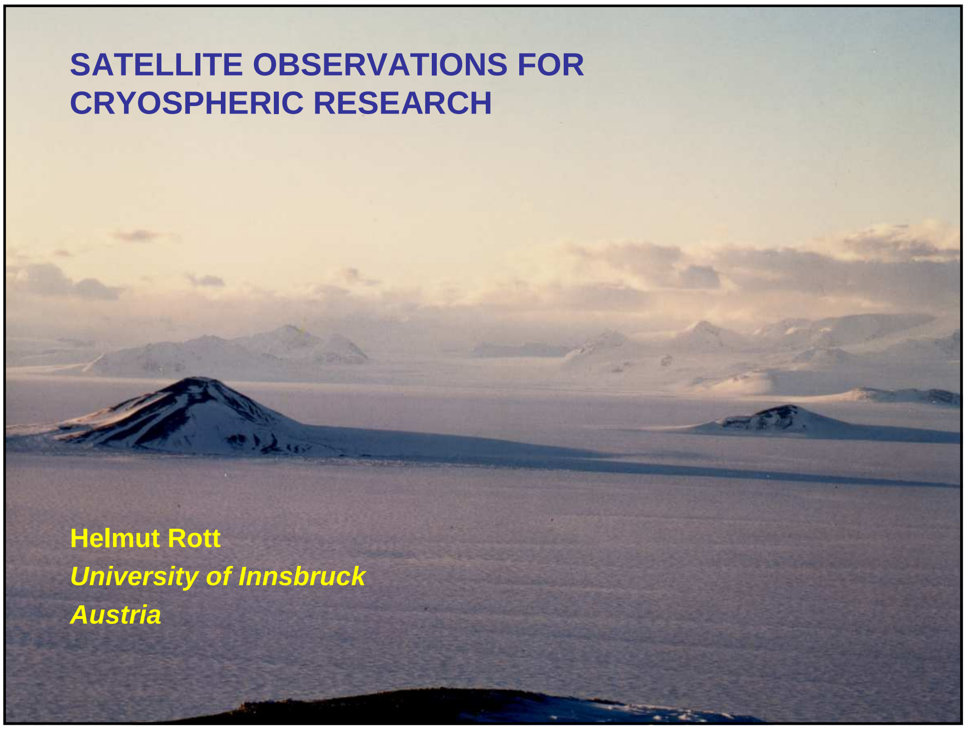
SATELLITE OBSERVATIONS FOR CRYOSPHERIC RESEARCH



Helmut Rott
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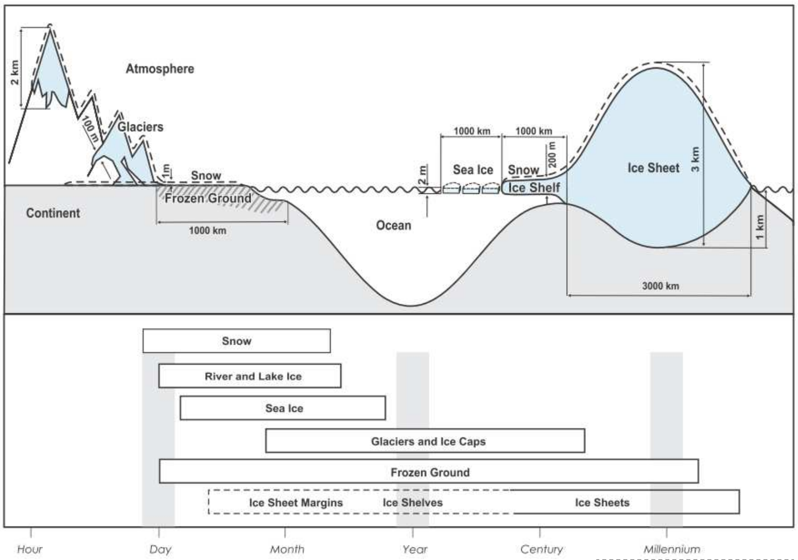
Contents of Presentation

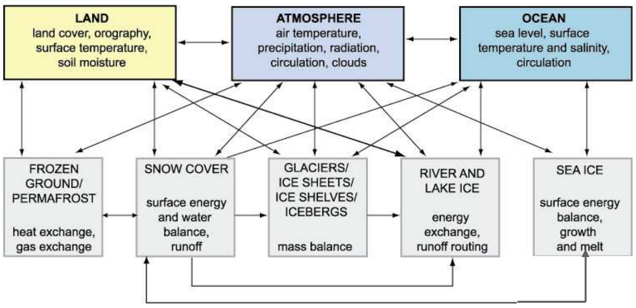
- Elements of the cryosphere
- Satellite observations of sea ice retreat
- Examples of snow and glacier products by means of optical sensors
- Interactions of synthetic aperture radar (SAR) signals with snow
- Snow retrievals by SAR and microwave radiometry
- Ice sheet mass balance by satellite altimetry and gravimetry
- Ice flow dynamics and calving rates by SAR interferometry and amplitude correlation
- Key scientific question
- References

Components of the Cryosphere and their Time Scales



Lemke et al., 2007

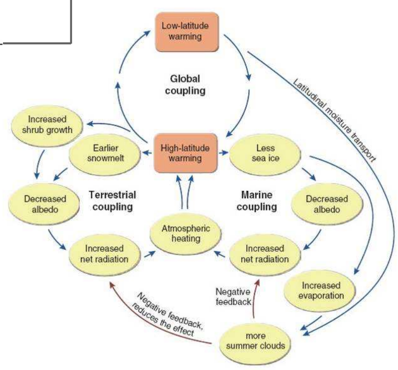
Interactions of Cryospheric Elements with the Climate System



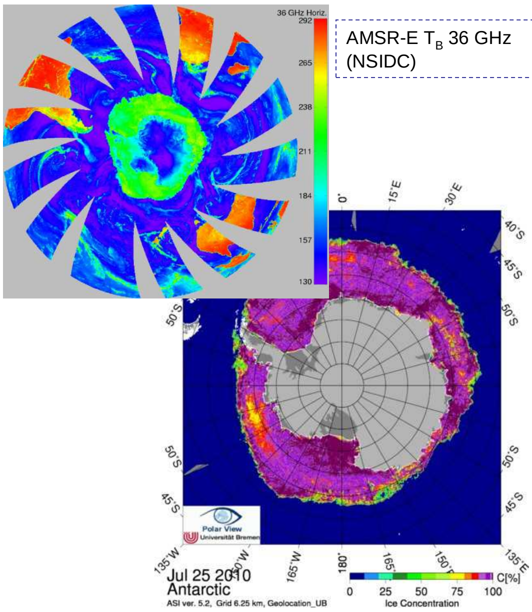
WCRP-CliC

Lists in upper boxes indicate important state variables.
Lists in lower boxes indicate important processes involved in interactions.
Arrows indicate **direct** interactions.

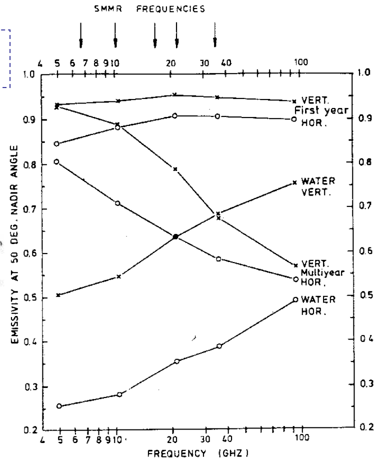
Connectivity between snow, climate, and ecosystems. Positive ice/snow albedo feedback, terrestrial snow and vegetation feedbacks and the negative cloud/radiation feedback (*UNEP, 2007)*



30 Years of Sea Ice Time Series based on Microwave Radiometry

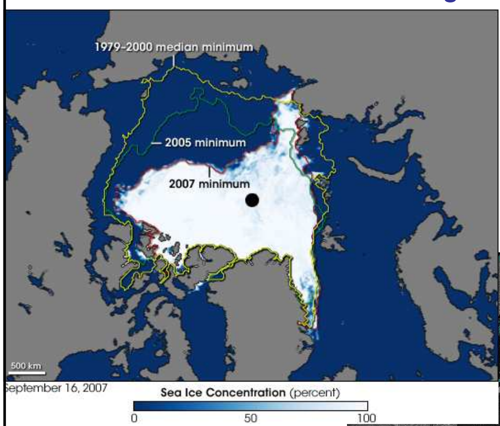


AMSR-E T_B 36 GHz (NSIDC)

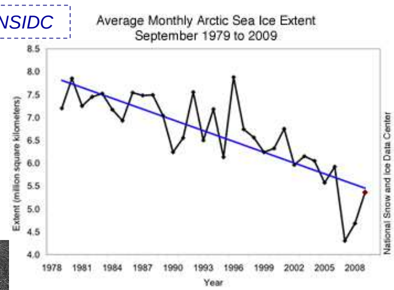


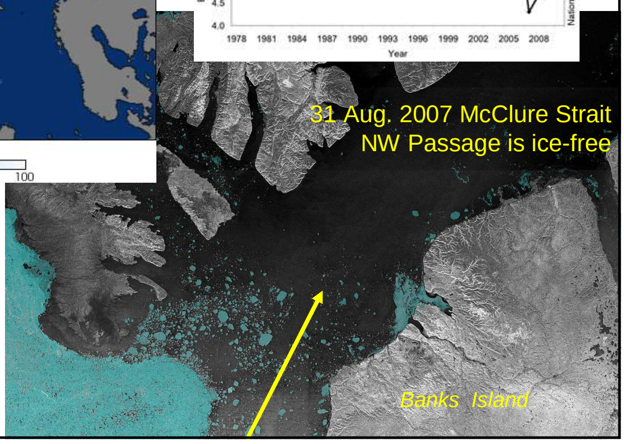
Separation of water, first year sea ice and multi-year ice by means of multi-frequency microwave emission

Arctic Ocean: Strong Decrease in Sea Ice Area



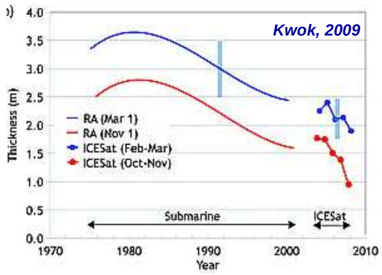
NSIDC





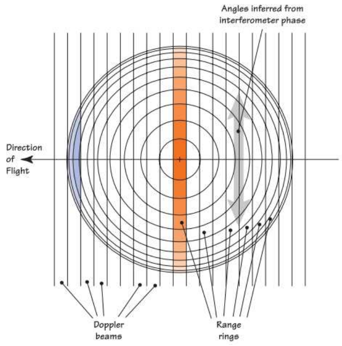
Envisat ASAR

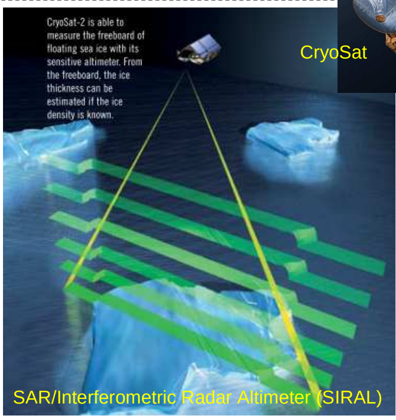
Arctic Ocean: Decrease in Sea Ice Thickness



← Decrease in mean thickness 1978 (Submarine) – 2003/08 (ICESat)

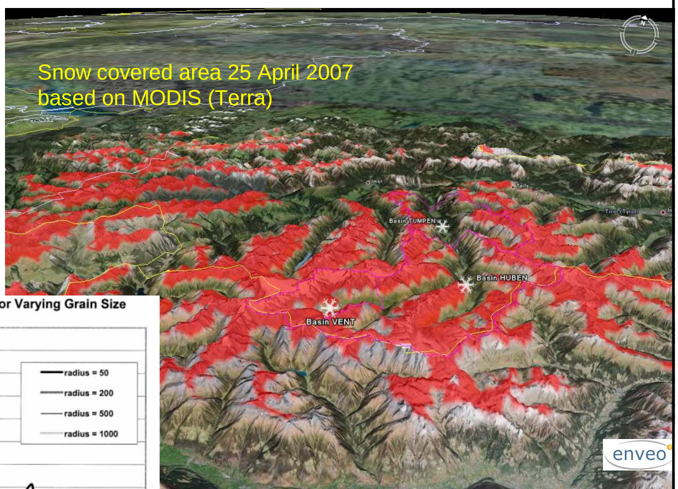
CryoSat-2: Improved Precision in measuring sea ice freeboard and estimating ice thickness

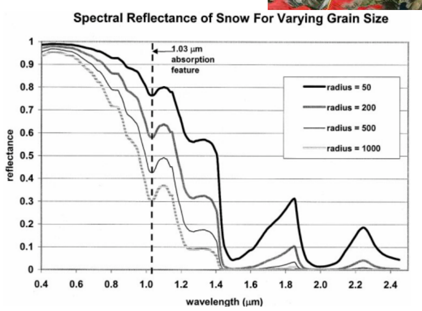




Monitoring Seasonal Snow Cover – Optical Sensors

Classification based on NDSI:
(VIS-SWIR)/(VIS+SWIR)
SWIR → 1.6 µm

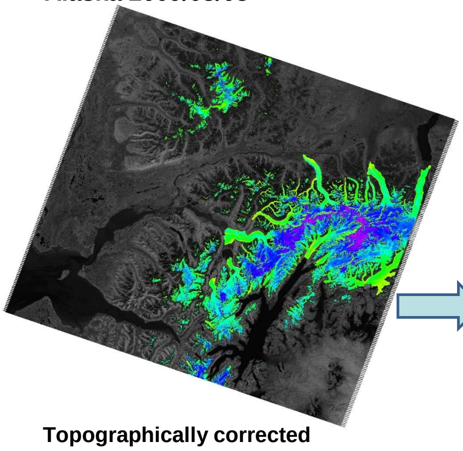




Spectral reflectance in dependence of grain size (*Nolin et al., 2000*)

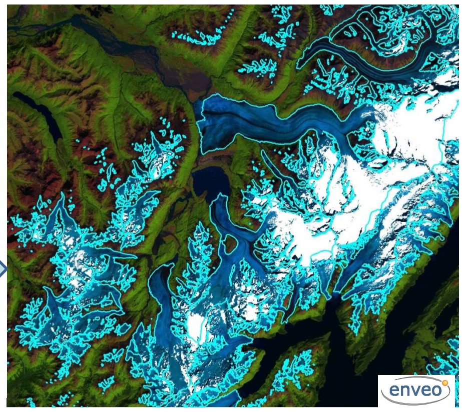
Mapping of Glacier Outlines and Snow/Ice Areas

Chugach Mountains - Alaska 2009/08/03

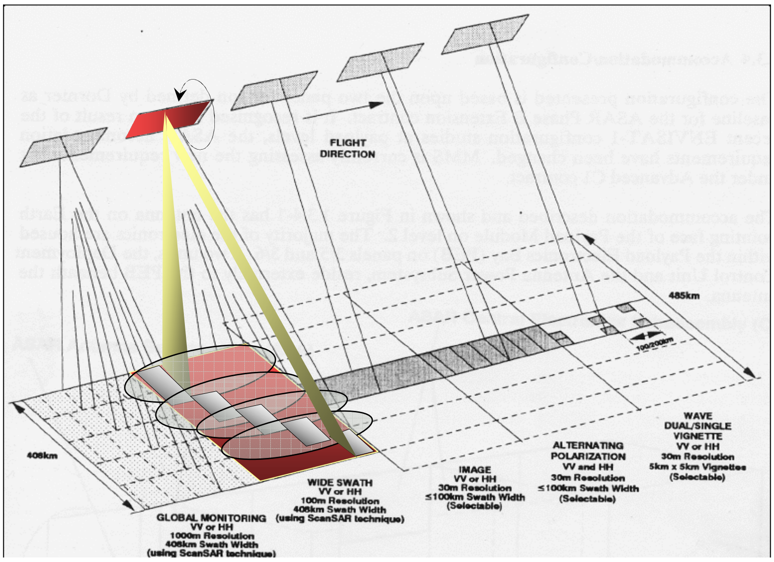


Topographically corrected radiance, Landsat TM Band 4

Map of Late Summer Snow and Ice Areas

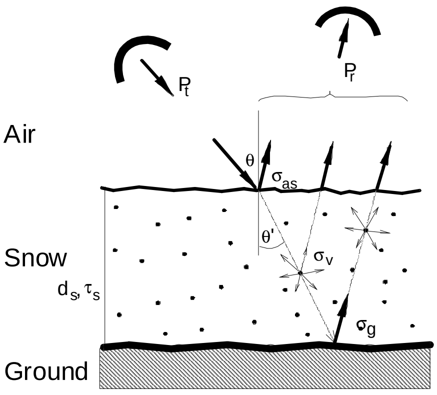


Snow and Glacier Observations by means of SAR



ASAR operation modes

SAR Application to Snow Mapping:
Radar Scattering Signatures of Snow



Scattering

$\sigma° = \sigma°_{as} + \Upsilon^2_{as} [(\sigma°_v / 2k_e) \cdot (1 - \tau'^2_s) \cos\theta + \sigma°_g \tau'_s]$

$\sigma°$ = observed backscat. coeff.

Υ = transmissivity of air/snow interface

$\sigma°_{as}$ = backscat. coefficient of air/snow interface

$\sigma°_v$ = volume backscatt. coeff.

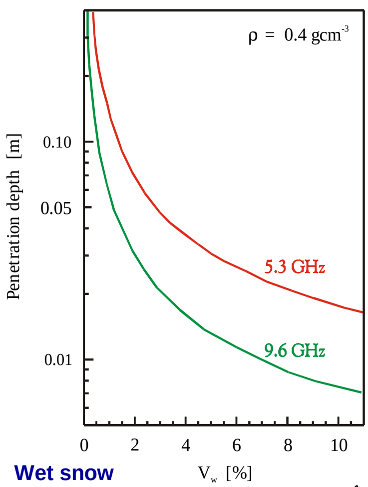
$\sigma°_g$ = backscatt. coeff. of ground

k_e = volume extinction coeff.

τ_s = transmissivity of snow layer

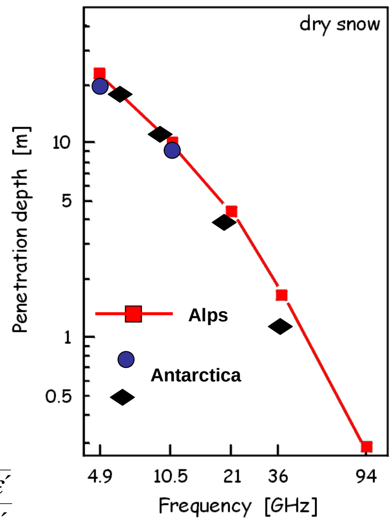
$\tau'_s = \exp(-k_e d_s / \cos\theta')$

Microwave Penetration Depth in Snow

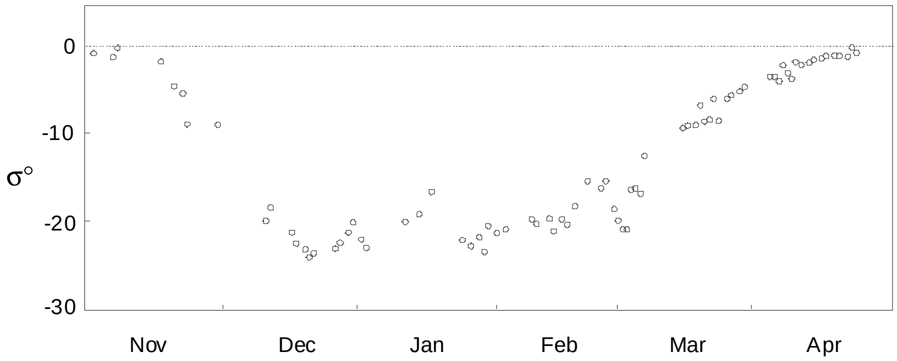


Wet snow

$$d_p = \frac{\lambda_0}{2\pi} \frac{\sqrt{\varepsilon'}}{\varepsilon''}$$



The Effect of Snow Melt on Backscattering



Backscatter coefficient of firn on Larsen Ice Shelf (67°S) from ERS Scatterometer Data (5.3 GHz) – Cycle of melt and refreeze

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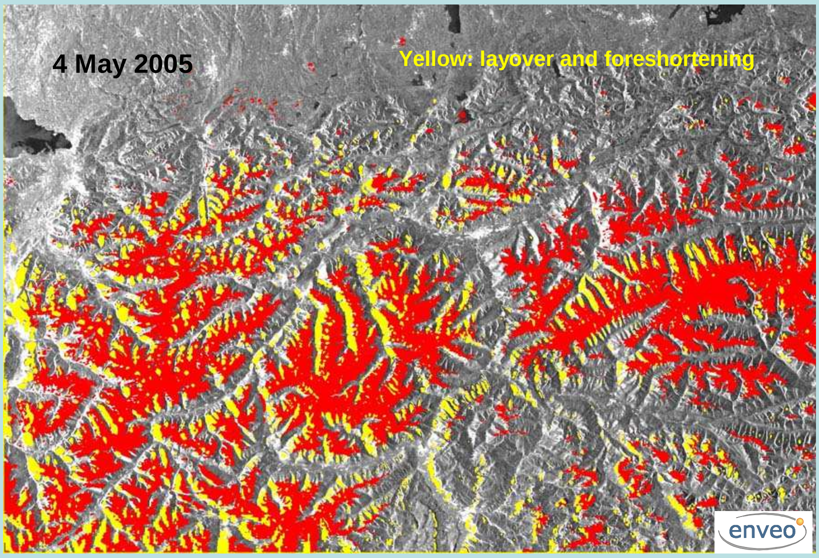
ASAR Wide Swath Mode - Snow Map



C-band SAR detects melting snow area

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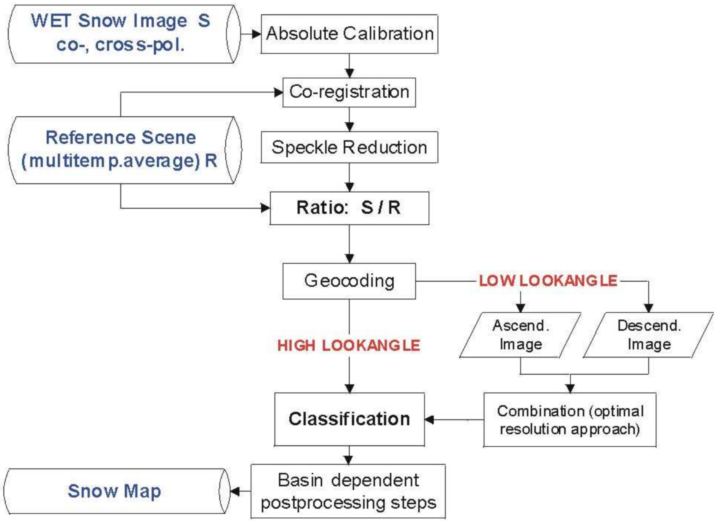
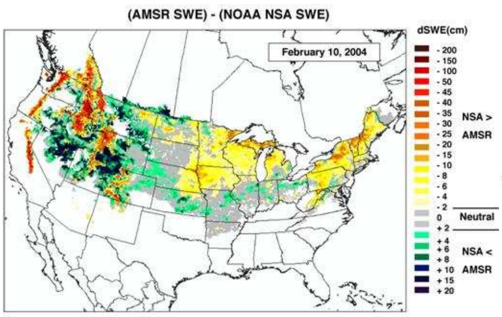
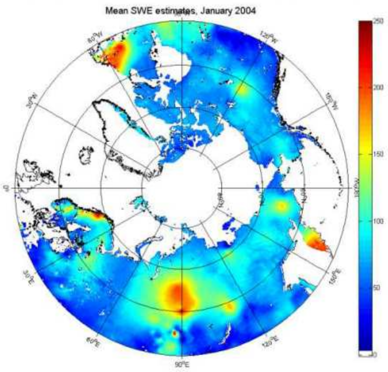
SAR Algorithm for Retrieval of Snowmelt Area



Retrieval of Snow Mass (SWE) by means of Microwave Radiometry



Baseline: AMSR-E derived SWE product
(both AMSR-E and SSM/I data available from 2002->)

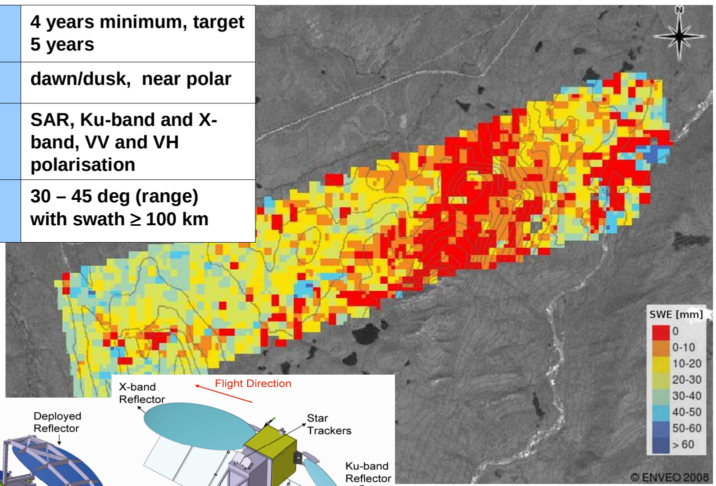


Differences between SWE by AMSR-E and SWE analysed from operational modeling and data assimilation (NOAA NSA)

Saturation at deep snow

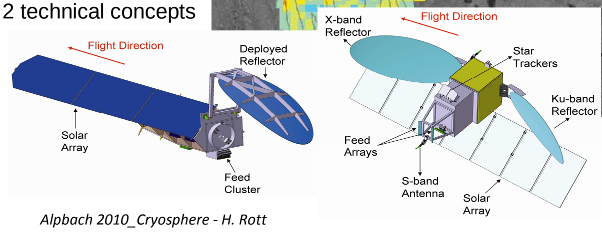
CoReH2O –Satellite for Measurement of Snow Mass (SWE)
ESA Earth Explorer Candidate Mission

Mission duration	**4 years minimum, target 5 years**
Orbit	**dawn/dusk, near polar**
Sensor	**SAR, Ku-band and X-band, VV and VH polarisation**
Incidence angle and swath	**30 – 45 deg (range) with swath ≥ 100 km**

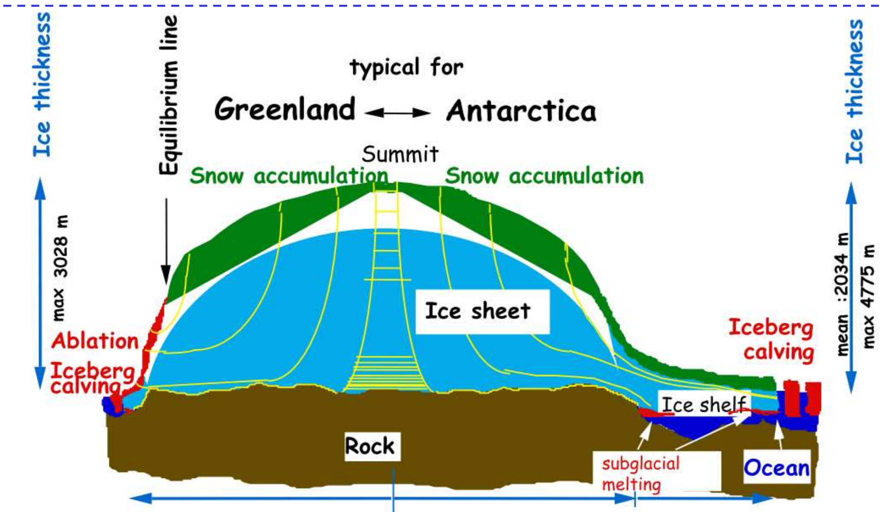


SWE Map, Kuparuk, Alaska
From Ku- and X-band data

2 technical concepts



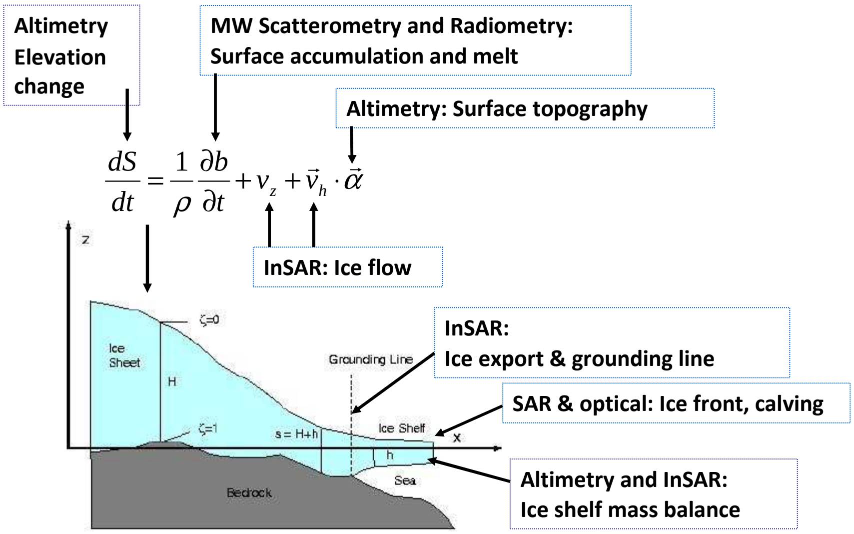
Ice Sheets – Mass Balance and Sea Level Equivalent

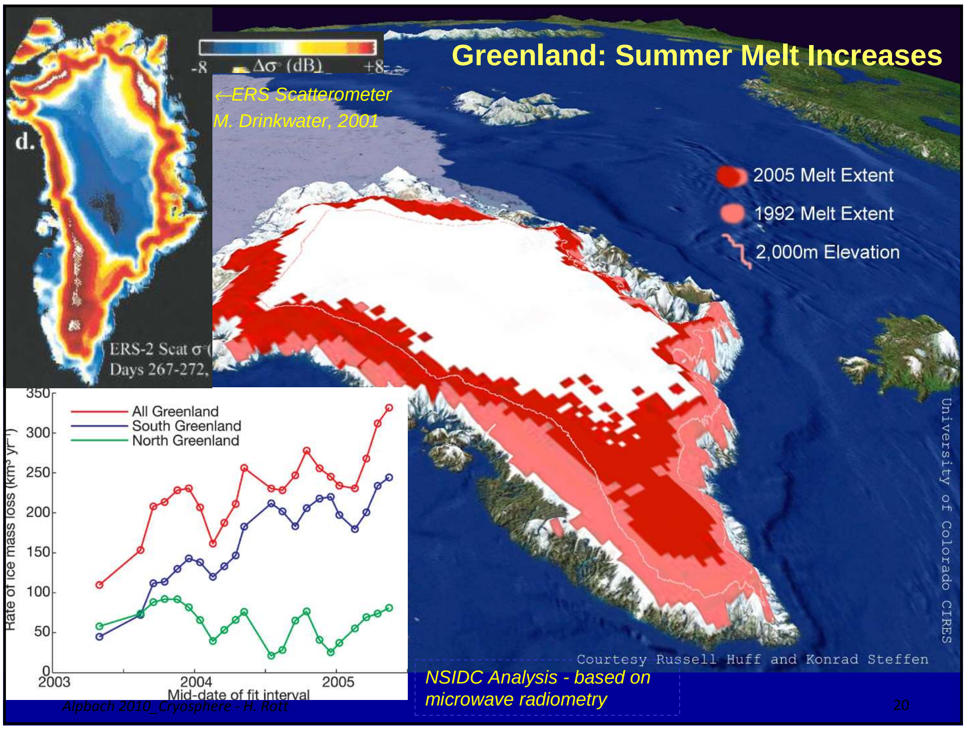


Dimension:	500 - 1000 km	Dimension:	ca. 2000 km
Area:	1.7 M km²	Area:	12.3 M km²
Volume:	2.9 M km³, 7.3 m SLE	Volume:	24.7 M km³, 56.6 m SLE
Total Acc.:	500 Gt a⁻¹, 1.4 mm SLE	Total Acc.:	1850 Gt a⁻¹, 5.1 mm SLE

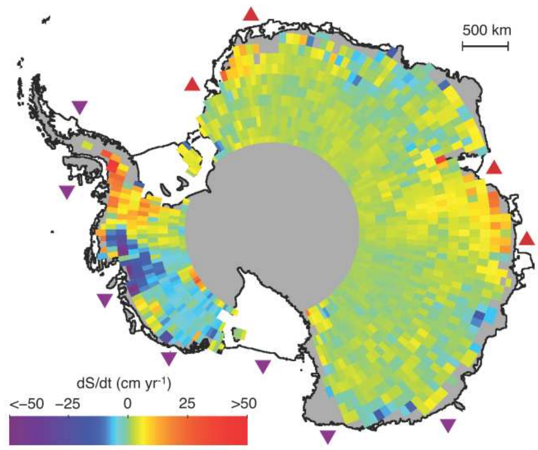
Fig. NSIDC

Satellite Measurements for Monitoring the Dynamics and Mass Balance of Ice Sheets





ERS Altimetry: Antarctic Elevation Change 1992-2002



Estimates of Antarctic mass balance 1993-2003 (different sources):

+50 to –200 Gt/year

Corresponding change in sea level:

–0.14 to +0.55 mm/year

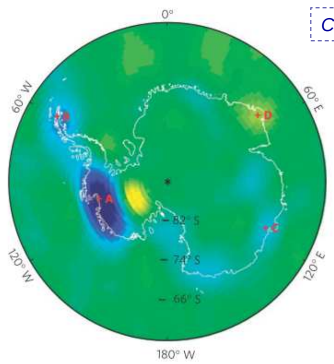
IPCC 2007
Davis et al., 2005

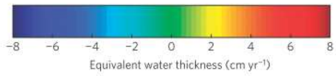
Ice shelf gets thinner

Ice shelf gets thicker

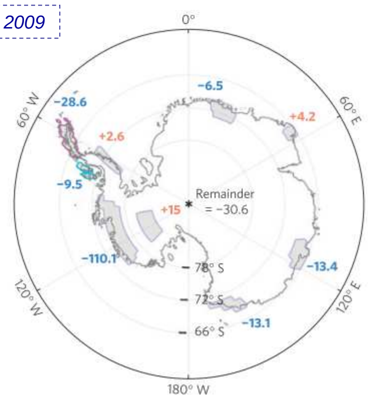
Antarctic Ice Loss from Satellite Gravity Measurements

Chen et al., 2009



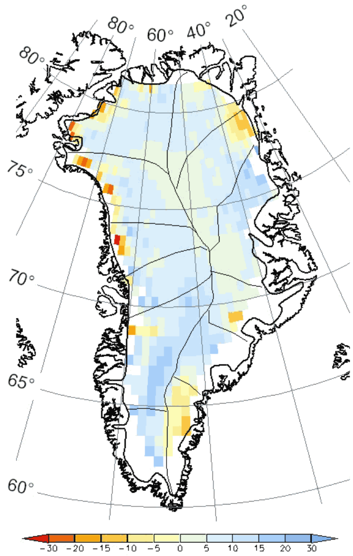


Mass rate over Antarctica (cm of equivalent water height change per year from GRACE 2002-2009



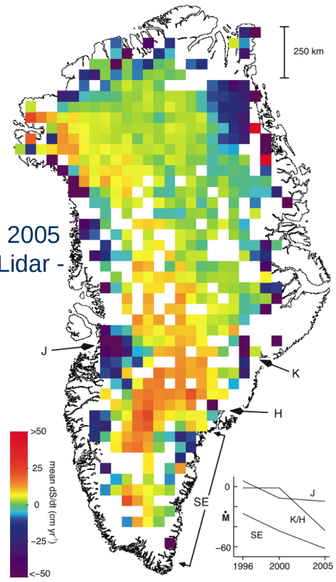
Forward modelling with mass rates (in units of Gt yr^{-1})
uniformly distributed over each area to match GRACE measurements

Greenland Elevation Change (cm/yr)



1992 -2003 ERS-1/2 Altimetry
O.M. Johannessen et al. 2005

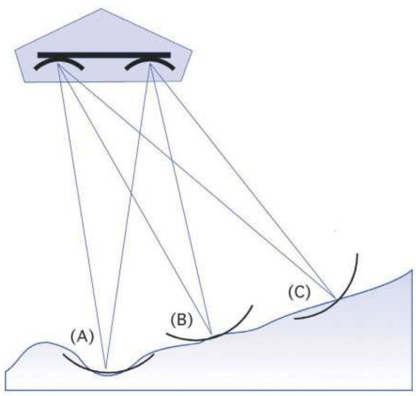
1998/99 - 2005
Airborne Lidar -
IceSat →

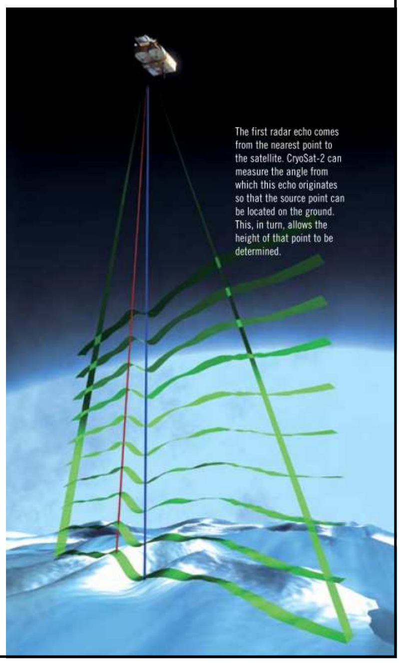


Lemke et al. 2007

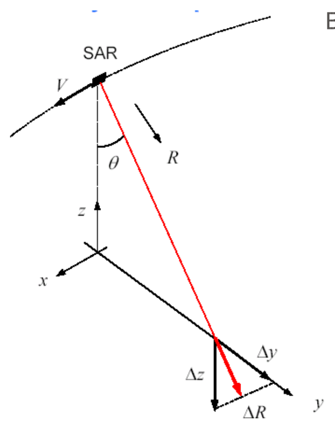
Croysat-2: Improved Precision for Ice Sheet Topography

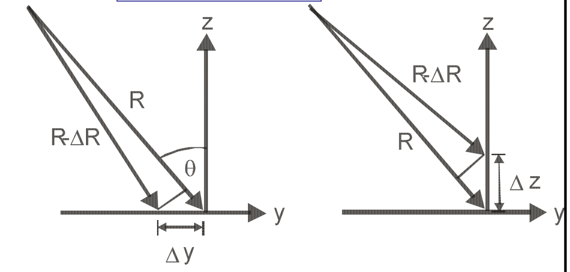
SAR-Interferometric Mode, SARIn: Major improvements on slanting surfaces.
The location of the echo is determined by means of phase measurement





Interferometric Measurement of Ice Motion



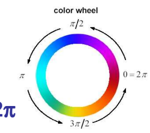


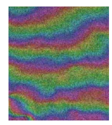
$$\Delta\phi_{dis} = (4\pi/\lambda)\Delta R = (4\pi/\lambda)(\Delta y \sin\theta - \Delta z \cos\theta)$$

C-band SAR (λ = 5.66 cm):
$\Delta\phi\ (2\pi) \Rightarrow \Delta R$ = 2.83 cm
Δy = 7.24 cm, Δz = 3.07 cm (23°)

InSAR measures the displacement in LOS of the radar beam

Phase cycle 2π





Ice Motion Retrieval: InSAR & Image Correlation

	INSAR	IMAGE CORRELATION
Velocity component	LOS only	LOS (range) **and** along track
Accuracy of displacement	~ 1 - 5mm slant range (0.4 - 1.8 m/yr) Depends on coherence etc	~ 0.5 - 1 m (ERS, ASAR) ~ 0.1-0.2 m (TerraSAR)
Typical time interval	1, 3 days (ERS) (5 weeks on ice sheet plateau with slow motion)	(for amplitude correlation) n *11 days (TerraSAR) n *35 days (ERS, ASAR) ≤5 weeks for speckle tracking
Main constraints	- Loss of coherence - No sensitivity to motion along track (single pass)	- Lack of stable amplitude features (for amplitude cor.) - Loss of coherence (for speckle tracking) - Lower sensitivity than InSAR

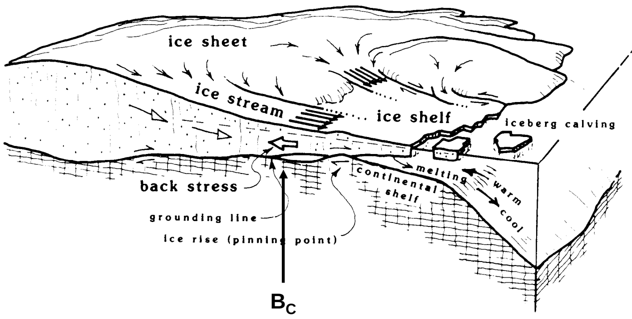
SAR Application to Measure the Ice Export (Calving Flux)

Demonstrated for Glaciers above Larsen Ice Shelf

Collapse of Ice Shelf Sections (15.000 km²) 1995, 2002

Science Question: The response of the grounded glaciers?

The Mass Balance of Grounded Ice is relevant for Sea Level Rise



The main export of Antarctic ice is routed through ice shelves and lost by iceberg calving.

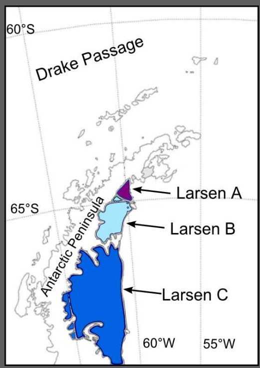
Ice shelf retreat affects the export of grounded ice

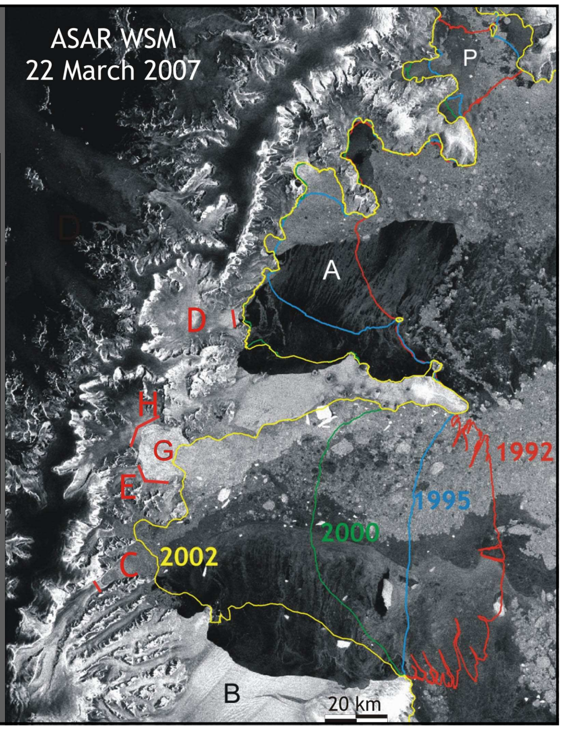
The contribution to sea level rise is determined by the imbalance of net accumulation, B_A, on grounded ice minus the export through a cross section at the grounding line or calving front, B_C: $B_N = B_A - B_C$

Satellite observations provide key input for computing B_C:
- The ice velocity at the cross section, u(y)
- The surface elevation at the front (by altimetry, SAR) enabling to estimate ice thickness H

$$B_c = \int_Y [\bar{u}(y)H(y)]dy$$

Disintegration of Northern Larsen Ice Shelf

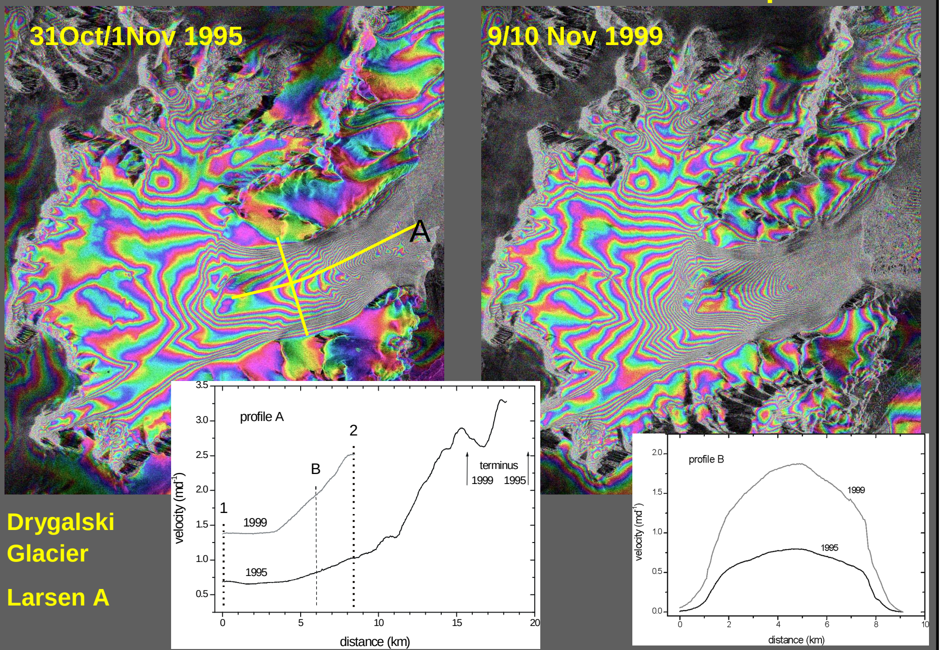




Outlet Glaciers:
C – Crane, D – Drygalski,
H – Hektoria, G – Green,
E – Evans Glacier

Drygalski Glacier October 1997

Acceleration of Glaciers after Ice Shelf Collapse



Drygalski Glacier

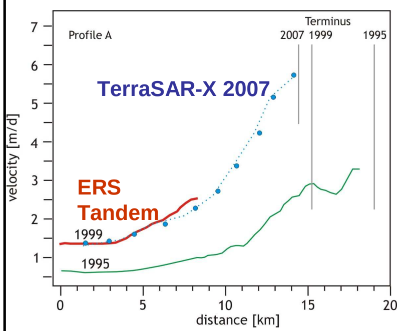
Larsen A

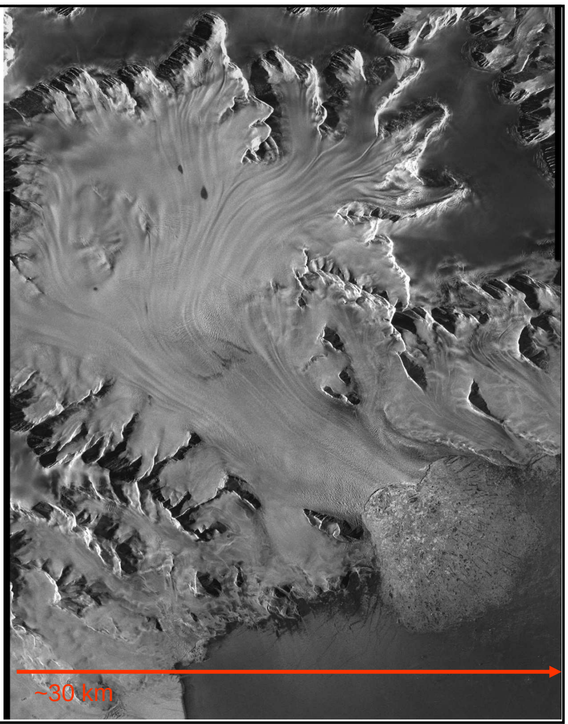
Ice motion of Drygalski Glacier

ERS and TerraSAR-X

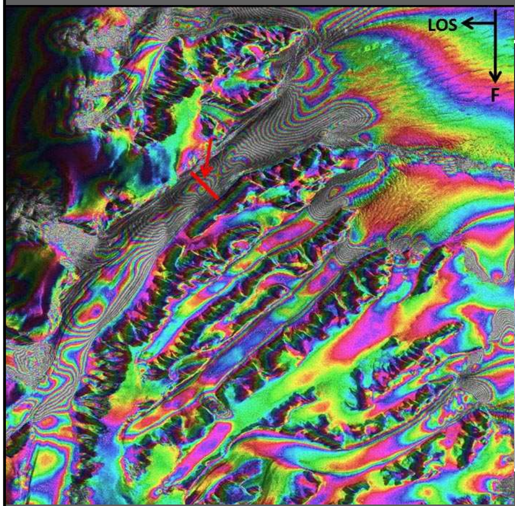
InSAR ***/*** incoherent amplitude correlation

N

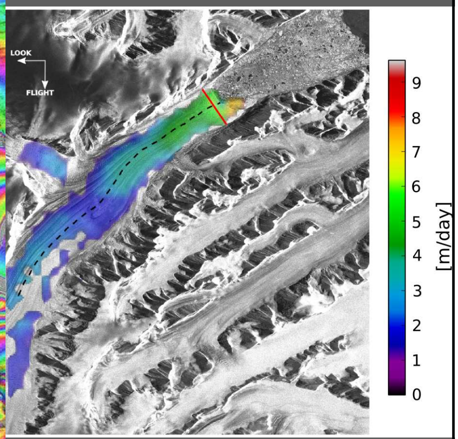




Acceleration and Ice Export of Crane Glacier



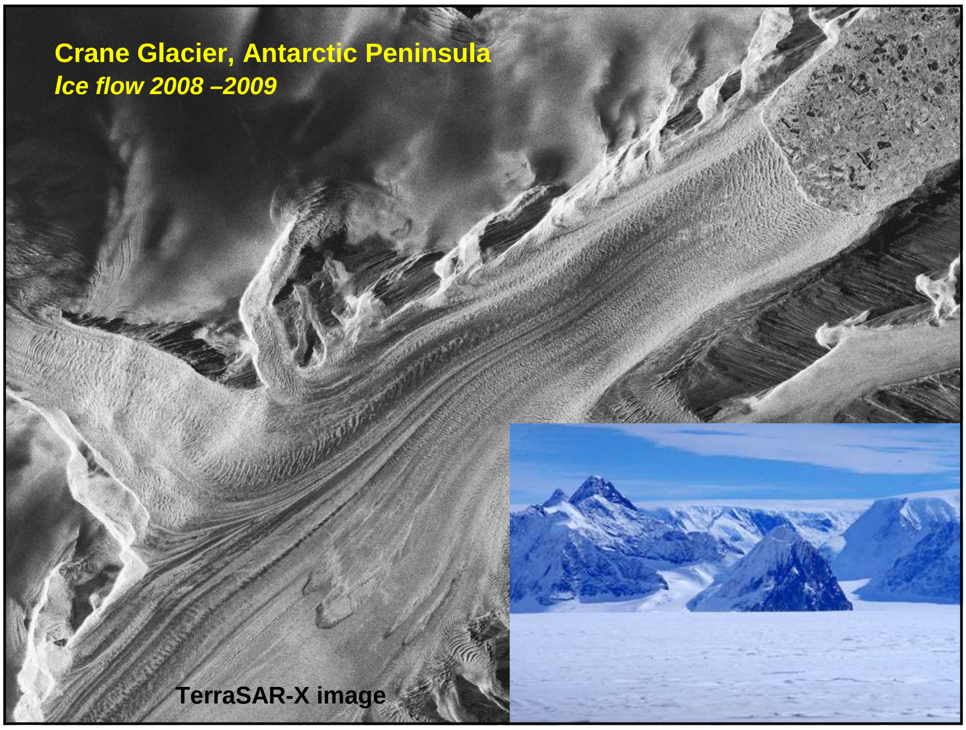
ERS Tandem 1995/10/31-1995/11/01



TerraSAR-X **18 - 29 October 2008**

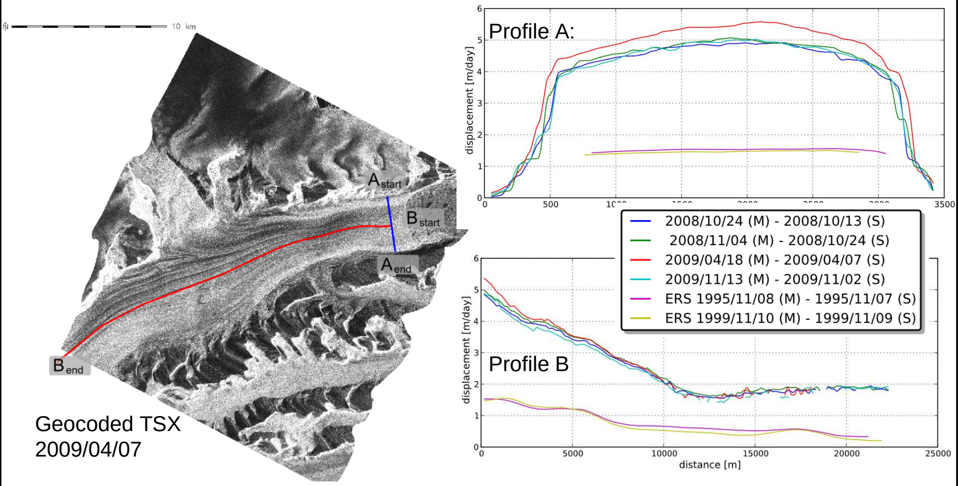
Crane Glacier, Antarctic Peninsula

Ice flow 2008 –2009



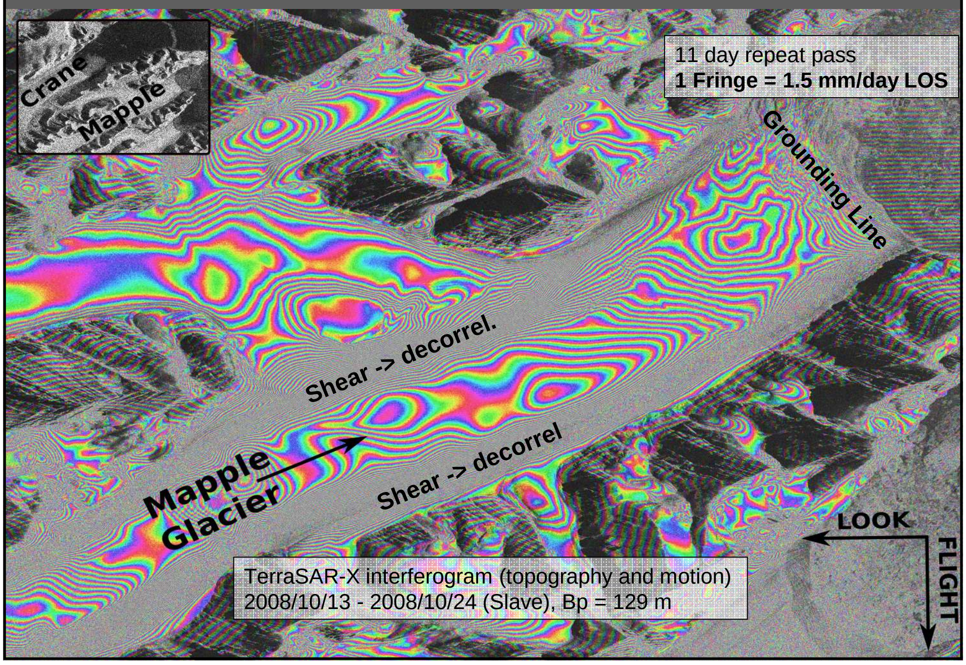
TerraSAR-X image

Crane Glacier: Ice Velocities 1995 - 2009



1995-1999: 1.095 Gt/yr ice export → 1036 kg/m^{2}yr – net accumulation
2008: 3.315 Gt/yr ice export → -2100 kg/m^{2}yr – mass deficit

TerraSAR-X Interferogram Mapple Glacier



Key Scientific Challenges for Cryosphere

1. Quantify the distribution of sea-ice mass and freshwater equivalent, … understand thermodynamic and dynamic feedbacks to the ocean and the atmosphere ***Ice thickness, snow on sea ice, polynyas, …***
2. Quantify the mass balance of grounded ice sheets, ice caps and glaciers, partition their relative contribution to eustatic sea-level rise, and understand their future sensitivity to climate change.
Reduce uncertainty in gravimetry and altimetry of ice sheets, better ice dynamic observations and models, global glacier mass balance
3. Understand the role of snow and glaciers in influencing the global water cycle and regional water resources, identify links to the atmosphere, and assess likely future trends
Improved data on snow mass on land; glacier accumulation and mass balance
4. Quantify the influence of ice shelves, high-latitude river runoff and land ice melt on global thermohaline circulation and understand the sensitivity of these fresh-water sources to future climate change
Ice shelf basal melt, flow dynamics, snow accumulation and melt
5. Quantify current changes taking place in permafrost and frozen-ground regimes, understand their feedback to other components of the climate system, and evaluate the sensitivity to future climate forcing
Link surface processes (snow, ice, erosion, thermokarst, ..) to permafrost

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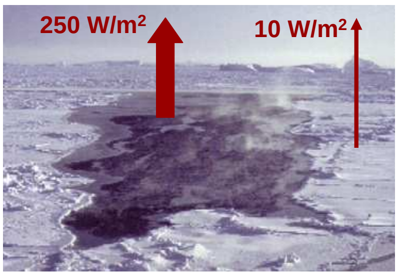
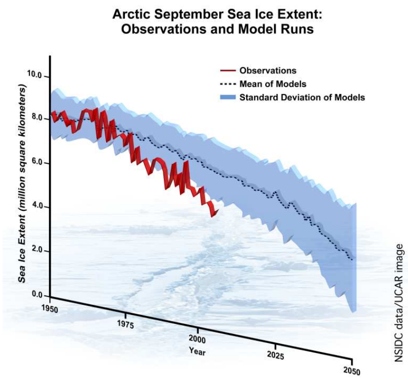
Sea Ice Thermodynamic and Dynamic Processes

- The thermal conductivity of snow is <15% of sea ice strongly affecting sea ice growth
- Open leads and polynyas are the primary heat source to the atmosphere over polar oceans in winter
- The resulting ice formation is an important source of deep water ventilating the Earth’s oceans
- Measurements of thin ice thickness are needed to quantify polynyas processes





Actual observations of September Arctic sea ice show a more severe decline than any of the 18 computer models cited in IPCC 2007

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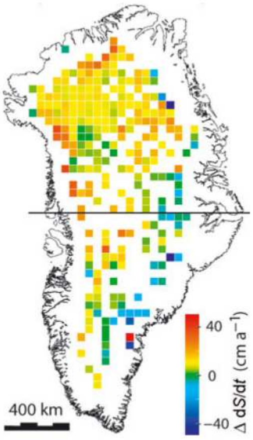
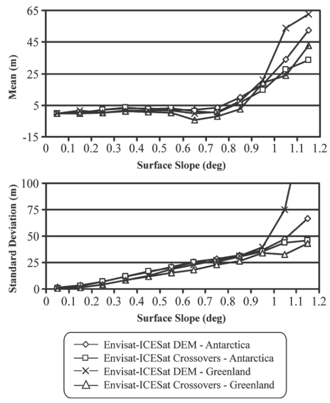
Ice Sheet Altimetry for Monitoring Mass Balance

Systematic differences between radar and laser altimetry

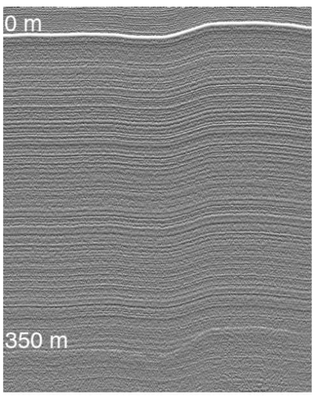


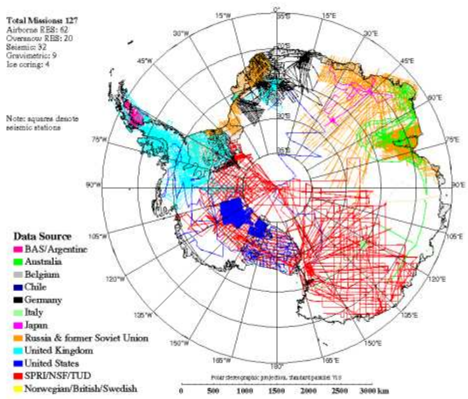


Differences in 1998/99-2003 elevation changes ERS2-GLAS/ATM

Envisat - IceSat DEM comparison
Brenner et al., 2007

Ice Sheet Dynamics - Sounding Basal Topography and Internal Layers





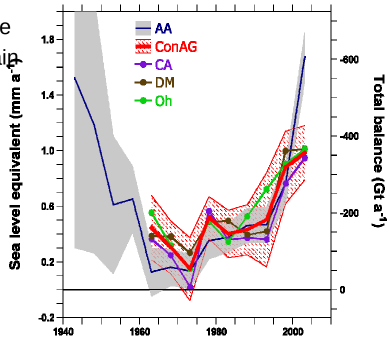
Internal ice layers by POLARIS (P-band) ice sounding measurements over Greenland *(Dall et al.)*

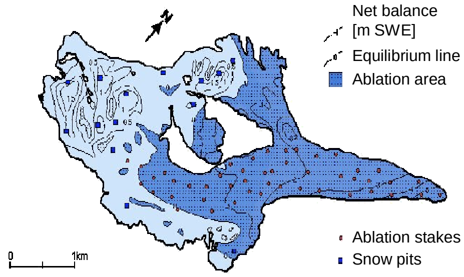
Flight lines for Antarctic bed elevation map (BEDMAP, BAS, 2001)

Glacier Mass Balance

- Essential climate variable, needed to quantify glacier response to atmospheric forcing and to predict climate impact on water supply
- Directly measured only on very few glaciers worldwide
- Global glacier mass balance models are very uncertain

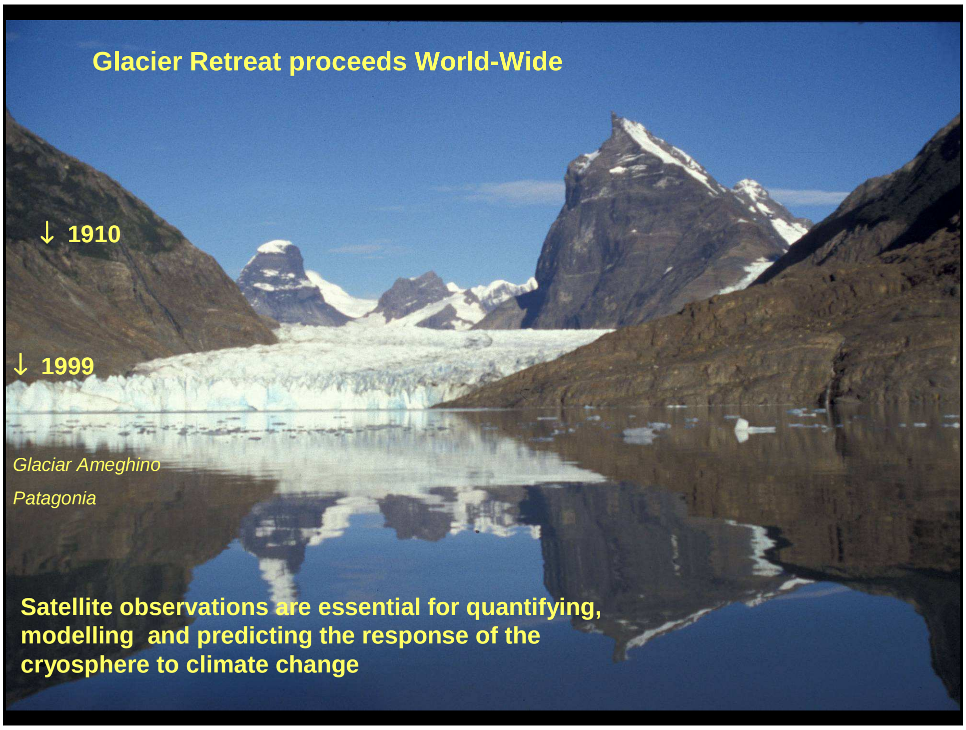
IPCC-2007 →





Field measurements of glacier mass balance 1994-95, Hintereisferner, Ötztal

TanDEM-X (DLR): Precise measurement of topography (→ volume changes)



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