# Automatic retrieval of thin sea-ice thickness by remote sensing

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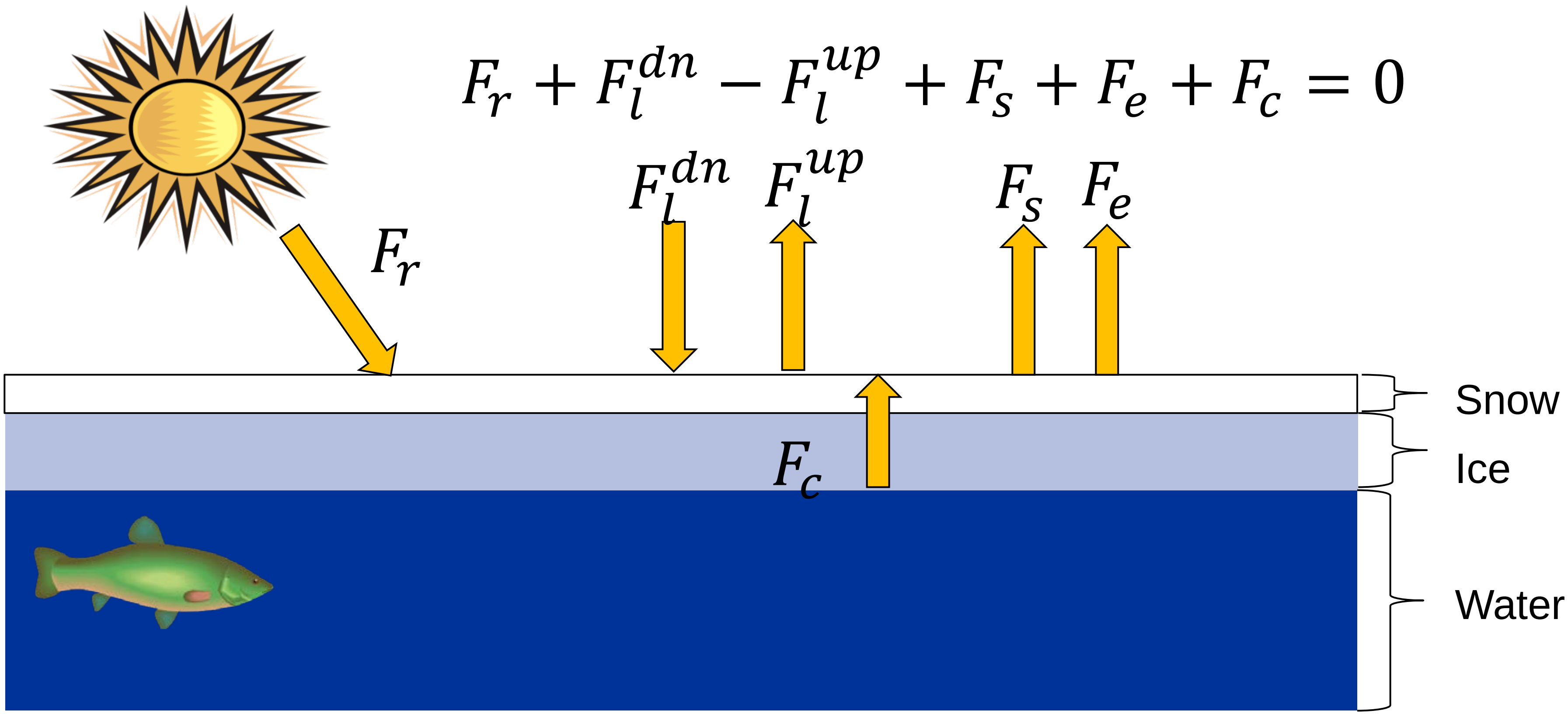
# Basic idea

- 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

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






Yu & Rothrock (1996)

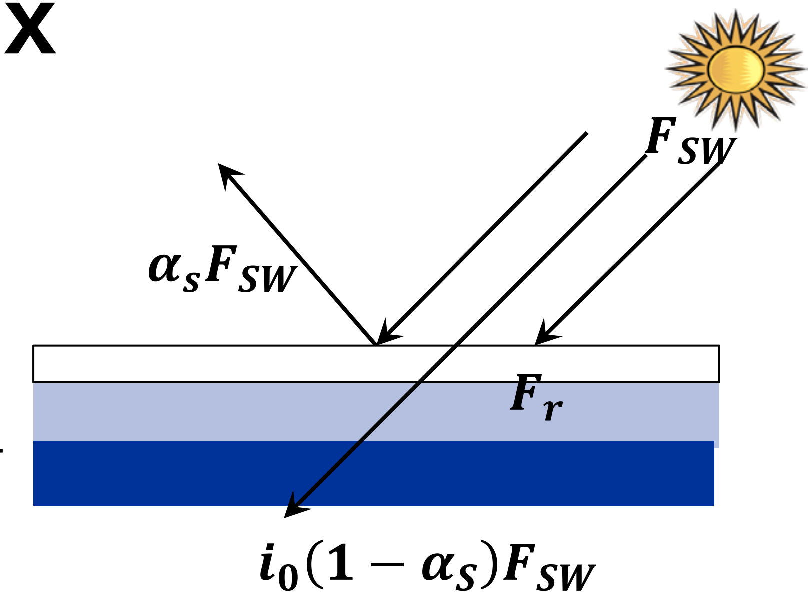
# Modelling of the heat fluxes

- Conductive heat flux: $$F_c = \frac{k_i k_s (T_f - T_s)}{k_s H + k_i h}$$
- Upwelling longwave heat flux: $$F_l^{up} = \varepsilon_i \sigma T_s^4$$
- Downwelling longwave heat flux: $$F_l^{dn} = \varepsilon_a \sigma T_a^4$$
- Latent heat flux: $$F_e = \rho_a C_e L u_2 (e_a - e_{s0}) 0.622 / P_a$$
- Sensible turbulent heat flux: $$F_s = const$$
- Short wave heat flux (for night images): $$F_r = 0$$

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

# Solar radiation heat flux

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




Incoming shortwave heat flux from Shine (1984):

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

**Albedo** and **transmittance** from parametrization by Grenfell (1979):

$$\alpha_S = \alpha_S(h_{ice}, h_{snow})$$

$$i_0 = i_0(h_{ice}, h_{snow})$$

$F_r$: shortwave radiation heat flux
$F_{SW}$: incoming shortwave heat flux
$\alpha_S$: surface albedo
$i_0$: ice/snow transmittance
$S_0$: solar constant
$e_0$: vapor pressure @surface
$\theta$: solar zenith angle

# Snow model (based on Doronin 1971)

- Wind and precipitation changes the snow distribution close to land
- $h = 0$ for $H < 5$cm

  $h = 0.05H \times L$ for $5\text{cm} <= H <= 20\text{cm}$

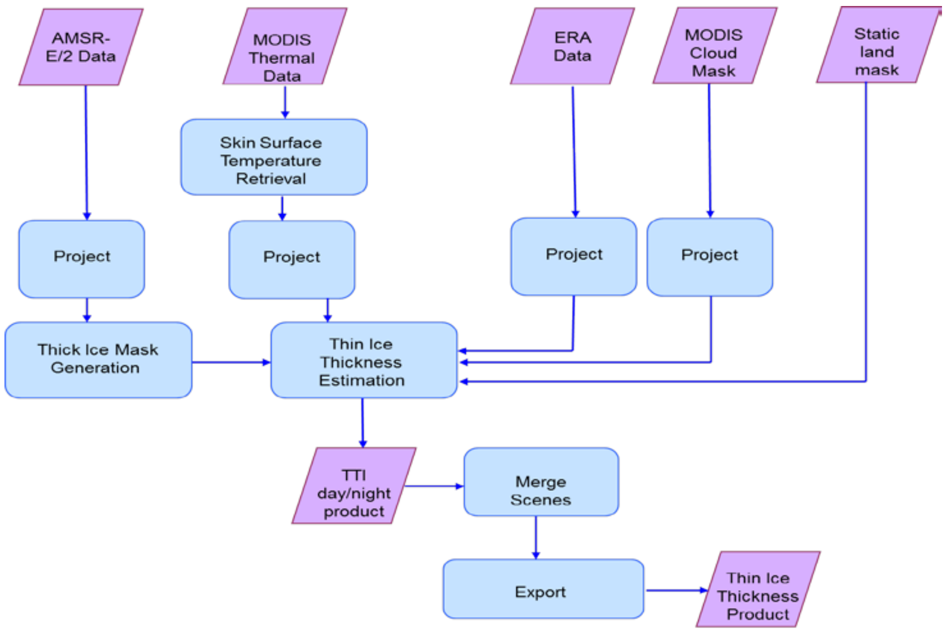
  $h = 0.25H \times L$ for $H > 20$cm
- *L* is a land proximity factor
- Obtained by smoothing a land mask with Gaussian filter *(σ=5km)* and scaling to *L=3.5* close to land, and *L=1.0* far away
- Accounts for more snow close to land

# Automatic processing chain

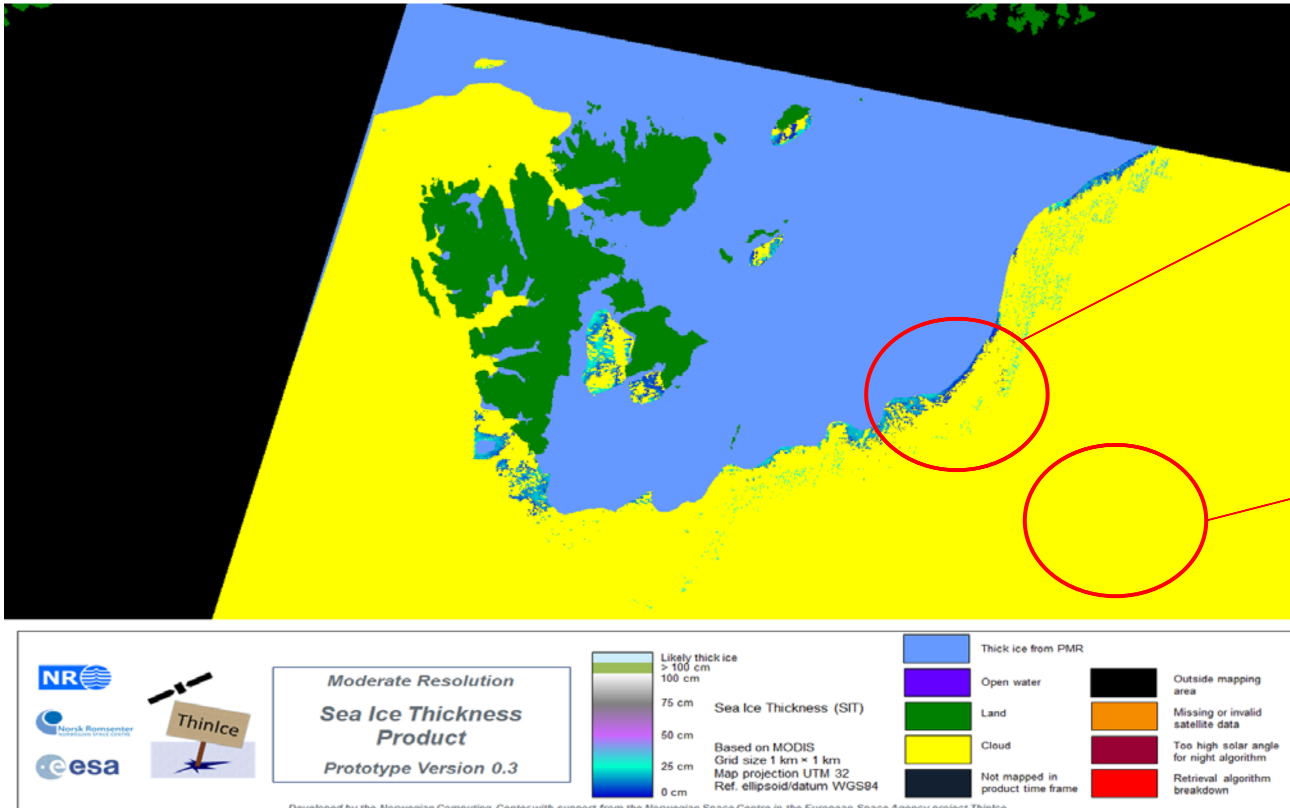
- Get $T_s$ (via Key's algorithm) from thermal MODIS bands of Aqua
- $T_a$ and $u_2$ from re-analysed ERA interim data
- Estimate ice thickness, H, for every pixel in image
- Use AMSR-E/AMSR2 microwave images to exclude areas with thick ice:

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

- Mask out land and clouds (using MODIS cloud mask)



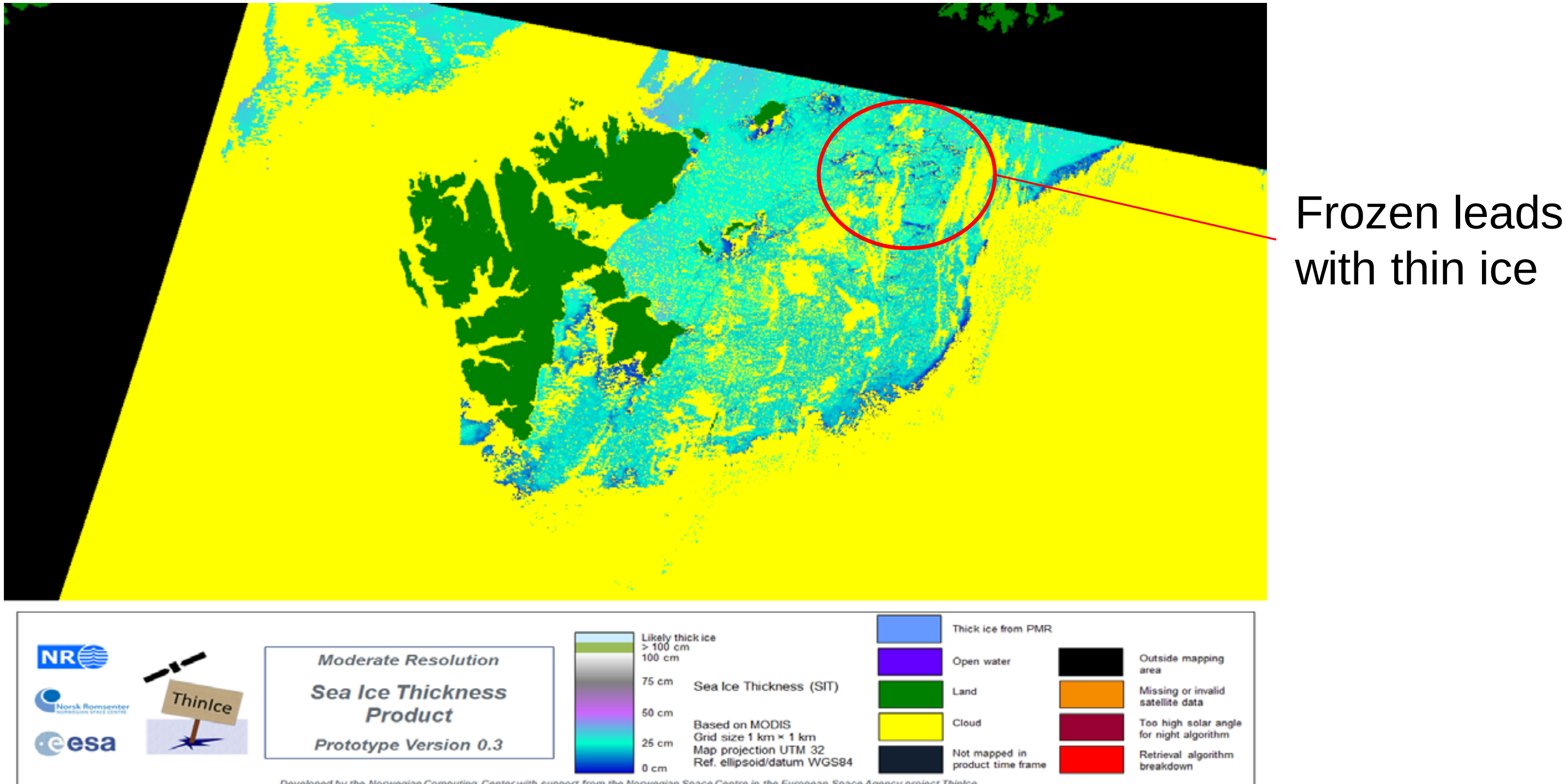
# Svalbard April 6, 2013, 01:25




Thin ice along the edge of the thick ice

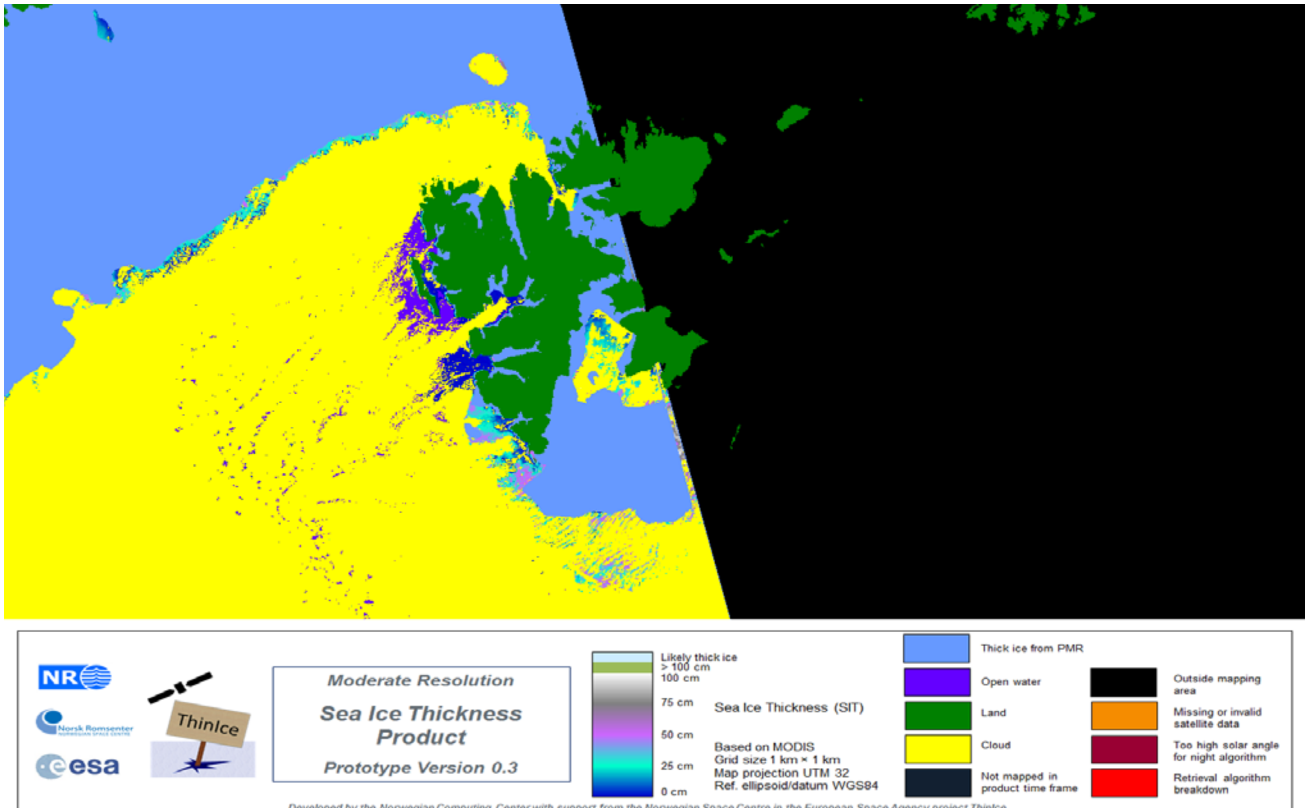
Very conservative cloud mask

# Svalbard April 6, 2013, 01:25

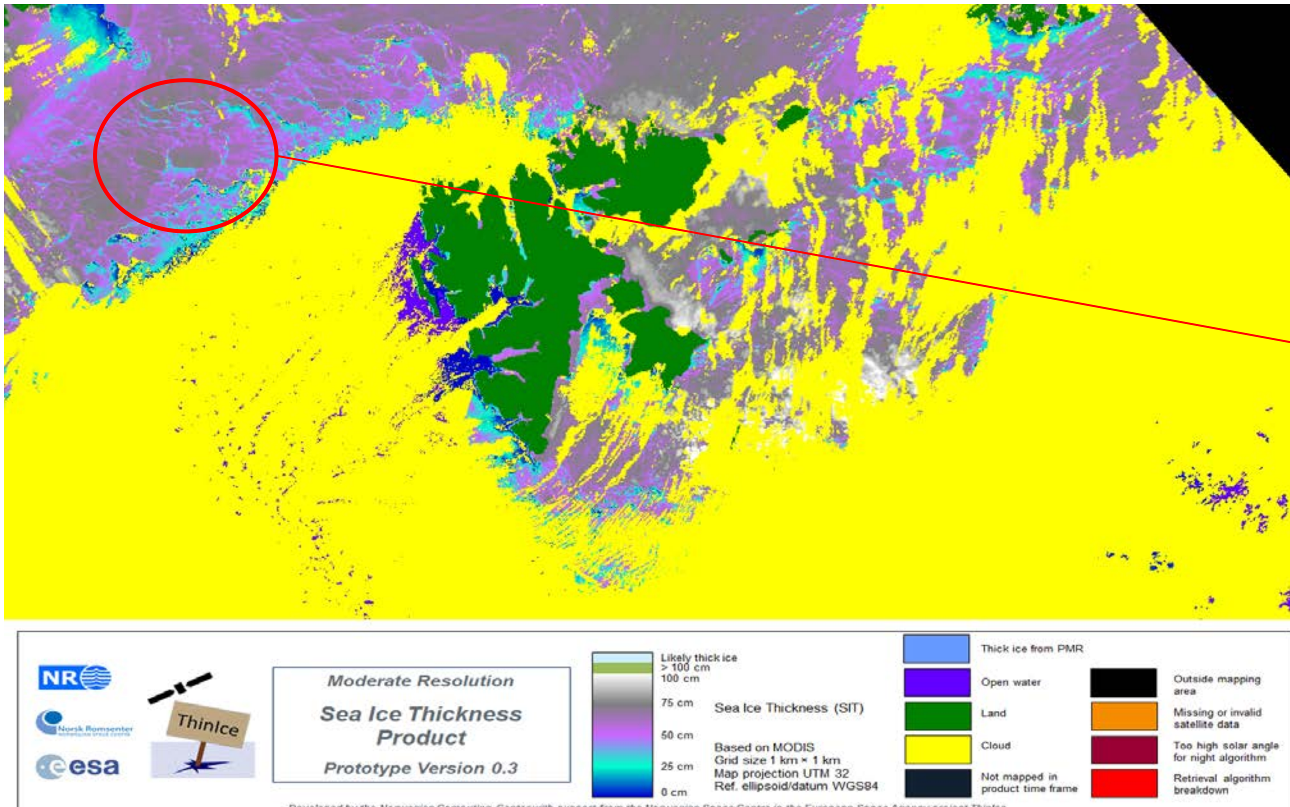



With thick ice mask removed

# Svalbard April 7, 2013, 10:15



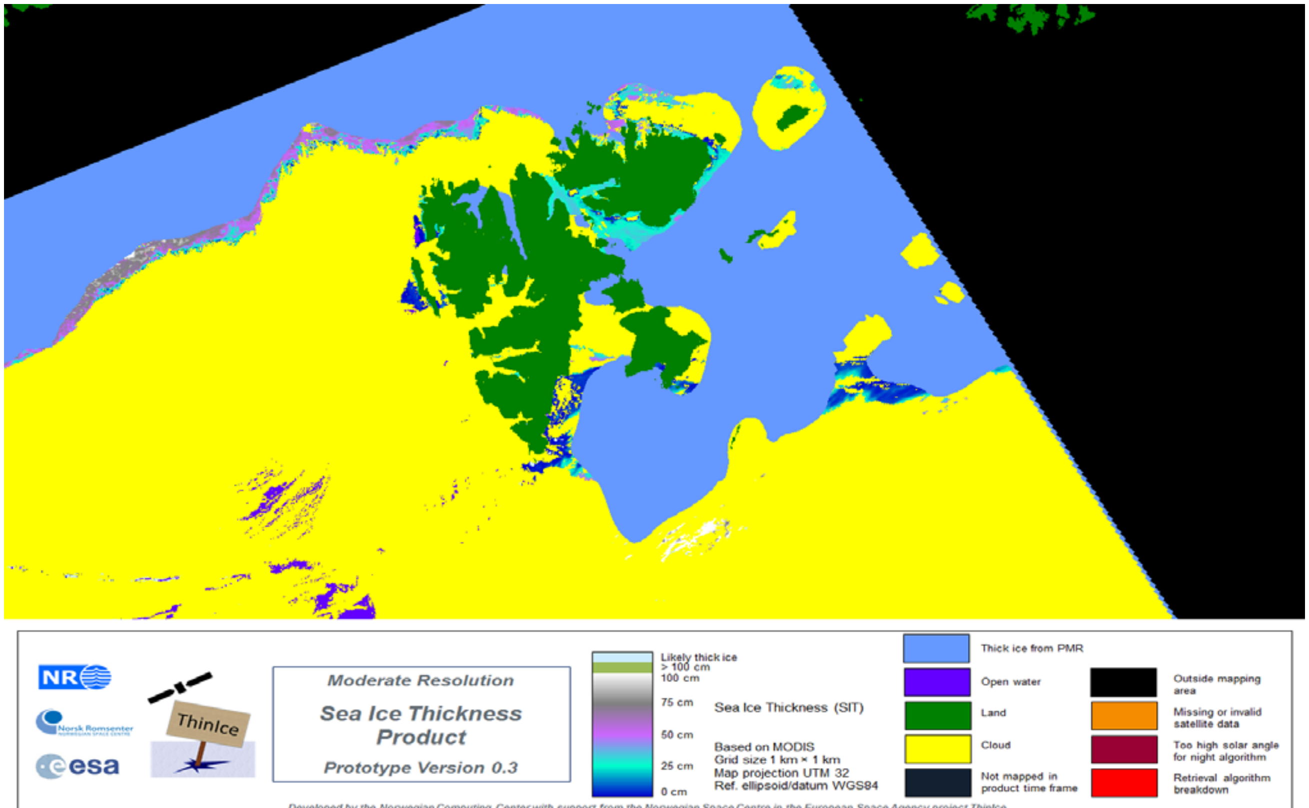
# Svalbard April 7, 2013, 10:15



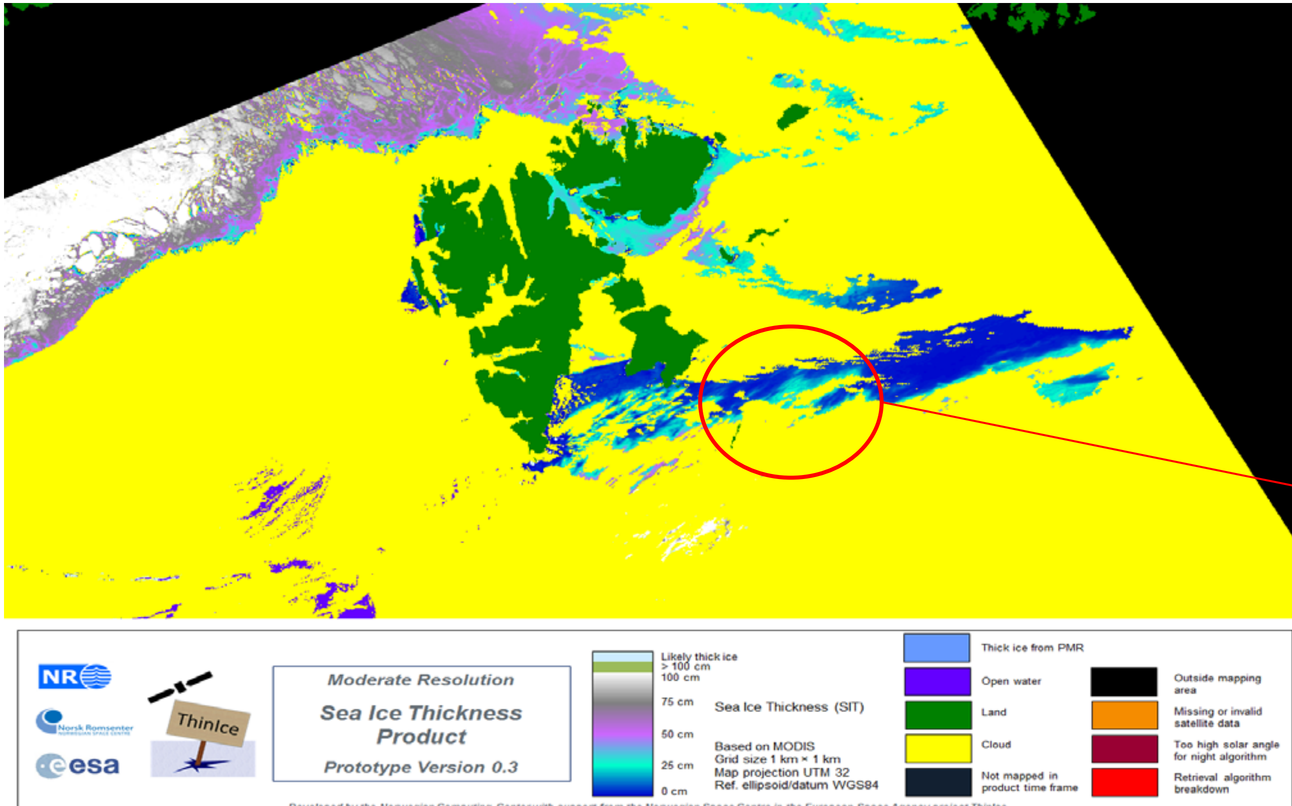

Variations in ice thickness clearly visible, though absolute ice thickness estimates are inaccurate

With thick ice mask removed

# Svalbard April 12, 2011, 10:50



# Svalbard April 12, 2011, 10:50



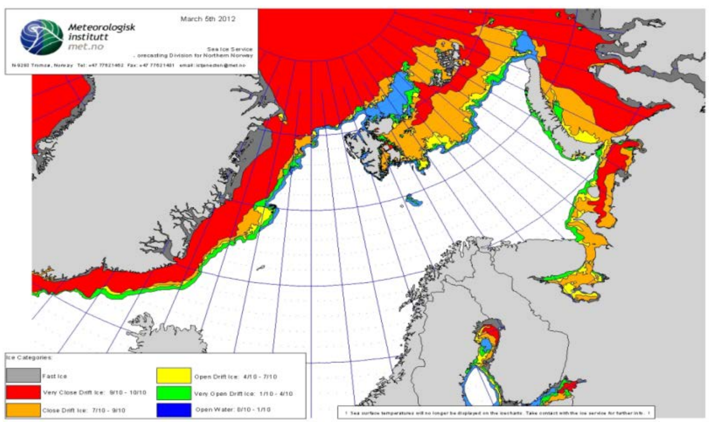

Some cloud contaminations persist

With thick ice mask removed

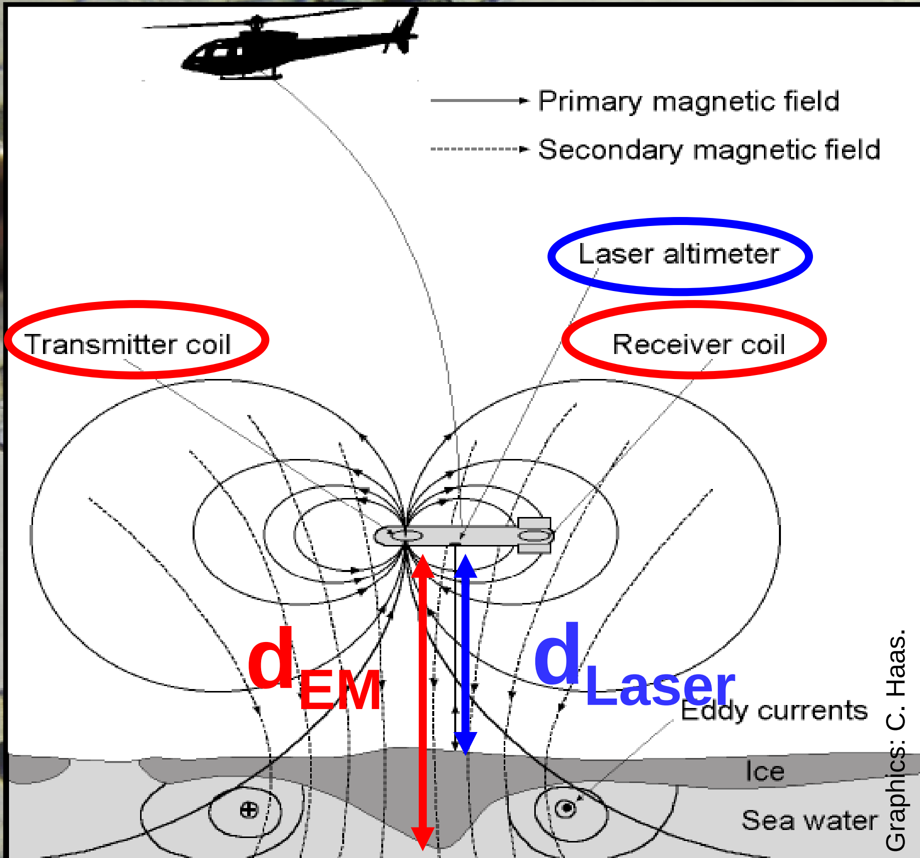
# Validation

- In situ ice thickness measurements on Svalbard by Norwegian Polar Institute
- Sea ice charts from Norwegian Meteorological Institute

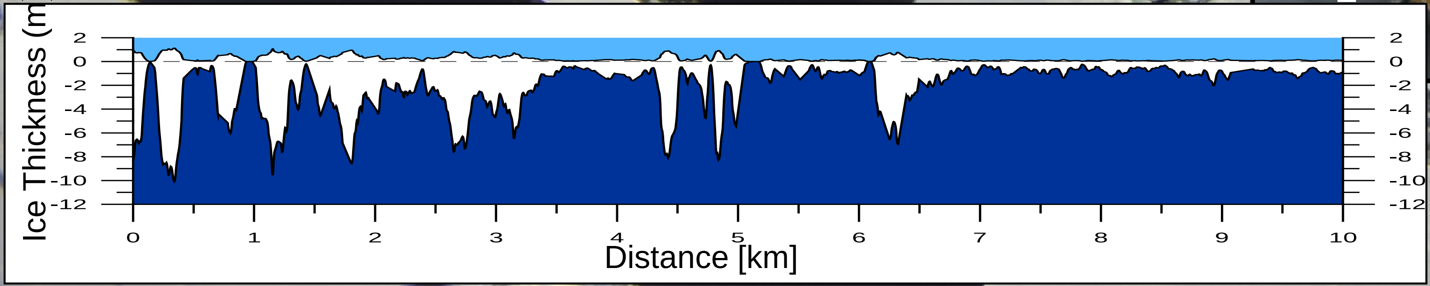
Image credits: A. Renner, Norwegian Polar Institute



# Airborne Methods

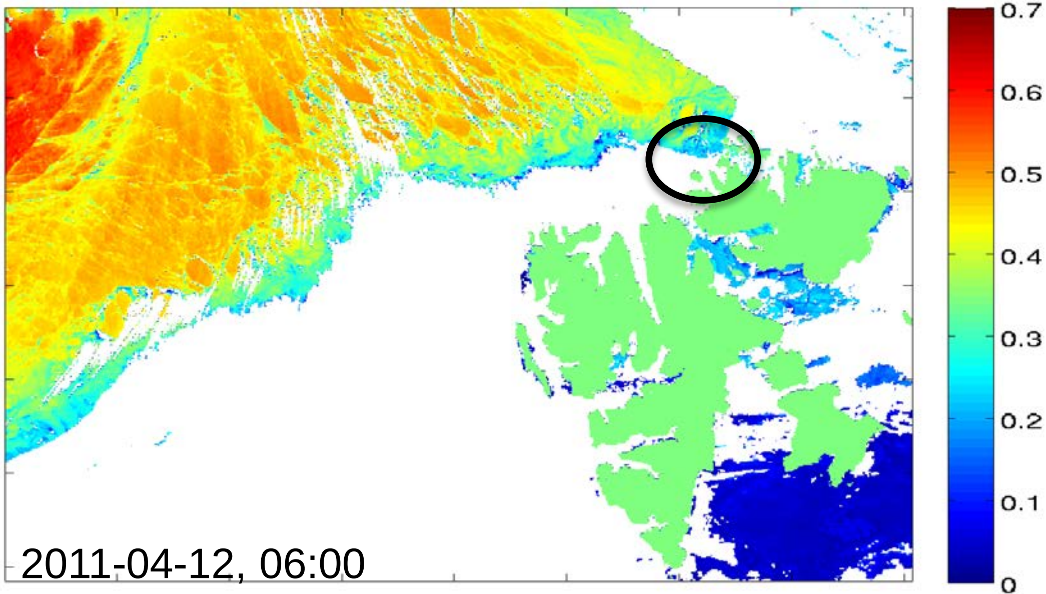


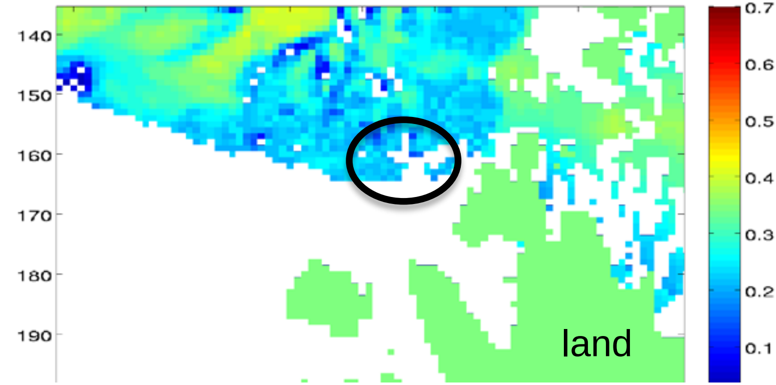

- EM Bird (ice thickness)
- Laser Altimetry
- Airborne photography

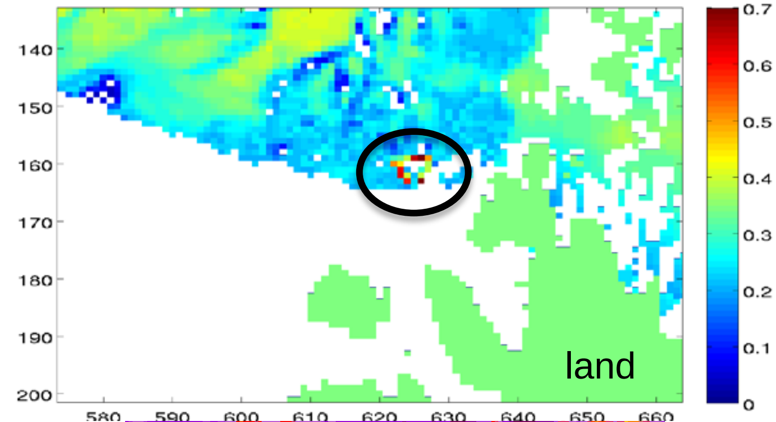



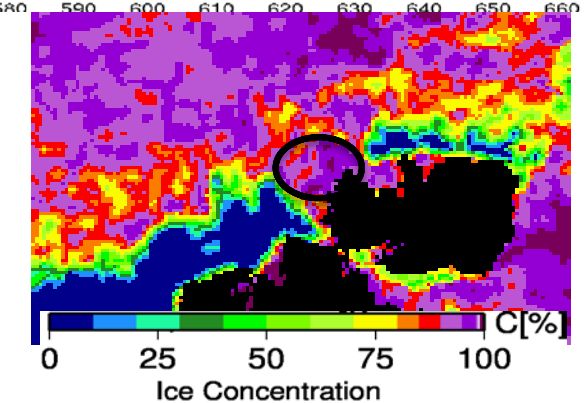
# North of Svalbard

- ► Apr 2011: MODIS shows reasonable spatial thickness distribution
- ► Nearly coincident EM-Bird ice thickness is thicker (Mean ~20 cm; Mode ~10 cm)
- ► Ice concentration might play a role: EM-Bird measures ice thickness without open water

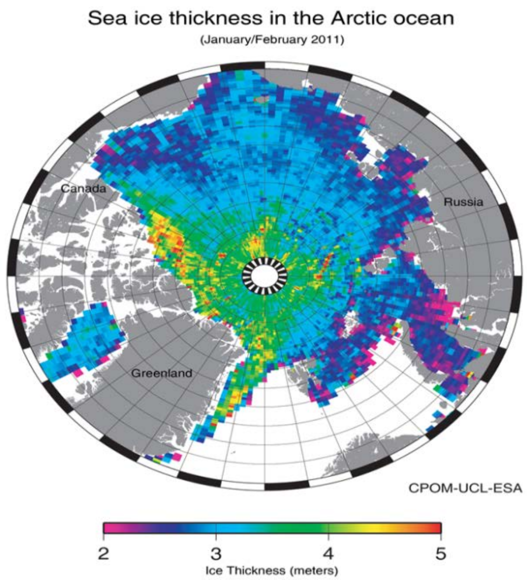


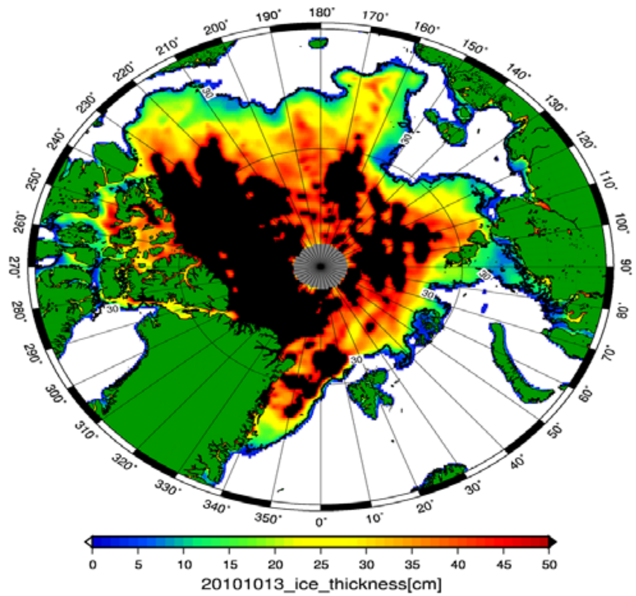



# Other sea ice thickness missions




CryoSat

Ice thickness H > 2m
Spatial resolution: 250m
Low temporal resolution




SMOS

Ice thickness H < 0.5m
Spatial resolution: 15 km
High temporal resolution

# Conclusions and way forward

Conclusions:

- Automatic production of high resolution sea ice thickness maps (~1 km) using both day and night time data
- Has applications in ship navigation, numerical weather forecasting, climate studies and studies of microwave ice products

Future work:

- Improve modelling of physical parameters to increase accuracy of ice thickness estimates
- Acquire thick ice mask from thermal data (higher spatial resolution)
- Validation and intercomparison

# Backup slides

# Initial test results

| RMSD | $h_{max}$=35cm | $h_{max}$=50cm | $h_{max}$=80cm |
|---|---|---|---|
| 2013-04-06, 01:25 | 13.3 cm | 18.5 cm | 22.7 cm |
| 2013-04-07, 02:05 | 12.8 cm | 13.4 cm | 16.1 cm |
| 2013-04-07, 03:45 | 8.9 cm | 11.6 cm | 18.2 cm |
| 2013-04-07, 07:00 | 9.7 cm | 11.9 cm | 19.4 cm |
| 2013-04-07, 08:35 | 10.8 cm | 12.7 cm | 23.5 cm |
| 2013-04-07, 10:15 | 11.1 cm | 18.8 cm | 23.7 cm |
| 2013-04-07, 11:55 | 9.1 cm | 11.8 cm | 20.4 cm |
| Total RMSD | 11.2 cm | 14.9 cm | 20.3 cm |

$$RMSD = \sqrt{\langle (h_{est} - h_{embird})^2 \rangle}$$

# Backup: empirical models

- Sea ice salinity:

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

  S = 7.88 - 1.59H  for H > 0.4m

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

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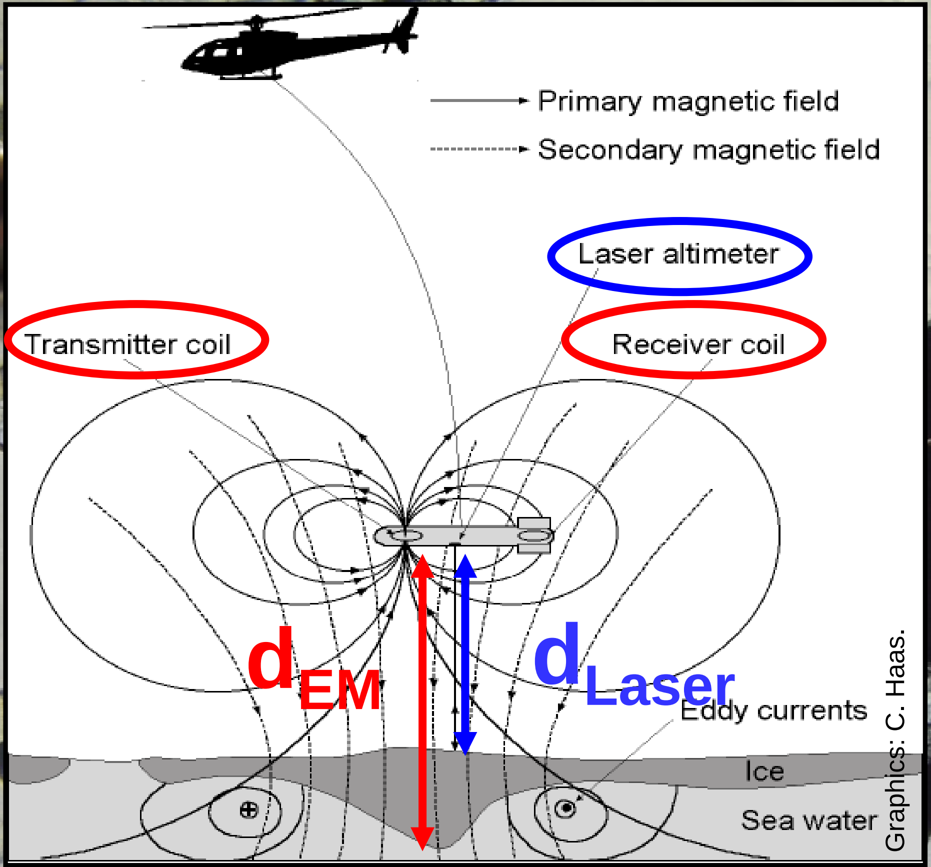


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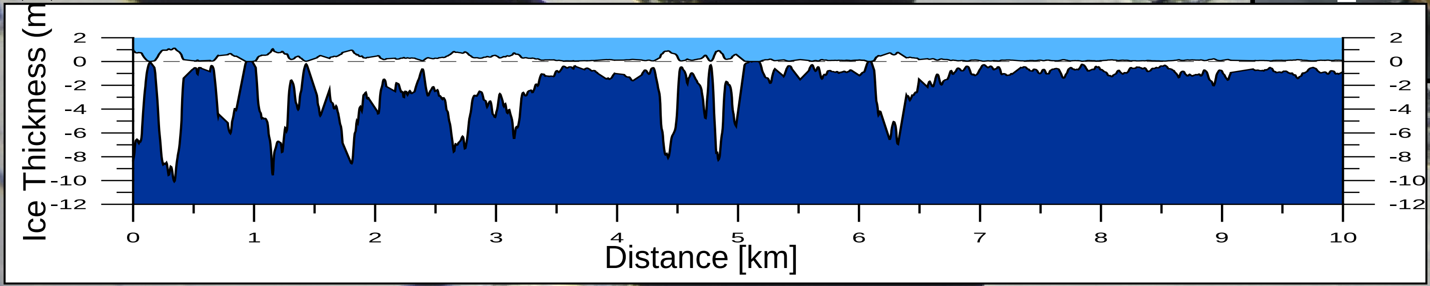
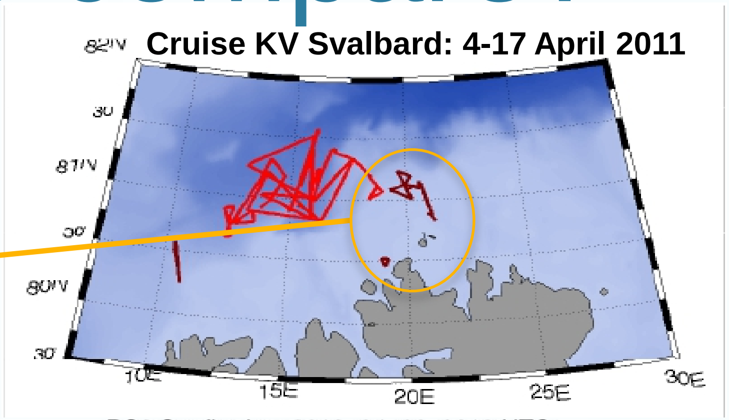
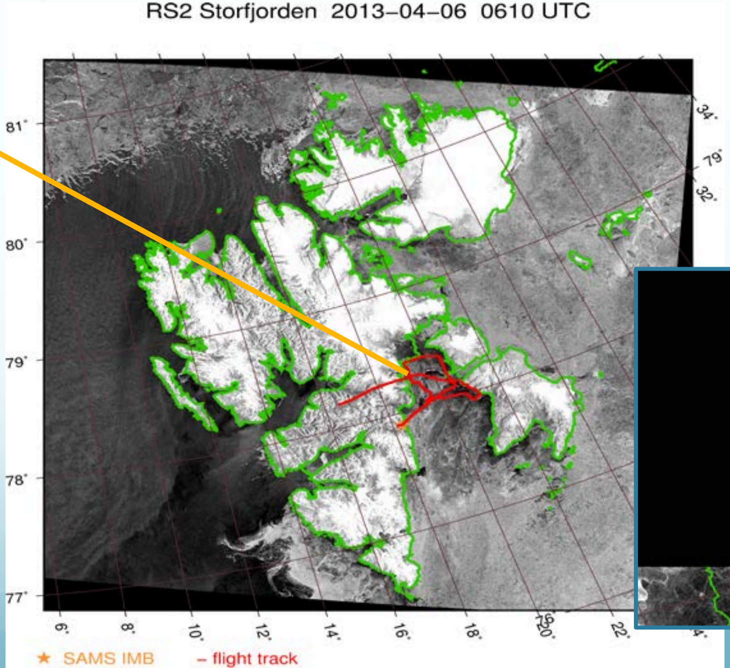
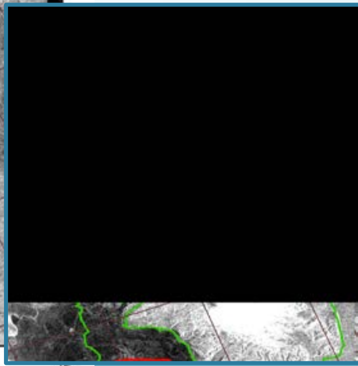


# What do we compare?

- Two EM-Bird campaigns
  - April 2011: North of Svalbard
  - April 2013: Storfjorden, Svalbard



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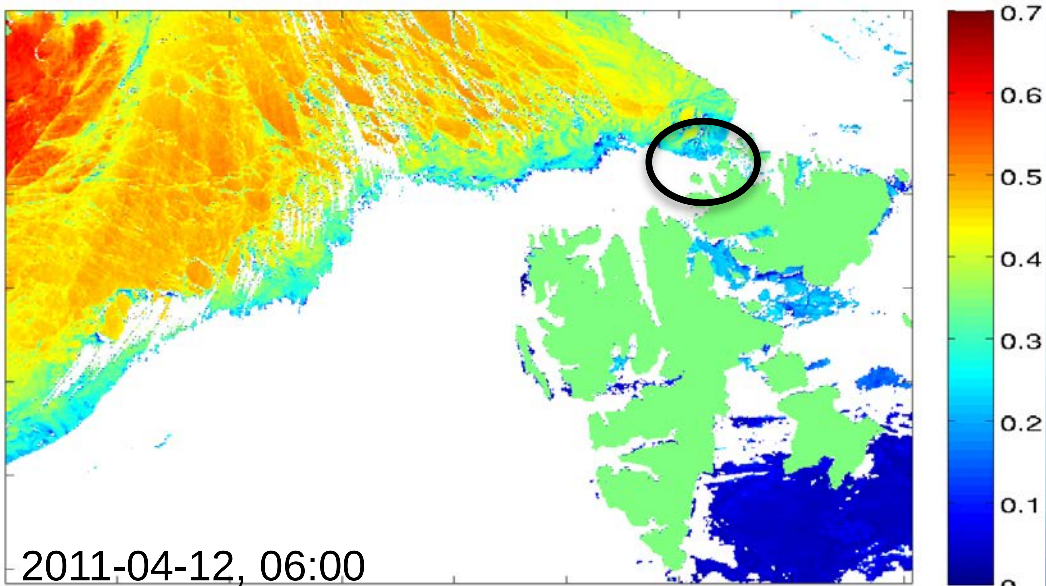
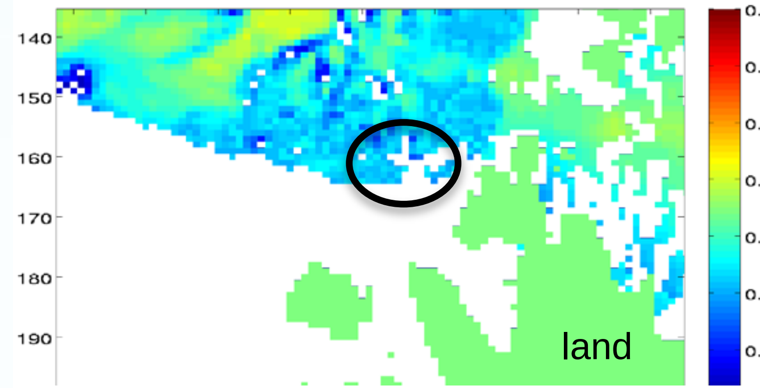
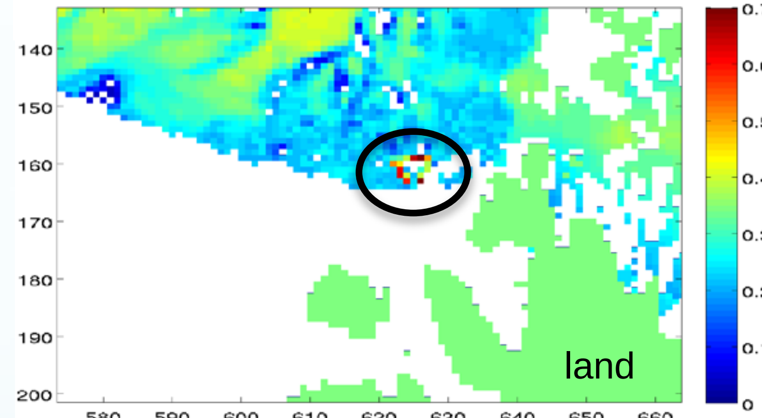
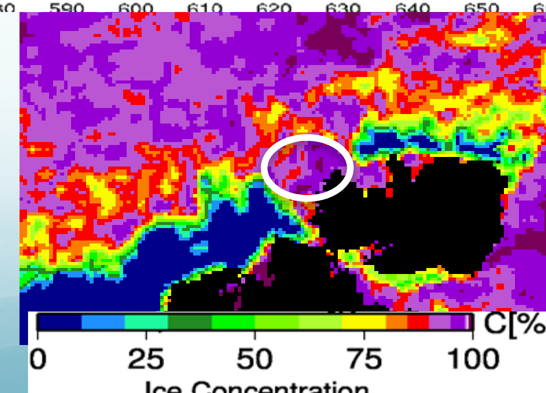
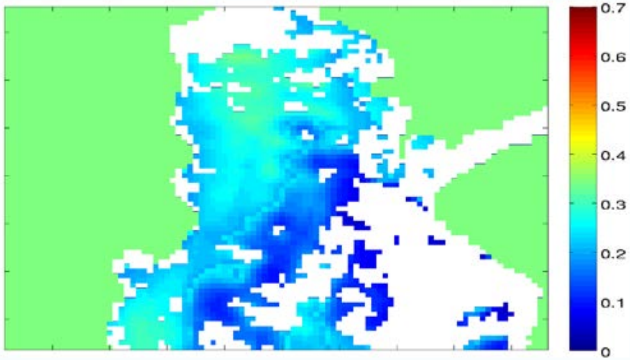


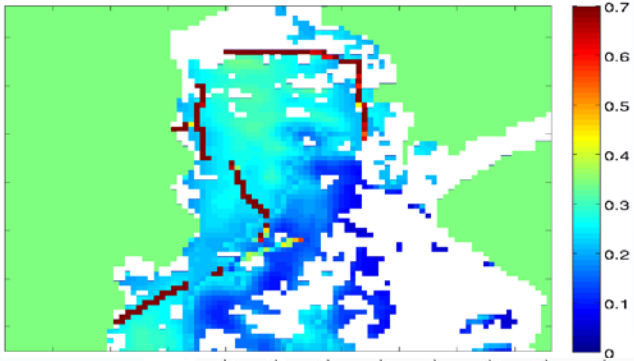



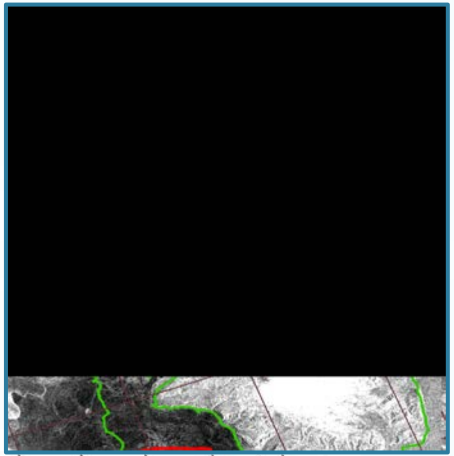



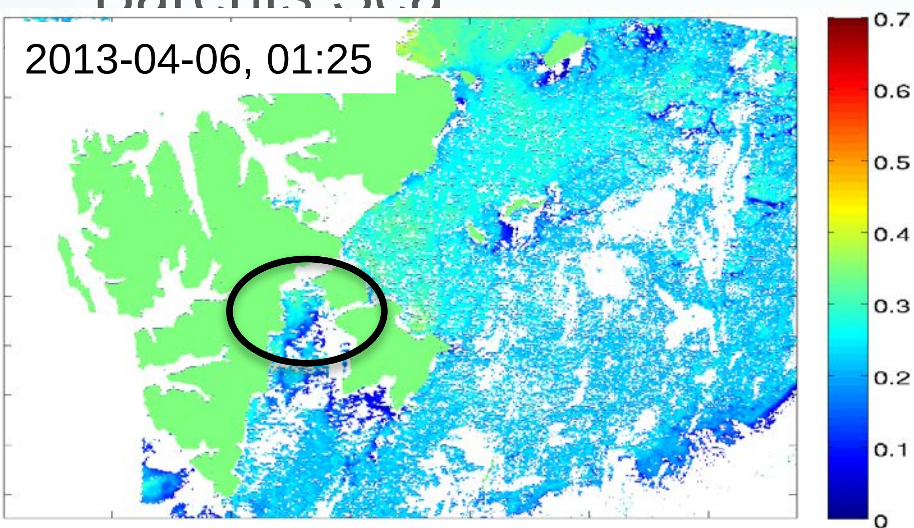
# Storfjorden

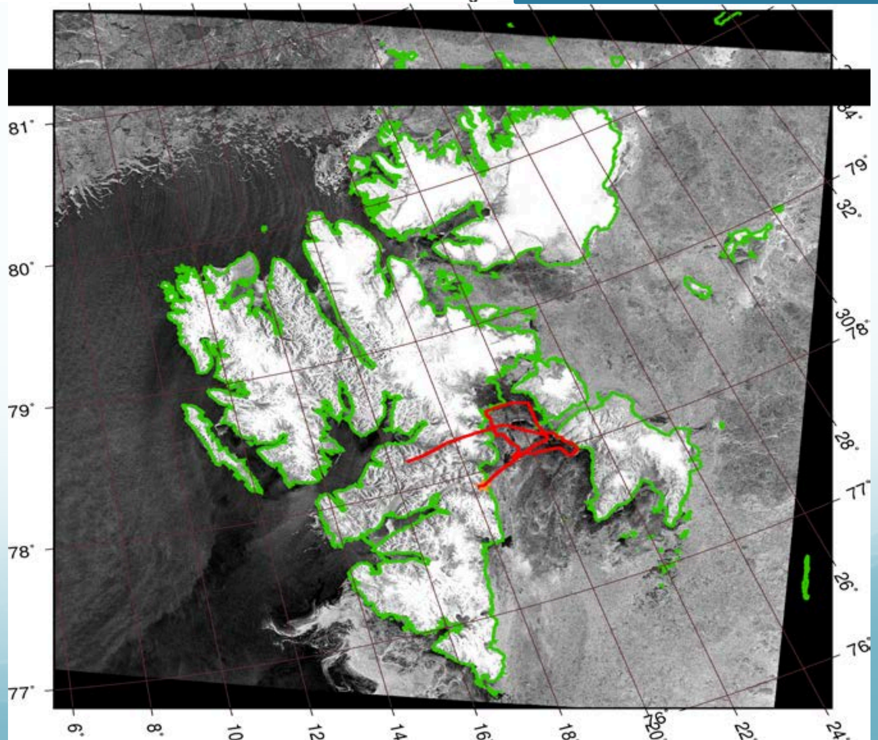


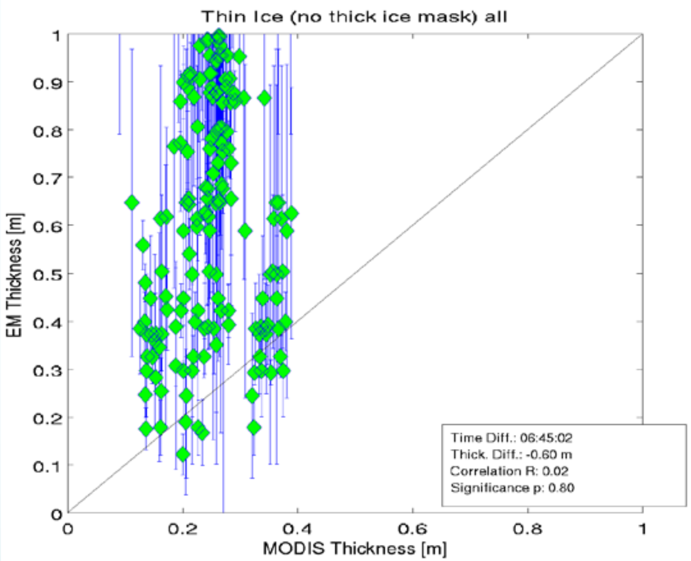
- Apr 2013: MODIS is too thin in Storfjorden and Barents Sea



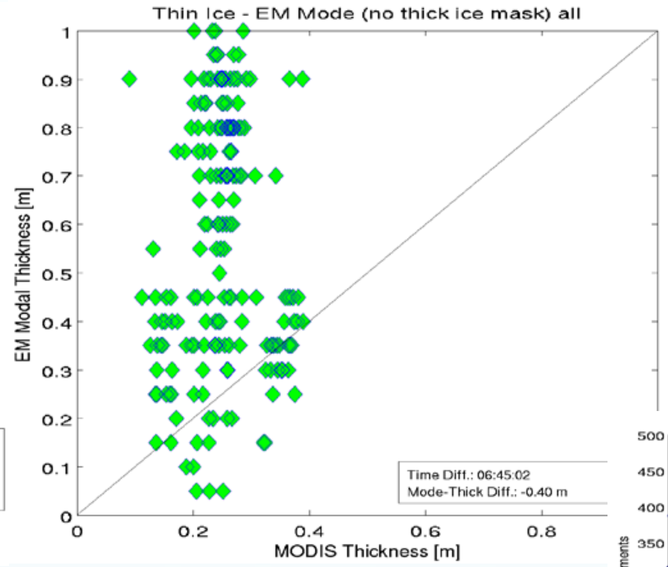



# All EM-Bird data 2011 & 2013

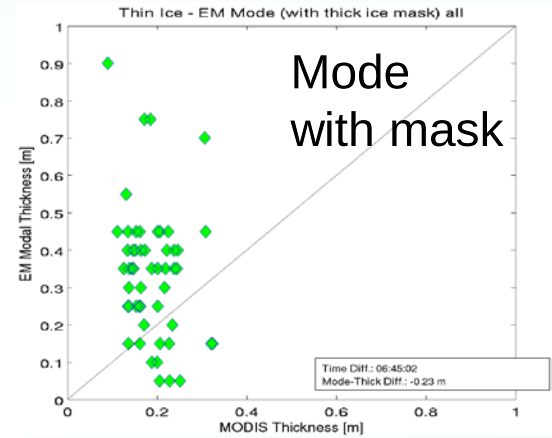
Mean



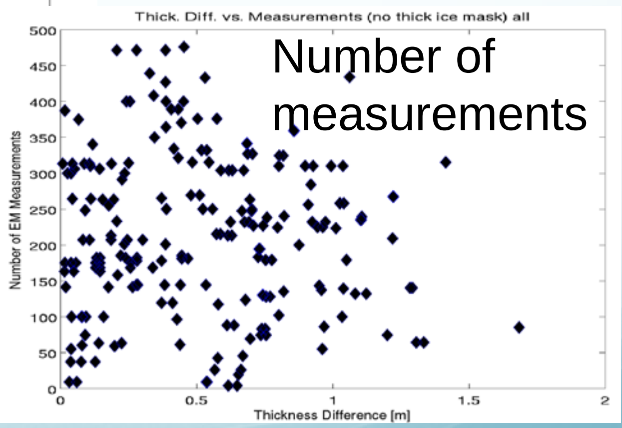

Mode




Mode with mask




Number of measurements




- Spatial distribution of MODIS thicknesses look reasonable
- First preliminary comparison: MODIS ice thickness is 60 cm thinner than mean and 23-40 cm thinner than modal EM-Bird ice thickness