Monitoring thin sea ice thickness with MODIS

Approach and preliminary results

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Why thin ice thickness?

- Sea ice is an important component in the climate system
- Sensitive indicator of climate change
- Areas of thin ice important for ship navigation
- Useful in numerical weather forecasting

Basic idea

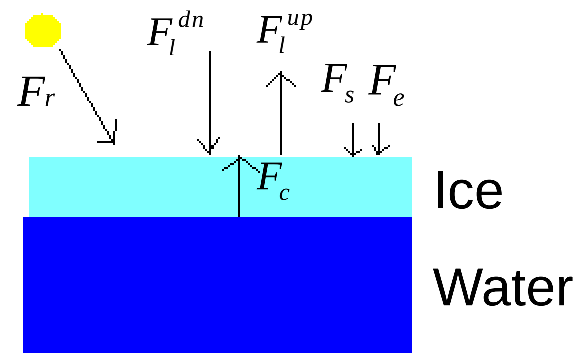
- Heat from the water beneath thin sea ice penetrates the ice
- Heat flux through the ice is assumed inversely proportional to the ice thickness
- If the surface temperature and atmospheric conditions are known, the ice thickness can be estimated

The thin ice thickness model

- Model by Yu & Rothrock (1996)
- Model the heat balance on the ice surface as

$$F_{total} = F_r - F_l^{up} + F_l^{dn} + F_s + F_e + F_c$$

- Thermal equilibrium: $F_{total} = 0$
- Night images: $F_r = 0$



$$F_l^{dn} - F_l^{up} + F_s + F_e + F_c = 0$$

$\boldsymbol{F_r}$: solar radiation heat flux
$\boldsymbol{F_l^{up}}$: upwelling longwave heat flux
$\boldsymbol{F_l^{dn}}$: downwelling longwave heat flux
$\boldsymbol{F_s}$: turbulent sensible heat flux
$\boldsymbol{F_e}$: latent heat flux
$\boldsymbol{F_c}$: conductive heat flux

The thin ice thickness model

- **Conductive heat flux**: $$F_c = \frac{k_i k_s (T_f - T_s)}{k_s H + k_i h}$$ Yu & Rothrock (1996)

- **Longwave radiation**: $$F_l^{up} = \varepsilon_i \sigma T_s^4 \qquad F_l^{dn} = \varepsilon_a \sigma T_a^4$$

$\boldsymbol{T_f}$: freezing temperature of sea water
$\boldsymbol{T_s}$: surface temperature of ice/snow
$\boldsymbol{T_a}$: air temperature
$\boldsymbol{h}$: snow thickness
$\boldsymbol{H}$: ice thickness
$\boldsymbol{\varepsilon}$: emissivity

The thin ice thickness model

- **Latent heat**: $F_e = \rho_a C_e L u_2 (e_a - e_{s0}) 0.622/P_a$ Maykut (1978)
- **Sensible turbulent heat**: $F_s = \rho_a c_p C_s u_2 (T_a - T_s)$ Yu & Rothrock (1996)

- Assume empirical models for snow thickness, $h(H)$, thermal conductivity of sea ice, $k_i(S)$, sea ice salinity, $S(H)$, and saturation vapor pressure, $e_s(T)$.
- Given values for T_s, T_a and u_2 we can solve for ice thickness, H.

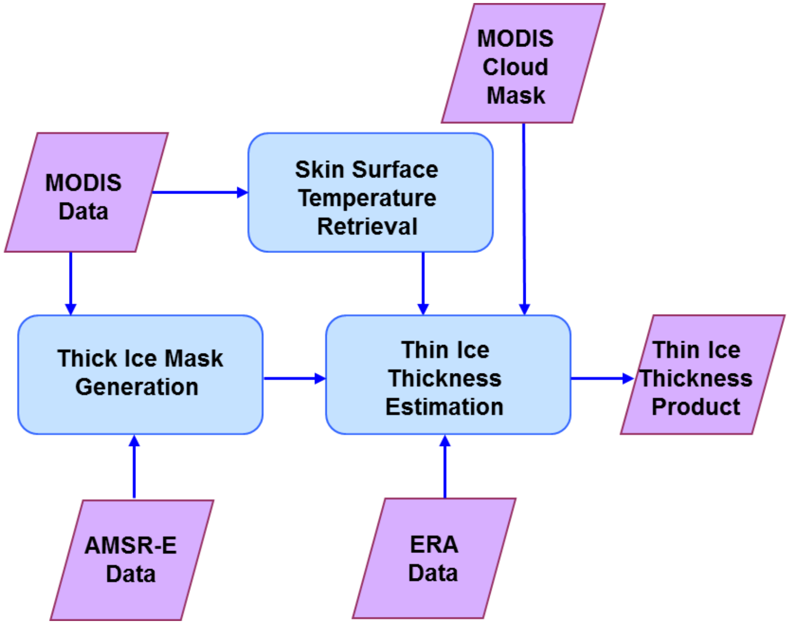
ρ_a: air density
$P_{\boldsymbol{a}}$: air pressure
$C_{\boldsymbol{s}}$ and C_e: bulk transfer coefficients
L: Latent heat of vaporization
u_2: 2m wind speed
c_p: specific heat of air
e_a: vapor pressure @2m
e_{s0}: saturation vapor pressure @surface

Automatic processing chain

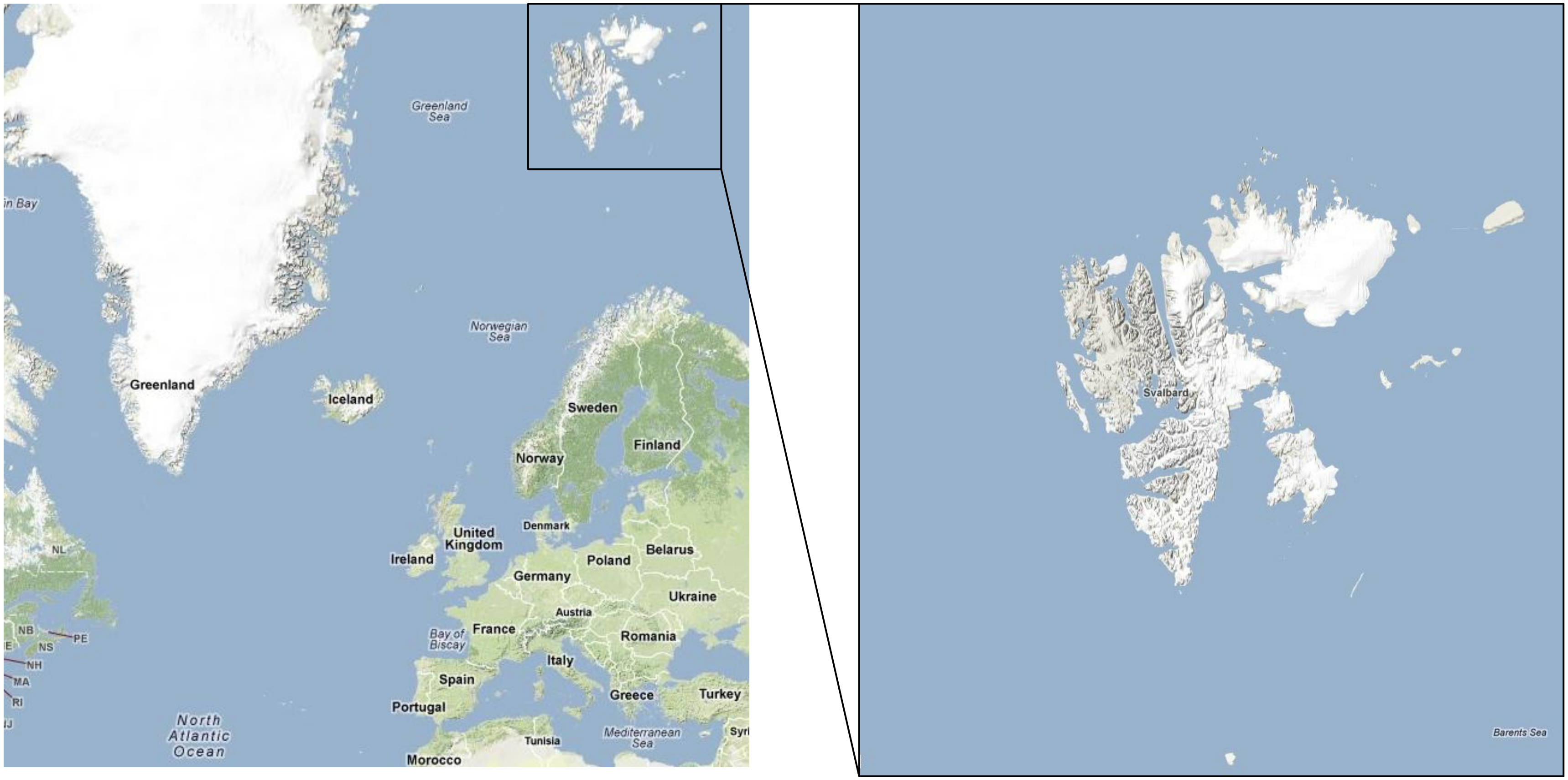
- Get T_s (via Key's algorithm) from thermal MODIS bands of Aqua
- T_a and u_2 from re-analysed ERA interim data
- Estimate ice thickness, H, for every pixel in MODIS image
- Use Aqua AMSR-E microwave images to exclude areas with thick ice:

$$\frac{T_{89GHz}}{T_{19GHz}} > 1$$

- Mask out land
- Use MODIS cloud mask

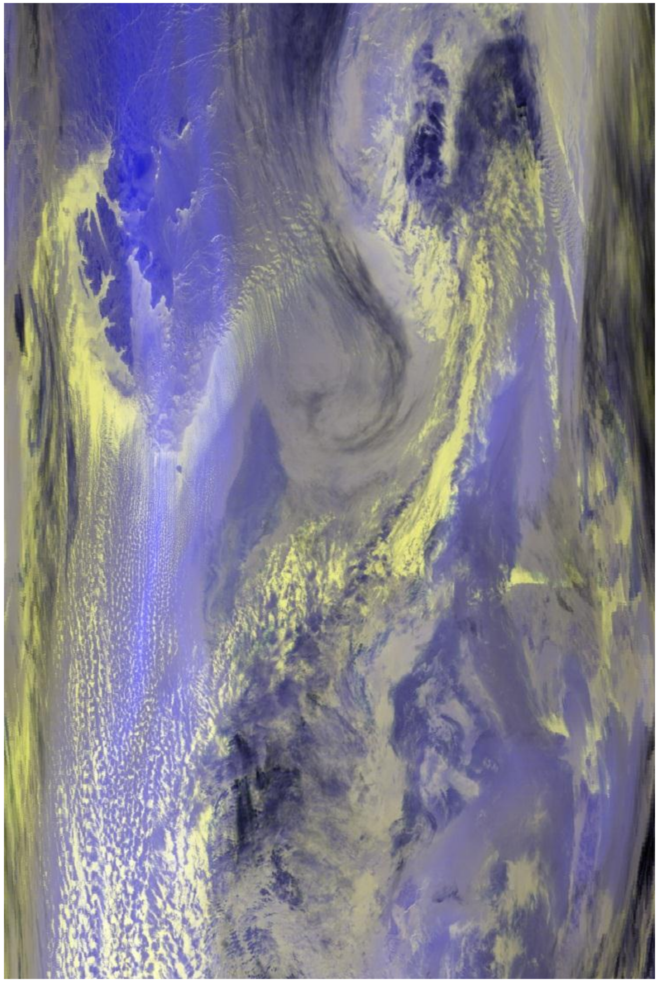


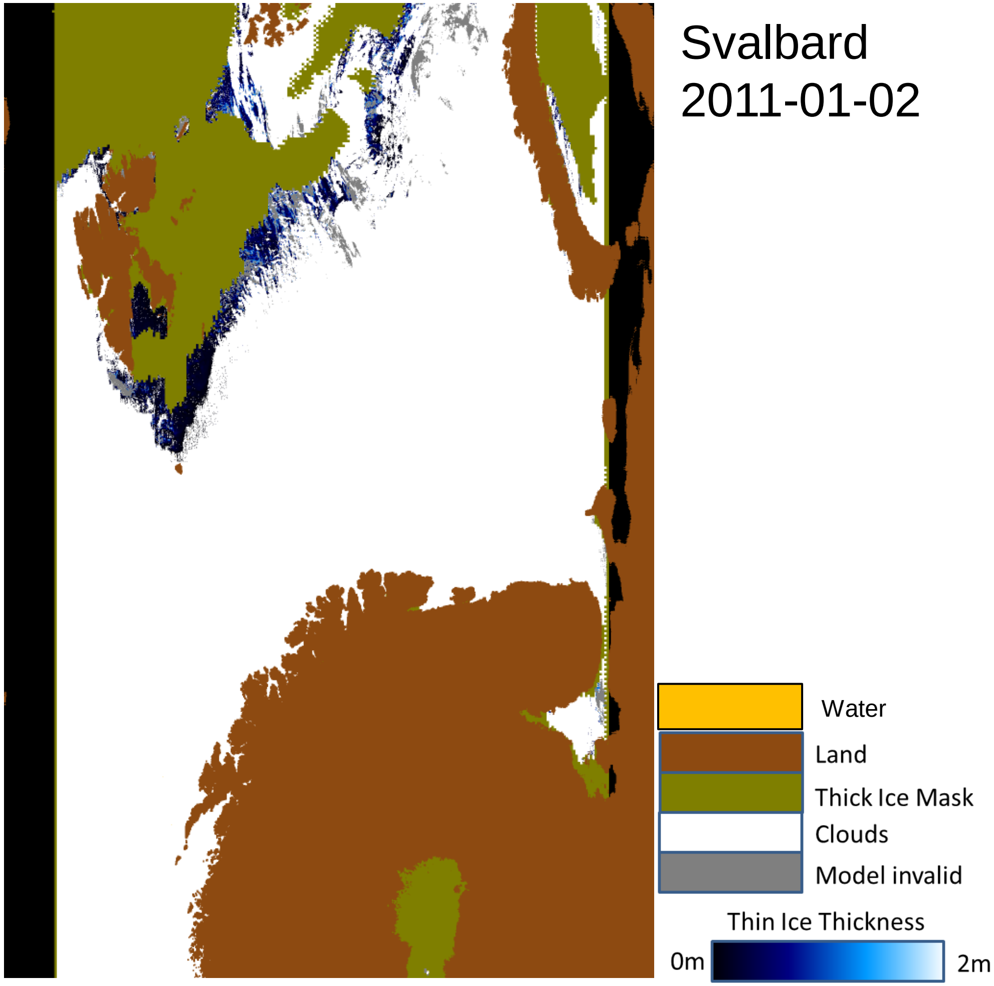
Area for testing



Svalbard, winter of 2010/2011

Results: Night time data





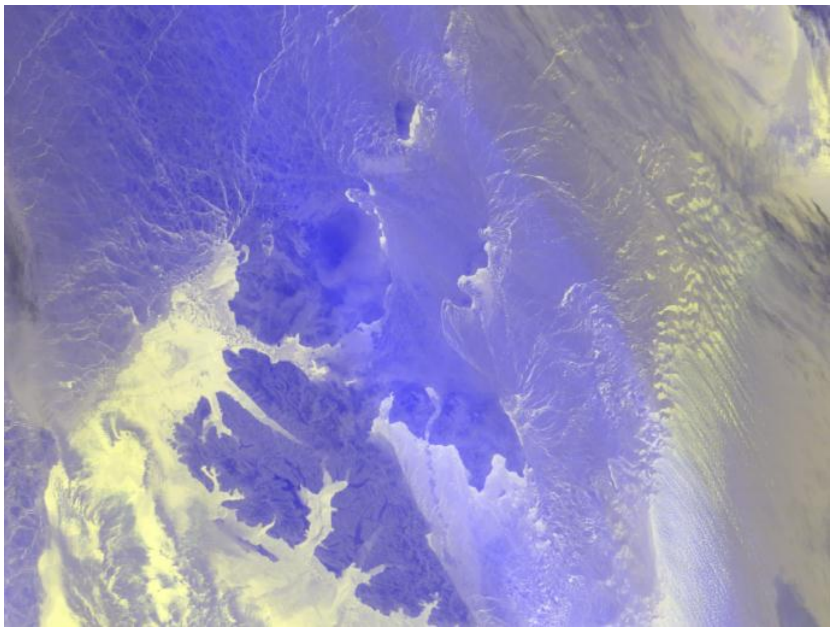
Svalbard
2011-01-02

Thermal composite
(R:12μm, G:11μm, B:6.7μm)

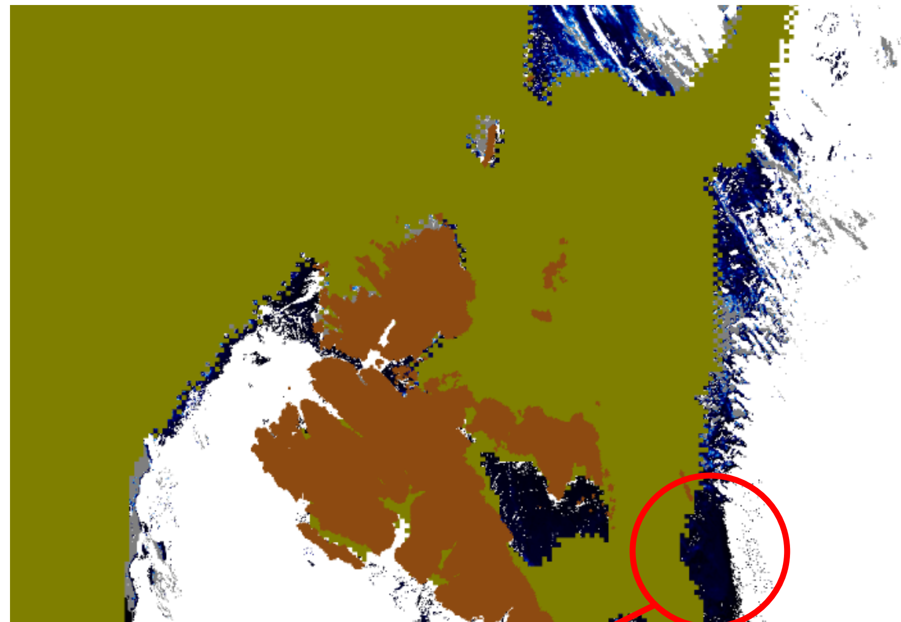
Output product

Results: Night time data

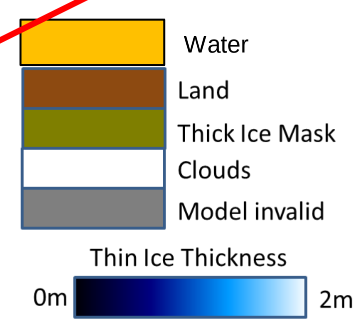
Svalbard
2011-01-02



Thermal composite image
(R:$12\mu m$, G:$11\mu m$, B:$6.7\mu m$)



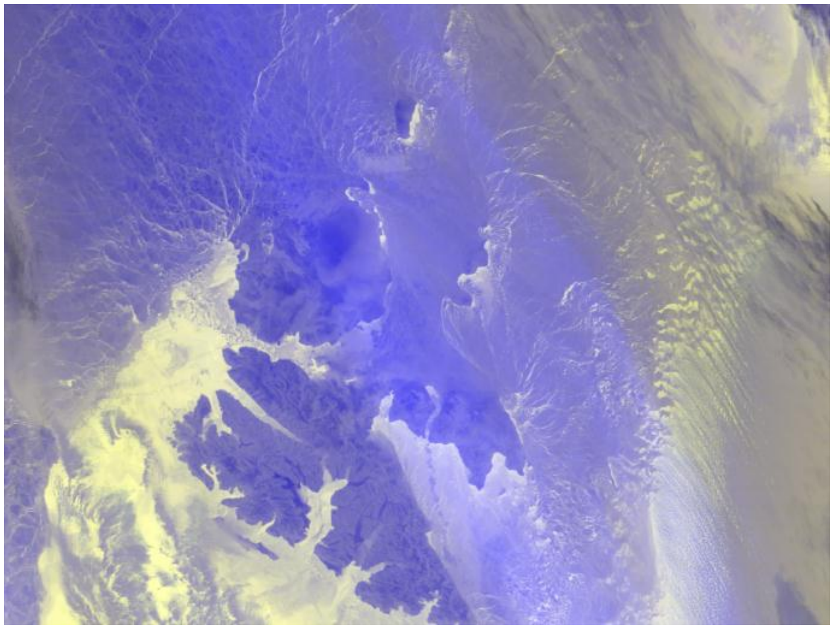
Output product

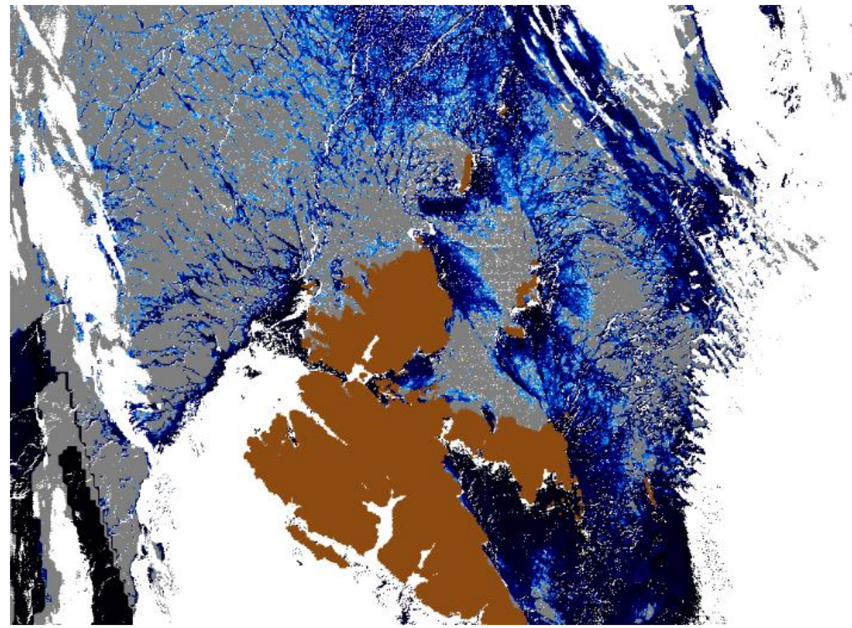


Typical thickness: 10-30 cm

Results: Night time data

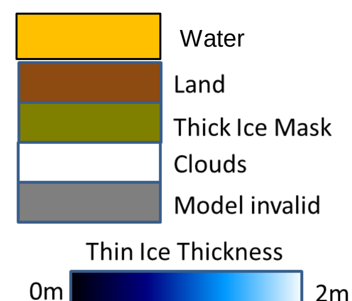
Svalbard
2011-01-02





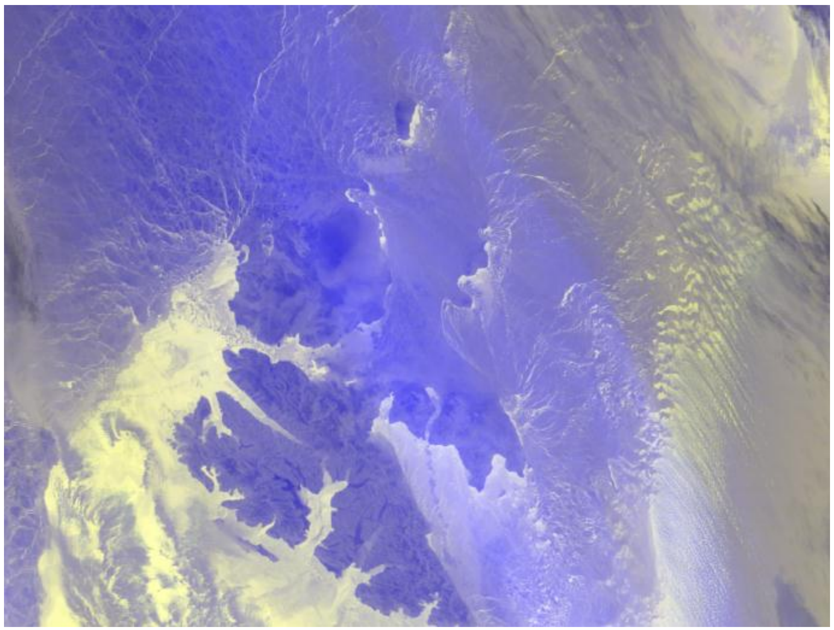
Thermal composite image
(R:$12\mu m$, G:$11\mu m$, B:$6.7\mu m$)

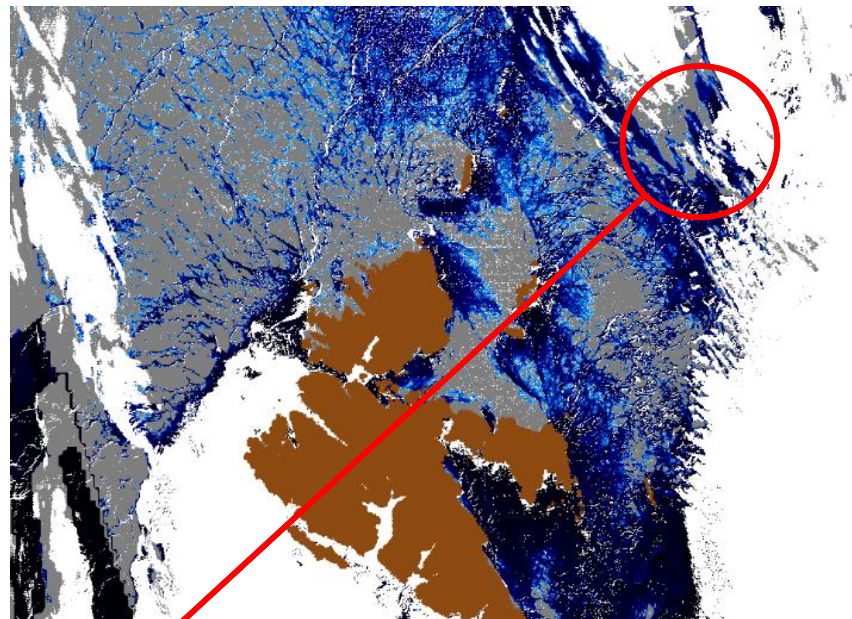
Output product
(without TIM)



Results: Night time data

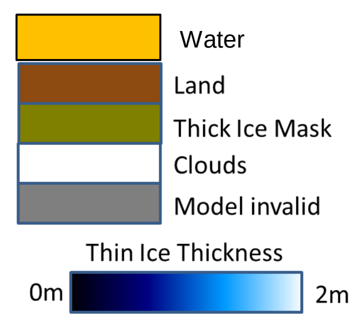
Svalbard
2011-01-02





Thermal composite image
(R:$12\mu m$, G:$11\mu m$, B:$6.7\mu m$)

Output product
(without TIM)



Cloud contamination

Validation

- ► In situ ice thickness measurements on Svalbard by Norwegian Polar Institute (EM31, EM-bird, drilling)
- ► Sea ice charts from Norwegian Meteorological Institute

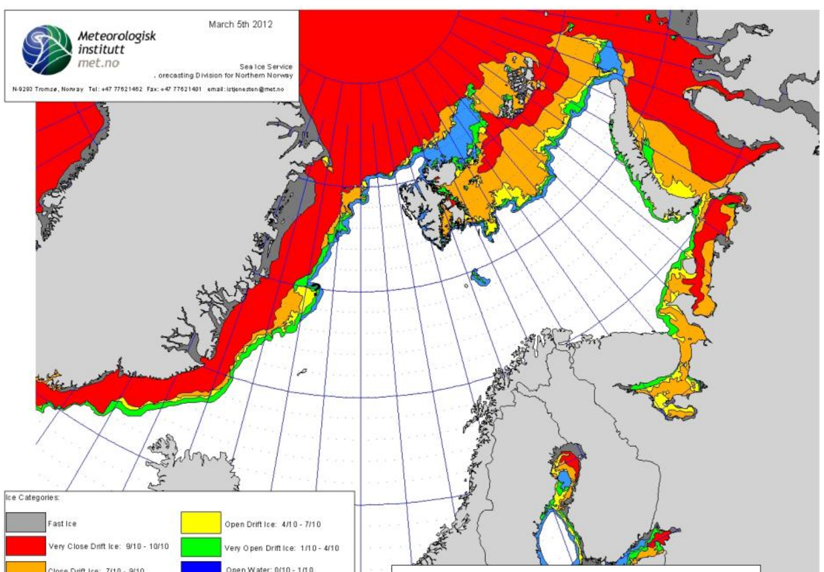


Image credits: A. Renner, Norwegian Polar Institute

Conclusions and way forward

Conclusions

- Automatic production of high resolution sea ice thickness maps (~1 km)
- Has applications in ship navigation, numerical weather forecasting, climate studies and studies of microwave ice products
- Results for night time data look plausible, but some work remains

Future work:

- Improve cloud masking of night images
- Improve modelling of sea ice thickness in daytime images
- Validation

Backup slides

Backup: empirical models

- Snow thickness:

  h = 0 for H < 5cm

  h = 0.05H for 5cm <= H <= 20cm

  h = 0.1H for H > 20cm

- Freezing temperature of sea water: $T_f = -0.055 S_w$
- Thermal conductivity of sea ice: $k_i = k_0 + \beta S/(T_s - T_0)$

Backup: empirical models

- Sea ice salinity:

  $S = 14.24 - 19.39H$ for $H <= 0.4m$

  $S = 7.88 - 1.59H$ for $H > 0.4m$

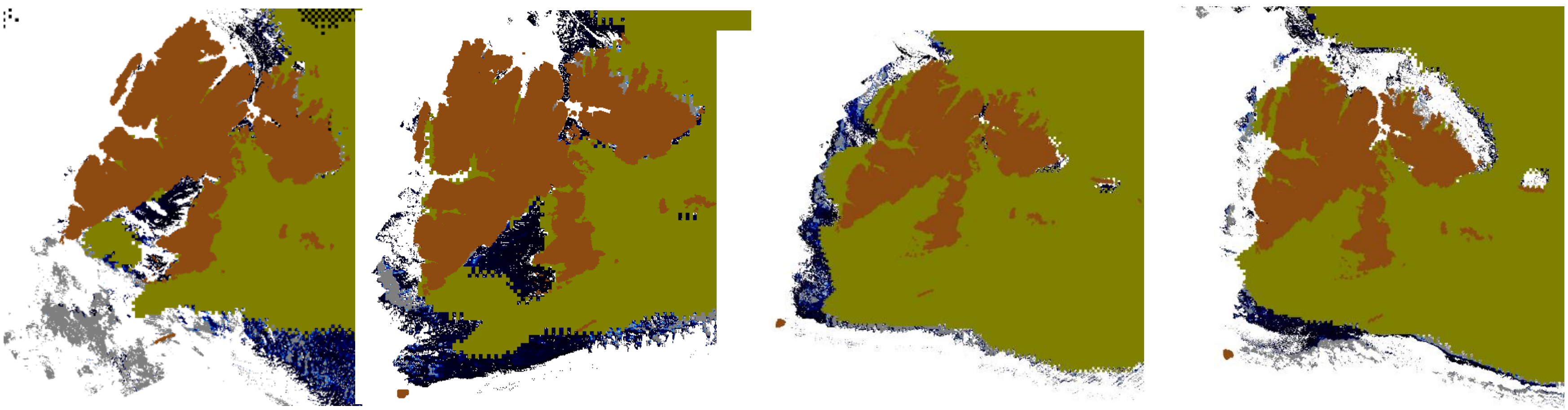
- Snow thickness:

  $h = 0$ for $H < 5cm$

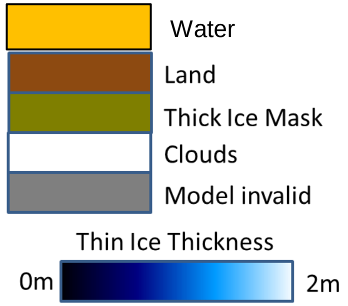
  $h = 0.05H$ for $5cm <= H <= 20cm$

  $h = 0.1H$ for $H > 20cm$

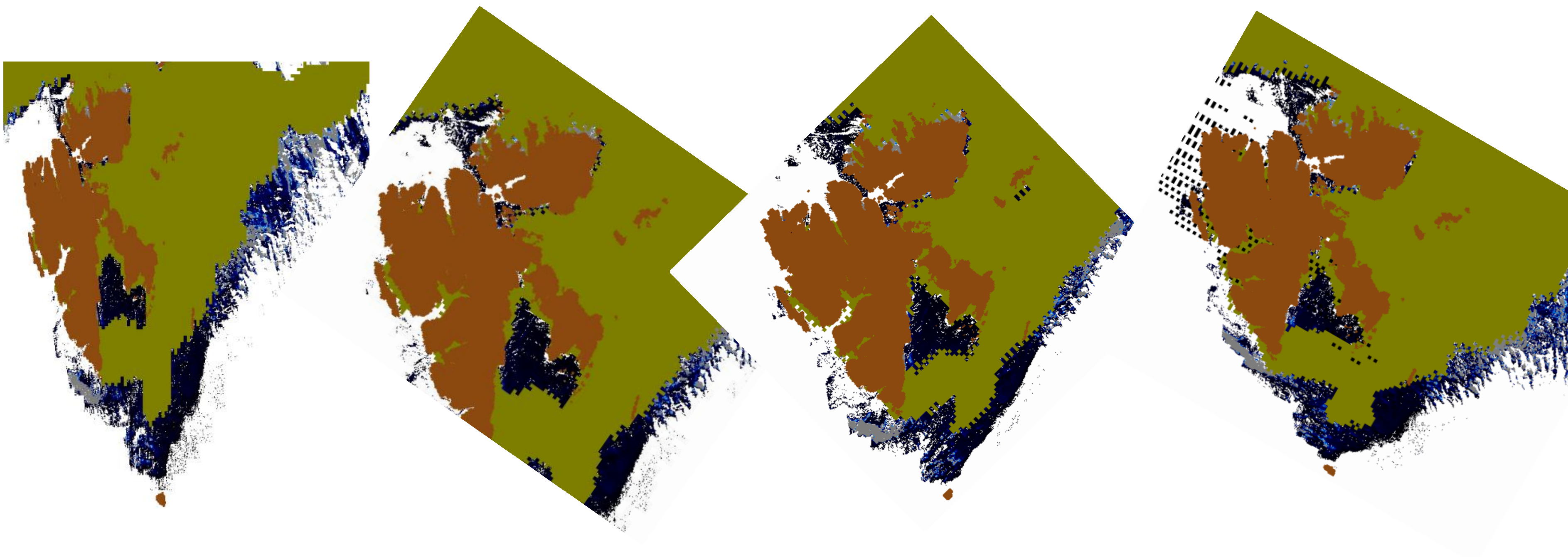
Svalbard winter 2010/2011



21-12-2010 02-01-2011 01-02-2011 08-02-2011

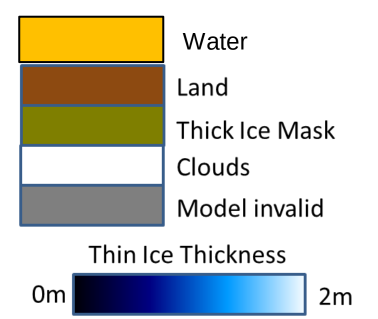


Concistency between same-day estimates



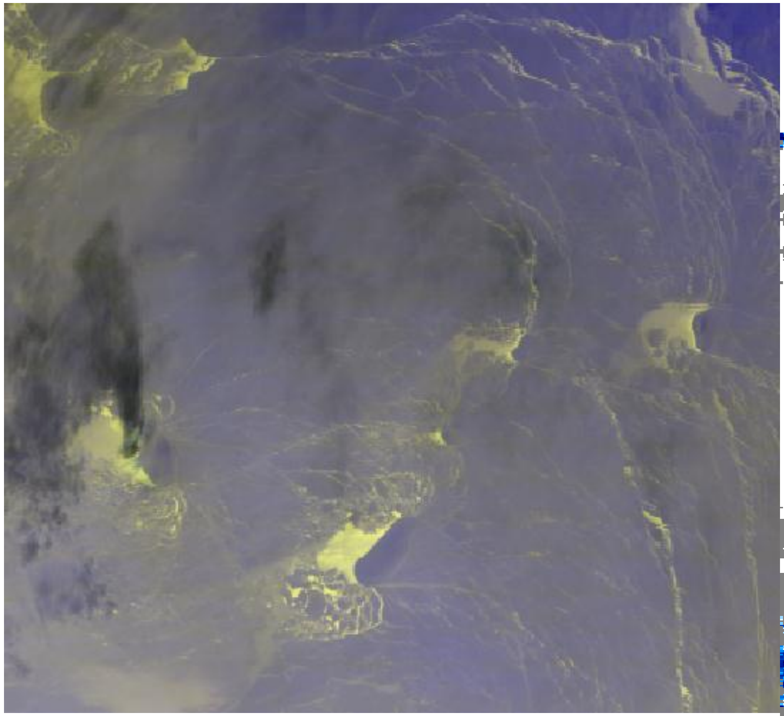
01:30 03:05 04:45 08:00

Svalbard, 2011-01-02

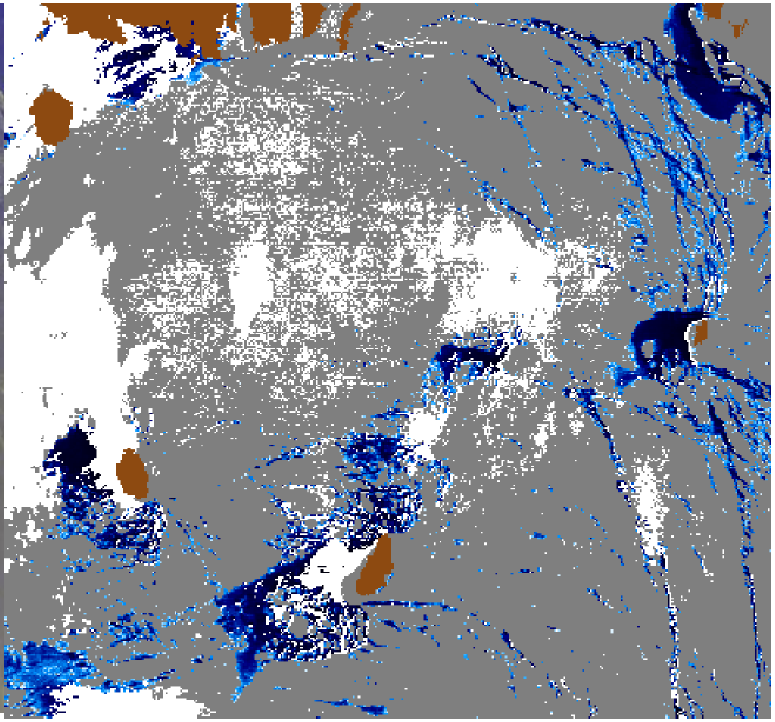


Undetected Haze

Kara sea 11-02-2011



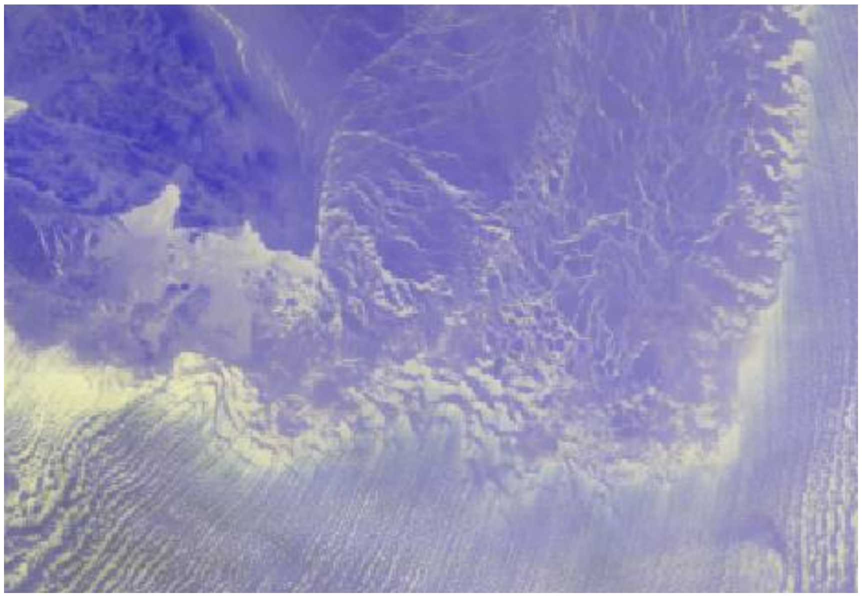
Thermal



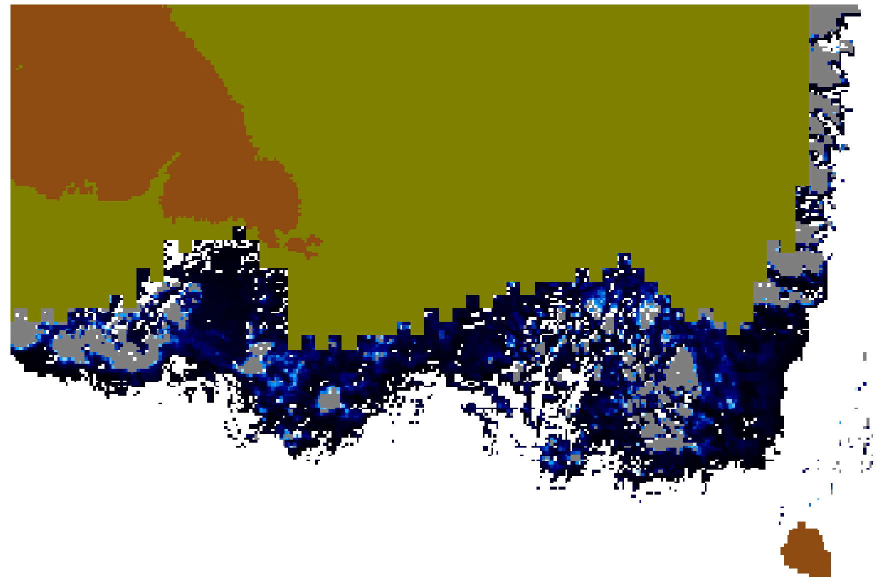
Thin ice product

Results: Night time data

Svalbard
2011-02-01



Thermal image



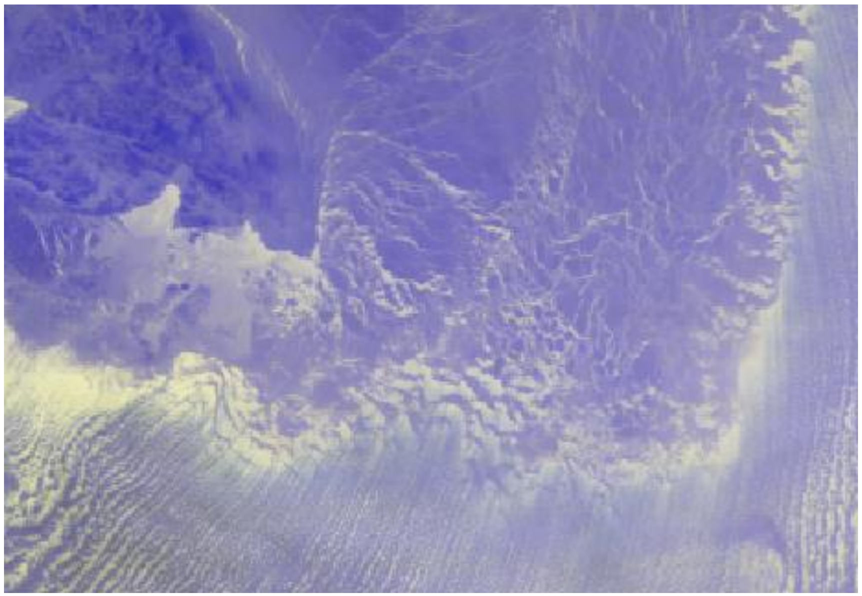
Output product

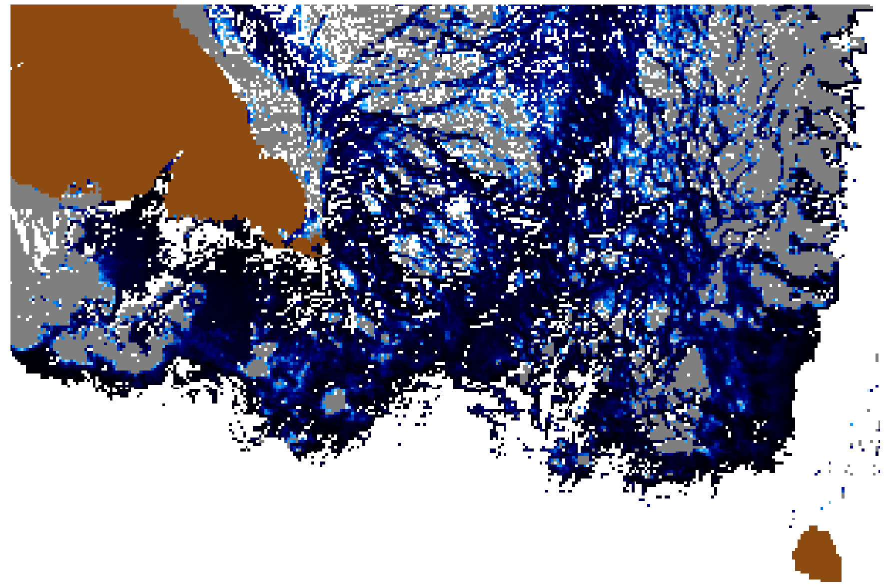
Water
Land
Thick Ice Mask
Clouds
Model invalid

Thin Ice Thickness
0m 2m

Results: Night time data

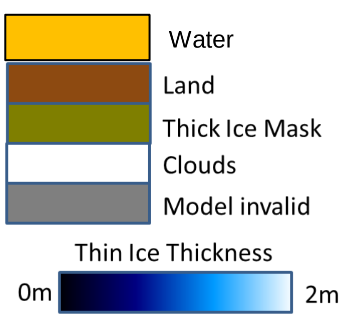
Svalbard
2011-02-01





Thermal image

Output product
(thick ice mask removed)



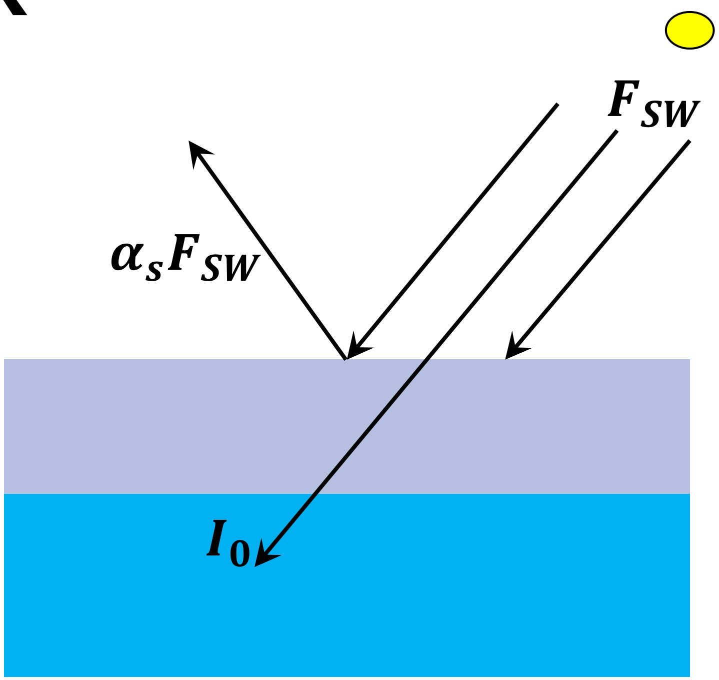
Daytime images

- More data available
- All bands available – better cloud masking
- Need to describe heat flux from solar radiation

Solar radiation heat flux

$$F_r = (1 - \alpha_S)F_{SW} - I_0$$

$$I_0 = i_0(1 - \alpha_S)F_{SW}$$



Albedo estimated from
MODIS SR product (Liang, 2000)

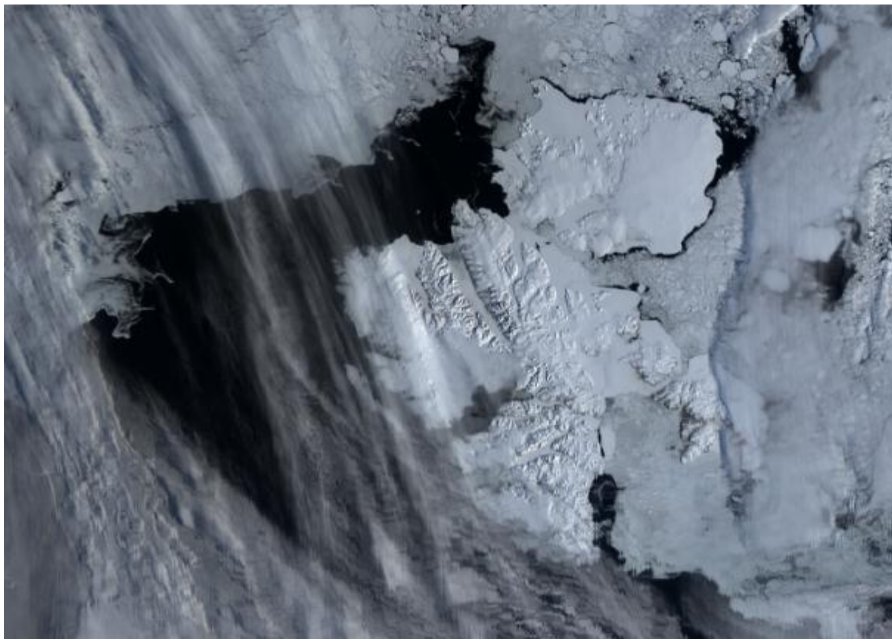
Transmittance set constant for ice
and snow

$$F_{SW} = \frac{S_0\,(\cos\theta)^2}{1.2\cos\theta + (1+\cos\theta)10^{-3}e_0 + 0.0455}$$

Shine (1984)

$$F_r + F_l^{dn} - F_l^{up} + F_s + F_e + F_c = 0$$

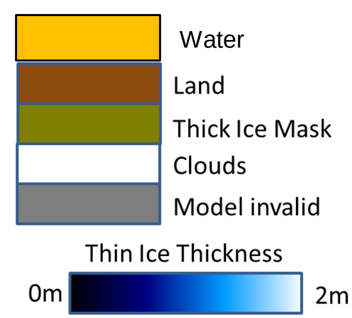
Results: Daytime data



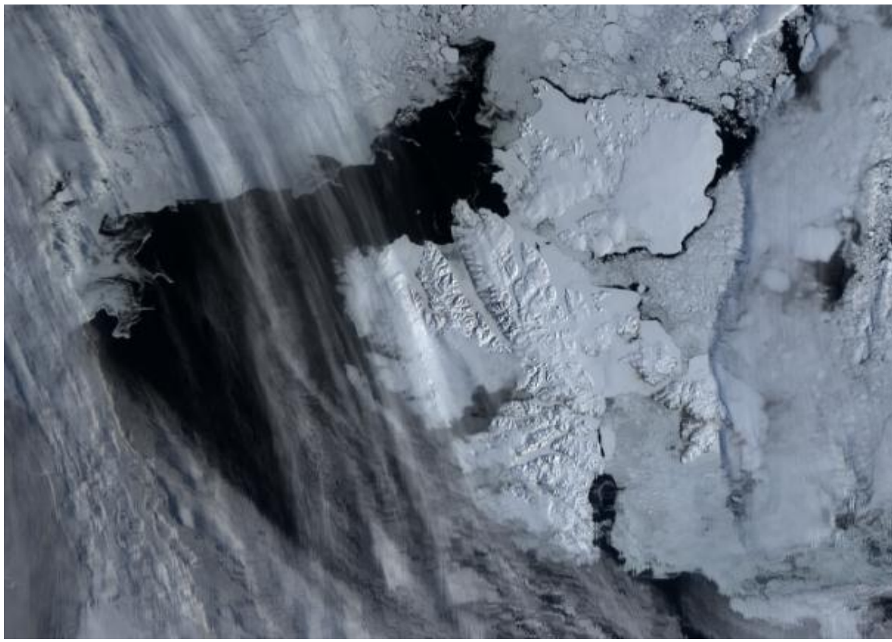
Reflectance color composite

Thin ice product

No detection of thin ice

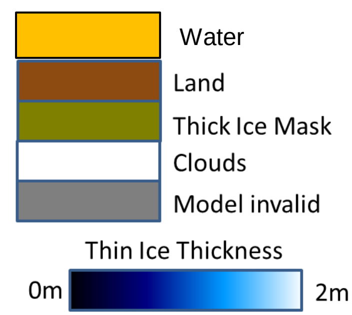


Results: Daytime data



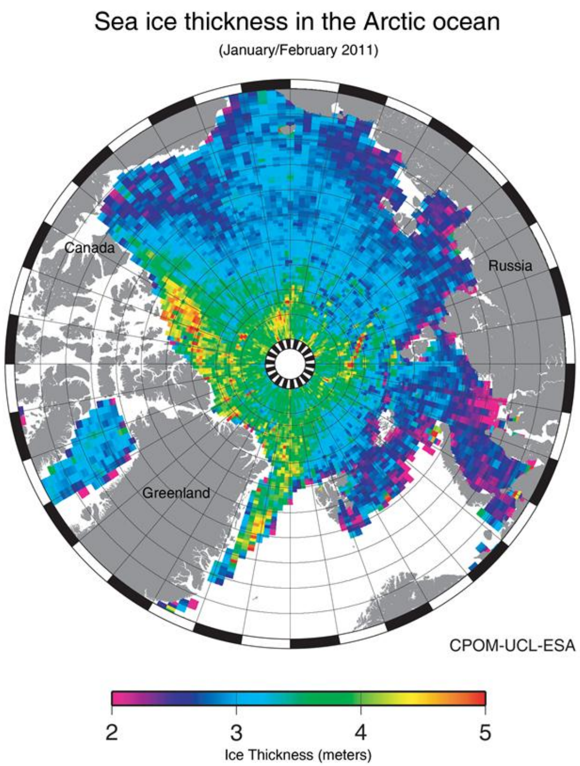
Reflectance color composite

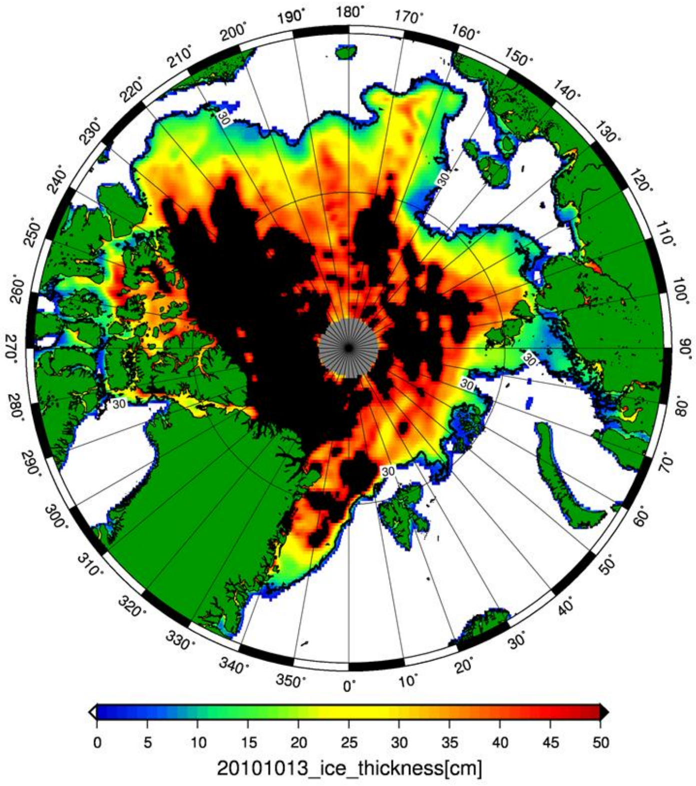
Thin ice product



No detection of thin ice

Other sea ice thickness missions

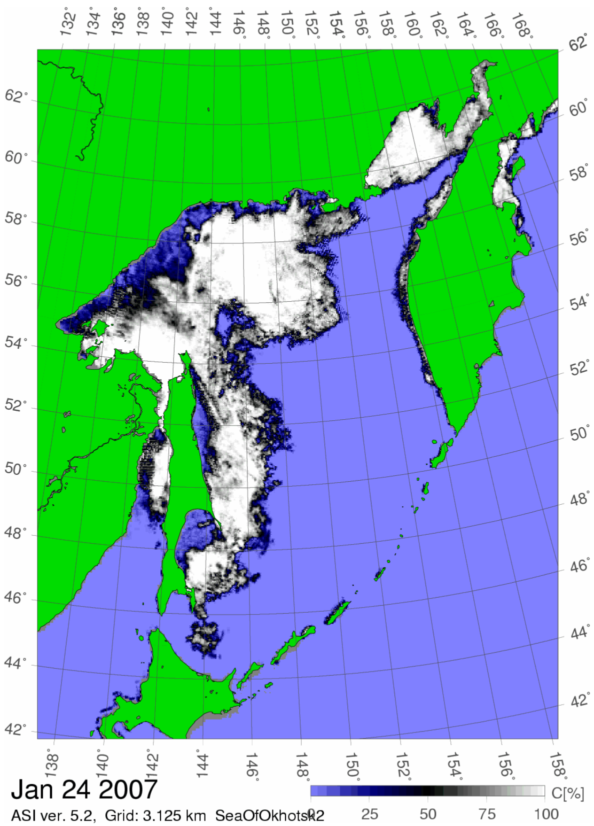


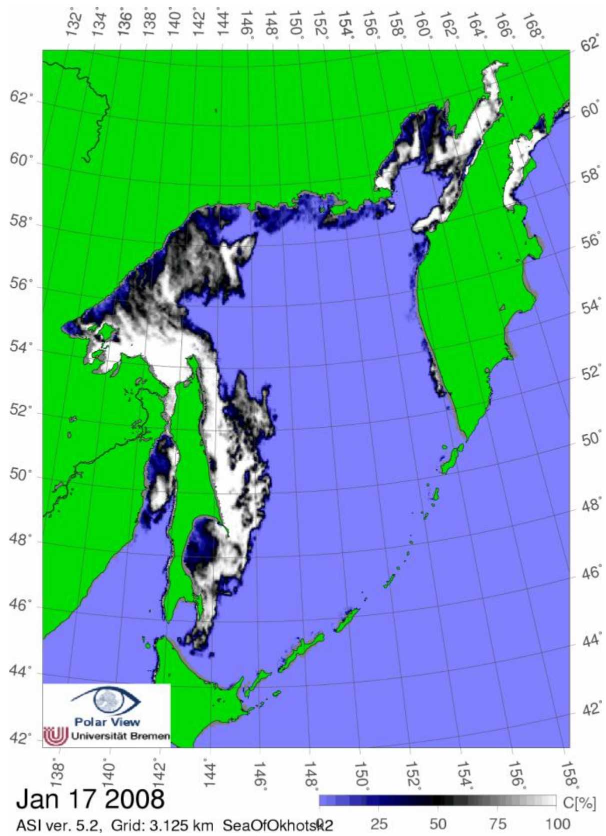


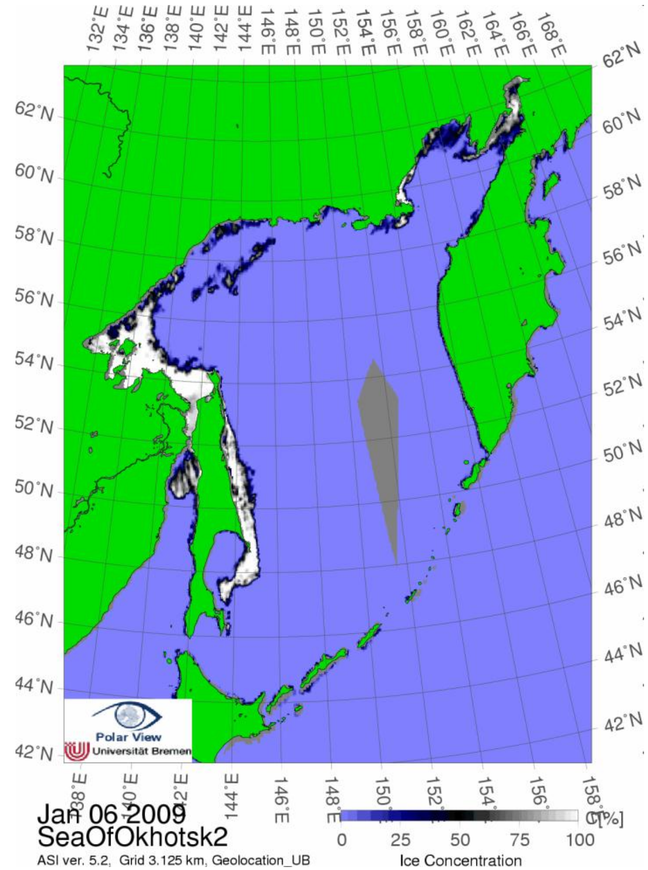
CryoSat

SMOS

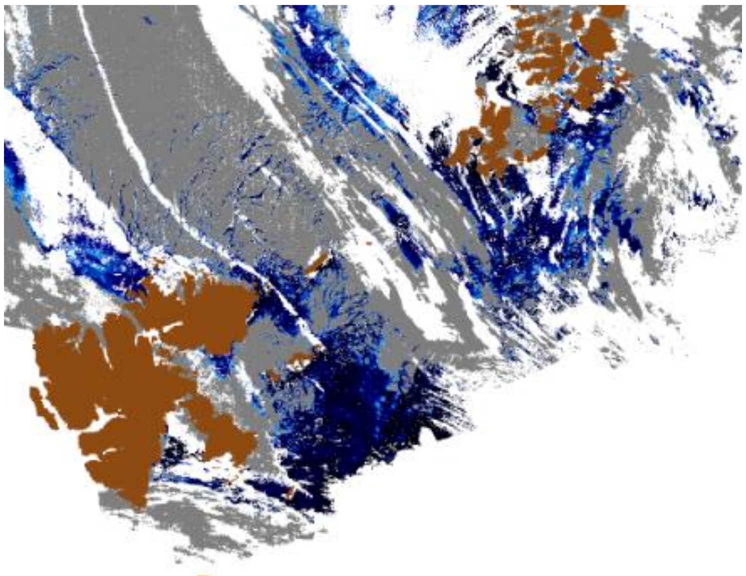
AMSR-E, SSMI sea ice concentration



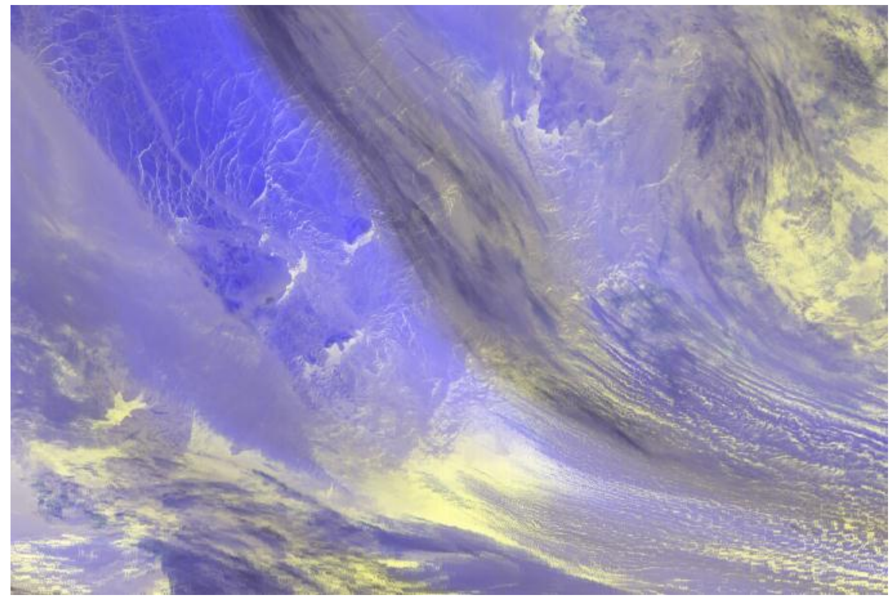




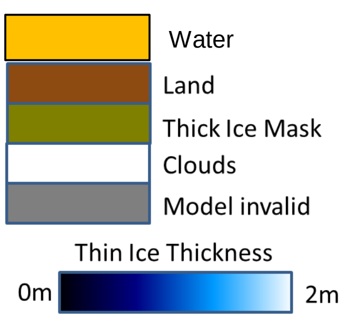
Not all clouds are detected



Thermal composite



Thin ice product



Svalbard 13-12-2010