STARS deliverable document D-3, SAP

Scientific Analysis Plan - SAP

A technical report

Øyvind Saetra, Steinad Eastwood, Jens Debernard and Pål-Erik Isachesen
The Norwegian meteorological Institute

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1. Introduction

The STARS Scientific Analysis Plan (SAP) outlines a detailed plan for implementation of tasks 3 to 8.

The SAP aims at identifying the following points:

- Steps in the technical performance of each task
- The technical and scientific requirement
- User requirement whenever relevant
- Identification and description of the data to be used
- Identification and description of the modeling tools
- Contingency plans whenever relevant

PHASE I

2. Task 1: Management

Objective: *To design the project web page for communication and project management, manage the project and organize meetings.*

A web page for the STARS project will be designed using Wiki technology. The web page will be set up on the common met.no Wiki server. All project participants will be given direct access to contribute to the content of the web pages. Some of the pages will be open to the public, while most of the pages will only be open to the project team and ESA representatives. The web page shall include at least the following pages and management services:

- Homepage with a description of the STARS project based on the SoW and Contractor proposal, a Gantt chart for the project, a list of project deliverables, a calendar of all meetings and events and contact details of key project staff. This section of the web page shall be visible by the general public and link to the STSE web site.
- A contacts page providing contact details for key project staff. This section of the web page shall be visible by the general public.
- A project 'blog diary' that that documents progress and activities within the STARS project.
- A project document library that allows on-line access to all project documents in Adobe pdf and/or Microsoft Word format that is cross referenced to the SoW and contract deliverables.
- Pages where documents and presentations required and used during meetings can be downloaded at least 1 week before the meeting.
- Pages indicating of progress against each work package and deliverable in percentage complete units.
- Pages where STARS data can be accessed and downloaded.
- A list of reference documents used by the project.
- A set of links to project and other useful resources.
- Other aspects relevant to the STARS project.

The STARS web page will be maintained by the project leader at least every month to include updated project deliverable items and content for the duration of the STARS contract.

At met.no internal project group meetings will be held weekly to update all participants on the progress. Project meetings with ESA will be organized as explained in the administrative proposal.

D-22 (monthly reports) will be delivered on a monthly basis in PDF format. The content will be as defined in chapter 6.2 in the SoW. They will be made available on the STARS web page. D-23 (Actions Database) will be set up using Microsoft Excel. The content will be as defined in chapter 6.2 in the SoW. The ADB will be updated on a monthly basis in accordance with the monthly reporting and will the latest version will be available on the STARS web page together with the monthly reports. The D-22 and D-23 will be delivered no later than 5 days after the last day of each month.

Deliverables from Task 1:

D-22: Monthly reports
D-23: Action database

3. Task 2: Preliminary analysis

Objective: *To conduct a comprehensive scientific and technical review of polar lows in the Nordic Seas and define the scientific and technical requirements for users, technical data sets, modelling and scientific analysis that will guide all subsequent tasks within the STARS project.*

Subtask 2.1: To collect scientific and technical information required to carry out the STARS study and write a literature review of polar lows

The first large scale concerted polar low project was lead by met.no during the 1980s. The full set of report from this is archived at the institute and available for this project. A state of the art review of polar low was also conducted by Rasmussen and Turner (2004). These will be the starting point for searching and reading the polar low literature. Based on the result of this, a comprehensive review of the polar low research will be written. The review will cover the following topics:

1. State of the art for polar low forecasting in the Nordic Seas.
2. Existing polar low and intense air sea interaction (e.g. extreme weather events) activities and projects both within and beyond Europe.
3. Current status, strengths and weaknesses of available satellite and in situ data sets in the Nordic Seas.
4. Past oceanographic studies using these datasets and their different techniques to study polar lows and ocean circulation in high latitudes.
5. Numerical models in the Nordic Seas
6. Heat potential of the surface ocean in the tropical region and use in hurricane forecasting and potential for an analogous approach in the Nordic Seas as a Polar Low Indicator. The requirements for a suitable data set for computation of a Polar Low Indicator field should be assessed.
7. Challenges and user requirements for improved forecasting of polar lows in the Nordic Seas.
8. Challenges and user requirements for the investigation of polar low impacts on ocean circulation in the Nordic Seas.
9. Other aspects relevant to the study.

The literature review (REP-1) will be made available to the general public through the STARS web page.

Subtask 2.2: To Review the STARS project requirements and to develop a Scientific Analysis Plan (SAP)

The SAP will identify:

1. All the user requirements, scientific requirements, data requirements, technical requirements,

development needs and open points to be addressed through the different tasks of the STARS project.
2. A description of the data sets that will be used during the STARS project and evidence of their availability.
3. A description of the proposed approach to characterizing polar low events using the STARS-DAT data set (Task 4).
4. A description of the proposed approach to developing and validating a PLI field in the Nordic Seas (Task 5).
5. A description of the modeling tools to be used by the STARS project and evidence of their availability (Task 6, Task 7 and Task-8).
6. A description of the NS-MODEL cross validation and sensitivity analysis experiments within Task-7, the proposed test cases, data required to conduct the test cases and evidence of their availability, and the methodologies proposed to analyze the results.
7. A description of the proposed experiments within Task-8, including a description of the data required to conduct the experiments and evidence of their availability, model/computer time required to conduct the proposed experiments and their availability, and the methodologies proposed to analyze the results.
8. Other aspects relevant to the project.

Deliverables from Task 2:

D-2: Scientific and technical review of of polar lows in the Nordic Seas (REP-1)
D-3: Scientific analysis plan (SAP)

4. Task 3: STARS data set

Objective: *To establish a multi satellite and in situ data set of ocean and atmosphere observations for the investigation of polar lows in the Nordic Seas region.*

Subtask 3.1: Assemble a multi-satellite and in situ data set of ocean and atmospheric observations for the investigation of polar lows in the Nordic Seas for a 5 year period.

A data set called STARS-DAT will be built for the investigation of polar lows in the Nordic Seas region, based on the analysis provided in REP-1 and SAP. This data set will contain multi-satellite and in situ data ocean and atmospheric observations covering the winter seasons from 2005 – 2009. The data to be collected is listed in the Error: Reference source not found, which covers all data necessary for the other tasks in this proposal.

The building of the STARS-DAT data set will be coordinated with complementary THORPEX-International Polar Year (IPY) activities to minimise duplication of activities, share data and other resources and to communicate results. met.no has been a central partner in THORPEX and this coordination will be done in together with colleagues at met.no.

The STARS-DAT will only contain data that can be distributed freely (see Error: Reference source not found). In case of restricted data being used in the project, such data will be built in a separate parallel data set, so that STARS-DAT can be freely distributed. The STARS-DAT will be designed so that it can easily be extended if required in the future.

The STARS-DAT data set will be built at met.no internal disk facilities (central RAID disk system, hosted on Linux architecture machine) and hosted there during the project period. The data set will be build using existing in-house software for reading and regridding both satellite data and numerical model data. A central tool for the regridding, will be Fimex, which is a GNU LGPL licensed tool developed and maintained at met.no (more details on Fimex are given here: https://wiki.met.no/fimex/start). The data set will be organised by placing all data for each calendar day in one directory, organised in yearday directories for each year. This way of building the STARS-DAT allow for easy archiving and re-located the dataset, as well as extending it if required.

The size of the data set will be in the order of 2Tb uncompressed. The data set will be distributed in compressed form (using the gzip compression tool). A copy of the data set will be provided to ESA on USB disk. Because of the large size of the data set, no direct external access web interfaces will be set up. The web interfaces that will be designed will be used for in-house access to the data, but will be designed to work on external servers.

The STARS-DAT data set will be built in NetCDF format (NetCDF version 3), following the CF-1.4 metadata convention. The satellite fields and NWP output will be gridded onto a common polar stereographic projection and grid.

Subtask 3.2: Provide an electronic metadata database that catalogues each data holding within the STARS-DAT data set.

From the STARS-DAT data set an electronic metadata database (STARS-DAT-DB) will be build that catalogues each polar low event within the STARS-DAT data set. The STARS-DAT data set will be searched for all polar low events in Task 4. From this list of events, the metadata database will be built, identifying all available and relevant data fields within STARS-DAT during each period of a polar low event. From these data fields key geospatial information will be collected to the metadata database (such as mean and max SST, mean and max wind speed, etc). The metadata database will be built in XML format. For each polar low event two XML files will be generated; one for the key geospatial information and one with references to the relevant files in the STARS-DAT. The geospatial metadata will use the ISO 19139 standard, the XML representation of the ISO 19155 standard. This way of building the STARS-DAT-DB allow for easy archiving and re-located the database, as well as extending it if required.

An interface to the metadata database will be built using PHP5 with basic search capabilities, and made available through a web interface. For each polar low event in the metadata base, this web tool will also contain a set of IR quick look images. This meta data base will be maid available for on-line search through the STARS web interface. The STARS-DAT-DB and the PHP5 web interface will be maid available at the STARS web portal as a compress TAR-file for anybody who wants to use it.

Subtask 3.3: Provide a STARS-DAT user manual.

A user manual documenting the STARS-DAT and STARS-DAT-DB will be provided. This user manual will include the following sections:

1. Introduction and purpose of STARS-DAT and STARS-DAT-DB
2. Data model used by STARS-DAT and STARS-DAT-DB.
3. User manual for the STARS-DAT metadata database (including a description of

the metadata model used).
4. Unique identification of each polar low event within STARS-DAT with STARS-DAT-DB references for all data corresponding to each event.
5. Documentation for each data holding within STARS-DAT including, but not limited to, data format description, spatial coverage of data, temporal coverage of data, missing data from time series, known data problems/issues, source of data, usage restrictions, data strengths and weakness.
6. One worked example demonstrating how to query and access the STARS-DAT data sets using STARS-DAT-DB for a particular polar low event.
7. Recommended future developments for STARS-DAT.
8. Procedures that allow users to update/extend/revise STARS-DAT.
9. Other aspects relevant to the STARS-DAT and STARS-DAT-DB.

Table 1: Data to be collected for STARS-DAT, covering the winter seasons from 2005 to 2009.

Dataset	Where to access	Restriction on access/use
SST L2P	GHRSST LTSRF (http://ghrsst.nodc.noaa.gov)	Freely available
SLA from Envisat and GFO, gridded and along-track data	AVISO http://www.aviso.oceanobs.com	Freely available
SLA from ERS-2, Gridded and along-track data	ESA, availability to be confirmed by ESA	met.no is Cat-1 user
Wind vector from QuikScat and ASCAT	OSI SAF	Freely available, met.no is partner in OSI SAF
Wind speed and water vapour from AMSR-E	RSS http://www.remss.com	Freely available
AVHRR VIS/IR images	Locally received data, available in local archive	No restrictions
In situ meteorological data (synop,buoy,ship)	Locally received data through GTS, available in local archive	No restrictions
In situ sub surface data (XBT, ARGO gliders etc)	Coriolis (http://www.coriolis.eu.org); Institute of Marine Research (http://www.imr.no)	Coriolis: Freely available IMR: Available through cooperation agreement
NWP model runs	ECMWF: MARS archive HIRLAM: local archive	ECMWF: met.no is national member, has free access.
Observational data from IPY campaigns	IPY database is hosted by met.no	Freely available

In Task 3 version 1 of the STARS-DAT system will be built. In Task 5 the STARS-DAT system will be updated and a new version will be built. Any new version of the data set and data base will be done based on a copy of version 1.

Deliverables from Task 3:

D-4: STARS-DAT data set, version 1.
D-5: STARS-DAT metadata database, version 1 (STARS-DAT-DB).
D-6: STARS-DAT user manual, version 1 (STARS-DAT-UM).

5. Task 4: Identify and catalogue polar lows in the STARS data set

Objective: *To analyze the STARS-DAT data set to identify, catalogue, describe and characterize all polar low events within the data set for use in the STARS project.*

Note that the order of subtasks below is somewhat different than the 'bullets' in the SoW:

Subtask 4.1: Identify, catalogue, describe and characterise the features and characteristics of each polar low event within the STARS-DAT data set.

As discussed in the introduction polar lows are almost exclusively observed over the open ocean during cold air outbreaks. To obtain a list of all polar low events during the period covered by the STARS-DAT data set, the work will start by manually inspect operational weather analyses to detect periods when the large scale atmospheric flow pattern indicates possible cold air outbreaks over the Nordic Seas. From the list of potentially interesting situations, polar low events will be identified from all available AVHRR images in STARS-DAT (10-15 satellite passes covering one area every day at these high latitudes). The events will then be labeled. The track of the polar lows will be registered with the latitude and longitude values of the polar low center for each available satellite image covering the evolving polar lows. Based on this information, the STARS-DAT-DB will be populated.

Subtask 4.2: Use the STARS-DAT to investigate potential SSH response in connection with SST changes observed in passive microwave SST data during polar low events.

During polar low events (as identified in the STARS-DAT data set during Subtask 4.1), the ocean SST and SSH (or Sea Level Anomaly, SLA) response will be investigated using infrared, microwave and altimeter data from satellite. In particular, events where surface warming is indicated in the microwave images, such as the case observed by Saetra et al. (2008), will be investigated against any possible response in SLA. The investigation will start with an analysis during cloud free conditions as this gives the advantage of additional information from infrared sensor. This subtask is therefore divided into two steps

1. Investigate the joint response of SST (from infrared and microwave instruments) and SLA (from altimeter instruments) during cloud free condition to detect possible correlations.

2. Investigate the joint response of microwave and altimeter data during cloud covered high wind speed situations.

A software tool developed by Remote Sensing Systems (RSS) will be used in supplement for this task. This tool is used to reproject data to a storm-centric frame-of-reference, which makes the analysis of the collected data sets (remote sensing data, numerical model data and in situ data) easier. Figure 1 gives an example of how this tool tracks the typhoon Man-Yi that passed Japan in July 2007. The lines orthogonal to the storm track provide the backbone of the reprojected data and all data around each orthogonal are collected for a time period before and after the storm has passed. In this way the response of the storm has passing on each of the collected data sets can be studied.

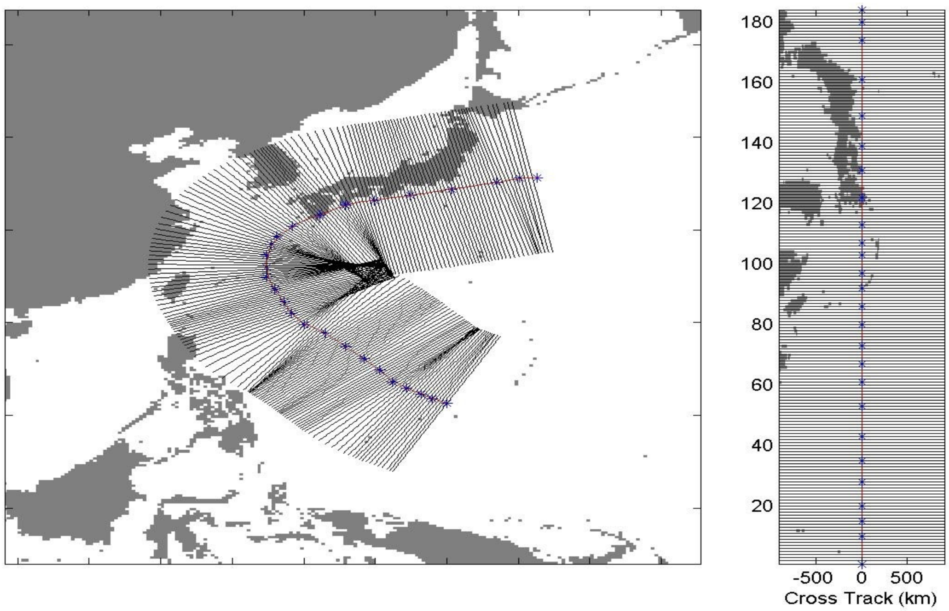

Figure 1: *Super Typhoon Man-Yi, 7 – 17 July 2007. The left panel shows the 6-hourly best track positions (blue stars), the interpolated position (red line), and the track orthogonals (black lines) every 25 km. The right panel shows how the evenly spaced orthogonals map onto a grid. Note that the transformation into the storm-centered coordinates does not retain coastlines in a familiar form.*

This tool was originally developed by RSS for application on tropical hurricanes, but can easily be used on high latitude polar lows as well. This has been discussed with Chelle Gentemann of RSS, and RSS has agreed to assist met.no in using this tool as an unfunded collaboration. More information about RSS and their archive of tropical cyclones can be found at www.remss.com/hurricane/active_storms.html.

Subtask 4.3: Measure the storm intensity of each polar low event using STARS-DAT surface wind speeds and significant wave height (Hs). Satellite data in synergy will form part of the analysis.

The intensity of the observed events will then be investigated using the wind speed observed by satellite scatterometer data and significant wave height from altimeter data combined with high resolution numerical model products from the operational forecasting system. Conventional observations are almost completely absent in areas where polar lows are formed. However, the current state of the art data assimilation systems for the atmosphere utilize large amounts of information for satellite that considerably improves the atmospheric analysis of polar low events. Experience from the IPY-THORPEX campaign, where polar low chasing was one objective, is that whenever polar lows are visible in the infrared images that are not present in the model forecast, the succeeding ECMWF analysis tends to catch the presence of the cyclone. This might be due to both upper-level temperature and moist information and the assimilation of surface winds from scatterometer. In this subtask both the direct satellite information and the ECMWF analysis will be used to estimate the polar low intensity. The intensity will be characterized according to the wind speed. The RSS tracking tool will described in Subtask 4.2 will be used in supplement for this task.

Subtask 4.4: Write a scientific and technical report

The report will include the activities performed during this task. The report will identify, catalogue, describe and characterize each polar low event within the STARS-DAT data set. A table of results will be included including entries for all polar lows identified. The specific situation for SST and SLA in synergy shall be clearly identified for each event including a summary of the situation prior to, during and following the event. The report will make recommendations for observation priorities for both satellite and in situ data sets in order to better characterize polar low events in the Nordic Seas.

The scientific and technical report (REP-2) will be made available to the general public through the STARS web page.

Deliverables from Task 4:

D-7: Scientific and technical report (REP-2)

Implementation:

In this activity, polar lows will be catalogued whenever the observed phenomena fulfills the requirements of the following definition:

"A polar low is a small, but fairly intense maritime cyclone that forms poleward of the main baroclinic zone (the polar front or other major baroclinic zone). The horizontal scale of the polar low is approximately between 200 and 1000 kilometres and surface winds near or above gale force".

The main tool for identification of polar lows will be infrared satellite images that are inspected visually. Polar low events are identified by the cloud structure following the general image classification system found in Rassmusen and Turner (2004). The resulting 5 year data set of polar low events will then be described by tracks of the hourly positions of the low pressure system together with a list of estimated wind speeds, sea level anomaly (SLA) and sea surface temperature (SST) response for all events whenever possible. To properly select real polar low events from other atmospheric phenomena that sometimes are confused with polar low events. Typically the following features are excluded in this study:

The *meso circulation* is related to the polar low in having a cyclonic appearance and with the same horizontal extent, but they are generally weaker in intensity. An example of this is given in Figure 1, which shows a meso circulation trailing the ice edge west of Novaya Zemjya.
Cloud tops are similar to the ambient cloud mass. Only in a few cells are protruding through the inversion layer, indicating potential for further intensification. They develop in a similar cold air outbreak as the polar low, but without the cold air aloft, they are confined to the mixed layer with cloud tops typically at 1-2km, the same as the ambient cloud mass. Typically they enhance the wind by 5-10 kts around the centre, and give just light precipitation. They are therefore of small significance to the public. They normally do not show up in the surface analysis, and are rarely referred to in the forecasts other than a more or less standard 1-2 Beaufort deviation from the main wind.

The *common low level trough* typically consists of an organised line of Cumulonimbus with deep convection and dense snow showers. The organised vertical motion generates a local surface low aligned along the line of showers, with a corresponding geostrophic wind field around. The inflow is not strong enough to develop a symmetrical cyclonic appearance with a concentrated point of convergence, on account of a less unstable air mass. The trough keeps its line shape, and with generally less intensity, this is what distinguishes it from the polar low.

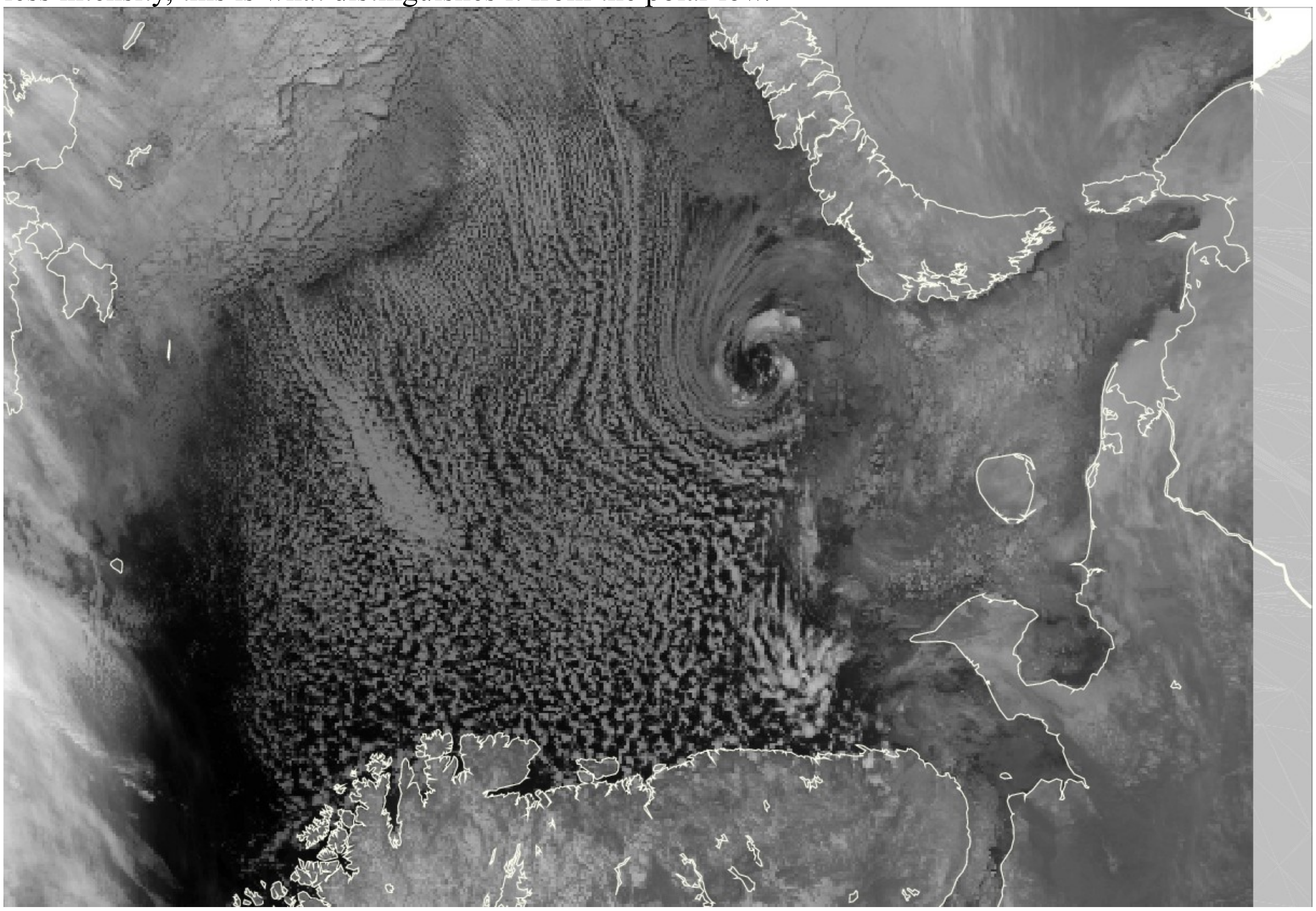

Figure 1: Example of Meso Circulation trailing the ice edge west of Novaya Zemjya 6 March 2010.

The *synoptic lows* should also be mentioned in this context, since they are frequently mistaken for polar lows. The synoptic lows are generally associated with the shifts of the large air masses. They are larger in size, are predominantly of baroclinic nature, and have their associated and easily distinguished frontal systems. The main reason to distinguish the polar low from the synoptic is that the polar low tends to be less predictable, with sharper gradients in wind and precipitation. The polar low tends to be less well taken by the numerical models since it is smaller and develops in areas with a great scarcity of observations. Thus the polar low has a larger capacity for surprise than the synoptic low. In the list, only those classified as polar lows are included. Trough lines, meso circulations and synoptic lows are omitted.

In this investigation the storm intensity will be defined by the maximum observed wind during the event. Mostly the wind speed estimates will be based on wind speed estimates from scatterometer data, which has a fairly good coverage at high latitudes. But whenever traditional meteorological observations are available, such as synoptic weather station data, these will be used as additional information to quantify the storm intensity. Only events with wind speeds of more that 15m/s (Gale force) will be classified as polar low events.

The ocean response to polar low events will be studied in SST and SLA observations. Based on Saetra et al. (2008), we expect rapid (order of 24 hours) changes in SST microwave signals over the life course of a polar low. A part of this investigation will be dedicated to look for possible links between SST and SLA responses. It is well known that at lower latitudes the SLA signal is strongly related to the ocean heat content and is currently used to identify areas of deep warm currents that has the potential to significantly intensify tropical hurricanes Leiper and volgenau, 1973; Law and Hobgood, 2007; Lin et al. 2008). This link between ocean temperatures and sea level heights are less obvious at high latitudes. For relatively warm waters the equation of state for sea water is dominated by the temperature and hence, yields a strong dependence of sea level signal to the oceanic heat content (defined as the vertically integrated ocean temperature. For high latitudes though, the equation of state is far more dependent on the salinity so that the sea level height, as observed by altimeters, is not a unique function of the heat content, but more an expression of the vertically integrated salinity.

As one of the key objectives of the STARS project is to investigate possible synergy and exploitation of satellite altimeter data for polar low events, a part of this task will be to study the sea level anomaly (SLA) response along the storm track before and after the passage of polar

Sea surface temperatures from microwave satellite observations has been observed to change rapidly during Arctic cold air outbreaks. Whether this is an artifact of the strong surface winds, large precipitations or other data contaminations will be an objective of this investigation. Here, SST from infrared sensors will be used to complement the microwave data whenever available.

This work will be carried out in the following steps:

1. First, infrared satellite images will be inspected visually and all events with cloud structure that are identified as real polar lows are listed identifying its date and position when first observed.
2. The IR images will be used to estimate the polar low tracks with hourly positions yielding a list of polar low tracks for the entire STARS period
3. Record the maximum wind speeds observed for each polar low events in the STARS period
4. Record any possible changes in the SLA signals before, during and after each polar low event in the STARS period
5. Record any possible changes in SST from microwave satellite data before, during and after each polar low event in the STARS period
6. Whenever available, record any possible changes in SST from infrared satellite data before, during and after each polar low event in the STARS period
7. Test if variations in microwave, SLA and IR data obtained during the polar low events in the STARS period are in any way correlated

Technical and scientific requirement:

This task requires the following:

1. Satellite infrared images for polar low detection from STARS-DAT

2. DIANA visualization software for inspection of IR images
3. Scatterometer wind speeds from STARS-DAT
4. Microwave wind speeds from STARS-DAT
5. In-situ wind speeds from coastal stations and ship/platform observations from STARS-DAT
6. Microwave SST from STARS-DAT
7. Infrared (IR) SST from STARS-DAT
8. Sea Level Anomaly (SLA) from STARS-DAT
9. R-software for statistical analysis of SLA and SST data

Data description:

All data used in this task is described under Task 3, STARS data set

6. Task 5: Creating a polar low indicator

Objective: *Use the STARS data set to develop a Polar Low Indicator (PLI) and demonstrate its use*
Subtask 5.1: Develop the Polar Low Indicator (PLI)

The marine nature of polar lows is a strong indication that warm ocean plays a crucial role for the development and intensity. Also the striking similarities to tropical hurricanes suggest that the ocean temperature is an important factor for the energy supply. In this task we aim to develop and test the use of satellite SST (from infrared and microwave instruments) and SLA (altimeter) to form a proxy of conditions favorable for polar low development. Emanuel and Rotunno (1989) proposed the view that the energetics of polar lows can be viewed as a Carnot engine, working between a warm reservoir (the ocean) and a cold reservoir (the tropopause). This view has lead a number of authors (for example Kolstad and Bracegirdle, 2008) to use the temperature difference between the sea surface and the temperature at the 500 hPa surface as an indicator for polar lows. When this difference exceeds about 43 degrees Celsius in a certain area, polar lows are very likely to be observed.

Here we propose to further develop this idea by using the satellite data for SST (possibly deduced also with the help of SLA) and upper level tropospheric temperatures from atmospheric weather prediction models, where tropospheric temperatures from satellite observations have been assimilated, to develop a pre-operational tool for probabilistic forecasting of polar low events. The work will take the following steps:

1. Implement software for retrieving and collocating satellite SST data and upper level tropospheric temperatures (partly based on the RSS tool described in subtask 4.2)
2. Construct the PLI index (from the surface to high level troposphere temperature difference)
3. To run the PLI over selected seasons in the STARS period to establish a threshold temperature difference for polar low events

Subtask 5.2: Documentation of the Polar Low Indicator (PLI)

The PLI will be documented in an Algorithm Theoretical Baseline Document (ATBD-1). The ATBD-1 will include the sections:

1. Introduction/Scope/Purpose of the PLI field
2. Algorithm Overview
3. Algorithm Description
4. Demonstration of results
5. Practical implementation
6. Other aspects relevant to the study
7. Conclusions and recommendations

Based on the findings in the literature review (REP-1), the STARS data set and from the list of polar low events detected in Task 4 (REP-2), the temperature threshold level will be decided. For this, the first half of the polar low events in REP-2 will be used. The second half of the polar low events list will be used as an independent data set for validation of the PLI and corresponding difference between SST – upperl-level temperaturs.

The Algorithm Theoretical Basline Document (ATBD-1) will be made available to the general public through the STARS web page.

Subtask 5.3: Implement the PLI filed data according to ATBD-1

The code for collocating the satellite SST and upper level tropospheric temperatures will be written in standard Fortran 90 and maintained under the Subversion (SVN) system. The resulting PLI fields will be stored in NetCDF format. This also enables visualization in the DIgital ANalysis tool DIANA, a meteorological visualization and production software developed at met.no. DIANA is used by forecasters at met.no to display numerical forecasts, satellite images, synoptic observations and radiosondes on maps. Currently, it is the main tool used operationally by forecasters at met.no. In DIANA, the PLI fields will highlight areas where the SST-upper air temperature difference is above the decided threshold level and enable forecasters to detect areas with high risk of being exposed to polar lows.

The PLI will be implemented under the Supervisor Monitor Scheduler (SMS) at met.no and run operationally for a limited test period. SMS is a software package that enables large number of programs to be run and monitored in a controlled environment and was developed for meteorological applications at the European Centre for Medium-Range Weather Forecasts (ECMWF). The SMS is for controlling and monitoring all operational computer activity at met.no. for a more detailed description of the SMS, see http://www.ecmwf.int/publications/manuals/sms/.

Subtask 5.4: Validate and verify the PLI fields

The main input to the PLI validation exercise will be the list of polar low events from Subtask 4.1. The first half of this list of events was used in Subtask 5.2 to determine the threshold level for the temperature difference between SST and the upper-level air. Here, the second part of the list is used as an independent data set to test the use of the PLI and the corresponding temperature difference. We will count the number of hits and false alarms and present the resulting hit and false alarm rates.

Subtask 5.5: Demonstrate the use of the PLI filed to monitor the potential intensification of polar lows

For this task the main input will be the measured storm intensity detected in subtask 4.2 and the polar low event list from subtask 4.3. The storm intensity, as measured by scatterometer winds and significant wave height from altimeter data, will be compared with the PLI (SST-upper air temperature difference) in each single polar low event from the list gathered in subsection 4.3.

Subtask 5.6: Prepare a PLI development, implementation and validation report (REP-3)

The report will summarize the activities and the results of task 5. The report will also describe each test case and the impact of the PLI to monitor the upper ocean thermal structure and possible improvements in polar low prediction in the Nordic Seas. The report will include description of the SST and SLA data in each case study and make recommendations for improvements to future Sentinel-3 and SLA data.

All test data sets and output data sets will be made available to ESA and the general public through the STARS web page.

The STARS-DAT version 2.0 will be updated to include the PLI data developed by this task. Also, the STARS-DAT-DB and the STARS-DAT-UM will be updated to version 2.0 by inclusion of the new PLI data.

Deliverables from Task 5:

D-8: Algorithm Theoretical Baseline Document (ATBD)
D-9: PLI development, implementation and validation report (REP-3)
D-10: Version 2.0 of STARS-DAT, STARS-DAT-DB and STARS-DAT-UM

Implementation:

Bracegridle and Gray (2008) found that the difference between the wet-bulb potential temperature at 700 hPa and the sea surface temperature (SST) is an effective discriminator between the atmospheric conditions associated with polar lows and other cyclones in the Nordic seas. A verification study shows that the objective identification method is reliable in the Nordic seas region. Kolstad et al. (2009) investigated the spatial and temporal distributions of marine cold air outbreaks (MAOC) over the northern North Atlantic using re-analysis data for the period from 1958 to 2007. They used a simple index for identifying cold air outbreaks: the vertical potential temperature gradient between the sea surface and 700 hPa. It was found that atmospheric temperature variability is considerably more important than the sea surface temperature variability in governing both the seasonal and the inter-annual variability of cold air outbreaks. Furthermore, a composite analysis revealed that a few well-defined and robust synoptic patterns are evident during cold air outbreaks in winter. Over the Labrador and Irminger Seas the MCAO index was found to have a correlation of 0.70 with the North Atlantic Oscillation index, while over the Barents Sea a negative correlation of 0.42 was found.

To develop a Polar Low Indicator (PLI) field, the work will build on previous work by Bracegridle and Gray (2008) and Kolstad et al. (2009), using the atmospheric heat potential, defined as the temperature difference between the SST and at the upper part of the troposphere. For example the temperature difference between SST and the 700 hPa surface. The tropical cyclone heat potential (or sometimes referred to as hurricane heat potential) is defined as the integrated vertical temperature from the sea surface to the depth of the 26°C isotherm (Leiper and volgenau, 1973; Law and Hobgood, 2007). This is based on the understanding that hurricane intensity is limited by the upwelling of cold water normally observed over waters with a shallow thermocline. This concept is hardly applicable to polar lows, for which the debate about relative importance of baroclinicity versus convective release of latent heat has been going on for as long as polar lows have been studied (see the historical section above and also Rassmusen and Turner, 2004). The view that polar lows are mixed systems of baroclinic and diabatic processes implies that the ocean temperature is not to the same degree controlling the cyclone intensity as in the case for hurricanes. This is also in agreement with the findings of Kolstad et al. (2009) and Linder et al. (2010) who argues that variations in the upper level temperatures are of greater importance than SST for controlling polar low intensity and formation.

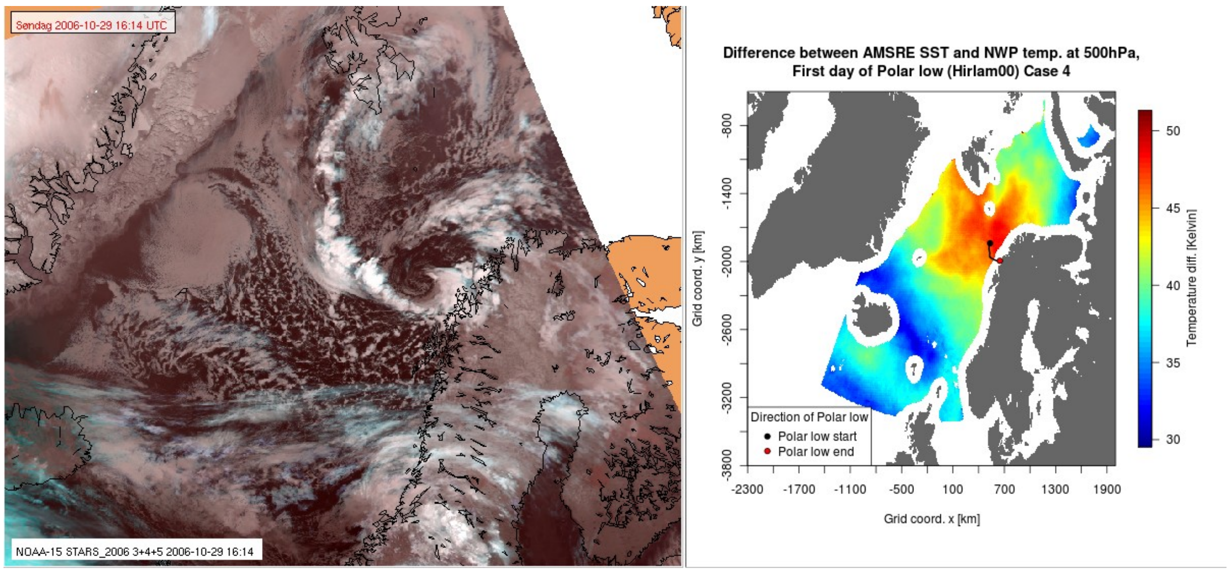

Figure 2: Plot on the left show a polar low about to landfall on the coast of Northern Norway on 29 November 2006. The plot on the right hand side shows the Atmospheric Heat Potential (AHP) as the temperature difference between the 500 hPa surface and the sea-surface temperature.

For each case in the list of the polar low events obtained in the STARS data under Task 4, the atmospheric potential will be calculated as the temperature difference between the 500 hPa, 700 hPa and SST. For the tropospheric temperatures we will use atmospheric analyses where upper level temperature from IR data and radiosondes have been assimilated into Numerical Weather Prediction Models. The SST will be estimated form a combination of infrared and microwave satellite data. In the first part of the analyses a threshold value will be established by determining the minimum observed temperature difference along the tracks in the first half of STARS list of polar low events. The second half of the list will then be used to verify the polar low indicator. We will correlate the temperature difference with the estimated storm intensity found in Task 4 and to estimate the potential numbers of false alarms.

The Atmospheric Heat Potential will be stored on in-hose files for archiving meteorological dat (felt files) and can be visualized in the DIANA software.

Technical and scientific requirement:

This task requires the following:

1. IT data for SST from STARS-DAT
2. Tropospheric temperatures from NWP analyses archived in the STARS-DAT
3. List of polar low events obtained in Task 4 for verification of PLI
4. R-software for statistical analysis of SLA and SST data
5. DIANA visualization software for visualization of PLI

Data description:

All data used in this task is described under Task 3, STARS data set

7. Task 6: Design description of the NS-Model

Objective: *To identify system requirements and implementation needs for a coupled Nordic Seas model. To design and describe the coupled Nordic Sea model. To investigate alternative methods for projecting SST and SLA observations into the ocean model.*

Subtask 6.1: Building on the contents of the SAP and activities of the STARS project, conduct a design study for a coupled ocean atmosphere model (referred to as NS-MODEL) in the Nordic Seas for use in the STARS project. The model shall be implemented with a specific emphasis on the use of ocean satellite data and PLI to (a) improve the forecast of polar low events and (b) understand the impact of polar low events on ocean circulation to be conducted in task-7 and task-8. NS-MODEL shall make full use of existing code and models as much as possible.

Today, met.no is running the Oslo Regional Climate Model (ORCM; Debernard and Køltzow, 2005), which consists of the atmosphere model HirHam (Christensen et al. 1996), coupled to the met.no-developed ice model MI-IM (Røed and Debernard, 2004), and to a local version of the ocean model MICOM (Miami Isophycnic Ocean Model; Bleck et al., 1992, see also references therein). The ORCM is used for coupled climate-type experiments over the whole Arctic at intermediate (50 km in atmosphere, 25 km in ice and ocean) resolution. At present the system is not suitable for studying polar lows due to a too coarse resolution. In addition, the ORCM have no data assimilation methods available.

The model components to be used in the coupled Nordic Sea Model (NS-MODEL) are instead the ROMS ocean model (Shchepetkin and McWilliams, 2005), with either existing ice code (Budgell, 2005) or CICE (Hunke and Lipscomb, 2008), and the HIRLAM amosphere model (Undén et al, 2002). All components are currently operational at met.no, and HIRLAM has also been coupled at met.no to the surface wave model WAM (WAMDI group, 1988). The coupling of NS-MODEL will be facilitated with the Model Coupling Toolkit (MCT, Larson et al., 2005; Jacob et al., 2005). MCT is already in use in several applications at met.no, including the Norwegian Earth System Model (NorESM) which will be used in the next IPCC assessment report. As a fall-back solution, parts of the ORCM can be used in the NS-MODEL. In this alternative configuration the MICOM ocean model should be replaced with the ROMS model to better model the ocean mixing processes relevant for this study. In addition, preferably, the MI-IM ice model should be replaced with the CICE ice code to better describe air-ice-ocean interaction over thin ice and in the Marginal Ice Zone. However, such a configuration would not have the opportunity for atmospheric assimilation, and would therefore completely rely on external analyzed initial conditions for the atmosphere.

Based on the status of the existing model components available at the time of the project, the alternative model configurations will be evaluated and a decision will be made about the final design of the NS-MODEL. A list of criteria relevant for the choice of the model design includes: physical completeness of the component models, earlier experiences with the atmosphere model for forecasting polar lows, alternative assimilation methods that are available, the flexibility of assimilating different types of data, the need for changes to model physics and code structure in a coupled framework, required model component resolution, scalability of the coupled system at supercomputers, required need for computer resources compared to what we have available to the project, and possible technical obstacles met when the alternative component models are interfacing the MCT library.

The HIRLAM model is written in Fortran77, while ROMS, CICE and MCT are written in Fortran90. All components use MPI-1 for interprocessor communication. In this task the important code changes needed when the models are coupled will be identified. The coupling routines will be designed in Fortran90/95.

The design study will also consider the available computational resources needed for implementing, testing and running the NS-MODEL. At present, alternative computers available are a IBM 575+ with 944 processors situated at NTNU in Trondheim, Norway, or a SUN X2200 Linux cluster with 2432 processors located at the University of Oslo, Norway. The first computer is used for operational atmosphere, ocean and wave forecasts from met.no, while the second computer is a development and research computer which is also used as backup machine for the operational forecasts. The HIRLAM and ROMS models are already implemented and running on both of these computers.

Subtask 6.2: Design the NS-MODEL configuration to be adjustable using dedicated configuration files limiting the need to re-compile code for model configuration changes.

Most input parameters relevant for polar low forecasting will be read from configuration input files, which do not force a recompilation of the code. However, major changes to the model setup as e.g. a change in the computational domain, or a major switch in the physical parameterizations, will most likely require a recompilation. The final decision on what parameterizations and changes that force a recompilation will be given by the impact of the final runtime efficiency of the system, and by the need of limiting the required code changes to the existing model components. The model input files and configuration files will be modified based on predefined templates and shell-scripts utilizing as much as possible of the existing script framework around the HIRLAM and ROMS models. The model script environment will be based on shell-scripts (bash, csh) and perl depending on the existing infrastructure around the component models.

Subtask 6.3: Design NS-MODEL to use at least ARGO subsurface profile data, satellite and in situ SST and satellite SSH for initialisation and, as far as possible, use data assimilation techniques to constrain NS-MODEL trajectory. Other data sources shall be used to constrain the model. The Contractor shall focus on the use of STARS-DAT data.

The NS-MODEL will be designed to assimilate satellite SST and SLA as well as in situ hydrographic profiles into the ocean component to give a proper initial condition for the polar low forecasts. The atmosphere component will also use the assimilated SST fields but will otherwise be fed by the same observational data as used today in the operational weather forecast system (to give a fair and realistic comparison with the operational, uncoupled forecasts). We will focus on the use of STARS-DAT ocean data in the assimilation phase.

The data assimilation will not take place under one unified framework. Assimilation for met.no's atmospheric models has reached a relatively mature stage and relies today on 3D-VAR schemes (moving towards 4D-VAR) whereas assimilation for our ocean and ice models is still relatively primitive. Depending on the advances in on-going work, assimilation schemes for the ocean and ice components of NS-MODEL will use either a Cressman analysis or an optimal interpolation (OI) scheme. The ocean modelling group at met.no is presently setting up model covariance matrices for ocean modelling of the Arctic Ocean and Nordic Seas for use in an OI scheme.

For this project we plan to rethink the way SLA and SST observations are assimilated into the ocean component of the coupled system, in particular the way these surface observations are projected down from the surface and into the ocean interior (where they should influence other prognostic model variables). Instead of relying on statistical estimates of model covariance matrices (e.g. from ensemble techniques) which are often noisy, we propose here to base the vertical projection on dynamical considerations. Specifically, we intend to investigate (by use of independent, uncoupled, ROMS runs) whether a significant fraction of upper ocean variability at daily to weekly time scales can be described in terms of simplified vertical dynamical modes, so-called quasi-geostrophic vertical modes perturbed around a state of rest or around a background flow field (in which case the modes may reflect growing disturbances). Should a significant fraction of SLA and SST variance and covariance turn out to project onto such vertical modes, we will be given a new method of projecting SLA and SST observations into the ocean interior and, thus, a way to construct vertical model covariances that are dynamically consistent. Such a projection method should greatly improve the utility of co-located SST and SLA observations in initializing the ocean model for the coupled forecasts of Task 8. If this method does not promise to be successful we will propose simpler vertical projection functions, e.g. decaying exponentials, as used in the UK Met Office FOAM model (Martin et al., 2007).

According to the SoW, the NS-MODEL should be designed to also directly utilize the PLI constructed in Task 5. However, as the PLI only gives a probabilistic measure of the chance of polar lows, we believe it may be more useful as an alert system for a weather forecaster than as a direct input (via assimilation) to the NS-MODEL. In a long term development perspective, the PLI can be included in a probabilistic ensemble forecast system, where the PLI could be used to change the size of the ensemble, or to optimize the ensemble with respect to polar lows in a given area. This would however be a large task to achieve, and we judge this to be outside the goal of this project. In addition, the required development time and computational needs for such a system would be far beyond any budget limits proposed for this project. Therefore, the NS-MODEL we propose to construct here will not directly utilize the PLI for forecasting polar lows.

Subtask 6.4: Based on the design study and building on the SAP and STARS deliverables, write a detailed scientific and technical description of the NS-MODEL in a Model Description Document (NS-MODEL-DD).

Based on the design study, and building on the SAP and STARS deliverables, a detailed scientific and technical description of the NS-MODEL in a Model Description Document (NS-MODEL-DD) will be written. The NS-MODEL-DD document will include:

1. A requirements analysis of Task 7 and Task 8 modelling activities listing all requirements.
2. A description for the proposed model design and justification of trade-offs and design decisions made with respect to the requirements of Task 7 and task 8.
3. Evidence of proposed model codes and their availability.
4. Resources required to run the model and their availability with respect to the requirements of Task 7 and task 8.
5. A review of data sets required to constrain the model and their availability with respect to the validation and sensitivity analysis experiments requirements of Task 7 and the hindcast and case study experiments in Task 8.
6. Description of the NS-MODEL Subversion (SVN) implementation and operation at the met.no computers.
7. The methodologies proposed to analyse the results with respect to the requirements of Task 7 and task 8.
8. A description of all relevant configuration parameters for the model and a summary assessment of their function, sensitivity, value range and likely impact on model output. This point will not cover all free model parameters in the system, as this would be a far too large job. Most of the parameters are already thoroughly described in the existing documentation of the model components, and this will not be repeated unless a significant change in model sensitivity due to a parameter is expected due to a full interactive coupling.
9. An implementation plan that clearly identifies development needs and open points to be addressed with respect to the requirements of Task 7 and task 8.
10. Other aspects relevant to the design, implementation and use of NS-MODEL in Task 7 and Task 8.

The NS-MODEL-DD will be made open to other communities.

Deliverables from Task 6:
D-11: Nordic Seas coupled model Description Document (NS-MODEL-DD)

User requirements:

The NS-MODEL should be fast, stable and reliable for predicting polar lows and their interaction with upper ocean.

The NS-MODEL-DD should written following the instructions given in the Technical proposal.

Scientific requirements:

There are different approaches that could be used when coupling together general circulation ocean and atmosphere models. However, in most models that are not from the beginning constructed to be part of a coupled system, different simplifications and compromises have to be made in model physics and numerics. These changes are necessary to make the system realistic, stable and convenient in a coupled setting. For atmosphere models most of the challenges comes when the sea surface contains both ice and open water, but also the land-mask definition can be troublesome. In global climate models, the two most important properties to conserve are the heat and freshwater contents. Violating these properties give long term drifts in the system. However, in a regional, coupled, short range, forecast system, this might not be equally important. Instead, proper treatment of the boundary layers, and upper ocean mixing seems important. Also the coupling frequency should be short enough to resolve the processes that are important for the short time development of polar lows. For the present investigations we expect a coupling time step of approximately 1 hour to be fast enough to give a realistic simulation of the mixing processes in the upper ocean and their modification of the atmospheric boundary layer.

The horizontal grid of the models should be fine grained enough to model the polar lows and the ocean response. For the atmosphere, a 8 km resolution model has shown to successful reproduce polar low developments. However, an 8 km ocean model will certainly not describe all interesting ocean adjustments to polar lows, but we expect the most important heat flux and upper ocean mixing to be adequately described. We expect these processes to be most important for coupling back to the polar low, and these will also be most interesting and important for the present study.

There are several different tools that have been used when building coupled models. In Europe, the OASIS3 and OASIS4 (Redler et al 2010) systems has been widely used, while in the U.S., several institutions work towards the ESMF system (http://www.earthsystemmodeling.org/). The OASIS4 system is a fairly complete library with grid interpolation, communication, etc, but are still in a beta test phase. The ESMF is more a suite of software tools for building multicomponent earth science applications. Instead of simple library calls as used in OASIS, it is more of a common model interface that 'glues' the different component models together to ensure smooth communication between different components. ESMF has been released in version 4. and are still in a development phase. In the span between these two systems, we also find the Model Coupling Toolkit (MCT) library (Larson et al., 2005; Jacob et al., 2005). This is a model communication library, that are capable of handling the complex inter processor communication between the models. This library has been used in many different systems as the NCAR CCSM3/4 and CESM1. In addition, it has been used for coupling the ocean model ROMS to the wave model SWAN and to the atmosphere model WRF. The MCT has proven to be robust, flexible and efficient for building coupled models.

For these coupled runs SST observations will be assimilated into the ocean model. The SST product will be OSI-SAF SSTs (approximately 10km horizontal resolution) which are used in lower boundary conditions for today's operational atmospheric model (HIRLAM) at met.no. The SST analysis will be a weighted combination of ocean model and observed SSTs. Model weights will be based on (static) ensemble statistics gathered from the 6-7 year long (uncoupled) Nordic4km run to be used in Task 8, and observation weights will be based on quality information delivered with the OSI-SAF product.

Since the ocean model will have approximately 8 km horizontal resolution while the OSI-SAF product comes at approximately 10 km resolution, the formation of the SST analysis should optimally be done only at the larger scales. Time permitting we will therefore apply a spatial filter (most easily done by Fourier or wavelet methods) to the process where the highest wavenumbers of the ocean model (the eddy field) are left unmodified.

To minimize the introduction of inconsistencies in the model vertical temperature (and density) field, the SST analysis will be projected into the ocean model water column using a one-dimensional Kalman filter. The vertical correlations will be modeled using second-order auto-regressive functions (e.g. Cummings, 2005) such that the correlations are inversely proportional to the local (model) stratification. The result will a synthetic profile complete with data in all vertical model grid points. This method, which can also be applied to assimilate in situ hydrographic profiles, is currently under testing at met.no.

Data requirements:

Data needed for running, initializing and validating the model will be listed in the NS-MODEL-DD. They include open boundary data for the atmosphere, sea ice and ocean models; background initial fields for these models; and data needed for assimilation and validation.

Technical requirements:

Updated status about the component models that should be used in the NS-MODEL.
Status of available supercomputer facilities.
Status on easy access to all relevant data.
Overview of, and eventually a plan for development of formating tools needed to interface all the different datasets.

Description of modeling tools

The model components to be used in the coupled Nordic Sea Model (NS-MODEL) are the ROMS ocean model (Shchepetkin and McWilliams, 2005), with either existing ice code (Budgell, 2005) or CICE (Hunke and Lipscomb, 2008), and the HIRLAM atmosphere model (Undén et al, 2002). The ROMS with the ice code of Budgell and HIRLAM are currently operational at met.no. The CICE model has been tested but are not operational. The coupling of NS-MODEL will be facilitated with the Model Coupling Toolkit (MCT, Larson et al., 2005; Jacob et al., 2005).

Development needs and open points

The model design depends on the status of the coupled CICE – ROMS ice/ocean model. If this system is not working satisfactory using the MCT, alternative solutions must be found during the design study.

The design will also depend on the status of the HirLam atmosphere model. There are ongoing initiatives to replace met.no forecast model HirLam with the Harmoni model for non-hydrostatic simulations on the horizontal scales from approximately 8 km and upwards. If this switch is done during the implementation phase of the NS-MODEL, the Harmoni model will be considered as an alternative for the atmospheric component.

PHASE II

8. Task 7: Implementation and testing of NS-Model

User requirements

The NS-MODEL should be fast, stable and reliable for predicting polar lows and their interaction with the upper ocean.

The NS-MODEL-DD should be ready and work as an implementation guide for the coupling and setup of the model.

Appropriate super computer resources must be available during the implementation and test phase with all relevant software.

Scientific requirements:

Initial full scale validation tests will be done by running the model for some of the most intense polar low events found in the polar low list compiled under task 5. The simulations will be verified against independent synoptic observations. The sensitivity to important coupling parameters will be investigated by running the same polar low event with different relevant values spanning the uncertainty in the parameter values. An uncoupled atmospheric forecast should be used as a reference experiment when the behavior and sensitivity of the coupled system is considered.

Based the co-located model data and in-situ observations of pressure, wind speed and precipitation, standard statistical scores will be calculated. This includes Root-Mean Square Errors (RMSE), Mean error (bias) and standard deviations between model runs and observations.

Data requirements

Data needed for running, initializing and validating the model will be listed in the NS-MODEL-DD.

They include open boundary data for the atmosphere, sea ice and ocean models; background initial fields for these models; and data needed for assimilation and validation.

The polar low list produced under Task 4.

Technical requirements

Setup of the SVN repository at computers at met.no.

All component models are fully ready to be coupled.

Formating tools for all relevant data must be ready.

Boundary data.

Running 8 km resolution in both atmosphere and ocean models, requires approximately 170 CPU-hours, and 40 minutes wall clock time per forecast cycle (assimilation/initialization) plus a 60 hour prognosis. This is based on using 256 CPUs on the present operational super computer running these models.

Development needs and open points

No special needs are identified as long as the NS-MODEL-DD is ready, an the status of all model components, data sets and formating tools are satisfactory.

Description of modeling tools

The same model will be utilized as listed under Task 6.

9. Task 8: Coupled atmosphere ocean simulations of polar low events

We will primarily evaluate the impact of a dynamic ocean on polar low forecasts, where the ocean model initial state has been made dynamically consistent with OSI-SAF SST via a simple assimilation scheme.

The activity will consist of a set of pairs of (uncoupled and coupled) model integrations, each integration centered on an interesting cold air outbreak (as revealed in Tasks 3 and 4).

For each such event an uncoupled control run will first be done with the atmospheric model feeling static OSI-SAF SSTs (as is done in today's operational forecasts). The integration will be conducted from an initial state given by the existing 3D-VAR assimilation system (which does not include information about SST).

Then the same forecast will be repeated with the coupled NS-MODEL. In the perturbation run(s), the initial state of the atmospheric component will be unchanged from that of the control run. But now the ocean model component will be integrated from an initial state where OSI-SAF SST has been assimilated in. The surface observations will be projected down to depth in a dynamically consistent manner (investigated in Subtask 6.3). Variations of this ocean initial state may also include assimilation of hydrographic profiles as a weaker constraint (the ocean model SST field will not be allowed to deviate too much from the OSI-SAF SSTs which the atmospheric model felt during the control run). Since the assimilation scheme is not multivariate, an adjustment of the entire ocean model field will be done via a nudging period leading up to the analysis time.

Data requirements

Same as in Task 7.

Technical requirements

Available super computing resources.

All boundary and input data ready for uploading to the high performance computer that will be used.

Description of modeling tools

The same model will be utilized as listed under Task 6.

Impact of polar lows on the ocean circulation

This activity is carried out under Task 8 according to the STARS Technical proposal.

The purpose of this subtask is to evaluate the thermodynamic and dynamics effects of cold air outbreaks and polar lows on the ocean and ocean circulation of the Nordic Seas. The study will involve a 7-year long uncoupled ocean model (ROMS) simulation forced by ECMWF operational analysis for the period 2003-2009. Both the atmospheric forcing fields and the ocean model dynamical response will be analyzed as described below.

Implementation:

We will begin by estimating the relative role of polar lows on the annual net heat, freshwater and buoyancy/density fluxes over the Nordic Seas. This is basically a book-keeping calculation of fluxes that take place during marine cold-air outbreaks (compared to periods of more normal atmospheric conditions). The ocean model will be forced by the ECMWF operational analyses, but since the air-sea heat and freshwater fluxes are *prescribed* (by the atmospheric model) these first calculations can be gathered without concern for the state of the ocean model itself.

Estimates will also be made of the density flux through the sea surface (Isachsen et al., 2007) from:

$$f = \frac{-\alpha}{C_p} Q + \rho(0,T)\beta S(-FW)$$

where Q and FW are heat and freshwater fluxes into the ocean, α and β are thermal and haline expansion/contraction coeffieients, T and S are surface temperature and salinity, C_p is heat capacity at surface pressure and $\rho(0,T)$ is the water density at zero salinity. For this calculation information about the ocean state (surface values of T and S) are required. From these estimates of the sea surface density flux we will then estimate the *transformation* of waters between different density classes, a measure of the volume transport of waters crossing isopycnal σ due to irreversible density changes from air-sea fluxes:

$$F(\sigma) = \frac{1}{T}\int_0^T \left[\frac{1}{\Delta\sigma}\int_\sigma^{\sigma+\Delta\sigma} f\, dA\right] dt.$$

Here T is the duration of the period in question, σ is the potential density and $\Delta\sigma$ a small density interval over which the integral is performed. These calculations will then form a first estimate of the relative influence of marine cold-air outbreaks and polar lows on the large-scale diapycnal overturning circulation within in the Nordic Seas.

The analysis above may be though of as a study of the *thermodynamic* impact of cold air outbreaks and polar lows on the ocean. Next, we will make a complementary analysis of the ocean's *dynamical* response to the anomalous buoyancy fluxes. In this study we can not do a close evaluation of the initial fast processes leading to local mixed-layer deepening since small-scale vertical mixing is parameterized in the ocean model to be used. The focus will instead be on the subsequent mesoscale adjustment to the anomalous buoyancy and wind forcing. Specifically, we will diagnose the evolution of horizontal Reynolds density fluxes in the ocean model and study the extent to which these can be explained by simplified quasi-geostrophic theory. The goals will be 1) to build an understanding of the key processes and chain of events that lead to the adjustment, and 2) to produce recommendations for parameterizations of the ocean response for use in later coarse-resolution studies of the impact of polar low on the global ocean circulation (as in Condron et al., 2008).

The mesoscale adjustment to increased baroclinicity in the system after the passage of a polar low is thought to be primarily of advective nature. Therefore we will evaluate if the adjustment, i.e. the restratification process after mixed-layer deepening, can be successfully described in terms of a parameterized eddy overturning streamfunction proposed by Ferrari et al. (2010):

$$\left(c^2\frac{d^2}{dz^2} - N^2\right)\Psi = (g/\rho_0)\kappa\nabla_z\rho, \qquad -H < z < 0$$

$$\Psi = 0, \qquad z = -H,\ 0.$$

Here Ψ is the eddy (quasi-Stokes) streamfunction, N is the buoyancy frequency, g and ρ_0 are the gravitational acceleration and a reference water density, and ρ is in situ density. The solution to the elliptical problem will create a velocity field which ensures that available graviational potential energy is released in the depth-integrated sense, conforming to very basic properties thought to govern baroclinic instability and eddy buoyancy transport.

Part of the study here will focus on finding the optimal choice for the two free parameters of this problem, namely the characteristic velocity c and the eddy diffusion coefficient κ. Attempts will be made to draw the velocity c from the solution to linear quasi-geostrophic modal calculations (Smith, 2007; Isachsen, 2010) where both stable and unstable (growing) solutions will be examined. For the diffusivity κ we intend to use an estimate based on (altimetric) observations of sea level anomalies (Holloway, 1986):

$$\kappa=(g/f)(\overline{\eta'^2})^{1/2},$$

where f is the Coriolis parameter and η' is the SLA field. This expression thus needs an estimate of the variability of the SLA field at each geographic position, and this will either involve the time variability or the spatial variability (localized in space by wavelet methods).

Note that the expression for diffusivity above is not a full parameterization that may be implemented into a coarse-resolution ocean model (the expression involves the surface response η' of the unresolved processes that actually need to be parameterized). But it will serve to close the problem of diagnosing the ocean's lowest-order response to the anomalous buoyancy forcing from cold air outbreaks and polar lows. With estimates of κ and c as described above we can make dynamical estimates of the residual overturning circulation for direct comparison with the thermodynamic calculations made initially. A good match between the two estimates will imply that we have understood the basic thermodynamic and dynamic response of the ocean to the passage of these atmospheric extreme events.

Technical and scientific requirements:

1. The ROMS integrations are presently carried out on a Linux cluster at the University of Oslo (http://www.notur.no/hardware/titan). A 7-year run (including one year spin-up) will require approximately 100 000 cpu hours.
2. Heat, freshwater and density fluxes through the sea surface as well as lateral fluxes between the boundary current and interior basins may be extracted from the stored model fields.
3. Detailed analysis methods are documented in the references given herein.

Data description:

- EWMWF operational atmospheric analyses for the period 2003-2009 (http://www.ecmwf.int/products/data/operational_system/) will supply sea surface heat and freshwater fluxes and will also be used for forcing the ocean model.
- The polar low list produced under Task 4 will be used to define "polar low periods" for the analysis.
- Sea Level Anomaly (SLA) fields will be taken from STARS-DAT.

10. Task 9: Prepare utility report, final report, data pack and a final presentation of results

Objective: *To report to ESA a final Technical Data Package, final Report and a final presentation of this project*

Subtask 9.1: Provide a Final Report (FR)

Prepare report and review of all activities in the project. The report will include sections that:

1. Identify potential application using STARS data set
2. Suggest and recommend future radiometer altimeter mission concepts
3. Provide roadmap for future work to facilitate the application of Sentinel-3 data
4. Review the conclusions of this work and the impact on the Sentinel-3 mission

Subtask 9.2: Provide summary report (SR) based on Final Report
As outlined in the SoW.

Subtask 9.3: Provide Power Point presentation (PPT) based on the Final Report and present this at the final meeting

The FR, SR and PPT will be made available to other communities through the STARS web page.

Subtask 9.4: Consolidate all deliverable into a Technical Data Package (TDP)
The TDP will be open to other communities.

Deliverables from Task 9:

D-16: Final report
D-17: Summary Report
D-18: Power Point presentation
D-19: Final Presentation
D-20: Technical Data Package

CHANGES TO PHASE II

The fundamental aim of the proposed modeling work is to investigate whether a regional coupled ocean-ice-atmosphere model constrained by observations of SLA and SSTcan produce improved forecasts of polar low events over the Nordic Seas. A second aim is to investigate any recurring effects of upper-ocean thermodynamic conditions on the birth and evolution of polar lows and, vice-versa, the general effects of polar lows on the upper ocean hydrography and circulation. In the Statement of Work (SoW), ESA proposes one long (4-5 year) coupled model integration which will be used to 1) improve forecasting of polar lows in the Nordic Seas and to 2) investigate the impact of polar lows on the general ocean circulation of the Nordic Seas. We believe, however, that one long coupled regional simulation, and the analysis of this, may not be the best route to addressing the goals of the project, as described below. A regional coupled model, adequate for studying polar lows and the upper ocean rapid response have to fulfill other requirements than a model normally used for regional climate simulations. First of all, the model system should run on a much higher resolution, and due to the rapid changes in surface fluxes and upper ocean hydrography, the coupling frequency have to be faster than normally done in climate models. In addition to atmosphere and ocean models, sea ice should be included in the system to give a realistic simulation of cold air outbreaks, conditions where polar lows normally forms, and the fading of polar lows over sea ice. Due to a very fast and tight thermodynamic ice-atmosphere coupling, there are technical/numerical challenges when coupling most short range atmospheric forecast models to an advanced sea ice model. Due to mathematical and numerical assumptions that are made in the atmospheric models, there is a problem to get a complete heat conserving, stable, and physical realistic coupling between the mixed ice/ocean surface and the atmosphere. If not all these conditions could be met at the same time, we think that for forecasting polar lows, it is best to keep high complexity and realism in the physics of the coupling and instead relax the requirement of complete heat conservation. This will, however, make the system less suitable for longer climate type simulations. A multi-year coupled integration is a computationally expensive undertaking which will quite likely suffer from the kinds of long-term drifts that are typically encountered in regional coupled climate models. Data assimilation can in practice correct for such drifts, but since long-term systematic drifts are a sign of model biases they should ideally not be countered by data assimilation methods (which, formally, are designed to account for random differences between models and observations). Instead we propose that testing whether a regional coupled model can produce improved forecasts of polar lows can be done in a set of shorter case-by-case coupled simulations which are run from initial conditions properly constrained by observational data. This type of short rang, initialized experiments, will also be the most relevant in the context of evaluating if a coupled model system improves the forecasts in a daily polar low / weather forecast system. In addition, we believe that a regional coupled ocean model is not the best tool to study the large-scale general ocean circulation response to polar lows. This is primarily due to the overwhelming influence of imposed lateral boundary conditions at longer time scales. For studies of the general circulation response a coarser large-scale, preferably global model (as in Condron et al., 2008), should be used. On the other hand, with a regional high-resolution model, we should be much better equipped to study the local, fast-timescale, interaction between upper-ocean thermal structure and polar lows. We also believe that these issues are best studied in a set of uncoupled ocean model runs that are forced with analyzed atmospheric fields, i.e. with as-good-as-can-be atmospheric fields which are also dynamically consistent with observed SST fields (via their assimilation into the atmospheric model). In such an arrangement we should be ideally set up to focus on the upper ocean dynamics---arguably the most unconstrained part of the coupled problem. Some questions which may be studied with such a model arrangement are: Which combination of ocean preconditioning and atmospheric forcing strength will enable wind-induced mixing to erode through a freshwater-stratified top layer to finally reach the temperature-stratified Atlantic Water layer beneath? What are the timescales of restratification due to ageostrophic mixed-layer instabilities as well as deeper quasi-geostrophic instabilities? Under what conditions will these restratification mechanisms suppress mixed layer deepening from mechanical mixing? What is the net effect of typical polar low events on Atlantic Water transformation in the Nordic Seas? An improved understanding of relationship between upper-ocean conditions and polar low events, both before and after, may also lead to improved techniques for assimilating SST and SLA observations into ocean models, coupled or uncoupled. Data assimilation in ocean models has a relatively immature stage compared to that in atmospheric models and, in particular, suffers greatly from the sparseness of profiling observations compared to the dominant eddy scales. High-resolution satellite observations of the sea surface state is well underway to achieve adequate sampling of the ocean eddy field. But the question of how to project these surface observations into the ocean interior in a dynamically consistent way is still largely open (statistical estimates of full model covariance matrices for assimilation based on ensemble methods are prone to noise due to insufficient ensemble sizes). Here, with the upcoming SENTENIEL mission in mind, we intend to utilize the findings of the uncoupled ocean model runs to test a dynamical method for assimilating SLA and SST into the interior fields of the ocean model. Specifically, we intend to pose the following additional question: Can the upper ocean response, at daily to weekly timescales, be adequately described in terms of quasi-geostrophic vertical modes? Are the traditional linear flat-bottom modes or the less commonly used sloping-bottom modes adequate? Or are surface quasi-geostrophic modes (SQG, LaCasce and Mahadevan, 2006) better suited to represent upper-ocean fields? Finally, recognizing that restratification via baroclinic instability probably underlies much of the upper-ocean variability, does the upper-ocean response project more robustly on unstable vertical modes (Eady, Charney)? Should a significant fraction of SLA and SST variance and covariance turn out to project onto such vertical modes, we will be given a new method to project SLA and SST observations into the model ocean interior or, alternatively, a way to construct model covariance matrices that are dynamically founded. Such a projection method should improve the utility of SST and SLA observations in ocean model assimilation greatly.

11. References

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