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D1.81 – Arctic forecast quality and assessment of state and impacts of the components of the Arctic observing system

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Contents

1. Introduction: The Arctic forecasting challenge

This report focuses on the quality of short-range weather prediction models, and tries to identify main challenges in improving forecasting in the Arctic, in particular the role of the observing network.

The numerical weather forecasts described here are with a typical forecast range of the order of one day, which is important for supporting operations in the Arctic. The ACCESS project also assesses forecasting on longer time ranges, such as seasonal forecasting and climate projections. These are covered elsewhere, and might have different challenges, although some of the issues described here are also relevant for them. The issues to be raised in this report are also relevant to reanalysis, as atmospheric reanalysis shares methods with operational Numerical Weather Prediction (NWP).

Even if we focus on atmospheric daily forecasting here, the results are also relevant for day-to-day ocean and sea ice forecasting, because wind, surface fluxes and other types of output from NWP model runs are used as forcing to operational numerical ocean and sea ice models. Thus many aspects of forecasting of metocean (weather, sea ice, current, sea state etc) conditions in the Arctic rely on accurate NWP forecasts.

Operations and economic activity in the Arctic can be challenging because of the special Arctic weather and climatological conditions. There are also challenges connected to the Arctic climate, physical processes and conditions in numerical weather forecasting.

NWP in the Arctic is based on the same fundamental laws of nature that applies anywhere, so in principle a well formulated NWP model with good parametrizations of sub-grid-scale processes should also work well here as well. However, the Arctic climate is so that some inaccuracies or approximations which have little influence elsewhere will be more important here. Some physical processes in the Arctic which potentially need to be described well in the NWP model include

- The presence of sea ice surfaces with varying ice concentrations and properties and their influence on the surface heat and moisture fluxes.
- Very stable boundary layers connected to strong surface cooling.
- Convection over leads and over outbreaks of air masses moving from the sea ice or cold land to the open ocean.

The atmospheric circulation at high latitude has a high degree of variability including various types of mesoscale circulation patterns and wind structures. Regarding the synoptic scale, the Arctic has less low pressure system activity than the westerlies further south. Still, the area to the North of the average position of the polar front have occurrence of moving cyclones and baroclinic activity. Several analyses of Serreze and colleagues have mapped the Arctic cyclone climatology (Serreze and

Barrett, 2008, Serreze et al, 1993 and Serreze and Barry, 1988). Their studies indicate a strong seasonality in cyclone activity with a minimum cyclone activity in the winter. The maximum in cyclone activity over the Arctic Ocean occurs in summer and the maximum is geographically centered near the North Pole in mean. In the winter, according to Serreze et al, 1993, cyclone activity is most common near Iceland, between Svalbard and Scandinavia, the Norwegian and Kara seas, Baffin Bay and the eastern Canadian Arctic Archipelago, where the strongest systems are found in the Iceland and Norwegian seas. Cyclone tracking shows that winter cyclones most frequently enter the Arctic Ocean from the Norwegian and Barents seas.

A special case of cyclones occurring in wintertime are polar lows (see Rasmussen and Turner, 2003, for an overview). They exclusively occur in Arctic cold air outbreaks over warm ocean in winter. They have special interest because of their smaller scale compared to classical baroclinic low pressures systems and therefore being more challenging to predict. Noer et al (2011) did a comprehensive climatological study of polar low occurrence in the North Atlantic sector of the Arctic, showing a high year-to-year variability in frequency with an average of 12 occurrences per year. Polar lows mainly occur from November to April with a maximum in January and a temporary (possibly not statistically significant) minimum in February.

Given the inherent predictability of the Arctic atmosphere, the forecast quality in NWP is limited by two factors

- The quality of the forecast model for Arctic processes. This includes the ability to describe physical processes in the Arctic.
- The quality of the initial state of the model runs determined in data assimilation. This is affected by the observation distribution and sparseness of observations.

Previous work, mainly presented at conferences (see for instance ECMWF, 2013), indicates a spatial variability of the forecast quality, and hints towards that the Arctic has generally lower forecast quality than mid latitudes.

Regarding challenging issues in process descriptions for Arctic forecasting, see for instance Schyberg (2006) and Kållberg (2008).

The scope of this report is first to quantify our present forecasting capabilities in the Arctic using data from lower latitude regions as a reference. Due to access to data our focus is on the Atlantic side of the Arctic, and on the forecasting capabilities of the ECMWF and the regional HIRLAM NWP models. We then focus particularly on the observing system and try to identify to what extent the forecast quality in the Arctic is affected by the sparseness of the conventional observing system.

2. Forecast verifications and its geographical variation

In this section we assess south–north variations in forecast quality from Southern Scandinavia and the North Sea up to the Svalbard area. We focus on forecasts from the HIRLAM 12 regional model and the ECMWF global model. HIRLAM 12 is a regional operational NWP model with 12 km horizontal resolution covering the domain shown in Figure 1. HIRLAM 12 has been in operational use at the Norwegian Meteorological Institute for several years, and produces forecasts with 6-hourly assimilation cycle four times daily up to a forecast range of 66 hours. The ECMWF global model has around 16 km horizontal resolution and produces forecasts twice daily with a range up to 10 days. The ECMWF model is the global NWP model which has best verification statistics of the available ones and is the main model for forecasts with longer range than 1-2 days at the Norwegian Meteorological Institute.

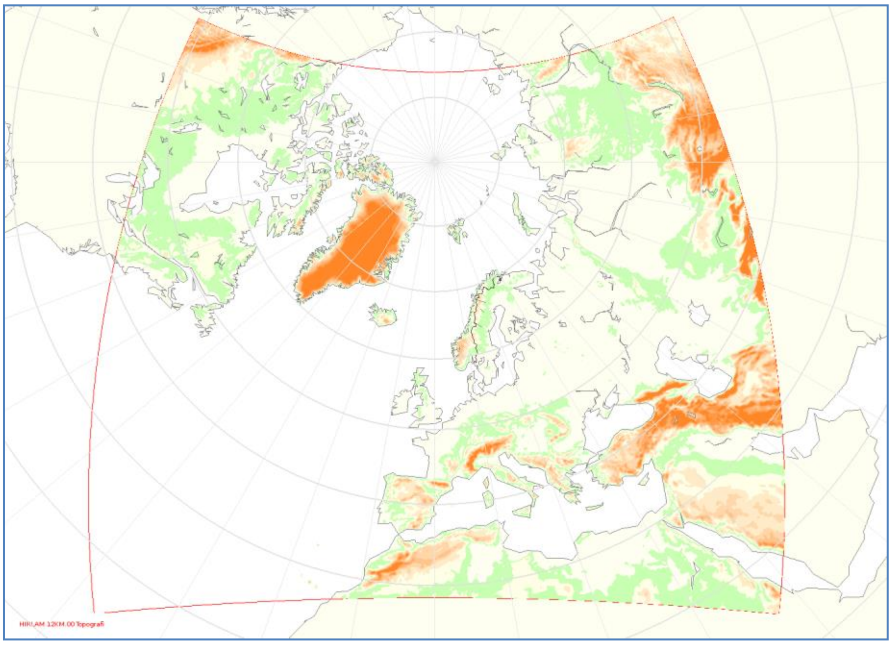

Figure 1: Domain of the HIRLAM 20 km model (including the model topography)

We have chosen to focus our attention on the verification of *pressure* forecasts from the two models. Even if pressure is not a weather parameter which is directly felt or affects us like for instance wind and temperature, the quality of pressure forecasts is strongly connected to getting the main weather system positions and circulation patterns at the right time and place. It has the advantage that it is not as strongly influenced by local conditions at the measurement stations as for instance wind and temperature would be. (These are heavily affected by local small-scale topography and surface conditions.) Pressure verification is thus more comparable between different observing stations as a measure of the general quality of the large-scale forecast fields.

In the verification we have chosen to use coastal stations only, and get a coverage spanning from the Ekofisk platform in the North Sea, through the long Norwegian coastline and north to Bjørnøya and several points on the Svalbard archipelago. Also the island of Jan Mayen further to the west is included. By using coastal stations, artifacts coming from reduction of pressure to sea level are minimized. (Height reduction of pressure to sea level makes use of an assumed artificial air column below the station with properties based on the observed surface temperature, and can be unrepresentative or problematic for stations at higher levels.) The dataset covers the period from January to September 2013.

As a background for considering the statistics of pressure errors in the forecasts, we first present the pressure variability. In Figure 2 we show a measure of the day-to-day pressure variability for the two NWP models. This is an indication of the real atmospheric variability in pressure which the model forecasts need to capture. One could think that more dynamic variability as measured in this way would also lead to more deviations between model and observation, this coming from the fact that there will be more variations to capture by the model. We observe that there is a maximum in variability at 65N, with generally decreasing variability north and south of that latitude. This is in accordance with for instance maps of transient eddy kinetic energy in the atmosphere (Peixoto and Oort, 1992) and the position of the maximum pressure variability coincides with the average position of storm tracks on the polar frontal zone. The pressure on the Svalbard stations has quite low day-to-day variability.

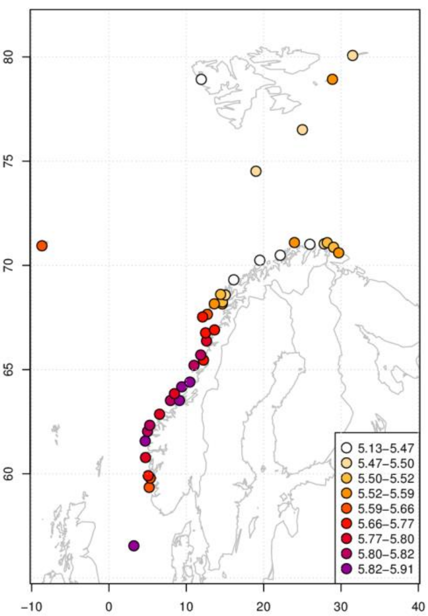

Figure 2: Mean absolute day-to-day observed pressure differences in hPa.

In Figure 3 we present the verification statistics in terms of root mean square (RMS) errors for the two NWP models, and in Figure 4 the same RMS error data plotted against latitude. For this sector of the Arctic, there is a striking general decrease in forecast quality when moving northwards, in particular for the HIRLAM 12 model. This is seen in spite of the fact that the day-to-day pressure variability is comparatively small at the highest latitude stations. A candidate for explaining the decline in the quality towards the north would be the corresponding decrease in the observation density of the conventional observing network. We will describe the observing network more in detail in the next section.

We also note some exceptions to the general trend of forecast quality decreasing northwards:

- The ocean station Ekofisk in the North Sea verifies worse than the southernmost coastal stations in Norway.
- Jan Mayen verifies worse than Norwegan coastal stations at the same latitude.

Both these two items are consistent with thinner conventional observing network over ocean. In addition we observe:

- The Norwegian coastal stations in East Finnmark generally verify worse than those in West Finnmark.

It is difficult to relate this last point to the observing system, a possible explanation could be higher frequency of off-land wind directions so that lee effects of the topography creates local pressure effects not captured by the large-scale NWP models.

In addition we see the trend of decreasing quality towards north is quite a bit more pronounced in the HIRLAM model than in ECMWF. It is worth noting that ECMWF uses much more satellite data in the assimilation than the HIRLAM system. As will be discussed in the next section, while the conventional observing network gets less dense towards north, the density of observations from polar orbiting satellites is actually increasing towards north. So use of more satellite data could be a candidate for explaining the difference between the two models here.

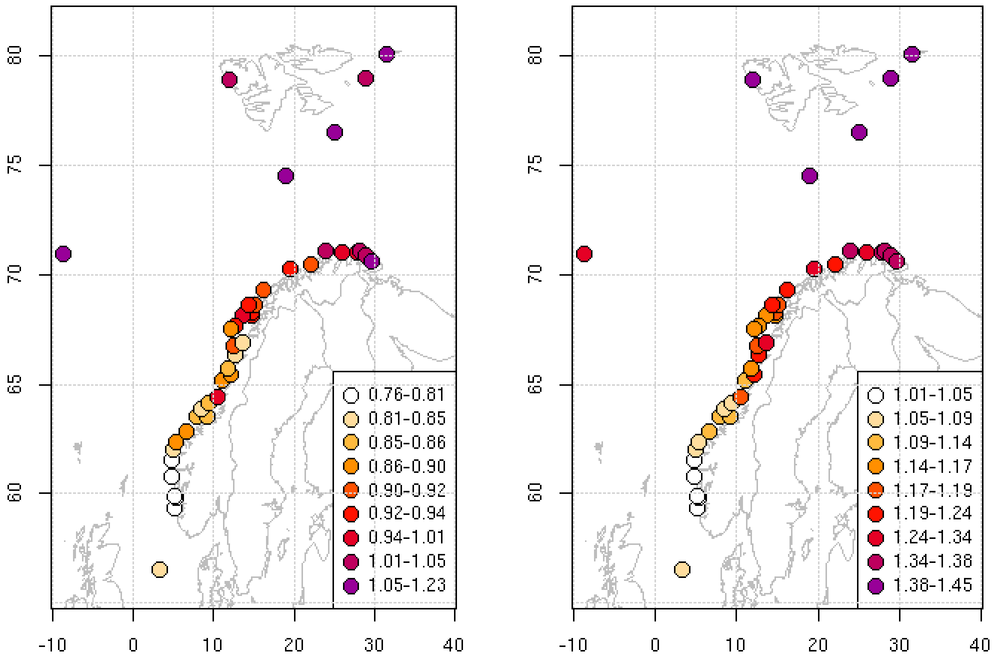

Figure 3: Root mean square errors in pressure (hPa) for forecasts in the range from 18 to 42 hours. Left: For ECMWF global model. Right: For HIRLAM 12 regional model.

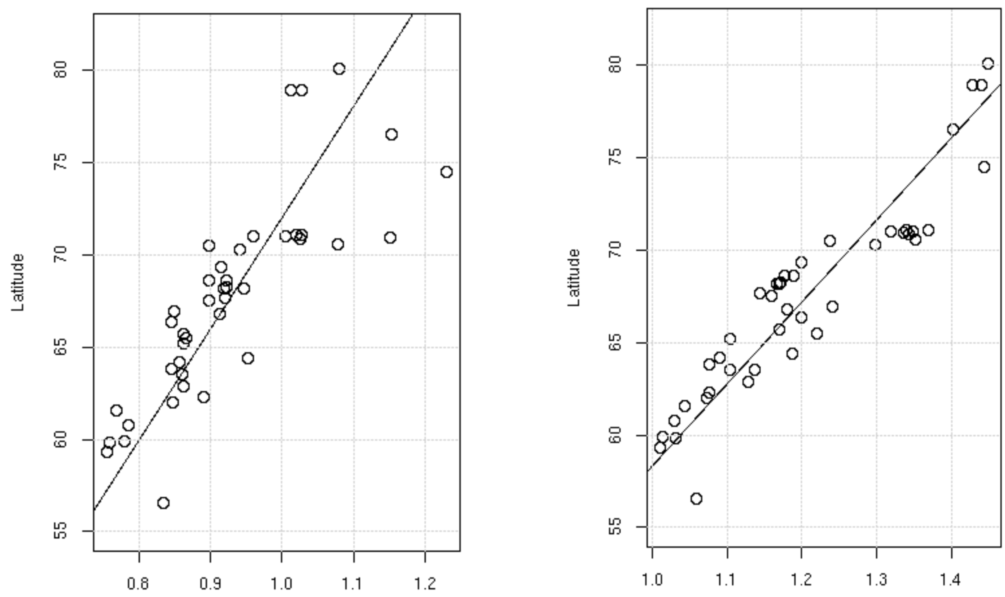

Figure 4: Root mean square error in pressure for forecasts (hPa, as in Figure 3, horizontal axis) plotted against latitude on the vertical axis. Left: For ECMWF model. Right: For HIRLAM model.

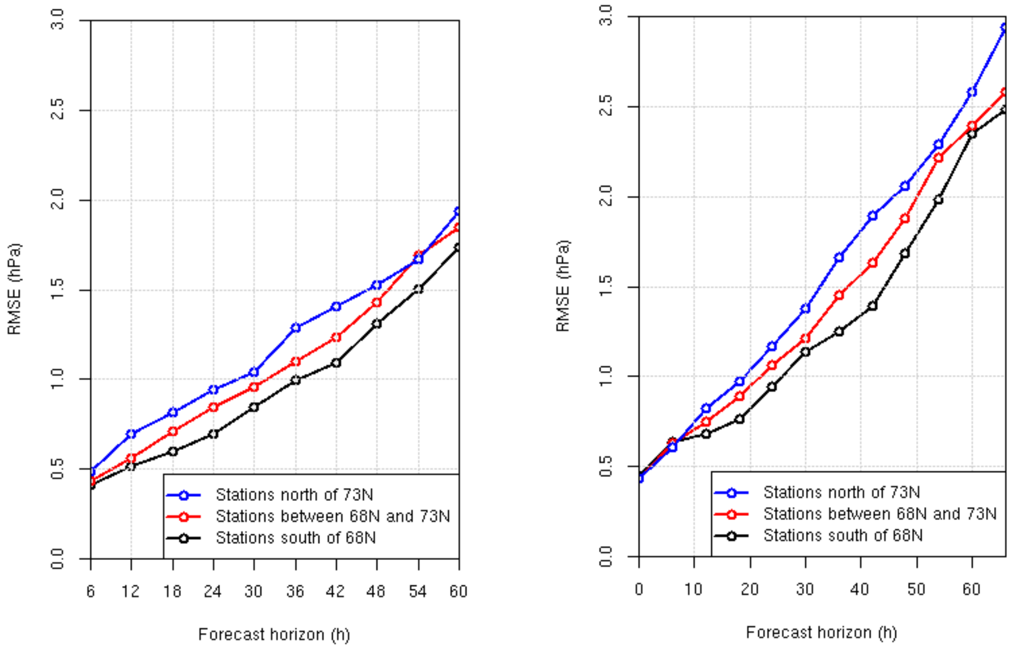

Figure 5: Pressure RMS errors for the same stations as above as a function of forecast range. Left: For ECMWF model. Right: For HIRLAM 12 model.

While Figure 3 and Figure 4 show average of the verification from 18 to 42 hours forecast times, Figure 5 shows the time evolution of the pressure RMS error for three latitude zones. We see that particularly in the beginning of the forecast that there is a difference in error growth between the three latitude zones.

Even if the increase of errors with latitude seen here is striking, we have only checked a North-Atlantic sector and such correlations do not necessarily hold for any longitude sector towards the Arctic.

One could set up at least three hypotheses or partial explanations behind the south-north trend in verification scores:

- It could be an issue related to the observing system

As already mentioned this will be a main hypothesis, and will be discussed further below.

- Various physical process descriptions in the NWP models connected to Arctic conditions

We note in particular that the stations in Svalbard are close to the ice edge for parts of the year, and a good description of surface fluxes would rely of having a correct depiction of the sea ice edge. Surface temperatures and surface fluxes can again affect baroclinic zones and the evolution of weather systems. So mispositioning of the ice edge could lead to forecast errors.

Sea ice information for both HIRLAM and ECMWF come from the daily products of EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSISAF). These maps are mainly based on microwave satellite information and have limited horizontal resolution. Sea ice is kept static throughout the NWP model integration, so rapid changes in ice edge could be one of several physical processes which could lead to forecast errors.

This could at least contribute to the lowered score of the Svalbard stations.

- Predictability issues

It is well known that the predictability of the atmosphere varies in time and space, that is for a given accuracy in the initial state, the resulting uncertainty at a forecast time ahead depends on the synoptic situations. There could be geographical variations in atmospheric predictability, possibly related to the Arctic climatology. It can be noted that the Arctic has less synoptic low pressure system activity than areas further to the south. However, we are not aware of any studies indicating that the inherent predictability of the Arctic atmosphere should on average be lower because of that.

3. The Arctic meteorological observing system

Here we follow up the hypothesis that the variations in verification scores are related to the observing system. We will describe the coverage and characteristics of the various components of the Arctic observing system. Some components (radiosonde and SYNOP) have a quite fixed coverage in time, while other components (buoys, aircraft, satellite) change its coverage in time. In the figures in this section we present data for the date of 13 September 2013, which is a randomly chosen date which serves as an illustration of the typical observation coverage.

3.1. Components

3.1.1. Conventional surface observations

There are two main types of conventional surface observations. Figure 6 shows the coverage of SYNOP and ship stations and Figure 7 shows the coverage of drifting buoy data. The SYNOP data usually consist of pressure, temperature and moisture information and possibly more, particularly in the case of manual observations. Drifting buoys provide pressure information, and sometimes also air and sea temperatures.

We see that SYNOP/ship mainly gives a good coverage over land. Some ships supplement the dataset over sea, but generally observations in the sea ice covered Arctic ocean and open ocean areas in general are very sparse.

The international Arctic Buoy Programme (IABP) is a cooperative effort of many institutes with an interest in the Arctic maintains a network of buoys in the Arctic. EUCOS (EUMETNET Composite

Observing System) also has a program for deploying ocean drifting buoys (E-SURFMAR). The buoys complement the SYNOP observations over ocean, and also provide some coverage of surface pressure information over sea ice areas. Still there are large parts of the ice sheet which remains uncovered by buoys.

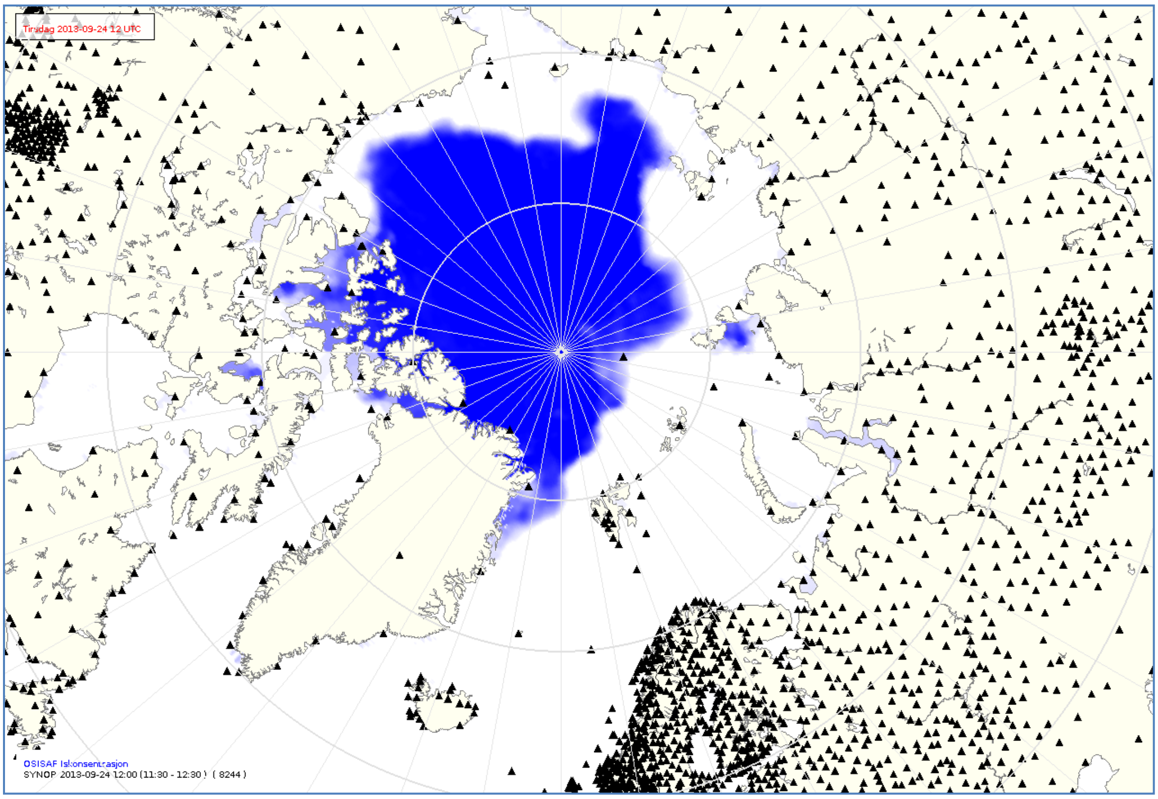

Figure 6: SYNOP observation coverage per 13 September 2013. (Blue shading indicates the sea ice concentration.)

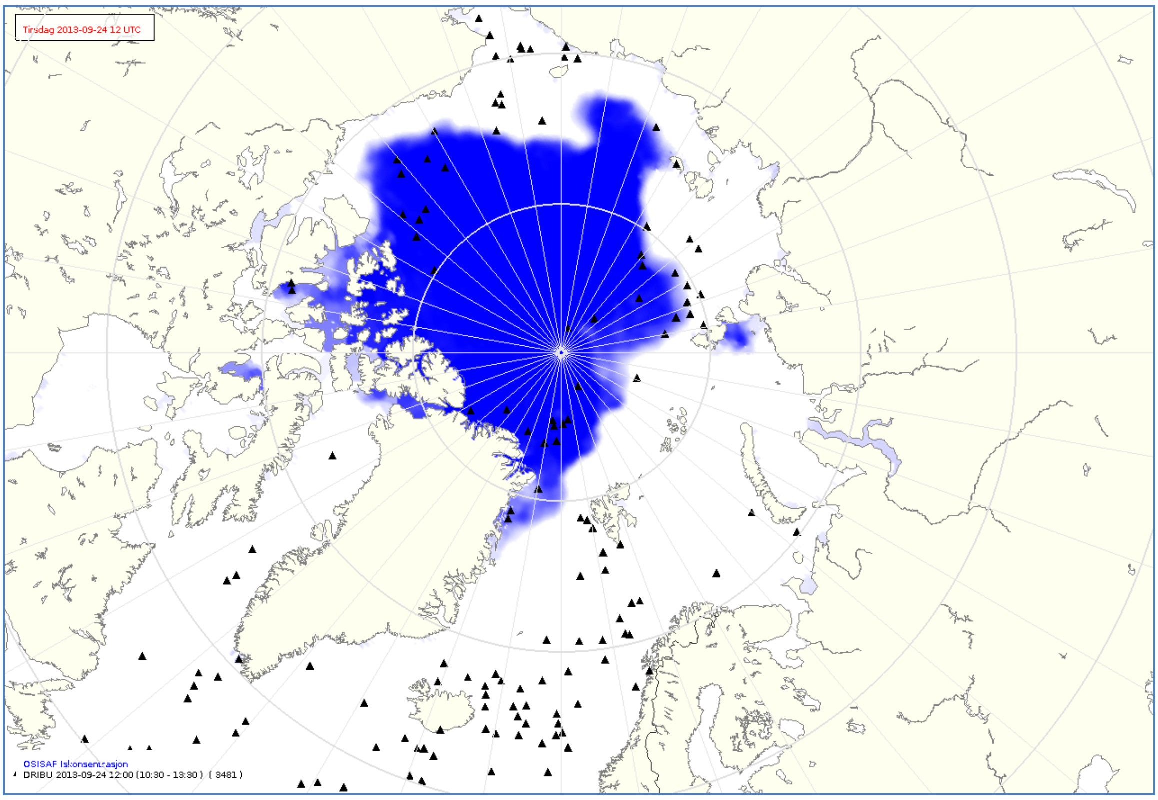

Figure 7: Drifting buoy observation coverage (on 24 September 2013 12 UTC). Blue shading indicates the sea ice concentration.

3.1.2. Conventional profile and upper-air observations

Conventional upper-air observations consist of radiosondes (Figure 8) and aircraft observations (Figure 9). Radiosondes cover a range of levels from the surface up to the stratosphere with temperature, wind and moisture information. Aircraft usually provide wind and temperature at flight level, so profile data are only available at ascent and descent, that is near airports. Both these observation types give coverage over continents and islands, but little coverage over ocean areas and in particular over the Arctic ocean.

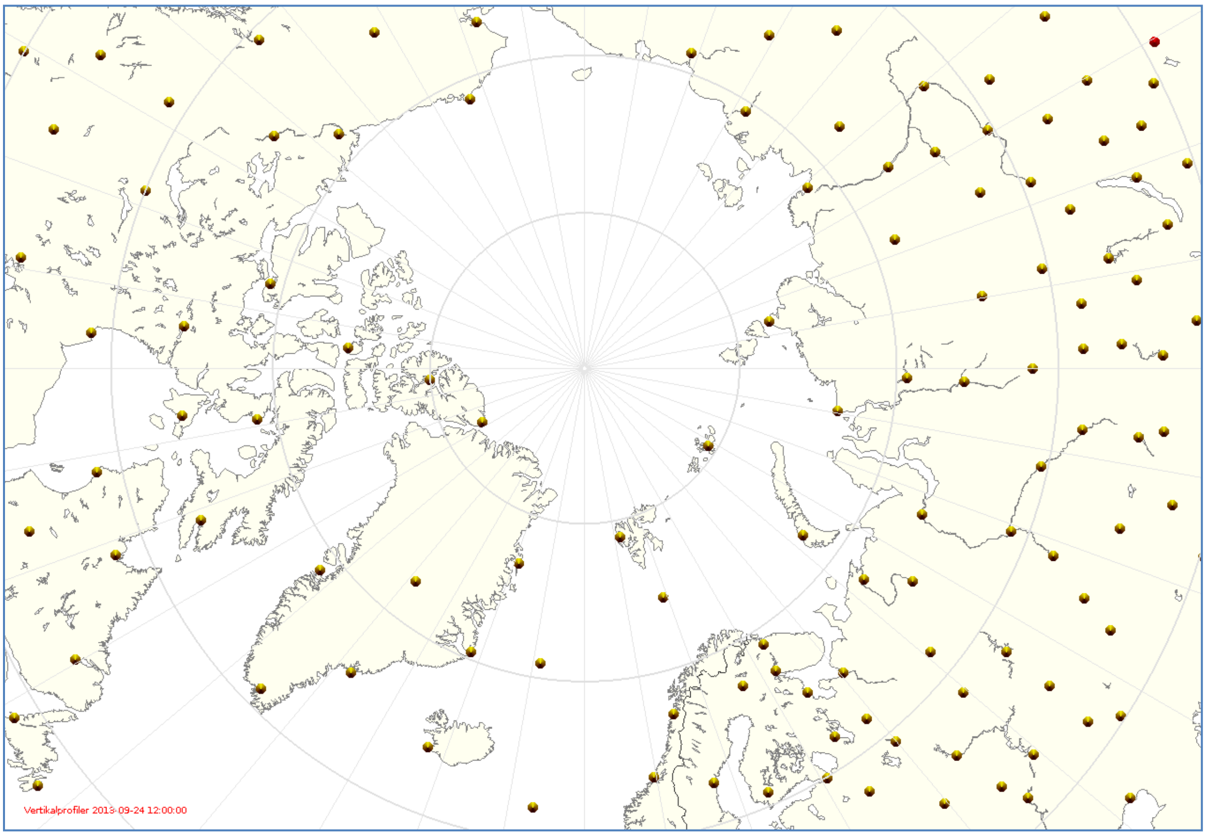

Figure 8: Radiosonde ascent coverage (on 24 September 2013 12 UTC)

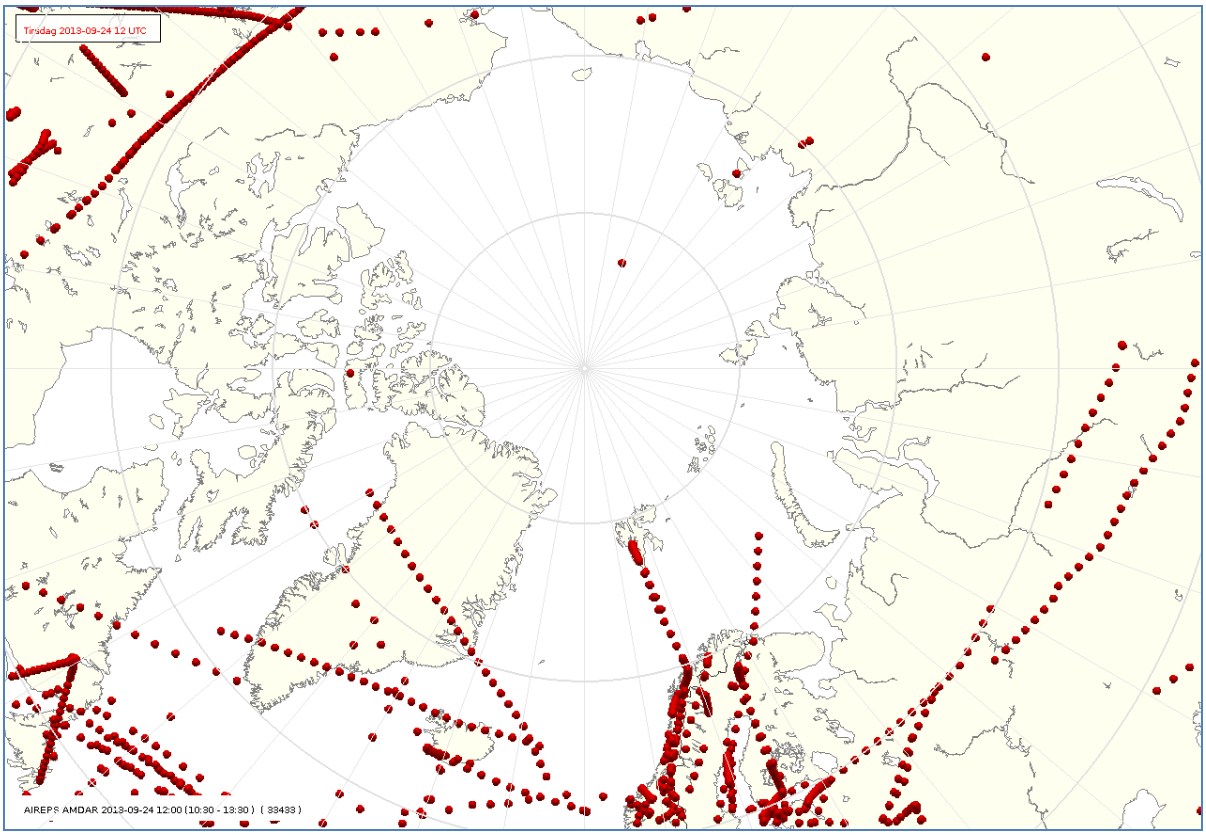

Figure 9: Aicraft observation coverage (on 24 September 2013 in a 3 hours time window around 12 UTC)

3.1.3. Satellite surface observations

Scatterometer provides near-surface wind vectors over ocean (not over sea ice or land). A typical coverage map is shown in Figure 10. Available scatterometers are on polar orbiting satellites, which have converging swaths at high latitudes. This gives a quite good coverage of near-surface wind information up to the ice edge.

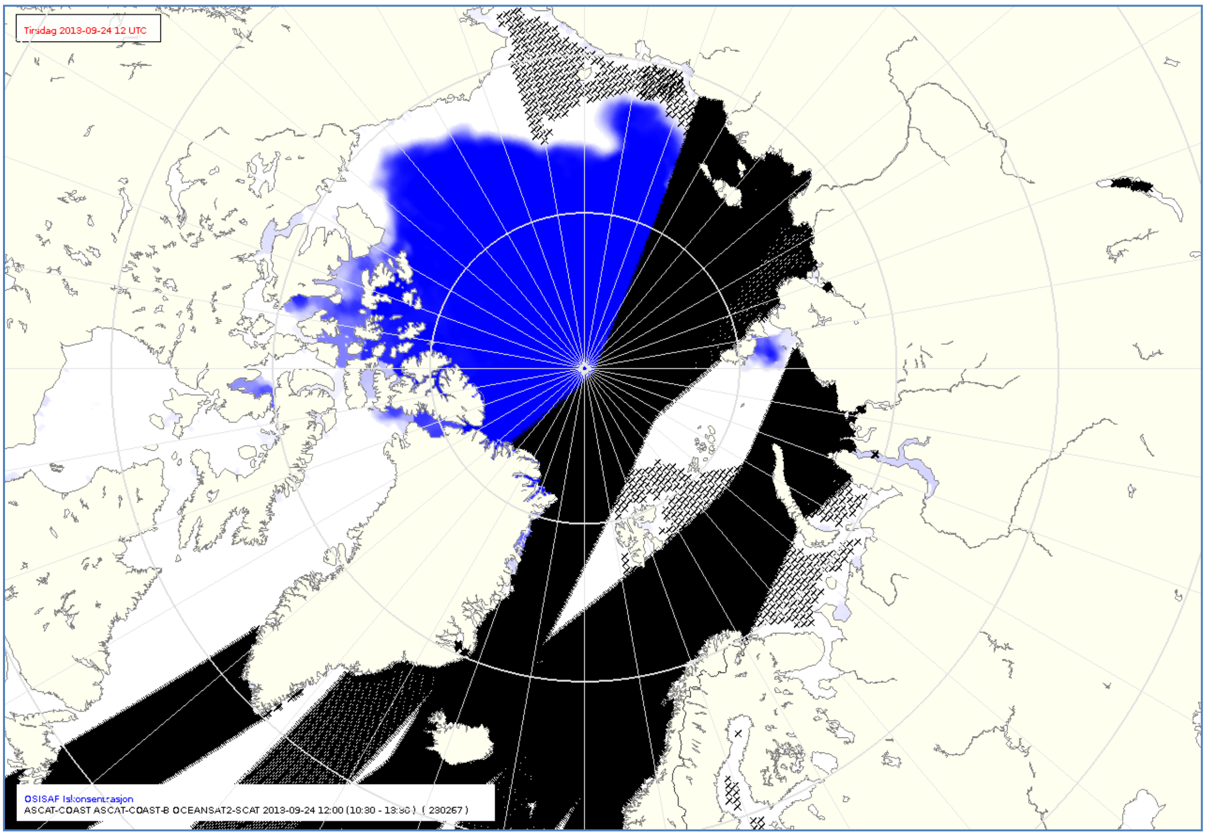

Figure 10: Scatterometer data coverage (on 24 September 2013 in a 3 hours time window around 12 UTC). Blue shading indicates the sea ice concentration.

3.1.4. Satellite upper-air observations

Satellite upper air observations have had a development with increasing coverage and increasing number of satellites, and by far overshadow conventional upper-air observations in terms of numbers. ECMWF, which is the centre utilizing most satellite data presently uses 8 AMSU-A sensors, 2 interferometric infrared sounding sensors (IASI, AIRS, CrIS), polar atmospheric motion vectors (AMVs) from 6 satellites and radio occultation data from 10 satellites. (Of these data the HIRLAM-12 model described above only uses AMSU-A observations.) We do not show here any figures of data coverage for all these sensors, but all satellites carrying these instruments are polar orbiting, so the orbit patterns give increasing coverage with latitude. This means that satellite data fills in a part of the “data gap” in conventional upper-air data in the Arctic.

3.1.5. Summary on observation coverage

Here we give a brief summary of the observation coverage of the Arctic based on the above, and try to identify data gaps or lacks in coverage in terms of parameters, levels or areas.

As for surface observation data, there is a general gap in pressure observations over parts of the sea ice and parts of the ocean areas as there is only limited coverage from drifting buoys. There is almost no coverage of near-surface wind observations over sea ice. The wind coverage over ocean is good due to satellite scatterometers and over populated continents due to SYNOP stations. Surface pressure gradient and near-surface winds are closely linked in the Arctic through the geostrophic relation. However, where only pressure gradient information is available through wind observations, the absolute value of the pressure field would need to be “anchored” with some coverage of surface pressure information.

Given the fact that a 3-dimensional coverage is needed for the atmospheric state to be initialized in NWP, it is important that the atmosphere is covered with observations also above surface.

The Arctic lacks conventional upper air data, but this is compensated by data from satellite sounding instruments. This requires that NWP assimilation systems are prepared to use them (ECMWF is using much more of these data than HIRLAM). It should be noted that it is difficult to use data from temperature sounding sensors in the lower troposphere because the signal will then have a surface contribution which is generally not well modelled. Also, AMVs and radio occultation do not give any coverage of winds or temperature profiles in the lowest part of the troposphere.

In summary there is a lack of both wind and temperature information in the lower troposphere in the remote ocean and ice areas in the Arctic, that is away from coasts and islands with radiosonde coverage.

3.2.Impact of observations

It is evident from the above description of the observing system that there is a partial gap in surface observations and lower tropospheric data over the Arctic Ocean and surrounding North Atlantic areas. The observing network is also thin in sparsely populated areas in Greenland, Siberia and the Canadian archipelago.

A main question here is what influence this issue has on the quality of weather forecasts and to what extent it explains the geographical variation in forecast quality discussed above.

Jung and Leutbecher (2007) assessed the NWP analysis quality in the Arctic, and it seems that there is at least some consistency between what they found in terms of analysis quality and the geographical distribution of forecast quality which we found above. They compared analyses produced from the operational ECMWF system with the reanalysis system, and found that the analysis uncertainty was generally larger in the central Arctic Ocean, Norwegian Sea and Greenland than in surrounding areas. In addition to the Arctic, ocean areas with lack of conventional observations also had generally lower analysis quality. This is again closely related to the coverage of the meteorological observing system.

In the following we discuss further the present status of knowledge on how observations affect forecast quality and we have also performed some experiments to further assess the impact of conventional observations in the Arctic by particularly assessing two radiosonde stations in the Atlantic sector of the Arctic.

3.2.1. Previous studies of the global observing system

Many studies have been performed on the impact of the observation types which constitute the components of the global observing system, so global and regional NWP centres as well as WMO, EUCOS and satellite agencies have a good overview of the relative impacts.

One approach for such studies is data denial studies using the present observing system (Observing System Experiments, OSEs), as done for instance by Kelly and Thepaut (2007). Studies from several different centres and NWP systems can be found in WMO (2008) and WMO (2012). Cardinali (2009) assesses impacts not by data denial studies, but by defining a measure for observation information content with respect to the forecast, "Forecast Sensitivity to Observations" (FSO) which can be computed routinely as a part of the assimilation procedure without full parallel data denial experiments.

The general view is that sensors which provide profiling information of the atmosphere are the ones which contribute most to the forecast quality in the present observing system. The components with largest contributions are the AMSU-A microwave sensors and the interferometric infra-red sounders. Radiosondes and aircraft observations also give important contributions, but are much fewer in numbers than the satellite sounding, so therefore their total impact is comparatively small and has been declining in parallel with the increase in the available amount of satellite data.

3.2.2. A study of effect of two Arctic radiosondes vs Scandinavian Peninsula sondes

An experiment was done to assess the impact of profile data in the Atlantic sector of the Arctic. There were two goals of the experiment

- To compare the impact of sondes in that area to sondes further to the south, in this case in the Scandinavian Peninsula
- To assess the effect of four versus two radiosondes per day at these Arctic stations

The experiment was performed during the THORPEX-IPY campaign (see Kristjansson et al, 2011) in February-March 2008 for the radiosondes at the remote islands of Bjørnøya and Jan Mayen, where number of daily lauches had been increased from two to four per day.

The NWP model applied was a version of the HARMONIE model with 11 km horizontal resolution, and the results presented here covers an experiment period from 25 February to 15 March 2008. Figure 11 shows the domain for the model runs together with the two radiosonde stations studies.

With this setup, 4 parallel runs with six-hourly data assimilation were made, where several scenarios for leaving out observation data sets were tested:

- (Ref) All observations
- (Exp 1) Leave out the extra (2/day left) Bjørnøya and Jan Mayen sondes
- (Exp 2) Leave out all (4/day) Bjørnøya and Jan Mayen sondes

- (Exp 3) Leave out 2 sonde stations (launching 2 times/day) on mainland Scandinavia

Comparing these experiments allows us to assess the above two questions we raised. We did the verification of the forecast quality by comparing the forecasts of the various experiments for geopotential and humidity with radiosonde stations within the model domain, the subset called the "EWGLAM" radiosondes, which are known to have a good quality and are regularly used for verification purposes. Bjørnøya and Jan Mayen are among these stations, but the bulk of these radiosondes are located in the European area.

Using measured vertical profile information for verification allows us to present the results in two-dimensional forecast time range – height (or pressure) diagrams.

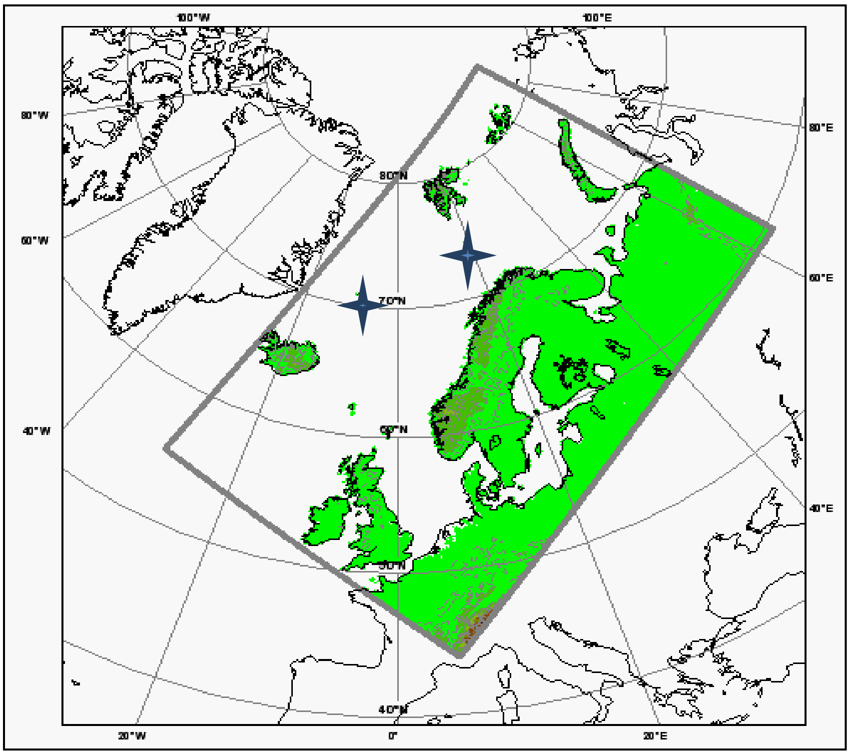

Figure 11: The domain of the HARMONIE model used for the radiosonde impact experiments. The two radiosonde stations assessed in the experiments are indicated with blue stars.

Figure 12 shows the difference in the verification score (in terms of RMS deviation from the observations) between Exp3 and that of Exp1 and indicates how much more valuable Bjørnøya and Jan Mayen are relative to an "average" mainland Scandinavia sonde. Positive values means that the Arctic stations give more positive impact to the forecasts than the Scandinavian stations even thought they represent the same number of radiosonde launches. As we see, in general the Arctic stations are more valuable than those on the Scandinavian mainland, both for the forecast of surface conditions and in general for the atmosphere as a whole. It is also interesting to note that the largest impacts are in the late part of the forecast. A possible explanation for that could be that many of the stations used for verification are in Europe and it takes some time for the impact to propagate from the Arctic stations in the experiments.

In a similar way, Figure 13 shows the difference in verification score between Exp1 and Exp2. This indicates how much impact a doubling of the number of radiosonde launches at the Arctic stations will give, and positive values means better scores with four launches per day than with two. Again we note high impact late in the forecast.

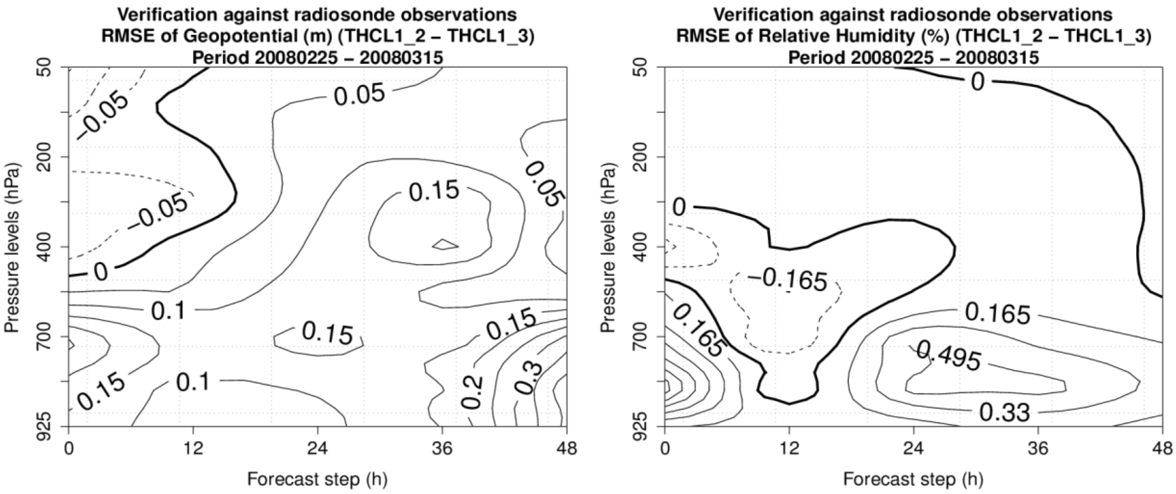

Figure 12: Verification of impact in a forecast range – pressure level diagram of two radiosonde stations Positive values mean larger forecast error when missing the two remote soundings compared to two randomly chosen inland stations. Left: Verification of geopotential. Right: Verification of relative humidity.

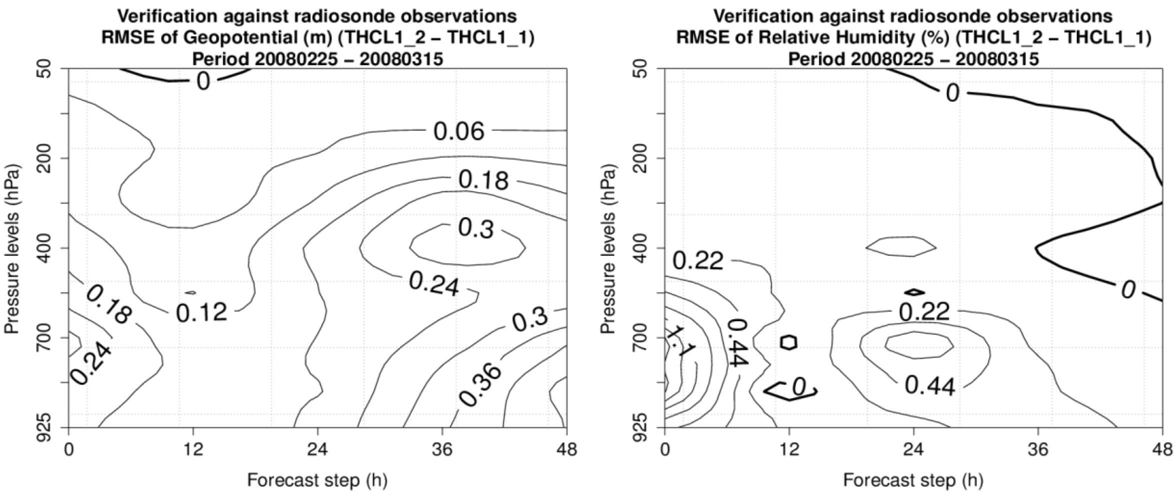

Figure 13: Verification of impact in a forecast range – pressure level diagram of two radiosonde stations Positive values mean larger forecast error when having four launches per day as compared to two launces per day. Positive values mean larger forecast error when missing the 00 and 12 UTC

soundings at remote stations (twice operations per day).. Left: Verification of geopotential. Right: Verification of relative humidity

4. Discussion and conclusions

In the previous sections we have shown clear evidence that the numerical weather forecast skill of two different operational NWP systems decreases northwards in a sector in the Arctic and that verification scores are quite a bit lower in Northern areas close to the sea ice edge as compared to for instance Scandinavia. A review of the actual observing network for the region shows that this coincides with sparseness in the network of conventional observations. There is a good coverage of satellite data in high latitudes, but problematic to get good coverage in the lower troposphere with satellite information. Also the ECMWF model which has state-of-the-art capabilities of assimilating satellite data shows a clear trend towards lower analysis quality in the North.

Although the observing system is clearly identified as a likely main reason for the geographical trend in the verification, it is still possible that other issues in our modelling capability of Arctic physical processes and surface conditions contribute, such as for instance inaccuracies in the description of the sea ice concentration and surface description for sea ice.

To give some quantification on the effect of the observing system in this region, we did an impact study of two island Arctic radiosonde stations in the area showing that they indeed give more impact on the forecast than radiosondes on the Scandinavian peninsula, which clearly must be related to a scarcity of the observing system in the region.

The results presented indicate that observation coverage is probably a major contributor to the reduction in forecast quality in the North.

Our next step is to perform further diagnostics on the effect of observations to quantify observation impact and to outline cost-effective scenarios for improving the situation.

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