Using Satellite Passive Microwave Data to Study Arctic Polar Lows

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Polar lows and their general characteristics

International Polar Year 2007-2008 initiated enhanced research activity on adverse weather in polar regions including polar lows in the Arctic sector of Atlantic Ocean

- Polar lows are short-living intense meso-scale maritime atmospheric low pressure weather systems, observed over high latitudes during wintertime
- Short lifetime: from several hours to 2 days (average 15÷20 hours)
- Small size: 100÷1000 км
- High surface wind speed: > 15 m/s (some time > 30 m/s)
- Typically marine phenomenon: polar lows rapidly break down over land and ice cover
Arctic polar lows significantly more intensive than Antarctic ones due to large fluxes of heat and moisture

Most intensive Arctic polar lows are called “Arctic hurricanes”

Nordic seas is one of the main genesis areas for polar lows in the Arctic
Polar lows – threat to man’s activities in the Arctic

- Polar lows are associated with heavy snowfalls and high surface wind speed, possessing high destructive power.
- They are one of the most frequent reason of ship icing.
- Polar lows represent threat to such businesses as oil and gas exploitation, fisheries and shipping.
- They can worsen because of shrinking Arctic sea ice due to global warming (Erik Kolstad: "The bad news is that as the sea ice retreats you open up a lot of new areas to this kind of extreme weather").

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Are polar lows climatologically important?

- This issue is not clear now and more studies are needed to assess climatological importance of polar lows.
- In any case, to be of climatological important, frequent occurrence of polar lows has to take place in considered area.

**Hypotheses:**

- Individual polar lows can have fluxes of heat of up to 1 000 W/m², therefore loss of heat from ocean surface can trigger downward convection in ocean.
- Polar low can lead to ocean surface warming of more than 1 C within few hours due to turbulent entrainment of subsurface warm water core caused by strong wind. It may be potential positive feedback mechanism for cyclone intensity *(Saetra et al., Tellus, 60A, 2008)*.
Earliest reference to polar lows and beginning of their satellite observations

One of earliest references to phenomenon known now as polar low was made by Peter Dannevig, who wrote about ‘instability lows’ over seas around Norway in book for pilots in 1954.

Since 1960s - general availability of satellite imagery

27 April 1985 13:08 UTC

Visible NOAA AVHRR image of polar air outbreak down coast of Norway and Denmark.

Three polar lows were formed at:
• North Cape
• Norwegian Sea at 65N
• over Denmark

Dannevig's 1954 schematic surface chart showing two 'instability lows' within northerly outbreak of polar air near Norwegian coast.
Complications in polar low detection, tracking, study and forecasting

- 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 most numerical weather models is not sufficient for polar low study
- Most of the polar lows are not revealed on surface analysis maps

Polar lows - highly complicated phenomena: their study, timely detection, tracking and forecasting still is a challenge for Earth sciences
Example: Polar low over Norwegian Sea 30-31 January 2008

Surface analysis maps: this polar low is not found on weather charts issued by local weather bureaus

Polar low is detected at Envisat ASAR archive images. It arose on 30 and destructed on 31 Jan 2008

German National Meteorological Service, Hamburg Branch Office

31 January, 06:00 UTC

31 January, 12:00 UTC

30 January 2008 20:16 UTC

31 January 2008 19:44 UTC

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Arctic polar low observations from satellites: milestones

- Infrared and visible observations during 1960s provided major advance in polar low study

- Low resolution sea surface wind field retrievals began in 1978 with first Ku-band scatterometer on board Seasat

- High resolution surface wind fields inside polar lows are available from spaceborne SAR since 1978 with the same satellite Seasat and from RAR since 1983 with Kosmos-1500 satellite

- Satellite passive microwave data, available since 1979 from SMMR, since 1987 from SSM/I and since 2002 from AMSR-E and AMSR are now one of the main sources of quantitative spatial information for polar lows study.
Satellite observations in infrared and visible: polar low north to Norway on 26-27 February 1987

NOAA AVHRR IR (10.3-11.3 µm) images

Development phase, 26 February 1987
04:28 UTC

Mature phase, 27 February 1987
04:18 UTC

Decaying phase, 27 February 1987
12:32 UTC
Satellite observations of polar lows with Synthetic Aperture Radar (SAR)

**Satellite SAR advantages:**
- Independence on day time
- Ability to see through clouds
- High spatial resolution
- High-resolution near-surface wind field retrieval
- Accurate location of atmospheric fronts and polar low centres at sea surface
- Indication of presence of small-scale organized variations of surface wind with various scales

Thus, SAR is powerful instrument for polar low study...

...however, it can not be used for polar low tracking due to long repeat times and scarcity of images
Satellite SAR – powerful instrument for polar low study

Wide swath SAR: Envisat ASAR, RADARSAT-1/2 SAR, ALOS-1/1 PALSAR, RISAT SAR, Sentinel can contribute to polar low studies

Envisat ASAR images

10 January 2005
18 January 2007
25 January 2008
Satellite observations of polar lows with passive microwave radiometers

**Advantages:**
- independent on day time
- independent on clouds
- regularity and high temporal resolution in polar region

**Retrieved parameters:**
- sea surface wind speed
- atmospheric columnar water vapor
- total cloud liquid water content
- sea surface temperature (AMSR-E)

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Radiometer</th>
<th>Period of data availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nimbus-7 - US</td>
<td>Scanning Multichannel Microwave Radiometer (SMMR)</td>
<td>1978-1987</td>
</tr>
<tr>
<td>Defense Meteorological Satellite Programme (DMSP) - US</td>
<td>Special Sensor Microwave Imager (SSM/I)</td>
<td>1987-2009</td>
</tr>
<tr>
<td>Aqua - US</td>
<td>Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E)</td>
<td>2002 - 4 October 2011 (failed)</td>
</tr>
<tr>
<td>DMSP - US</td>
<td>3 radiometers: Special Sensor Microwave Imager / Sounder (SSMIS)</td>
<td>2005-now</td>
</tr>
<tr>
<td>Global Change Observation Mission – Water (GCOM-W1) – Shizuku - Japan</td>
<td>Advanced Microwave Scanning Radiometer AMSR2</td>
<td>Launched on 18 May 2012</td>
</tr>
</tbody>
</table>

Fields of brightness temperatures measured by AMSR-E

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General approach for polar low detection and tracking using satellite passive microwave data

- Retrieval of atmospheric columnar water vapor fields from satellite passive microwave data (e.g., SSM/I and AMSR-E)
- Detection of vortex structures in these fields
- Polar low parameter (life time, size, location, moving speed) estimation and trajectory tracking

Bobylev et al., IEEE TGRS, 2010 – NN-algorithm for columnar water vapor retrieval
Bobylev et al., IEEE TGRS, 2011 – polar low detection and tracking approach

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**Case study 1**: Polar low tracking over the Norwegian Sea from SSM/I and AMSR-E 30-31 January 2008

**SSM/I**
- 31 January 14:30 UTC
- 31 January 12:47 UTC
- 31 January 7:58 UTC

**AMSR-E**
- 31 January 2:10 UTC
- 31 January 9:35 UTC
- 31 January 3:50 UTC
- 31 January 11:14 UTC

**Polar low trajectory**

30 January 20:00
31 January 21:00

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**Case study 1**: Polar low over the Norwegian Sea
30-31 January 2008 (continuation)

Comparison of AMSR-E detected polar low with IR image

AMSRE
31 January 9:35 UTC

AVHRR NOAA image (10.3-11.3 µm, 4 ch)
31 January 10:11 UTC

AMSRE
31 January 11:14 UTC

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**Case study 1**: Polar low in the Norwegian Sea
30-31 January 2008 (continuation)

Comparison of AMSR-E detected polar low with surface wind field from scatterometer data

- AMSR-E retrieved columnar water vapor (Q) field (31 January, 03:50 UTC)
- QuikSCAT sea surface wind speed (V) field (31 January, 03:40 UTC)
Case study 2: Polar low tracking over the Barents Sea from SSM/I and AMSR-E 7-8 January 2009

SSM/I 7 January 05:49 UTC
SSM/I 7 January 15:48 UTC
SSM/I 8 January 07:16 UTC

AMSR-E 7 January 10:34 UTC
AMSR-E 8 January 02:00 UTC
AMSR-E 8 January 08:00 UTC

SSM/I 7 January 14:05 UTC
SSM/I 8 January 05:34 UTC
AMSR-E 8 January 09:40 UTC

Q, kg/m²

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**Case study 2:** Polar low in the Barents Sea
7-8 January 2009 (continuation)

Comparison of AMSR-E detected polar low with MODIS image and high-resolution surface wind field from ENVISAT ASAR.
<table>
<thead>
<tr>
<th>Year</th>
<th>Paper</th>
<th>Period</th>
<th>Type of data</th>
<th>Area</th>
<th>Method</th>
</tr>
</thead>
</table>

- Large interannual but little decadal variability of polar low occurrence
- No significant long-term trends in overall or regional polar low activity

Number of detected polar lows per polar low season

Polar low density distribution. Unit: detected polar lows per 250 km²
Comments to Zahn-von Storch climatology

- Mesoscale cyclones/polar lows are under-represented in current reanalysis datasets (*Condron et al., 2006*):
  - up to 80% of cyclones larger than 500 km can be detected in mean sea level (MSL) pressure
  - up to 40% - for 250-km-scale cyclones, and
  - only 20% - for 100-km-scale cyclones

- Modal size of AVHRR-derived mesoscale cyclones/polar lows is 100-150 km (*Harold et al., 1999*)
Creating polar low climatology for the Nordic Seas over 1995-2011 based on atmospheric water vapor field analysis

<table>
<thead>
<tr>
<th>Data</th>
<th>Period</th>
<th>Purpose</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite passive microwave:</td>
<td>1995-2011</td>
<td>Atmospheric columnar water vapor field retrieval and vortex structure identification, polar low parameter estimation, trajectory tracking</td>
<td>Well calibrated data are unavailable before 1995</td>
</tr>
<tr>
<td>DMSP SSM/I, SSMIS</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Satellite scatterometer:</td>
<td>2002-2009</td>
<td>Polar low detection confirmation by means of surface wind speed field analysis (presence of high wind speeds)</td>
<td>Few scarce data from ERS-1/2 and NSCAT before 1995</td>
</tr>
<tr>
<td>QuikSCAT SeaWinds</td>
<td>2009-2011 (ASCAT)</td>
<td></td>
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<tr>
<td>Metop ASCAT</td>
<td></td>
<td></td>
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<tr>
<td>Envisat ASAR</td>
<td>2005-2011</td>
<td>Study of polar low manifestation in the sea surface wind field vortex structure, PL case studies</td>
<td>The highest resolution. Scarce and rare data</td>
</tr>
<tr>
<td>Aqua and Terra MODIS</td>
<td>2002-2011 (MODIS)</td>
<td>Cloud structure analysis, PL case studies</td>
<td></td>
</tr>
<tr>
<td>NOAA AVHRR IR and visible images</td>
<td>1995-2011 (AVHRR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCEP/NCAR re-analysis</td>
<td>1995-2011</td>
<td>Geopotential field analysis, comparison with results obtained from water vapor field study</td>
<td></td>
</tr>
</tbody>
</table>
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

Malye Karmakuly station

10.7 kg/m² at 00 UTC
12.7 kg/m² at 12 UTC

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

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

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Polar low over the Barents Sea on 5 March 2010

Aqua AMSR-E
- Total water vapor content
- 6:45 UTC

Metop ASCAT
- Wind speed
- 9:45 UTC

Terra MODIS
- Cloud structure
- 8:40 UTC

NCEP/NCAR
- Geopotential
- 6:00 UTC

Envisat ASAR
- 05:00 UTC

NOAA-16 AMSU-B
- Rain rate
- 13:00 UTC
Polar low over the Barents Sea
5 March 2010

Total atmospheric water vapor content retrieved from Aqua AMSR-E

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12 March 2011, two polar lows south to Spitsbergen

Terra and Aqua MODIS

Envisat ASAR

NCEP/NCAR

Geopotential, m²/s²

Metop ASCAT

V·m/s

Aqua AMSR-E

Water vapor content

Q, kg/m²

Cloud liquid water

W, kg/m²

Surface wind speed

11:15 UTC

12:50 UTC

12:00 UTC

11:32 UTC

13:09 UTC

11:35 UTC

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12 March 2011: water vapor content over Bjornoya island:

Bjornoya station radiosounding observation data:

<table>
<thead>
<tr>
<th>Time</th>
<th>Water Vapor Content (kg/m²)</th>
</tr>
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<tbody>
<tr>
<td>00:00</td>
<td>4.35 kg/m²</td>
</tr>
<tr>
<td>06:00</td>
<td>3.53 kg/m²</td>
</tr>
<tr>
<td>12:00</td>
<td>4.01 kg/m²</td>
</tr>
<tr>
<td>18:00</td>
<td>3.59 kg/m²</td>
</tr>
</tbody>
</table>

Starting from 1 January 2010
4 radiosoundings per day
WRF - The Weather Research and Forecasting hydrodynamic mesoscale model. It was created through a partnership that includes the NOAA, NCAR and more than 150 other organizations and Universities in the United States and abroad.

Barents Sea
Three levels of nests, with nest d01 acting as the parent for nest d02 and nest d02 acting as the parent for nest d03

d01 grid - 100 x 100 points, space step 10 km, time step 60 s
d02 grid - 100 x 100 points, space step 3 km, time step 20 s
d03 grid - 100 x 100 points, space step 1 km, time step 6 s

Forecast fields – see level pressure and water vapor 9.01.2009