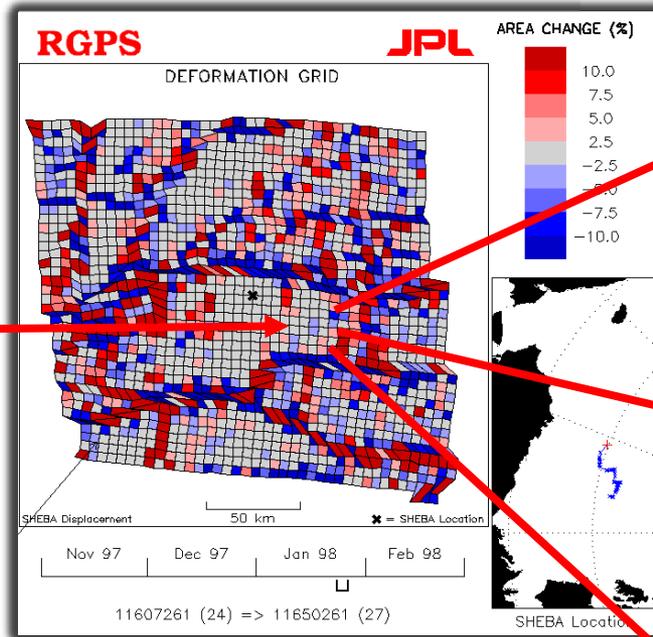
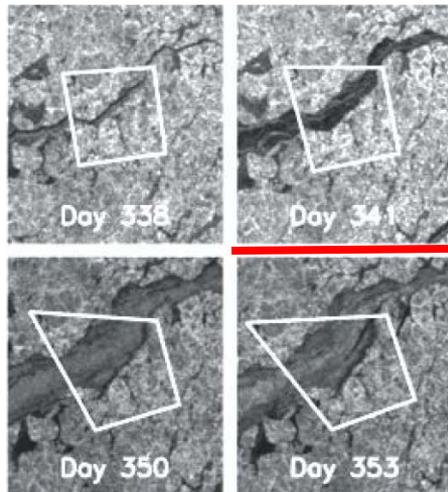
Div - ice prod
Conv- ridging

← Ice production

Satellite mapping of time-varying fractures in the ice cover



Grid resolution: 10 by 10 km

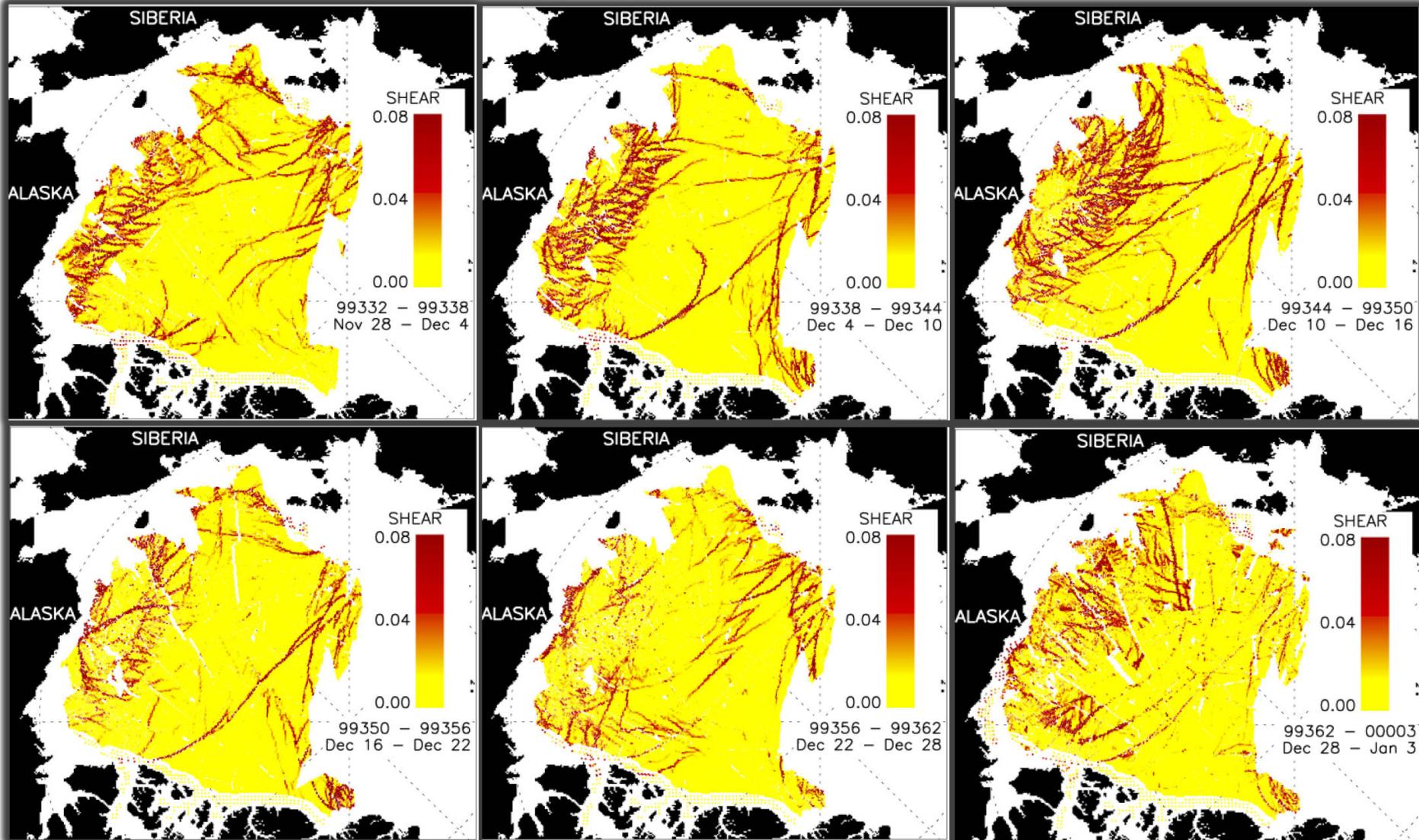


10^1 km

10^2 km

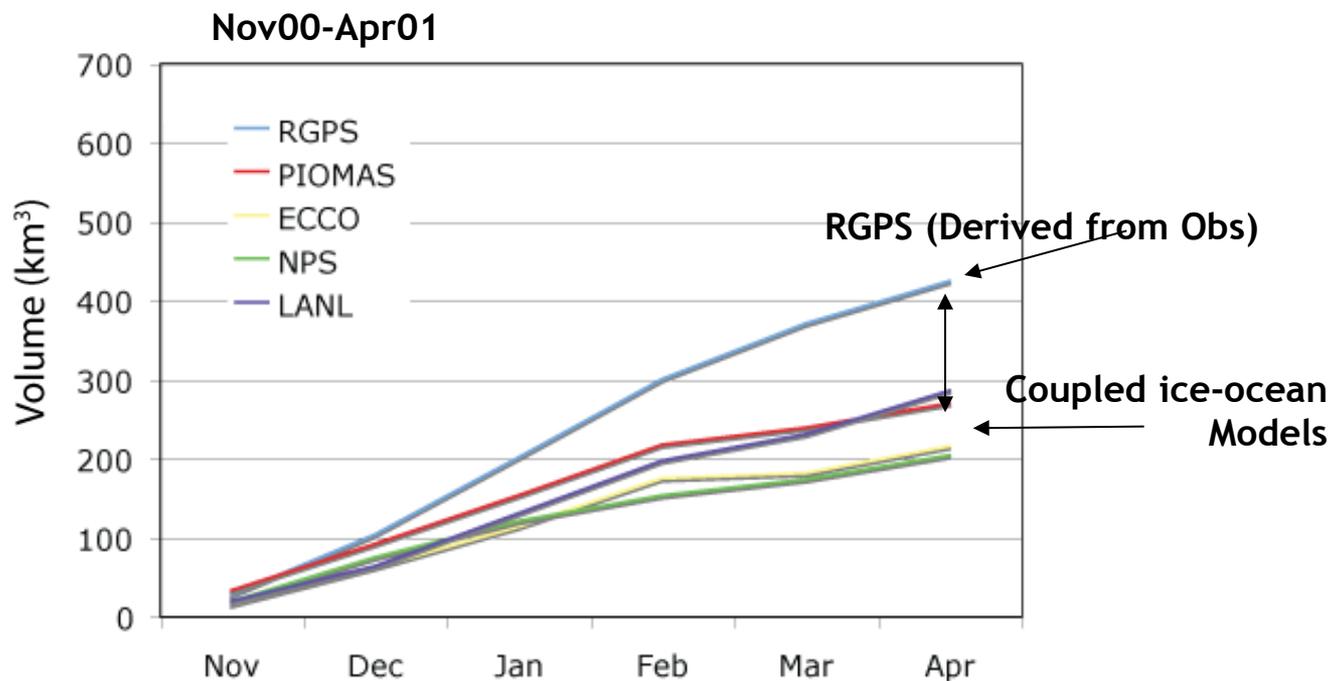
10^3 km

Shear patterns - density, orientation, persistence





Model vs RGPS ice production



Model simulations produce less ice because deformation is poorly simulated



Ice Thickness

Sea Ice Drilling/Coring

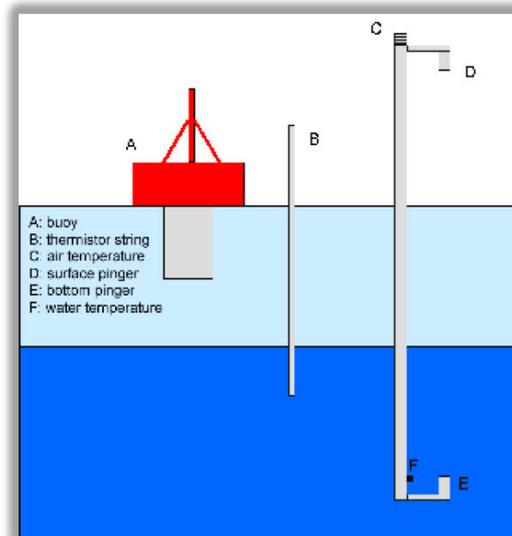
Not the way to get a basin-scale picture
of the time-varying thickness field!



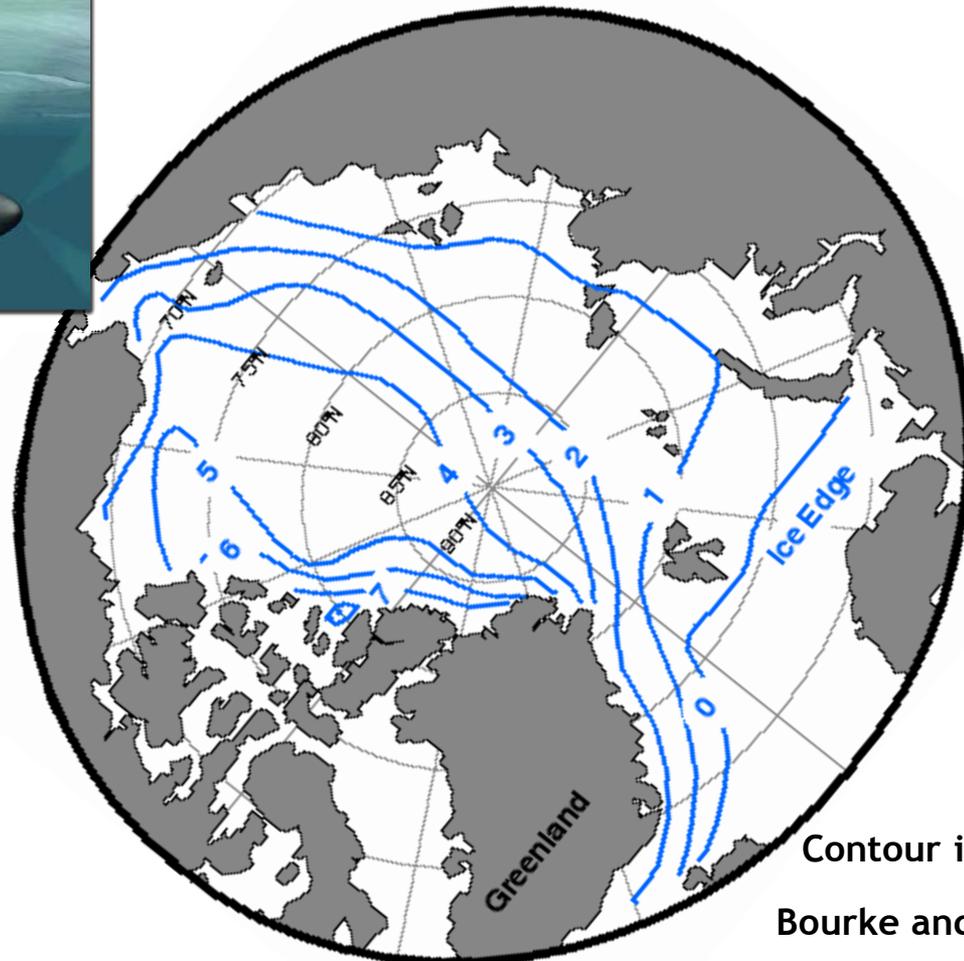
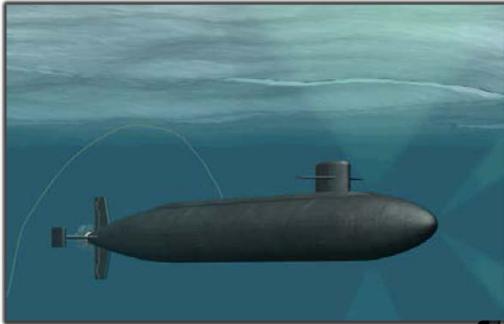
Other means of measuring ice thickness



- *Coring and Drilling*
- *EM induction*
- *Ice Mass Balance Buoys*
- *Wide-band ice penetrating radar*
- *Airborne lidar or radar profilers for freeboard*



Rough contour of Arctic ice draft from US Navy submarines



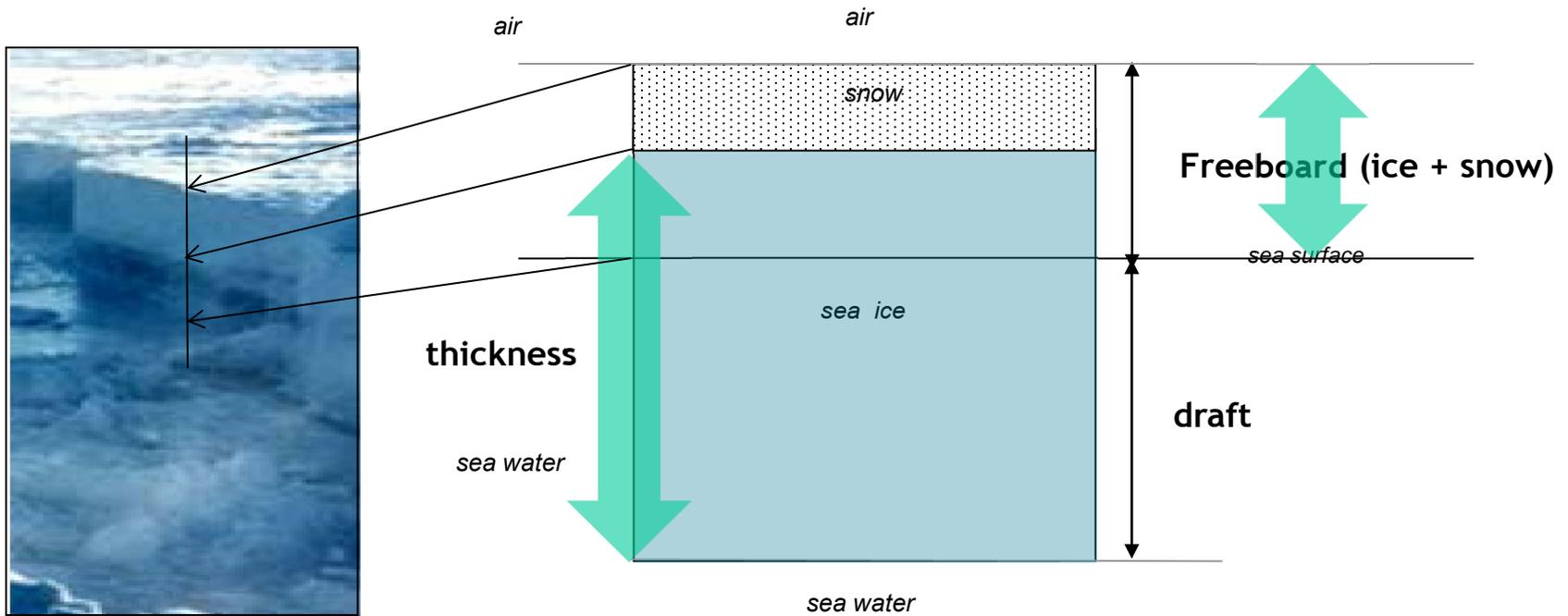
Contour in meters

Bourke and McLaren (1992)

Measurement of freeboard from Space



Freeboard, Snow depth, Ice Draft and Thickness

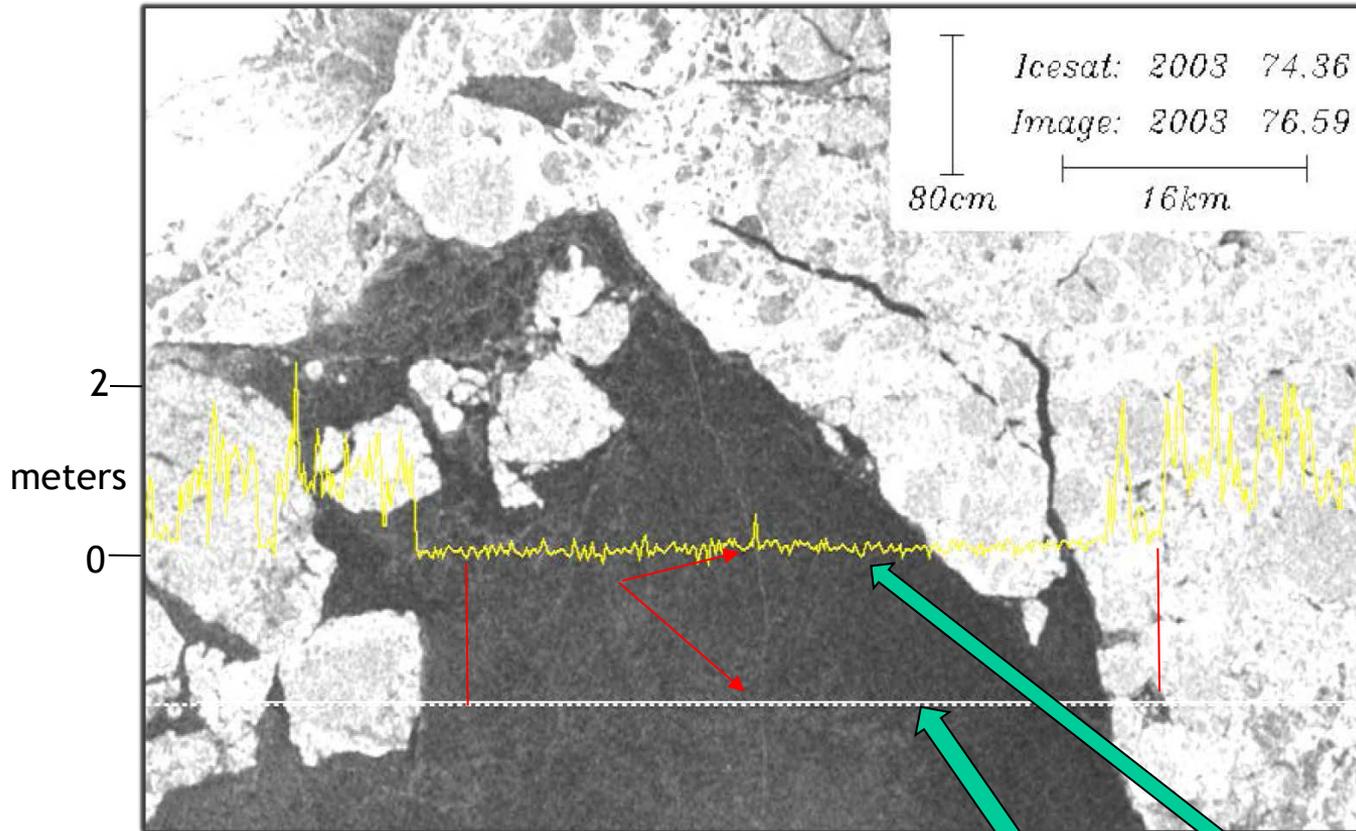


Freeboard to thickness:
$$h_i = \left(\frac{\rho_w}{\rho_w - \rho_i} \right) h_f - \left(\frac{\rho_w - \rho_s}{\rho_w - \rho_i} \right) h_{fs}, \text{ (lidar)}$$

Measurement of freeboard from Space



Pulse-to-pulse precision of the ICESat lidar



- At 10 km -
 - ~1.5 - 2 cm



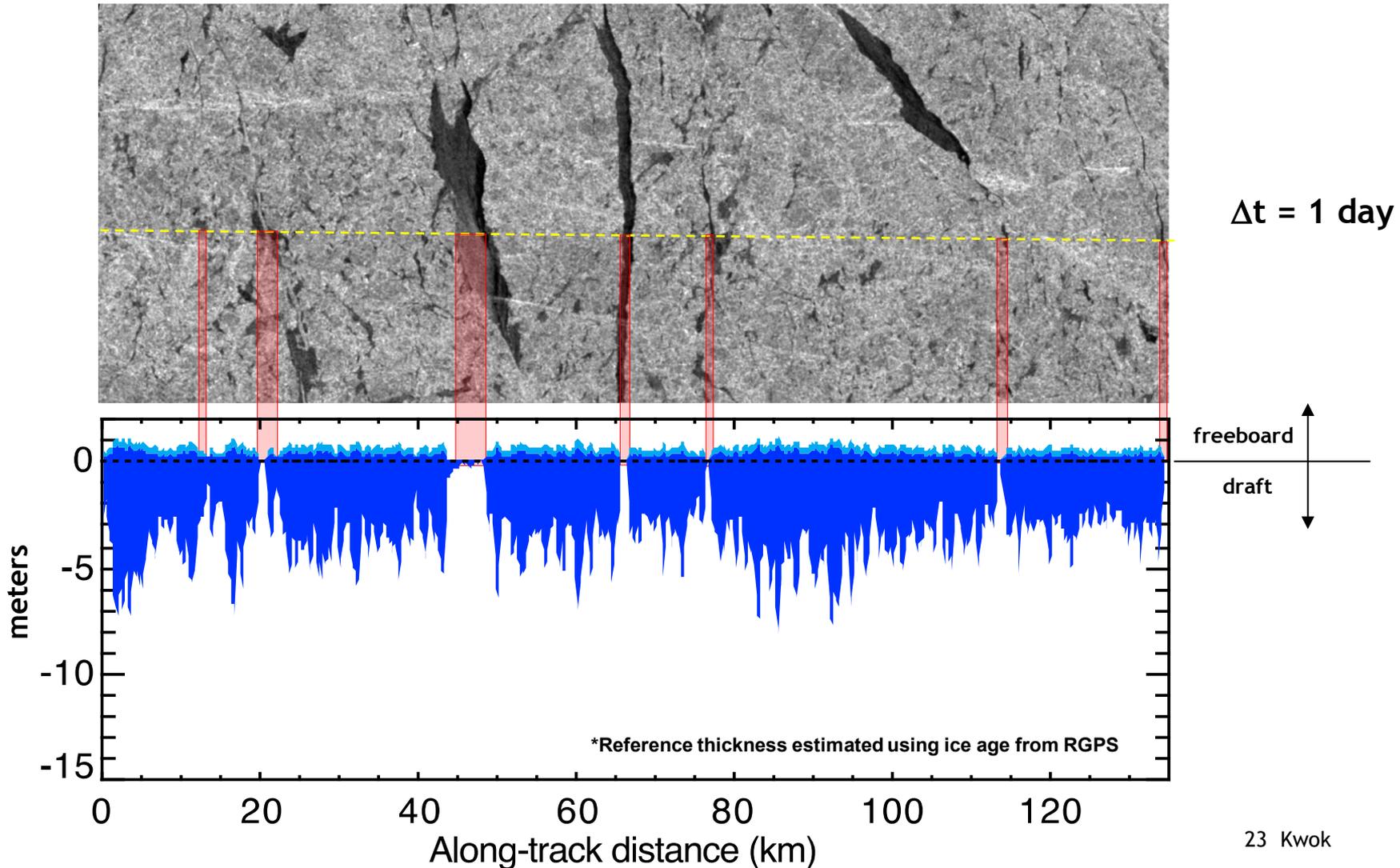
ICESat Elevation Profile (yellow)

ICESat Track (white)

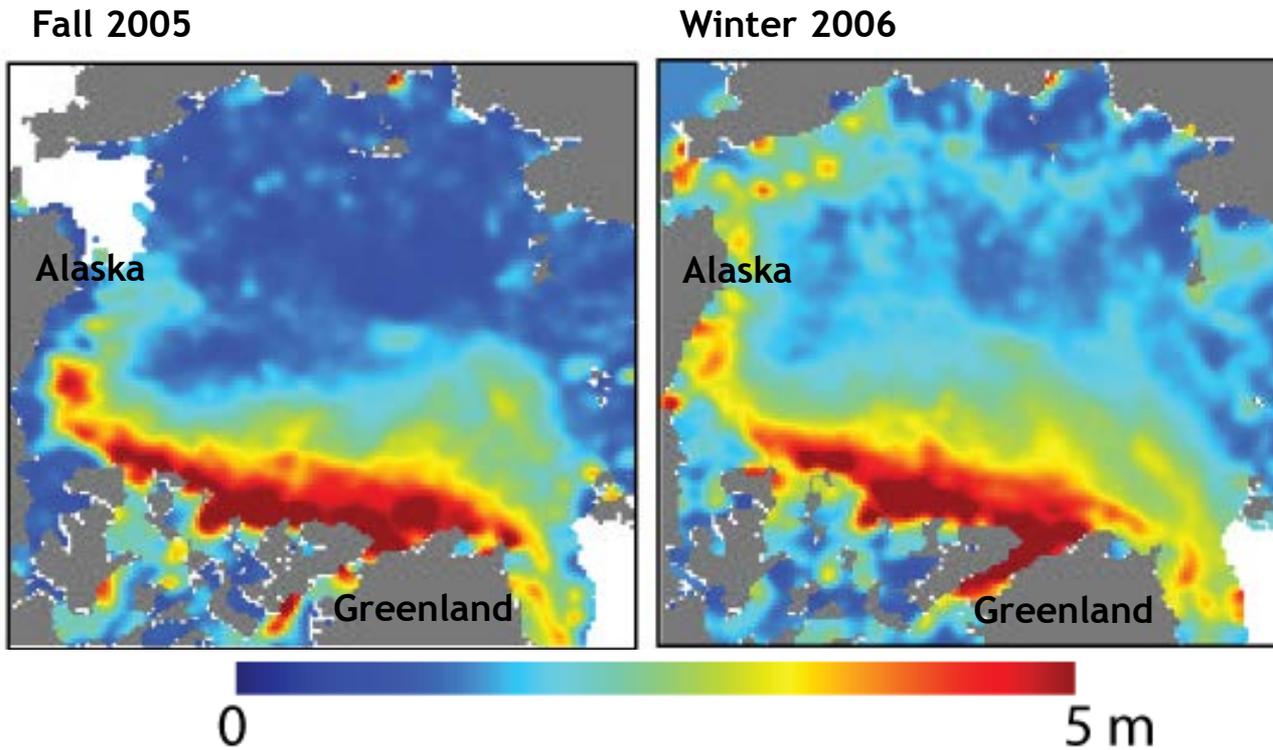
ICESat (profiling lidar) and RADARSAT (image)



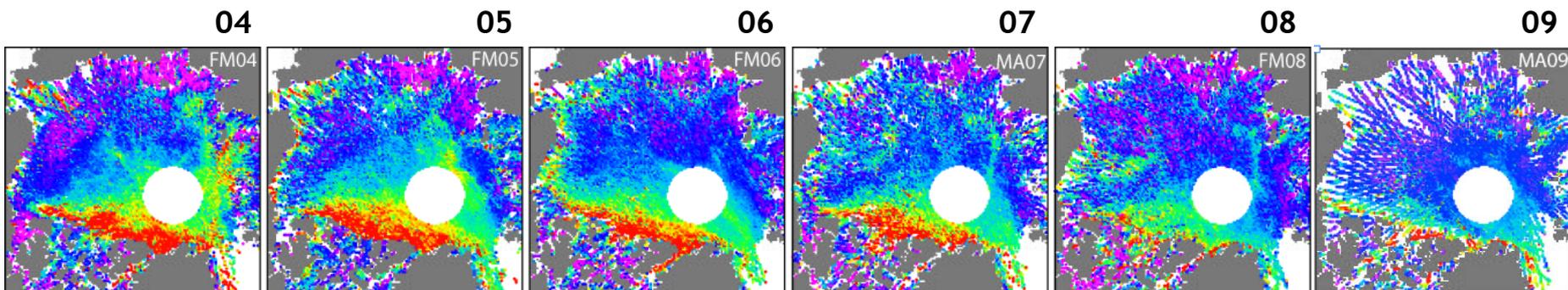
ICESat track on RADARSAT image



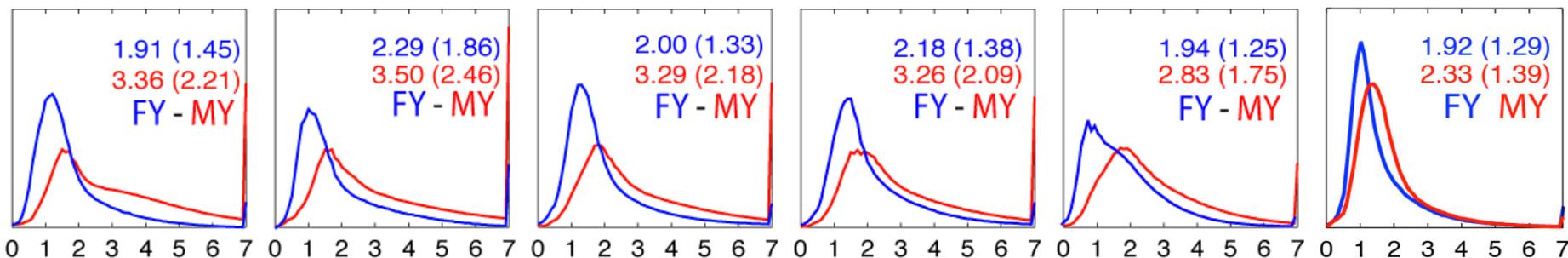
Basin scale ice thickness pattern from recent ICESat acquisitions



Winter sea ice thickness from ICESat



0.0 Thickness (m) 5.0 m

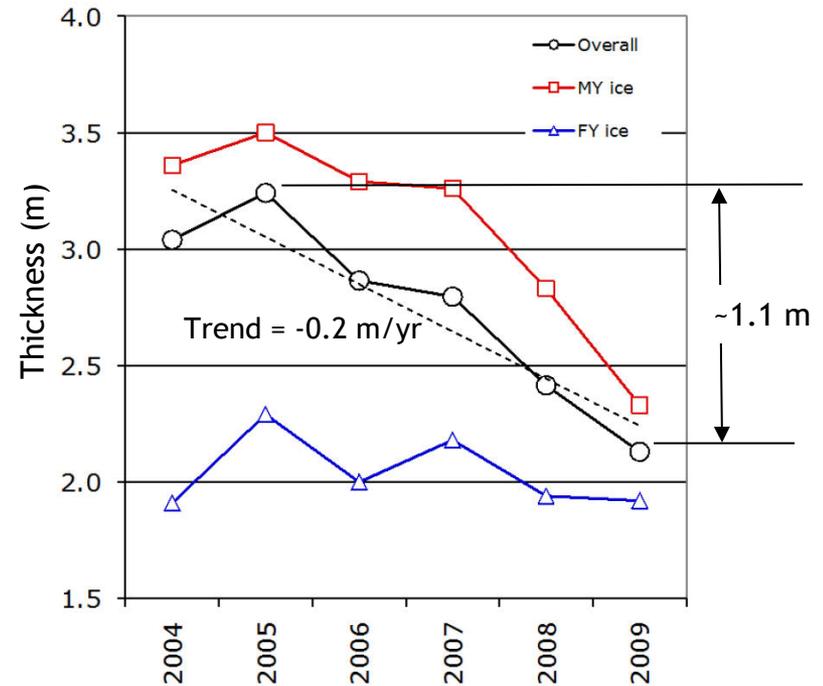
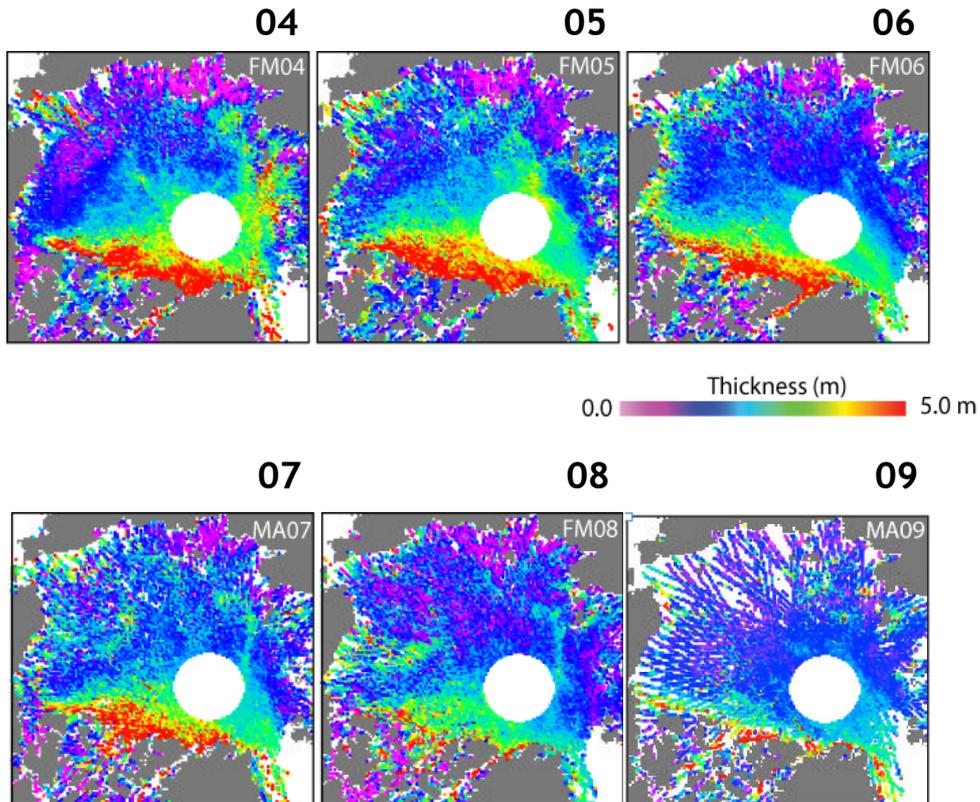


Thickness (m)

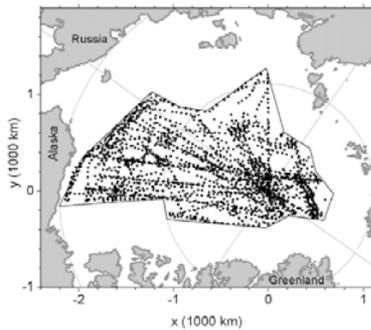
(Kwok et al., 2009)

MY = all ice with MY fraction > 50%

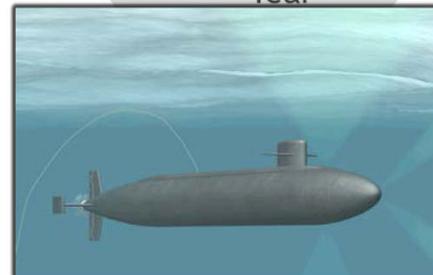
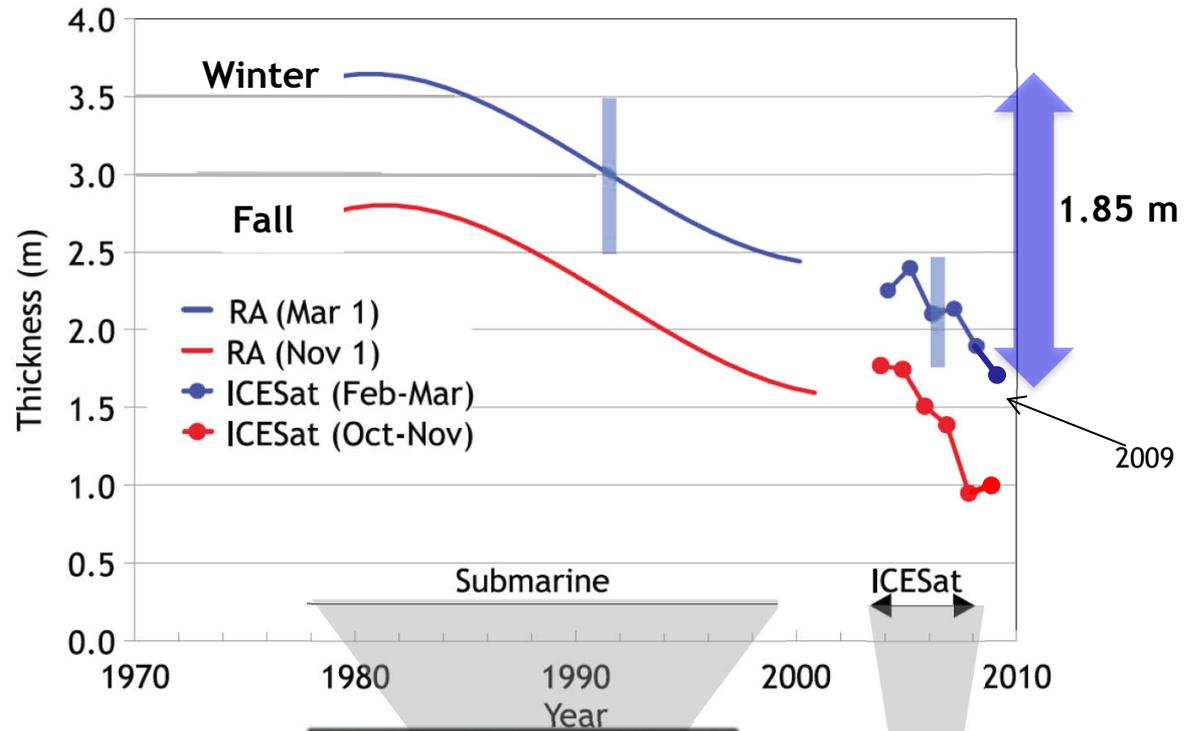
Winter sea Ice thickness from ICESat



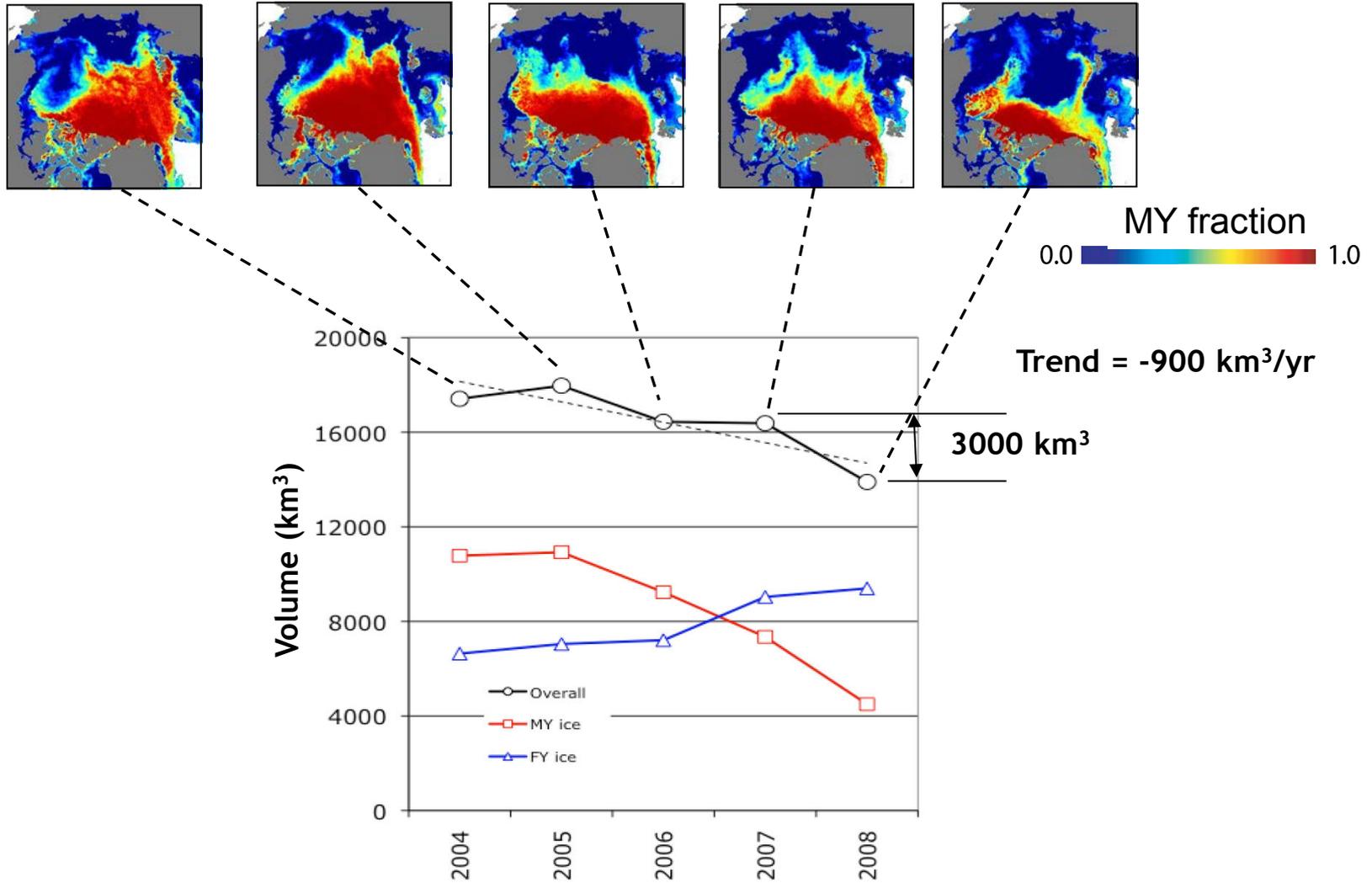
Decline in sea ice thickness from submarine and ICESat records: 1978 - 2009



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



Trend in winter sea ice volume



Instruments and measurements



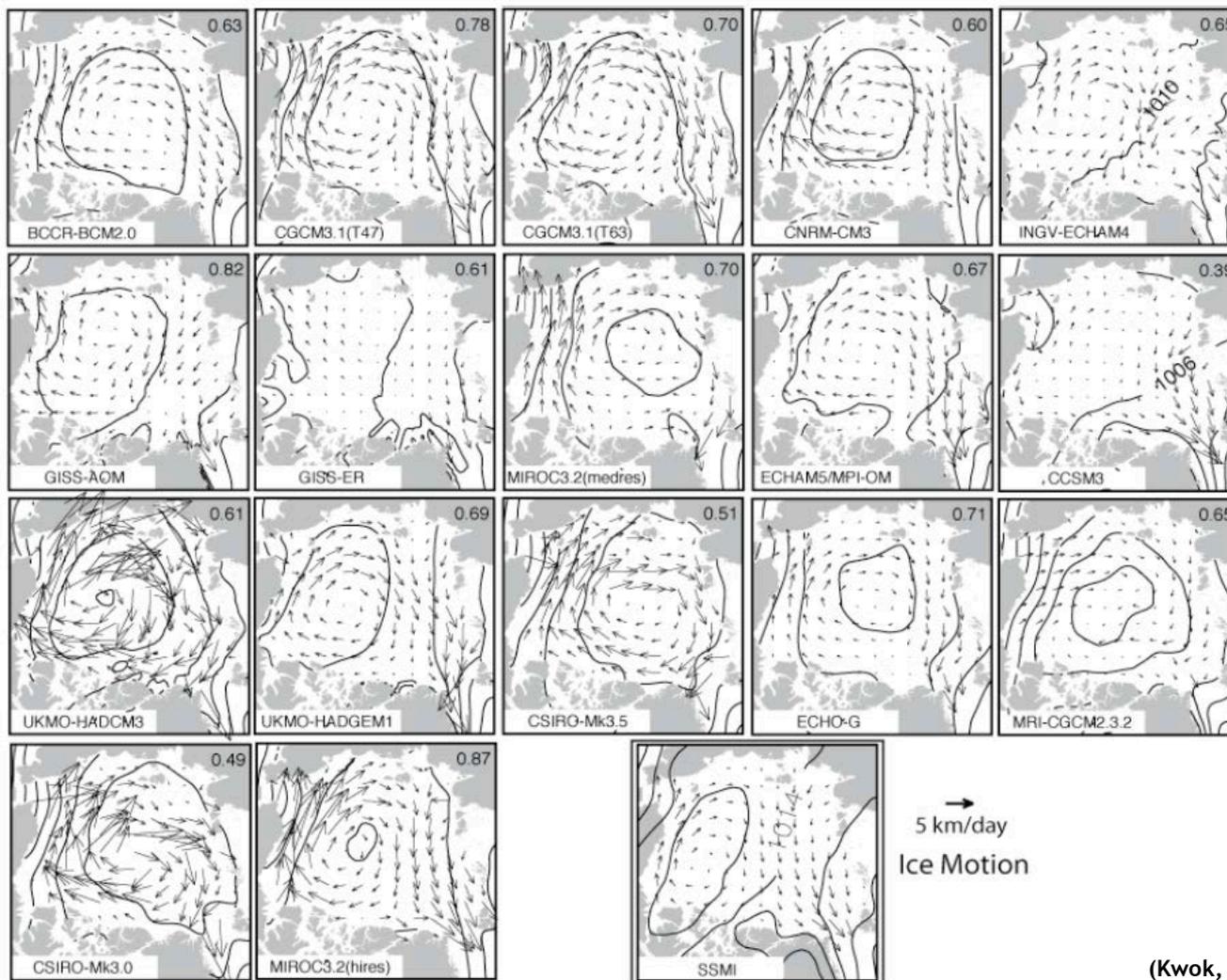
- *Synthetic Aperture Radar(SAR) / scatterometer*
 - *ice kinematics, ice type*
- *Altimeters*
 - *sea ice freeboard/ thickness, dynamic topography, sea surface height*
- *Ultra-wideband radars*
 - *snow thickness*
- *High resolution panchromatic imagers*
 - *melt ponds, deformation, ridge height*
- *Passive microwave radiometers*
 - *Motion and concentration*



Comparison with climate models



CMIP3 – sea ice motion

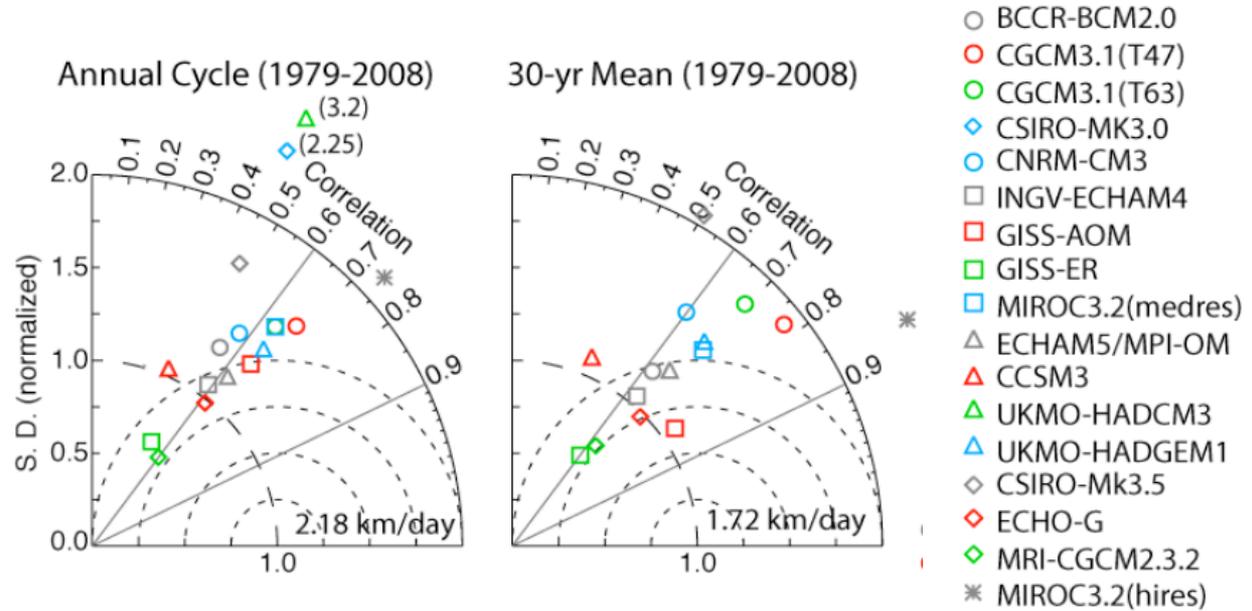


(Kwok, 2011)

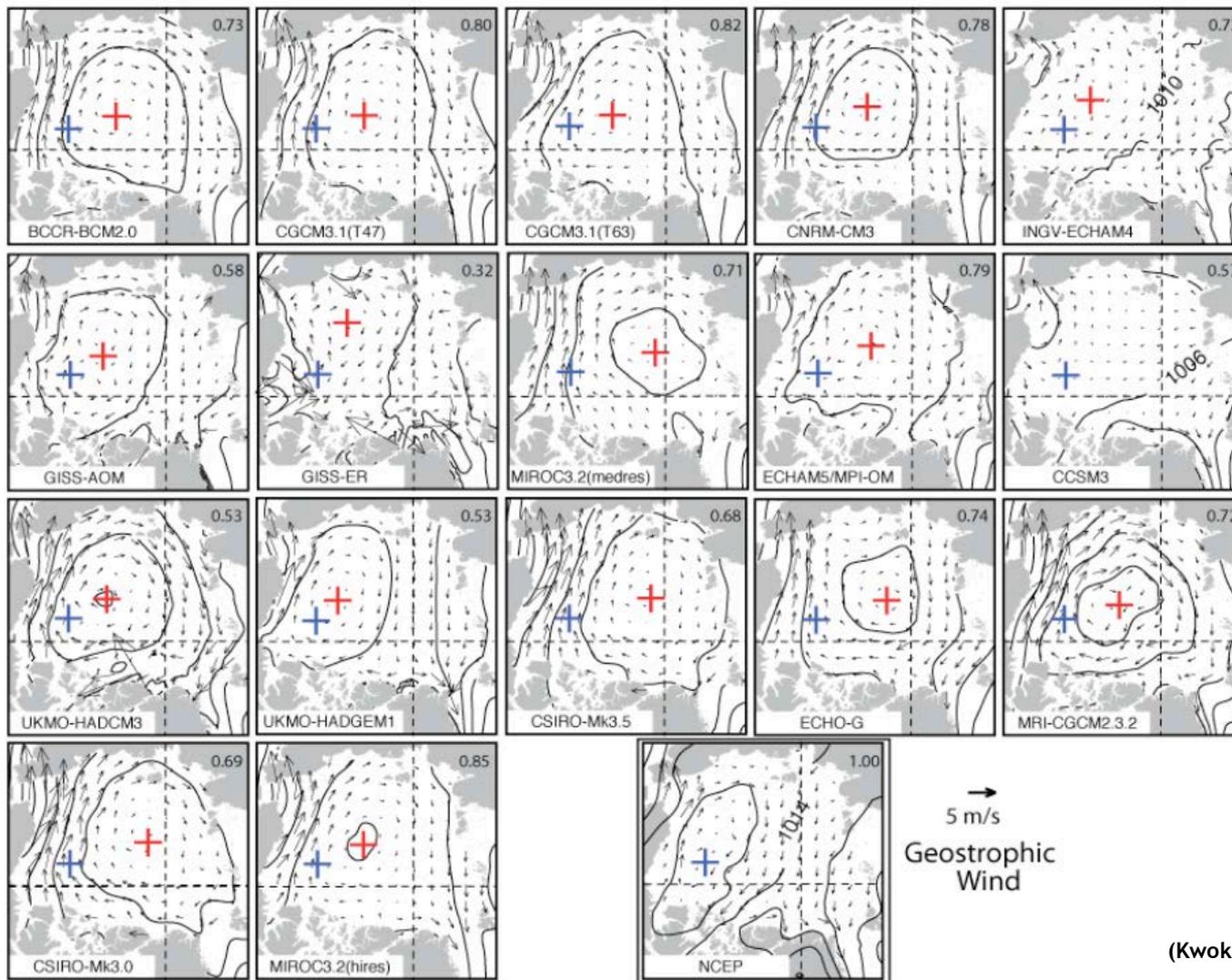
Ice Motion



(a) Ice motion



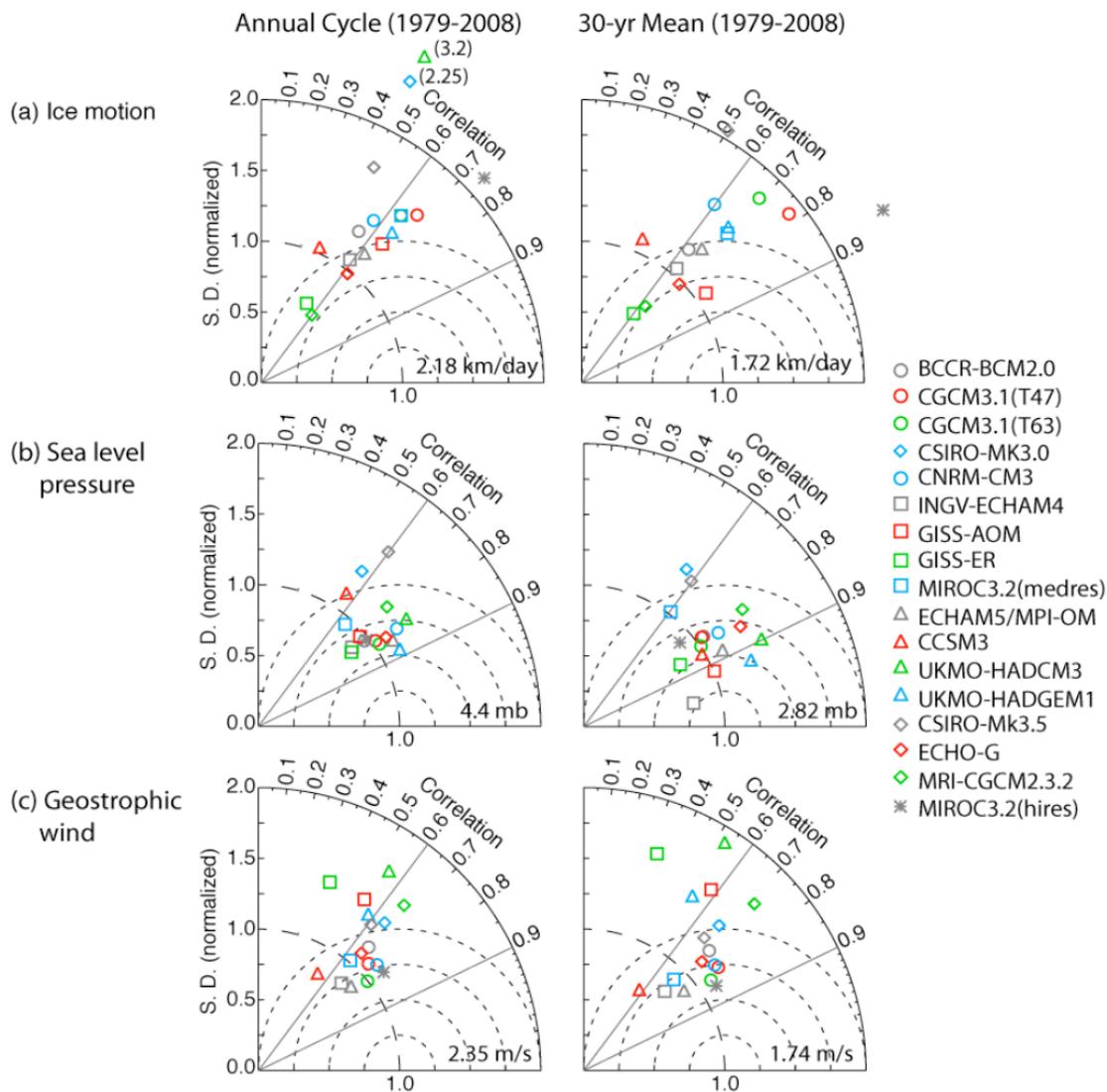
CMIP3 – sea ice motion



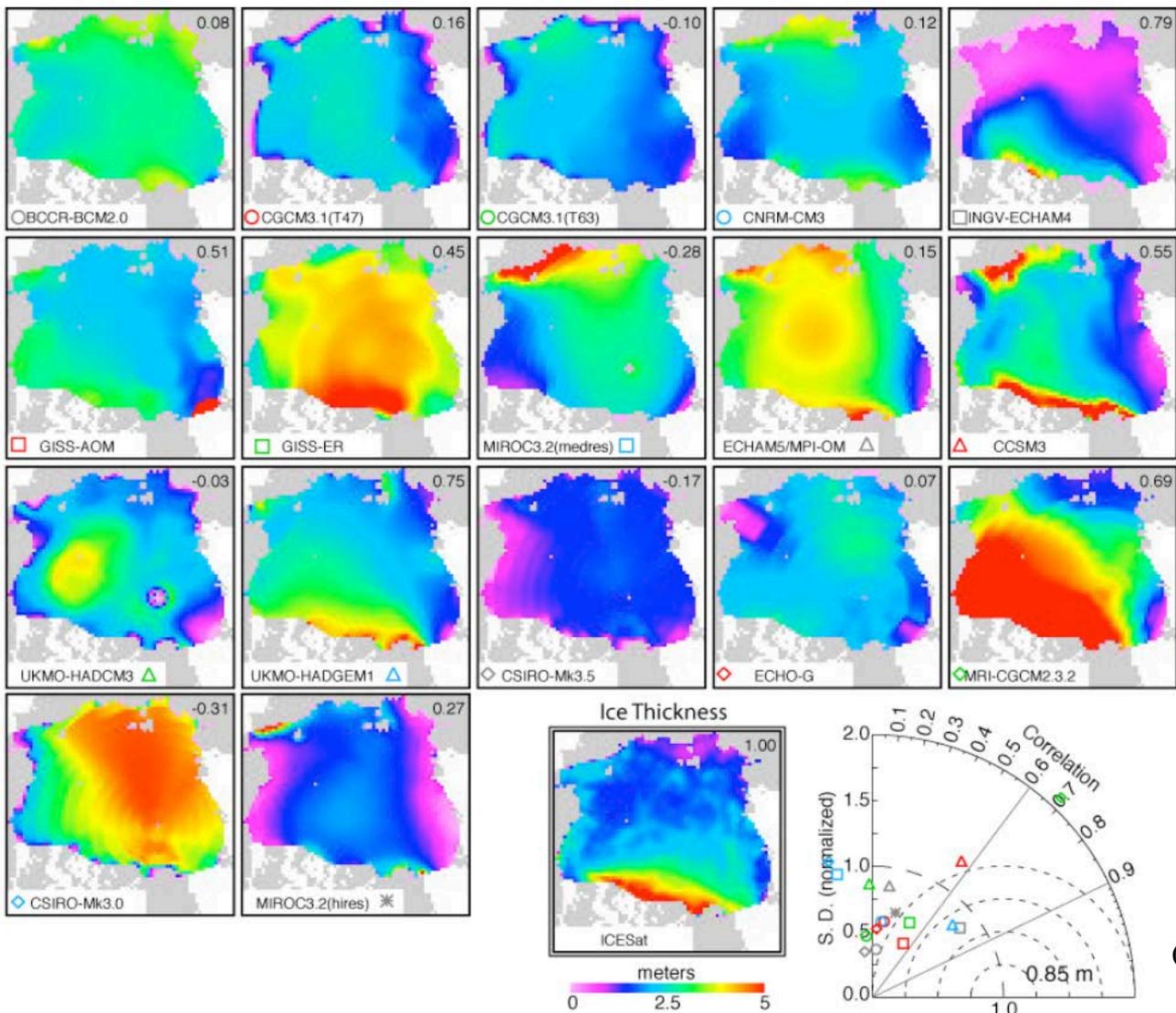
(Kwok, 2011)



Taylor Diagrams



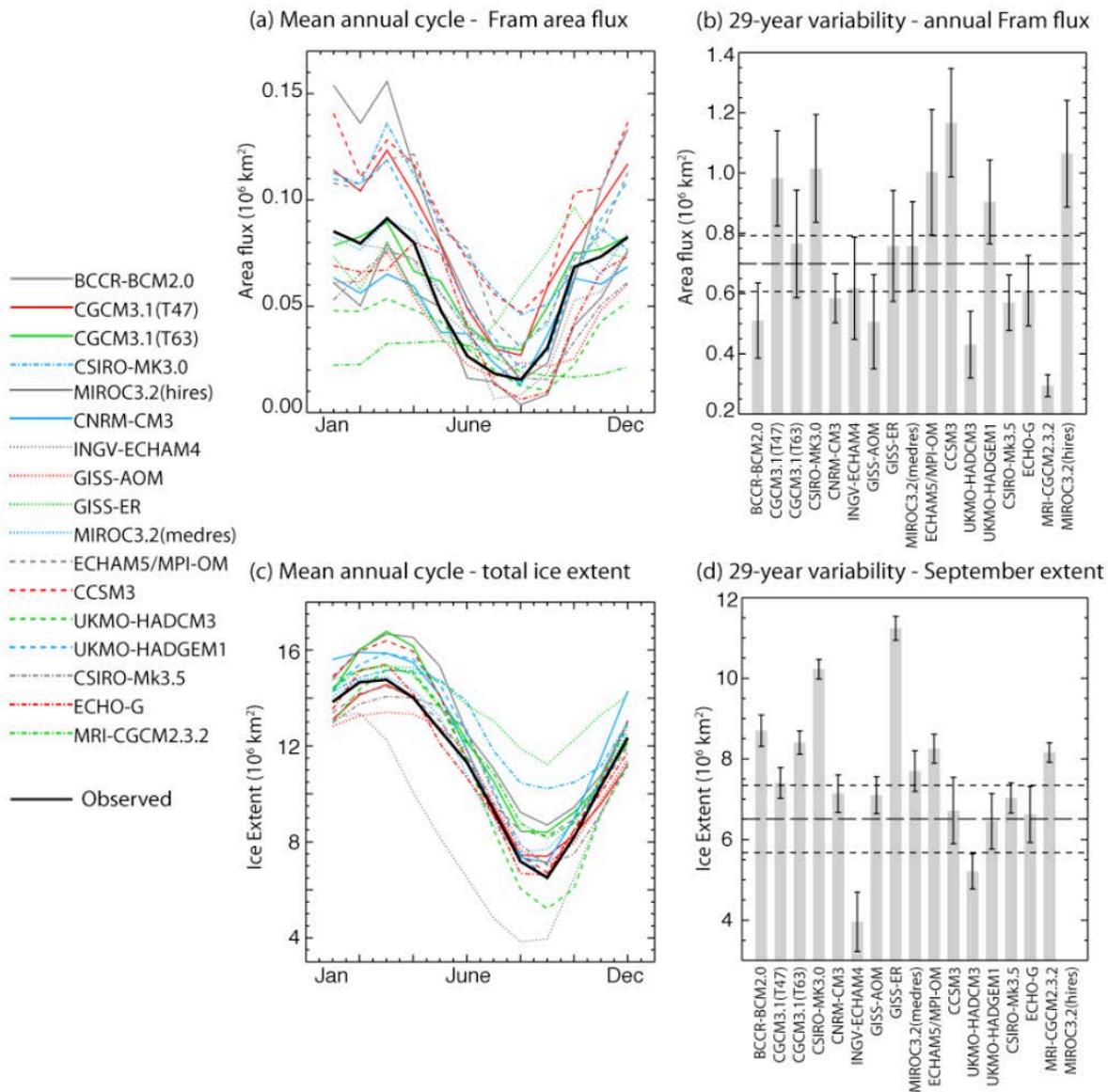
CMIP3 – sea ice thickness



(Kwok, 2011)



Ice Export and Extent



Topics



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