SATELLITE OCEANOGRAPHY LABORATORY RSHU

Satellite microwave observations and investigations of extreme events (polar lows) in the Arctic

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Outline of the talk - I

- Polar low (PL) definition and general characteristics;
- Typical manifestations on satellite visible and infrared images;
- Development conditions;
- Difficulties in detection and study;
- Polar low monitoring from satellites:
  - Brief history;
  - Infrared and visible imagery;
  - Active microwave;
  - Passive microwave

3rd CRAICC–PEEX Workshop Climate Change for Arctic Seas and Shipping
24-25 August 2015, Copenhagen, Denmark

Outline of the talk - II

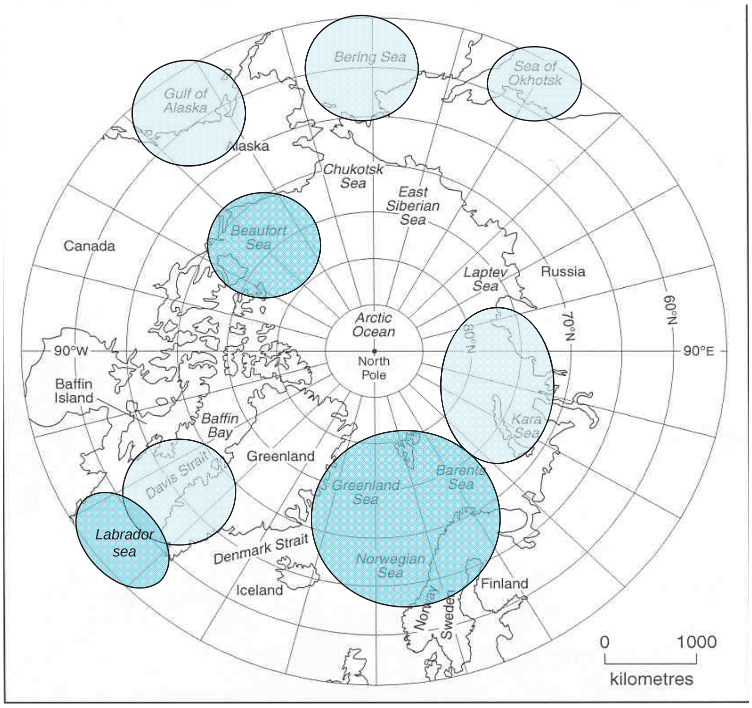
- A new approach for PL detection and tracking;
- SOLab algorithms for geophysical parameter retrievals;
- PL evolution modeling
- PL wind waves;
  - Anomalously high waves due to wave trapping by a moving PL;
  - Modeling;
- PL synergistic study and forecast of PL wind wave evolution using Arctic SynTool;

Polar low general characteristics

- Polar lows – short-living intense mesoscale atmospheric low pressure weather systems, associated with high surface wind speeds
- Small size: 100÷1000 км
- Lifetime: from 3 hours to 2 days (average 15÷20 hours)
- Typically marine phenomena: polar lows rapidly break down over land and ice cover
- Surface wind speed: > **15 m/s**

Occurrence of polar lows

Arctic polar lows are significantly more intensive than Antarctic ones due to larger fluxes of heat and moisture

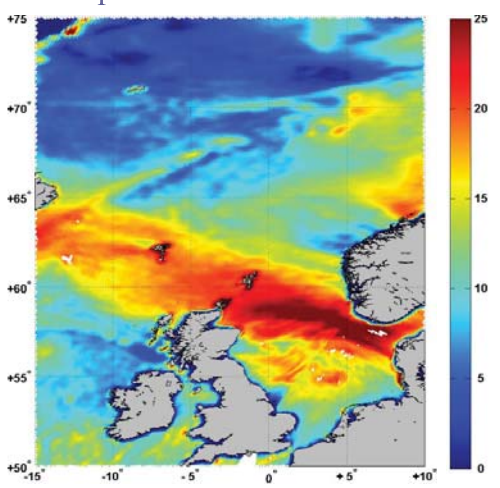


Terminology:

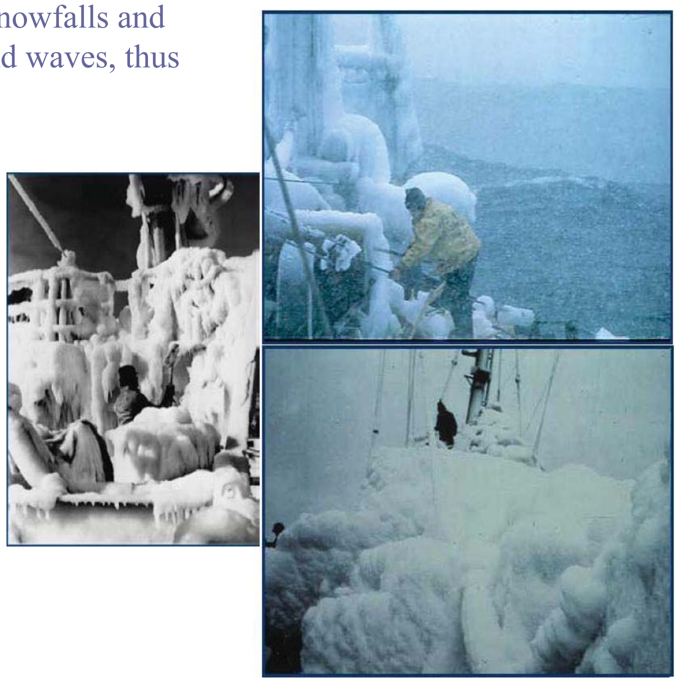
- comma cloud
- mesocyclone
- polar mesoscale vortex
- Arctic hurricane
- Arctic low
- cold air depression

Polar lows – extreme events

- Polar lows are associated with heavy snowfalls and high surface wind speeds and high wind waves, thus possessing high destructive power
- They are the threat to such businesses as oil and gas exploration, marine transportation and fisheries



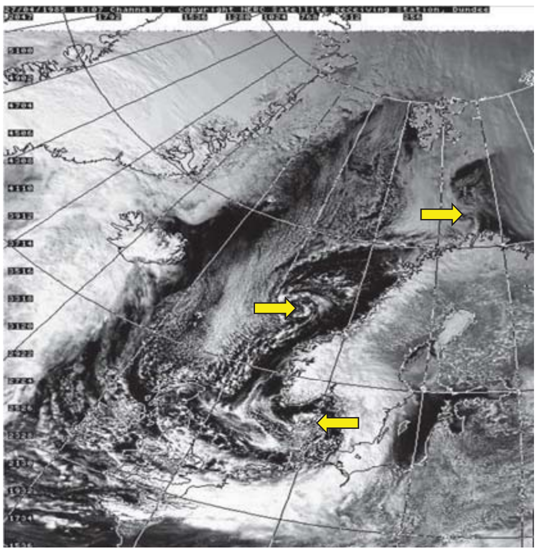
AMSR2 Sea Surface Wind field in the polar low over the North Sea on 15 December 2012



ship icing as a result of a polar low

- Polar lows may have a significant influence on the strength of ocean currents in the North Atlantic. They lead to a larger northward transport of heat to northern Europe and North America, and southward transport of deep water through Denmark Strait (*Condron, A. and I. A. Renfrew (2013). The impact of polar mesoscale storms on northeast Atlantic Ocean circulation. Nature Geoscience*)
- Recent studies predict a decrease in the number of polar lows over the northeast Atlantic (*Zahn, M. & von Storch, H. (2010) Decreased frequency of North Atlantic polar lows associated with future climate warming. Nature*)
- Decreasing number of polar lows may lead to the colder climate in Europe and North America!

Polar low typical signatures on satellite visible images



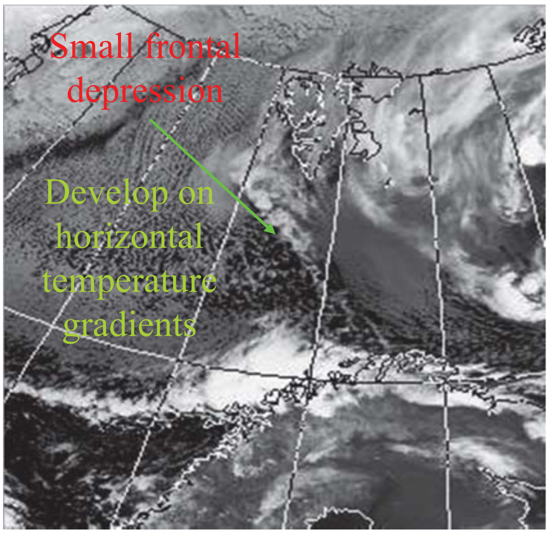
AVHRR NOAA 9 (0.58-0.68 µm), 27 April 1985, 13:08 GMT (Image courtesy of NERC *Satellite Receiving Station, University of Dundee)*

1954 - one of the earliest references - by Peter Dannevig, who wrote about ‘instability lows’ over the seas around Norway in a book for pilots

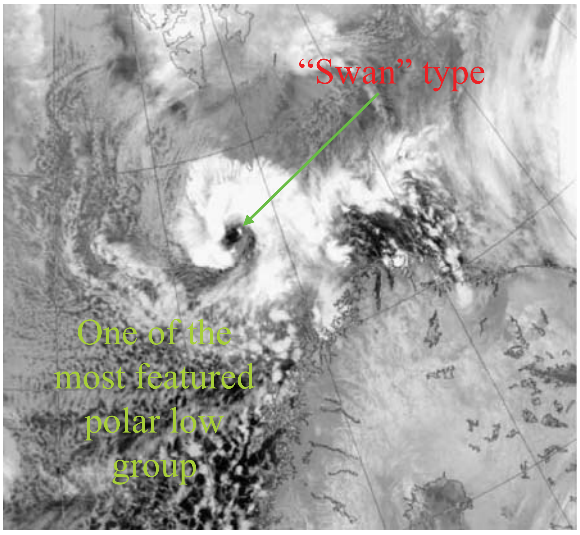
1960s - general availability of satellite imagery

Up to recent times mostly visible and infrared images have been used for PL detection and study

Polar low typical IR signatures

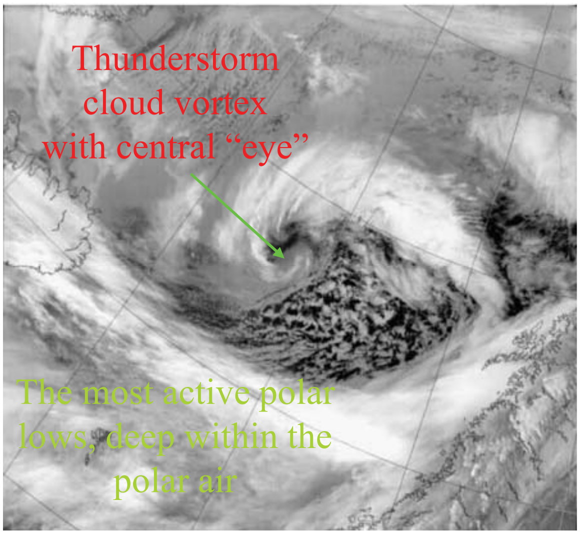


AVHRR infrared image of the Norwegian and Barents Seas
30 January 2008, 20:24 UTC

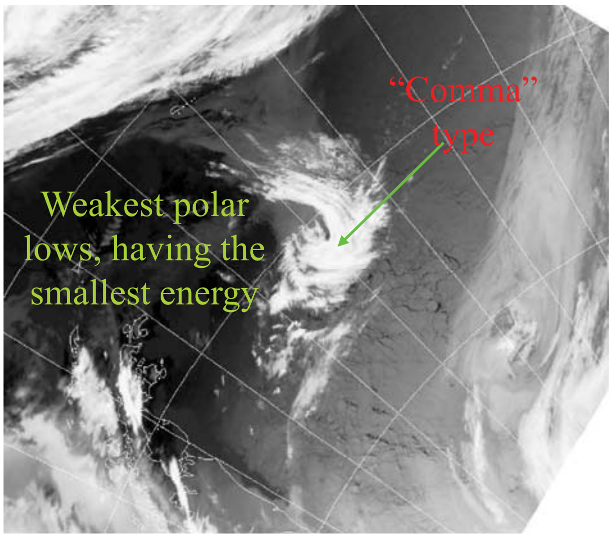


AVHRR infrared image of the Barents Sea
13 December 1982, 02:40 UTC

Polar low typical IR signatures

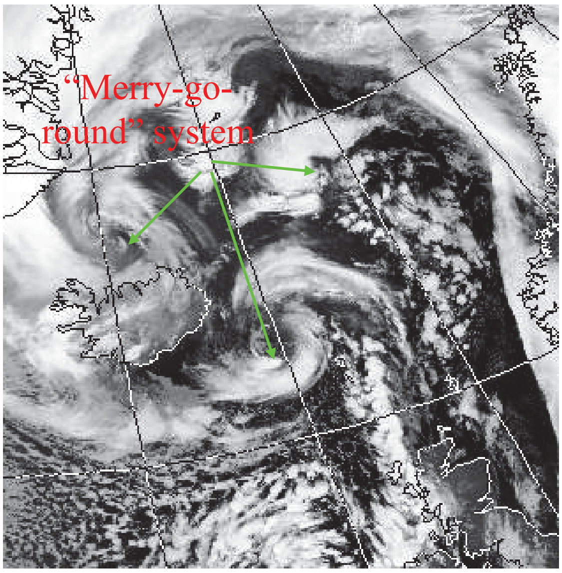


AVHRR infrared image of the Norwegian sea
27 February 1984, 13:40 UTC

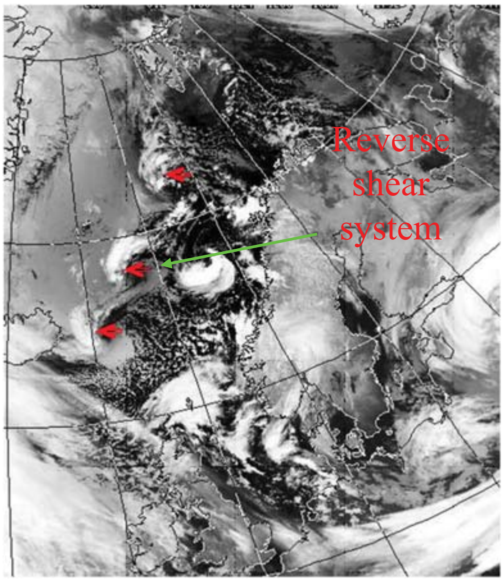


AVHRR infrared image of ice covered the Weddell sea
6 October 1995, 17:30 UTC

Polar low typical IR signatures



AVHRR infrared image of Greenland and Norwegian sea
18 December 1994, 08:53 UTC



AVHRR infrared image of Greenland and Norwegian sea
20 March 1994, 05:26 UTC

Polar Low development conditions

- Under cold upper level troughs and cold lows
- In cold air that flows over a warm body of water (Cold Air Outbreak)
- In shallow baroclinic zones
- Along the main baroclinic zone
- Triggered by convection / sensible heat flux
- Instable atmospheric environments:
  - baroclinic instability (barotropic instability)
  - conditional instability of second kind

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Difficulties in polar low detection and study

- Small size and short lifetime of polar lows makes them difficult to detect;
- Sparse synoptic observations cannot provide sufficient data for modeling and forecasting;
- Resolution of global numerical weather models is not sufficient for polar low study;
- Many of the polar lows are not revealed on surface analysis maps;

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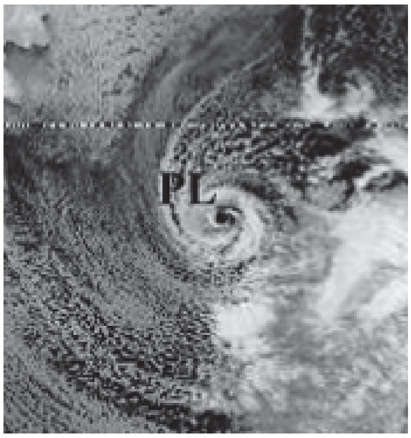
Polar low monitoring from satellites

Only satellite data provide regular spatial Arctic maps enabling both polar low operational detection and monitoring, various climatological and other PL studies

- Infrared and visible during the 1960s provided a major advance in PL studies;
- The first Ku-Band microwave scatterometer to derive wind fields was flown on SeaSat in 1978;
- Starting with Seasat in 1978, spaceborne SAR systems have provided us with the high resolution wind fields inside Polar Lows;
- Satellite passive microwave data: Special Sensor Microwave Imager SSM/I onboard DMSP series satellites, starting from 1987 - the main source of quantitative spatial information to study Polar Lows

Infrared and Visible

- ✓ Starting from 1960s revealed a wide range of cloud signatures associated with polar lows;
- ✓ Infrared (NOAA AVHRR; Aqua and Terra MODIS) images are more appropriate for PL detection in the Arctic comparatively to visible (dark winter season);
- ✓ High temporal resolution over the whole Arctic is ensured by a large number of polar orbiting satellites with spectraradiometers;
- ✓ Moderate spatial resolution (~ several hundred meters for visible, ~ 1 km for infrared);
- ✓ Some polar lows can be missed due to upper clouds!



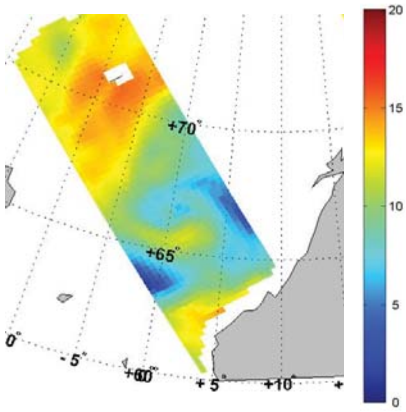
NOAA AVHRR ch 4 image (IR);
Mature polar low (north of Norway)
26 February 1987, 04:28 UTC

Active microwave (scatterometer)

- ✓ Regular active microwave data allow Sea Surface Wind Speed (SWS) retrievals and polar low detection and monitoring;
- ✓ Ability to see through clouds;
- ✓ Independence on day time;
- ✓ Wind field retrievals

Terra MODIS visible
1 June 2015

- ✓ GMF for the Arctic regions are poorly developed since they are trained mostly on buoy data of moderate and low latitudes
- ✓ Besides, active microwave signal saturates at high winds, so the real winds are underestimated by scatterometer data;



Metop-B ASCAT SWS
the Norwegian Sea
1 June 2015, 19:15 UTC

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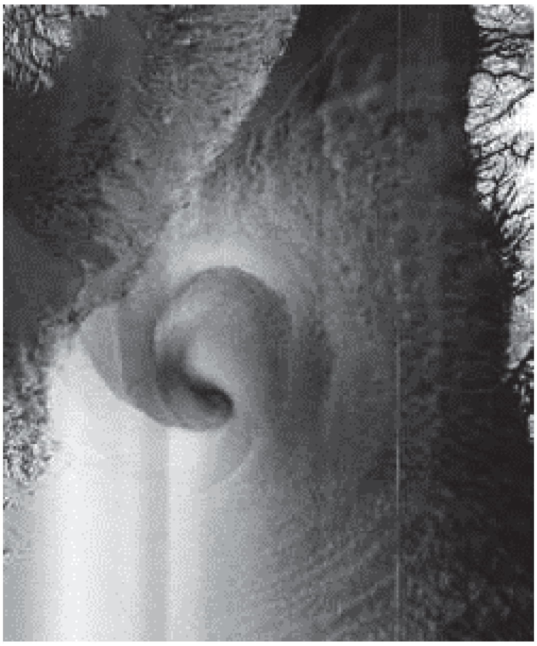
Active microwave - Synthetic Aperture Radar (SAR)



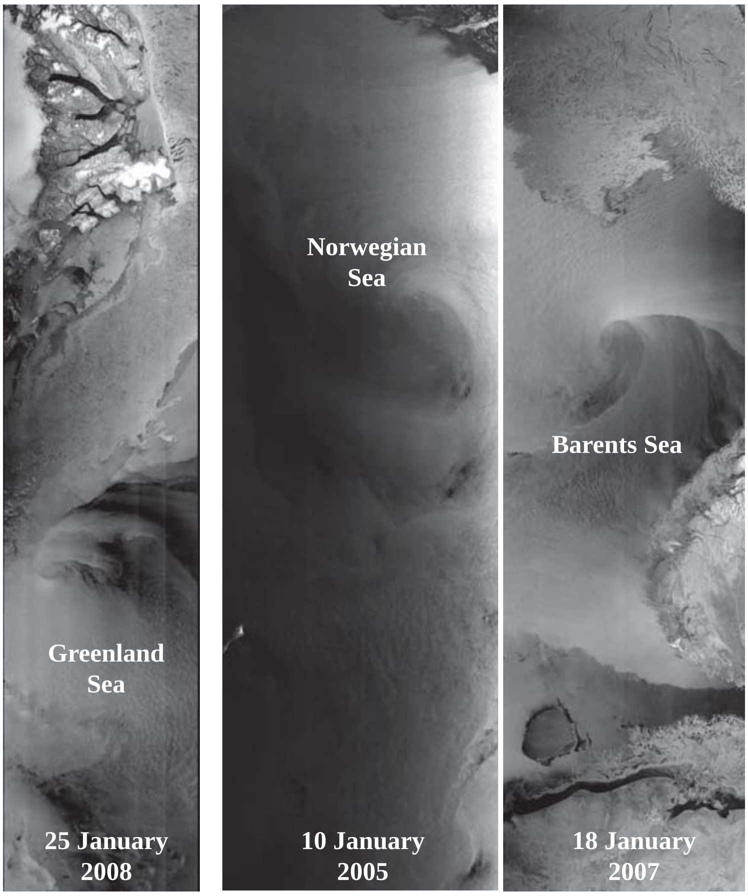
RADARSAT-1 ScanSAR image
Northern Labrador Sea
29 December 1997, 21:00 UTC

- ✓ High spatial resolution;
- ✓ Ability to see through clouds;
- ✓ Independence on day time;
- ✓ Wind field retrievals;
- ✓ Long repeat times and scarcity of the images!

Envisat ASAR, RADARSAT SAR ALOS PALSAR, new Sentinel provide us with deep insight into internal properties of polar lows since it can:

- ➢ contribute the high-resolution near-surface wind field;
- ➢ mark the accurate location of the atmospheric fronts and polar low centres at the sea surface;
- ➢ indicate the presence of the small-scale organized variations of surface wind with various scales

Envisat ASAR images →



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Satellite passive microwave data

-Invaluable source of regularly available remotely sensed data, estimating quantitatively a number of geophysical parameters

- Advantages:
  - independent on day time
  - independent on clouds
  - regularity and high temporal resolution in polar region
- Retrieved parameters:
  - sea surface wind speed
  - atmospheric total water vapor content
  - total cloud liquid water content
  - precipitation rate

Instruments:

SSM/I, SSMIS onboard DMSP

AMSR-E onboard Aqua satellite

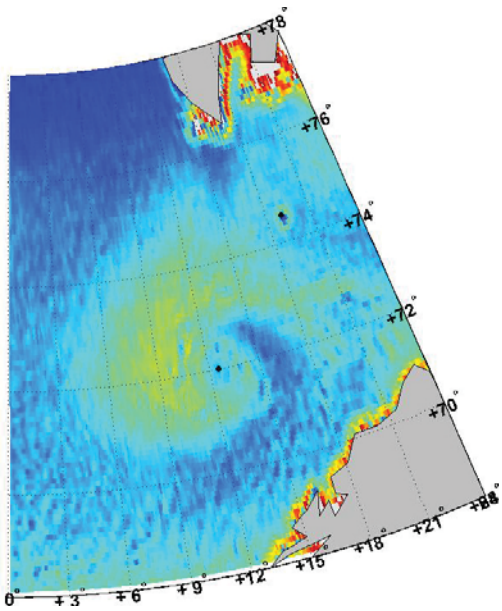
AMSR2 onboard GCOM-W1

WindSat polarimetric radiometer

General concept of polar low detection and monitoring using satellite passive microwave data

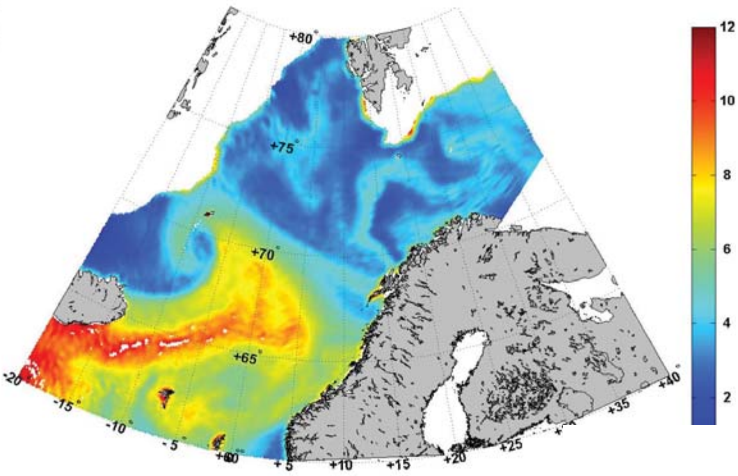
- Retrieval of atmospheric total water vapor content fields from satellite passive microwave measurement data;
- Detection of vortex structures in these fields;
- Retrieval of Sea Surface Wind Speed

Vortex structures in the integrated atmospheric water vapor content fields allow the best detection of a PL – even when there are upper clouds obstructing PL from IR and visible



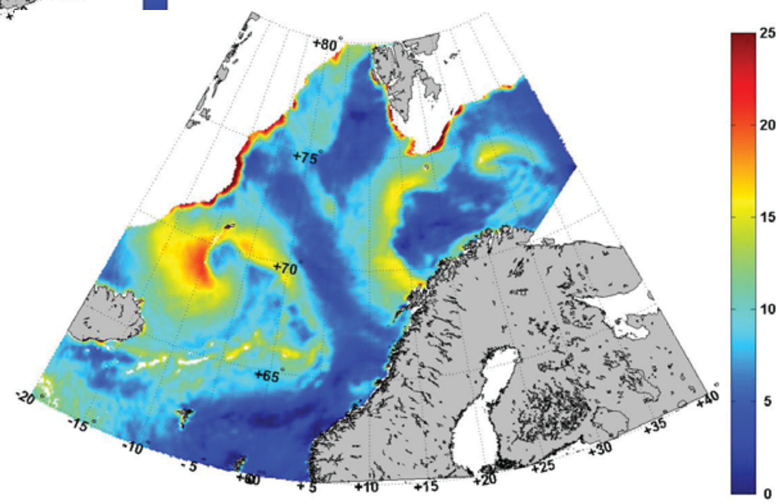
AMSR-E retrieved total atmospheric water vapour

31 January 2008, 11:14UTC



AMSR2 retrieved
total atmospheric water vapour
30 March 2013, ~03:00 UTC

AMSR2 retrieved
sea surface wind speed
30 March 2013, ~03:00 UTC



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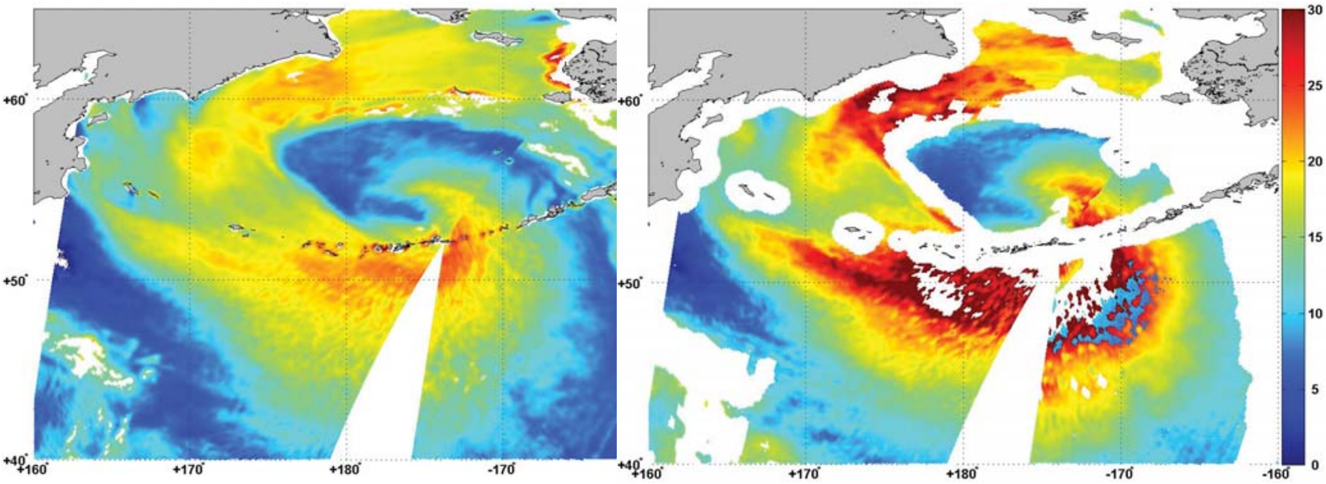
SOLab algorithms for geophysical parameter retrievals from satellite passive microwave data

- ✓ Are based on numerical simulation of brightness temperatures and their inversion by means of Neural Networks
- ✓ Have high retrieval accuracies under wide range of environmental conditions;
- ✓ Use calibrated swath brightness temperature data of original sensor resolution (higher than in ready satellite products)
- ✓ Use newly developed atmospheric filtering based on the value of total atmospheric absorption as a criterion for weather masking
- ✓ Are extensively validated against in-situ data (oil platform high wind speed data, radiosonde data)

Higher retrieval accuracies comparing to standard algorithms

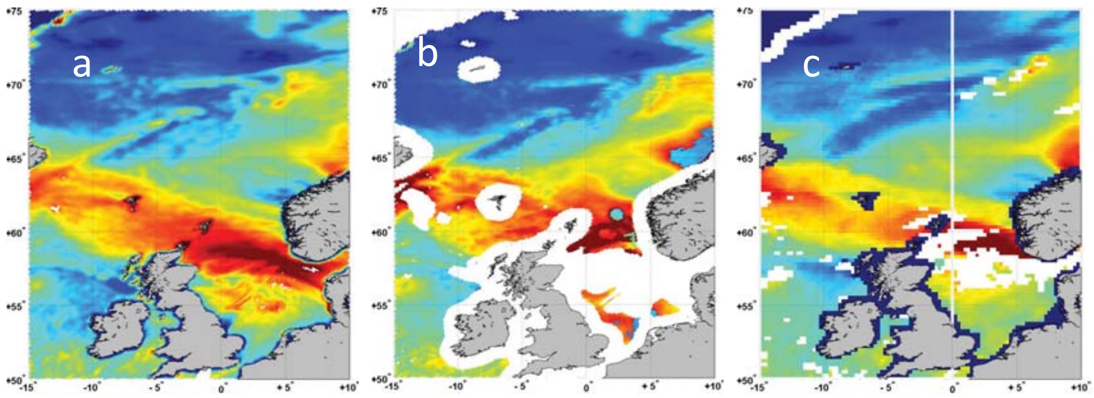
Sea surface wind in the extratropical cyclone over the North Pacific retrieved from GCOM-W1 AMSR2 measurements on 13 November 2012

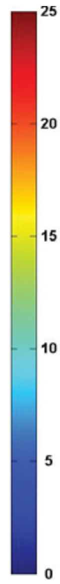


SOLab SWS product

JAXA standard SWS product

Expansion of the ocean retrieval areas using new approaches





Sea Surface Wind fields in the polar low over the North Sea on 15 December 2012: (a) retrieved from AMSR2 using NN algorithm; (b) GCOM-W1 JAXA SWS product; (c) WindSat SWS Remote Sensing Systems product

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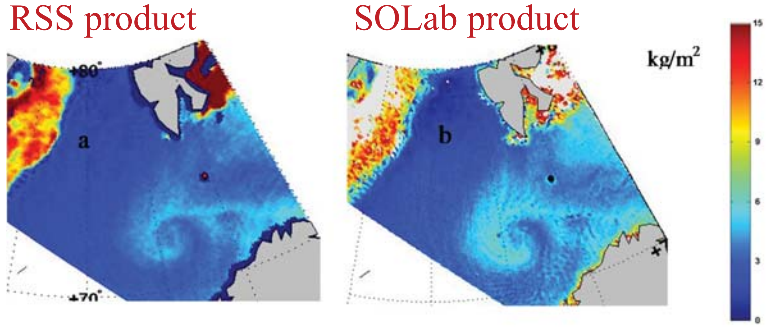
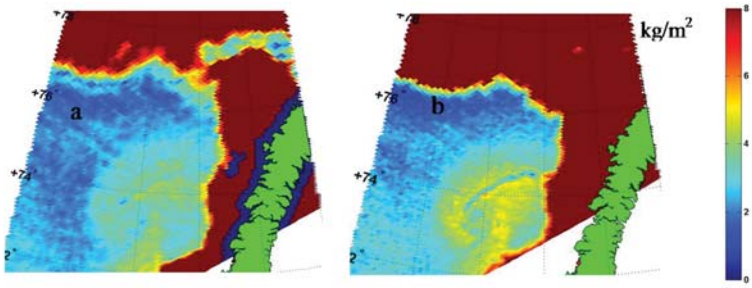
Importance of algorithm accuracy in PL detection

RSS product SOLab product



Total atmospheric water vapor content field over Norwegian Sea on 31 January 2008, 9:30 UTC



Total atmospheric water vapor content field over Barents Sea on 5 March 2010 at 9:35 UTC

The research is approved by reviewers in highly rated publications

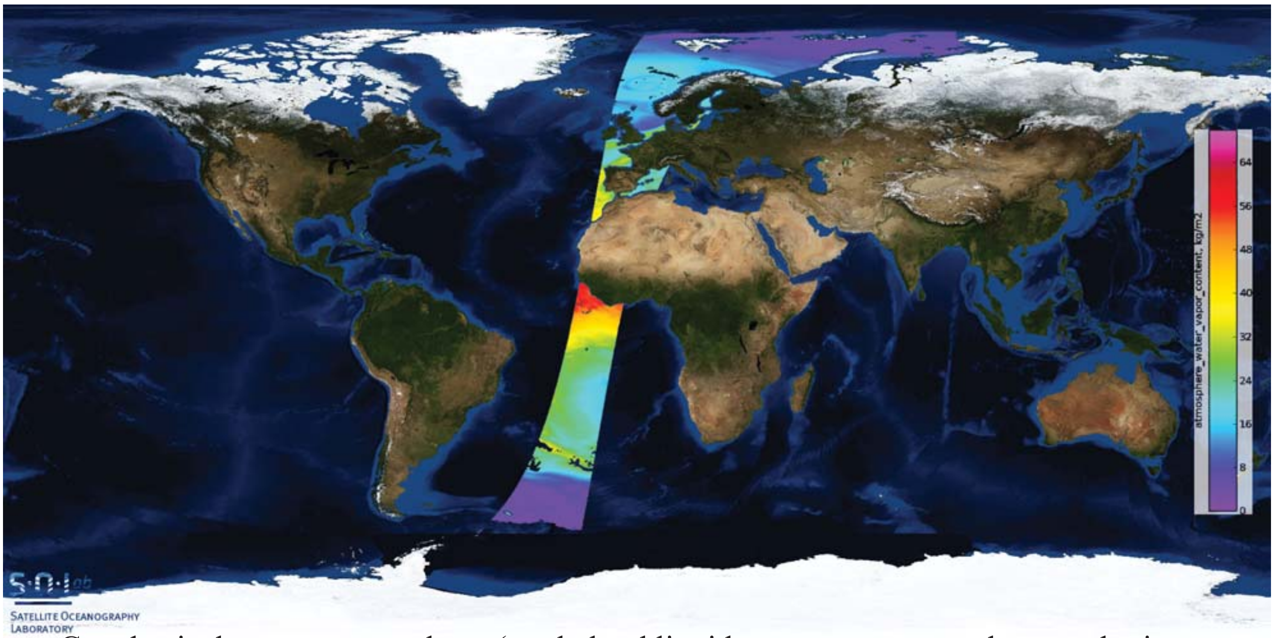
Zabolotskikh E.V., B. Chapron, (2015). Validation of the new algorithm for rain rate retrieval from AMSR2 data using TMI rain rate product. *Advances in Meteorology*. Article ID 492603, doi:10.1155/2015/492603.

Zabolotskikh E.V., L.M. Mitnik , B. Chapron, (2014). GCOM-W1 AMSR2 and MetOp-A ASCAT wind speeds for the extratropical cyclones over the North Atlantic. *Remote Sensing of Environment*, doi:10.1016/j.rse.2014.02.016

Zabolotskikh E.V., L.M. Mitnik , B. Chapron, (2014). An updated geophysical model for AMSR-E and SSMIS brightness temperature simulations over oceans. *Remote Sensing*, vol. 6(3), pp. 2317-2342, doi:10.3390/rs6032317

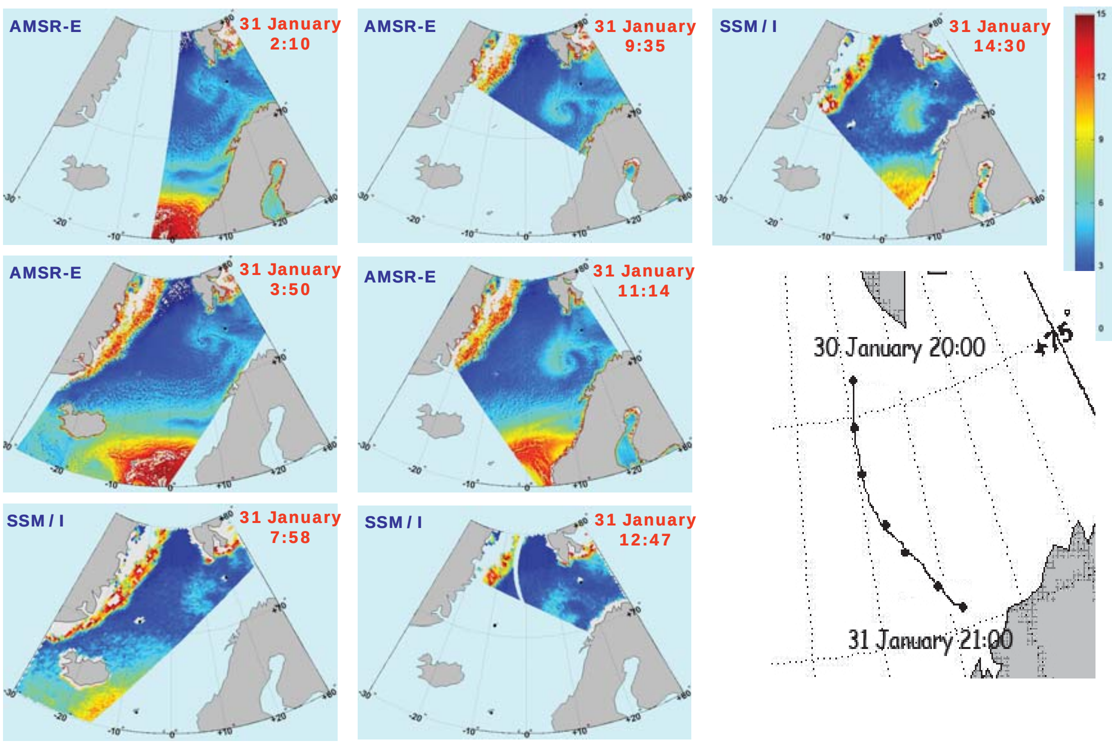
Zabolotskikh E.V., L.M. Mitnik, B. Chapron, (2013). New approach for severe marine weather study using satellite passive microwave sensing. *Geophys. Res. Lett*., Vol. 40, 1–4, doi:10.1002/grl.50664.

SOLab geophysical parameter products, based on satellite passive microwave data



Geophysical parameter products (total cloud liquid water content, total atmospheric water vapor, sea surface wind speed, sea surface temperature, rain rate and total atmospheric absorption), developed at SOLab, can be downloaded at satin.rshu.ru

Polar low over the Norwegian Sea 30-31 January 2008



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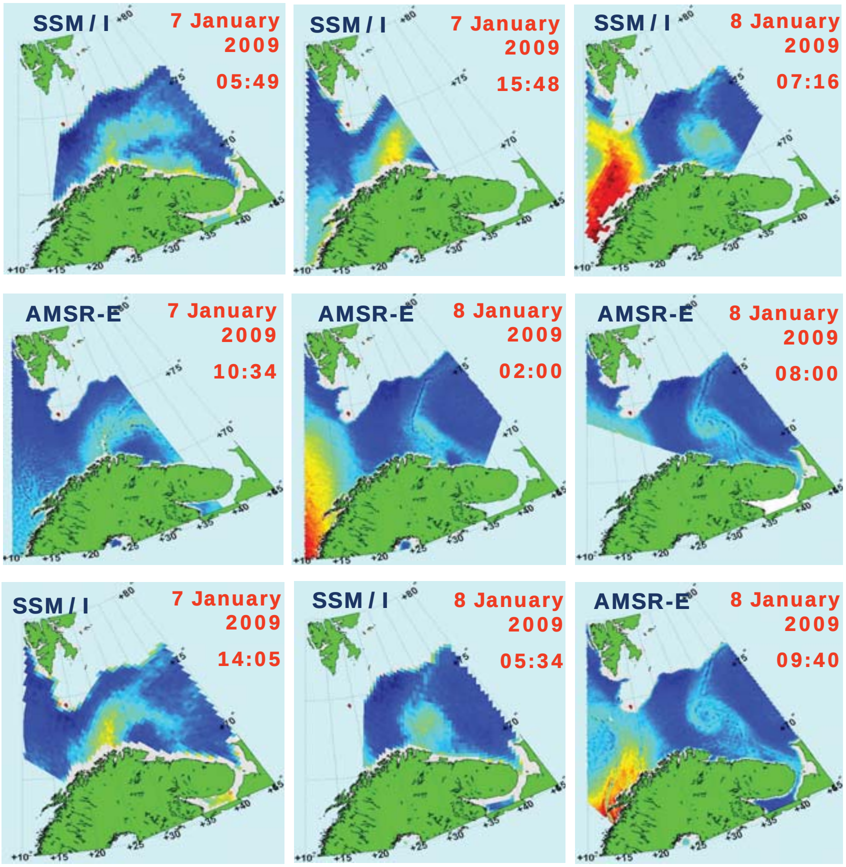
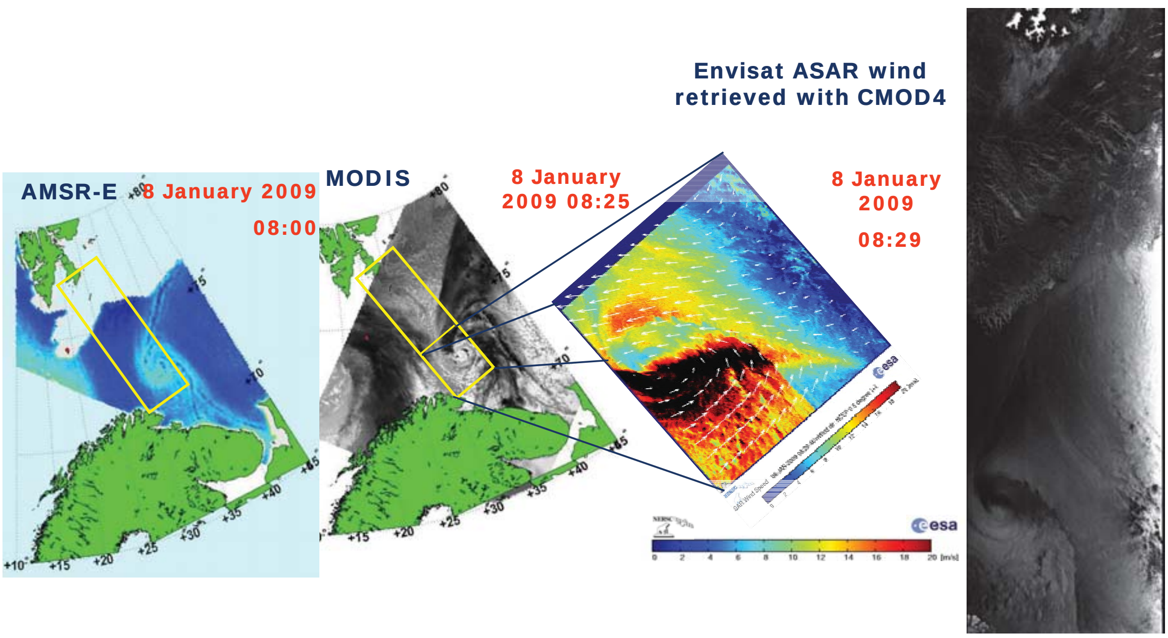
Polar Low over the Barents Sea 7-8 January 2009



Polar Low over the Barents Sea 7-8 January 2009



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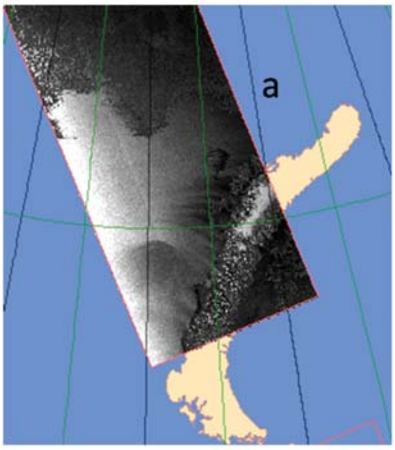
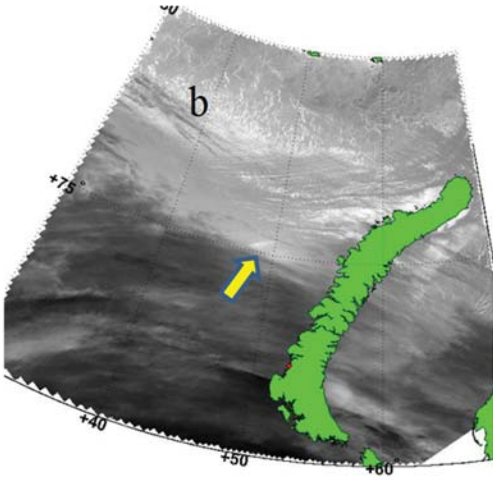
Polar low over the Barents Sea on 27 January 2010

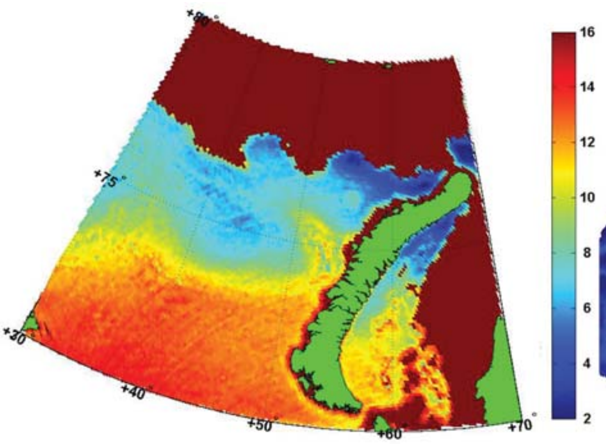


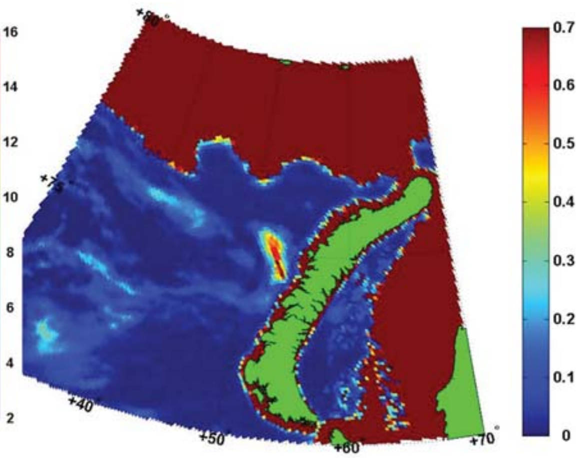


Envisat ASAR image
27 January 2010, 17:15 UTC

Terra MODIS infrared (10.78-11.28 µm) image
27 January 2010, 16:10 UTC

Polar low over the Barents Sea on 27 January 2010



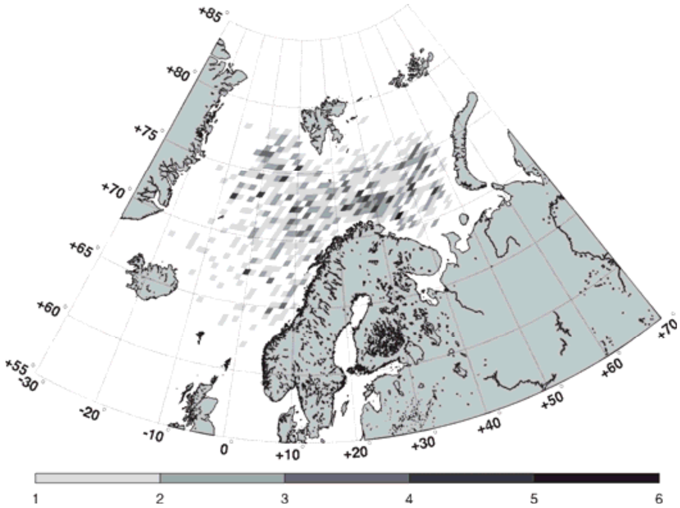


Total atmospheric water vapor content
retrieved from Aqua AMSR-E
27 January 2010, 16:15 UTC

Total cloud liquid water content
retrieved from Aqua AMSR-E
27 January 2010, 16:15 UTC

New polar low climatology over the Nordic and Barents seas based on satellite passive microwave data for 1995-2009

- more polar lows are identified comparatively to other studies
- a slight positive trend (~1.2 cases per a year) is discovered (also new finding comparatively to other climatologies)



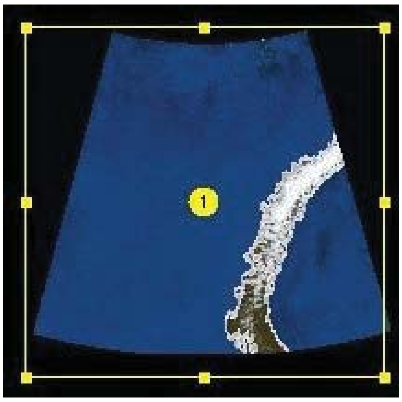
Spatial distribution of detected polar lows over the Nordic Seas from September 1995 to April 2009

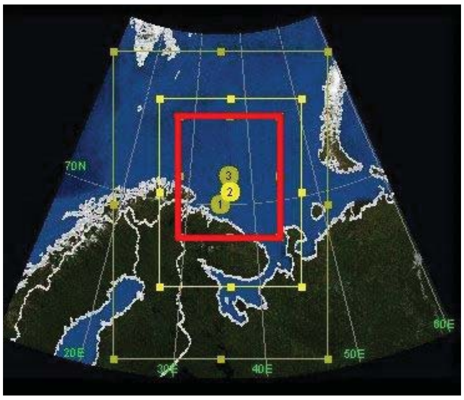
Smirnova J.E., P.A. Golubkin, L.P. Bobylev, E.V. Zabolotskikh, B. Chapron, (2015). Polar low climatology over the Nordic and Barents seas based on satellite passive microwave data . Geophysical Research Letters, doi:10.1002/2015GL063865

PL modeling using hydrodynamic WFR model and satellite data

- Hydrodynamic regional WFR model was adjusted to the Barents Sea region;
- NCEP/NCAR data 2.5°×2.5° were used for initial parameter fields;
- 2 areas were selected and for each of the optimum gridding for integration and the set of physical processes parameterization were selected;
- The model was verified by comparison with in-situ and satellite observation data;
- High probability of the forecast of the fields of such parameters as pressure, temperature, wind speed and humidity was proved;
- The assimilation of satellite data (integrated atmospheric water vapor content) provided means for the forecast improvement (3-D Var algorithm);
- 16 PL evolution was successfully modeled;
- It is supposed to assimilate in the future the fields of pressure, sea surface wind and sea surface temperature

Weather Research and Forecasting (WRF) -
one of the most up-to-date system of the numerical forecast and atmospheric process modeling

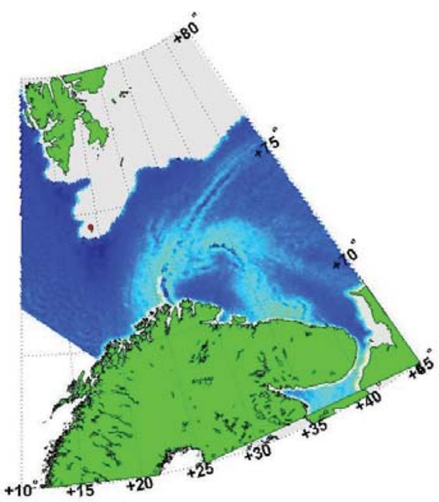




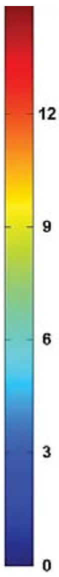
Time step	60 c	60 c
Horizontal spatial step	10 км	9 км
Grid node number	112 x 108	140 x 200
Vertical level number	28	28

Polar low over the Barents Sea 7-8 January 2009

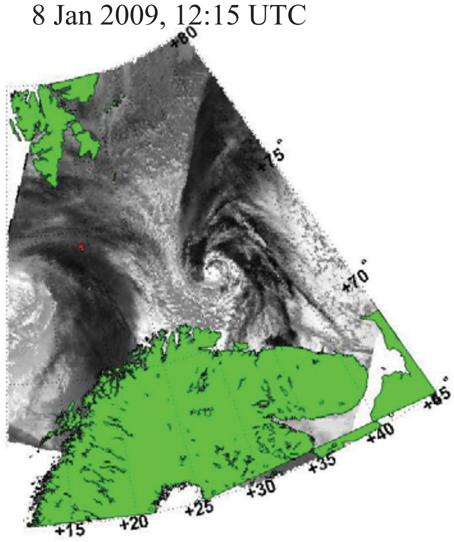
7 Jan 2009, 8:35 UTC



AMSR-E integrated water vapor



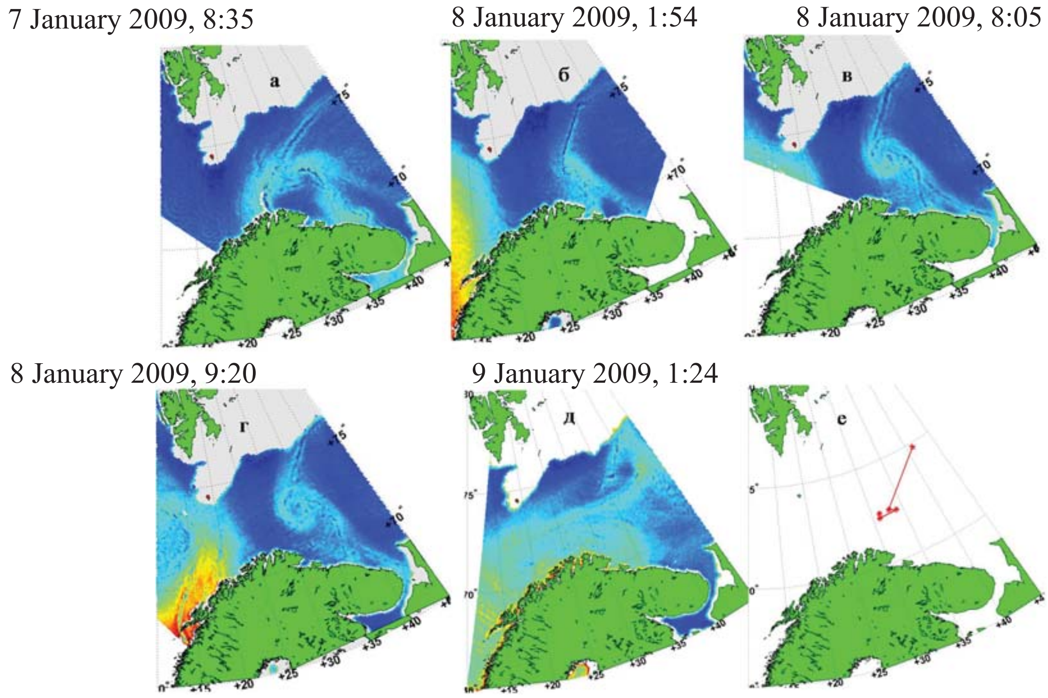
8 Jan 2009, 12:15 UTC



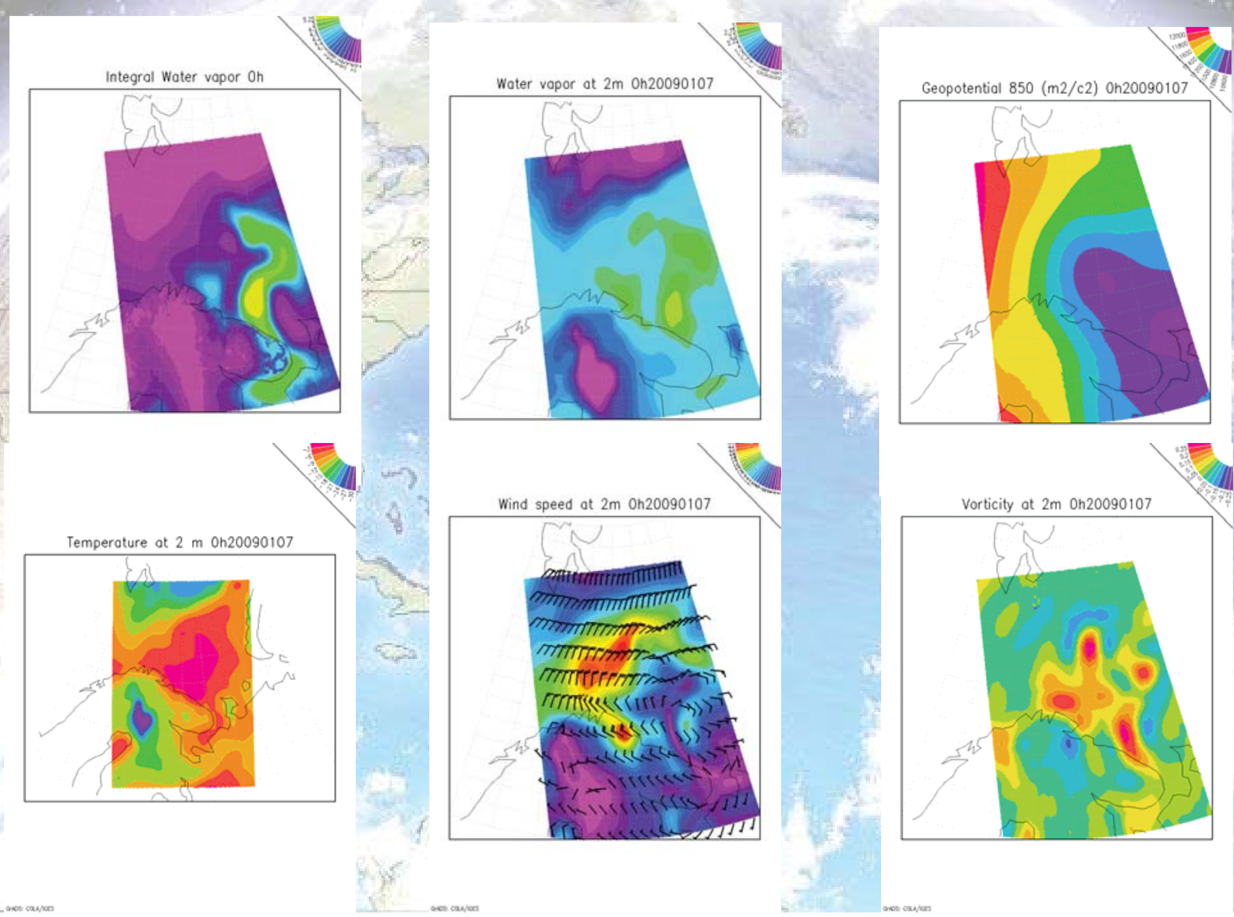
AVHRR visible

once a PL is detected its evolution can be predicted!

Polar Low over the Barents Sea 7-8 January 2009



Initial fields in the model 7 January 2009 0:00 UTC



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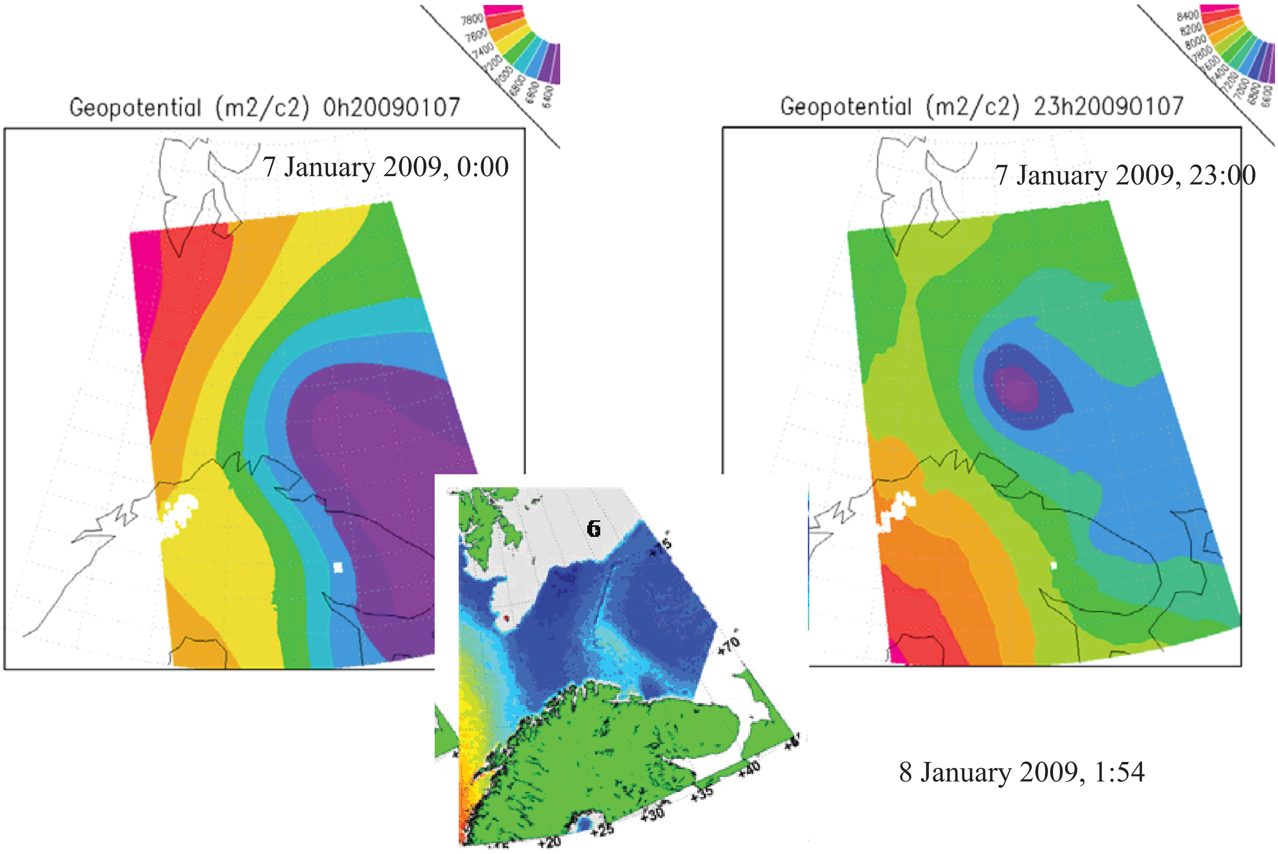
Forecast for 24 hours – geopotential



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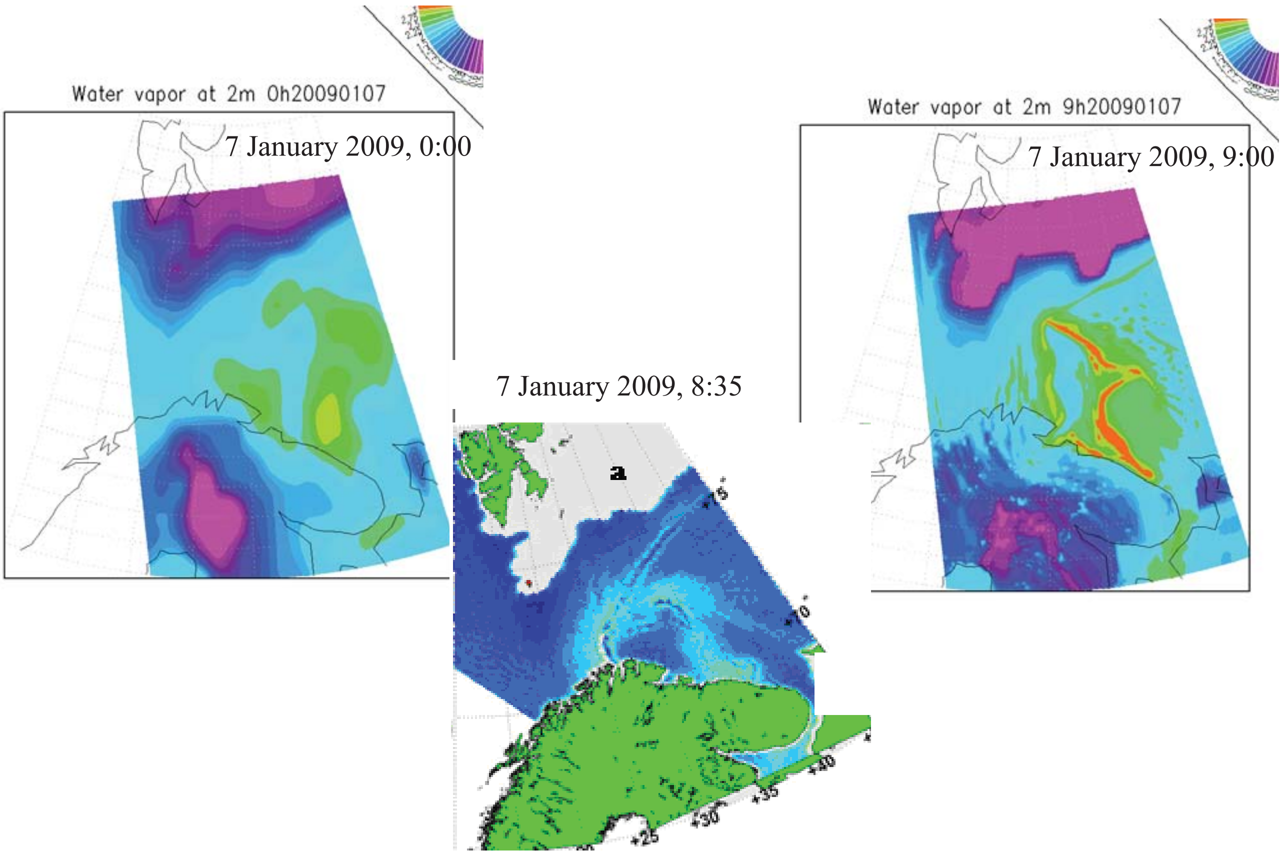
Forecast for 9 hours – water vapor



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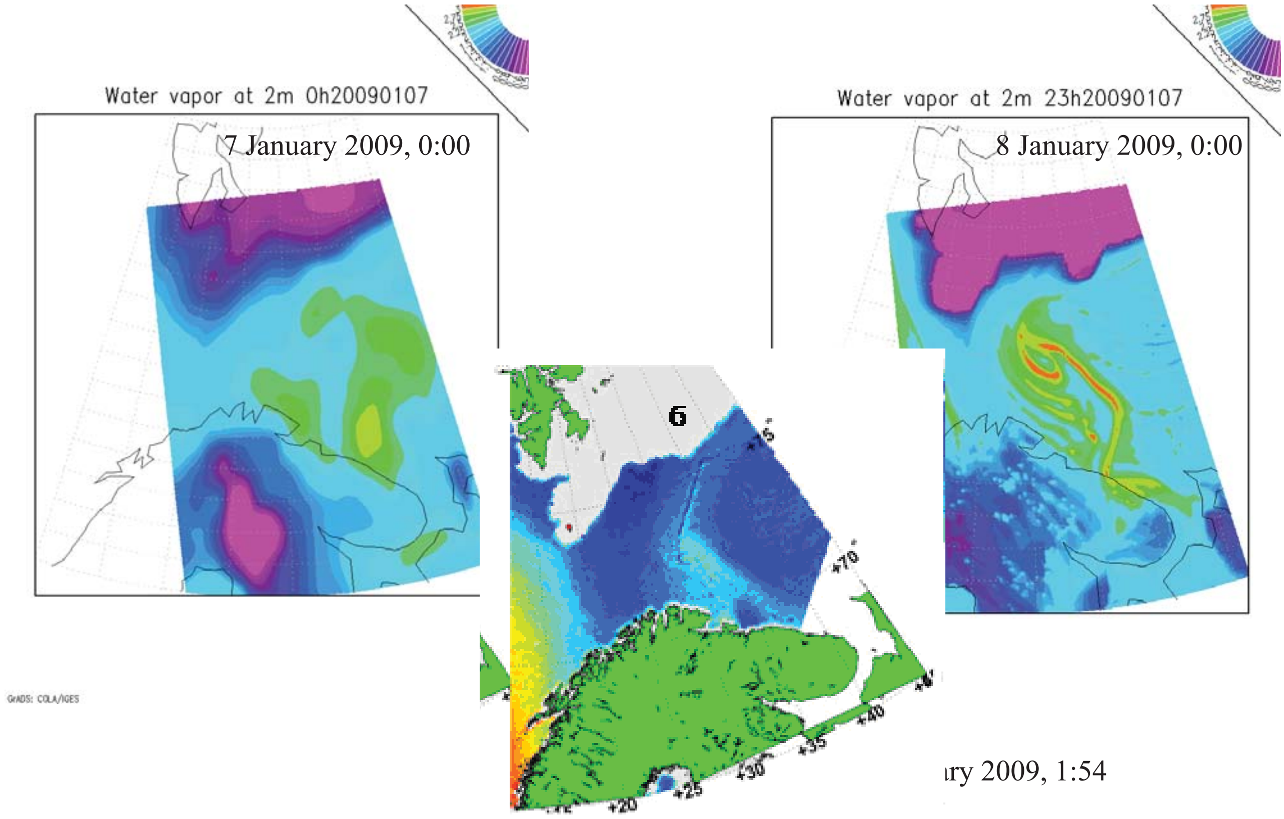
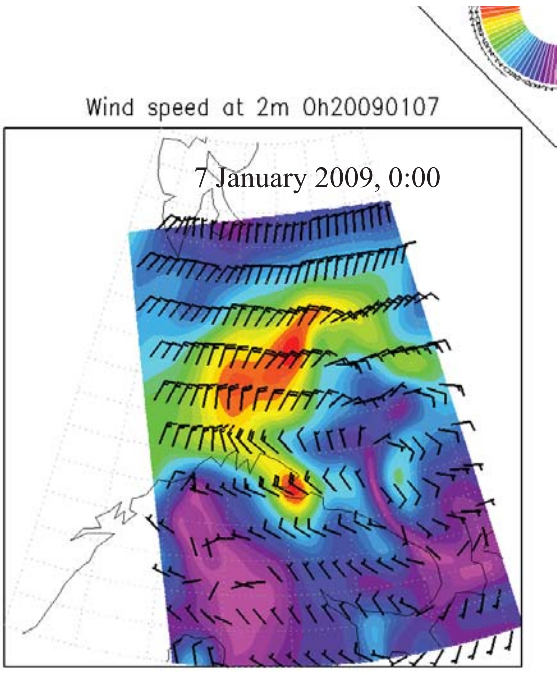
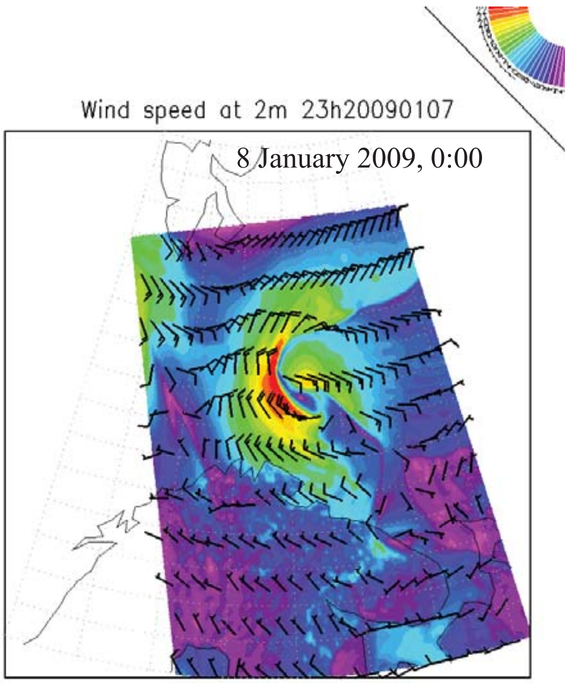
Forecast for 24 hours – water vapor



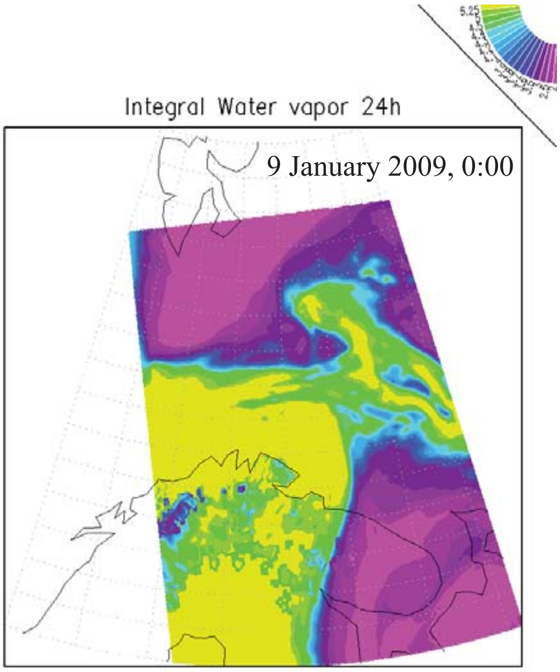
S·O·Lab Satellite Oceanography Laboratory RSHU

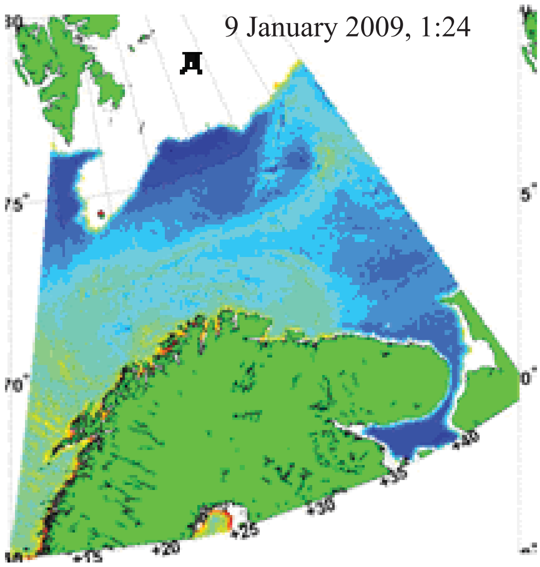
Forecast for 23 hours – wind speed





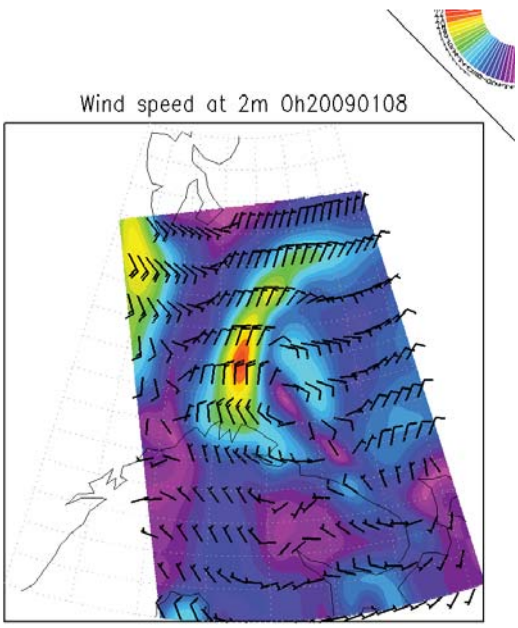
Forecast for 48 hours – water vapor



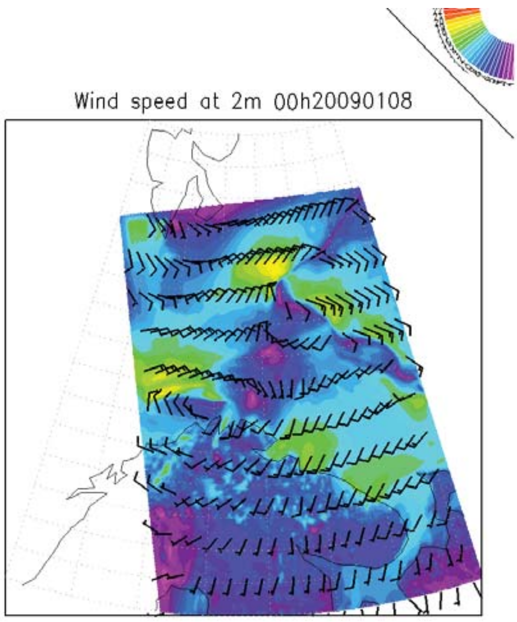


Forecast for 24 hours – wind speed

with water vapor assimilation

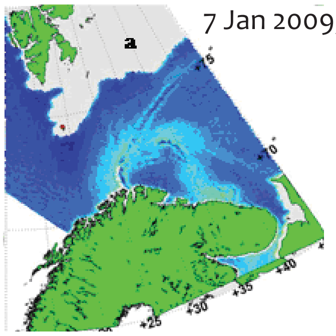


without water vapor assimilation

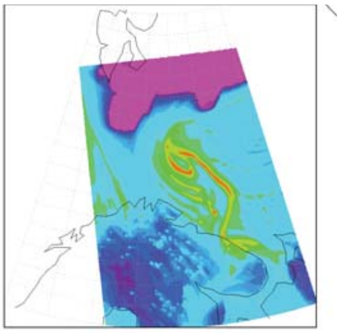


AMSR-E integrated water vapor

7 Jan 2009, 8:35

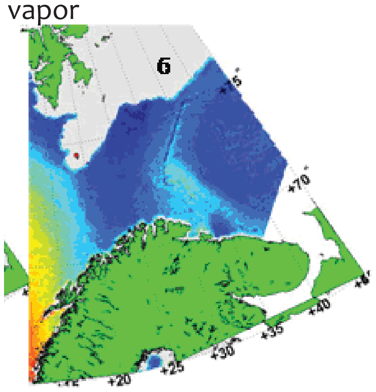


WRF forecast of integrated water vapor



8 Jan 2009, 0:00

AMSR-E integrated water vapor



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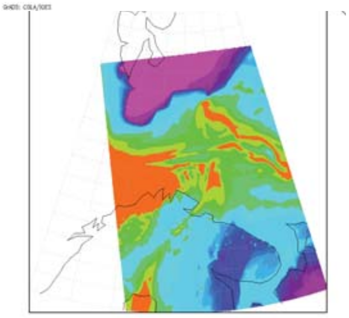
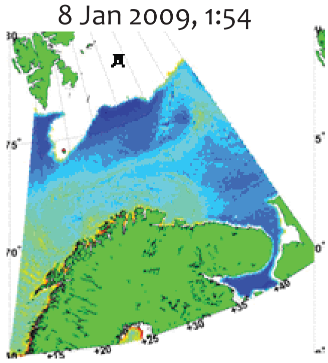
following improvements are anticipated with <u>assimilation</u> of water vapor, surface pressure and wind fields



9 Jan 2009, 0:00



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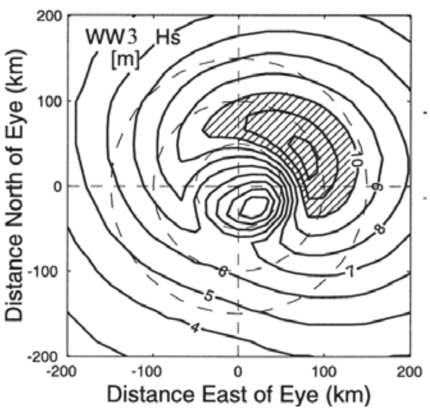
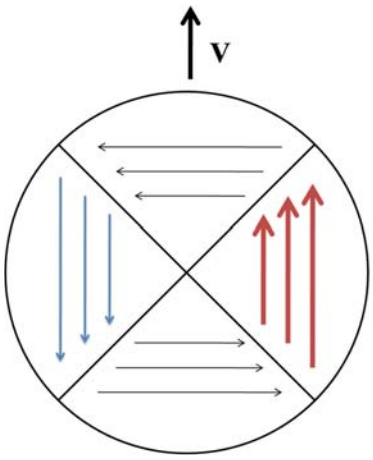
PL wind waves

- A polar low is associated with high winds (>15 m/s)
- When a polar low is moving, it can generate anomalously high waves due to wave trapping;
- Wind waves can be modeled:



- ➢ using numerical models (Wavewatch 3). Their advantage is that they may accurately reproduce two-dimensional wave field, but they are very computationally expensive (calculations may take up to 20 hours).
- ➢ using semi-empirical models based on JONSWAP parameterizations, which connects the dimensionless SWH to dimensionless fetch. The general problem is to define the fetch in a moving cyclone.

Model approach: application to PL



Right sector (wave enhancement):

$$(\alpha_L/\alpha_0)^{1/q}\left[1-(1+q)^{-1}\alpha_L/\alpha_T\right]=1-\tilde{L}_{cr}/\tilde{L}$$

$$\tilde{e}_L/\tilde{e}_0=(\alpha_L/\alpha_0)^{p/q}$$

Left sector (wave diminution):

$$(\alpha_L/\alpha_0)^{1/q}\left[1-(1+q)^{-1}\alpha_L/\alpha_T\right]=1$$

$$\tilde{e}_L/\tilde{e}_0=(\alpha_L/\alpha_0)^{p/q}$$

where $\alpha_L,\ \tilde{e}_L$ - inverse wave age and energy, respectively;

$\alpha_0=c_\alpha\tilde{L}^q;\ \tilde{e}_0=c_e(\alpha_0/c_\alpha)^{p/q}$ - expected wave parameters (not accounting for TC movement);

$c_\alpha,\ c_e,\ p,\ q$ - "standard" coefficients in JONSWAP parameterizations;

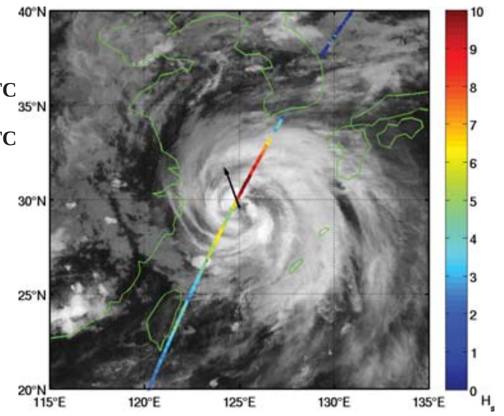
$\alpha_T=u/2V$ - wave age of trapped waves, u - wind speed, V - translation speed;

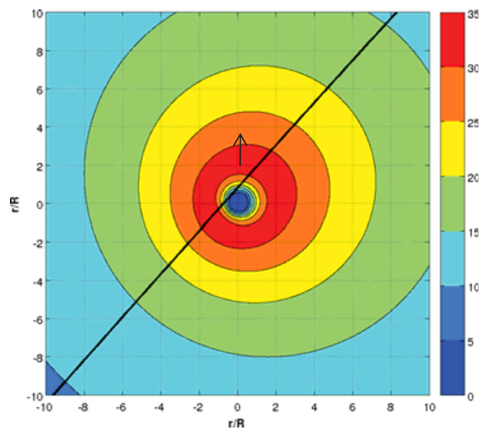
$\tilde{L}_{cr}=-c_\alpha^{-1/q}\dfrac{q}{1+q}\alpha_T^{1/q}$ - critical fetch;

$\tilde{L}$ - dimensionless fetch.

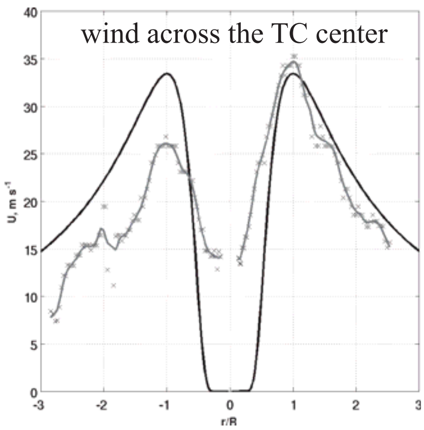
Example: TC Muifa (2011)

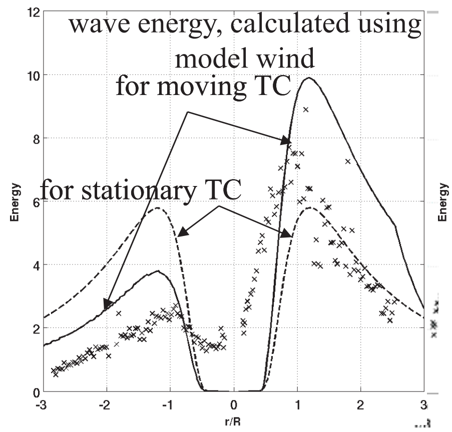
MTSAT-2:
06/08 1230 UTC
Jason-1:
06/08 1220 UTC

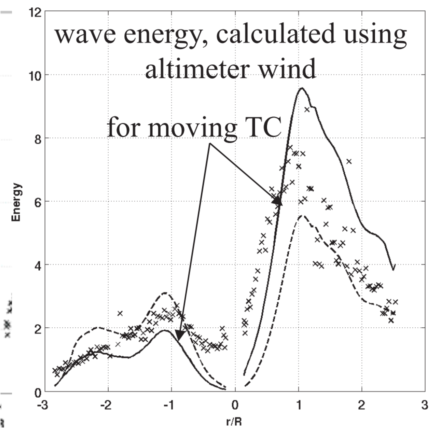




Wind field reconstructed from the best-track data for: 06/08 1200 UTC

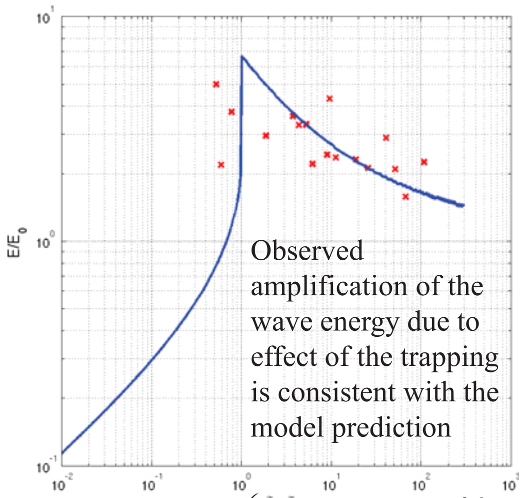






Wave enhancement factor

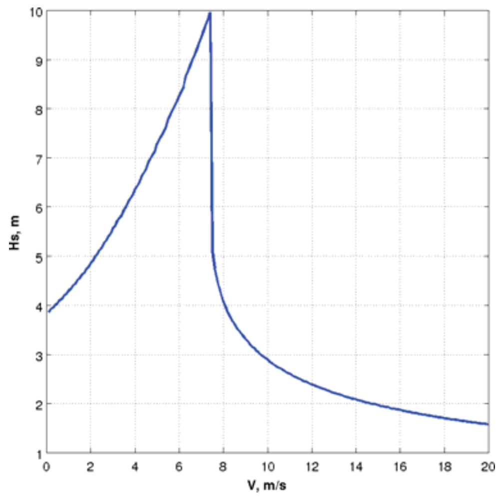
We only need three parameters to know if a storm would generate abnormally high waves or not: that is the storm length L, its translation speed V, and wind speed u. And if L/L_{cr} is 1 - 3, the wind energy would be 4 - 6 times higher than expected.



$$\text{if } \tilde{L}/\tilde{L}_{cr} = \sqrt{2rg} \Big/ \overset{\tilde{L}/\tilde{L}_{cr}}{\left(7.4\times10^{3} \left(\frac{u}{2V}\right)^{-3.6} u^{2} \right)} = 1..3,$$

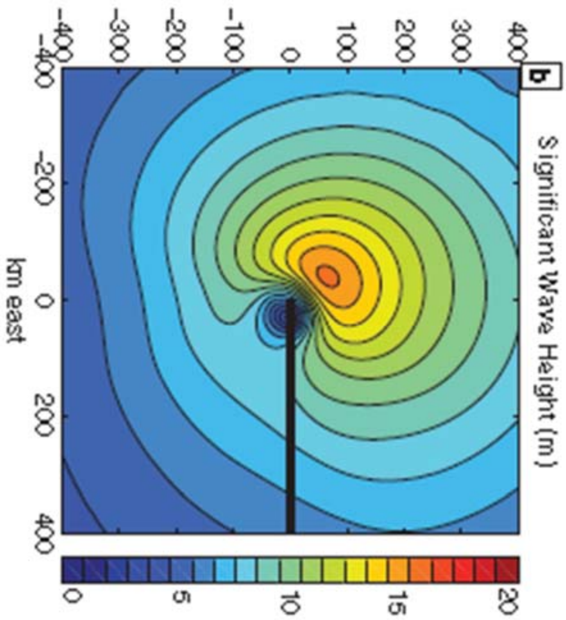
$$\text{then } e = (6..4)\times 4.41\times10^{-7}(\sqrt{2r})^{-0.275}U^{2.275}g^{-2.275}.$$

Dependence of significant wave height on storm translation speed V
(storm parameters: u = 25 m/s, L = 50 km)



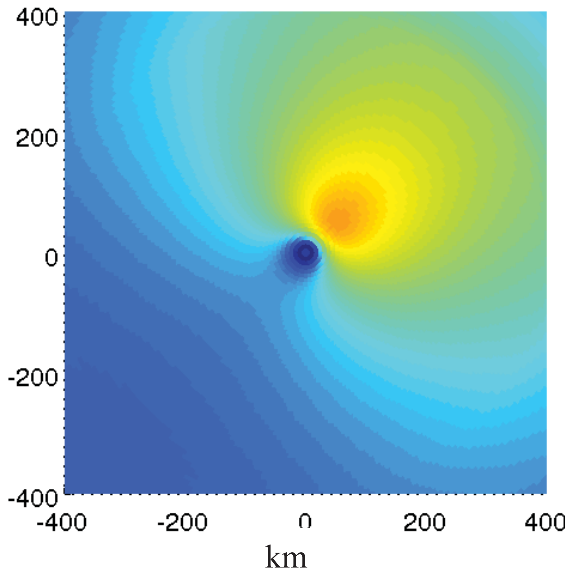
2D wave field reconstruction (ongoing work)

Numerical model (WAVEWATCH III)

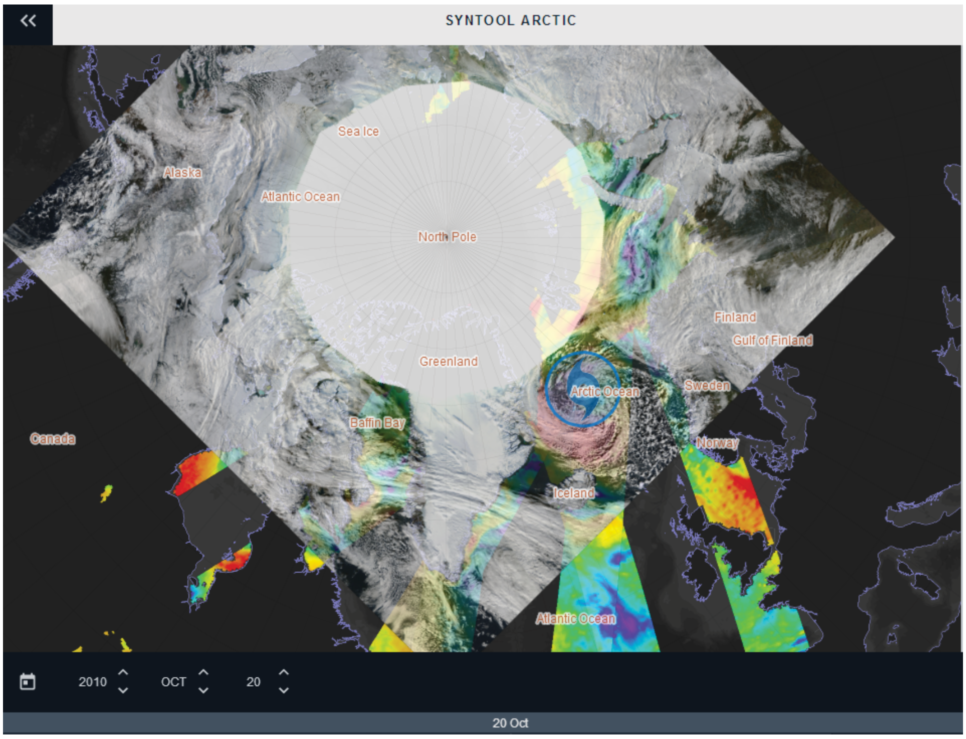


Reichl et al. (2014). Sea state dependence of the wind stress over the ocean under hurricane winds. *Journal of Geophysical Research: Oceans, 119*(1), 30-51.

The suggested simplified model



PL synergistic study and forecast of PL wind wave evolution using Arctic SynTool



PL synergistic study and forecast of PL wind wave evolution using Arctic SynTool

- Today the developed satellite web portal Arctic SynTool (http://arctic.solab.rshu.ru/) provides the capabilities to analyze synergistically various satellite products
- Polar lows can be detected by visual analysis;
- Their evolution can be modeled;
- The evolution of PL wind waves can be modeled;
- In the nearest future the system of PL semi-automatical detection will be developed ;
- The system of PL and PL wind wave evolution modeling will be implemented ensuring extreme event (high winds and waves) early warning capabilities

3rd CRAICC–PEEX Workshop Climate Change for Arctic Seas and Shipping
24-25 August 2015, Copenhagen, Denmark