A multi-sensor multi-temporal algorithm for snow cover extent retrieval from optical and passive microwave data

Rune Solberg[1], Øystein Rudjord[1], Arnt-Børre Salberg[1] and Mari Anne Killie[2]

[1]Norwegian Computing Center (NR), rune.solberg@nr.no

[2]Norwegian Meteorological Institute (MET Norway)

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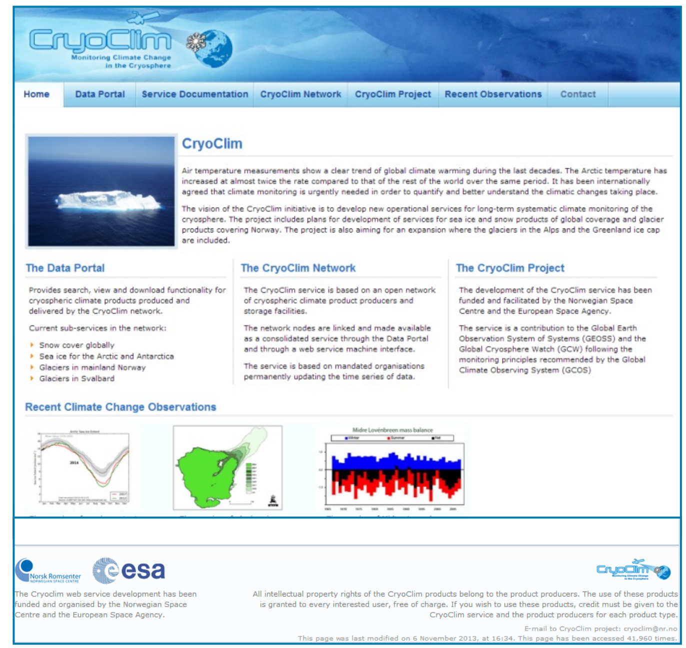
The CryoClim service

- The Norwegian Space Centre (NSC) and ESA project CryoClim (2008-2013) developed algorithms, products and a service for cryospheric climate monitoring
- Operational service from 7 November 2013: www.cryoclim.net
- Products:
  - Sea ice (MET): 1979-present, global
    - Sea ice concentration (SIC)
    - Sea ice edge (SIE)
  - Snow cover (MET/NR): 1982-present, global
    - Snow cover extent (SCE)
  - Glaciers Norway (NVE): 1952/1988–present
    - Glacier area outline (GAO)
    - Glacier lake outline (GLO)
    - Glacier lake outburst flood (GLOF)
    - Glacier periodic photo series (GPP)
  - Glaciers Svalbard (NPI): 1936/1992–present
    - Glacier area outline (GAO)
    - Glacier surface type (GST)
  - Extended with Greenland in 2014 (GEUS): 2000-present
    - Glacier surface type (GST)

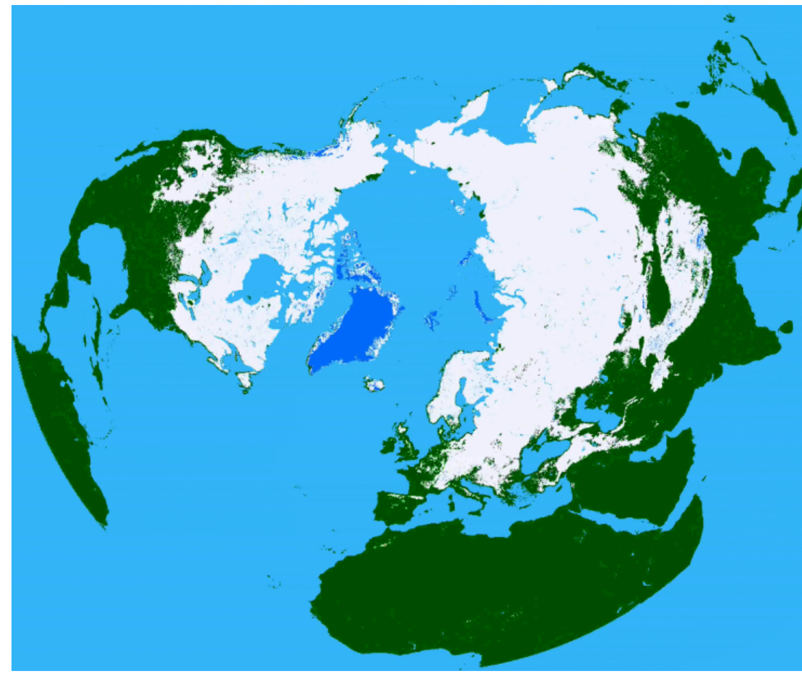


Norsk Romsenter NORWEGIAN SPACE CENTRE

CryoClim Monitoring Climate Change in the Cryosphere

Sub-service snow

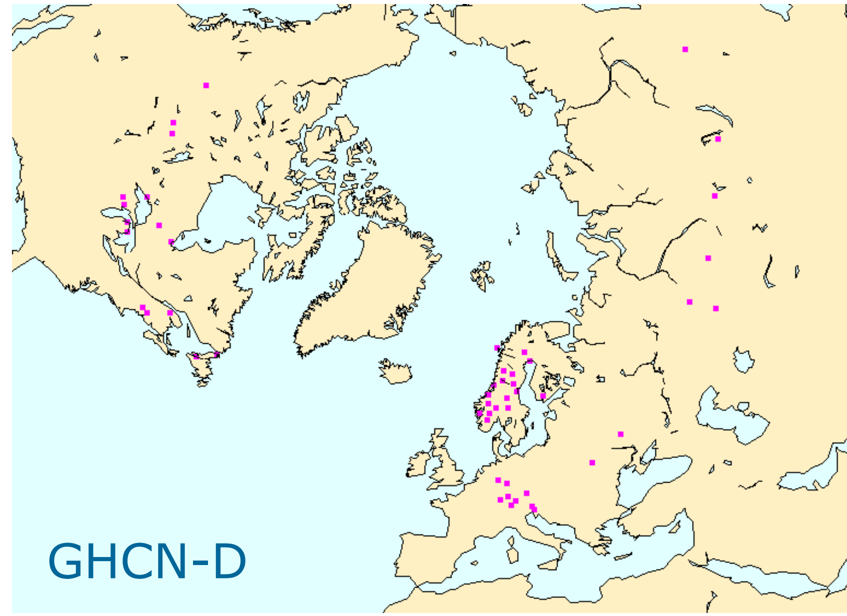
- Snow Cover Extent (SCE)
- Developed three prototype products:
  - SCE from PMR (10 km)
    - Based on SMMR (1978-1987) and SSM/I (1987-present)
  - SCE from optical (5 km)
    - Based on AVHRR GAC (1982-present)
  - SCE multi-sensor/temporal (5 km)
    - Combination of optical and PMR
- Final time series: 1982–present
- Climate-change indicator products: Snow season length, first and last day of snow

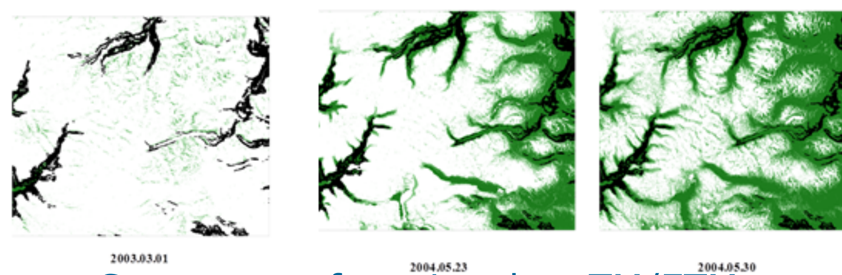


Multi-sensor multi-temporal snow cover 1 March 2005

Validation data

- Snow depth from the Global Historical Climatology Network Daily (GHCN-D) SYNOP database
- Filtered out stations with suspicious behaviour, taking into consideration that zero snow depth is not reported explicitly
- Set of snow reference maps based on Landsat (Scandinavia only)





Snow maps from Landsat TM/ETM+

The PMR product is based on the SMMR and SSM/I sensors

SMMR
25 Oct. 1978 - 20 Aug. 1987

Coverage: Every other day

Freq.: 18 and 37 GHz

V and H polarizations

SSM/I
18 June 1987 - present

Coverage: Twice a day

Freq.: 19, 21*, 37 and 85 GHz

V and H polarizations

The PMR SCE algorithm is based on an estimate of the probability of snow

$$P(S_k \mid x_1, x_2, \ldots, x_n) = \frac{P(x_1 \mid S_k) \cdot P(x_2 \mid S_k) \cdots P(x_n \mid S_k) \cdot P(S_k)}{\sum_{m=1}^{C} P(x_1 \mid S_m) \cdot P(x_2 \mid S_m) \cdots P(x_n \mid S_m) \cdot P(S_m)}$$

SMMR

Snow classes:

Snow & no snow

Features:

x1=T18v-T37v
x2=T18h-T37h

SSM/I

Snow classes:

Dry snow, wet snow, no snow & no snow with a large portion of water

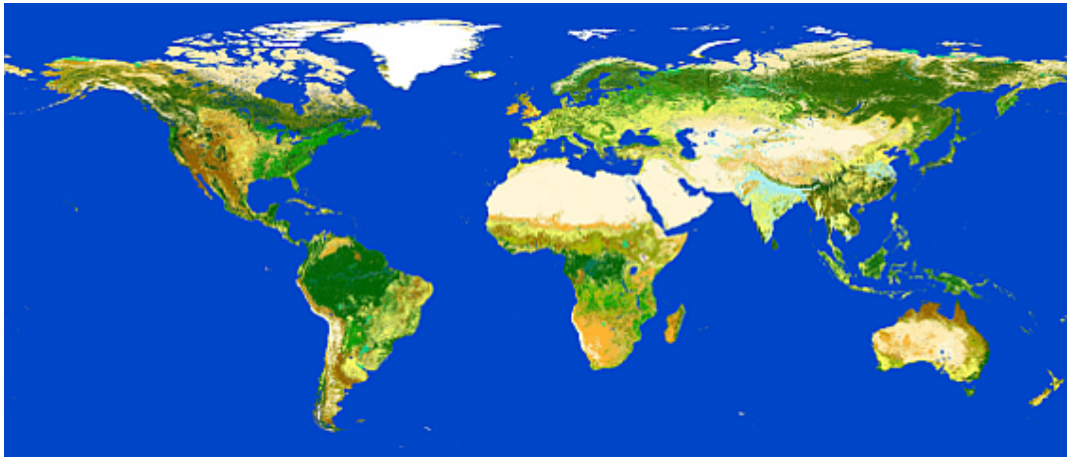
Features:

x1=T37v-T37h
x2=T19v-T37v
x3=T22v-T85v
x4=(1.95·T19v-0.95·T19h)/0.95
x5=T22v

To mitigate the influence from ground cover/vegetation, we stratify the snow cover estimation to similar land cover

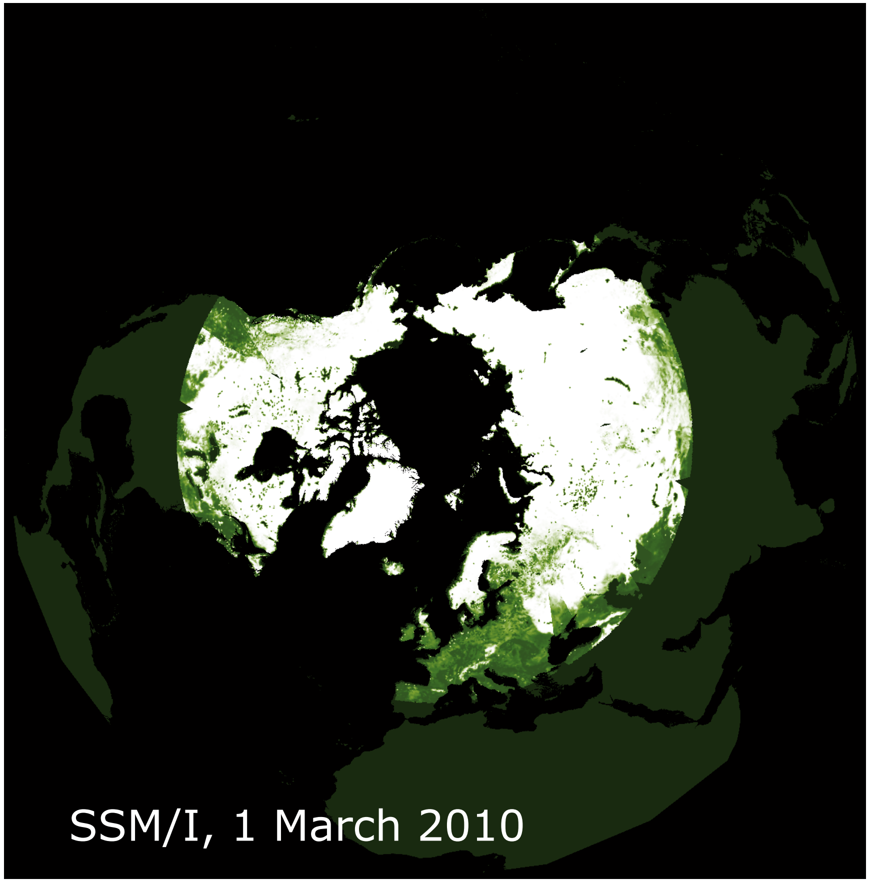
SMMR:
11 land cover groups

SSM/I:
7 land cover groups



Land cover groups based on the ESA GlobCover product

Example snow cover maps



Algorithm performance

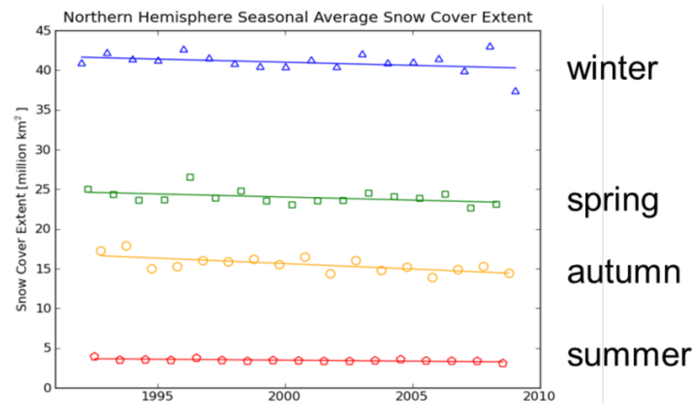
SMMR:

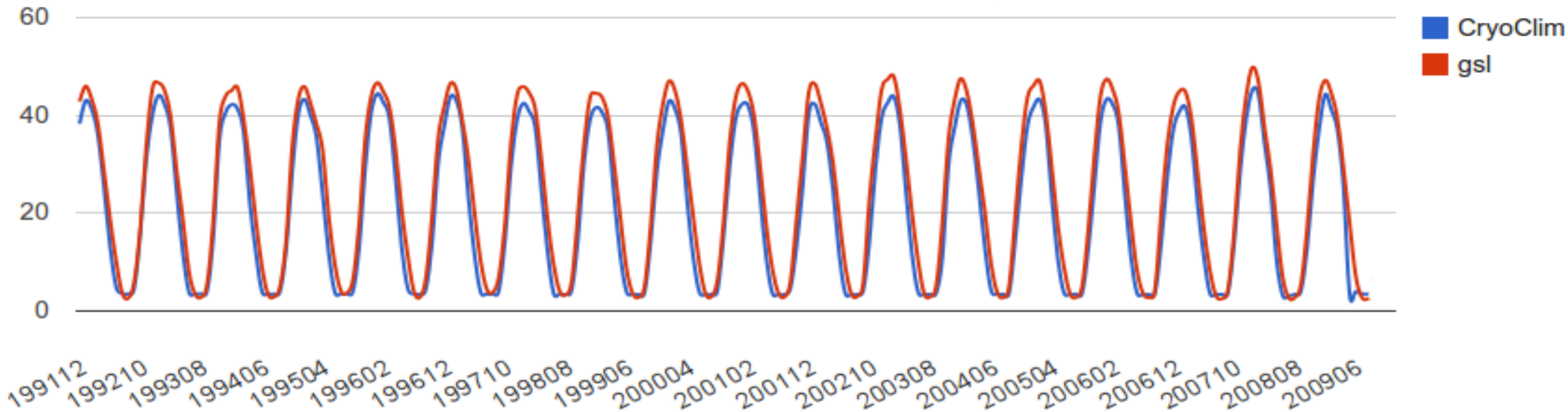
- Probability of correctly classified snow covered samples: **72%**
- Probability of correctly classified no-snow covered samples: **95%**

SSM/I:

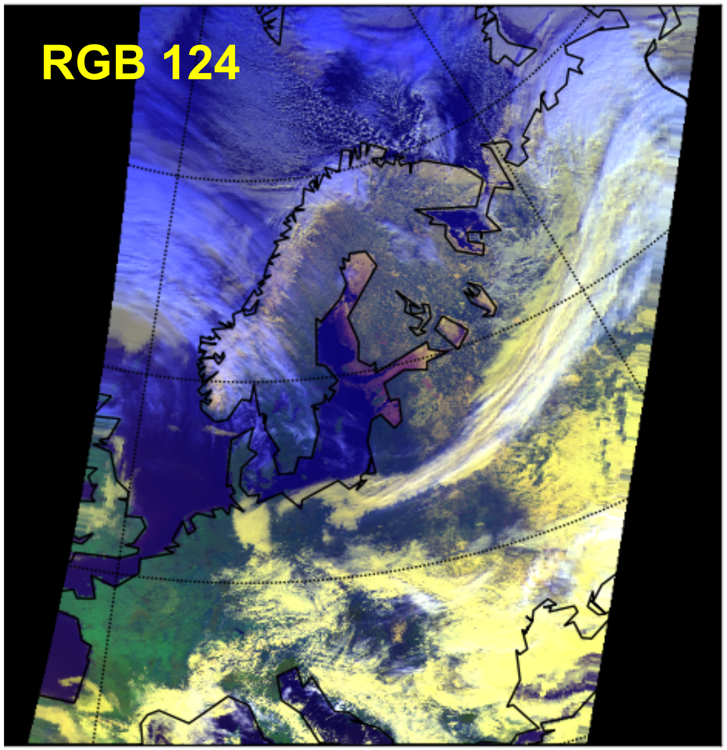
- Probability of correctly classified snow covered samples: **86%**
- Probability of correctly classified no-snow covered samples: **86%**

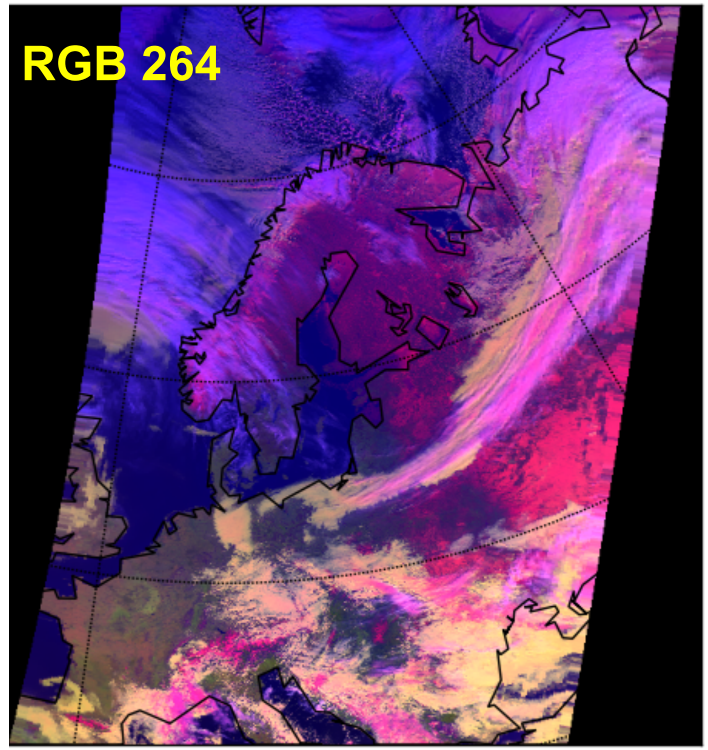
Comparison with GSL shows typical characteristics for a PMR time series





Optical SCE is based on AVHRR GAC data





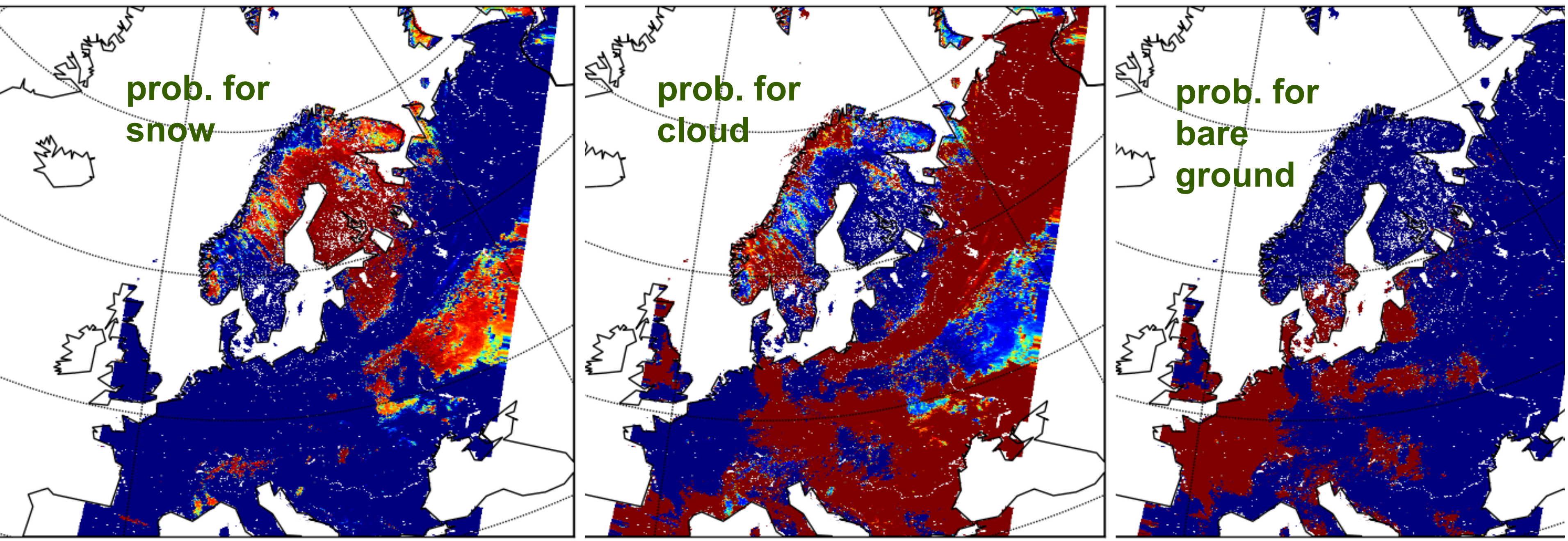
AVHRR GAC passage product. NOAA-17, 15 March 2003, 09:15 UTC

Satellite	Service start	Service end
TIROS-N	19 Oct 1978	30 Jan 1980
NOAA-6	27 Jun 1979	16 Nov 1986
NOAA-7	24 Aug 1981	7 Jun 1986
NOAA-8	3 May 1983	31 Oct 1985
NOAA-9	25 Feb 1985	11 May 1994
NOAA-10	17 Nov 1986	17 Sep 1991
NOAA-11	8 Nov 1988	13 Sep 1994
NOAA-12	14 May 1991	15 Dec 1994
NOAA-14	30 Dec 1994	23 May 2007
NOAA-15	13 May 1998	Present
NOAA-16	21 Sep 2000	Present
NOAA-17	24 Jun 2002	10 Apr 2013
NOAA-18	30 Aug 2005	Present
NOAA-19	2 Jun 2009	Present
MetOp-A[8]	20 Jun 2007	Present

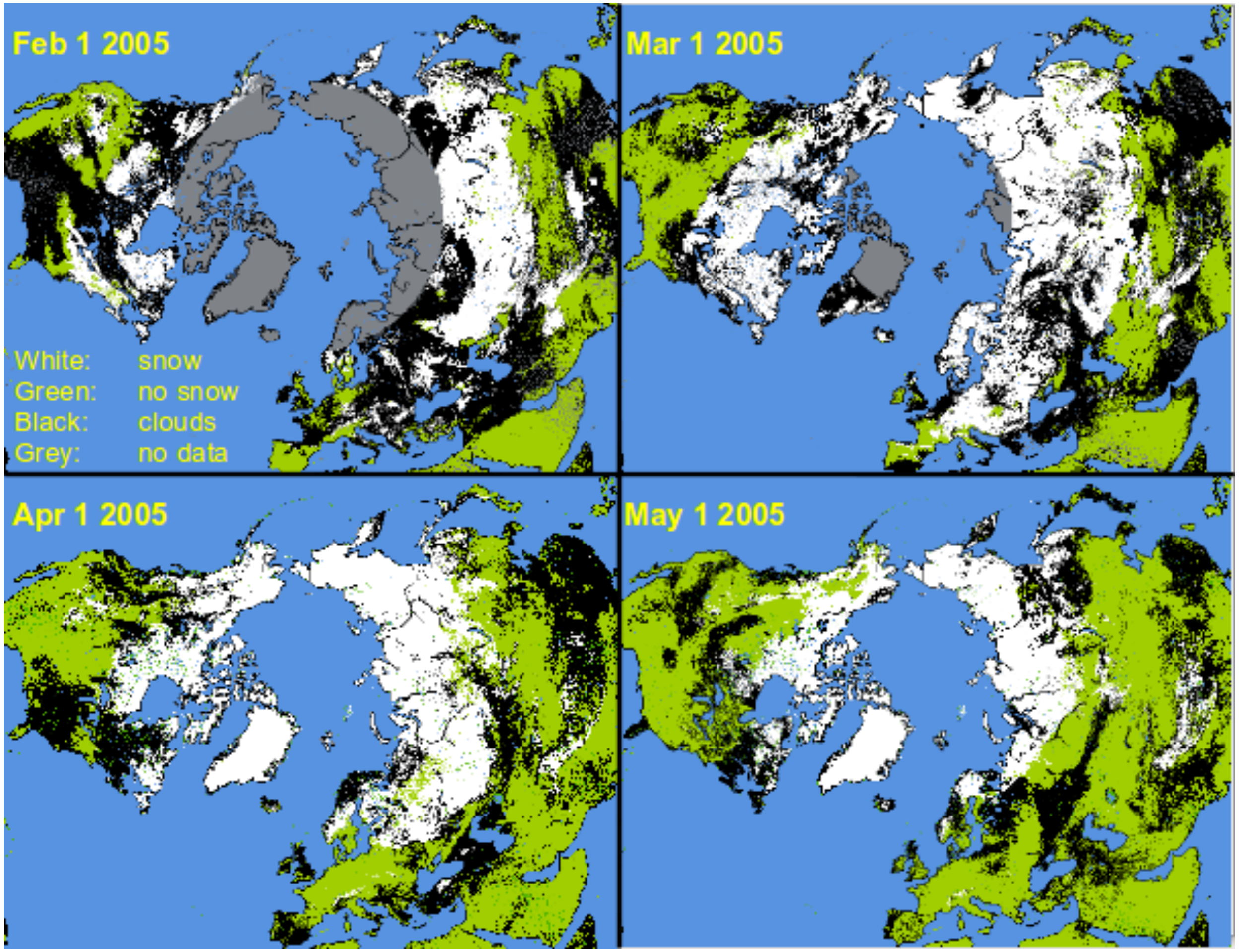
Band	Wavelength (µm)
1	0.58 - 0.68
2	0.725 - 1.00
3A	1.58 - 1.64
3B	3.55 - 3.93
4	10.30 - 11.30
5	11.50 - 12.50

The optical SCE algorithm is based on an estimate of probability of snow

$$P(S_k \mid x_1, x_2, \ldots, x_n) = \frac{P(x_1 \mid S_k) \cdot P(x_2 \mid S_k) \cdots P(x_n \mid S_k) \cdot P(S_k)}{\sum_{m=1}^{C} P(x_1 \mid S_m) \cdot P(x_2 \mid S_m) \cdots P(x_n \mid S_m) \cdot P(S_m)}$$



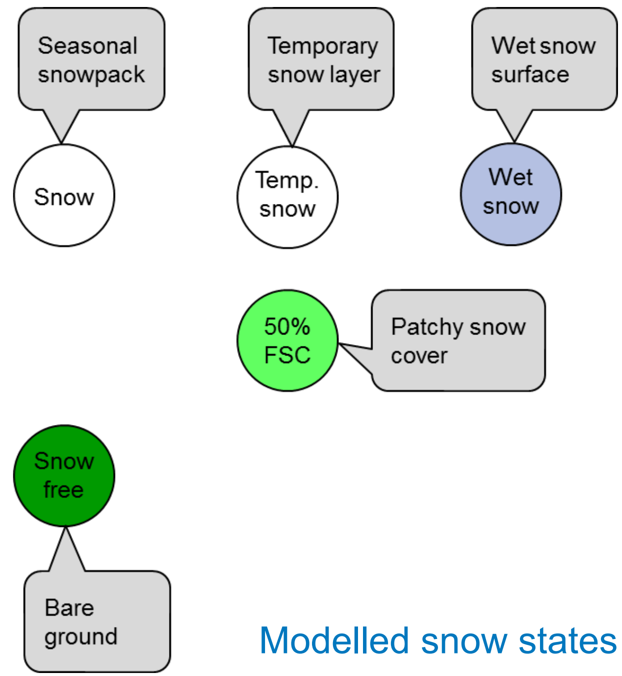
Optical SCE validation



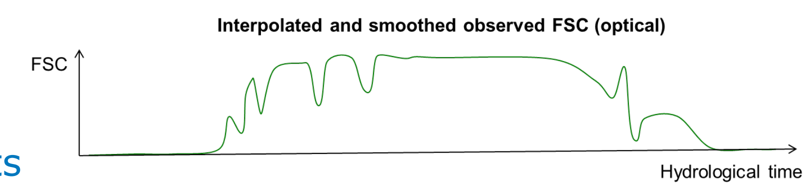
Month	Hit	Miss	Total
200501	93%	7%	446
200502	97%	3%	650
200503	96%	4%	755
200504	88%	12%	604
200505	96%	4%	810
200506	99%	1%	1024
200507	100%	0%	1159
200508	100%	0%	1012
200509	100%	0%	900
200510	100%	0%	671
200511	94%	6%	232
200512	90%	10%	284
Sum 2005	**97%**	**3%**	**8547**

Multi-sensor multi-temporal optical + PMR

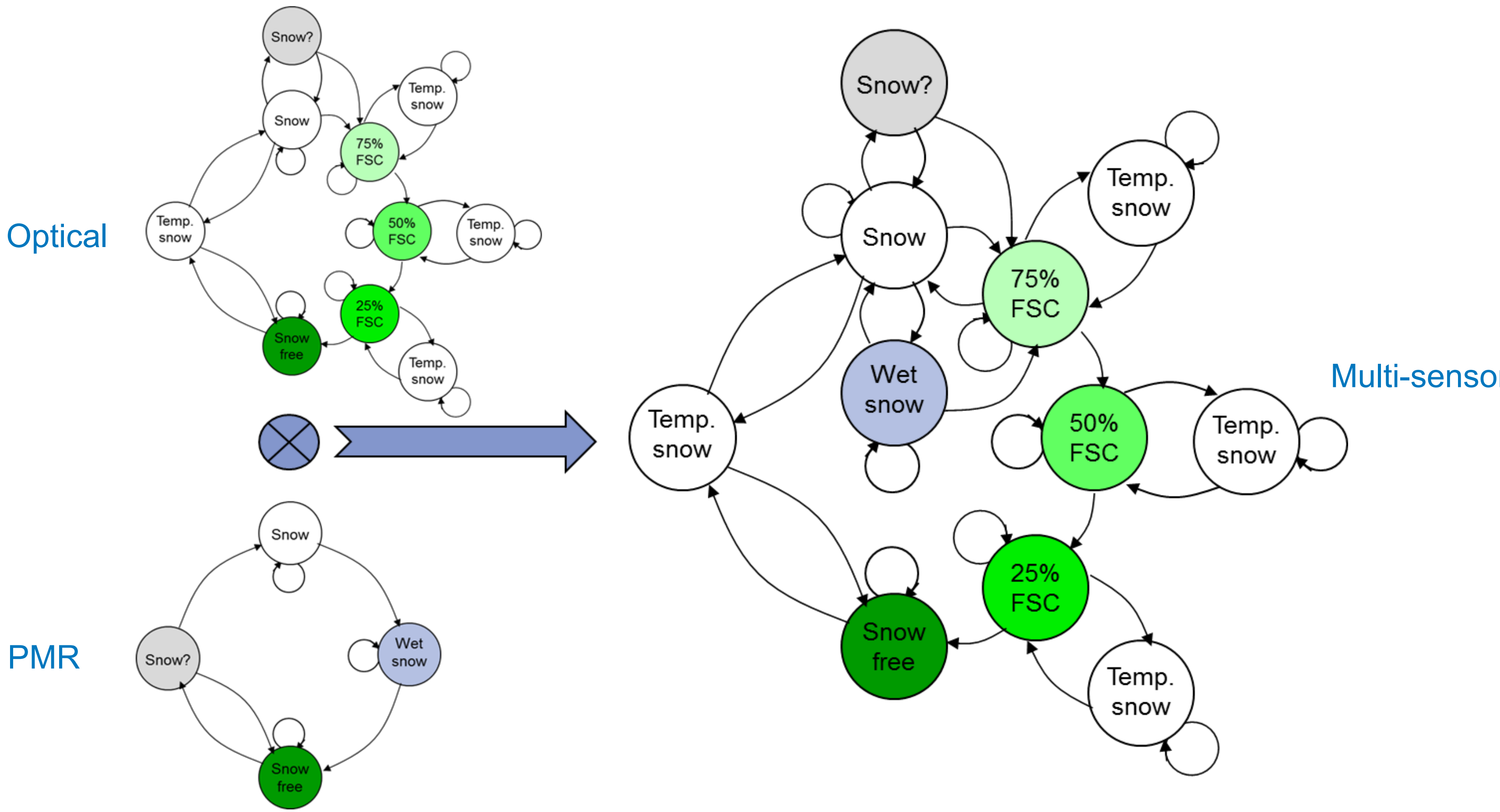
- The vision was to combine the best from optical and PMR:
  - Optical hampered by clouds, but otherwise very accurate except for dense forests
  - PMR hampered by shallow snow depth and wet snow, but otherwise reliable and independent of daylight
- We have knowledge about the development of the seasonal snowpack; calling for multi-temporal approach:
  - Snow season start-up: Fluctuations between snow and bare ground
  - Winter season: Accumulation with snowpack present
  - Spring season: Gradual snowmelt with advent of patchy snow cover and temporal snow events



Modelled snow states



A state model based on fusion of single-sensor state models



Implemented the model applying the Hidden Markov Model framework

- In HMM we observe a system assumed to evolve through a series of different states
- Transitions from one state to another happen with certain probabilities
- While in a given state the system will produce observables with a certain probability density

States: $Q=\{S_1, S_2, \ldots, S_v\}$

Observables: $X^T=\{X^1, X^2, \ldots, X^T\}$

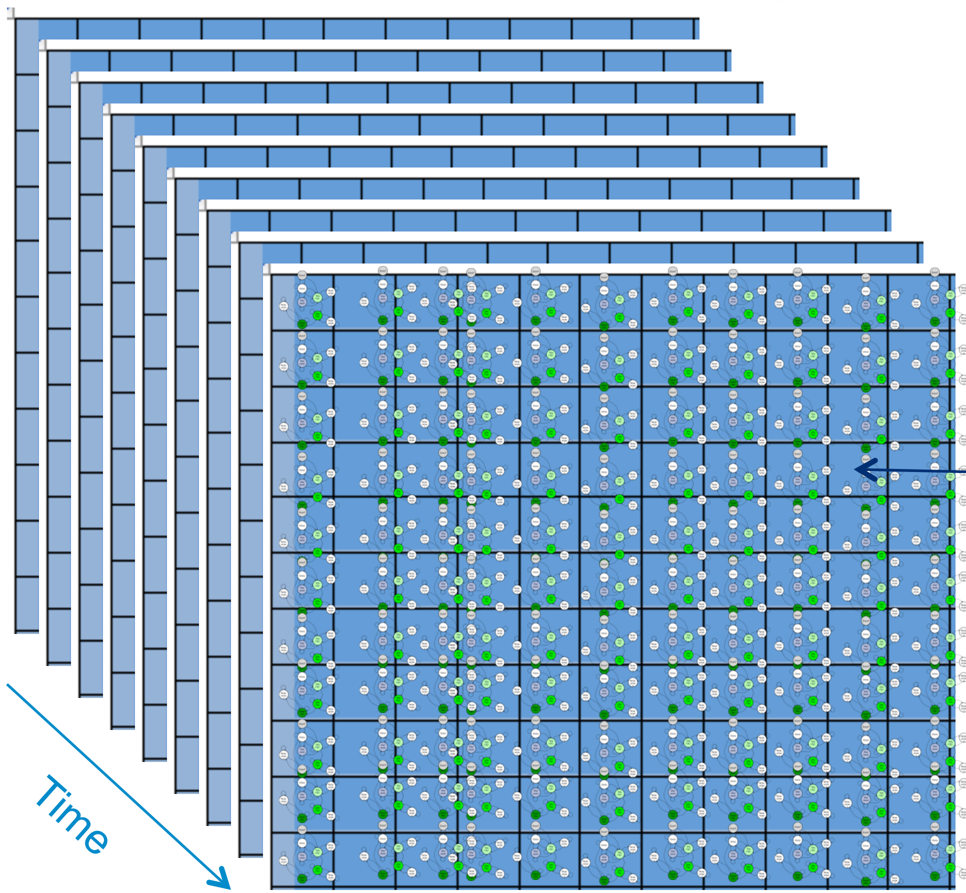
Prob. distr.: $p X^t\ E^t = S_i\ , i=1, 2, \ldots, v$

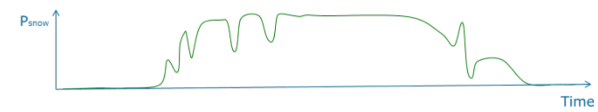
Transition probabilities.:

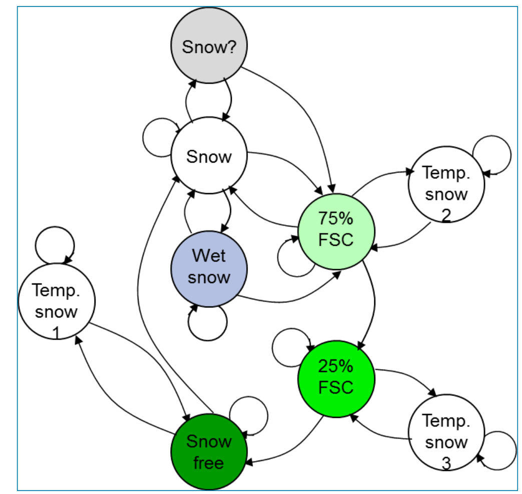
$$p E^t = S_i\ E^{t-1} = S_j\ , i,j=1, 2, \ldots, v$$

Initial conditions: $p(E^1 = S_i), i=1, 2, \ldots, v$

Note that a there is one state model per grid cell



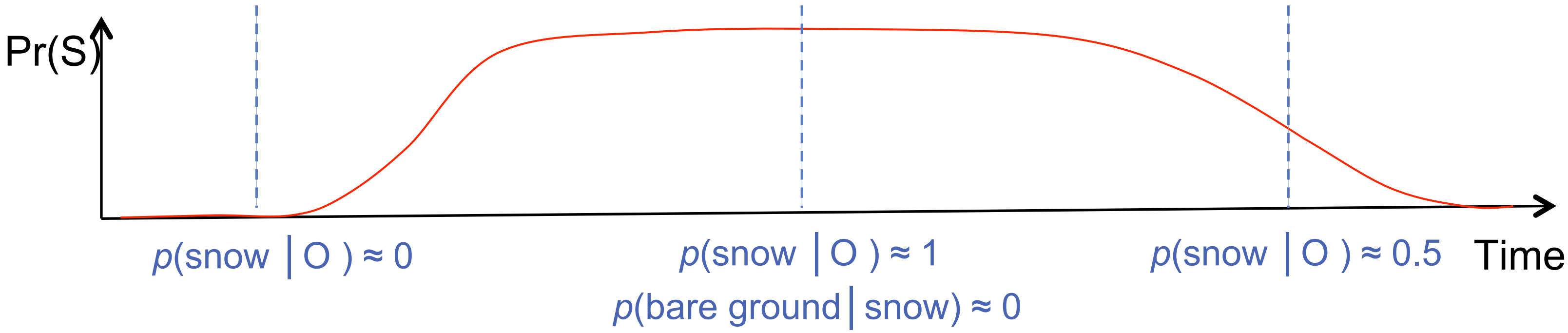




$$p X^{t} E^{t} = S_{i}$$

$$p E^{t} = S_{i} E^{t-1} = S_{j}$$

Estimating the probabilities



Climatological probability of snow

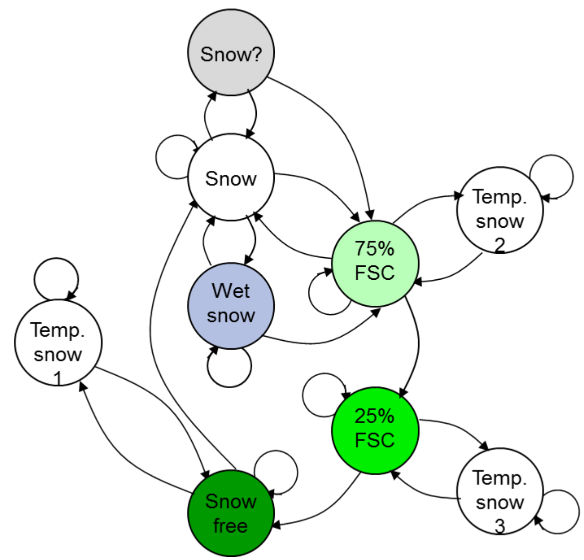
- Per pixel daily climatological probability of snow computed from Savitzky-Golay smoothed PMR snow probabilities
- Used to estimate transition probabilities

Using the Viterbi algorithm to determine the model sequence best explaining the temporal observations

- The Viterbi algorithm is a dynamic-programming algorithm for finding the most likely sequence of hidden states (the Viterbi path) that result in a sequence of the observables
- The algorithm requires as input the state probability density functions, the transition probabilities between the different states and the initial probability of each state

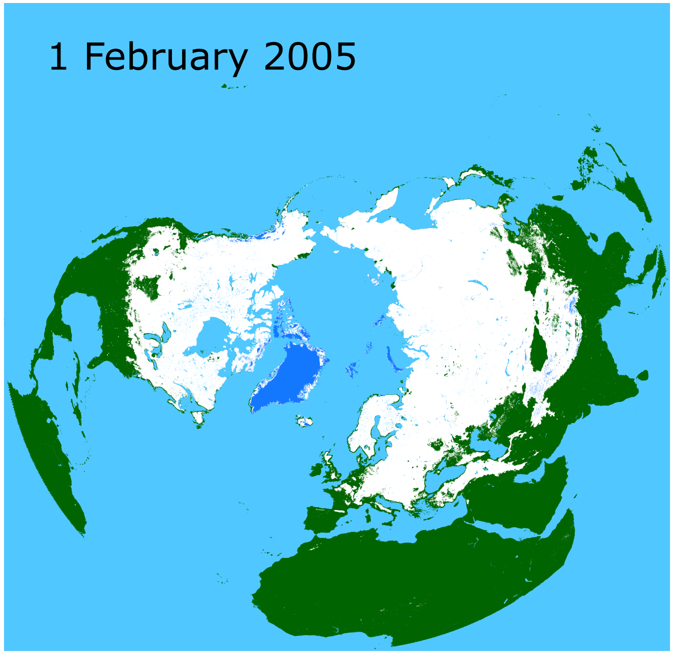
$$V_{1,k} = p_{X^{1}\,k}\; p(E^{1} = S_{k})$$

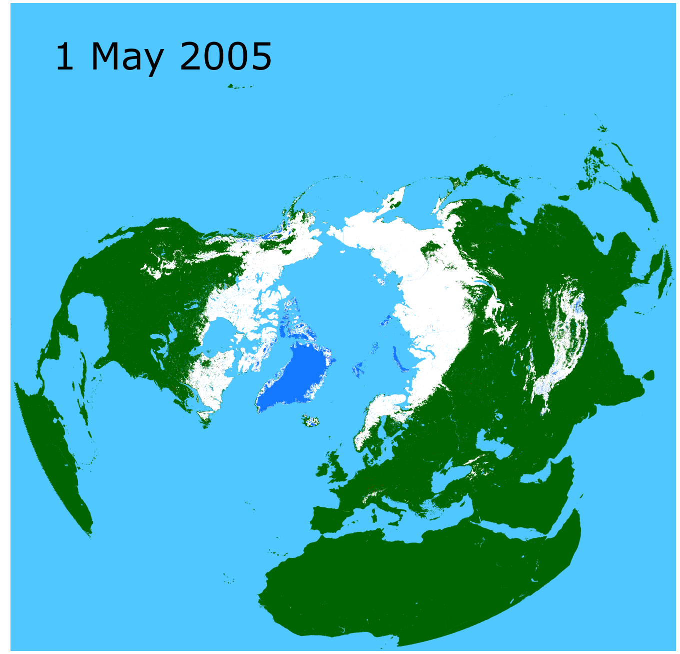
$$V_{t,k} = p_{X^{t}\,k} \max_{i} \left(p E^{t} = S_{i}\; E^{t-1} = S_{j}\; V_{t-1,k} \right)$$



Final state model chosen

Examples of results





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
True	0.82	0.90	0.94	0.88	0.93	0.99	1.00	1.00	1.00	0.98	0.78	0.76
False	0.18	0.10	0.06	0.12	0.07	0.01	0.00	0.00	0.00	0.02	0.22	0.24
Total pixels	1298	1318	1385	1008	1254	1437	1488	1488	1427	1225	702	1170

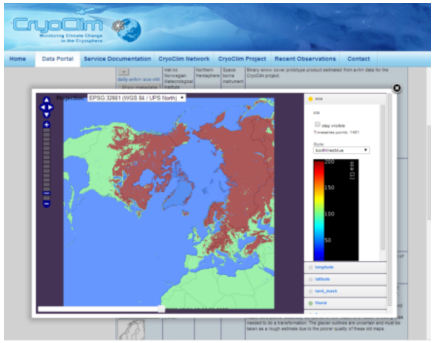
Overall accuracy: 92.4 %

Conclusions

- Developed a multi-sensor time-series optical + PMR fusion algorithm for estimation of Snow Cover Extent (SCE) based on a Hidden Markov Model approach
- Key requirement: Observational product; not modelled product
- Overall accuracy 92.4%
- Version 1.0 product time series (1982-present) is processed now
- Version 2.0 with improvements planned to be released by the end of 2014

Planned improvements:

- Snow along coastlines
- Overestimation in the Tibetan Plateau?
- Extending validation with new data:
  - Former Soviet Union HSDSD and FSUHSS datasets
  - VHR and HR snow maps
- Develop an error model



Norwegian Meteorological Institute

cryoclim@cryoclim.net
www.cryoclim.net

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