Remote Sensing of Polar Ice

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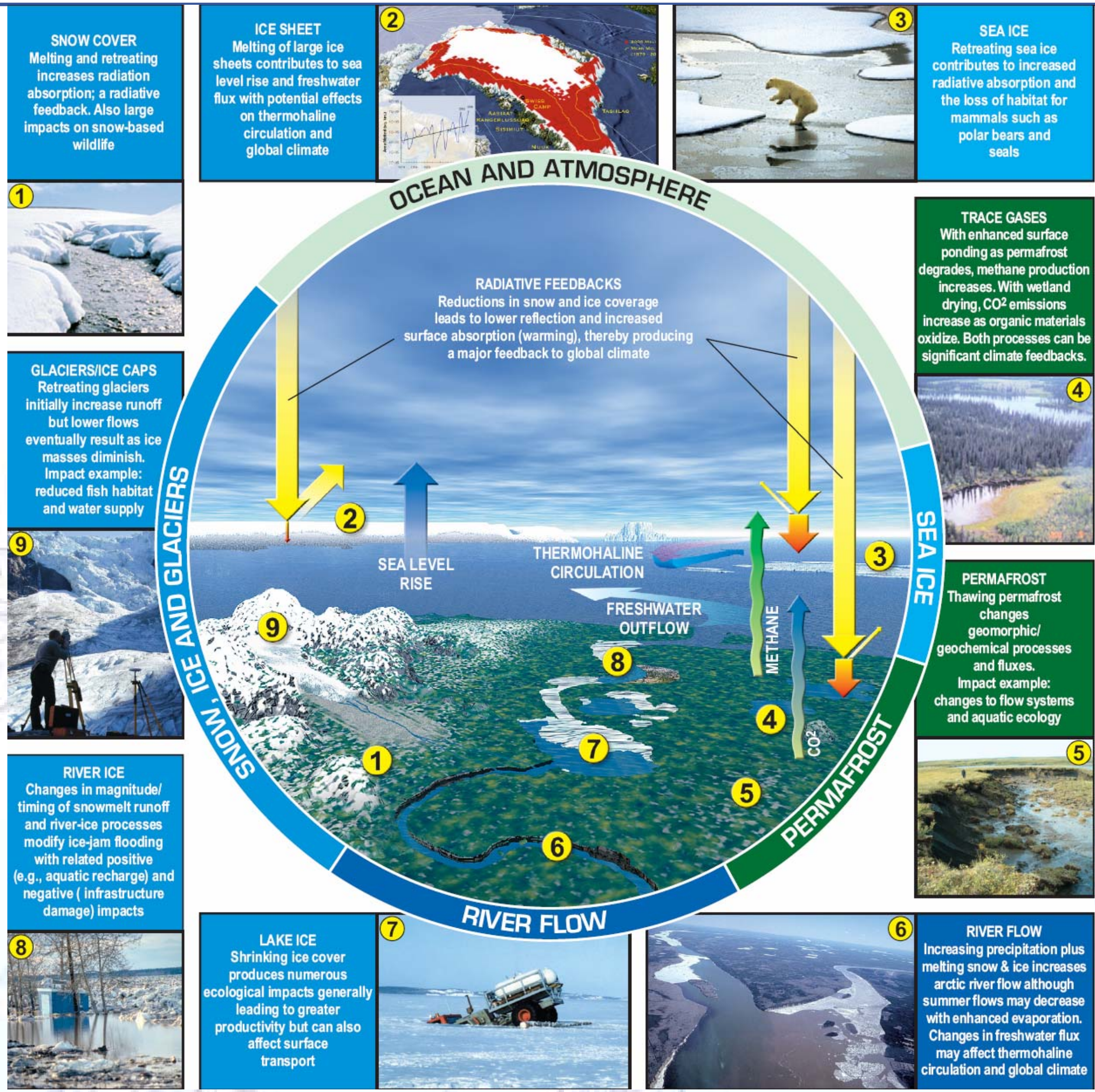
- The polar regions and their icy cover are well documented indicators of climate change
- High latitude processes are important drivers in climate change and sea level rise
- Observations, modeling and prediction of high latitude processes must be a key element of any climate research strategy
- Remote sensing is an essential tool for exploring these most remote parts of our planet

Impacts of Cryosphere

Courtesy

T. Prowse



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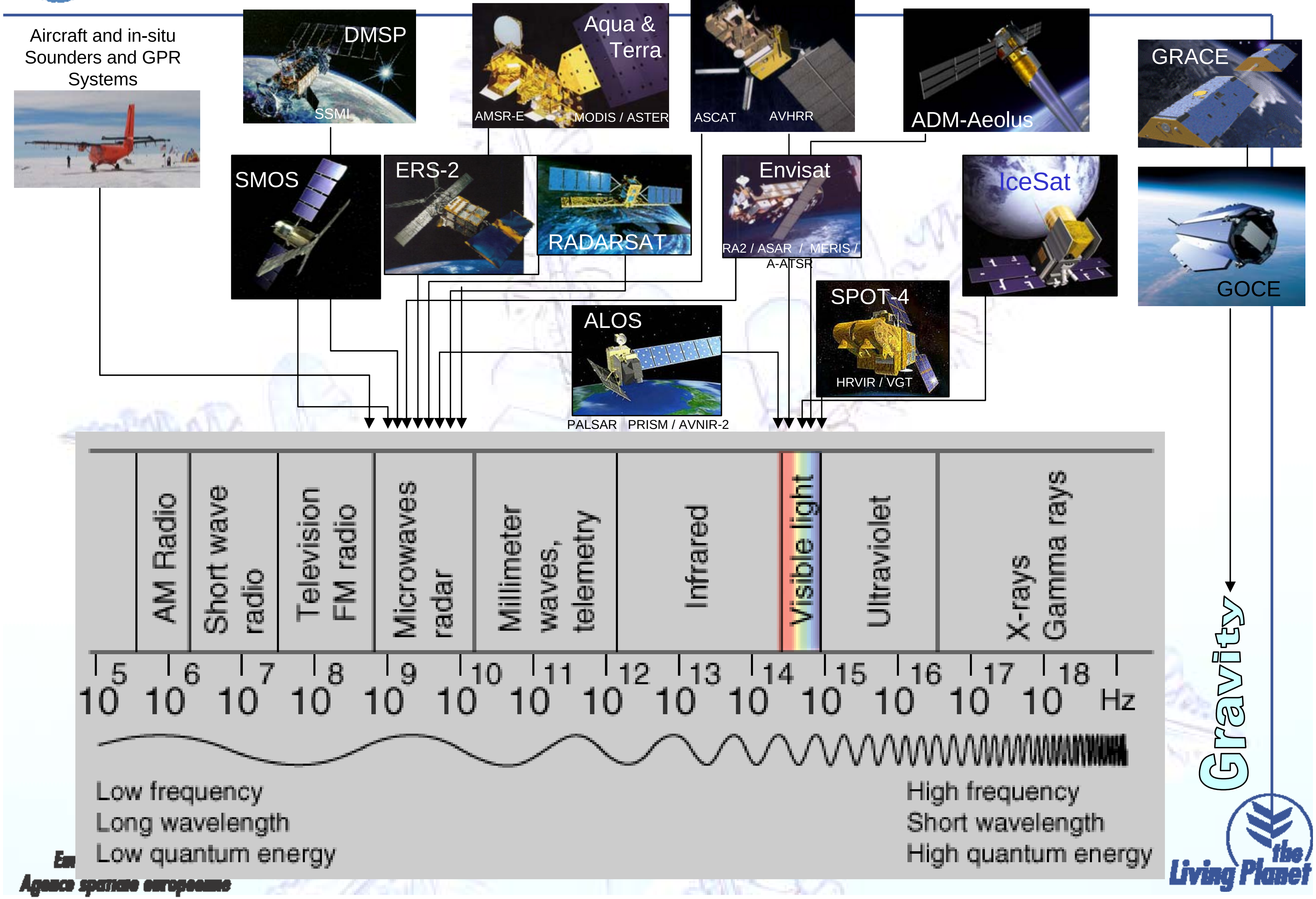
Introduction

- Excluding AVHRR, passive microwave (PM) radiometers have compiled one of the longest uninterrupted Arctic time-series
- Optical imagers are compromised by cloud and daylight
- Microwave remote sensing has revolutionised the study of the polar regions
- Talk focuses on the terrestrial and marine ice covers
  - such extensive regions illustrate the advantages of the remotely sensed perspective

Microwave Remote Sensing of Polar Ice

- Focus largely on Microwave measurements
  - Scope of all remote sensing contributions is too broad to do justice
- Microwaves provide day/night, year-round data
  - Longest uninterrupted PM radiometer measurement series from ESMR, SMMR; SSM/I; AMSR on ADEOS-2 and AQUA
  - Longest uninterrupted high-lat. (82^o) microwave radar altimeter (RA) datasets: ERS-1, ERS-2, Envisat
  - Longest uninterrupted C-band radar measurement series from ERS-1/-2 AMI (SAR and Windscat) and RADARSAT; and piecewise from SASS, NSCAT, SeaWinds on QSCAT and ADEOS-2
- Atmospheric effects minimised, such that surface processes can be studied effectively

Remote Sensing of Polar Ice



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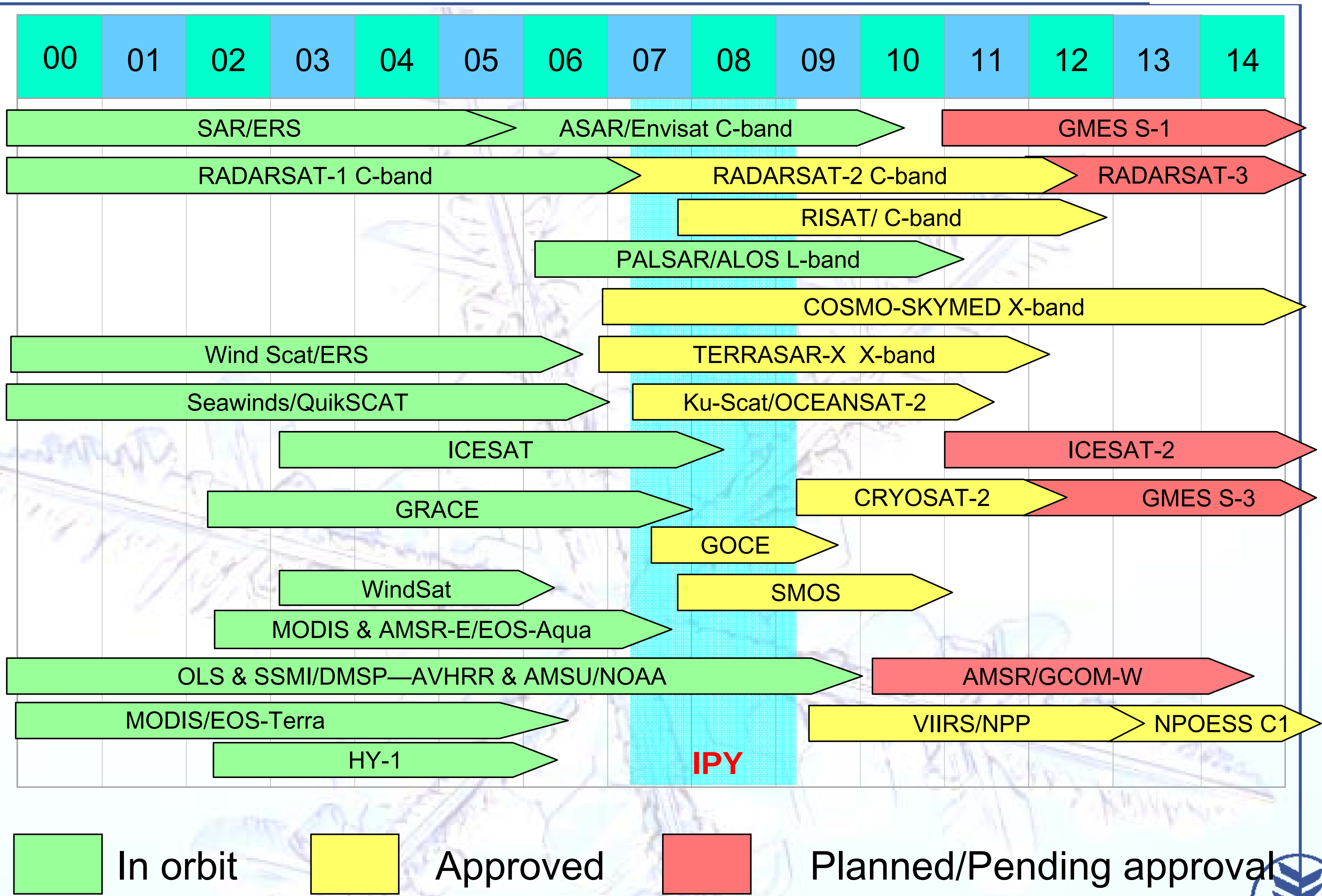
Cryosphere Satellite Missions

IGOS Theme on Cryosphere



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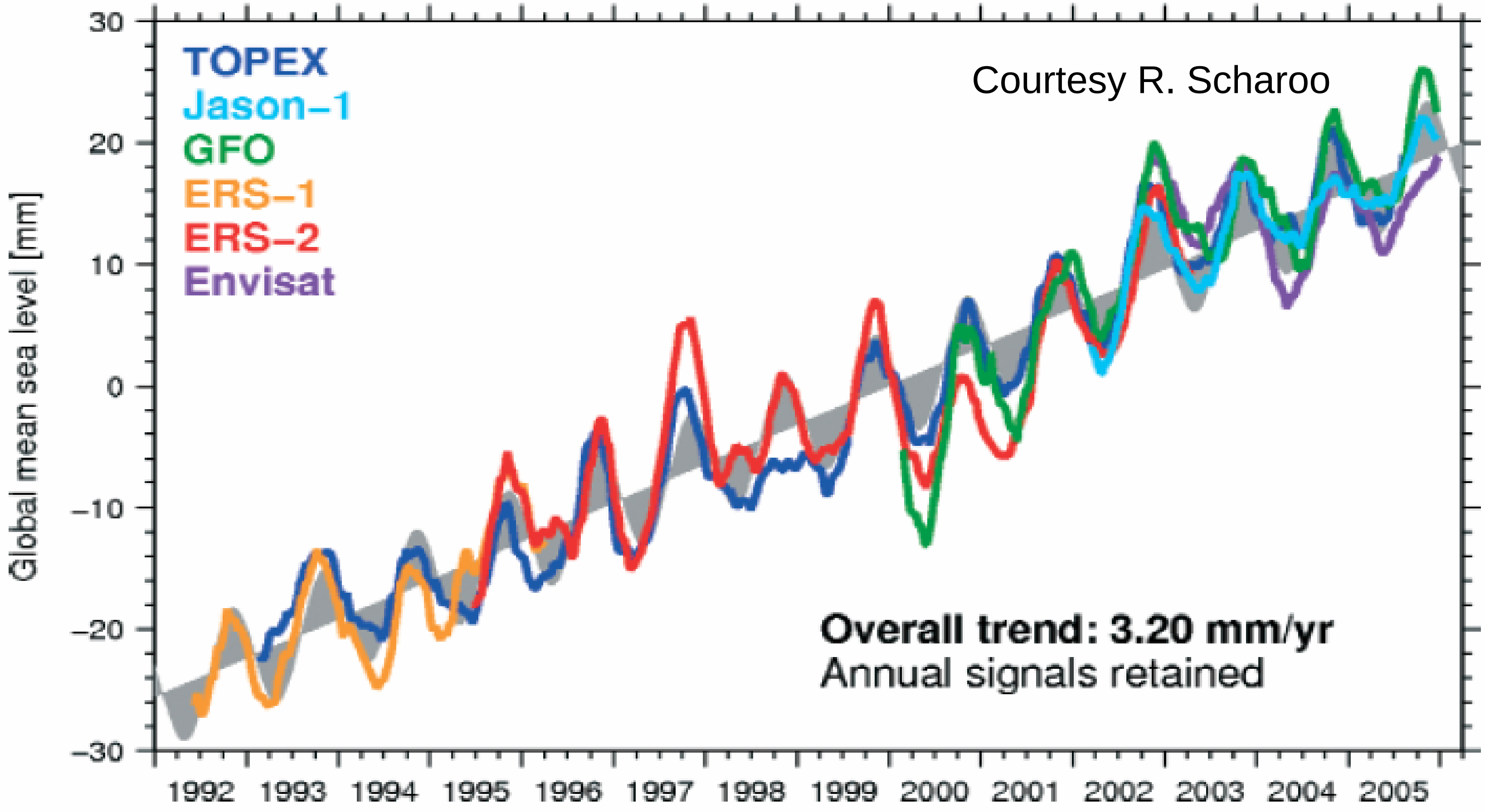
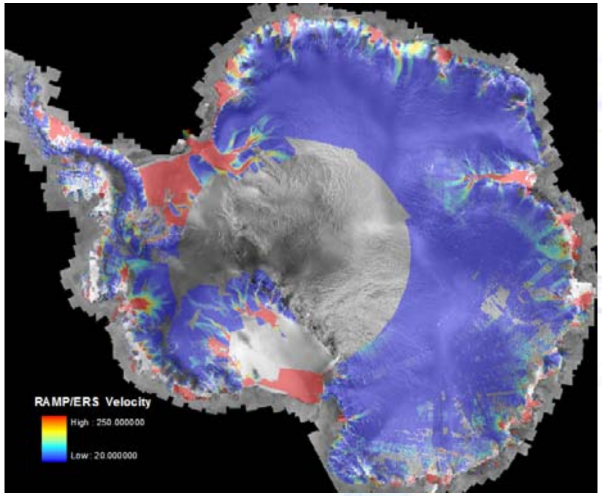
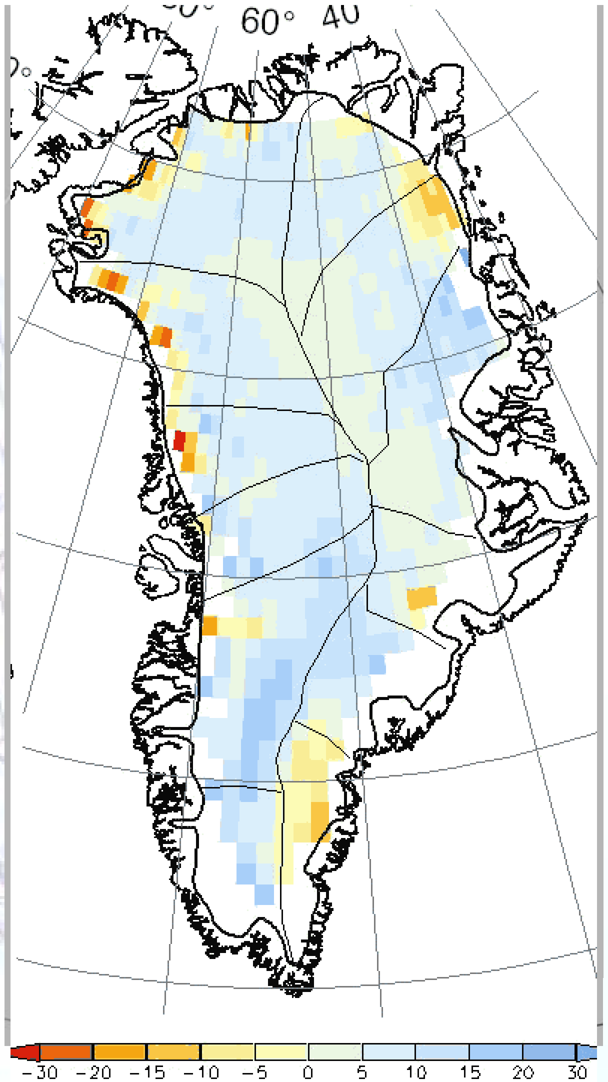
Land Ice

Global Sea-Level Change



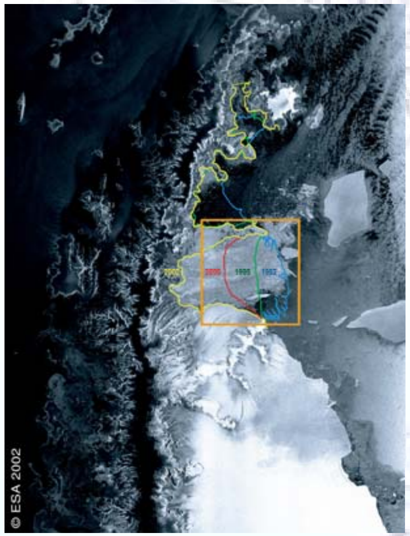
Greenland and Antarctic Ice Sheets





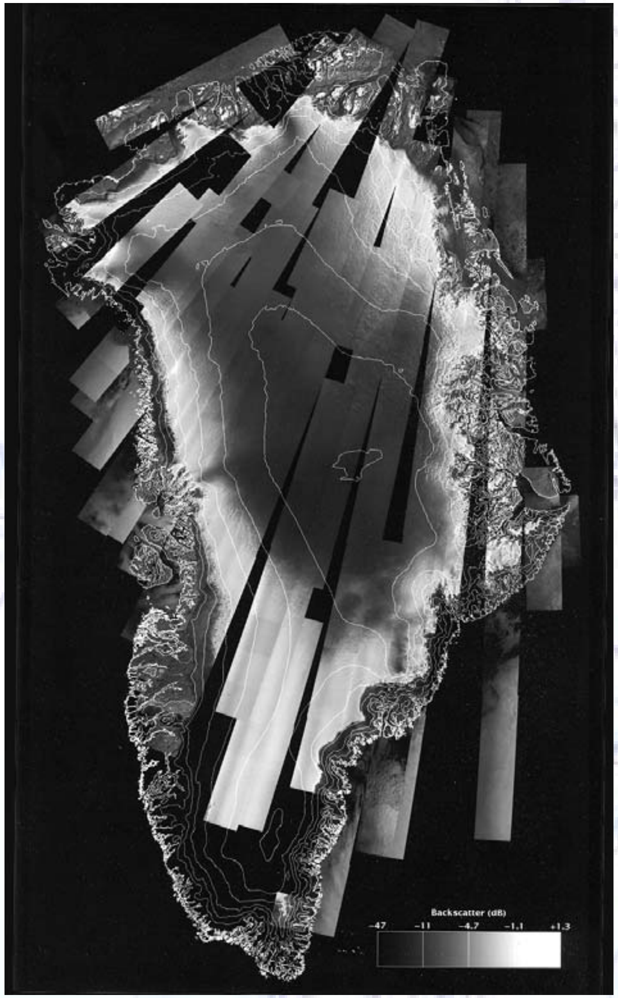
Science Goal:

Understand the polar ice sheets sufficiently to predict their contribution to global sea level rise



Ice Sheet Imaging – time/space coverage

ERS-1 C-band SAR (1992 – 1995)



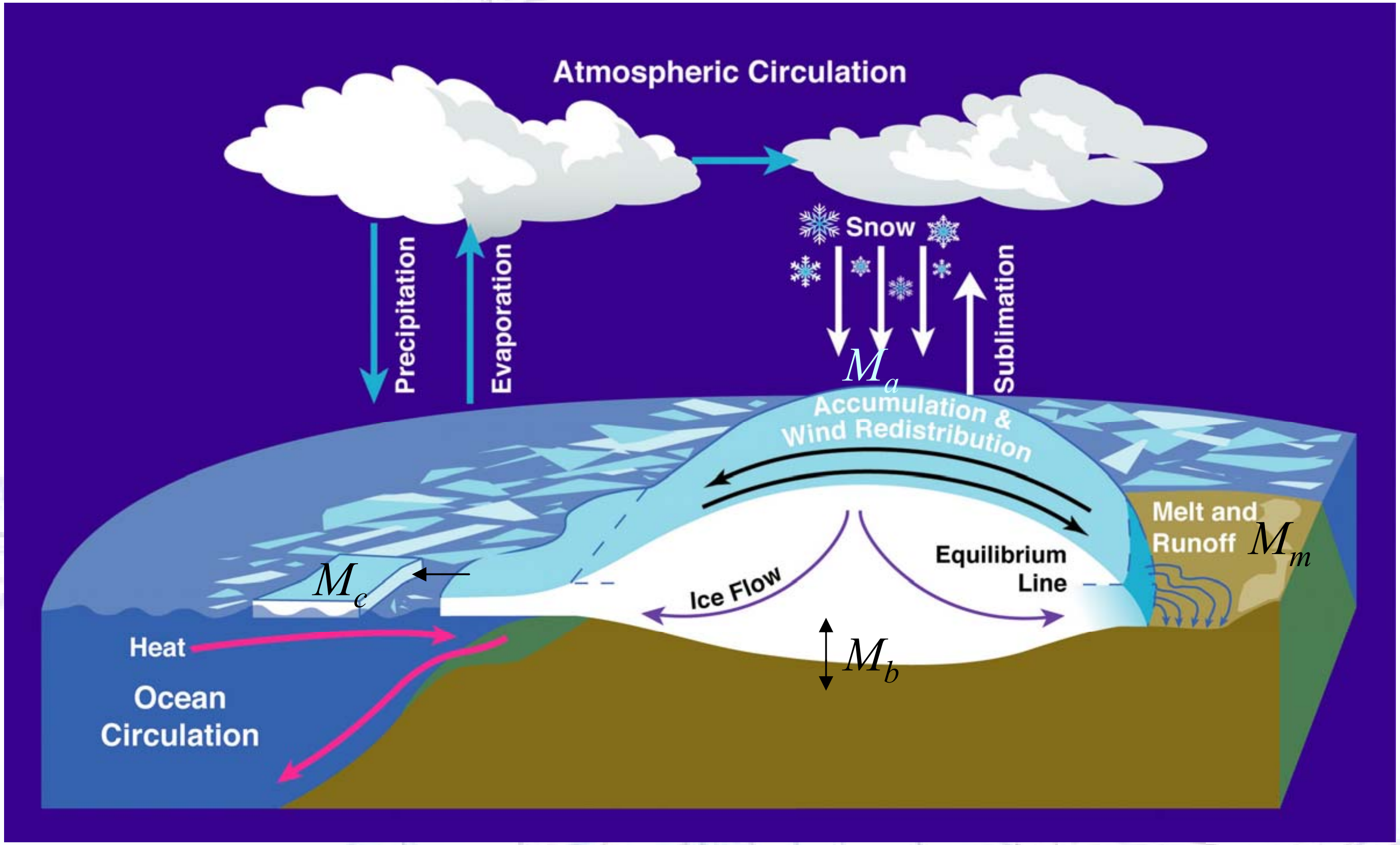
Courtesy, Kwok et al.

SeaWinds

Courtesy NASA SCP project

http://scp.byu.edu

Ice Sheet Mass Balance



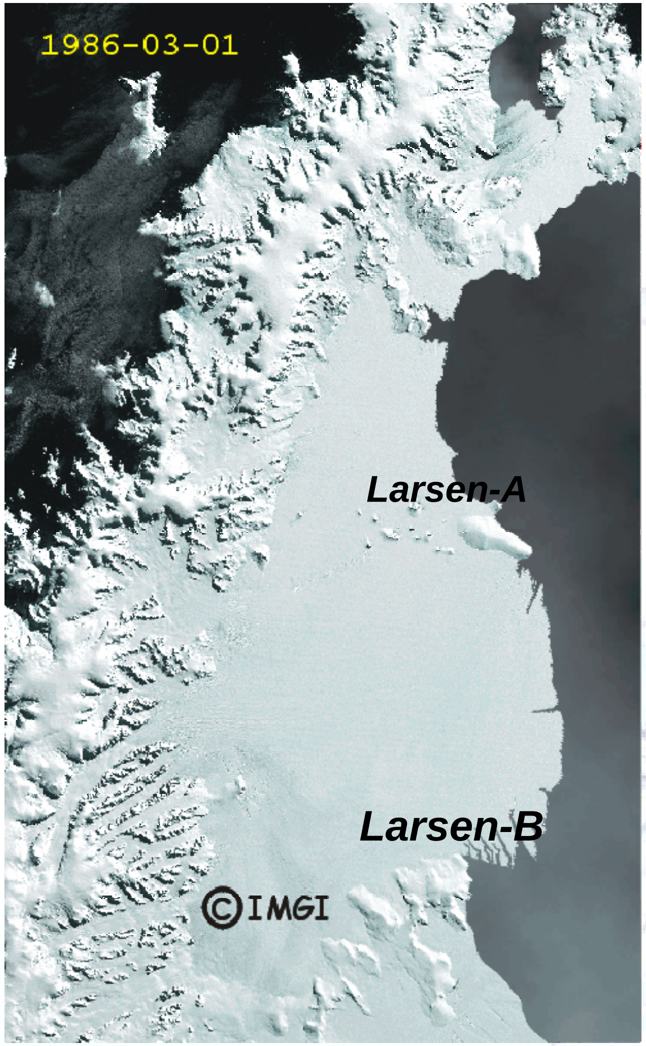
$$\delta V / \delta a = M_a - M_m - M_c$$

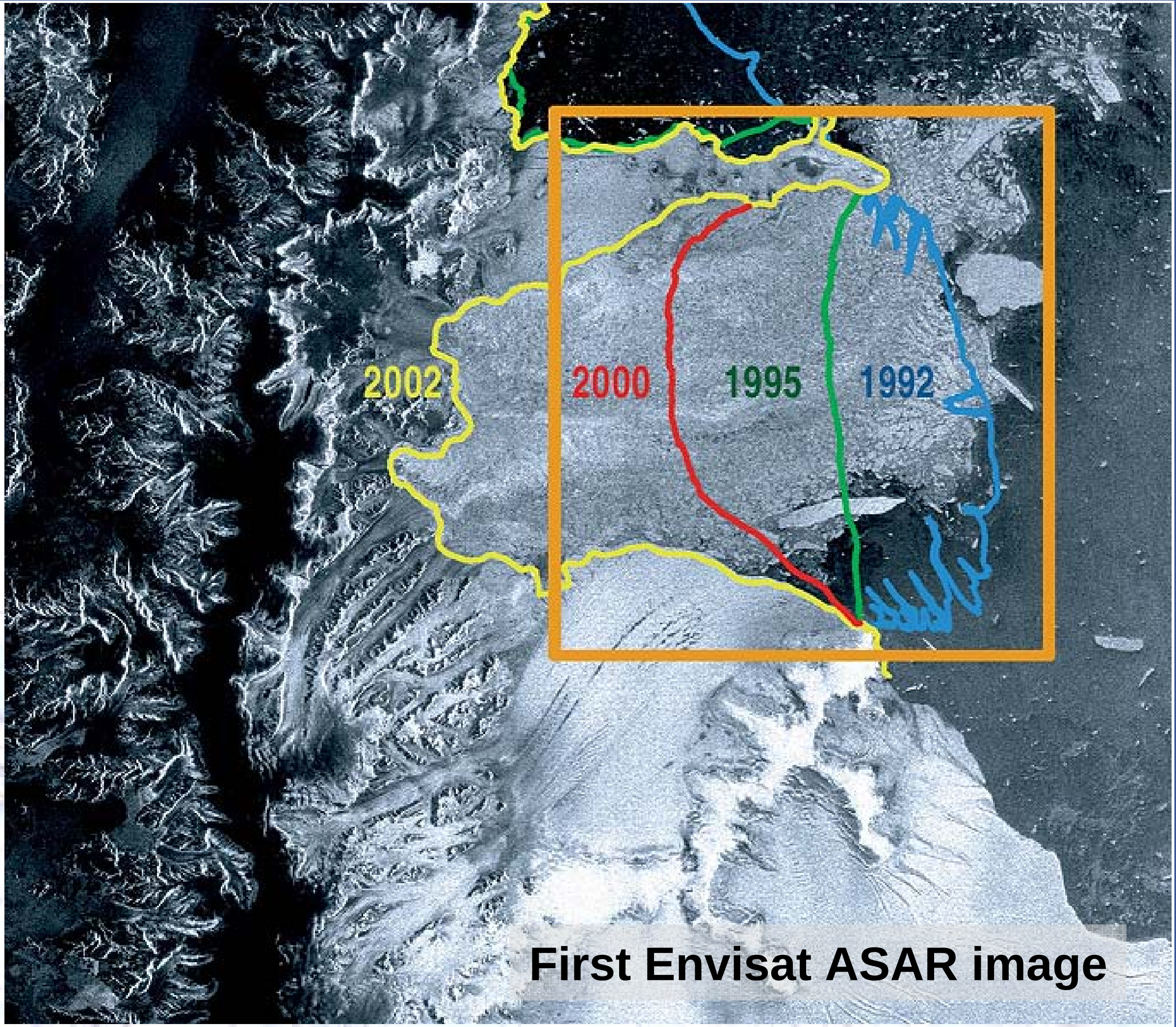
Volume change per year — Accumulation — Surface Melt — Calving

Mass Balance: Calving Mass Loss

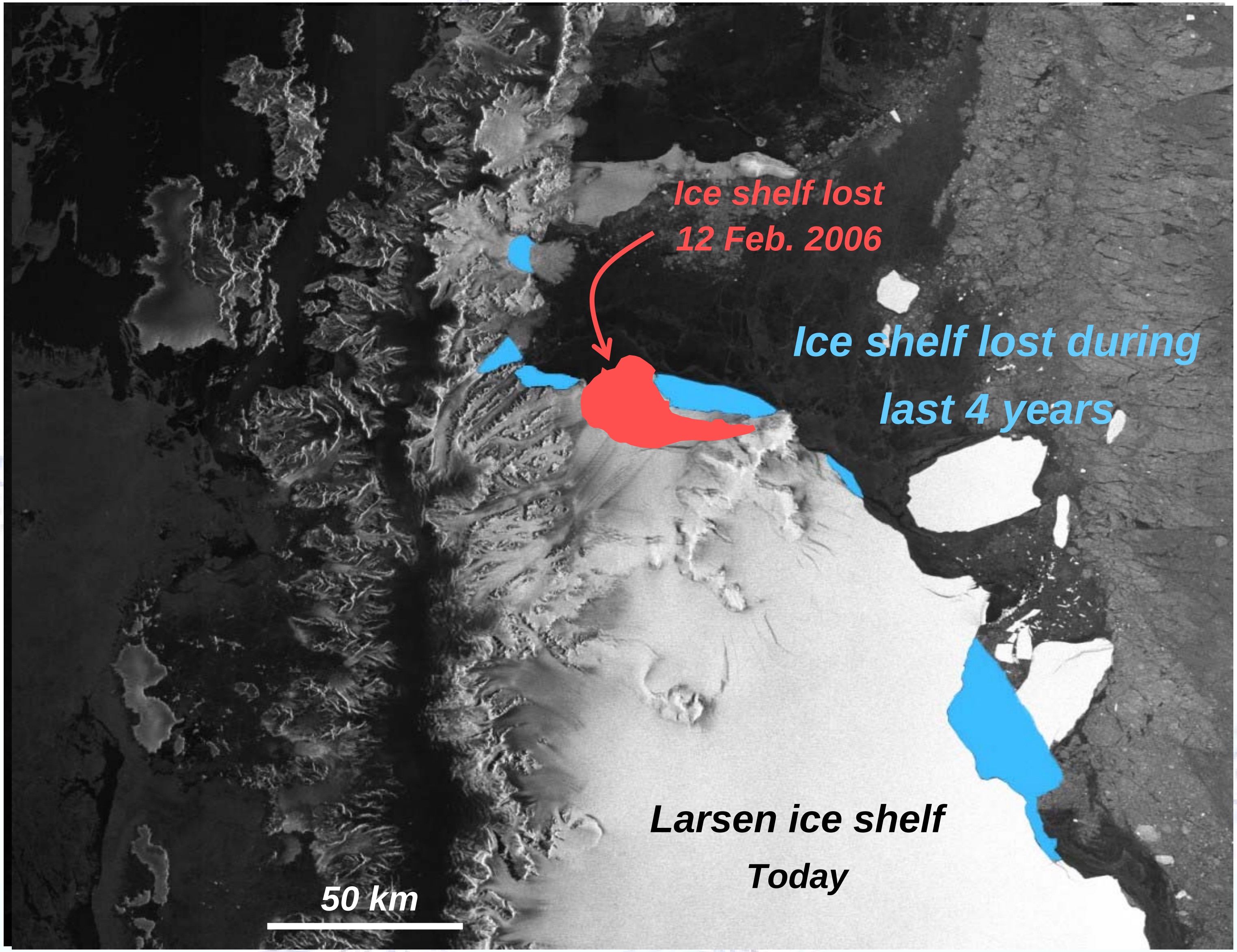
$$\delta V / \delta a = M_a - M_m - M_c$$

Larsen Ice Shelf Disintegration



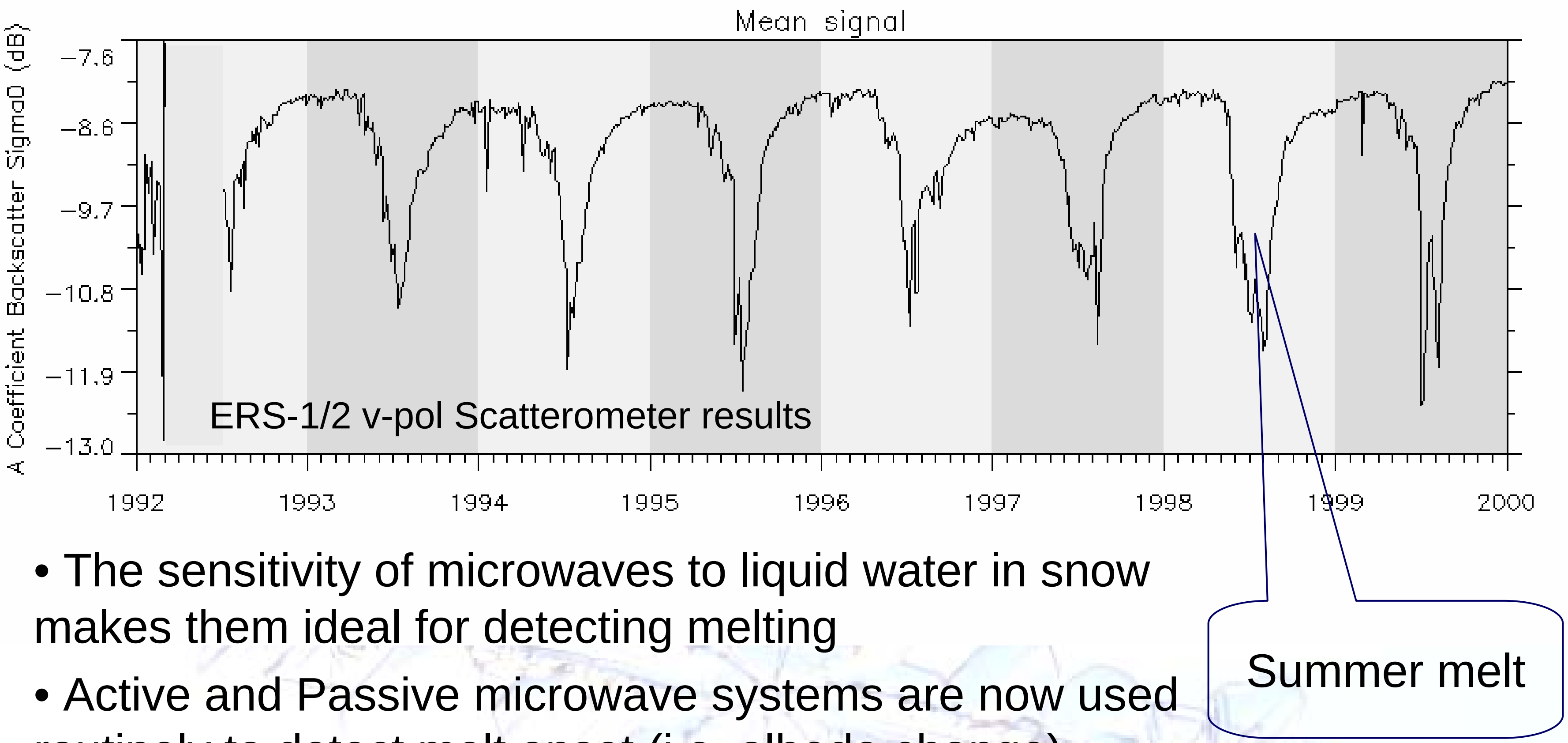


Larsen Calving events since 2002



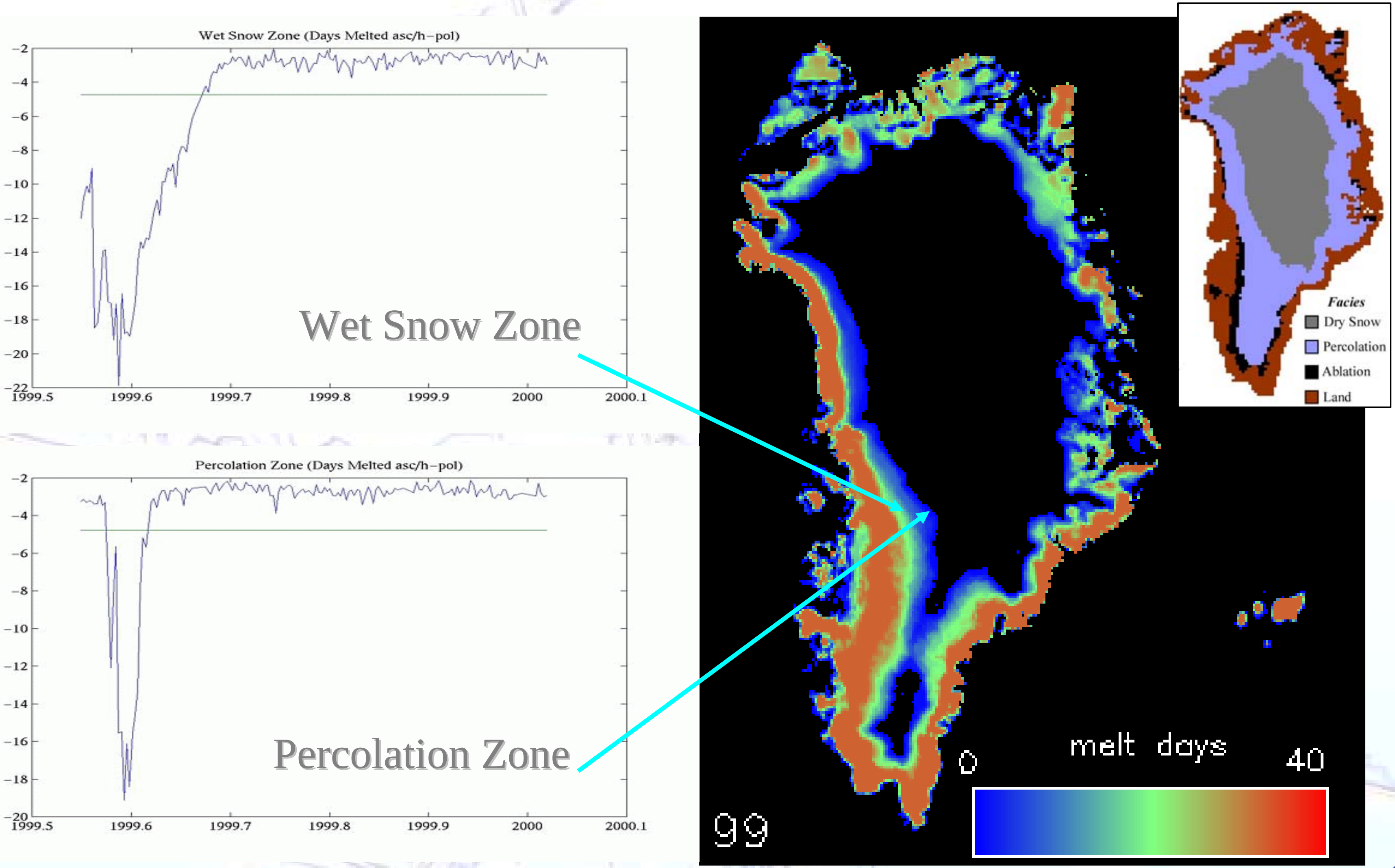
$$\delta V / \delta a = M_a - M_m - M_c$$

Greenland Ice Sheet Melt

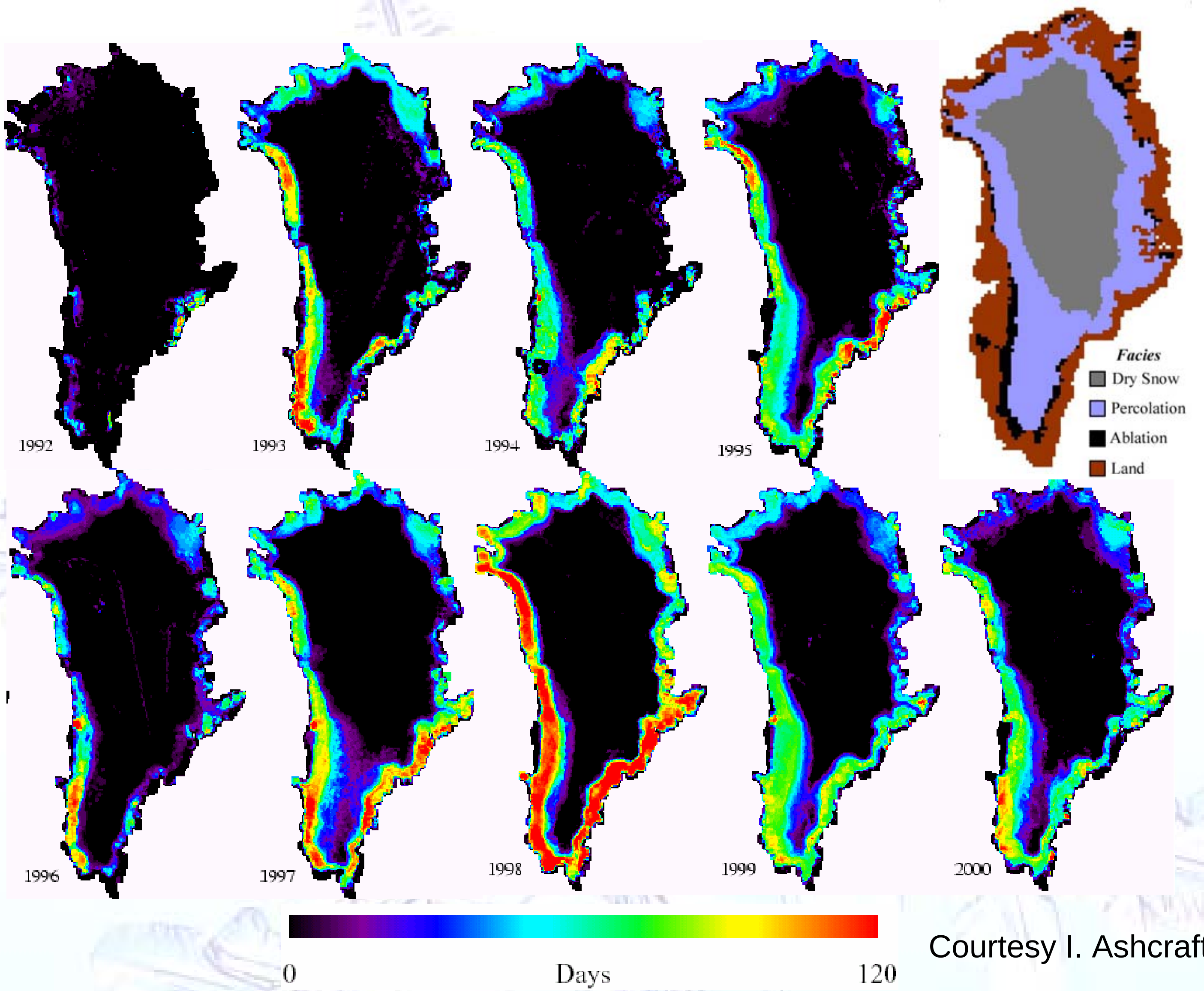


- The sensitivity of microwaves to liquid water in snow makes them ideal for detecting melting
- Active and Passive microwave systems are now used routinely to detect melt onset (i.e. albedo change)
- Advantage of longer wavelength radar is to penetrate beneath the surface to see archaeological evidence for melting/refreezing

Summer Melting

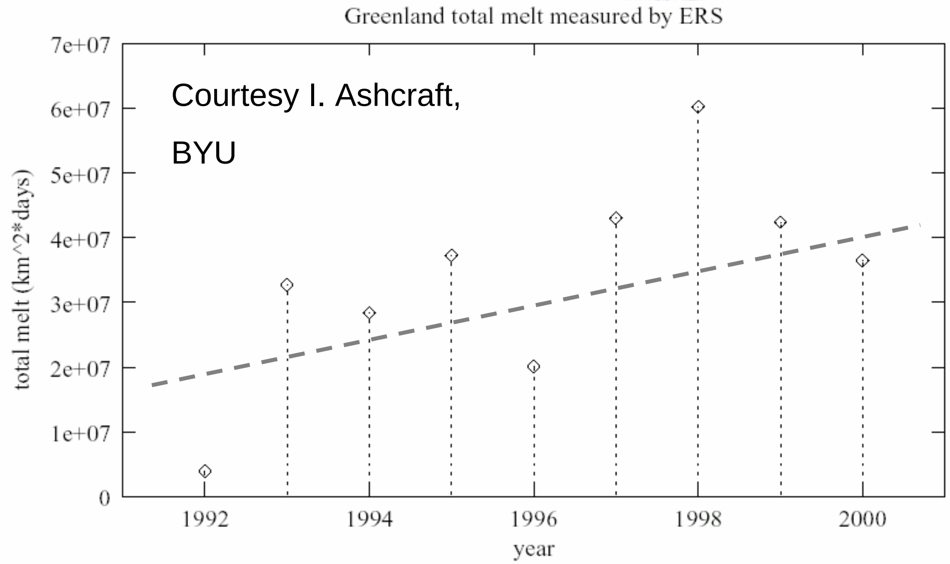


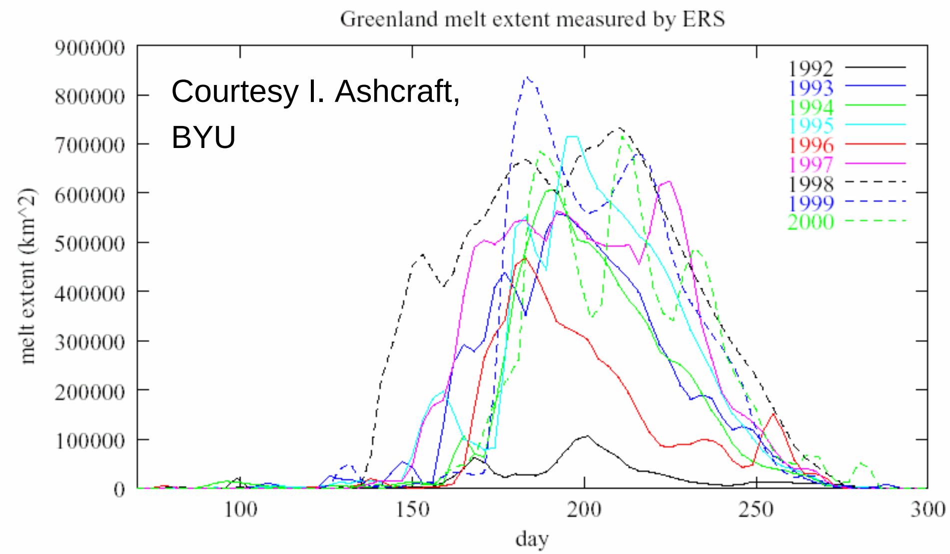
Ice Sheet Melt Duration - ERS Scatterometer

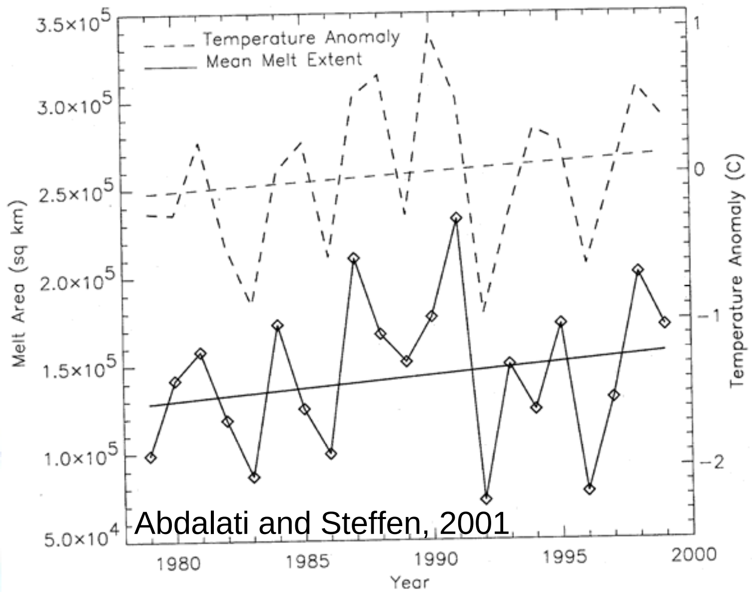


Courtesy I. Ashcraft, BYU

Interannual Variability in Summer Melt







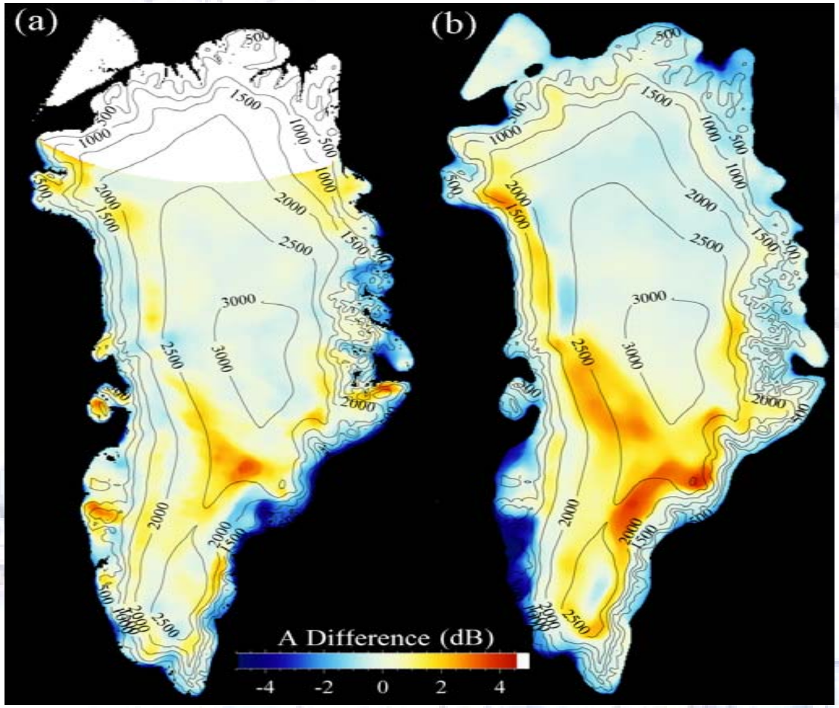
- Active and Passive sensors observe similar temperature-dependent melt trends on ice-sheet scale
- Radar – Radiometer differences observed on regional scales require further examination
- QSCAT, ADEOS-2 and SSMI, AMSR semi-diurnal image data enable energy balance studies with AWS data

Melting Extent Wandering Upslope

ERS-NSCAT ('96)

$\Delta\ \sigma^o$ = -1.8 dB contour delineates upper boundary of melting zone.

1996-1978 1999-1996



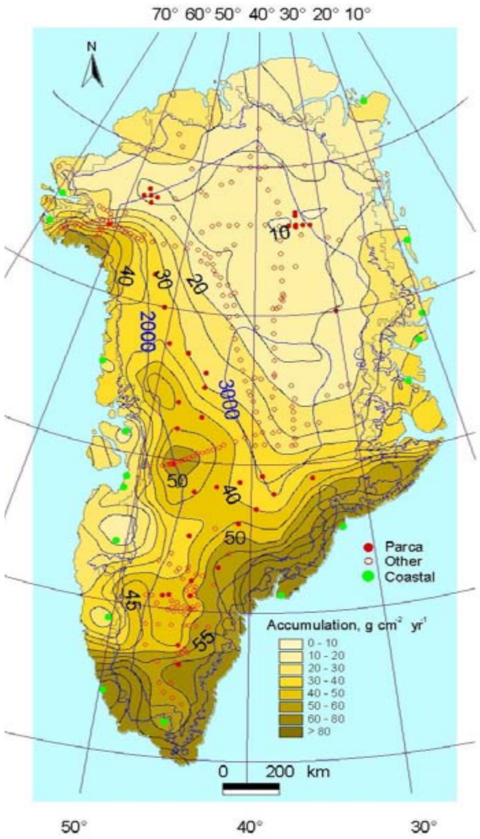
Drinkwater et al. (2001)

- ERS – NSCAT or QSCAT frequency difference image used to map dry snow, and ablation regions
- Penetration used to delineate percolation zone and ablation facies
- Impact of melting on upslope migration of percolation features

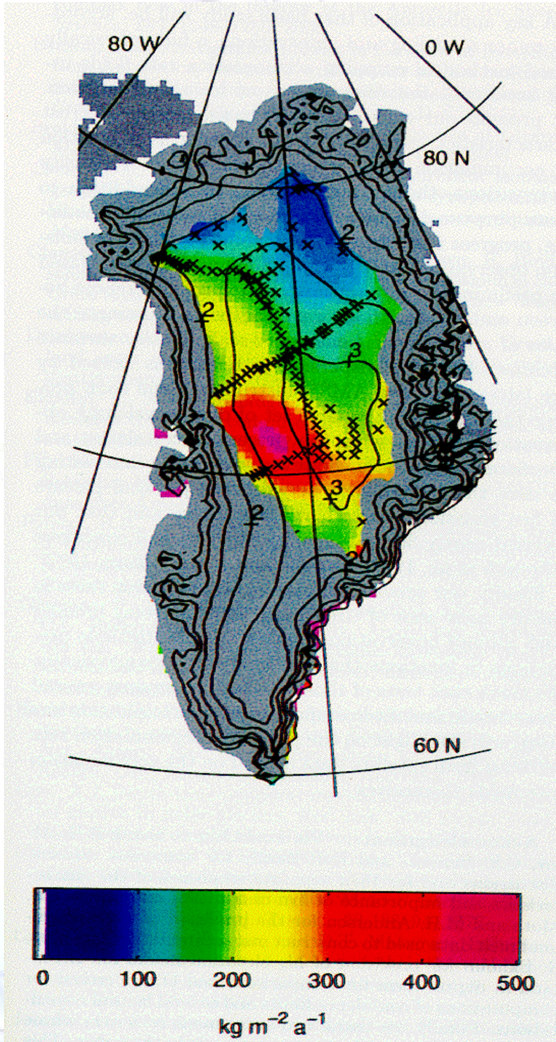
Mass Balance: Snow Accumulation

$$\delta V / \delta a = M_a - M_m - M_c$$

Ice Sheet Accumulation – with microwaves



Bales et al. (2001)



Arthern and Winebrenner (2001)

- Passive microwave:
  - 5 GHz polarisation dependency on layering
  - Jezek and Bolzan (2001)
  - Flach et al. (2005)
- Active Microwave:
  - Drinkwater et al (2001) Ku-band Scatterometer
- Annual accumulation estimates accurate to within ±5% of mean
- Equivalent to shallow core accumulation estimation accuracy

At a given point the vertical change in the surface associated with the mass balance of the ice sheet is described by the continuity equation

$$\frac{dh}{dt} = \nabla \bullet H\vec{U} + \dot{a}$$

Elevation Change

Dynamical thickening/ thinning

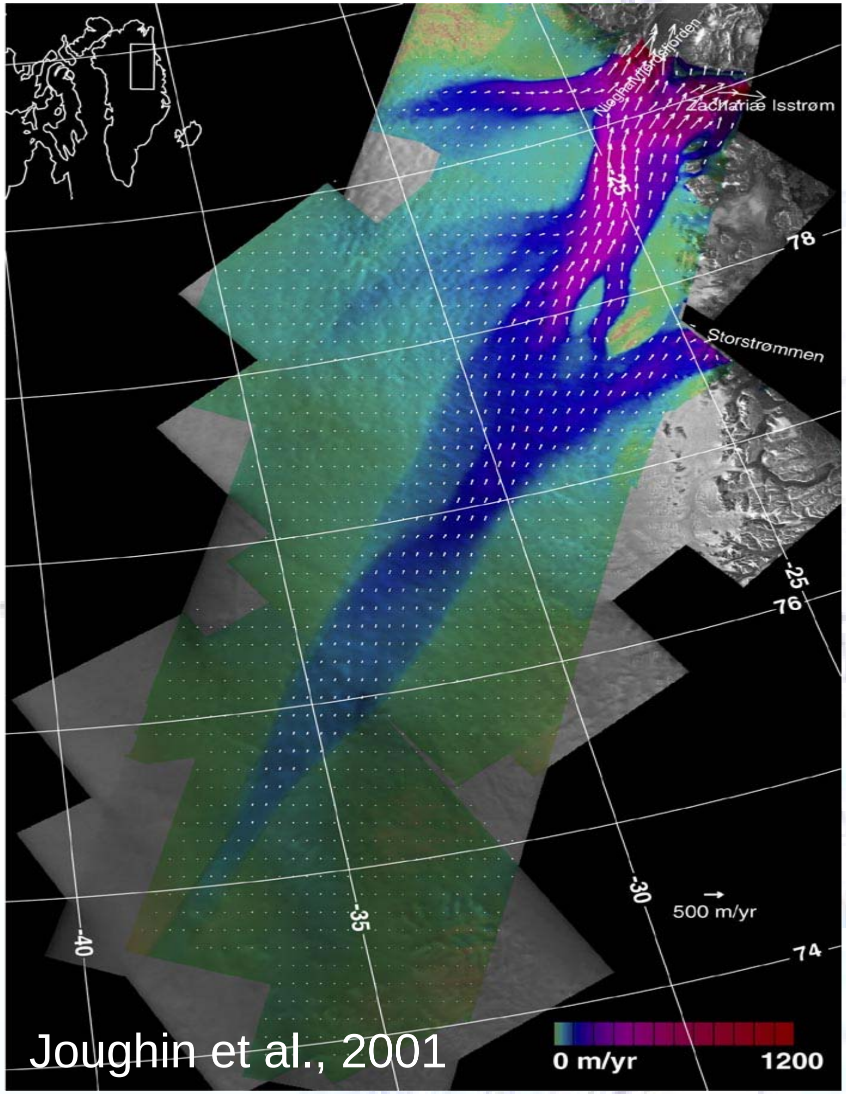
Rate of Change in accumulation

Mass Balance: Quantifying Ice Dynamics

$$\frac{dh}{dt} = \nabla \bullet H\vec{U} + \dot{a}$$

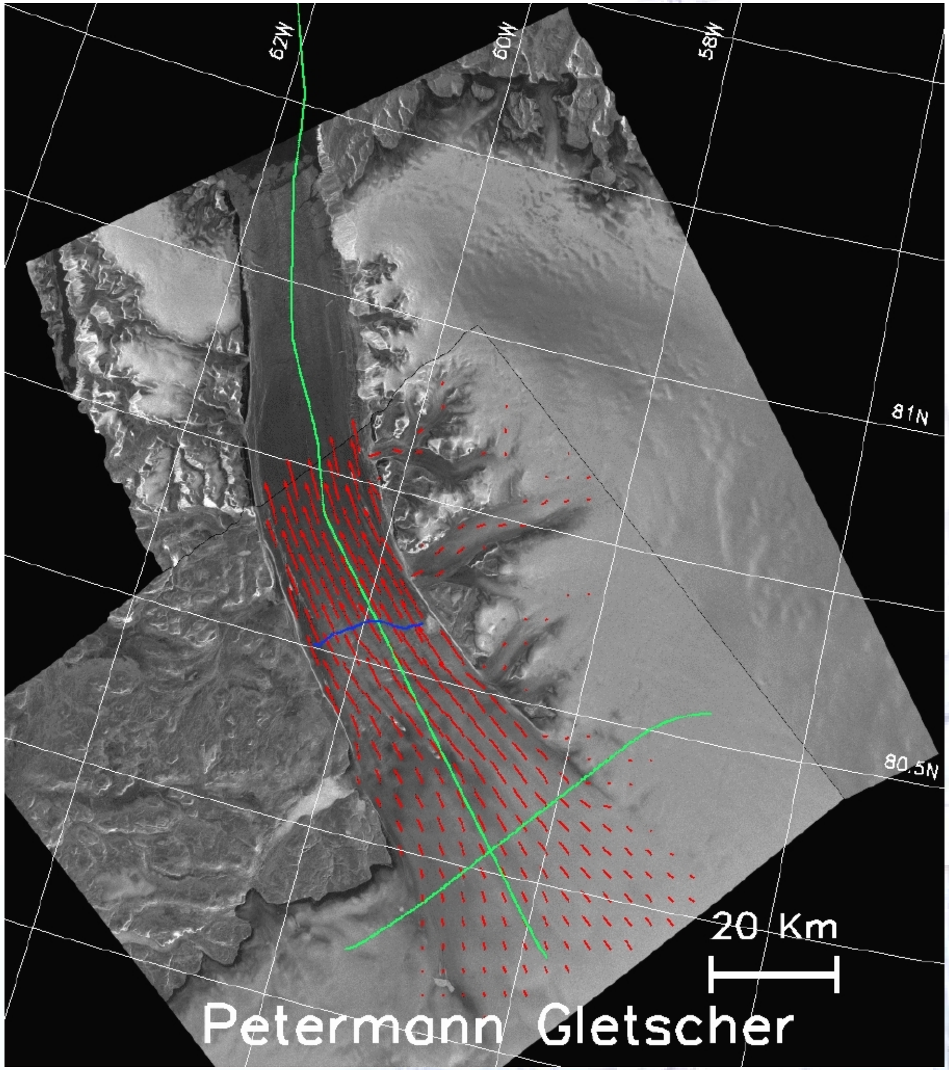
Dynamical thickening/ thinning

SAR Interferometry



- Repeat pass interferometry on crossing orbits allows separation of DEM and line of sight velocity
- Mosaicking of InSAR results facilitates ice sheet-wide velocity mapping
- Together with altimetry and echo sounding InSAR provides valuable method for measuring ice volume flux

Interferometric SAR Results



Courtesy E. Rignot, JPL

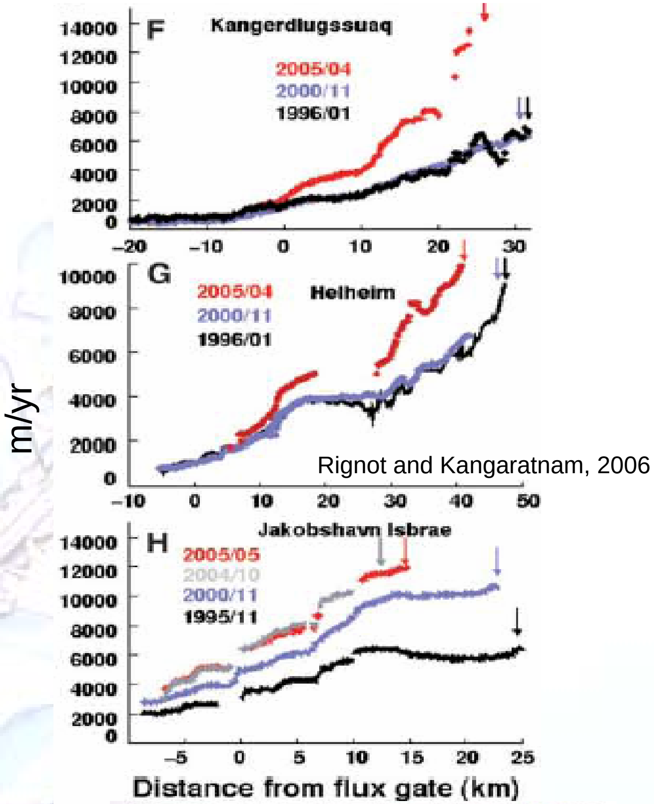
- ERS SAR interferometry provided a new stimulus in ice-sheet research
- Revolutionised understanding of timescales of variability in ice stream dynamics
- Provided a capability to understand short-term adjustments in ice-stream dynamics
- Interferometry has enabled location of hinge-line/grounding line for tide-water glaciers and floating ice shelves

Mass Balance: Ice Stream Dynamical Adjustments

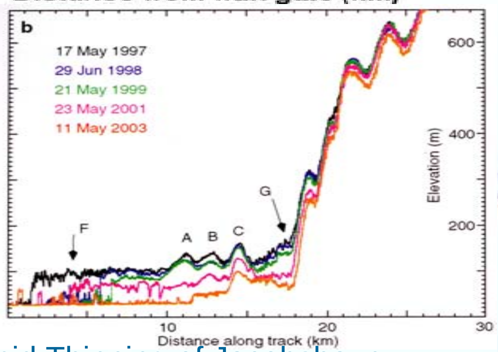
- Zwally (2006) suggests central Greenland gaining mass (-0.03 mm a^{-1} sea level rise)
- Rapid thinning of Jacobshavn Glacier, Greenland (> 10 m a^{-1}, Thomas, 2003)
- Glacier acceleration and increased mass deficit about Greenland periphery (Rignot and Kanagaratnam, 2006) loss of 224 +/- 41 km^3 ice/year in 2005
- Results suggest increased accumulation in central ice sheet, and increased net ablation and rapid dynamic adjustment at lower altitudes

*<u>Observed rapid changes in Greenland and Antarctica are not predicted by climate models (</u>*slow and linear response to climate forcing; fast glacier flow not included)

Outlet Glacier Acceleration



Rignot and Kangaratnam, 2006

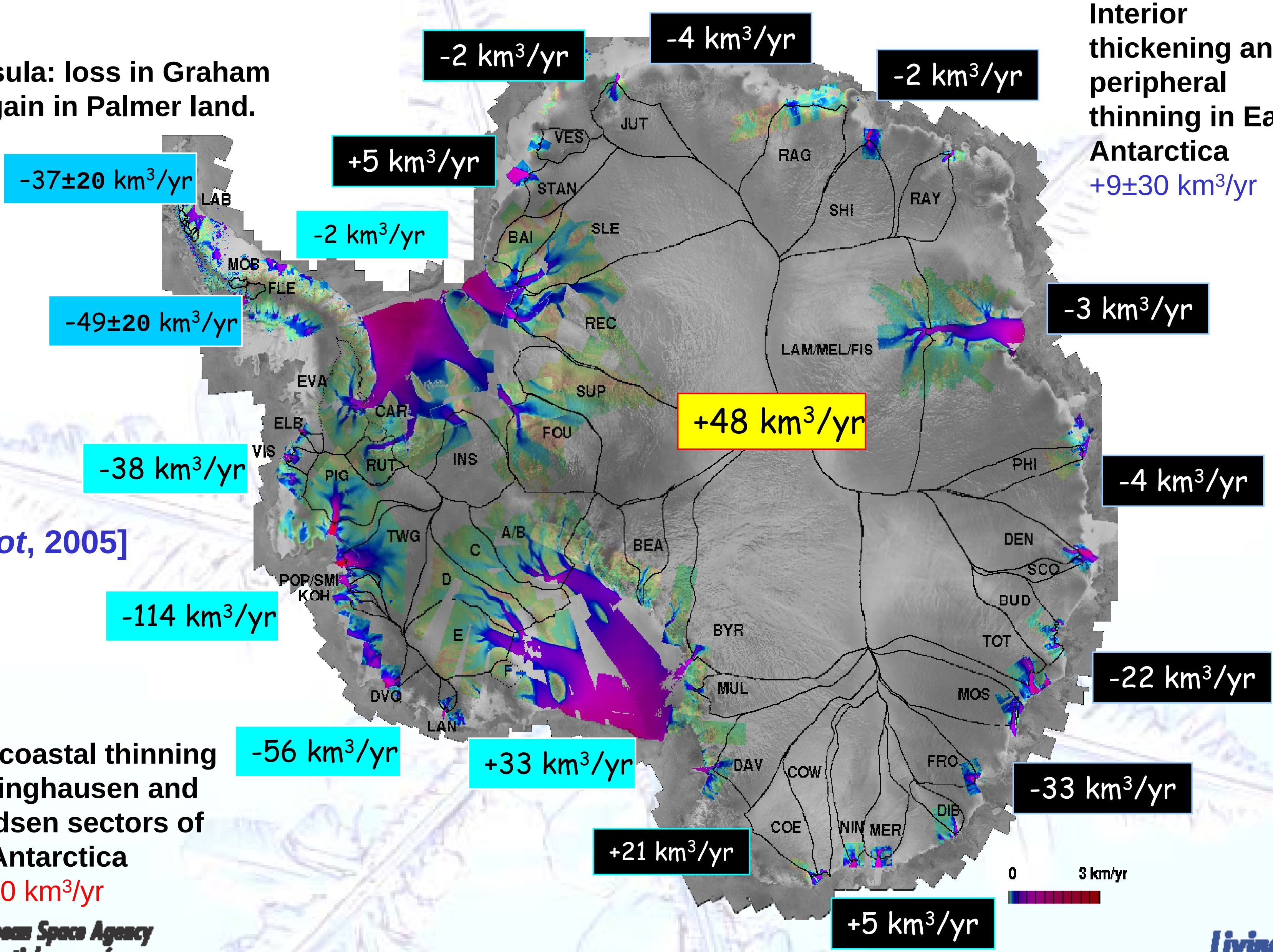


Rapid Thinning of Jacobshavn Glacier, Thomas (2003)

Antarctic Ice Mass Flux from InSAR

Peninsula: loss in Graham land, gain in Palmer land.

Interior thickening and peripheral thinning in East Antarctica
+9±30 km³/yr



[*Rignot*, 2005]

Rapid coastal thinning in Bellinghausen and Amundsen sectors of West Antarctica
-177±30 km³/yr

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Mass Balance: Measuring Elevation Change

$$\frac{dh}{dt} = \nabla \bullet H\vec{U} + \dot{a}$$

Elevation
change
over time

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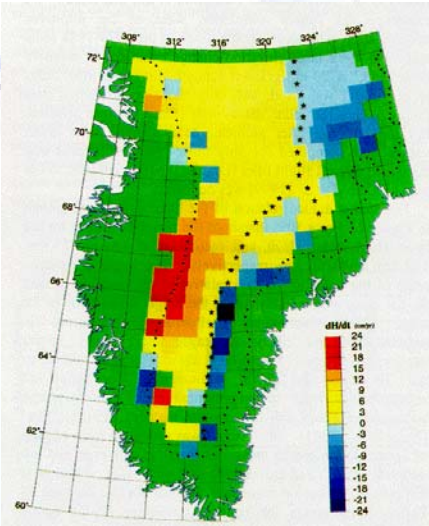
Laser vs. ERS-1/2 Altimeter-derived dh/dt

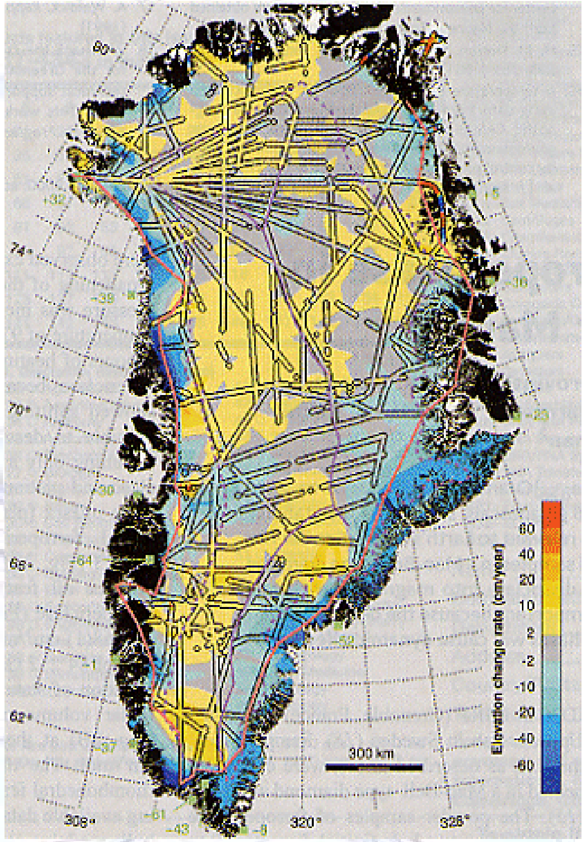
* Little change in Central Greenland
  – spatial variations associated with dA/dt
* Dramatic changes in periphery of ice
  – sheet attributable to a combination of dynamic changes and melting

1978 - 1988
Geosat - Seasat



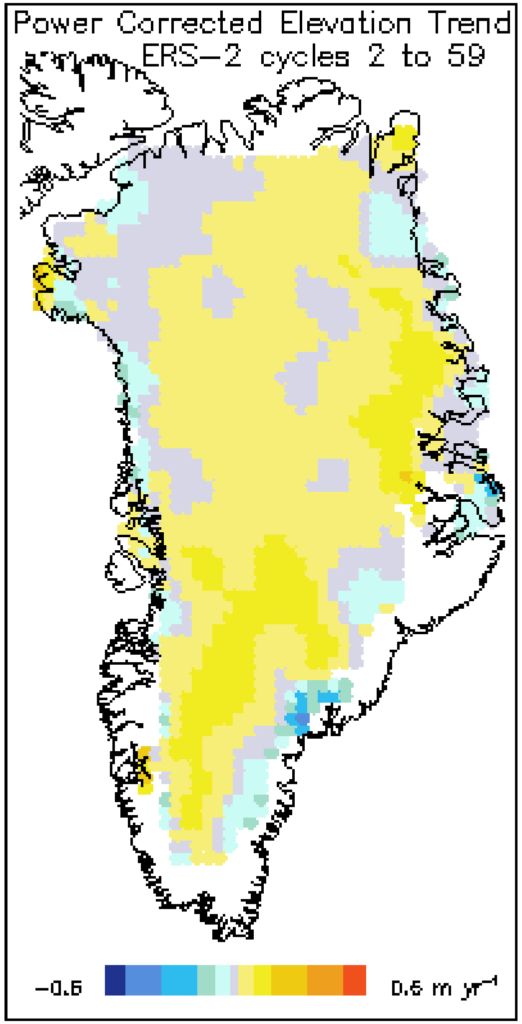
Davis et al. 2001

PARCA
ATM flights 1993-1997



Courtesy W. Krabill

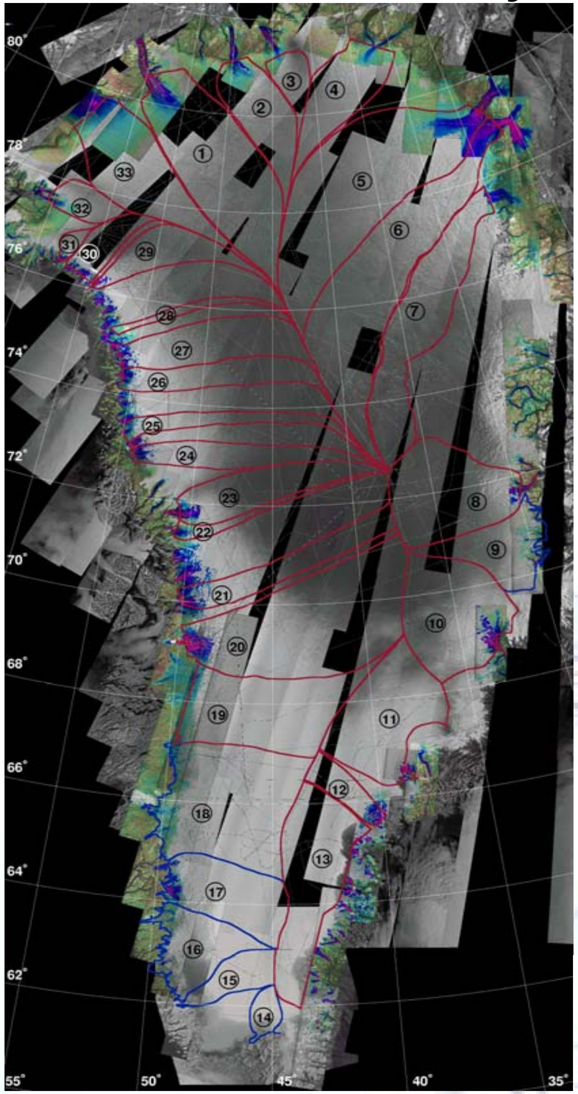
ERS-2: 1995 - 2000



Courtesy Wingham, UCL

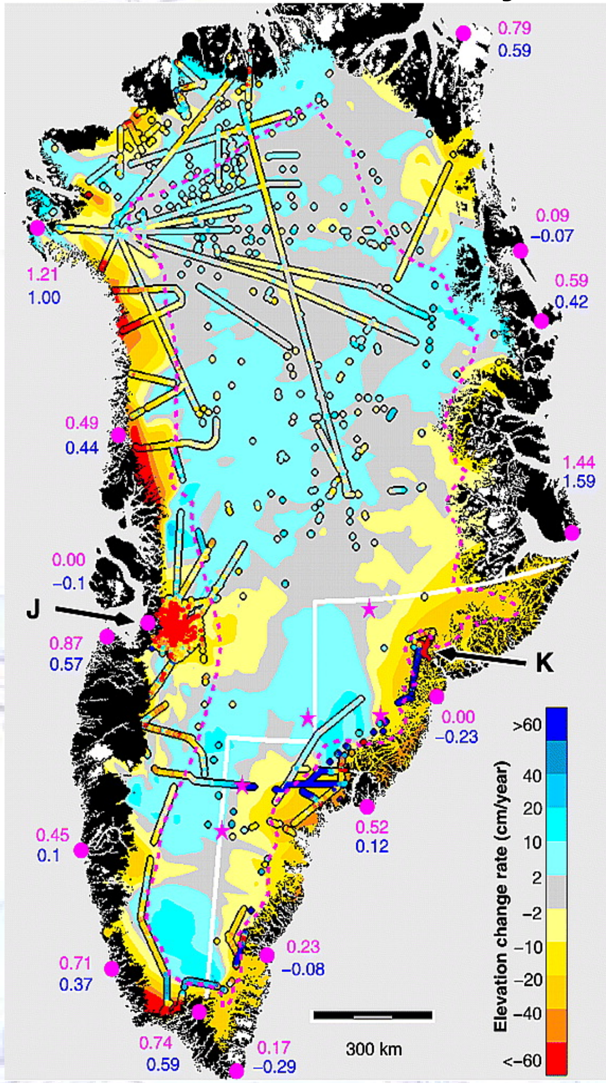
Greenland: Net Sea-level Contribution

InSAR: 0.23-0.55 mm/yr



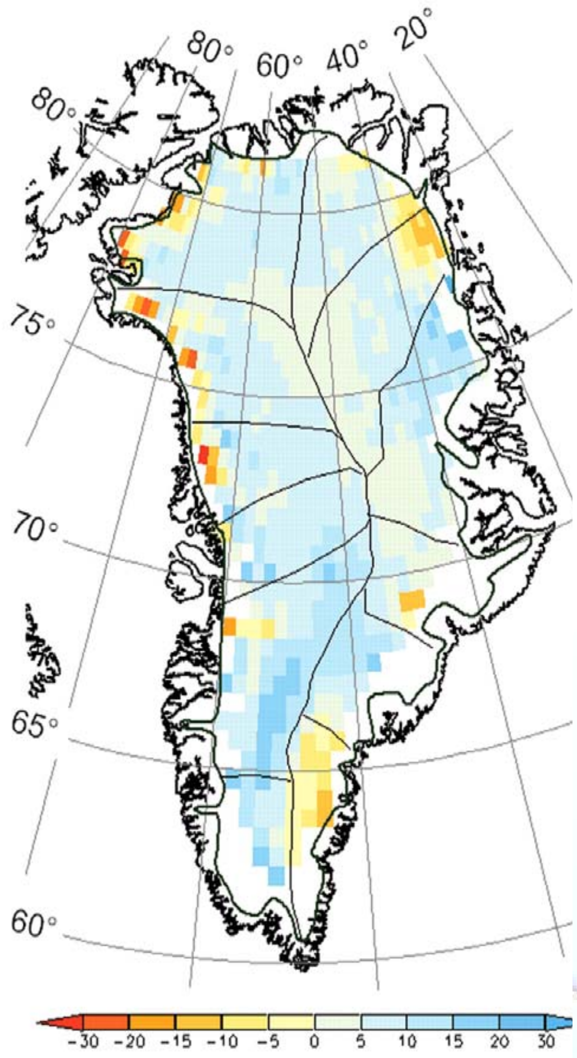
[*Rignot and Kanagaratnam*, 2005]

Laser Alt: 0.25 mm/yr



[*Krabill et al.*, 2004]

Radar Alt: Accumulation



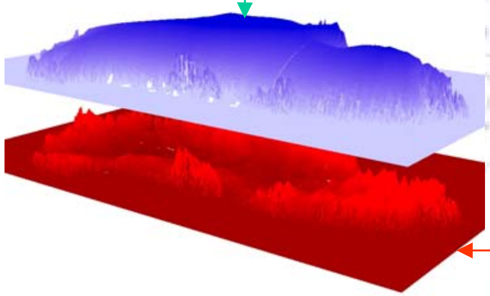
[*Johannessen et al.*, 2005]

Ice Sheet Mass Balance

- We can now successfully quantify all contributions to the continuity equation

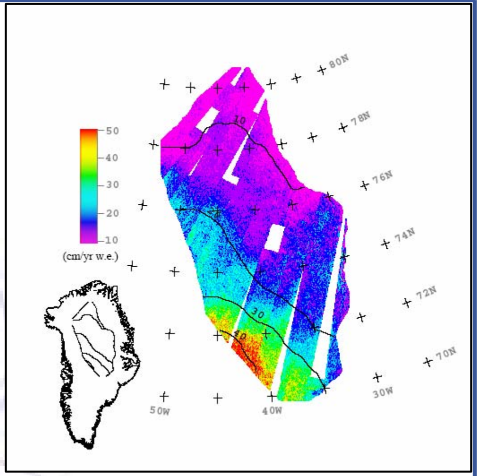
$$\frac{dh}{dt} = \nabla \bullet H\vec{U} + \dot{a}$$

Satellite Altimeters

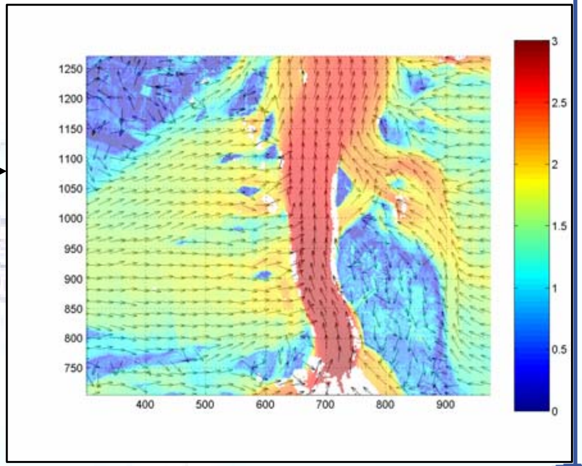


Airborne Radar
Seismics

InSAR
(*assumes* U constant with depth)



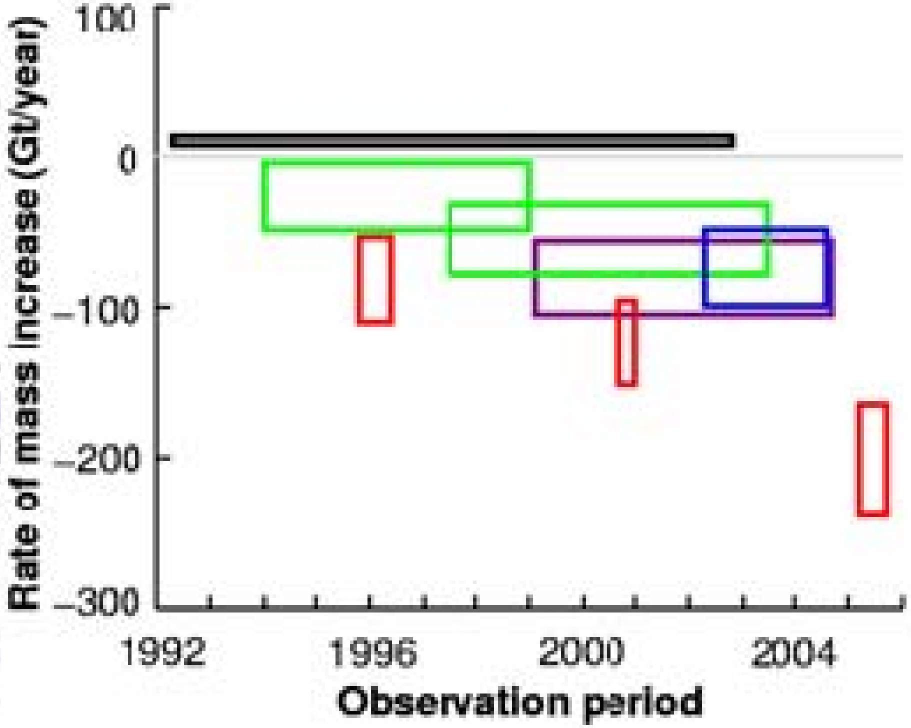
Act/Pass. Microwave
Airborne wideband



Greenland Mass Balance

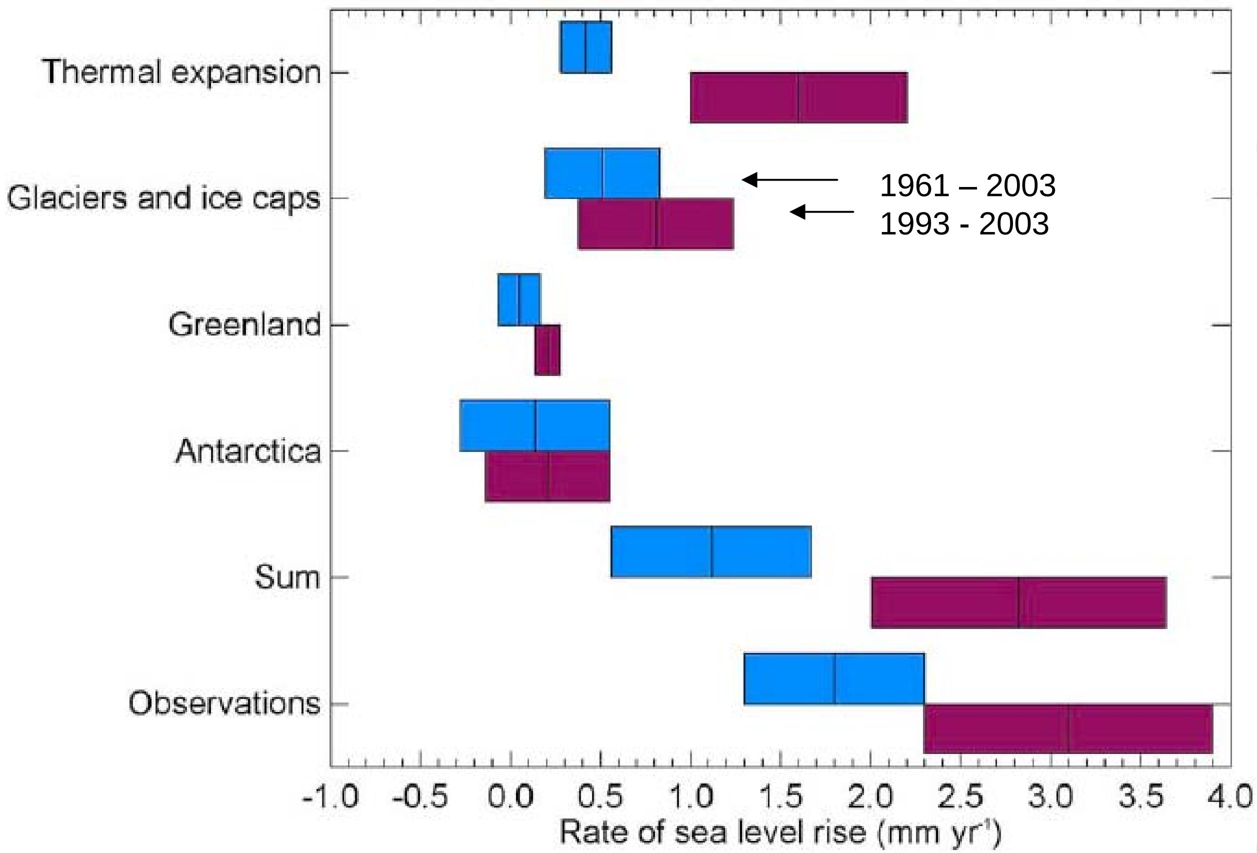
Green - ATM *(Krabill et al., 2000; 2004*); blue – GRACE (*Velicogna and Wahr, 2005*); red - mass budget (*Rignot and Kanagaratnam, 2006*); purple – ATM/ICESat (*Thomas et al., 2006*); black – from SRALT, combined with ATM (*Zwally et al., 2005*).

Uncertainty limits are as published, assuming high-elevation thickening by firn of density 600 ± 300 kg m^{-3}, low-elevation thinning of ice at density 900 kg m^{-3}, and basal uplift rates of 0 ± 1 mm a^{-1}.



> *Source: IPCC 4th AR*

Mean Sea-Level Change Contributions

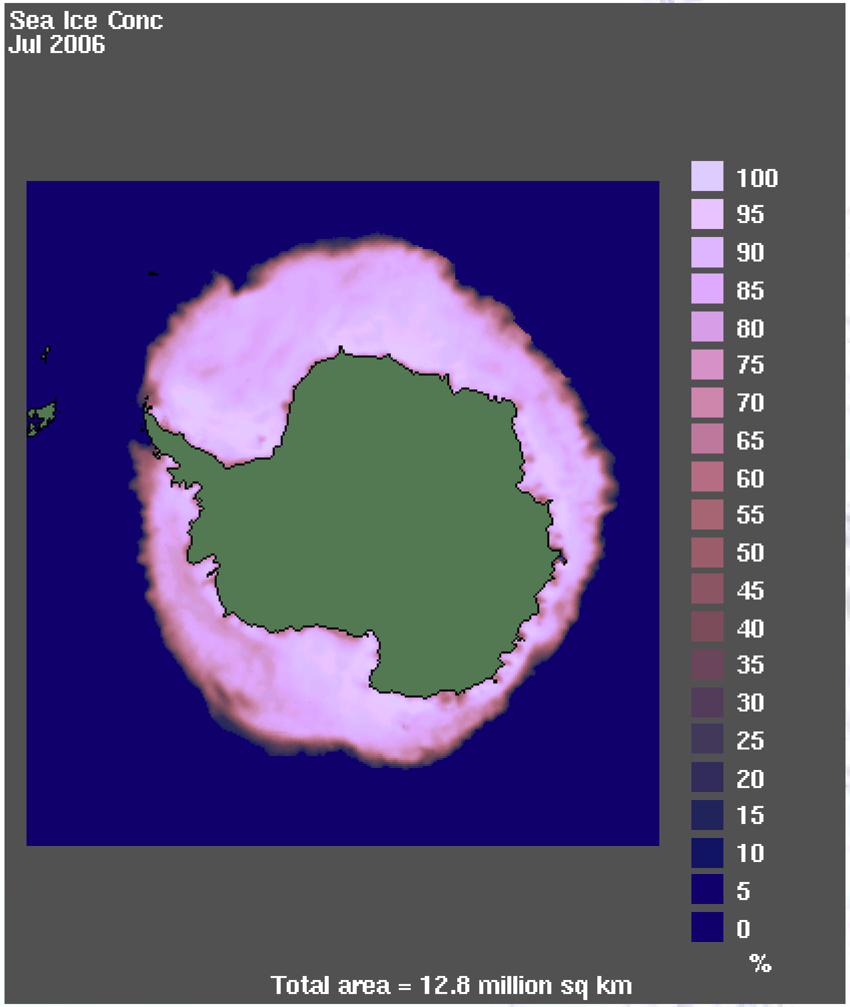


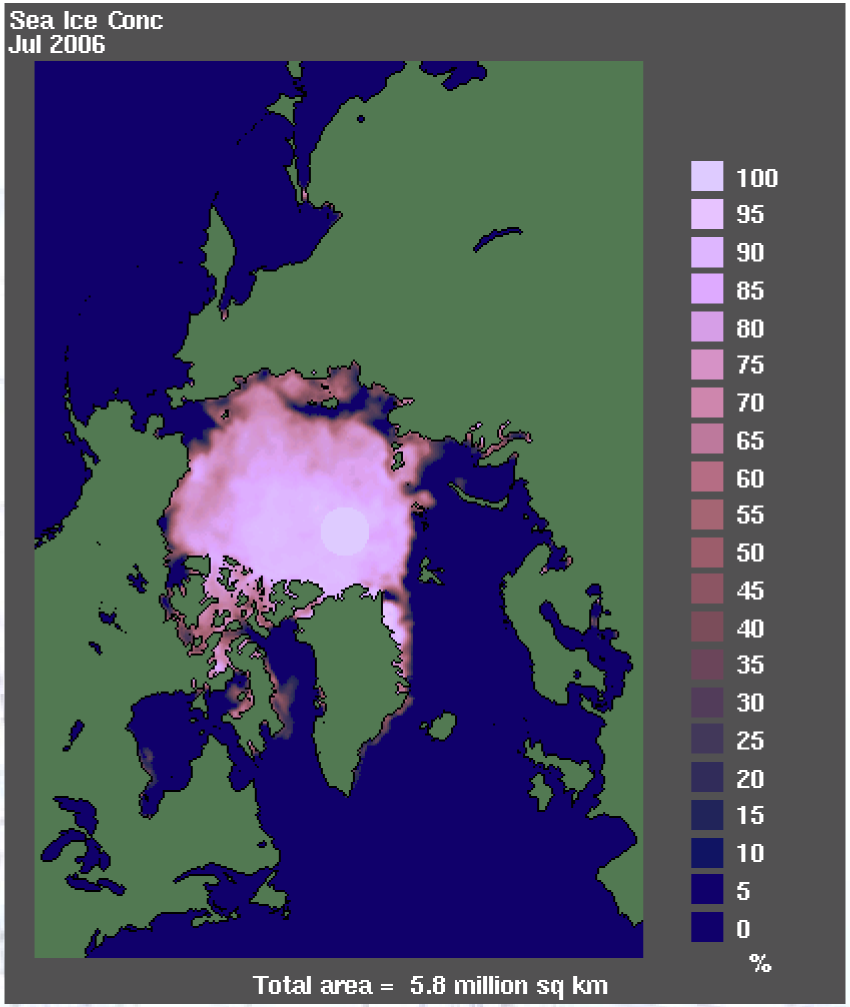
Estimates of the various contributions to the budget of the global mean sea level change compared with the observed rate of rise for 1961–2003 (blue) and 1993–2003 (red). The bars represent 95% errors.

Source: IPCC 4th AR

Marine Ice

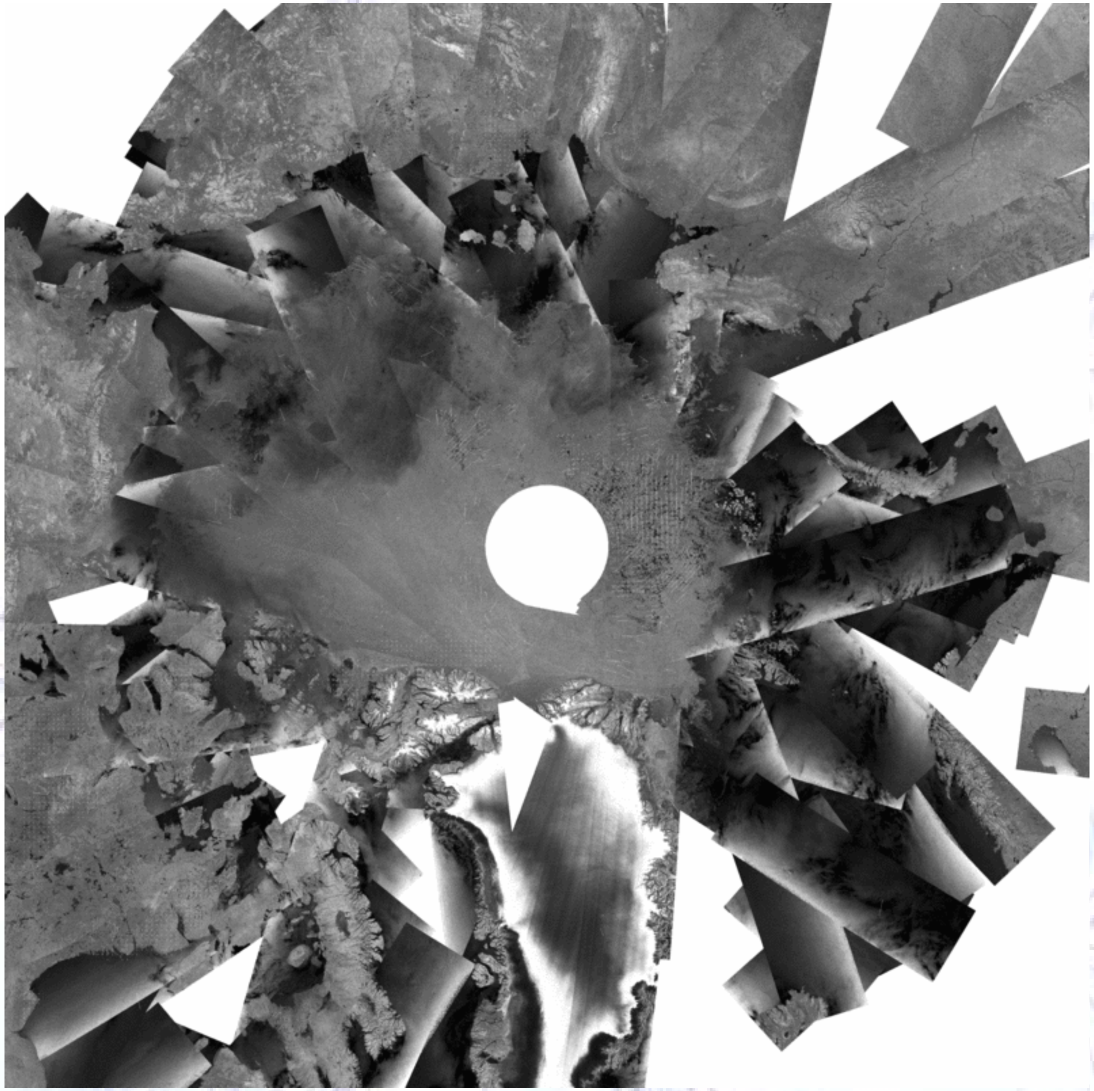
Sea Ice Concentration & Extent





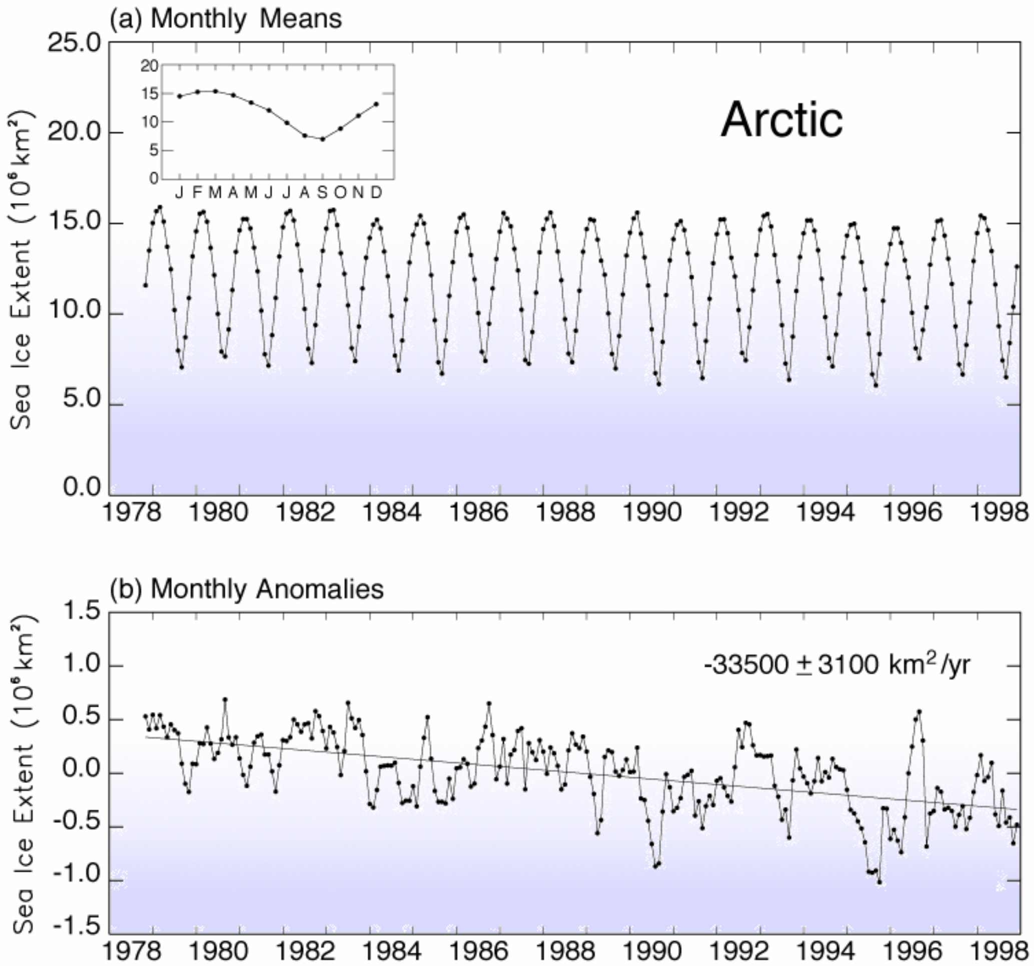
Derived since 1972-1976 (ESMR: Nimbus-5) and contiguously from several multichannel Passive Microwave satellites since 1978: SMMR (Nimbus-7) & SSMI & AMSR

GMM 1km Sea-ice drift



See: http://polarview.met.no/gm_drift/

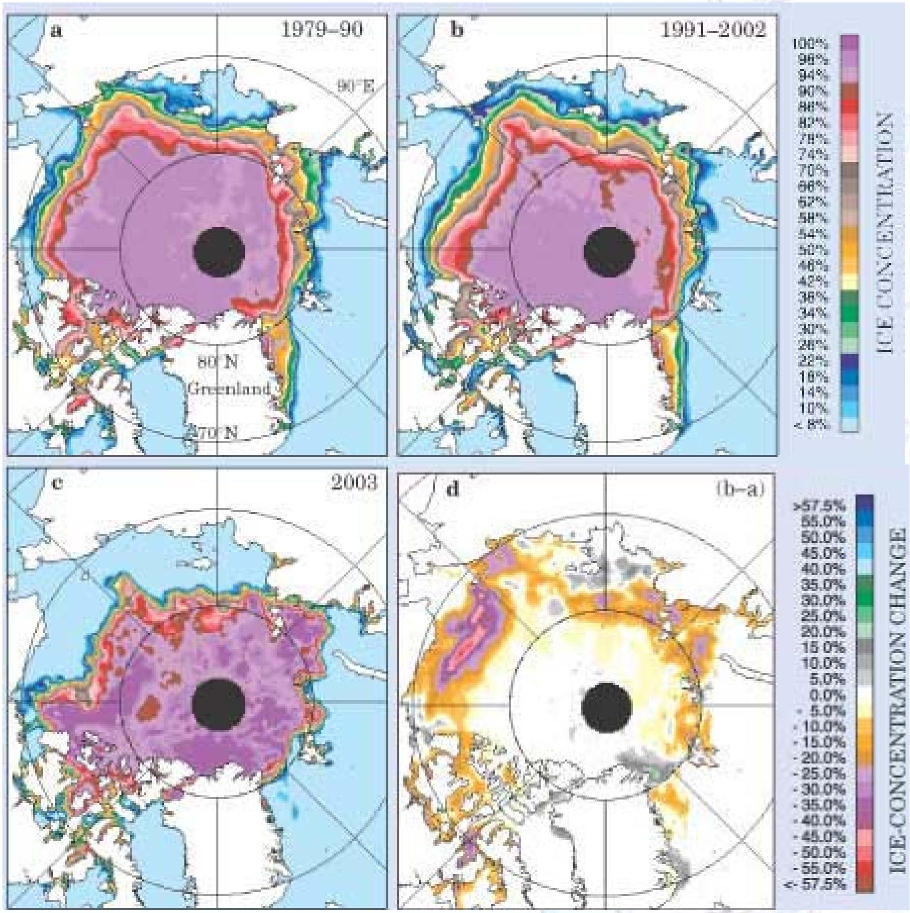
Ice Area and Concentration trend



Courtesy Zwally et al. (2002)

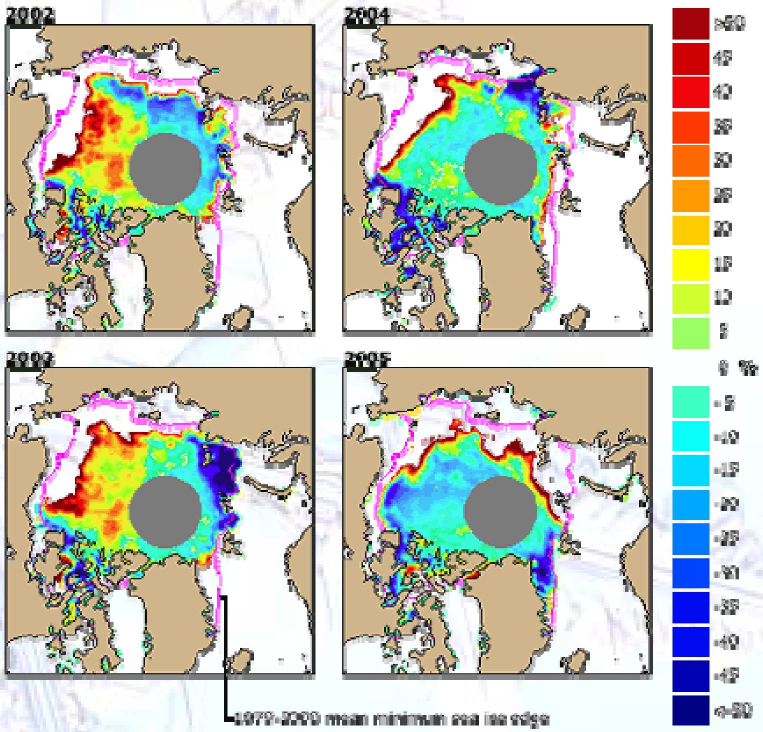
- Quasi periodic fluctuations evident with 3-5 year period
- 20 year period indicates reduction of 0.3 million km^2/decade or 3%/decade of ice area
- Regional trends vary significantly

Arctic Ice concentration changes



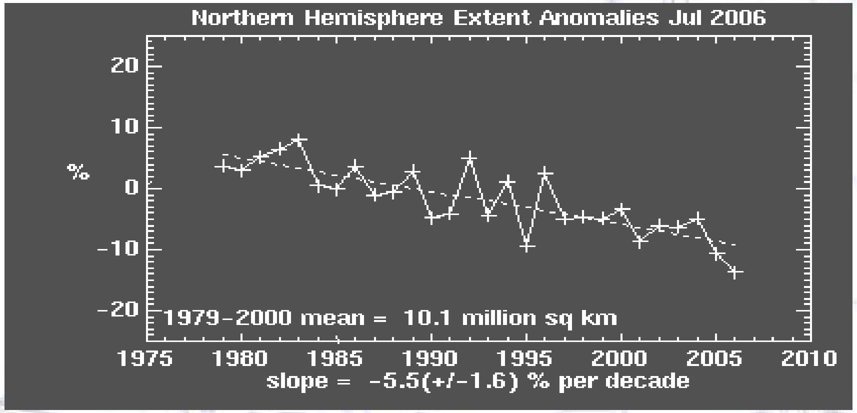
Courtesy Comiso and Parkinson (2004)

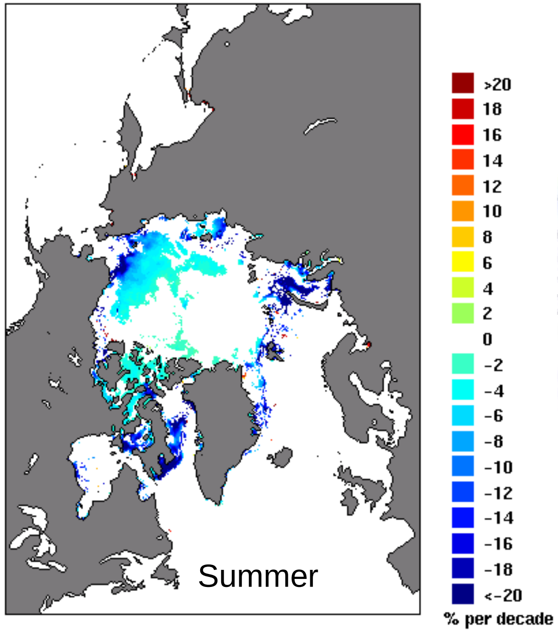
- Panels at left shows decadal mean residual summer ice after summer melting in 80’s and 90’s
- 2003 strong anomaly followed by successive anomalies in 2004 and 2005



Courtesy NSIDC

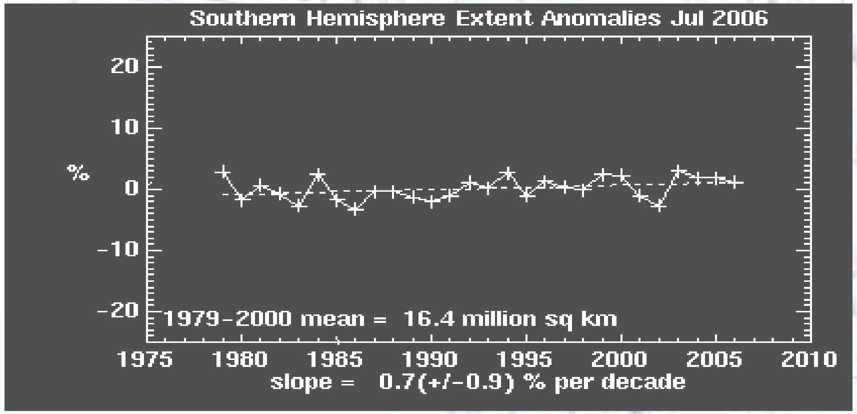
Sea-ice extent anomaly trends



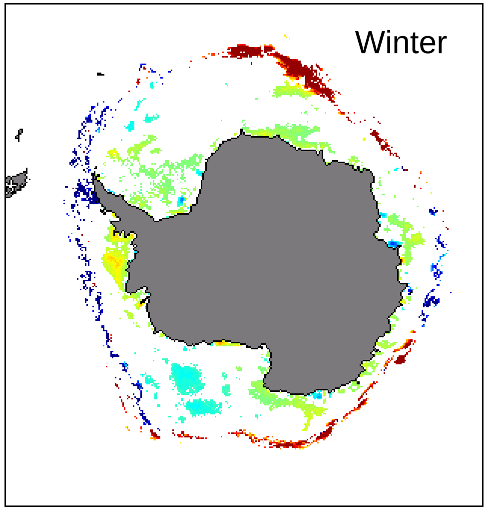


July

Anomaly trends

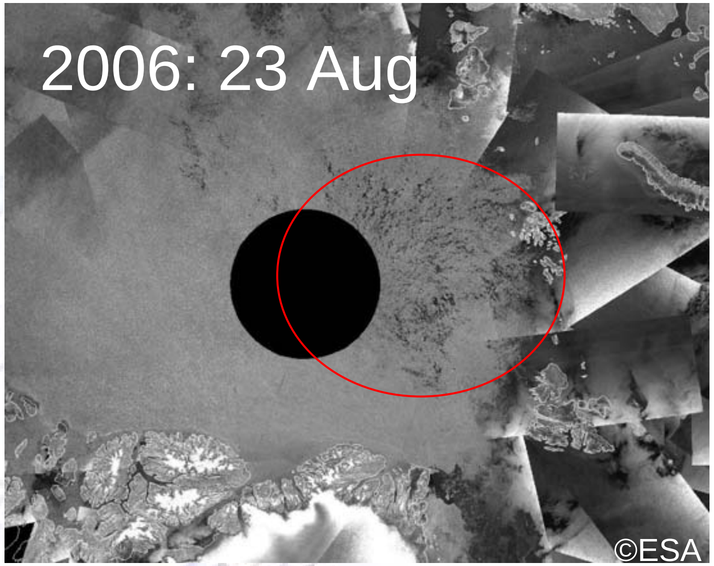


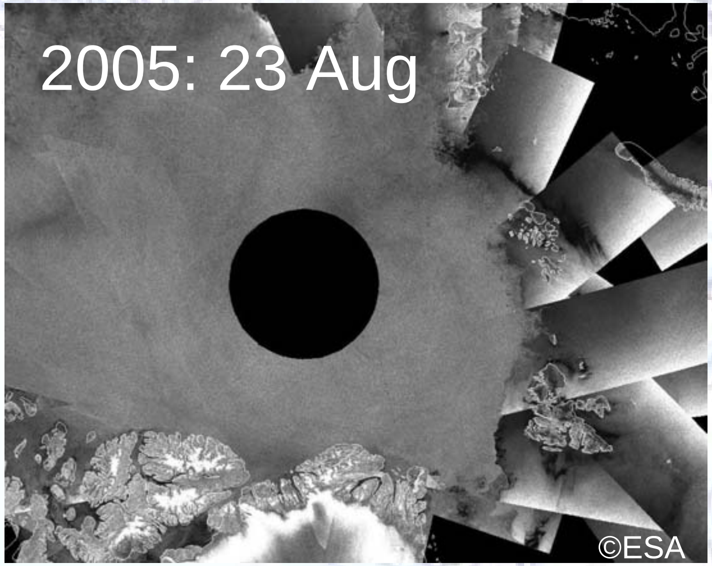
Courtesy NSIDC

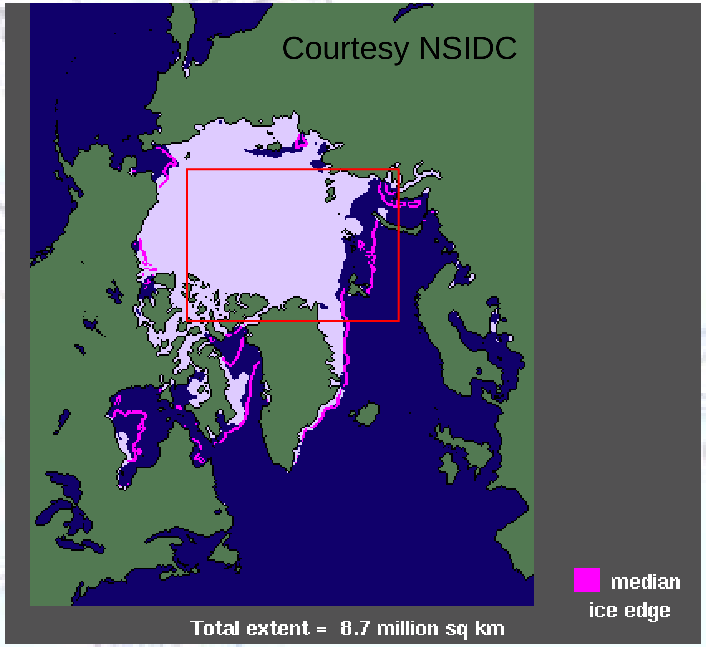


Anomaly trends and accompanying image trends in ice concentration show how the concentration of ice has changed for a given month over the period 1979-2000.

ASAR GMM: Arctic sea ice decay







Sea Ice Mass Balance

$$\frac{dg(h)}{dt} = -\frac{d(fg)}{dh} - \nabla \bullet g\vec{U} + \psi + L$$

(after Thorndike et al 1975)

Where *dg(h)/dt* represents the rate of change of the thickness distribution *g(h)*

- *d(fg)/dh* is the rate of change of thermodynamically controlled growth and changes in *g(h)* (negative since thicker ice grows more slowly)

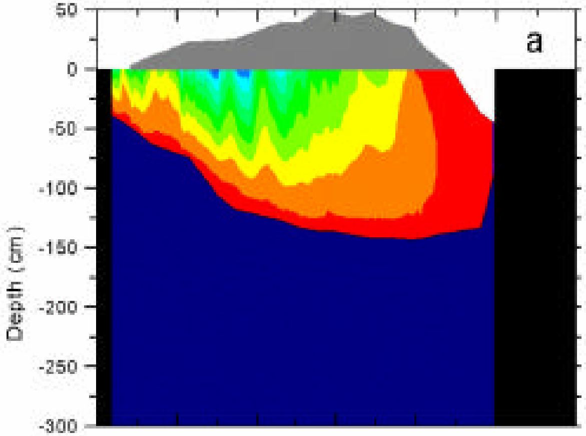
- $\nabla \bullet g\mathbf{U}$ represents the ice dynamics (divergence/advective) impact on thickness (negative since divergence implies net thinning)

ψ is a redistribution function - that converts thin ice to thick ice via deformation and sea-ice ridging

L is the lateral melting of floes (from floe-size distribution changes)

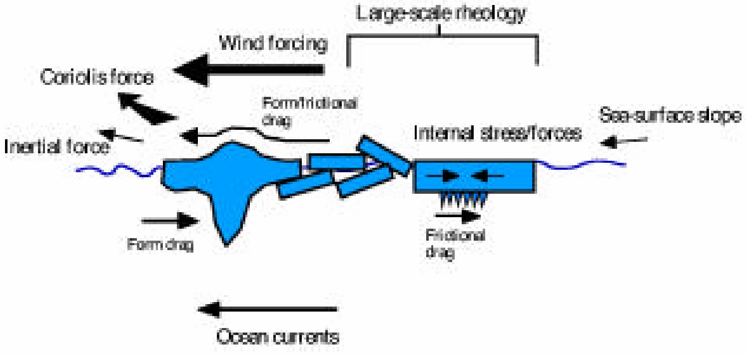
Thermodynamics vs. Dynamics

Thermodynamics



Perovich, *Ann, Glaciol.*, 2001.

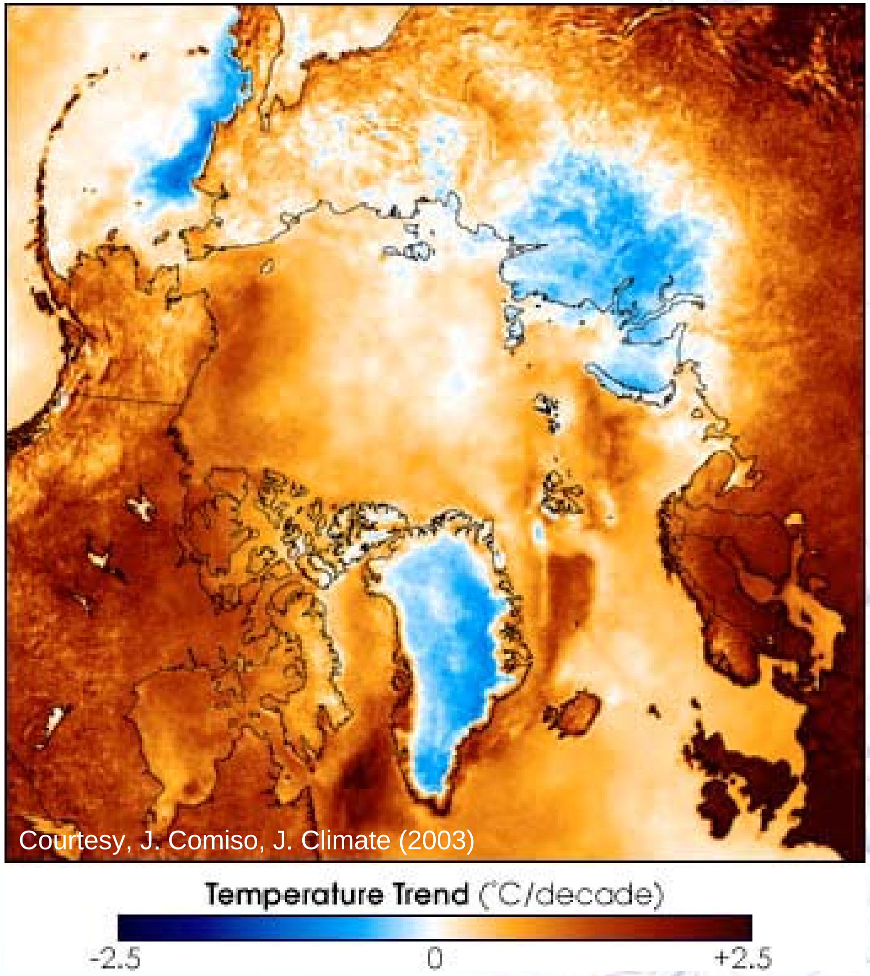
Dynamics



Mass Balance: Thermodynamics

$$\frac{dg(h)}{dt} = \boxed{-\frac{d(fg)}{dh}} - \nabla \bullet g\vec{U} + \psi + L$$

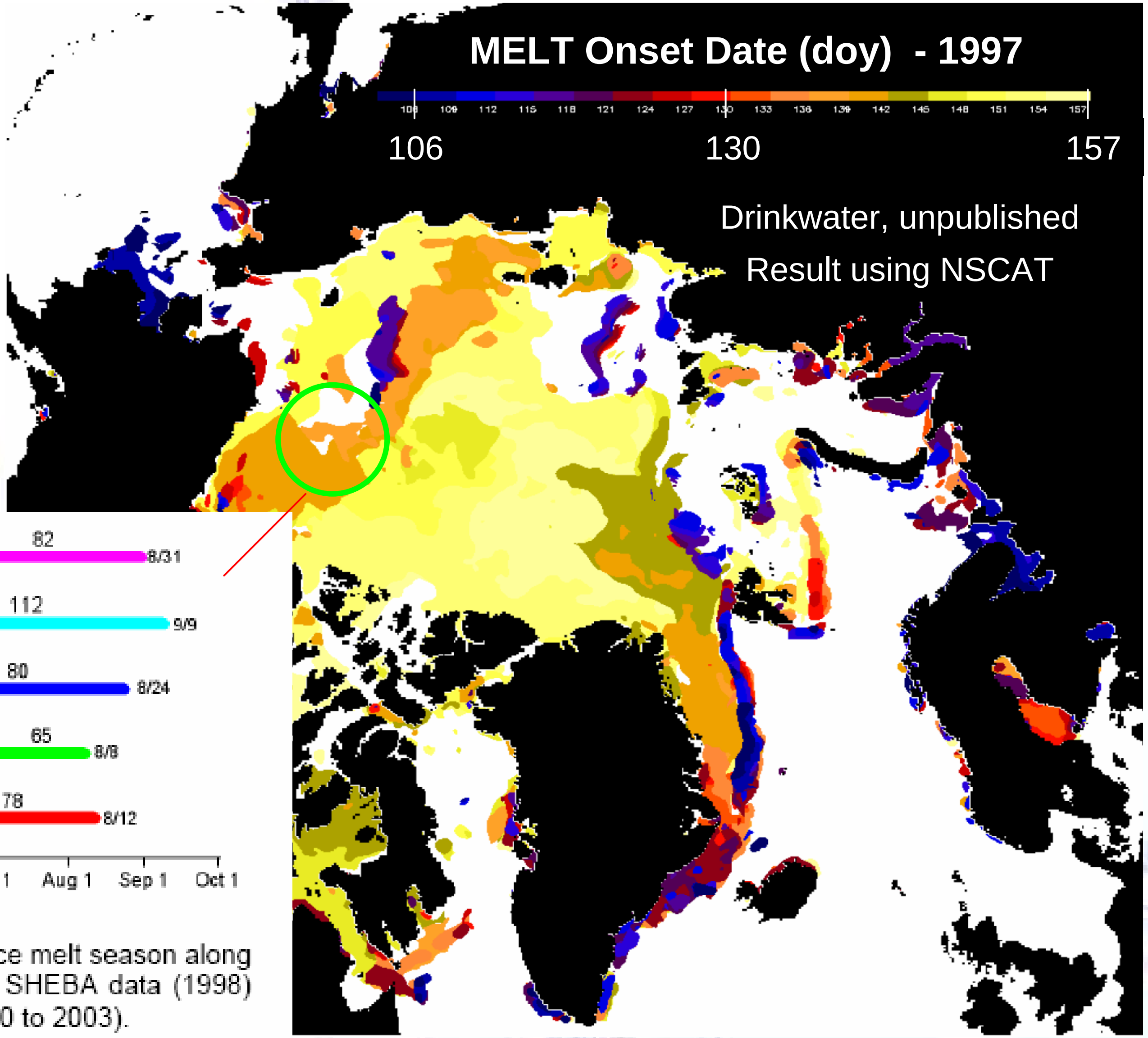
Arctic Surface Temperature Trends



- > 60°N, the trends are highest in North America and Europe
- Trends are moderate in the Central Arctic because of upper limit in sea ice temperature
- Trends are slightly negative in parts of Russia and Greenland.
- Data also indicates increases in melt period of 9 to 17 days per decade over sea ice, Eurasia, Greenland, and North America.
- These data can be used in estimating the atmosphere-induced melting *-d(fg)/dh*

esa

Onset and Duration of Seasonal Sea-Ice Melt



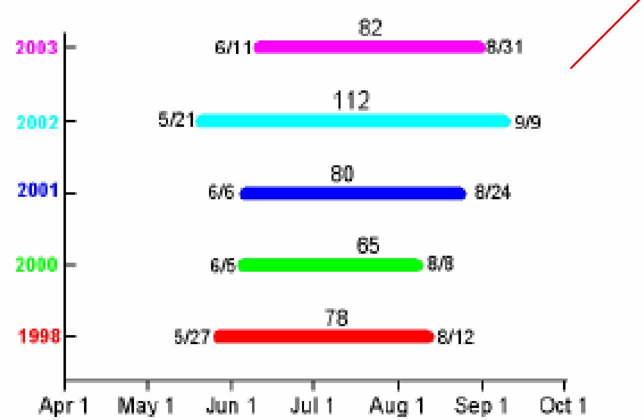


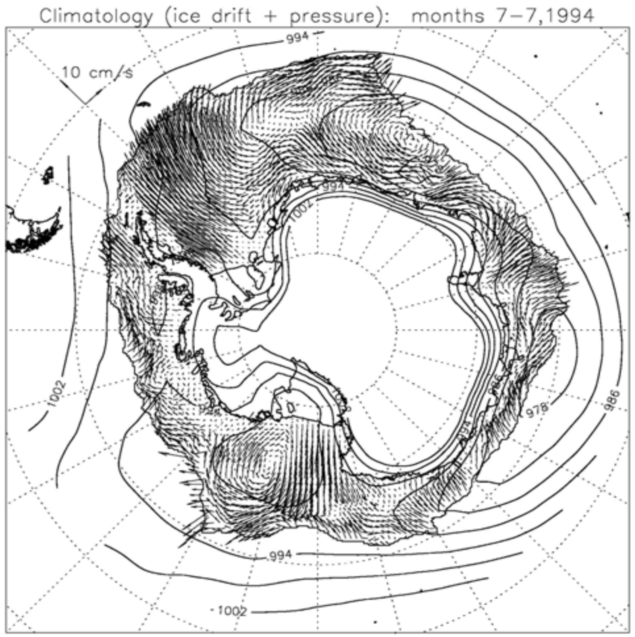
Figure 1. Dates of sea ice melt season along SHEBA drift track from SHEBA data (1998) and from QuikScat (2000 to 2003).

Courtesy, Weatherly et al

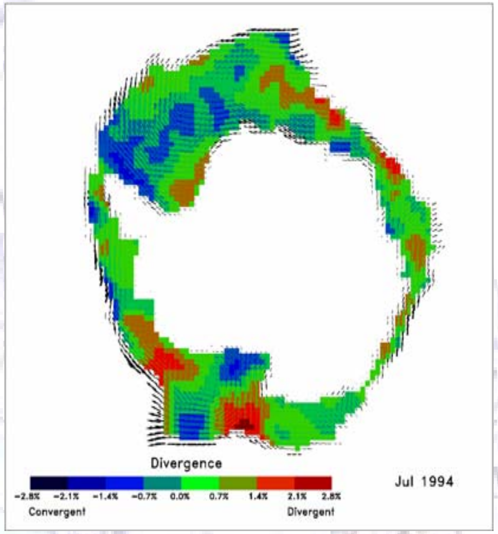
Mass Balance: Dynamics and Ridging

$$\frac{dg(h)}{dt} = -\frac{d(fg)}{dh} - \nabla \bullet g\vec{U} + \psi + L$$

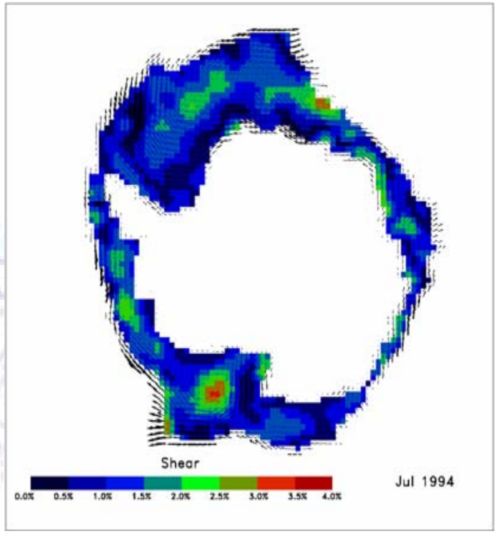
Climatologies: SSMI Sea-ice Dynamics



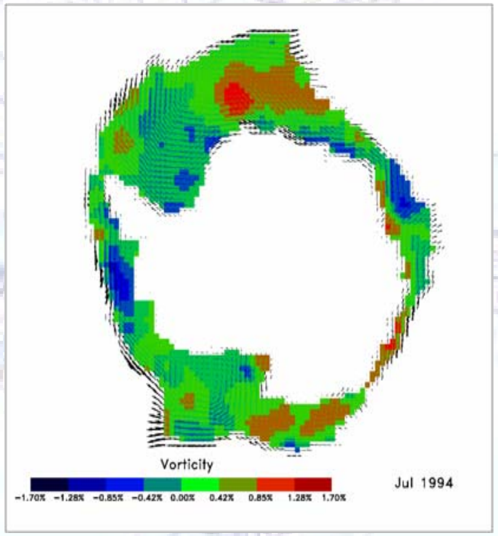
$div(\vec{v}_{ice}) = du/dx + dv/dy$



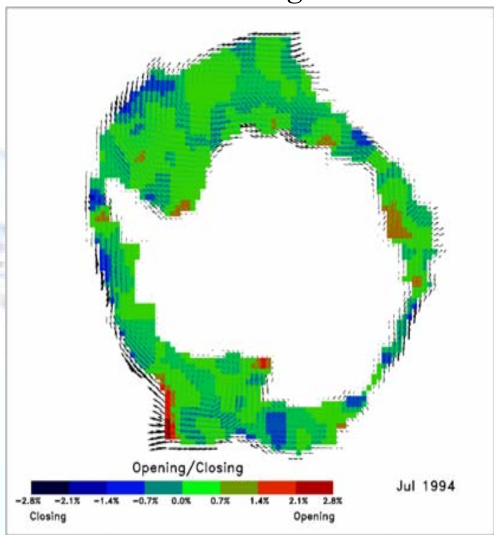
$shear(\vec{v}_{ice}) = \sqrt{(du/dx - dv/dy)^2 + (dv/dx + du/dy)^2}$



$vor(\vec{v}_{ice}) = dv/dx - du/dy$



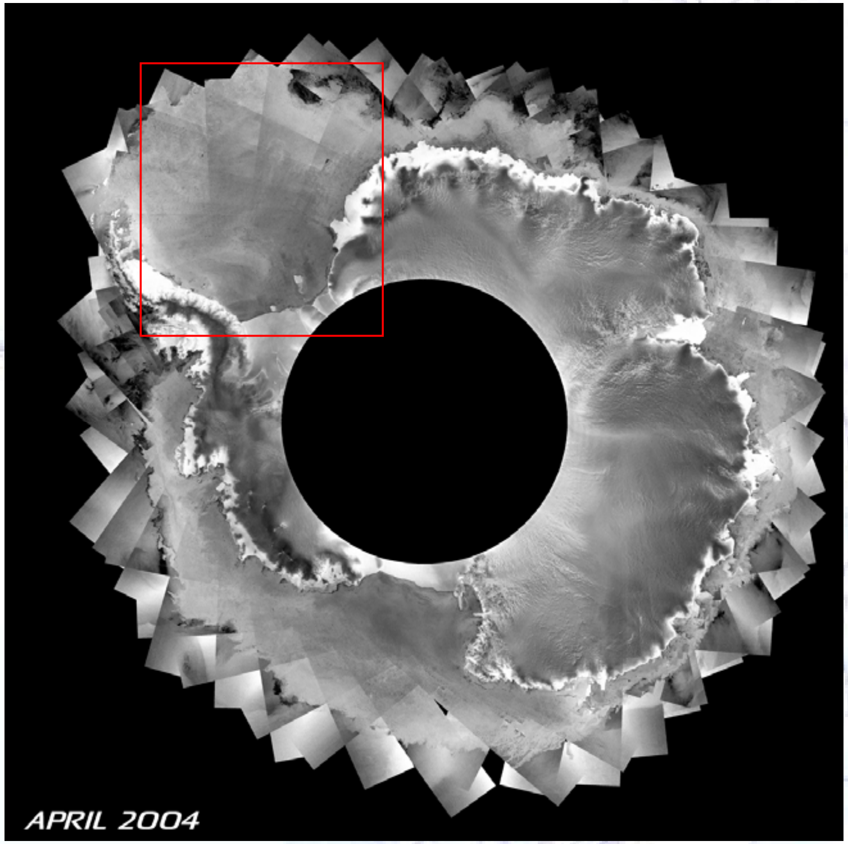
Grid cell area change: 3 x 3 cells



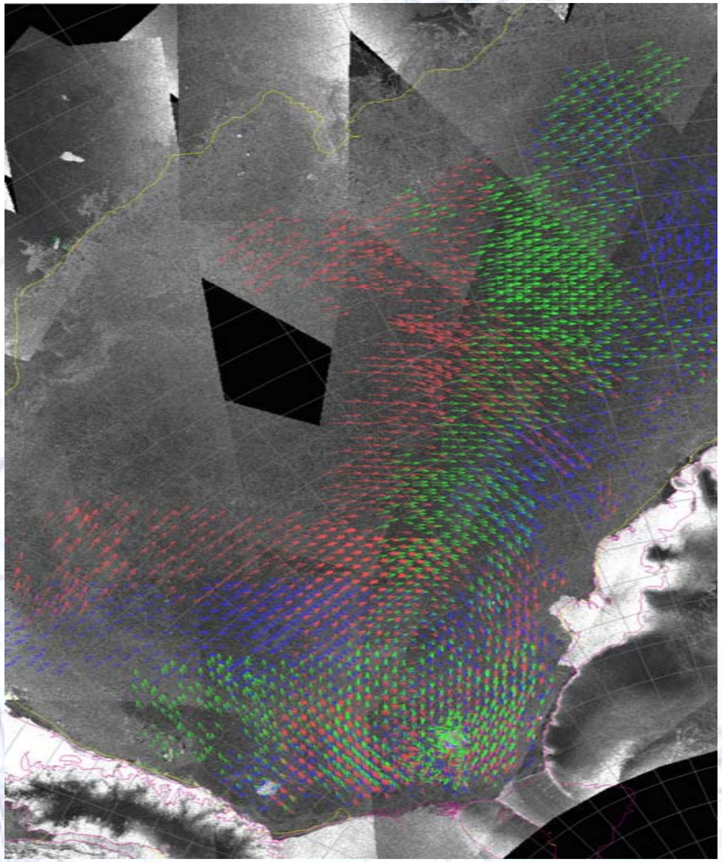
- Monthly mean drift uncertainties of order 1.5 cm/s
- Differential Kinematic parameters:
  - Div; Vor; Shear
  - computed from monthly mean vector velocity components (u,v)
- Net area change (opening/closing)

Routine Global SAR Sea-Ice Data

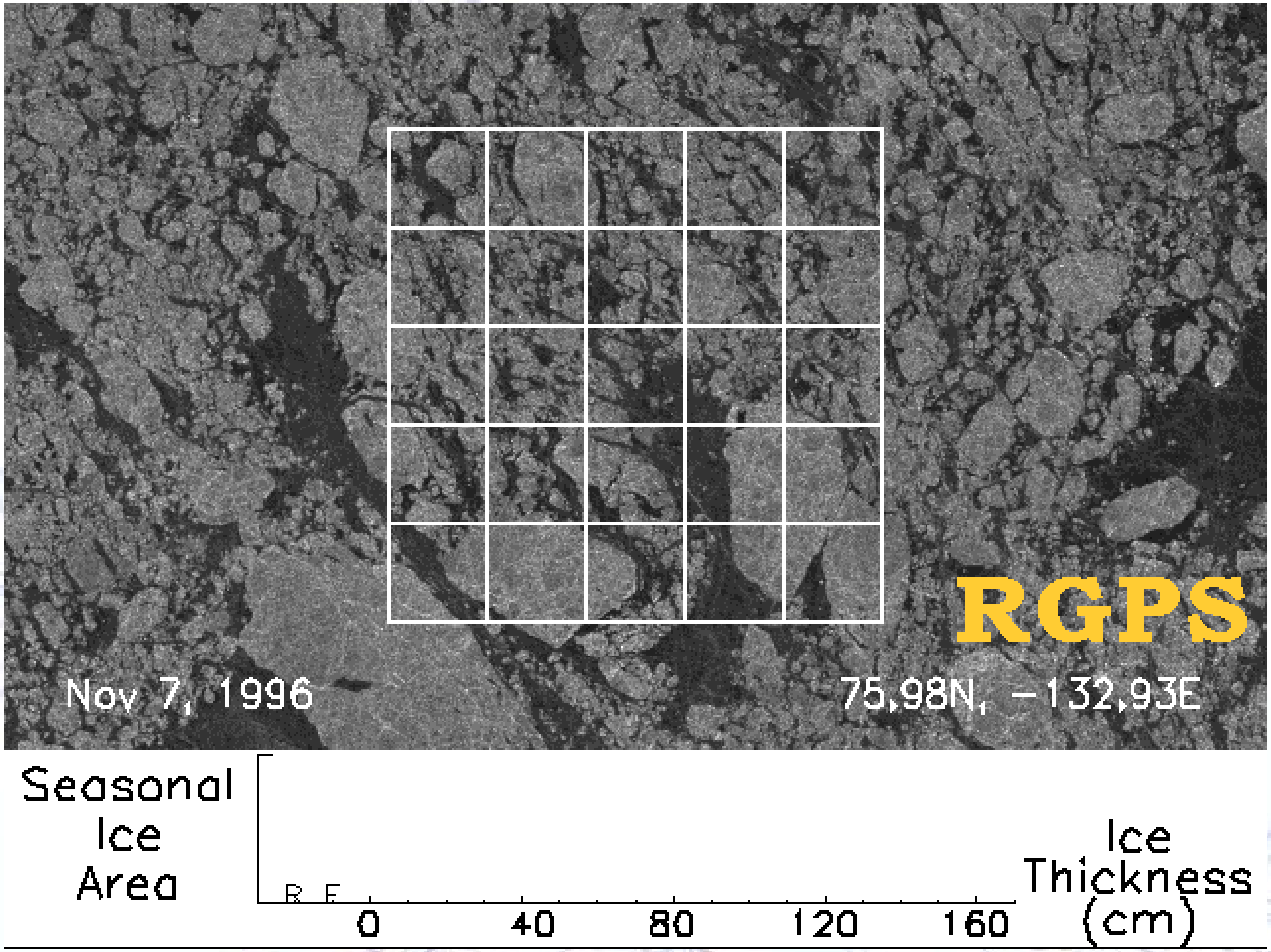
Routine ASAR Global Monitoring Mode (GMM) image data adds a new operational perspective to PMW ice concentration timeseries



Operational Drift tracking at 1km resolution in GMM data

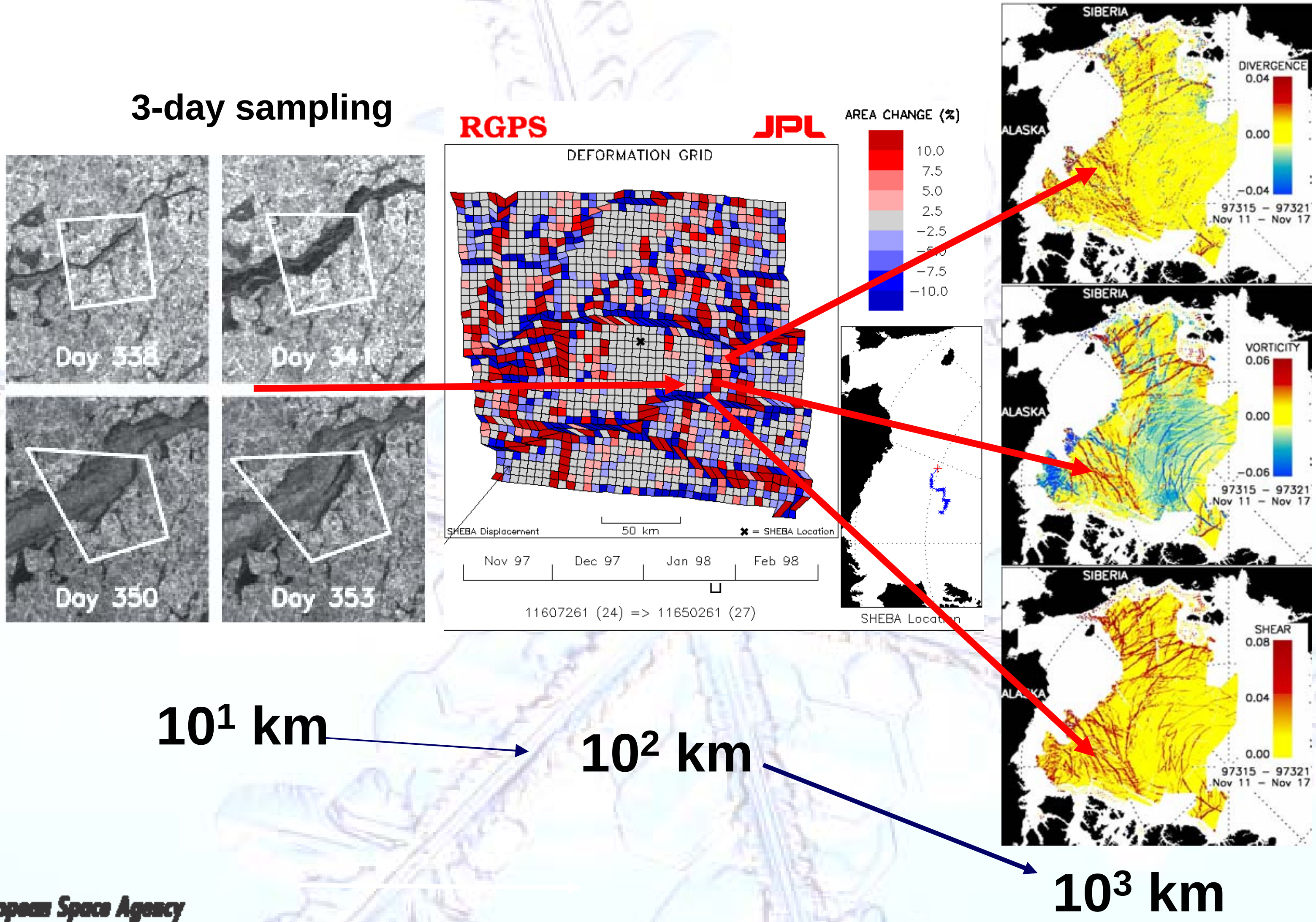


RGPS: Lagrangian Tracking

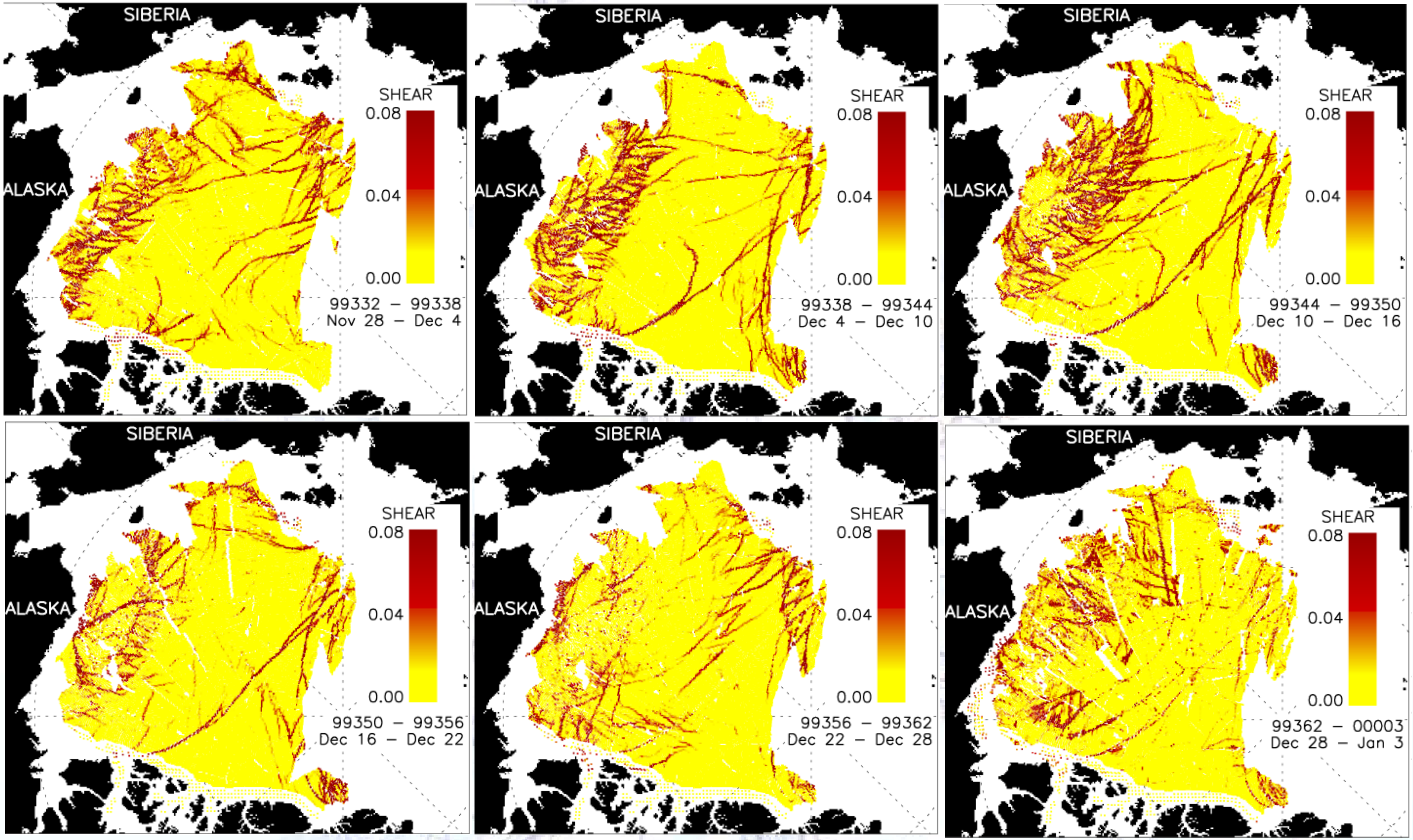


RGPS: Lagrangian Observations of Ice Motion and Deformation

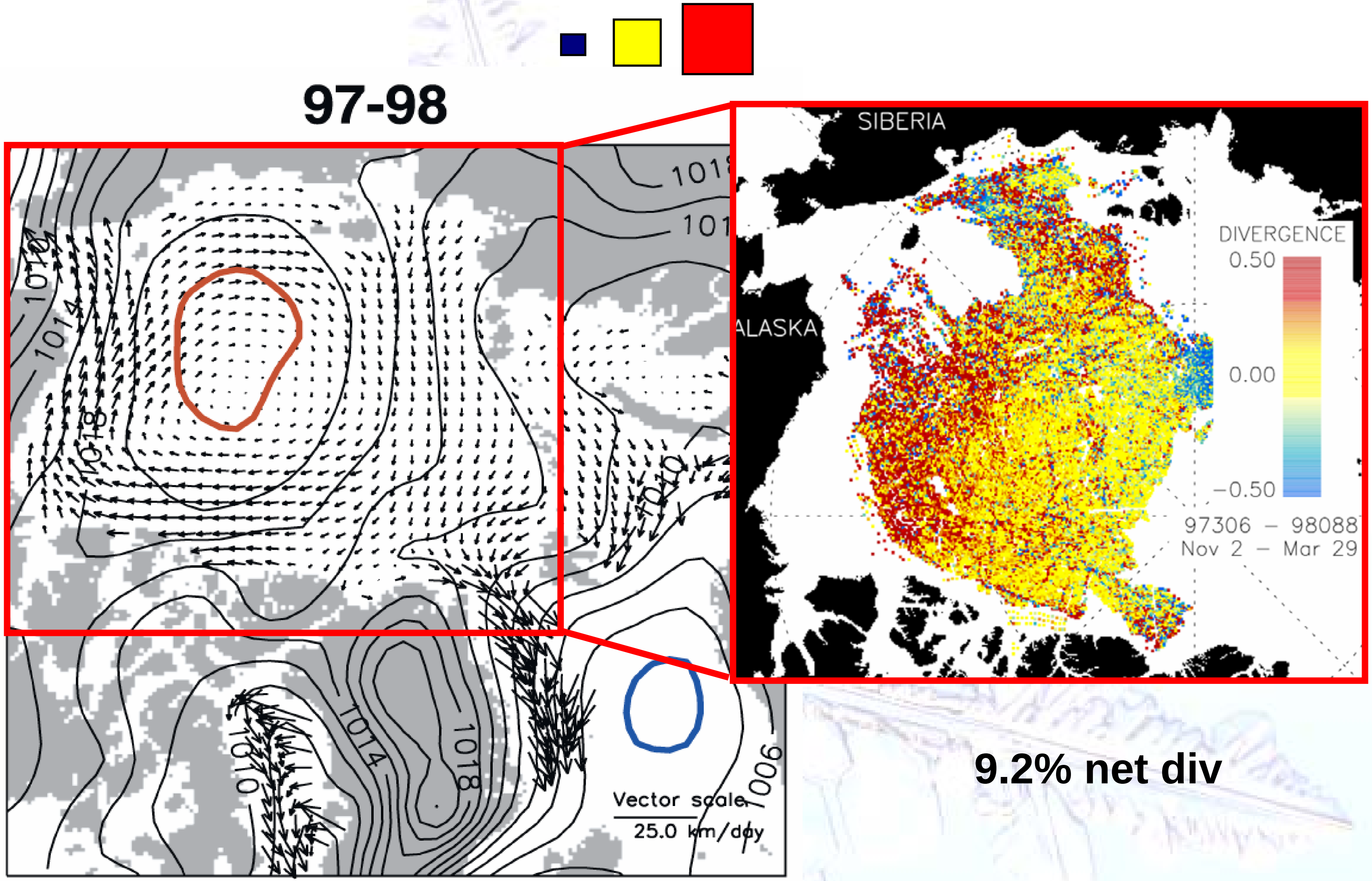
3-day sampling



Sequential Shear Patterns Nov 28-Dec 28,1999



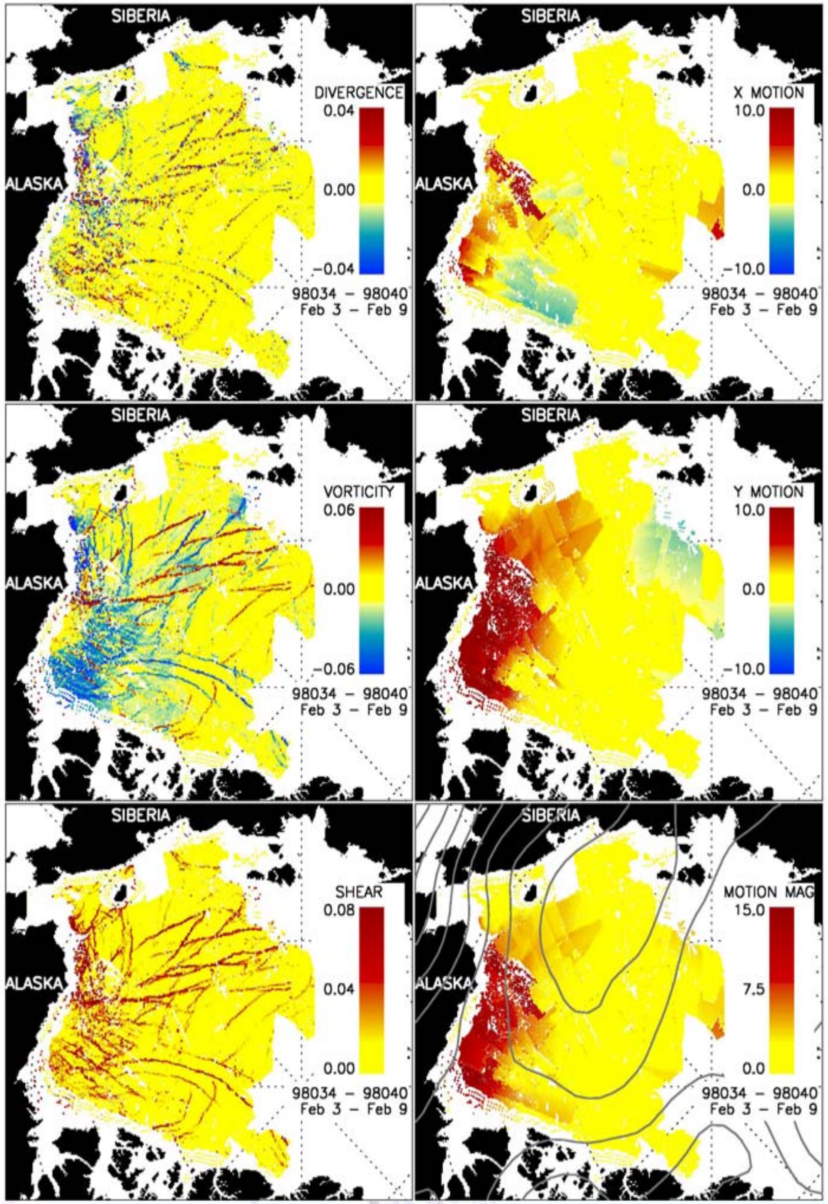
RGPS: Net Divergence (Nov - May, 1997/98)



Mean motion field and SLP (Nov-May)

9.2% net div

RGPS Example: 3 – 9 Feb, 1998

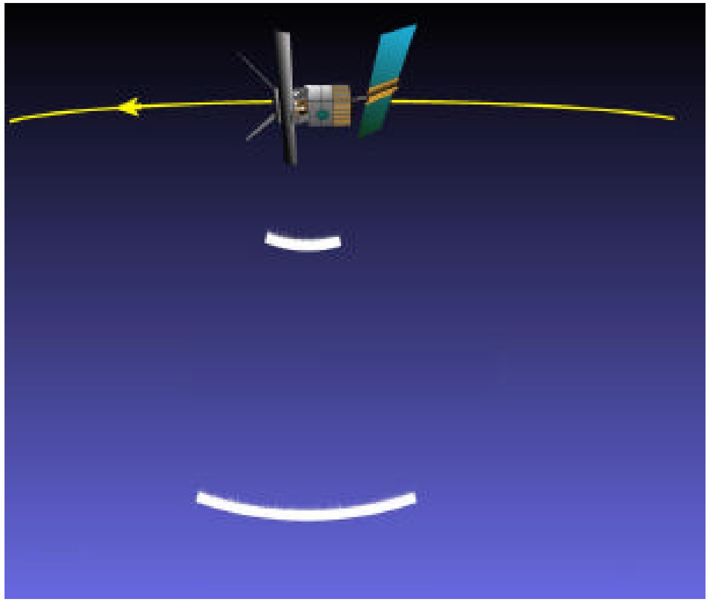


Changes in thickness distribution *dg(h)/dt*

$$\frac{dg(h)}{dt} = -\frac{d(fg)}{dh} - \nabla \bullet g\vec{U} + \psi + L$$

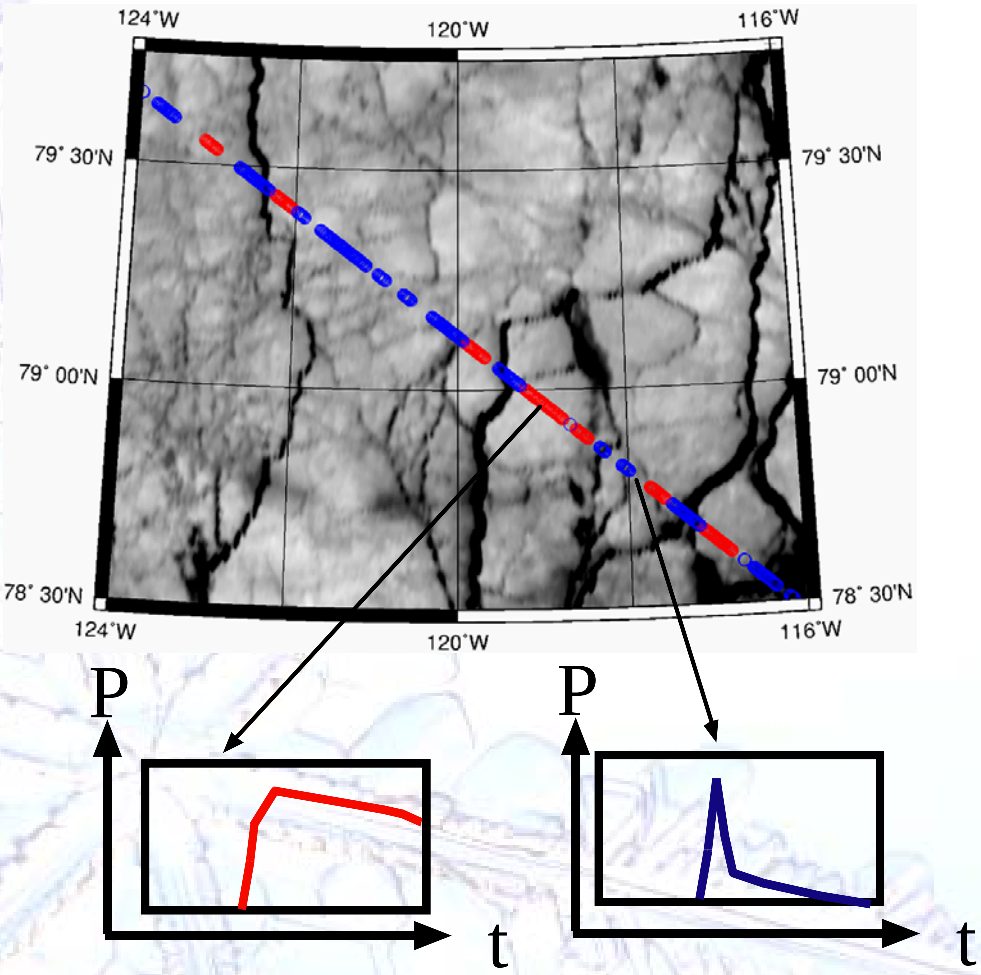
Satellite Altimetry Measurement Principle

$$h = \frac{ct}{2}$$



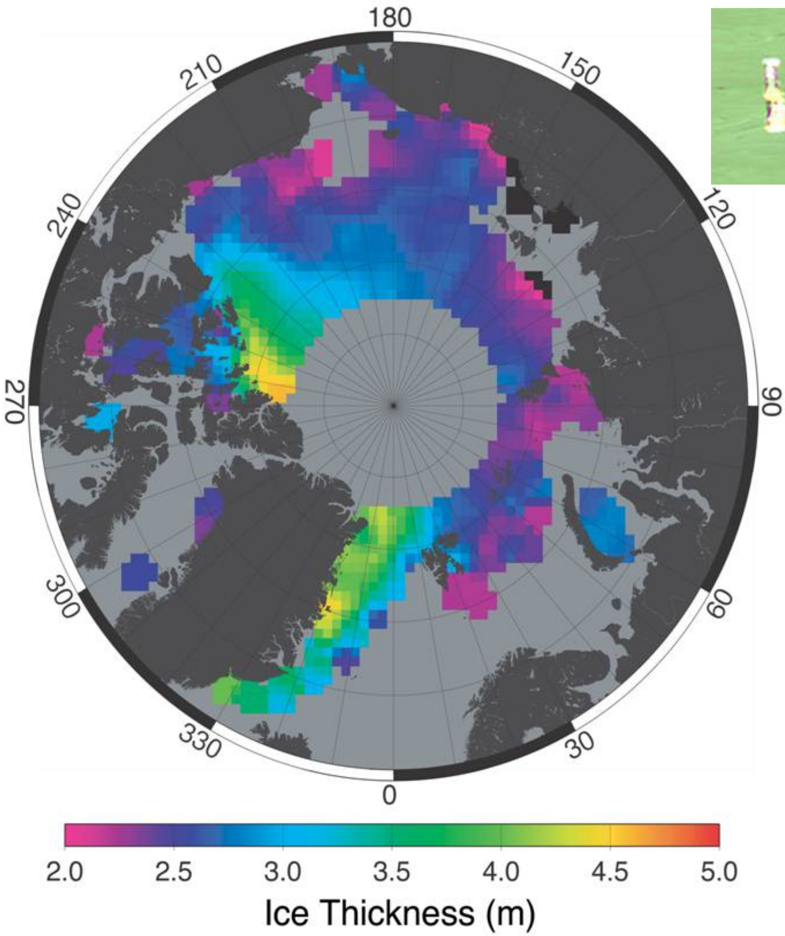
Origin of Radar Altimeter Sea Ice Echoes

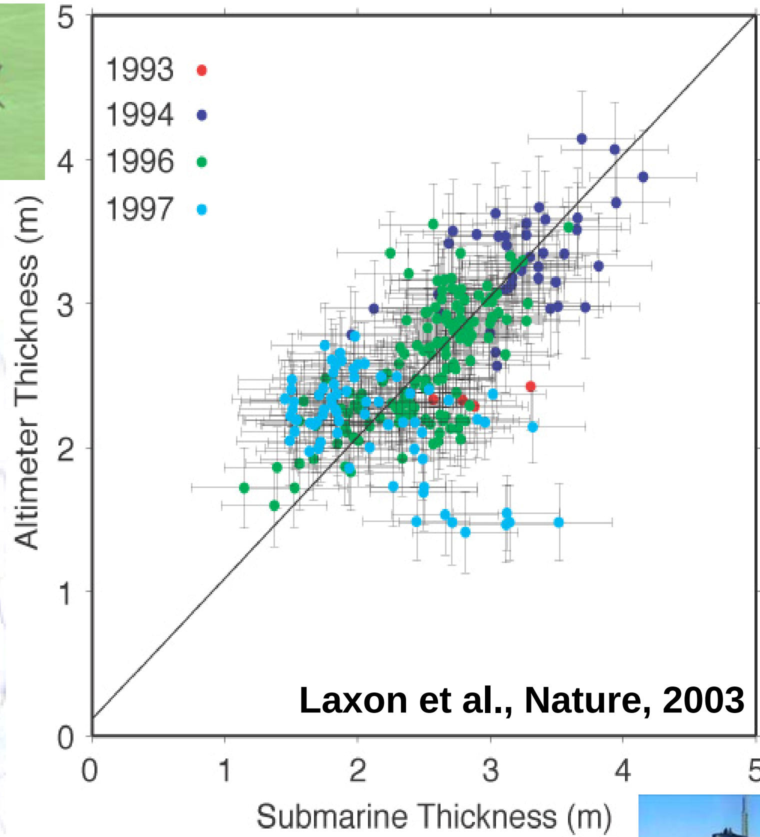
- Co-incident ATSR imagery reveals the origin of Diffuse and Specular echoes over sea ice
- Diffuse echoes originate from ice floes
- Specular echoes originate from leads and smooth thin ice surfaces
- Gaps are caused by Complex echoes which are excluded



Courtesy S. Laxon, UCL

Ice Thickness Estimates: ERS-1/2 Altimeters



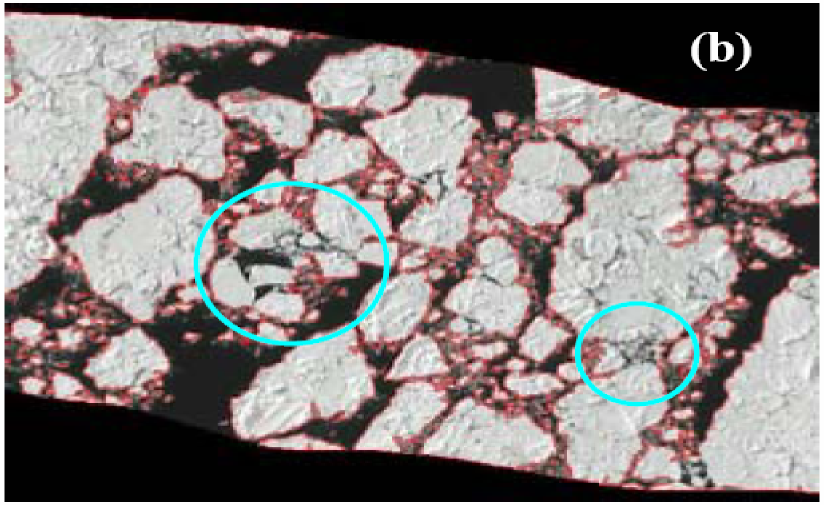


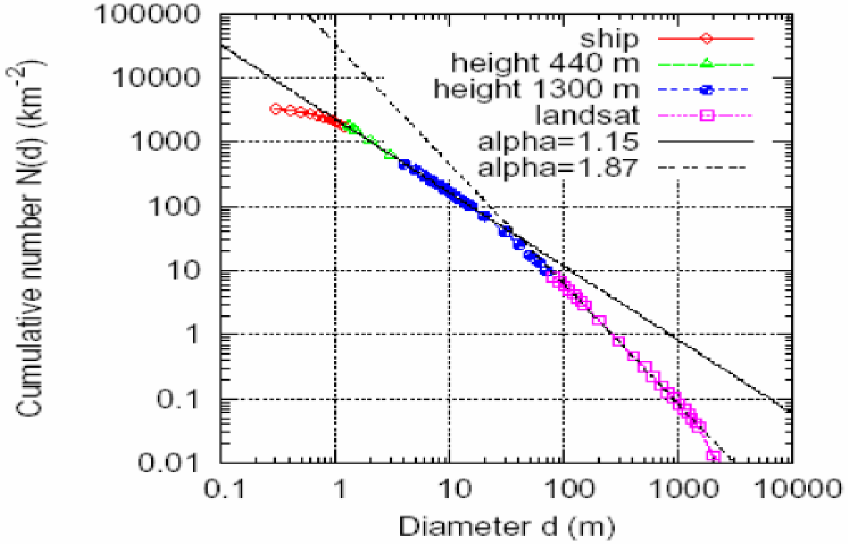
- ERS covers more than half the permanent sea ice in the Arctic
- Main source of error is variability in snow loading and water/ice/snow density
- Unobserved thin ice fraction contributes ±10cm to mean winter ice thickness

Sea-Ice Mass Balance: Lateral Melting *L*

$$\frac{dg(h)}{dt} = -\frac{d(fg)}{dh} - \nabla \bullet g\vec{U} + \psi + L$$

Floe-size distribution changes

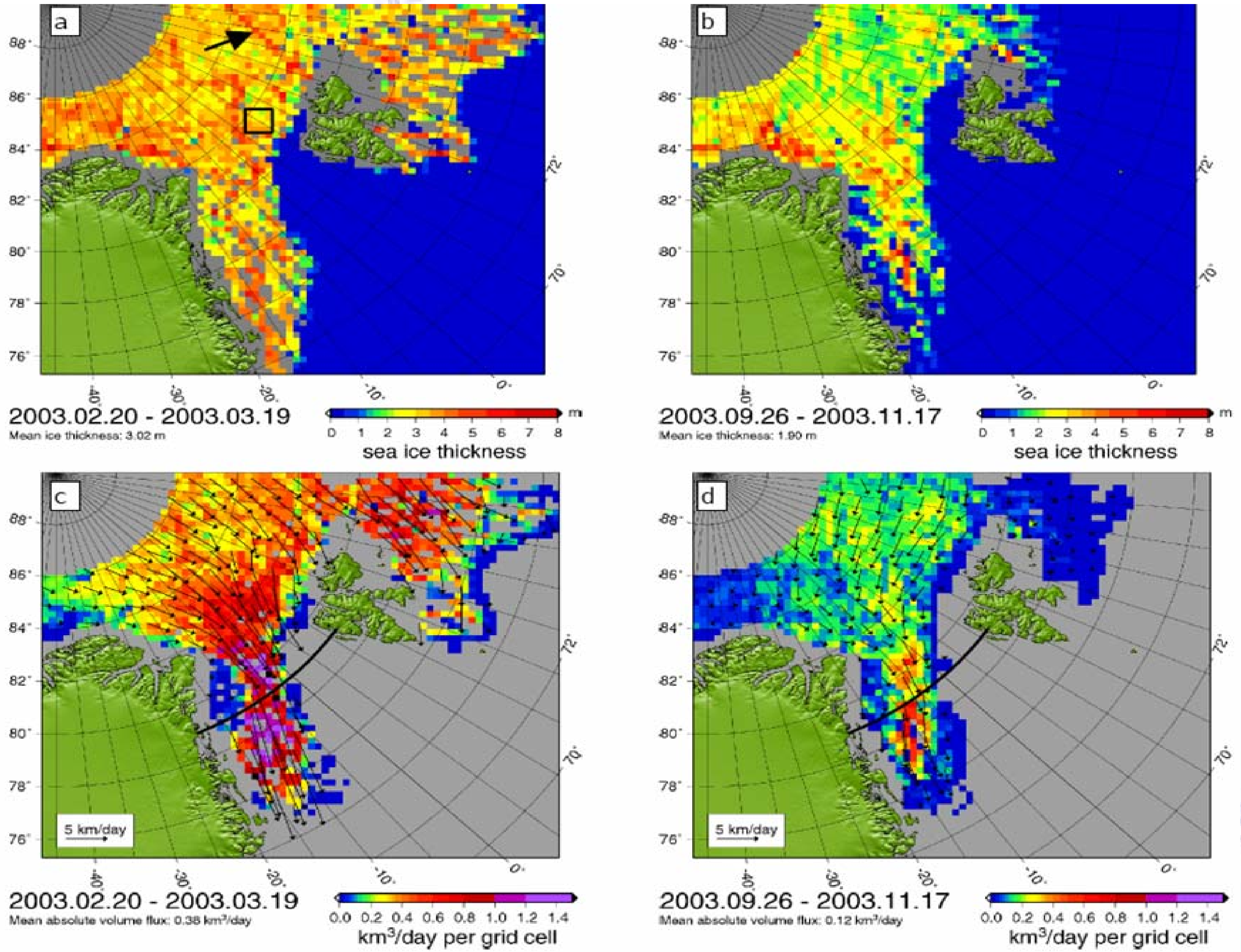




Courtesy Toyota et al, GRL

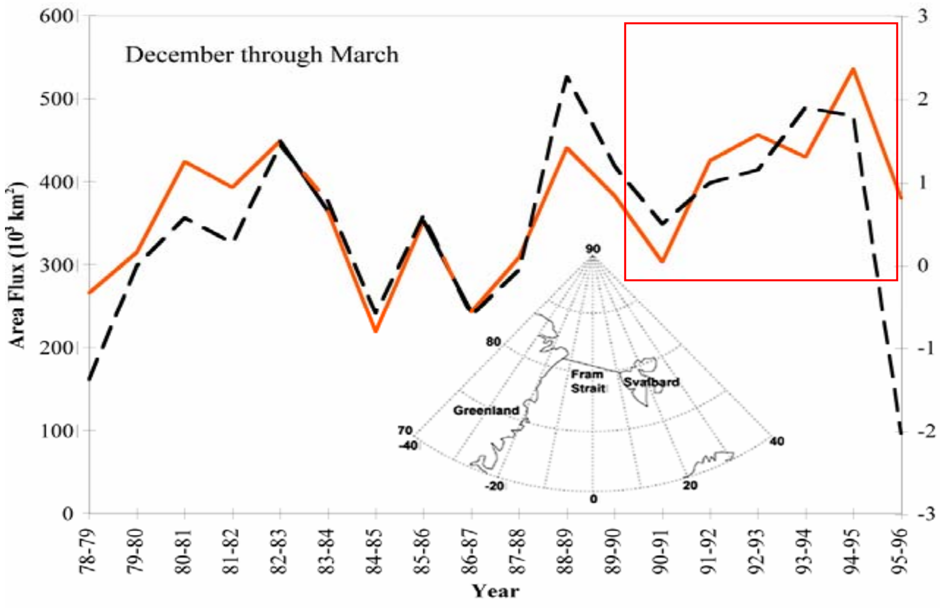
- It is possible to measure floe-size distribution changes, to obtain the lateral melting component of the sea-ice mass budget, *L*.
- *L* can be calculated using high resolution optical data (e.g. SPOT), or SAR image data (e.g. ERS-2, RADARSAT or EnviSat)
- Submarine ULS data have demonstrated relationship between changes in *L* and the thickness distribution *g(h)*

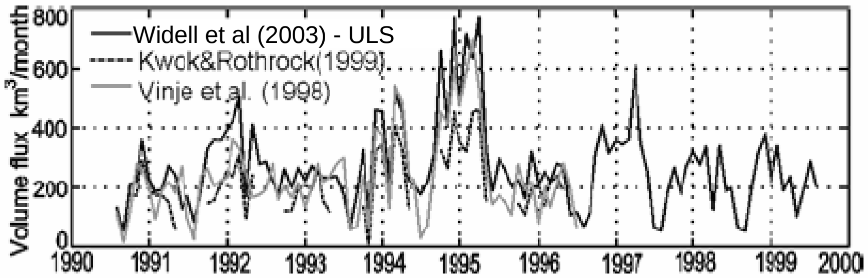
Generating Sea ice volume flux records

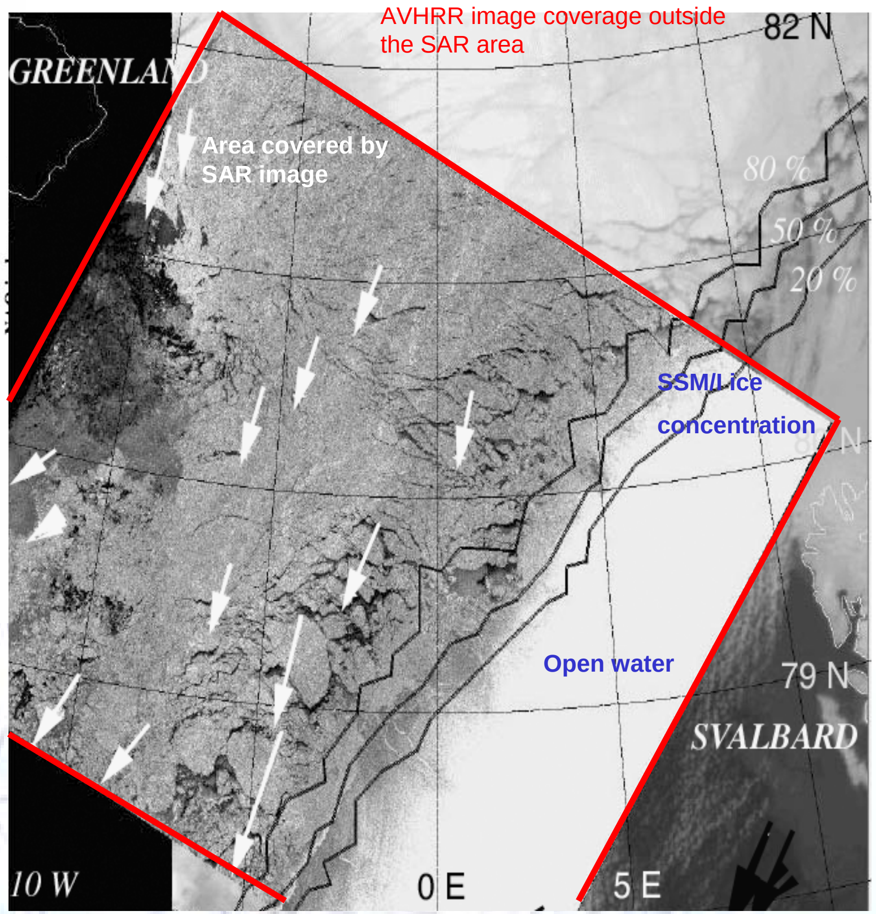


Courtesy, Spreen et al. (In Press), IGS Annals

Area and Volume Flux via Fram Strait







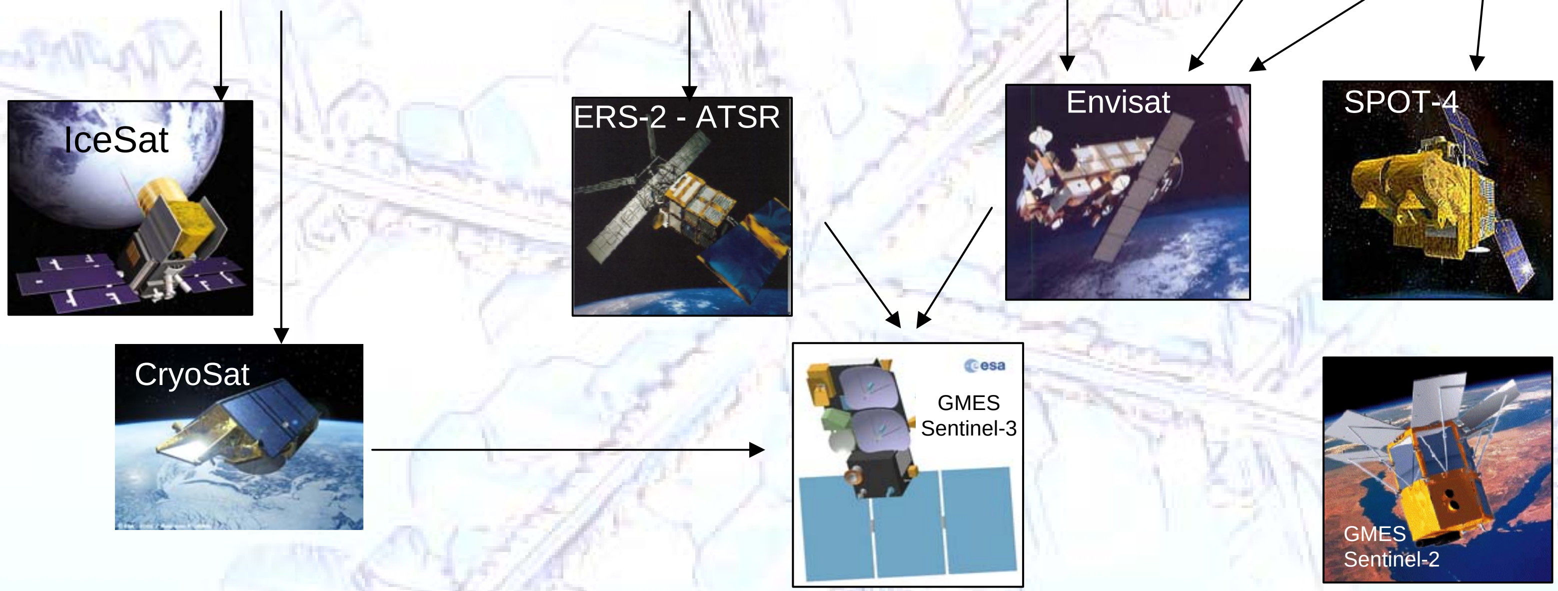
Courtesy S. Sandven

The Arctic FW budget includes a sea-ice export of ~ 8000 km^3 yr^{-1} that is balanced by an average oceanic FW inflow of ~ 2500 km^3 yr^{-1} via Bering Strait, and an atmospheric moisture flux convergence (over Arctic Ocean & watershed) of ~ 5500 km^3 yr^{-1}

Sea Ice Summary

- We are now able to characterise all elements of sea-mass contribution to FW budget using remote sensing data:

$$\frac{dg(h)}{dt} = -\frac{d(fg)}{dh} - \nabla \bullet g\vec{U} + \psi + L$$

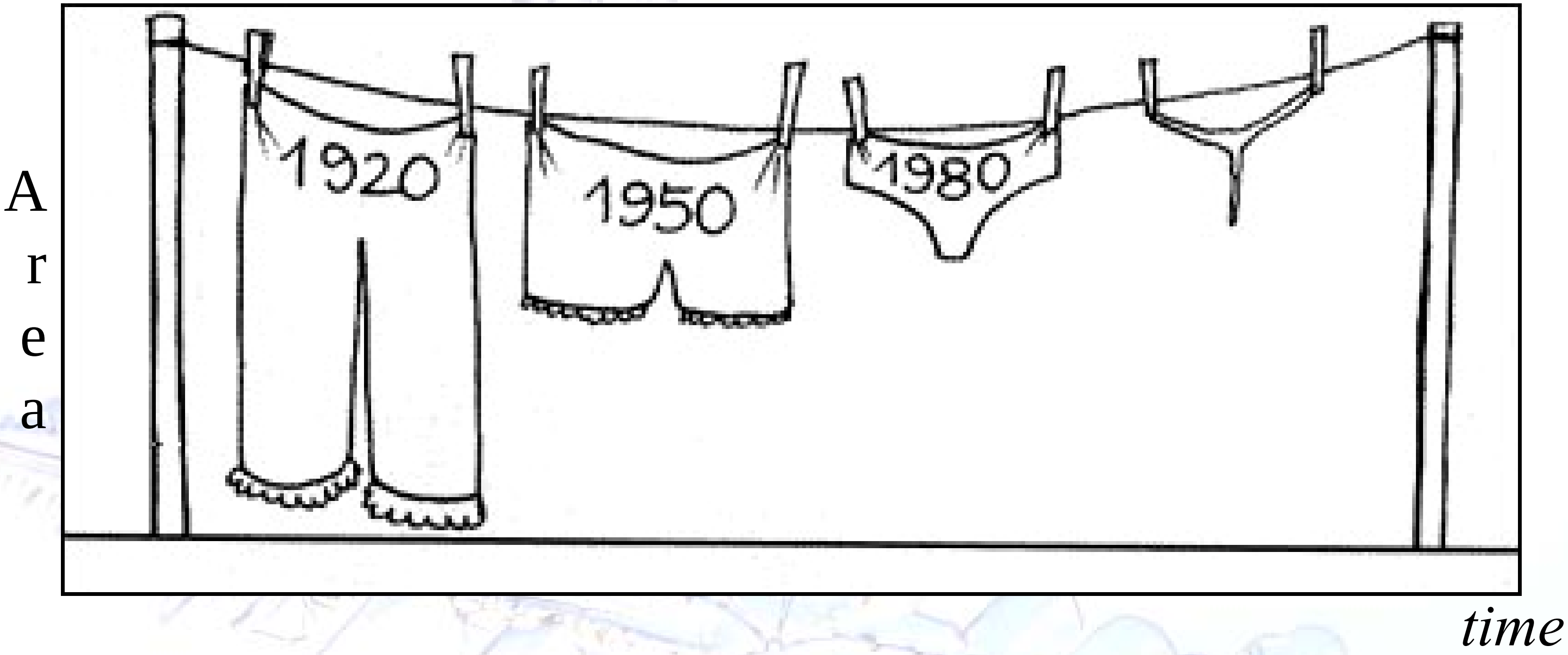


Conclusions

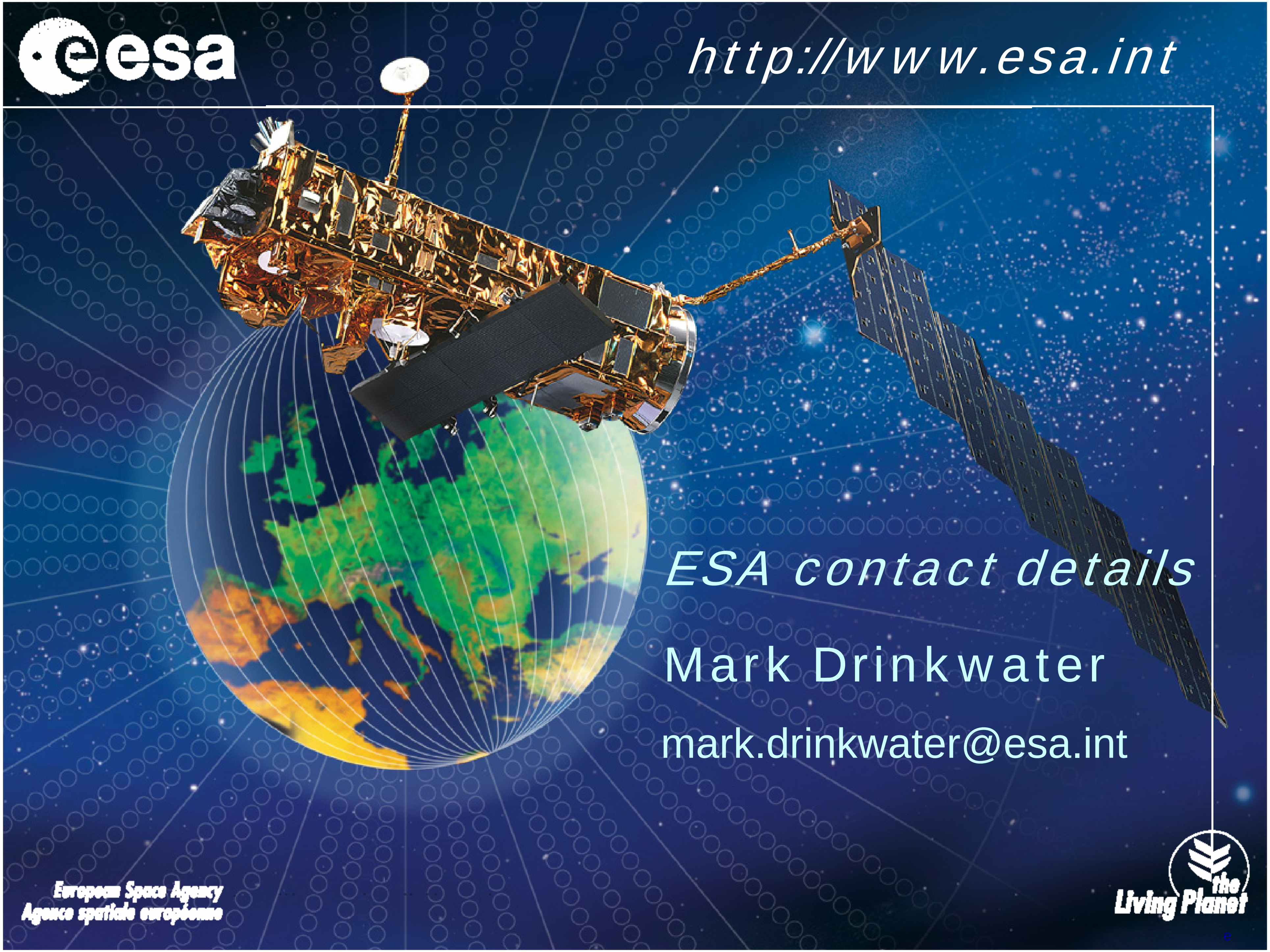
- Satellite Remote Sensing has revolutionised the study of mass balance of polar ice
- All tools exist to quantify role of ice in global water cycle, provided all critical elements of the observing system are sustained
- IPY will provide critical climate benchmark
- IGOS-P Cryosphere Theme justifies the key requirements of the cryospheric observing system
- ESA is committed to delivering critical data on the polar regions and climate variability
  - METOP (Oct ’06); GOCE (Sept’07); SMOS (’08); CryoSat (’09) ADM-Aeolus (’09);

Disappearing ice impacts many polar communities

(Photograph courtesy NOAA Photo Library)



Thank You


esa
http://www.esa.int
ESA contact details
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European Space Agency
Agence spatiale européenne
the Living Planet

Obtaining ESA EO Data

Access to a large dataset of EO data

Announcement of Opportunity for IPY 2007-2008
[ESA IPY-AO]

❑ The selected ESA IPY-AO projects will be granted access to data free of charge.

❑ The selection of IPY-AO projects currently envisaged by ESA would be through an opening limited to the projects already selected by ICSU-WMO.

❑ The selected ESA IPY-AO projects will be subject to the ESA data policy.

The project leader shall sign the Category 1 use Terms and Conditions:

- ✓ to use the data provided for Category 1 use only within the project team (i.e. PI and co-PIs) and only for the purpose described in the project proposal,
- ✓ to widely publish the project results in scientific publications or presentations (with data citation: *"Data provided by European Space Agency"*).

Dedicated ESA-IPY workshop in 2008 ?

Access to a large dataset of EO data

Which EO data is proposed in ESA IPY-AO ?

ESA missions:

Envisat

- access to a large dataset with focus on ASAR data, but also including MERIS, AATSR, Altimetry and Atmospheric Chemistry data,
- ASAR dataset will be acquired through the ASAR background mission with specific priority over polar areas (however priority still given to operational services in case of conflict, e.g. sea ice monitoring, in particular over Arctic),
- consequently Project Leaders will not be authorised to request ASAR instrument tasking over Polar areas.
- geographical areas: Antarctica and Arctic, including Greenland.

ERS-2

- access to SAR data (in visibility of acquisition stations because no recorder on-board ERS-2)

Other ESA missions

- Proba: some focus on particular places
- GOCE, SMOS: according to data release status
- Cryosat: launch date 2009

Access to a large dataset of EO data

Continued….

ESA Third Party missions

ALOS (JAXA - Japan):

- access to a dataset including SAR data (L-band) and optical data,
- no instrument tasking directly authorised to Project Leaders,
- geographical areas: European Arctic and Greenland,
- for Antarctica data, ESA agreement sought with JAXA.
- contribution to costs for data repatriation may apply if data not acquired in Europe (TBC).

SPOT-4 (SpotImage - France):

- access to a dataset free of charge.
- geographical areas: Antarctica and Arctic, including Greenland.
- contribution to costs for data repatriation may apply if data not acquired in Europe (TBC).

Other data opportunities under discussion:

- SAR C-band: Radarsat-1/-2 (with Canadian Space Agency - CSA)
- SAR X-band: Terrasar-X (with German Space Agency – DLR):
- Optical very high resolution: Kompsat (with Korean Space Agency – KARI)

ESA support to IPY 2007-2008

• Mainly providing access to a large dataset of Earth Observation (EO) data, *free of charge*.

• Additionally through the European GMES Services Element project dedicated to Polar areas, *Polar View*

→ **primary portal to geospatial information derived from SAR data**

GMES = Global Monitoring for Environment and Security (EC + ESA)

GMES Services Element = ESA-funded services (2006-2008)