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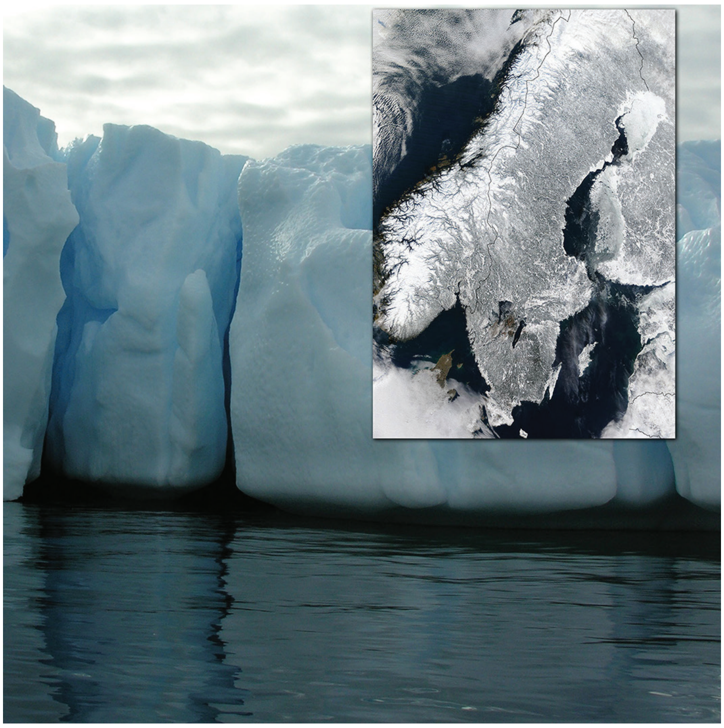

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Sea ice analyses for the Baltic Sea

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Concentration of sea ice (CI) is a key parameter in the exchange processes between ocean and atmosphere. It strongly influences albedo, surface fluxes of latent and sensible heat, and surface wind drag. For atmospheric numerical modelling applications and weather forecasting, the CI analysis is a useful product as a comprehensive diagnostic of the ocean-atmosphere system. In addition, the CI analysis has a particular value as the initial state and it can be used to check the quality of the sea surface temperature analysis. Consequently, real-time sea ice products are of fundamental importance for those NWP centres that do not run fully coupled ocean-atmosphere models and/or do not analyse this surface field in-house.

In the operational Integrated Forecast System (IFS) for medium-range forecasts, sea ice concentration and sea surface temperature analyses are based on the corresponding daily 0.5° data sets produced by NCEP (National Centers for Environmental Prediction). Both products are re-sampled from their original regular latitude/longitude grid to the reduced Gaussian model grid using bi-linear interpolation. Technically, the analyses are performed six hours before the atmospheric variational analysis is done. The first guess (i.e. the previous analysis) is only updated when a new analysis is available. CI fields remain constant during the ten-day forecast period. Consequently, there is no feedback from the atmosphere to the ocean.

In the monthly and seasonal forecast systems CI evolves with time. In the current model version, CI is limited to values of 100% or 0%. At every model time step, the presence of sea ice is determined through a threshold algorithm based on modelled SST and a weak relaxation to sea ice climatology. A new treatment of CI has been formulated and is being tested in research mode: Initial CI is obtained from the atmospheric analysis used for the medium-range forecasts as described above. For the first 10 days of the coupled integration the CI is kept constant. After an integration time of one month climatological values of CI derived from ERA40 are used. For days 10 to 31 CI is linearly interpolated between the analysed field and climatology.

At the Swedish Meteorological and Hydrological Institute (SMHI), sea ice concentration, sea ice thickness, and sea surface temperature are analysed operationally for the Baltic Sea twice a week. It was found that significant differences exist between the NCEP and SMHI analyses of CI for the Baltic Sea. Two experiments have been performed to study the impact of these analyses on the medium-range forecast fields:

- CTRL — the control run based on the global NCEP analysis.
- EXP — the experimental run, where the SMHI analysis is used for the Baltic Sea.

The results of these experiments showed that the impact of the high-resolution CI analysis for the Baltic Sea on the medium-range weather forecast on the continental scale is neutral if temperature and geopotential height are analysed. But even for these fields there are indications of minor improvements in the 24-hour forecast and the forecast period covering days four to seven. However, on regional to local scales, the differences in the surface parameters (surface fluxes, temperature, humidity, and planetary boundary layer height) are non-negligible and can influence forecast cloud cover. For a number of practical applications (e.g. icing of ships, fog forecasts, air quality, and dispersion of pollutants) the differences in the planetary boundary layer can be crucial. In the next major upgrade of the operational IFS (cycle 29r2) the SMHI sea ice analysis will replace the NCEP analysis in the Baltic Sea.

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Analyses of sea ice concentration

The global NCEP analysis of CI is based on passive microwave observations from the Special Sensor Microwave/Imager (SSM/I). CI is calculated from the daily composite brightness temperature grids following a tie-point algorithm described in *Cavalieri et al.* (1991). In a final step, a number of quality checks are applied and there is polar gap filling. A detailed description of the automated analysis process and the final quality-controlled data set is given in *Grumbine* (1996).

The footprint size of SSM/I, which is ~ 69 × 43 km2 at 19 GHz, determines the resolution of the NCEP analysis. However, it has been shown (e.g. *Drusch et al.,* 1999) that only 50 % of the information obtained through an individual observation from SSM/I originates from this area. Consequently, SSM/I measurements in coastal areas and small basins are strongly contaminated by land. For the Baltic Sea, with its ragged coastline and a number of small islands, it is almost impossible to find a land-free SSM/I footprint.

The SMHI analysis is done manually by an analyst using AVHRR (Advanced Very High Resolution Radiometer) data and in-situ observations. The final maps are digitised and archived at 1 km (sea ice and thickness) and ~ 10 km (sea surface temperature) resolution. For the applications at ECMWF the high-resolution product has been linearly averaged to the reduced Gaussian model grid.

Sea ice season 2003/2004

The SMHI and NCEP analyses have been compared for the sea ice season 2003/2004 for the entire Baltic Sea and three sub-basins:

- Gulf of Bothnia
  (GoB, 60.25° N to 65.85° N, 16.5° E to 26.0° E).
- Gulf of Finland
  (GoF, 59.5° N to 60.6° N, 22.6° E to 30.8° E).
- Gulf of Riga
  (GoR, 56.9° N to 59.0° N, 21.7° E to 24.8° E).

Time series for mean CI and sea ice extent, as defined by grid boxes containing more than 20 % sea ice, are shown in Figure 1. In general, mean sea ice fractions calculated from the SMHI and NCEP analyses are in reasonable agreement. In all three sub-basins the high-resolution SMHI analysis results in higher concentrations during the peak time of the ice season from mid-February to mid-March. For individual days differences exceeding 20 % can be found for the Gulf of Finland. During the growing and melting seasons, mean sea ice concentration from SMHI tends to be slightly smaller for the Gulf of Riga and the Gulf of Finland. The agreement between both analyses for the Gulf of Bothnia is very high.

The differences in sea ice extent are significantly higher than for the concentrations. In all three sub-regions the sea ice extents can differ by more than 30 %. In general, the NCEP analysis leads to higher ice extents, which is due to the coarse resolution of the SSM/I satellite footprint. For the Gulf of Riga a plateau is obtained for the winter period from mid-February to the end of April. This plateau is an artefact of the interpolation of the coarse-resolution NCEP analysis to the limited number of model grid points in the array defining the Gulf of Riga region. For the Baltic Sea area the differences in sea ice extent and sea ice concentration exceed 10 % and 5 %, respectively.

Sea ice concentration for 5–24 January 2004

The results presented in Figure 1 show significant differences between the two CI analyses for the Baltic Sea and the three sub-basins. Consequently the impact of these differences on surface parameters (e.g. turbulent fluxes of sensible and latent heat), the boundary layer, and eventually on the quality of the medium-range weather forecasts has been assessed. The most accurate quantification of the impact on the forecast is obtained using the operational version of the IFS, which includes the full 4D-Var atmospheric data assimilation system. However, these experiments are computationally expensive and therefore the study period is limited to the 20 day period from 5 to 24 January 2004.

In general, the gradients in CI in CTRL are smaller when compared to the corresponding values in EXP (Figure 2). In the northern part of the Gulf of Bothnia the CI in CTRL hardly exceeds 60 % with a maximum value of 78 %. Minimum CI is 28 % in the central northern part. In contrast EXP produces a CI of 97 % along the very northern coastline and a small almost ice free area of 3 %. These differences are primarily due to the coarse resolution of the satellite product and the contamination by land. Significant differences in CI also occur along the eastern coast of Sweden north of 60° N and in the Gulf of Finland, where an overestimation of low CI can be found in CTRL. The same holds for the Gulf of Riga, which is almost ice free in the EXP analysis.

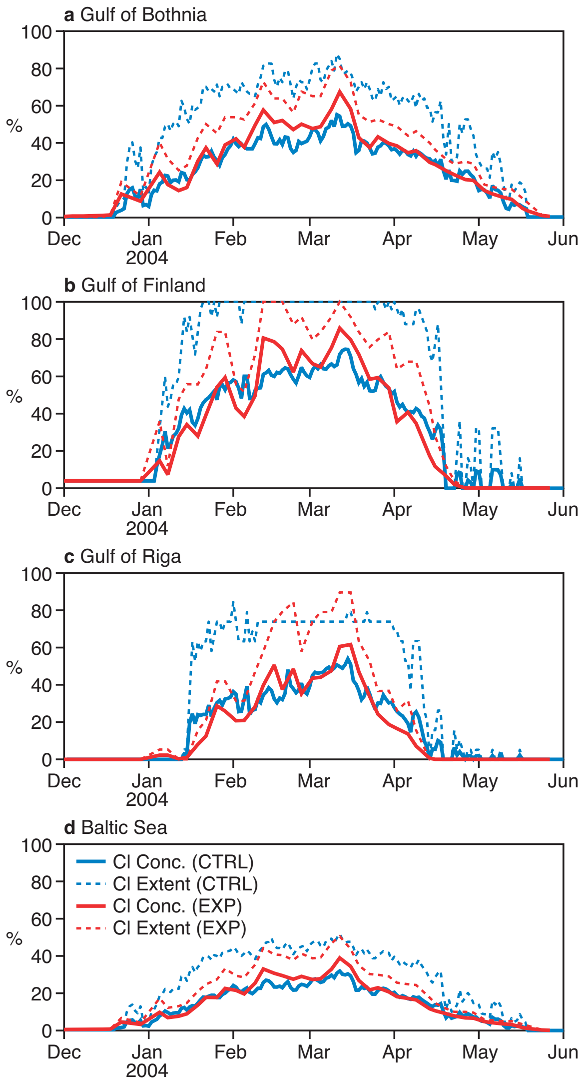

Figure 1 Sea ice extent (solid lines) and sea ice concentration (dashed lines) for winter 2003/2004 for (a) Gulf of Bothnia, (b) Gulf of Finland, (c) Gulf of Riga, and (d) Baltic Sea. Values from CTRL (NCEP analysis) are in blue and from the EXP (SMHI analysis) are in red.

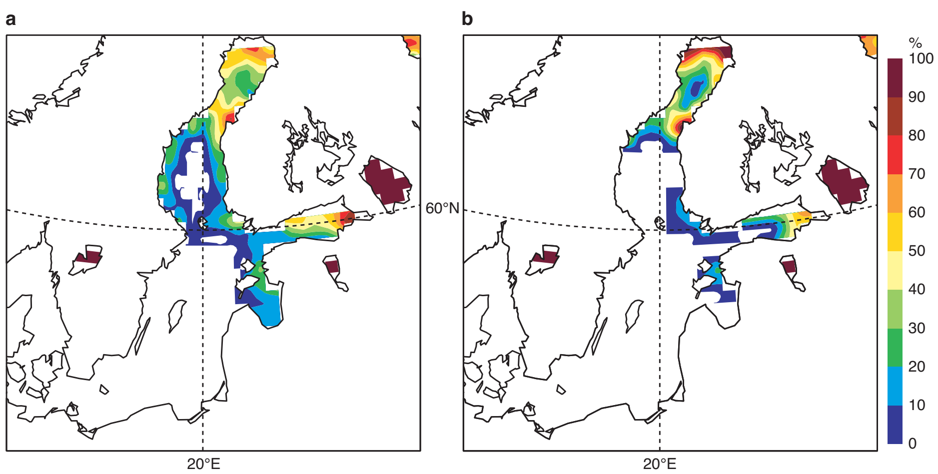

Figure 2 Mean sea ice concentration for the study period 5–24 January 2004: (a) CTRL and (b) EXP.

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Turbulent surface fluxes

Differences in CI have a direct impact on the turbulent surface fluxes. Figures 3(a) and 3(b) show spatially integrated daily values of latent and sensible heat fluxes from CTRL based on 24-hour forecasts. The time series for the Baltic Sea and the three sub-basins exhibit substantial temporal variability during the study period. The Gulf of Finland and the Gulf of Riga regions are characterized by high upward fluxes of up to 160 Wm^{-2} for latent heat and 180 Wm^{-2} for sensible heat from 7 to 10 January. During this period, a strong spatial gradient in 2 m temperature was present, leaving the Gulf of Riga, the Gulf of Finland, and the very eastern part of the Baltic Sea under the influence of cold air with temperatures below -9 °C.

From the 11th onwards, warm air moved eastward, reducing the surface fluxes. During this part of the study period, the turbulent fluxes in the three sub-basins look similar. From 20 January onwards, the entire Baltic Sea region was under the influence of cold air masses characterized by 2 m temperatures between -4 °C (central part) and -12 °C in the Gulf of Finland. The strong vertical temperature gradient between the ocean and the atmosphere results in fluxes of up to -200 Wm^{-2} (Figure 3(a)). In general, fluxes are smaller in the Gulf of Bothnia and the Gulf of Finland due to the presence of ice.

The differences between CTRL and EXP are presented in Figures 3(c) and 3(d). For the Gulf of Riga, where CI is very low in both analyses, the differences in fluxes do not exceed 3 Wm^{-2} until 15 January. During the last days of the study period, CI increases (Figure 1) and differences up to 55 Wm^{-2} can be found (Figure 3(c)). The most pronounced differences are obtained for the Gulf of Finland, where large fluxes and significant differences in CI are present. The difference of 80 Wm^{-2} in sensible heat flux, which is caused by differences in CI, is comparable to the temporal variability during the study period (Figure 3(a)). For the Gulf of Bothnia area, the two CI analyses result in spatially averaged flux differences of up to 30 Wm^{-2}.

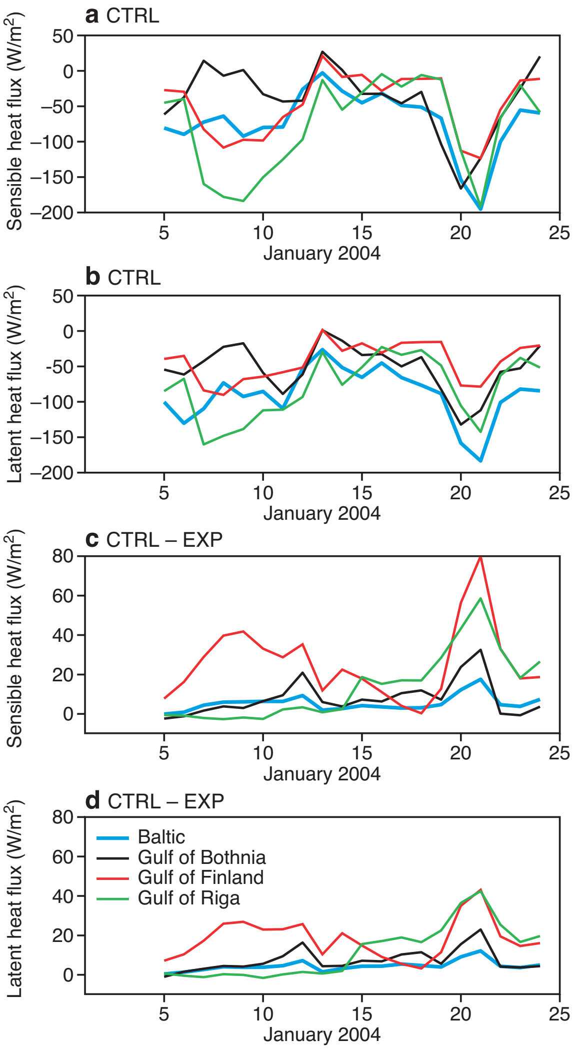

Figure 3 Spatially integrated turbulent surface fluxes for 5–24 January 2004 as computed from the CTRL experiment for (a) sensible heat flux and (b) sensible heat flux. The corresponding differences between CTRL and EXP are shown in (c) and (d). Individual curves represent the Baltic Sea area (blue line), Gulf of Bothnia (black line), Gulf of Finland (red line), and Gulf of Riga (green line).

		GP1 (64.4°N, 22.4°E)		GP2 (65.1°N, 24.0°E)	
Forecast time	Parameter	CTRL	EXP	CTRL	EXP
18 UTC	CI (%)	47	9	64	94
	PBLH (m)	295	320	216	98
	LCC (%)	6.0	9.2	14.4	14.7
	TCC (%)	6.0	9.2	14.4	14.7
	TCWV (kg m^{-2})	3.44	3.43	3.58	3.57
06 UTC	CI (%)	47	9	64	94
	PBLH (m)	199	196	147	88
	LCC (%)	85.0	78.0	99.0	59.3
	TCC (%)	85.0	78.0	99.0	59.3
	TCWV (kg m^{-2})	2.09	2.17	1.91	1.89

Table 1 Selected surface parameters at two model grid points for 21 and 22 January: Sea ice concentration (CI), planetary boundary layer height (PBLH), low cloud cover (LCC), total cloud cover (TCC), and total column water vapour (TCWV). The table shows data from the 6-hour and 18-hour forecasts. Forecast base time is 12 UTC on 21 January 2004.

Impact on the planetary boundary layer

21 January has been selected to study the impact of the different sea ice analyses on the planetary boundary layer (PBL). This particular day was characterized by a northerly flow, leaving the Gulf of Bothnia under the influence of cold air with 2 m temperatures varying from -14 to -7 ° C.

The differences in the forecast are studied using data from two grid point: GP1 (64.4° N, 22.4° E) and GP2 (65.1° N, 24.0° E). In CTRL both points are partly ice covered with a CI of 47 % at GP1 and 64 % at GP2. The spatial gradient in CI in EXP is much higher. GP1 is in the centre of the northern part of the Gulf of Bothnia, which was almost ice free in the high-resolution analysis; GP2 is characterized by almost complete ice coverage of 94 % (Table 1).

Vertical profiles of temperature and specific humidity for the six-hour forecast from 12 UTC on 21 January are shown in Figures 4(a) and 4(b). The differences at GP1 in the vertical profiles are comparatively small. Surface temperature is slightly higher in EXP, since more open water is present. Above 800 hPa, the two curves are almost identical. The most striking difference occurs in the low-level temperature profile at GP2. The CI of 93 % causes a stable boundary layer up to almost 970 hPa. In the presence of 36 % open water in CTRL an unstable structure is created near the surface. The differences in surface temperature are ~ 3 °C (Figure 4(a)). In addition, full ice coverage reduces the specific humidity up to a height of 900 hPa. The difference at the surface is almost 0.3 gkg^{-1}.

Atmospheric column water vapour, low cloud cover, and total cloud cover for both grid points are listed in Table 1. For the six-hour forecast (i.e. at 18 UTC) there are hardly any differences between CTRL and EXP in these parameters. The synoptic situation, with a comparably strong northerly flow and extensive cloud fields east of the Gulf of Bothnia, suggests that the lower boundary conditions have little influence on the atmospheric state. In the 18-hour forecast (i.e. at 06 UTC) differences in low-level cloud cover of almost 40 % occur at GP2.

In general, negative differences in downward sensible heat flux result in deeper boundary layers. Areas for which the flux differences are positive are characterized by shallower boundary layers. The differences in PBL height for the two grid points vary from 3 m (06 UTC forecast for GP1) to 118 m (18 UTC forecast for GP2), which is a substantial amount compared to the absolute value of 216 m. Due to the lack of in-situ observations, it is impossible to validate these results. However, it has been demonstrated that local differences in CI affect the boundary layer and cloud cover even in a coarse-resolution global model.

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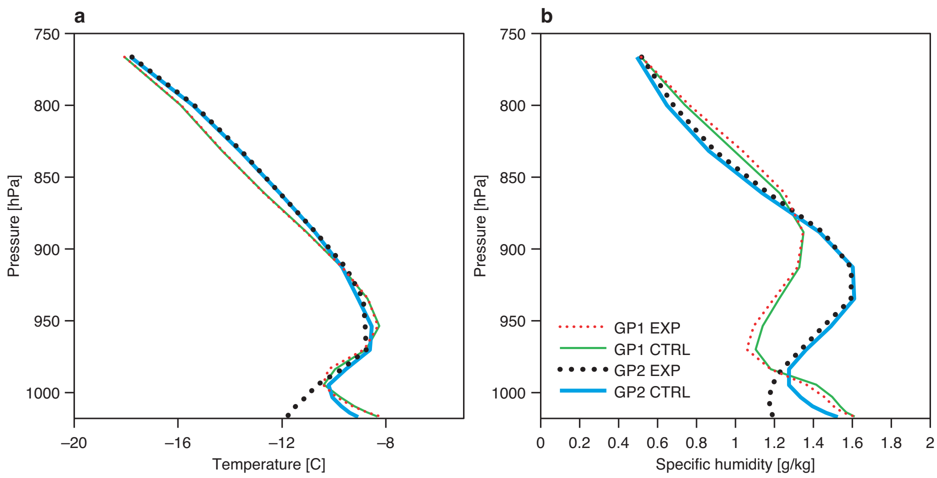

Figure 4 Vertical profiles of (a) temperature and (b) specific humidity for GP1 (64.4° N, 22.4° E, green and dotted red lines) and GP2 (65.1° N, 24.0° E, blue and dotted black lines) from the six-hour forecast from 12 UTC on 21 January 2004. The solid lines show data from the CTRL experiment, the dotted curves refer to the EXP run.

Impact on NWP skill scores

Changes in the turbulent surface fluxes over the Baltic Sea do not necessarily have a direct impact on the atmosphere on larger spatial scales. Effects of changes in sea surface temperature and CI in the Baltic Sea — and consequently in the turbulent fluxes — are superimposed by advective influences. The response of the atmosphere is transported downstream and spatially spread. The dynamic structure of the atmosphere and its upper layers can only be altered in stationary conditions. However, it has to be ensured that the high resolution CI analysis from SMHI does not have an adverse impact on the forecast quality.

The anomaly correlations for 1000 hPa geopotential height for Northern Europe are shown in Figure 5. Again, the differences between CTRL and EXP are small. For forecast days one and two the anomaly correlations for EXP are slightly higher when compared with CTRL. The same holds for the period from days four to eight.

The anomaly correlations presented in Figure 5 suggest a neutral to slightly positive impact of the SMHI analysis on the forecast. Since the actual sample size of twenty forecasts is comparatively small, the evaluation of the forecast impact has been extended to the 500 hPa level. In addition, the t-test and the sign-test have been used to quantify the statistical significance of the differences between CTRL and EXP for forecasts up to 168 hours.

- For the sign-test, CTRL performed significantly worse in five cases; in twenty-three cases the performance has been equal.
- For the t-test, significant changes have been obtained for six cases; in twenty-two cases the performance has been equal.

Although there are indications of a positive impact for days four to seven and for the 24-hour forecast it has to be noted that the results have been derived from a limited number of forecasts. Further testing is necessary to obtain statistically significant results at a higher confidence level.

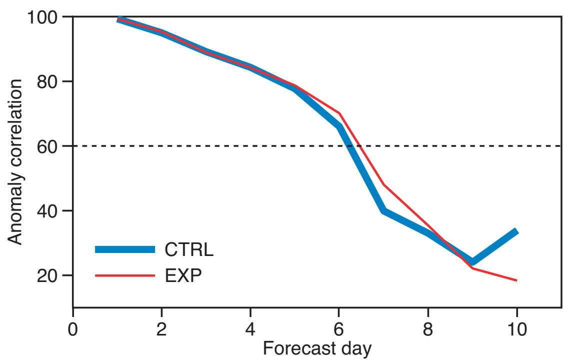

Figure 5 Anomaly correlations for 1000 hPa height for Northern Europe for CTRL (blue line) and EXP (red line). Correlations below 60% (dashed line) are considered not to be useful in weather forecasting.

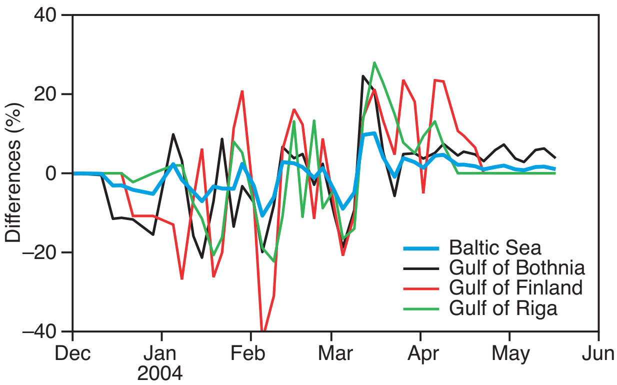

Figure 6 Differences between the mean CI concentration at the beginning of the forecast and the maximum value for the ten-day forecast period for Baltic Sea (blue line), Gulf of Bothnia (black line), Gulf of Finland (red line) and Gulf of Riga (green line). Ice concentrations have been computed from the SMHI high-resolution data set.

Should the sea ice field be updated during the forecast period?

Since ECMWF does not run a coupled ocean-sea ice-atmosphere model for the medium-range forecast, the initial sea ice conditions have to be kept constant throughout the forecast range. The SMHI high-resolution analyses can be used to assess the temporal variability during the forecast period.

Figure 6 shows the difference between the CI at the beginning of a ten-day forecast period and the maximum value for the forecast period. For all three sub-basins differences exceeding 20 % occur during the 2003/2004 winter season. For the Gulf of Finland a single period with a maximum difference of 40 % has been detected. Based on the absolute values for the differences, mean values of 7.7 % (GoB), 10.6 % (GoF), 7.1 % (GoR), and 3.2 % (Baltic Sea) have been obtained for the season. These differences are comparable with the differences introduced through the two CI analyses. Consequently, significant errors in the surface fluxes can be introduced by not updating the sea ice field. Similar results have been found with high-resolution models for shorter forecast periods of up to 48 hours (*Gustafsson et al.,* 1998). This indicates that it would be desirable to use a coupled sea ice-atmosphere model or to include offline sea ice concentration forecasts as lower boundary conditions.

Further Reading

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