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Application of satellite snow and ice measurements in NWP

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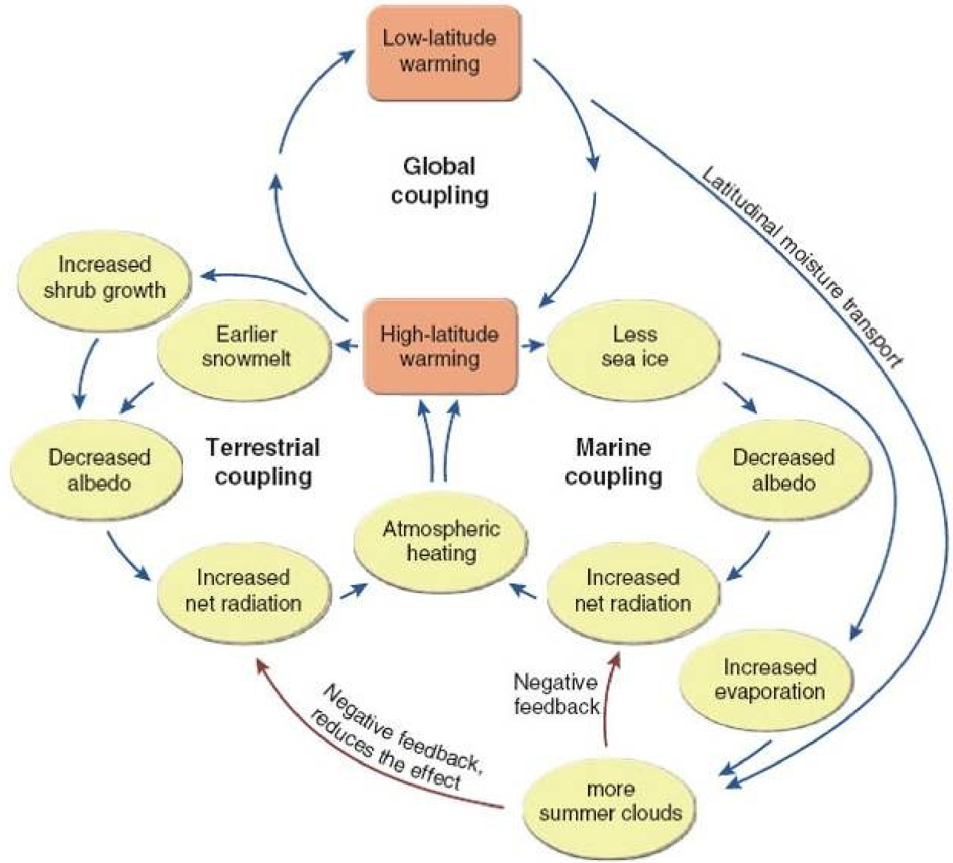
FMI, Arctic Research

Climate and water cycle at northern latitudes

Conceptual diagram on the connectivity of the positive ice/snow albedo feedback, terrestrial snow and vegetation feedbacks and the negative cloud/radiation feedback (From UNEP, 2007).



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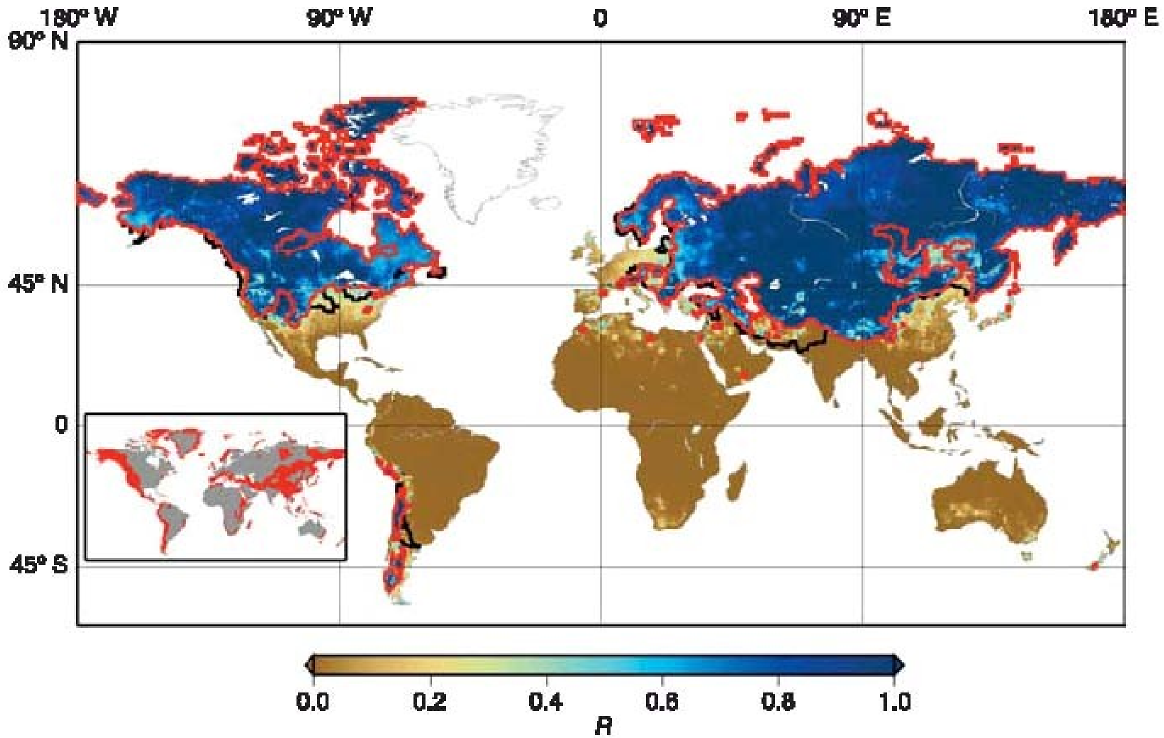
Significance of snow information for runoff

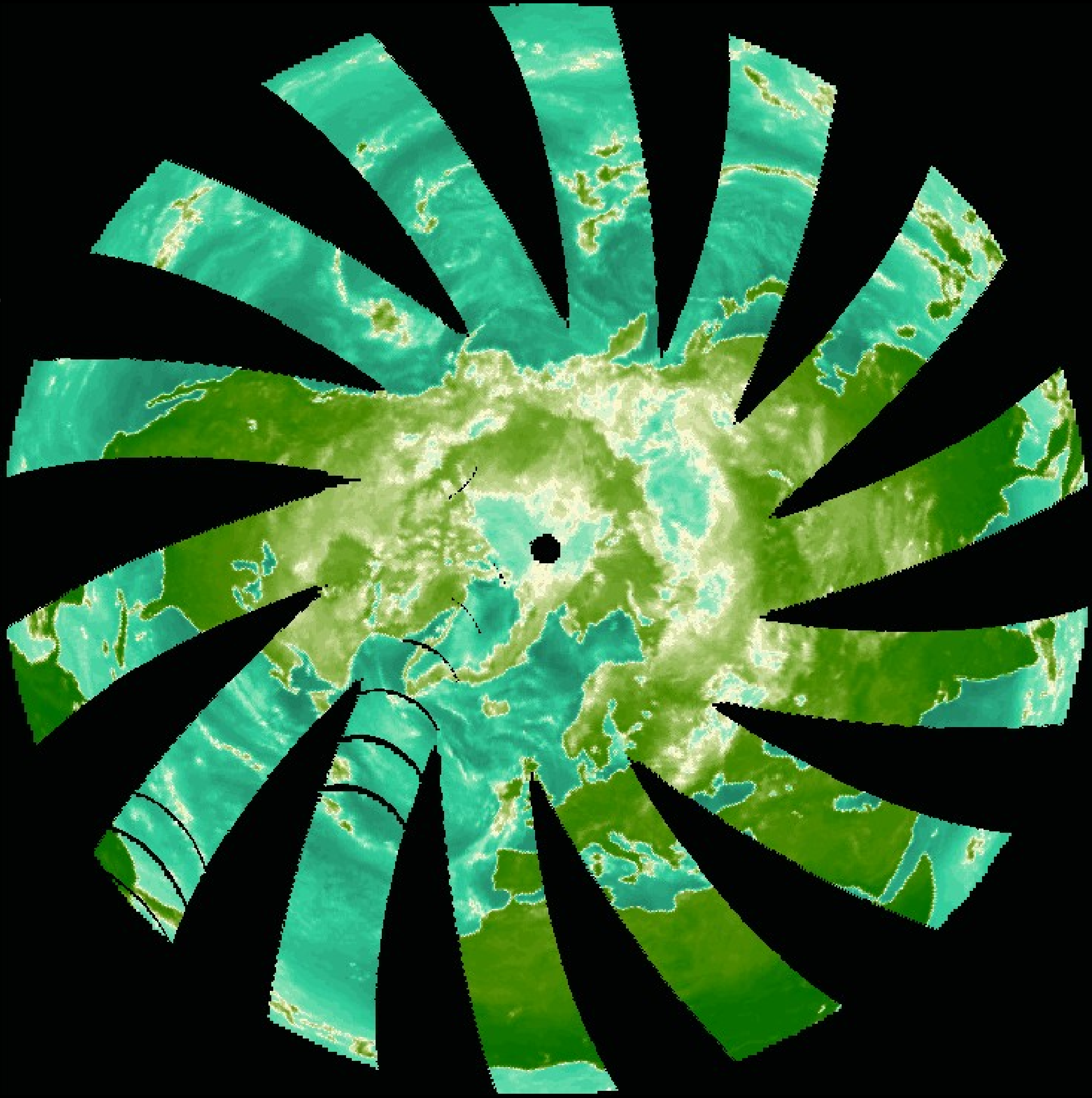
- **Accumulated annual snowfall divided by annual runoff (colour scaled between 0 and 1). Red lines: streamflow is snowmelt-dominated, no adequate reservoir storage capacity to buffer shifts in the seasonal hydrograph.**
- **Black lines: additional areas where water availability is dominantly influenced by snowmelt**
- **Inset: regions of the globe that have complex topography. (From Barnett et al., 2005).**



Background (I)

- Present satellites able to provide snow and ice observations on daily basis with full spatial coverage:
  - Snow extent and fractional coverage within pixel/calculation area (e.g. sub-drainage basin)
  - Snow water equivalent (SWE) and snow depth
  - Snow melt (on-set, snow clearance, patchiness during melt)
  - Lake ice information
  - Sea ice concentration
  - Ice types (winter-time navigation)
- Current feasible instruments applicable for global and regional monitoring
  - Microwave radiometers (SSM/I, AMSR-E, SMOS)
  - Microwave radars
    - High/moderate resolution SAR (Radarsat-2, Envisat ASAR)
  - Optical imagers (MODIS, AVHRR, MERIS)
    - Coverage limited by clouds

Ascending node SSM/I microwave radiometer observations of the northern hemisphere from a single winter day, 1.1. 1999 (37 GHz horizontal polarization)



Background (II)

- Satellites measuring Earth’s surface and atmosphere are only means of getting frequent spatial information on Essential Climate Variables (ECV) with a full coverage
  - However, the use has been limited until recently due to inaccuracies of satellite data retrievals
  - Assimilation and calibration schemes (e.g. combination with *in situ* data) has provided improved quality
- Assimilation to dynamic models
  - Operational assimilation of snow information to hydrological forecasting systems successfully implemented e.g. in Finland

    => providing improved discharge forecasts
  - Same approaches can be applied to numerical weather prediction

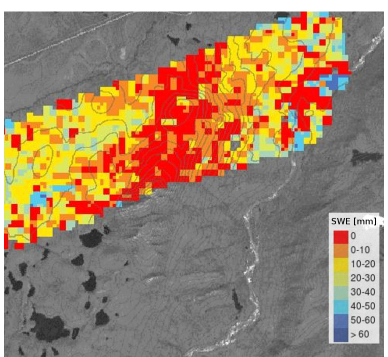
Example on assimilation of satellite data retrievals to dynamic models

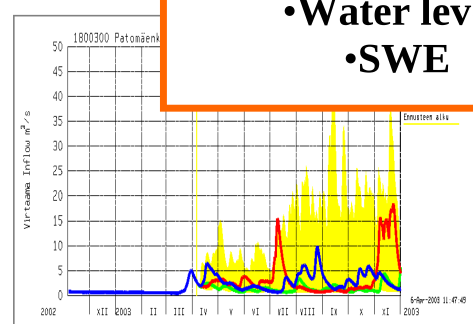
SWE from satellite data

Hydrological model

Model input:
SWE
Iterate precipitation and temperature

Model output:
- **Discharge**
- **Water level**
- **SWE**





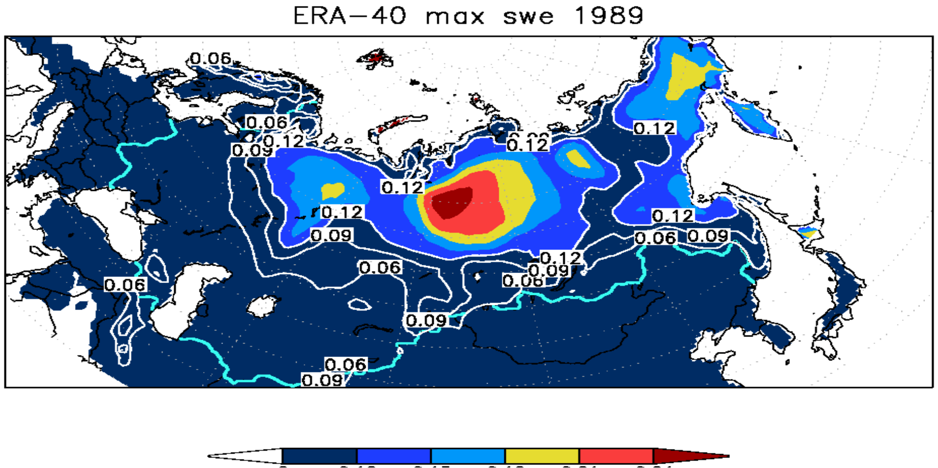
Drawbacks of current snow information

- Interpolation of weather station or snow course data
  - Dense weather station observations only available for some countries (e.g. Finland), sparse networks especially in north of Eurasia and North America
  - Single point measurements typically in open areas (e.g. vicinity of airfields) => systematic errors possible
  - Problems due to topography in mountain regions
  - Snow course observations typically rare
- Re-analysis data
  - Models may suggest false predictions

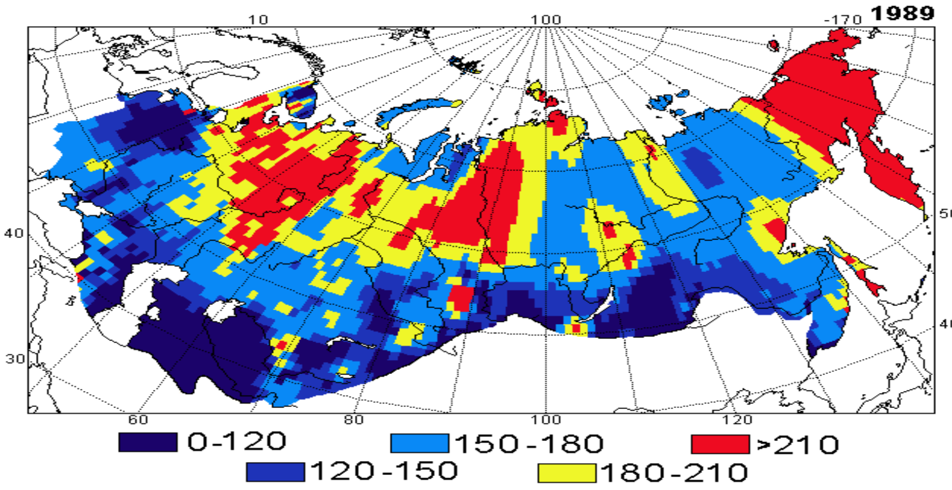
Deficits of re-analysis data and ground data interpolation

- ERA-40 re-analysis data of ECMWF:
  - Maximum SWE in 1989

  (SWE = snow water equivalent indicating the total amount of snow)



- Corresponding INTAS-SCCONE Russian ground based observations (SWE from 210 snow courses around northern Eurasia)



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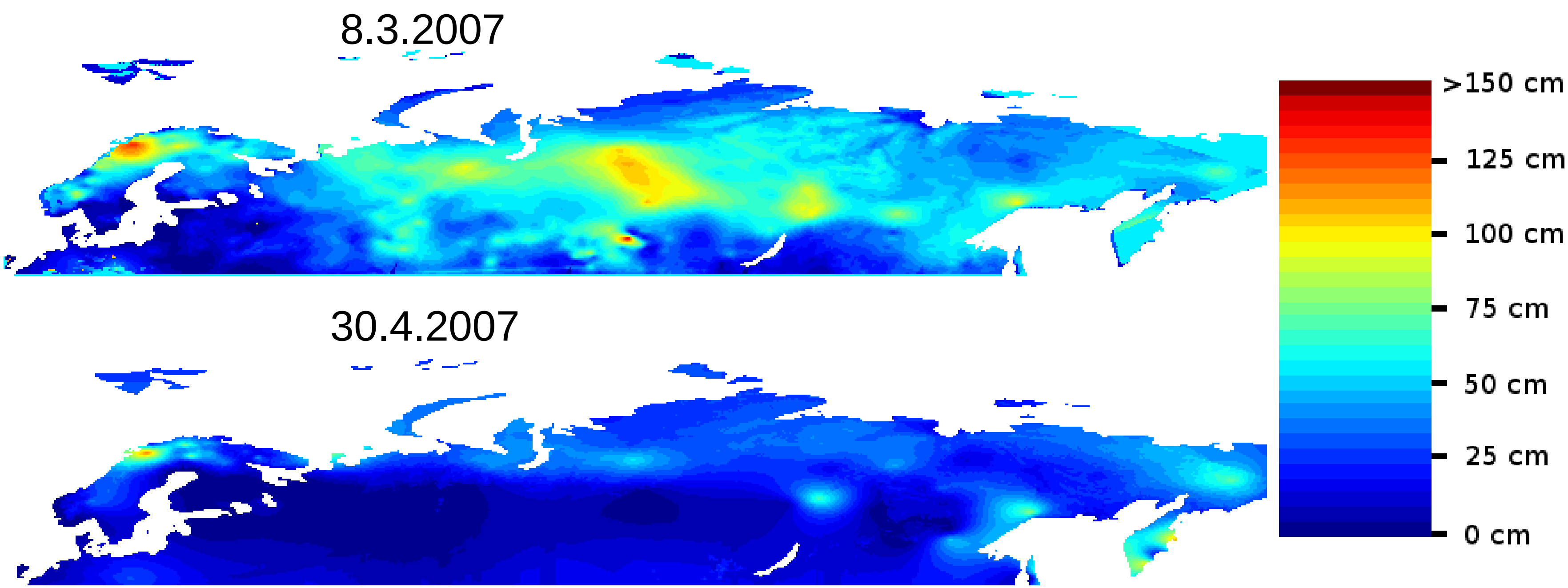
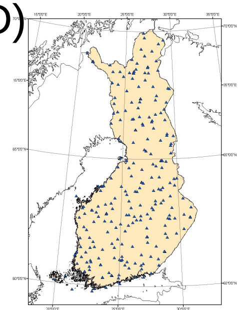
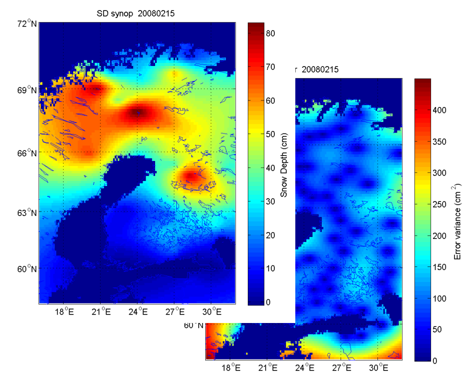
Current ESA GMES PolarView Service of FMI: Northern Eurasian Snow Monitoring

- Snow Water Equivalent (SWE) and Snow Depth by assimilating AMSR-E microwave radiometer and synoptic weather station data
- Production of bi-weekly 30-year ECV time-series on SWE currently ongoing in ESA GlobSnow project



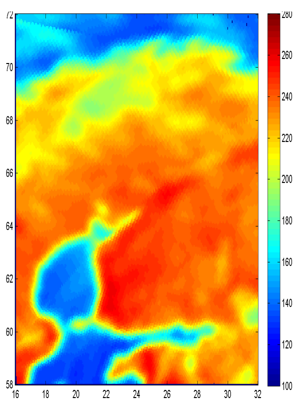
(2) Weather station obs. (SD)

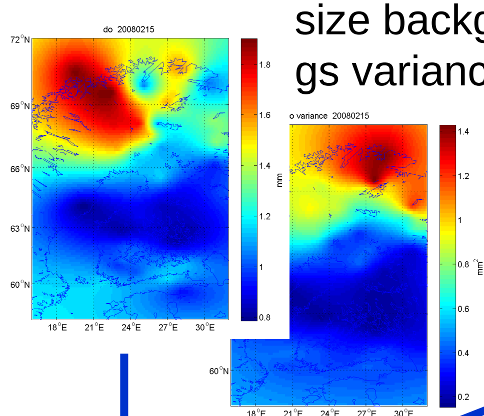




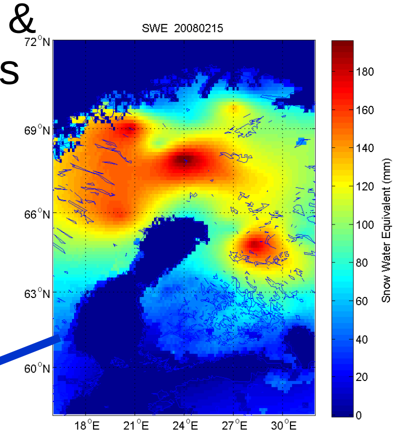
(4) Kriged SD & SD variance maps

(1) Satellite observation

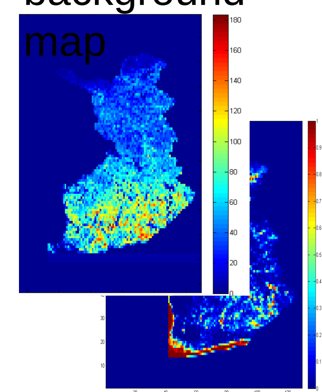




(3) Kriged grain size background & gs variance maps



(5) Vegetation background map



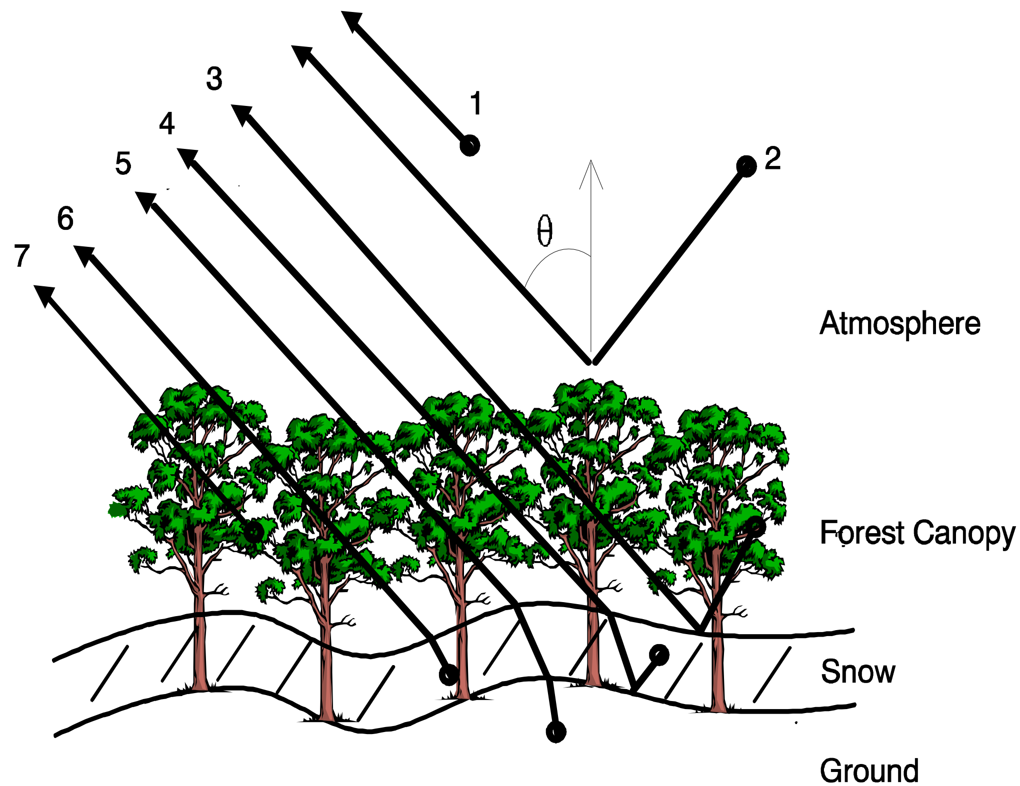
HUT emission model applied

SD/SWE

(6) Other data (e.g. lake fraction)

HUT snow emission model

- Background of the applied model
  - Semi-empirical model simple enough to be used for parameter retrieval from space-borne or airborne data (e.g. by statistical inversion)
- Basic characteristics
  - scalar radiative transfer model for single snow layer
  - semi-empirical formulas for snow permittivity and extinction coefficient
  - empirical coefficient for radiation contribution scattered in snow layer
  - incoherent approach used for medium boundary effects
  - soil-snow reflectivity by empirical soil emission models
  - empirical formulas for atmospheric and forest cover effect



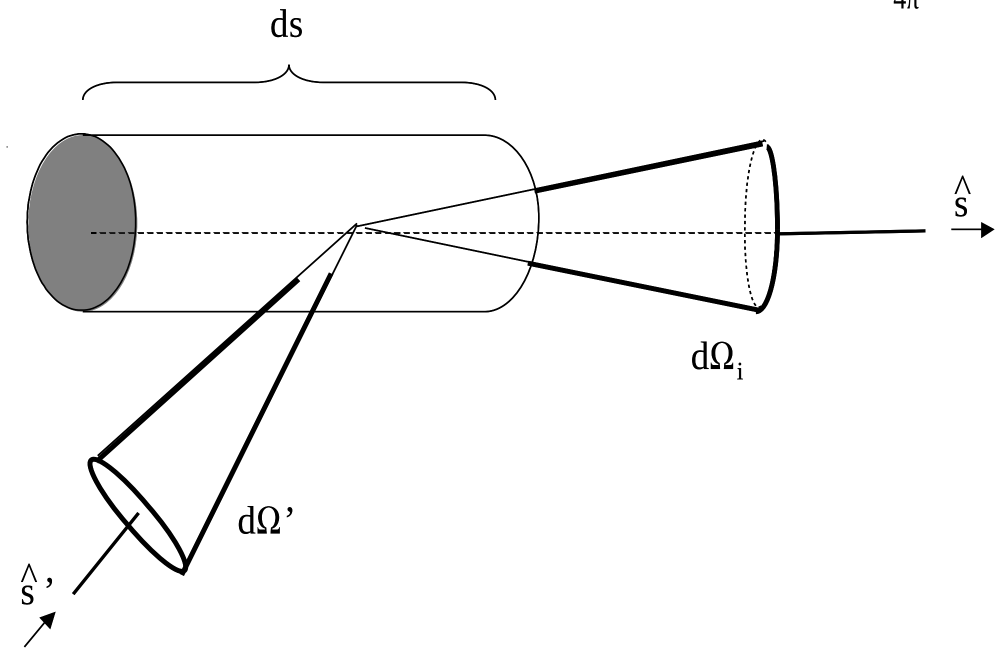
Model principle:

- **Attenuation of radiance**

$$\frac{dL(r,\hat{s})}{ds}\bigg|_{\text{vaimennus}} = -(\kappa_a + \kappa_s)L(r,\hat{s})$$

- **Increase of radiance due to scatter**

$$\frac{L_s(r,\hat{s})}{ds} = \int_{4\pi} \frac{N_v}{V} |f(\hat{s},\hat{s}')|^2 L(r,\hat{s}') d\Omega'$$



$$\frac{N_v}{V} = \rho$$

- And when the emission from a volume unit is: $\kappa_a J(r,\hat{s})ds$

the general formula of the radiative transfer equation is obtained:

$$\frac{dL(r,\hat{s})}{ds} = -(\kappa_a + \kappa_s)L(r,\hat{s}) + L_s(r,\hat{s}) + \kappa_a J(r,\hat{s})$$

$$= -(\kappa_a + \kappa_s)L(r,\hat{s}) \;+\; \int_{4\pi} \rho \left|f(\hat{s},\hat{s}')\right|^2 L((r,\hat{s}')d\Omega' \;+\; \kappa_a J(r,\hat{s})$$

$$\Leftrightarrow$$

$$\frac{dL(r,\hat{s})}{ds} = -\kappa_e L(r,\hat{s}) \;+ \frac{\kappa_s}{4\pi}\int_{4\pi} \frac{4\pi\left|f(\hat{s},\hat{s}')\right|^2}{\sigma_s} L(r,\hat{s}')d\Omega' \;+\; \kappa_a J(r,\hat{s})$$

GlobSnow: An Overview

❖ ESA DUE GlobSnow

- Global products on Snow Water Equivalent (SWE) and Snow Extent (SE) for climate research
  - Fundamental Climate Data Record (FCDR) aiming for ECV-record
- Team including Finnish, Austrian, Swiss, Norwegian and Canadian partners

ESA GlobSnow (2008 – 2011)

- Production of new global snow extent (SE) and snow water equivalent (SWE) climate data records, with a demonstration of a near-real-time processing capability.

- Consortium led by the Finnish Meteorological Institute (FMI) with collaborators: ENVEO IT (Austria), GAMMA Remote Sensing (Switzerland), Norwegian Computing Center (NR), Finnish Environment Institute (SYKE), Environment Canada and Norut (Norway).

- Project details including technical reports and newsletters available at globsnow.fmi.fi.

Products and Database

- **The selection of features and details of the SE and SWE products will be made based on the outcome of this Workshop**
  - Aggregation of daily products
    - Potentially e.g. monthly averages, weekly averages and sliding averages
  - Meta-data
  - Accuracy characteristics will be delivered for both products
    - Pixel-wise temporally changing statistical accuracies already available for the SWE product (error maps concurrent with SWE maps)
    - Additionally, evaluation of accuracies against independent reference data (both products): snow courses, station observations and high resolution reference images
- **30-year-long SWE and 15-year-long SE datasets will be made publicly available for the climate research community (FCDR)**
- **Demonstration of near-real-time product delivery**

Coverage of products

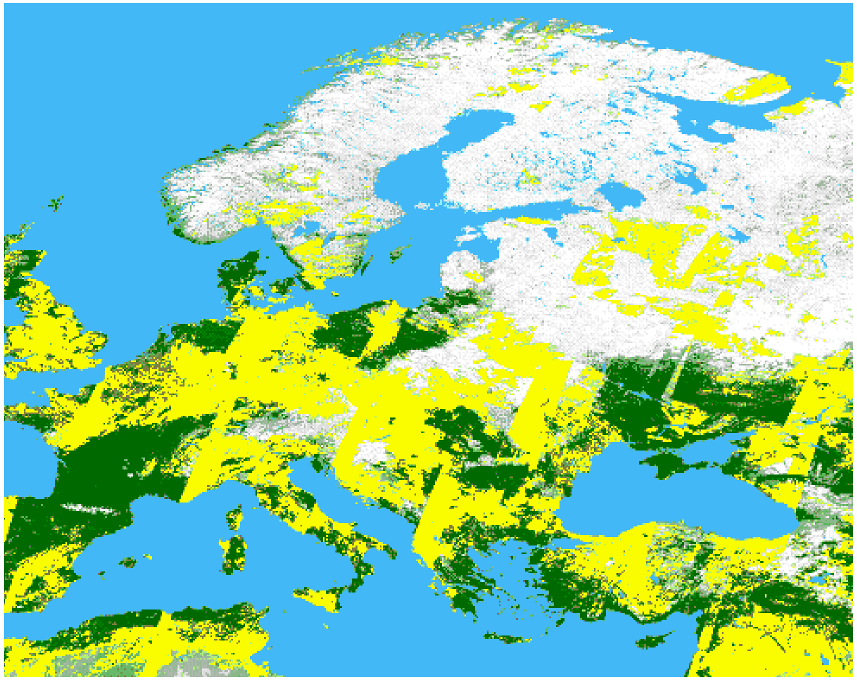
- **SWE**
  - Northern hemisphere, 35°- 85° (SWE for dry snow-covered non-alpine regions)
  - First demonstrations and protype data sets made for the whole region
- **SE**
  - Snow regions of both hemispheres:
    - 35° - 85° in northern hemisphere
    - Snowy mountain regions of southern hemisphere
  - Prototype dataset provided for the pan-European test region

Use of GlobSnow Products

- **Potential of products for different climate research applications**
  - Reference for climate models (model development and validation)
  - Input data for spatially distributed environmental/atmospheric process models
  - Climate trend analyses
    - As in case of climate model analyses, typically time-series from 25 to 30 years are required as the minimum
- **Daily demonstration product can be applied for NWP and hydrological forecasting**

GlobSnow SE Product

- Snow Extent based on optical ATSR (1995-) and AATSR (2002-)
- Two main techniques selected:
  - SCAmod algorithm for FSC by SYKE applicable to non-mountainous regions (including forested areas)
  - Norwegian Linear Reflectance (NLR) algorithm by NR for fractional snow cover (FSC) at mountain areas
- New features:
  - Improved accuracy for forested regions compared with current algorithms (e.g. NASA MODIS)
  - Enables longer time-series than MODIS
  - Enables higher performance than AVHRR (most AVHRR sensors do not include the 1.6 μm channel)
- Operational near real time service will be demonstrated during 2010/2011.



yellow – clouds
green – bare ground
white – snow cover

GlobSnow AATSR daily product (Fractional Snow coverage)

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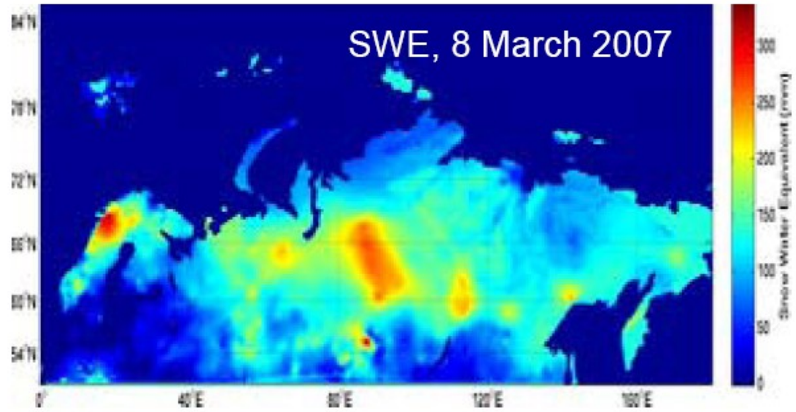
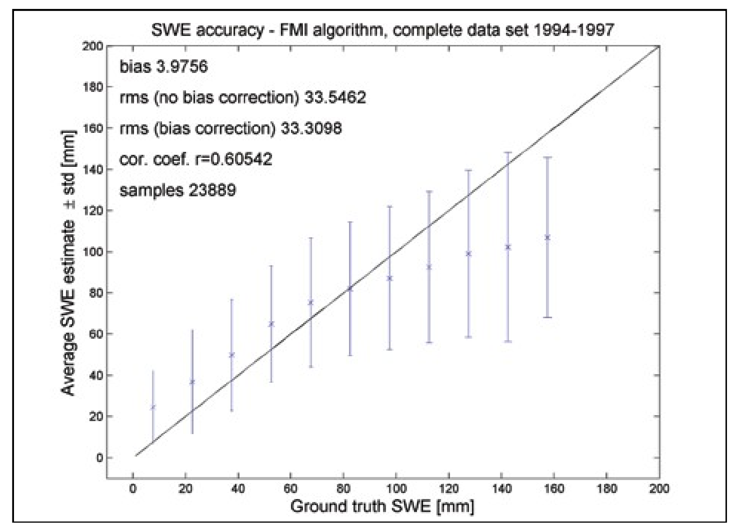
GlobSnow SWE Product

- Proposed approach: Assimilation of satellite data with *in situ* observations-derived bckground field on snow depth.
  - Only approach utilizing passive microwave radiometer observation providing sufficient accuracy level on a global scale
- Statistical error estimate produced for each grid cell.
- SWE retrievals for all terrestrial snow regions of northern hemisphere excluding alpine regions and glaciers.
- Time series extending from 1978 to present:
  - Full coverage for dry snow cover areas (combined mapping of melting regions)
  - Daily estimates calculated (aggregated to more practical end-products)
- Operational near-real-time service will be demonstrated during 2010/2011.

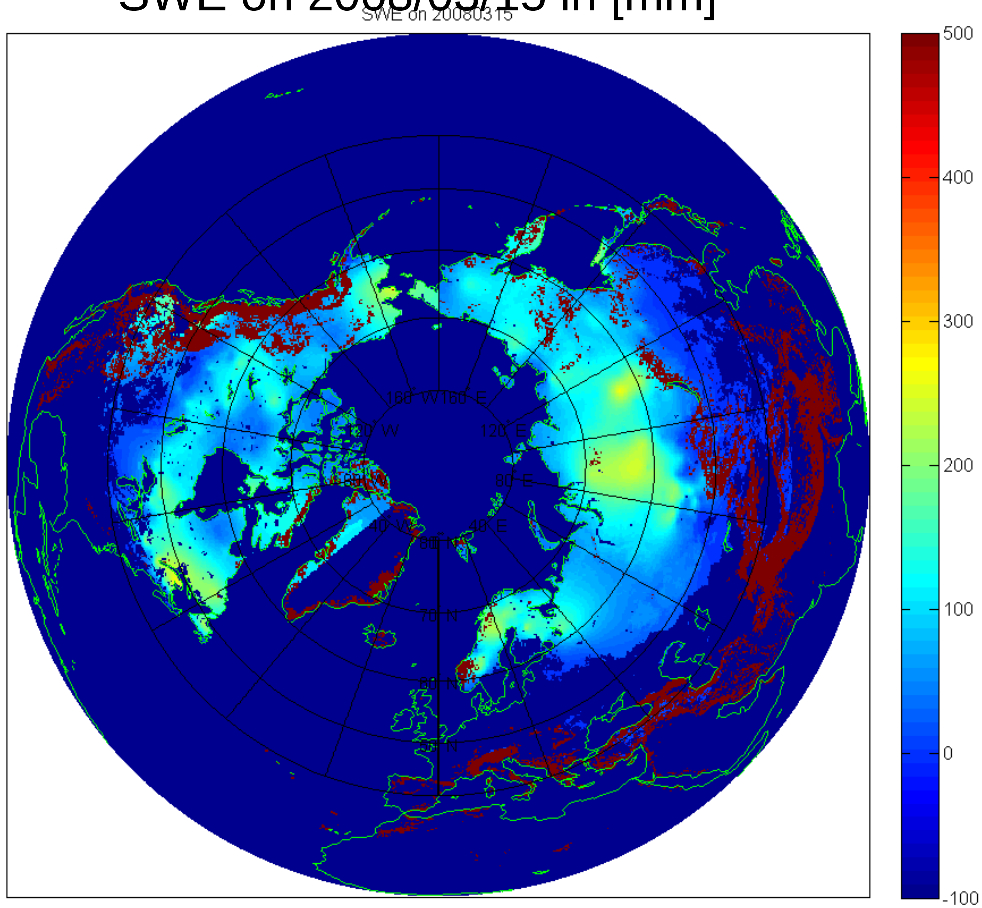




Prototype of Final SWE Product

- Daily maps of hemispherical snow cover:
  - Total snow area
    - Permanent sesonal snow cover
  - SWE for the snow area
- Regions with high topograpical variability are masked off
  - Alpine regions
  - Glaciers will be also masked
- NRT production of SWE will be demonstrated in 2010-2011

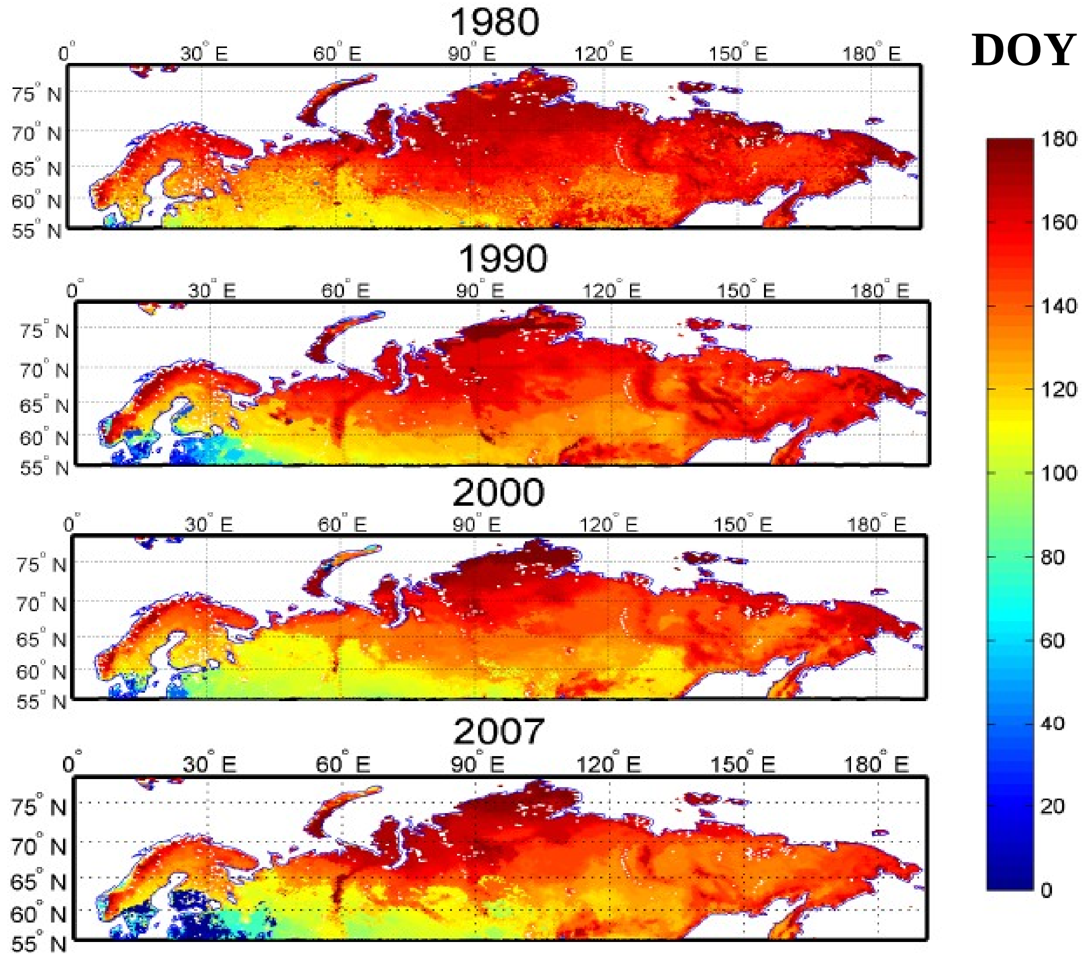
SWE on 2008/03/15 in [mm]



Snow Melt Estimated from Radiometer Data

- Analysis of time-series of satellite data (change of emissivity due to the snow melt)
- Calibration here against ground-based observations at ~200 stations

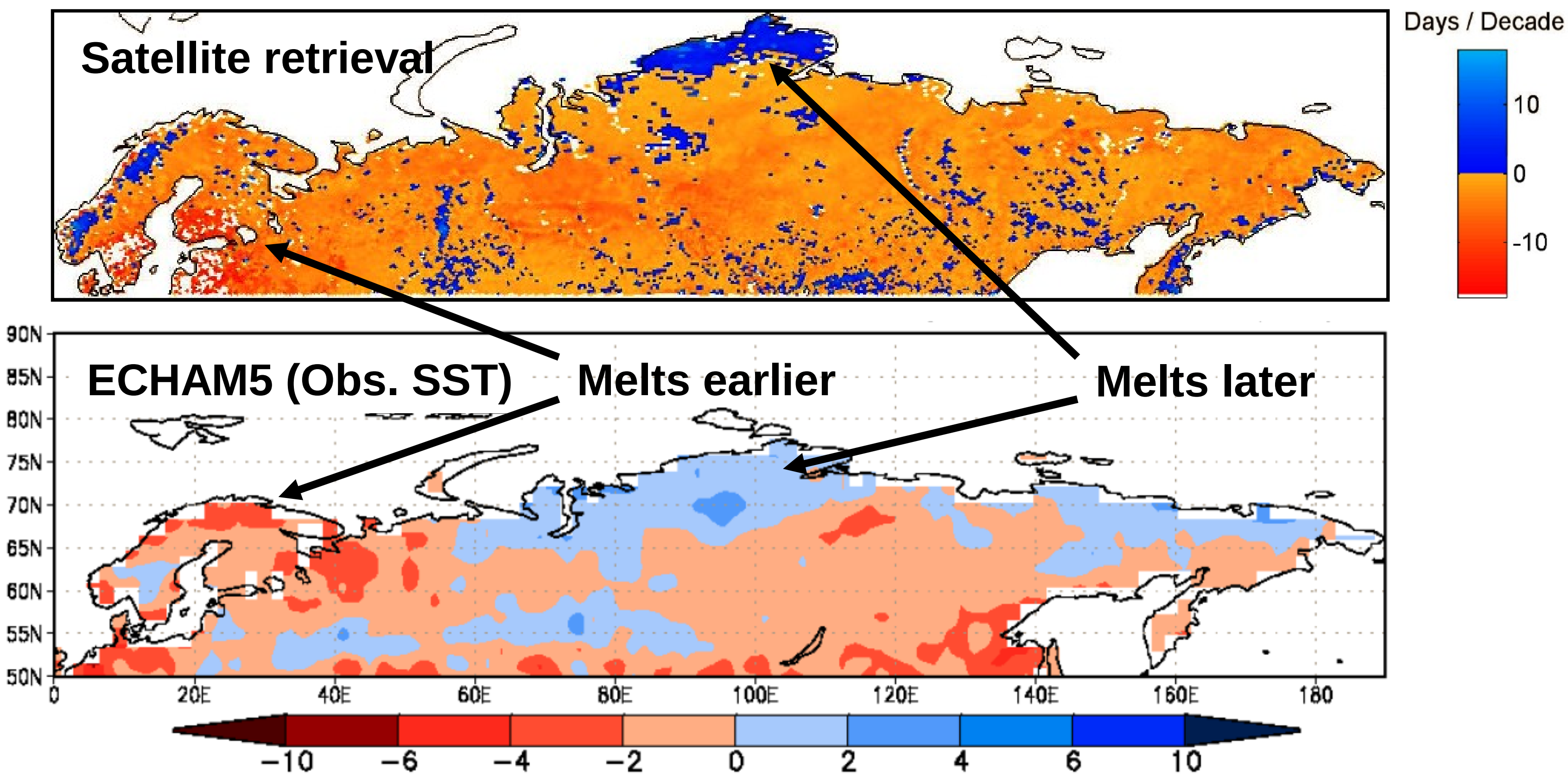
Reference:
Takala, M., Pulliainen, J., Metsämäki, S., and Koskinen, J. (2009), Detection of snow melt using spaceborne microwave radiometer data in Eurasia from 1979-2007. *IEEE Transactions on Geoscience and Remote Sensing*, 47: 2996-3007.



The color code is the number of the melt date since January 1.

Example on Trend Analysis

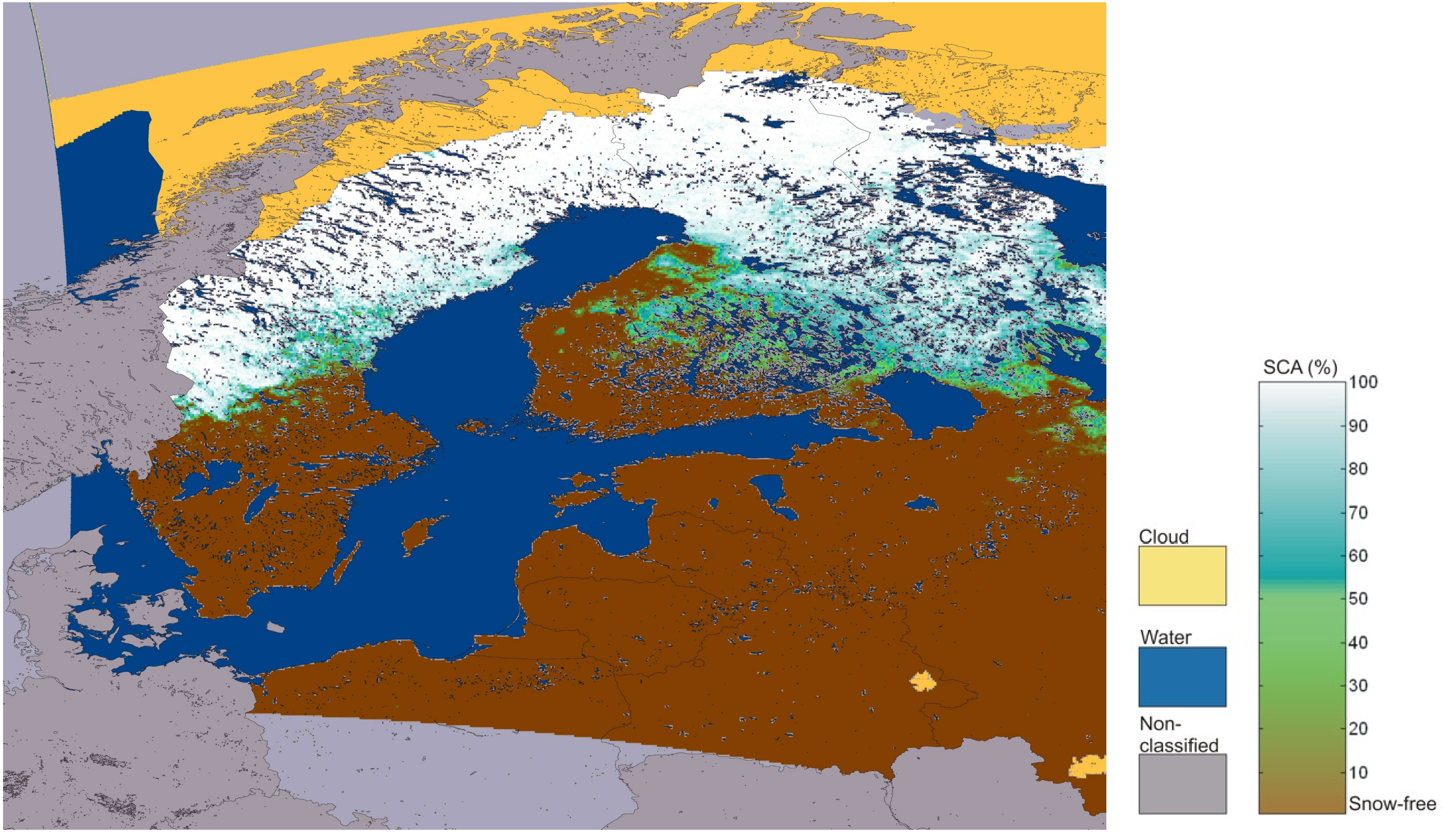
Change in snow clearance date in days/decade



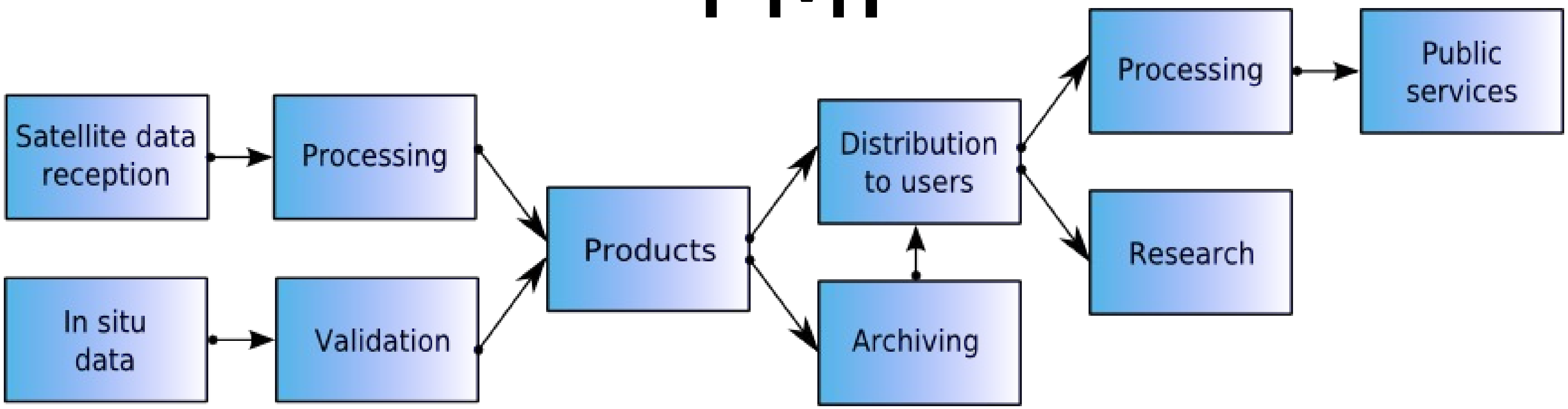
SCAmod-method for Fraction of Snow Cover (FSC) estimation

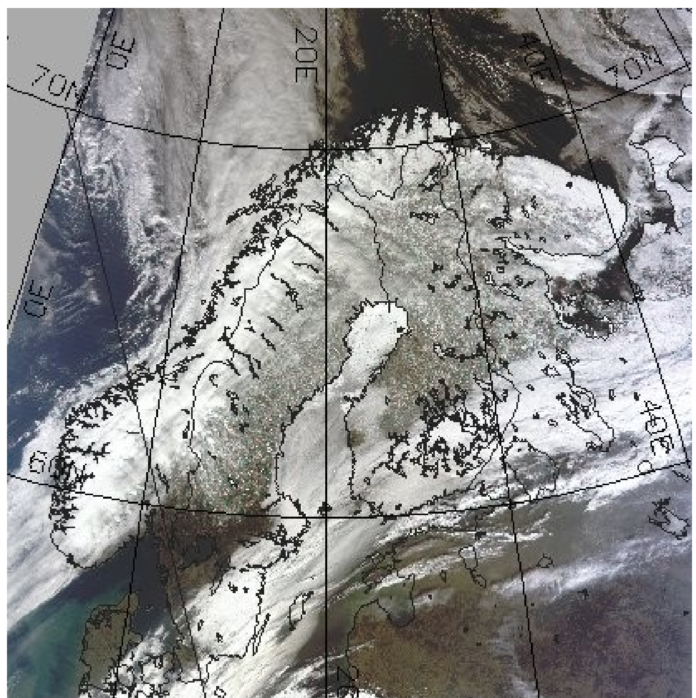
- Based on a reflectance model with three major reflectance contributors (snow, forest canopy, snow-free ground)
- An average forest transmissivity must be known for each calculation unit area (estimated from EO-data using SYKE’s model)
- No land cover data is needed (except water mask)
- Method usable for a variety of optical instruments

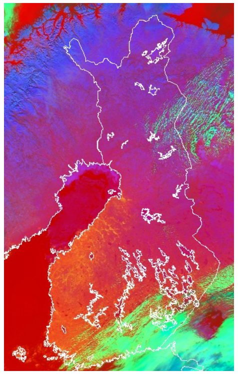
SCA in Baltic region from MODIS data: 28 March 2007 by operational SYKE SCAmod



NRT-satellite operations by FMI

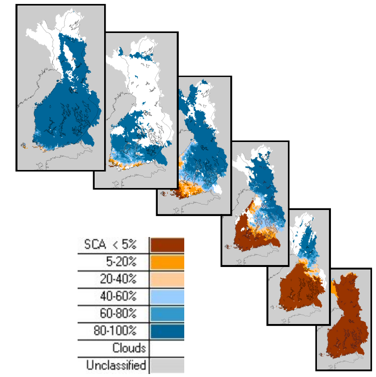






Reflectance model:

SCA for each basin



hydrological model

SCA

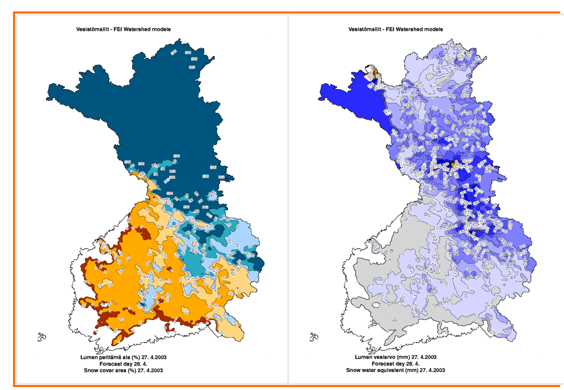
Model input:

•Precipitation
•Temperature

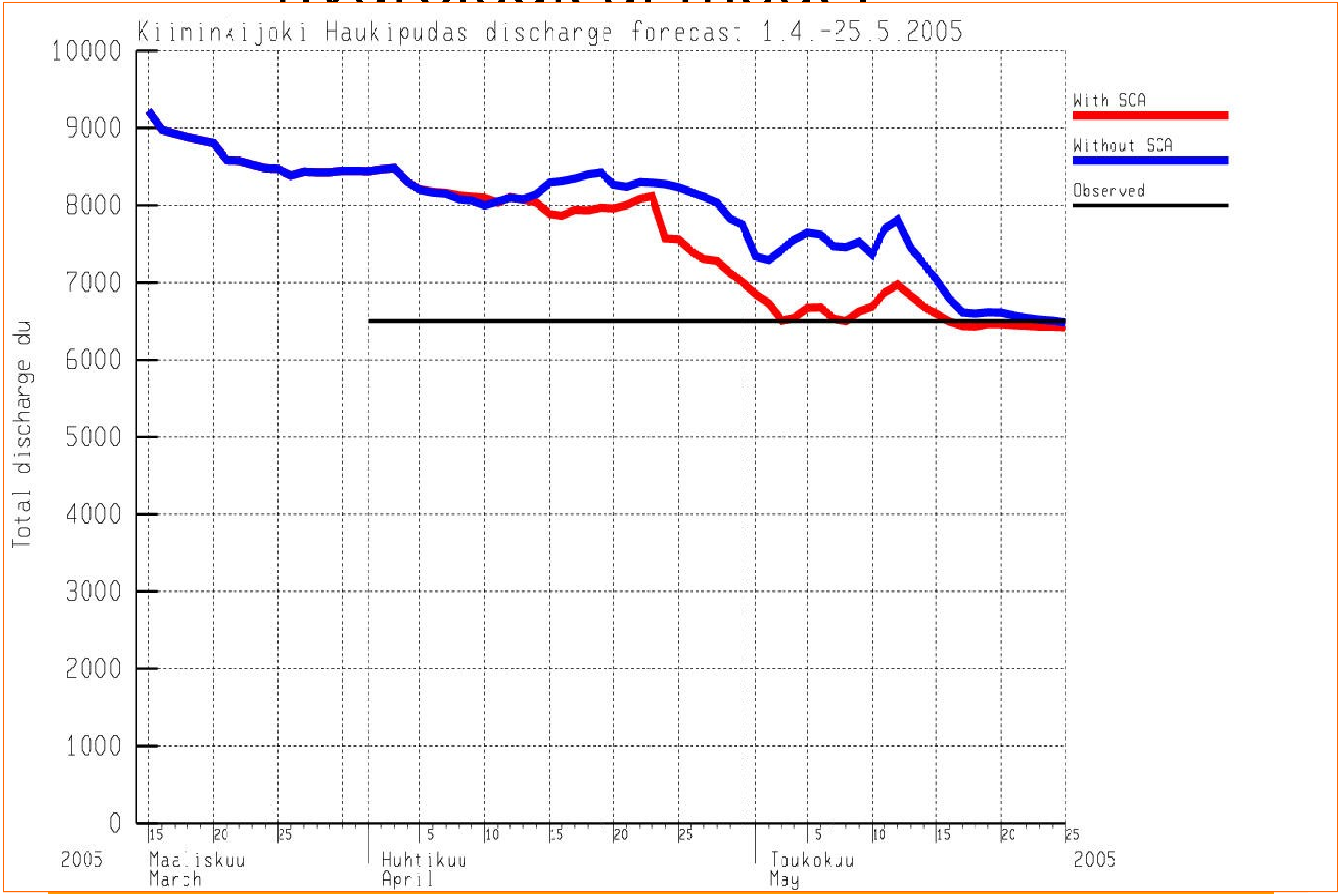
Snow CoveredArea

Field observations:

•Discharge
•Water level
•SWE



SCA data assimilated to hydrological model



Reflectance model

$$\rho(SCA) = (1 - t^2) * \rho_{forest} + t^2 \left[SCA * \rho_{snow} + (1 - SCA) * \rho_{ground} \right]$$

$$SCA_i = \frac{\frac{1}{\hat{t}_i^2} * \rho(SCA) + \left(1 - \frac{1}{\hat{t}_i^2}\right) * \rho_{forest} - \rho_{ground}}{\rho_{snow} - \rho_{ground}}$$

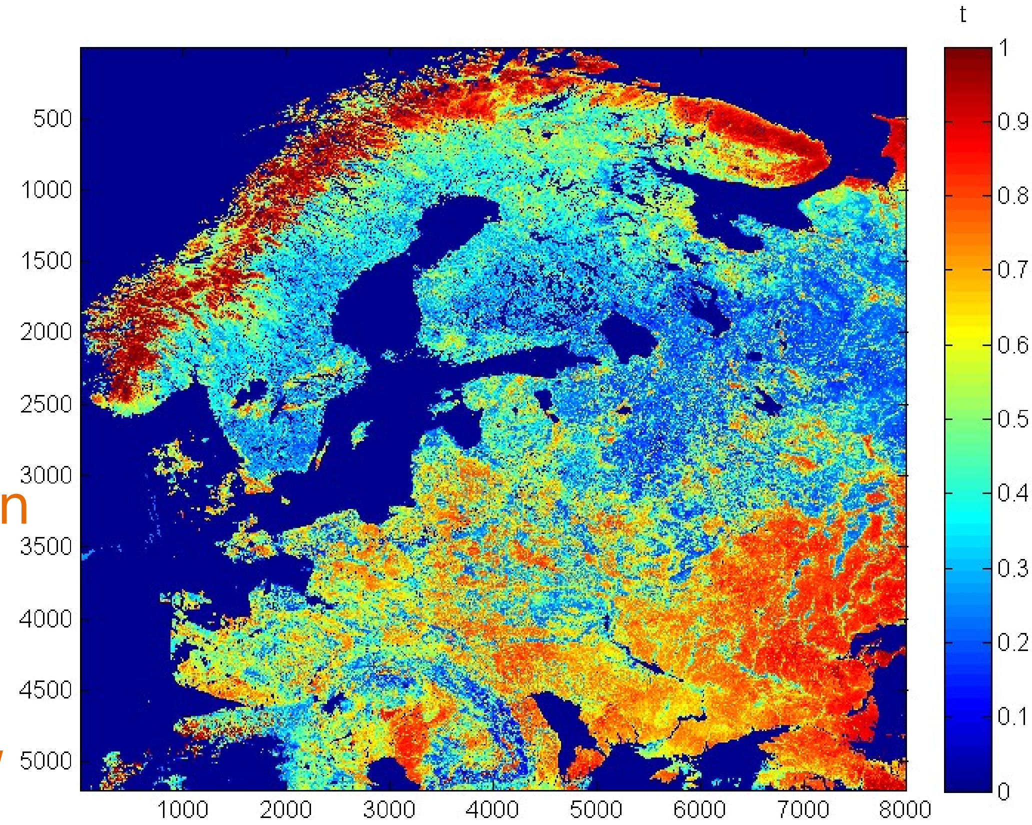
$\rho(SCA)$	observed reflectance from unit ar
ρ_{snow}	reflectance for wet snow
ρ_{ground}	reflectance for snow-free ground
ρ_{forest}	reflectance for forest canopy
t	forest canopy transmissivity for u
SCA	fraction of snow covered area

Forest transmissivity

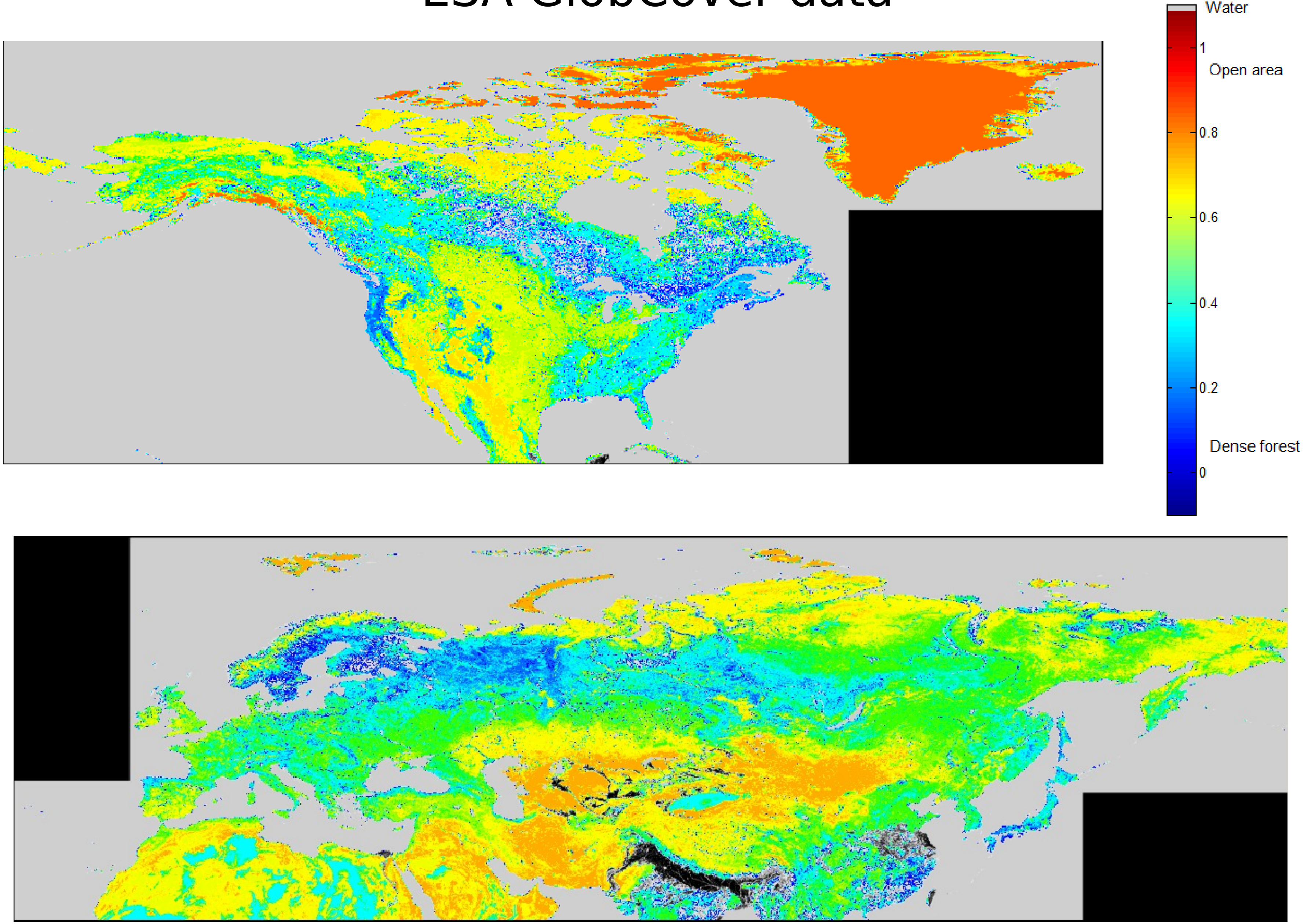
Forest transmissivity map for 0.01°×0.01° grid:

$$\hat{t}^2 = \frac{\rho(SCA=100) - \rho_{forest}}{\rho_{snow} - \rho_{forest}}$$

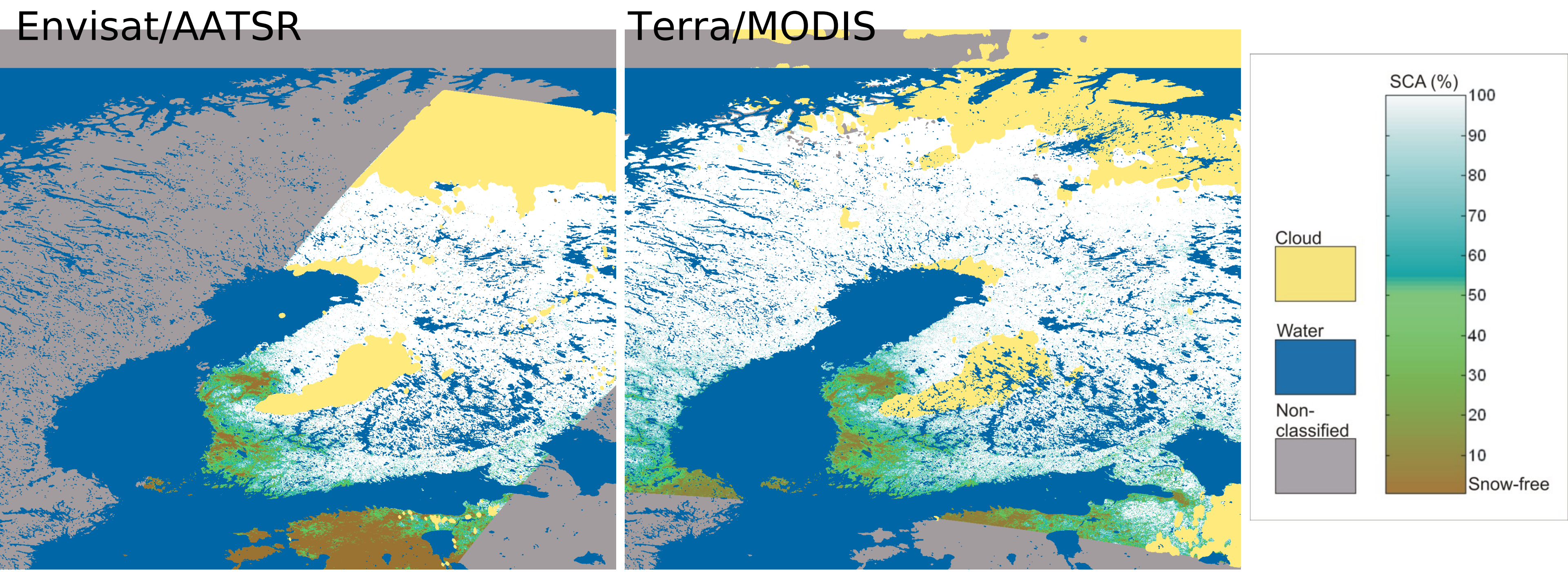
- How much the canopy blocks the two-way radiation
- Calculated for each cell using optical data at full dry snow cover conditions
- Nodata for areas without seasonal snow coverage



Northern Hemispherie transmissivity generated from ESA GlobCover data



Fractional Snow Cover maps by *SCAmod*

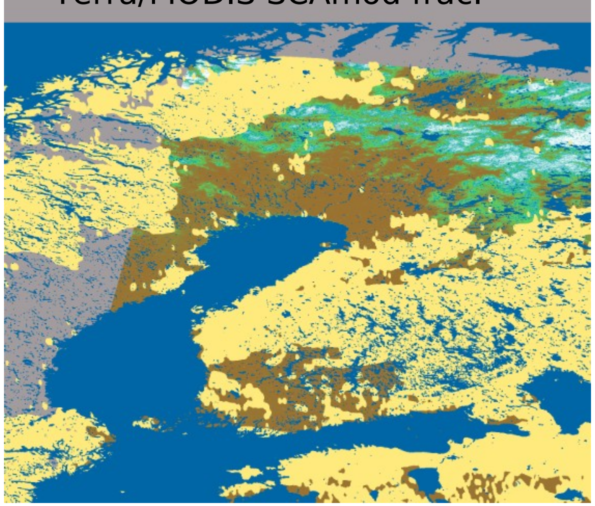


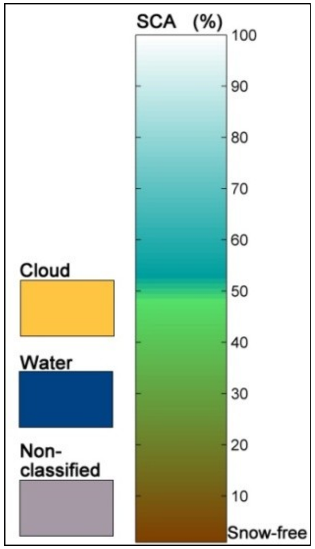
SYKE *SCAmod*-method: examples of
Fractional snow cover maps on April 2, 2004

SYKE

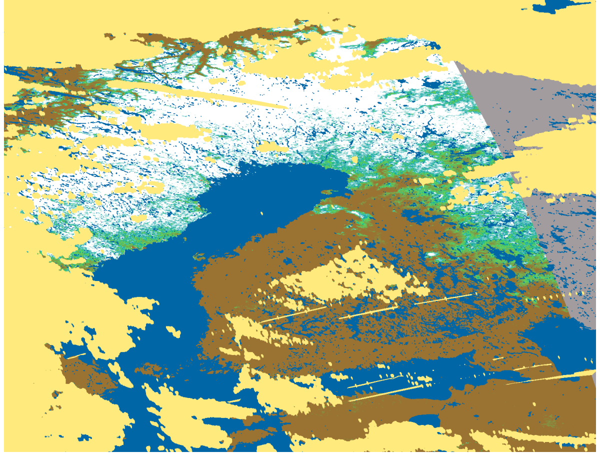
Examples of Snowmaps by different optical sensors and algorithms

Terra/MODIS SCAmod frac.

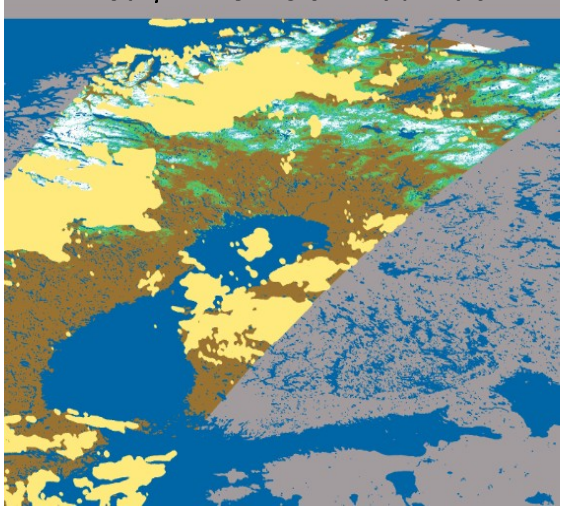




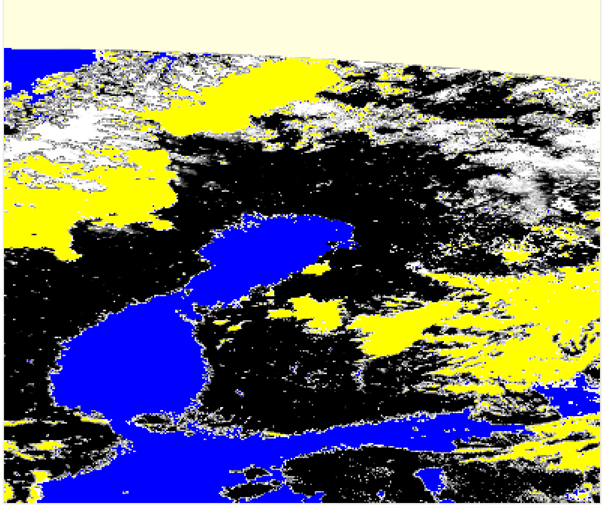
NOAA/AVHRR SCAmod fractional



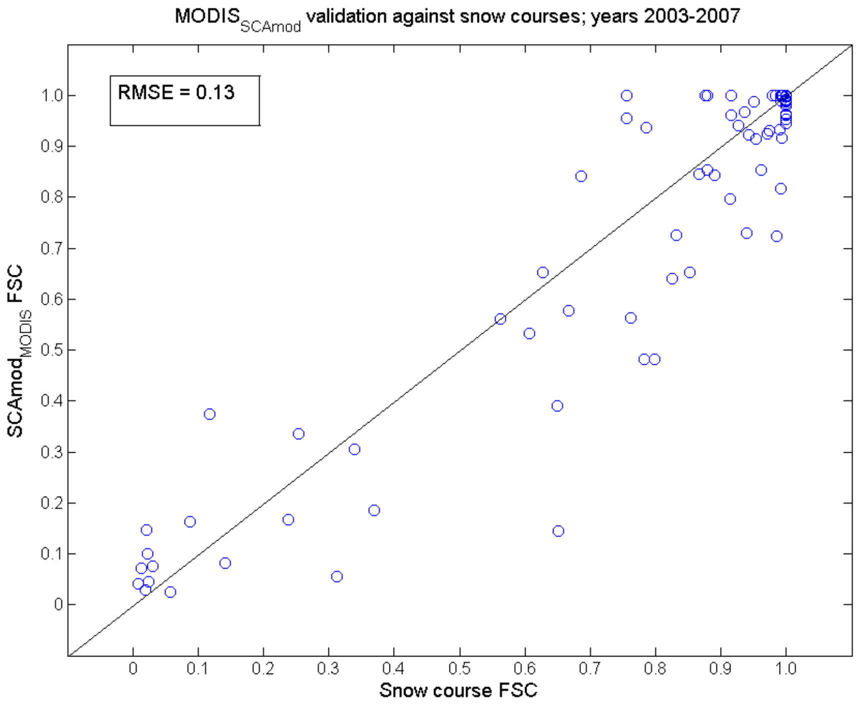
Envisat/AATSR SCAmod frac.

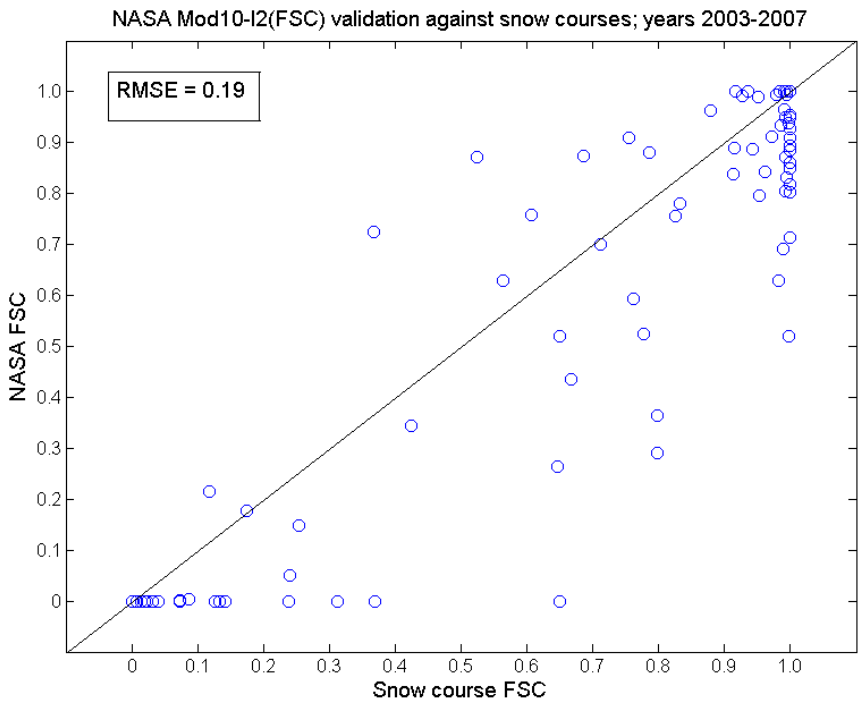


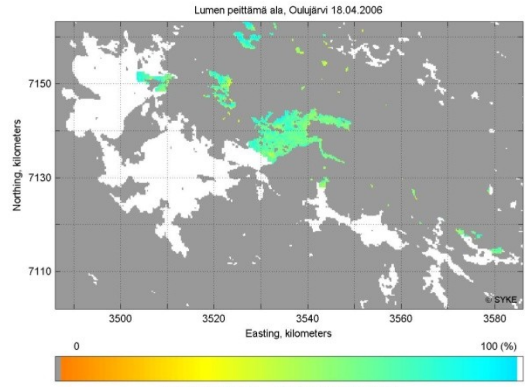
NASA Fractional

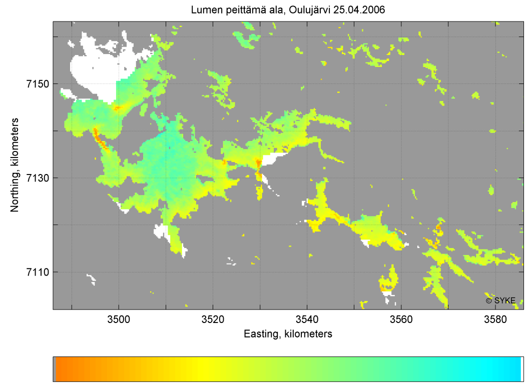


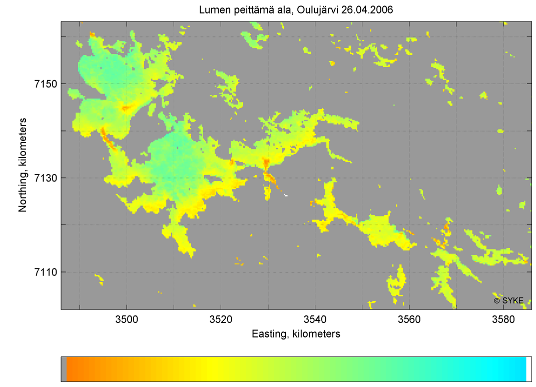
FSC validation against ground truth (snow courses)

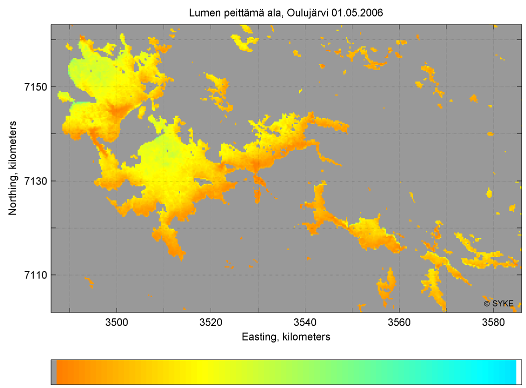


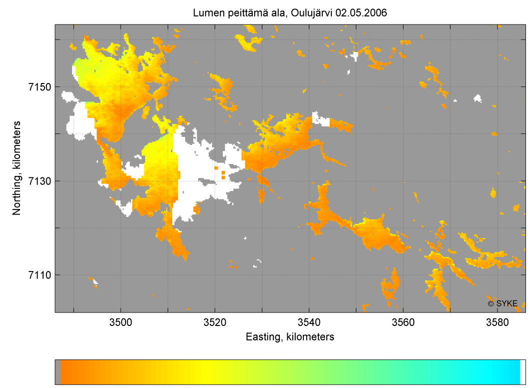


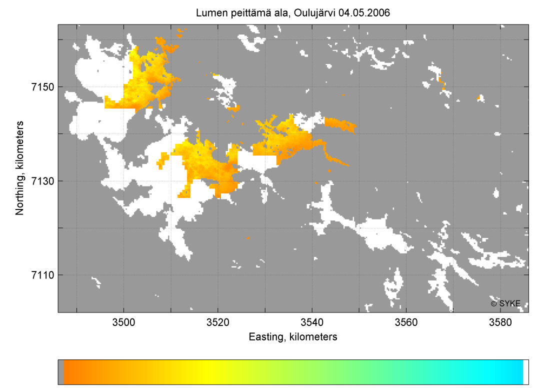


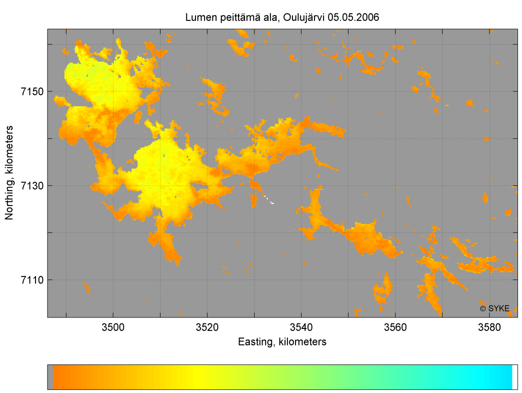


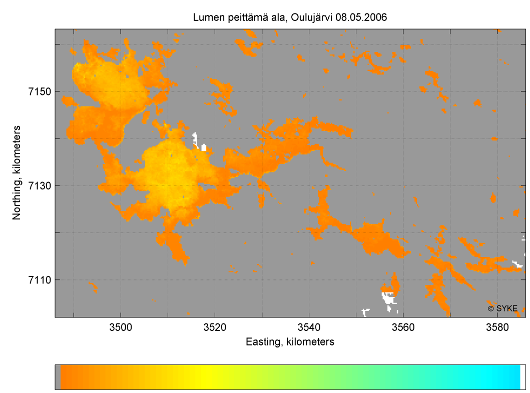






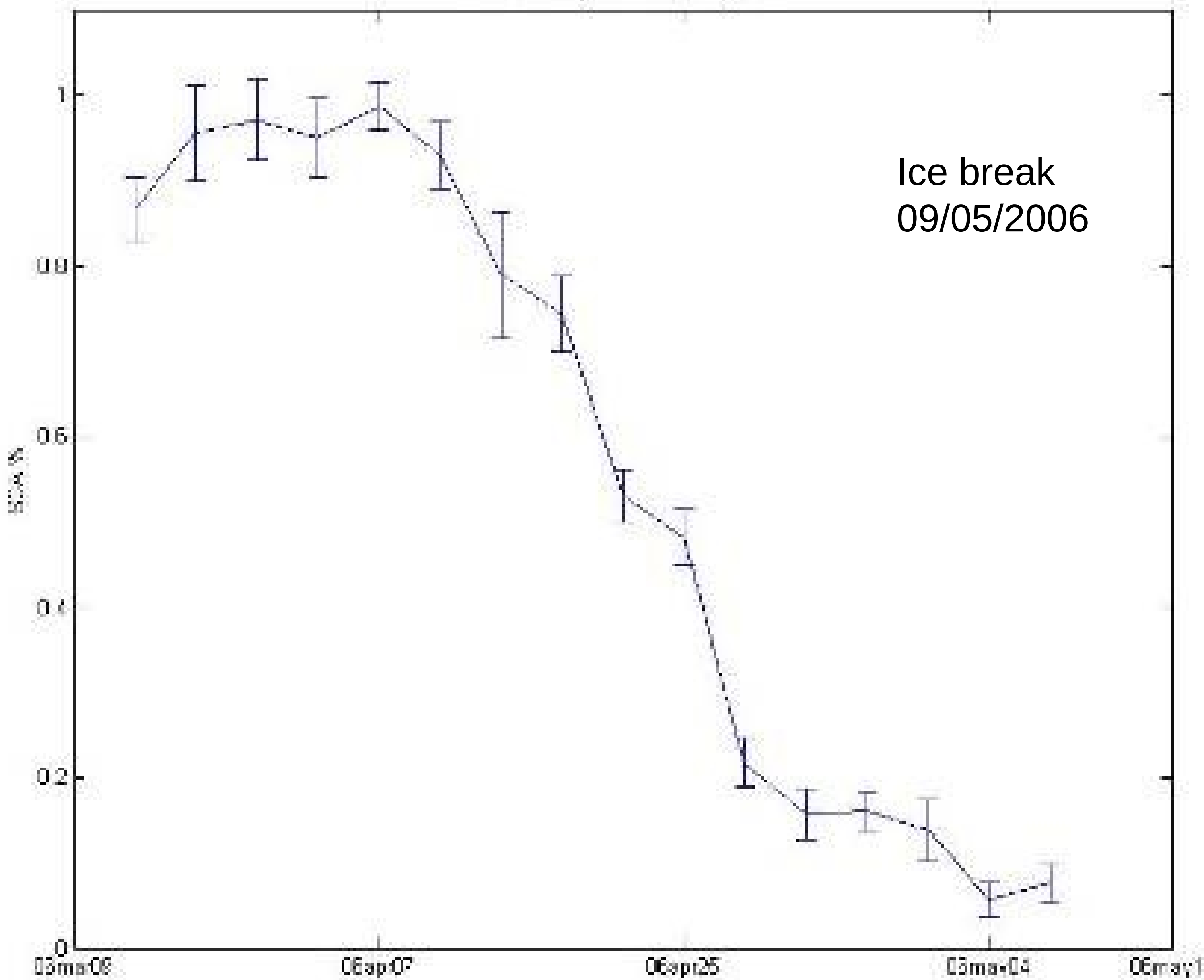




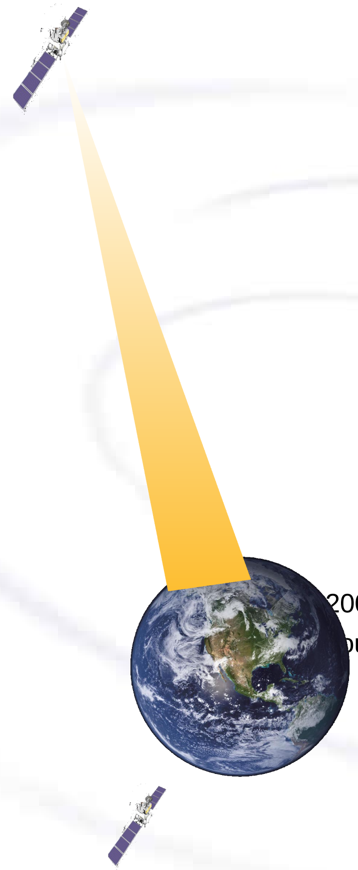


Lake Oulujärvi 2006

Average Sol% Lake Oulujärvi 2006

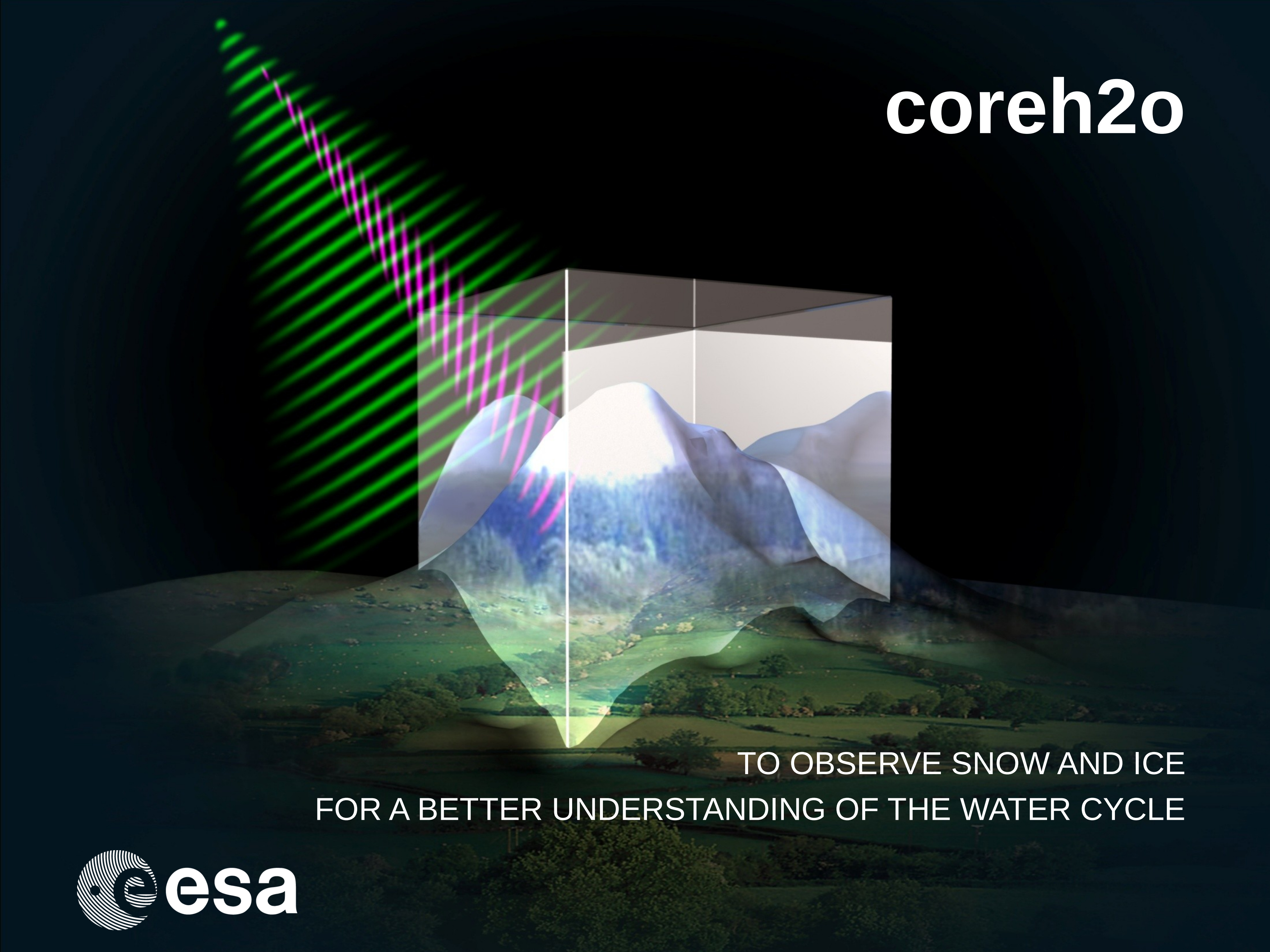


Polar Communications & Weather (PCW)/ PolarSat Mission



2009

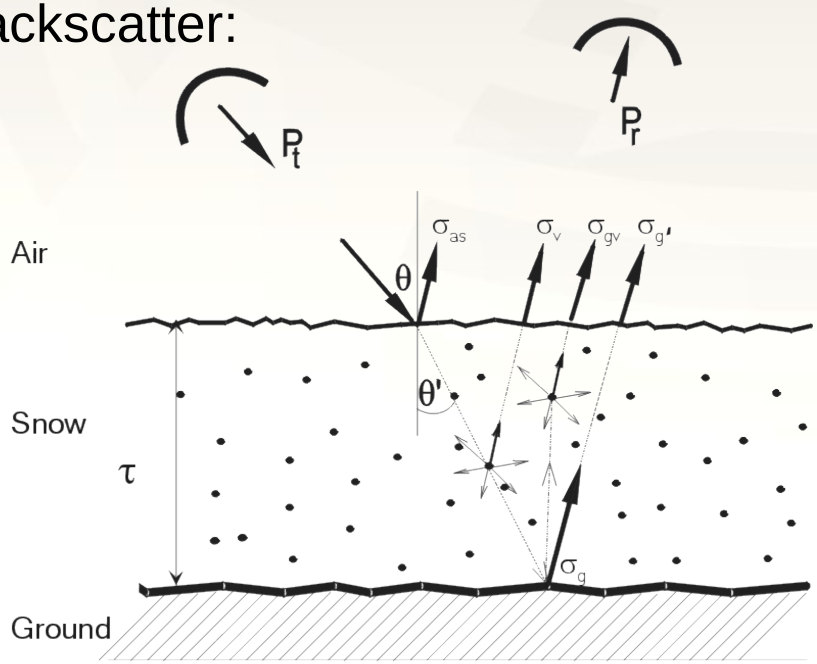
upnik


coreh2o
TO OBSERVE SNOW AND ICE
FOR A BETTER UNDERSTANDING OF THE WATER CYCLE
esa

Measurement principle: radar backscatter

Main parameters relevant for snow backscatter:

- Snow water equivalent
- Grain size
- Soil background signal
- Liquid water content (if melting)



Backscatter contributions:

Volume, surface, and interaction terms

$$\sigma^0 = \sigma^{as} + \sigma^v + \sigma^{gv} + \sigma^{g'}$$

Mission objectives – water cycle and climate

Quantify the amount and variability of fresh water stored in terrestrial snow packs and snow accumulation on glaciers in order to:

- Reduce the **uncertainty of snow water storage** in regional and global water budgets
- Specify **snowmelt and glacier contributions to river discharge** modelling and forecasting
- Improve the **parameterisation and downscaling of snow and ice processes** in regional/global weather and climate models
- Validate the **magnitude and feedbacks of snow and ice processes** in climate models


Thank You for Your Attention!