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Validation of HIRLAM boundary-layer structures over the Baltic Sea

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The boundary-layer structures of the operational atmospheric model HIRLAM were validated over the Baltic Sea on the basis of rawinsonde soundings and surface-layer observations during *r/v Aranda* expeditions. The validation was made for two regions in 1999: a coastal sea ice zone in March and the Baltic Proper in October. In March, HIRLAM wind analyses and six-hour forecasts were very good. The main discrepancies were related to the surface and *2-m* temperatures: in cold nights the inversions were too weak and delayed in HIRLAM. Experiments applying a two-dimensional mesoscale model suggested that HIRLAM results could be improved by updating the values of surface albedo and the parameters of the force-restore surface temperature scheme on the basis of the snow age and temperature. In October, the temperature profiles were accurate within 0.5 K, on average, but the boundary layer was too moist in HIRLAM. The wind speed in the analyses and six-hour forecasts was accurate within 1 m s^{-1}, and errors in the sea surface temperature had a strong effect on the turbulent surface fluxes.

Introduction

The operational atmospheric model HIRLAM serves at the basis for weather forecasts in several European countries. It is additionally used as forcing for several marine models (Myrberg 1997, Gustafsson *et al*. 1998, Ennet *et al*. 2000). The good accuracy of HIRLAM over land surfaces is well known, although discrepancies from the observations can occur near the surface in cases of a stable boundary layer (Savijärvi and Kauhanen 2001, Ganske *et al*. 2001). Studies

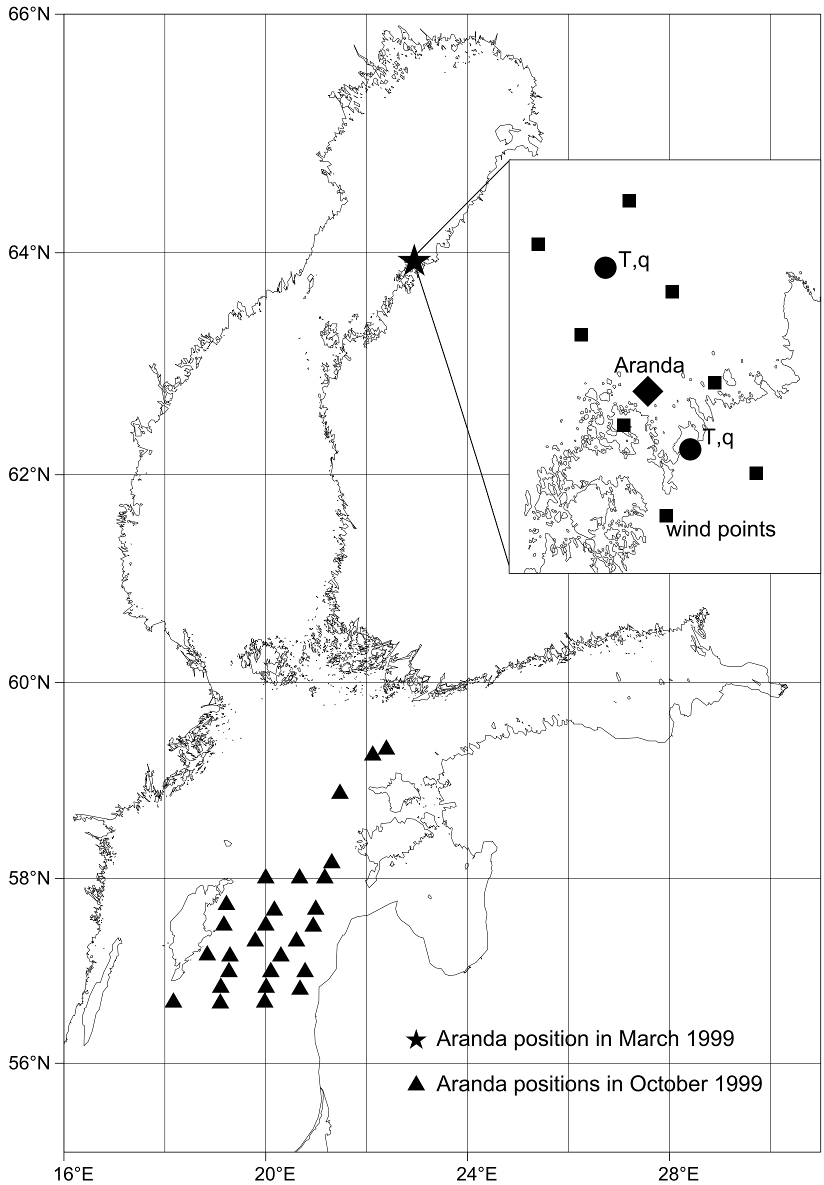

Fig. 1. Location of *r/v Aranda* at the time of the rawinsonde launchings in March 1999 and October 1999. On the right, the area of March location drawn in more detail to show the HIRLAM grid points used in the comparison.

to validate HIRLAM over the sea far from the coasts are rare (Tisler and Fortelius 1999). In this study, we validated the HIRLAM analyses and forecasts over a coastal sea ice region in winter and over the open Baltic Sea far from the coasts in autumn. Our objective was, in particular, to study the applicability and accuracy of HIRLAM data as a forcing for marine models, and we therefore focused our attention in the surface and the atmospheric boundary layer (ABL).

Observations and the model

The analyses as well as 6 and 48 hour forecasts (6hfc, 48hfc) of the HIRLAM version 4.6.2, implemented into operational use at the Finnish Meteorological Institute in autumn 1999, were compared with observations of *r/v Aranda* operated by the Finnish Institute of Marine Research. The comparisons were made for two regions (Fig. 1) and periods: over sea ice close to Kok-

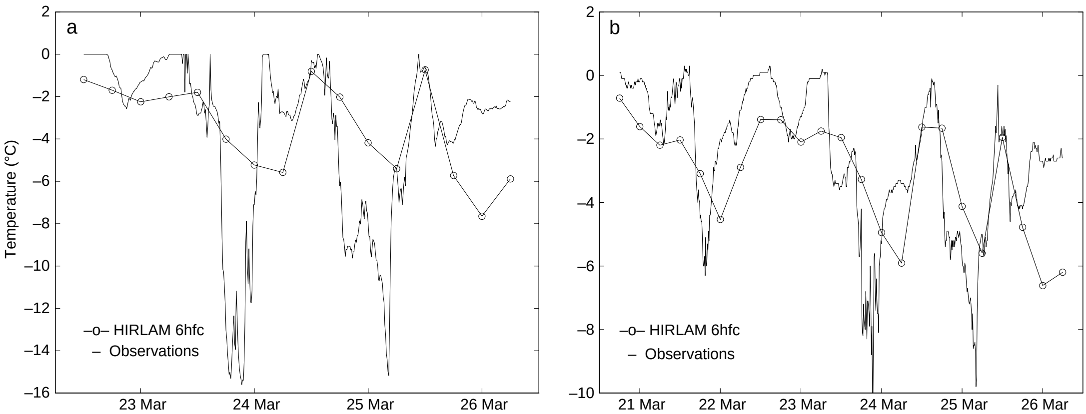

Fig. 2. Time series of the observed and modelled (**a**) surface temperature and (**b**) 2-m air temperature over sea ice in March 1999. The time scales in **a** and **b** differ due to the shorter observation period of the surface temperature.

kola, from 18 to 26 March, 1999, and in the Baltic Proper east and north-east of Gotland, from 11 to 18 October, 1999. The bases for the validation were rawinsonde sounding data, which were not assimilated into HIRLAM. In addition, in March measurements (profile mast, radiative and turbulent fluxes) were made at a sea ice station close to *r/v Aranda*, and in October the ship weather station data were applied. The 48hfc were available only for the October comparisons.

The data of the fine mesh suite runs of HIRLAM 4.6.2 with horizontal resolution of 0.2 degrees were used. For the winter comparisons over the sea ice, the HIRLAM data were taken from the grid points over land and sea nearest to the *r/v Aranda* location (63.97°N, 22.95°E). The distances from the ship to the land and sea grid points were 17.6 km and 24.5 km, respectively. The wind speed and direction were calculated to the mass grid points of the Arakawa C grid. During the autumn comparisons over the open sea, *r/v Aranda* was cruising in the Baltic Proper (Fig. 1). The HIRLAM data were both interpolated to the ship location and taken directly from the nearest grid point (whose distance from the ship varied). There were no significant differences between the interpolated values and those of the nearest grid point. In 1999 HIRLAM sea surface temperature field was based on climatology corrected by ship observations and ECMWF analyses at a few points. The sea ice concentration was updated three times a week on the basis of the ice charts of the Finnish Institute of Marine Research.

ABL over sea ice in March

In the comparisons, there was not much difference between the HIRLAM data at the nearest land and sea grid points. This is partly due to the small thermal differences between the snow-covered land and frozen, snow-covered sea. The only exception occurred in the wind direction profiles up to 1000 m, in which the HIRLAM values for the sea grid points where closer to the observations both for the analysis and 6hfc cases. The mean errors from the rawinsonde sounding wind directions were in any case small in both land and sea grid points, ranging respectively from 7° to 10° and from 0° to 5° in the lowest 300 m. Also the wind speed was well described in the HIRLAM analyses and 6hfc with a mean error of less than 1 m s^{-1}.

During the cold nights with a surface-based temperature inversion, the surface and 2-m temperatures were often too high in HIRLAM, and the minimums were delayed (Fig. 2). The boundary layer was also too moist before the occurrence of the coldest night temperatures (three cases on 21–25 March). An opposite case was the night of 25–26 March, when a fog layer up to 460 m thick was observed. HIRLAM only produced fog up to the height of 130 m, and this may be the reason for the –4 K error in the 2-m air temperature of the 6hfc.

Since the HIRLAM data were available with six-hour intervals, it was not always possible to validate the model performance during

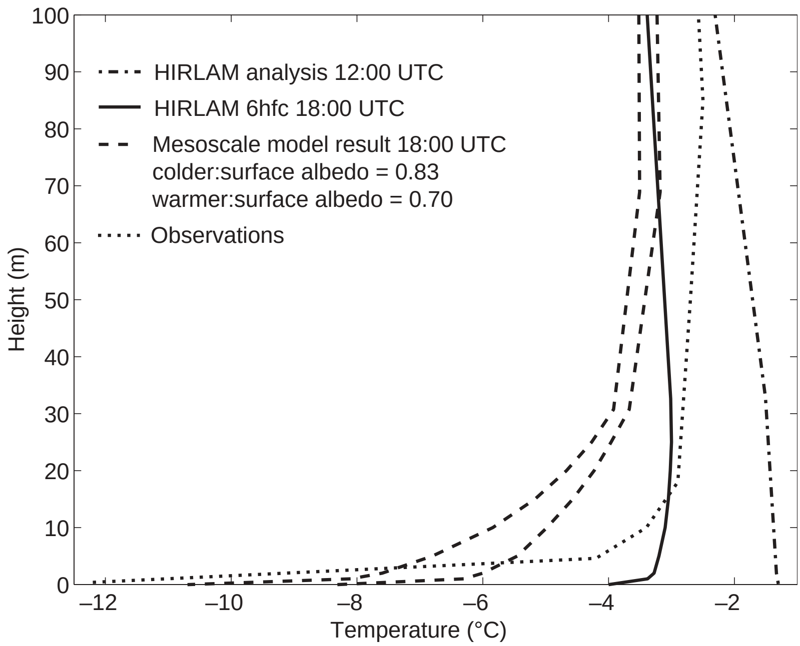

Fig. 3. Air temperature profiles at the *r/v Aranda* site on 23 March, 1999, at 18:00 UTC as observed and modelled in six hours by HIRLAM and the mesoscale model. The HIRLAM analysis at the Swedish coast at 12:00 UTC was used as an inflow boundary condition for the mesoscale model. Profiles between the surface and the lowest model level (approximately at 30 m) are calculated diagnostically.

the coldest hours (Fig. 2). We concentrate on 23 March, 1999, 18:00 UTC, which was a cloud-free evening (also according to HIRLAM) and the HIRLAM surface temperature was 8.2 K too warm. The best method to analyze the reasons for the discrepancies would be to make re-simulations using HIRLAM with modified boundary conditions and/or boundary-layer parameterizations. In the lack of opportunity for that, we applied another strategy. We used the two-dimensional mesoscale model of the University of Helsinki to simulate the night of 23–24 March. The model dynamics are as described in Alestalo and Savijärvi (1985), and physical parameterizations as in Savijärvi (1997) and Vihma and Brümmer (2002). The latter paper also provides model validation over the Baltic Sea ice cover.

The HIRLAM analyses on 23 March at 12:00 UTC were used as the inflow boundary conditions for the mesoscale model. On the basis of the HIRLAM wind speed and direction, the analyses were interpolated to a location from which the air mass had advected to the *r/v Aranda* site in six hours (Swedish coast at 63.6°N, 20.0°E). The mesoscale model was forced by HIRLAM geostrophic wind at the height of 3 km, and run for six hours.

We applied the same vertical resolution and surface boundary conditions (ice concentration, surface albedo, and roughness lengths for momentum and scalars) as in HIRLAM. The sea ice albedo in HIRLAM ranges from 0.5 to 0.7 depending on the snow cover, and it was 0.7 in this case. The basic differences between the models were in the turbulence closure (TKE-based in HIRLAM and a first-order closure in the mesoscale model) and in the calculation of the snow and ice thermodynamics. In the latter, HIRLAM uses the same force-restore scheme for sea ice and snow-covered land surfaces, while in the mesoscale model the force-restore method is tailored for sea ice. Further, since snowfall was observed on 22 and 23 March, we adjusted the parameter values (snow density, volumetric heat capacity, and heat conductivity) for new snow according to Stull (1988: p. 643). The resulting air temperature profile was compared with the observations and HIRLAM 6hfc (Fig. 3). We see that also the mesoscale model produced too warm surface and 2-m temperatures, although they were closer to the observations than those of HIRLAM. Our observations at the *r/v Aranda* ice station indicated, however, a surface albedo of 0.83. We therefore repeated the mesoscale model run using this value, and the results were closer to the observations (Fig. 3).

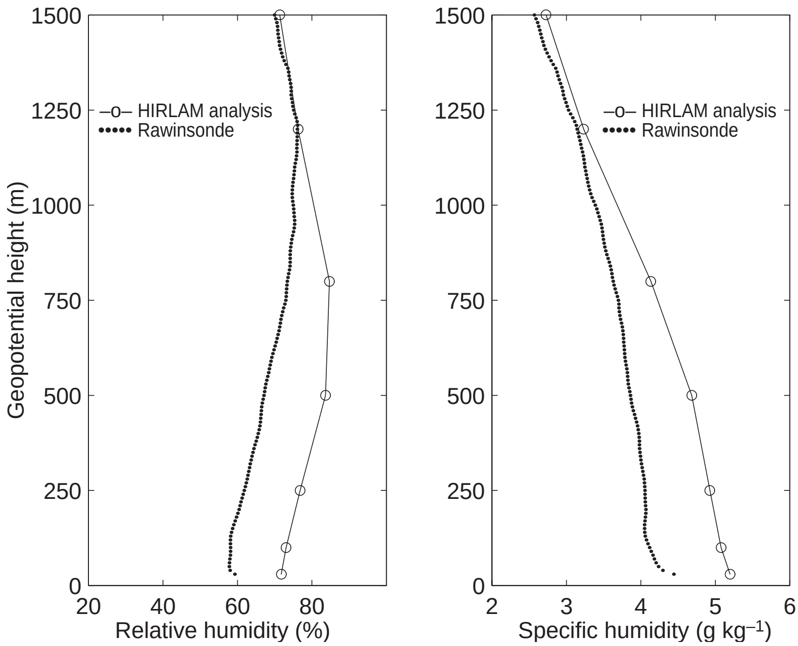

Fig. 4. Mean humidity profiles from the rawinsonde data and HIRLAM analyses in October 1999 over the Baltic Proper.

Changes in the turbulence parameterizations (roughness lengths, stability function for the transfer coefficients, maximum mixing length, level of background turbulence) had a smaller effect in the results than albedo. Since the HIRLAM result at the lowest prognostic model level in the air (~30 m) was good, our study suggests that the TKE-based turbulence scheme of HIRLAM worked well in this case. The force-restore scheme of HIRLAM, using parameter values for old snow, causes, however, some delay in the surface cooling. According to sensitivity runs with the mesoscale model, this can explain some 3 K of the surface temperature error. The rest of the error may originate from the fact that, although the HIRLAM cloud cover was correct at the *r/v Aranda* site at 18:00 UTC (clear skies), over the air-mass trajectory HIRLAM produced more clouds than the mesoscale model. In addition, the HIRLAM specific humidities were larger than observed at the Aranda site.

ABL over the open sea in October

In October 1999, the model validation was based on measurements over the open sea mostly far from the coasts (Fig. 1). The mean vertical temperature profile was accurate within 0.5 K, and the wind direction profile within 10°. With respect to the wind direction, air temperature and humidity in the ABL, the analyses, 6hfc, and 48hfc were almost equally good. In the wind speed, the bias in the ABL grew from 0.5 m s^{-1} in the 6hfc to 1.5 m s^{-1} in the 48hfc.

The lowermost 1200 m were too humid in HIRLAM (Fig. 4). The relative humidities based on our rawinsonde soundings were much lower than typically observed over the Baltic Sea (A. Niros *et al*., unpubl.). Most of our cases were, however, related to cold-air advection from the north, and our data are in agreement with other observations under similar conditions in October 2000 and 2001 (Gerd Müller, pers. comm.).

If the error in the specific humidity in the lowermost 1200 m results solely from an erroneous parameterization of evaporation from the sea surface, we could expect a correlation between the error and the fetch over the sea. There was, however, no correlation (r = 0.01). We could also expect that the rawinsonde soundings made daily at 00:00 and 12:00 UTC in Visby, Gotland, would have a strong effect on the HIRLAM analyses. The mean error in the specific humidity in the lowermost 1200 m did not, however,

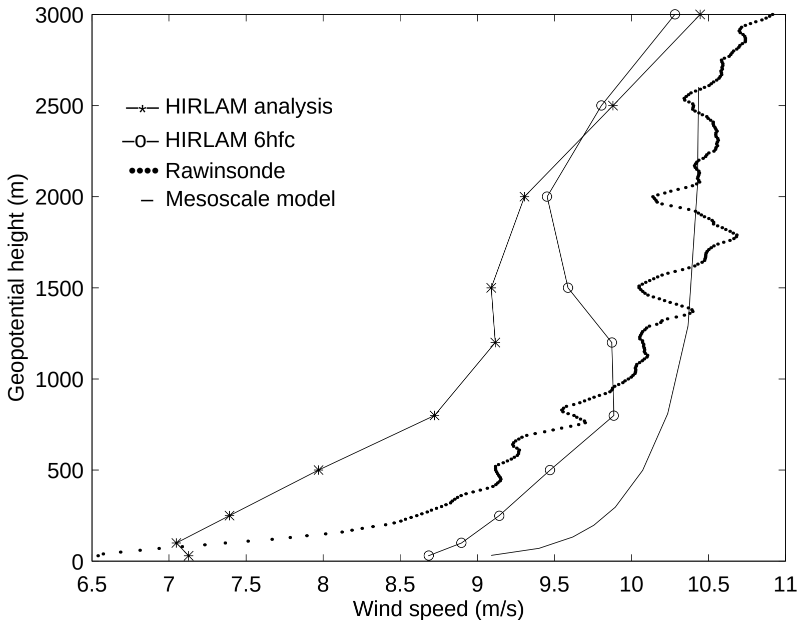

Fig. 5. Mean wind speed profiles from HIRLAM analysis and 6hfc, the rawinsonde data and the mesoscale model in October 1999 over the Baltic Proper.

depend on the availability of the Visby data (not available for the daily analyses at 06:00 and 18:00 UTC).

In the lowermost 300 m, the rawinsonde soundings suggested much larger wind shear than HIRLAM (Fig. 5). However, we have to bear in mind that the rawinsondes were launched from the rear deck of the 14-m-tall *r/v Aranda*, which usually had its bow towards the wind during the launch. A wake growing downwind was therefore generated, and the sonde first ascended (in an angle of 20–30°) in this wake. (In March 1999 the profiles did not suffer from this effect because the sondes were launched from the sea ice and not downwind of the ship.)

In order to better understand the shape of the mean wind profile in the lowermost 300 m, we made a simulation forcing the mesoscale model by the HIRLAM 6hfc wind at the height of 3 km, averaged over the October observation period. We run the model into a steady state, and studied the wind profile at a site 350 km downwind of the coast (in the mesoscale model domain) corresponding to the observed mean fetch over the sea.

We see from Fig. 5 that the steady-state profile of the mesoscale model agrees better with the shape of the HIRLAM 6hfc profile than with the observations. This supports our suspect of erroneous sounding profiles in the lowermost 200–300 m, and suggests that the weak wind shear in HIRLAM is not any peculiar result of the TKE scheme. We point out these comparisons, because disturbed rawinsonde wind profiles may form a common problem for soundings made from ships. Such profiles are then used in the analyses of operational models over the oceans. Over the Baltic Sea no ship-based sounding data are assimilated into HIRLAM. Errors can, however, be generated when the analyses over the sea are affected by land-based sounding data, which naturally have a larger wind shear due to a larger surface roughness. We indeed note that in the HIRLAM analyses the near-surface wind speeds are almost 2 m s^{-1} lower than in the 6hfc (Fig. 5). The problem may, however, also be related to such limitations in the HIRLAM optimal interpolation scheme that do not directly result from the land-based wind observations. Such is, e.g., the requirement of a near geostrophic balance.

The HIRLAM 6hfc and 48hfc fluxes of sensible heat (H) and latent heat (LE) were compared with the surface fluxes calculated from the ship weather station data applying the bulk-method. The wind data were taken from the ship anemometers in the main mast, and they are proved to be accurate within 10%–15% (A.

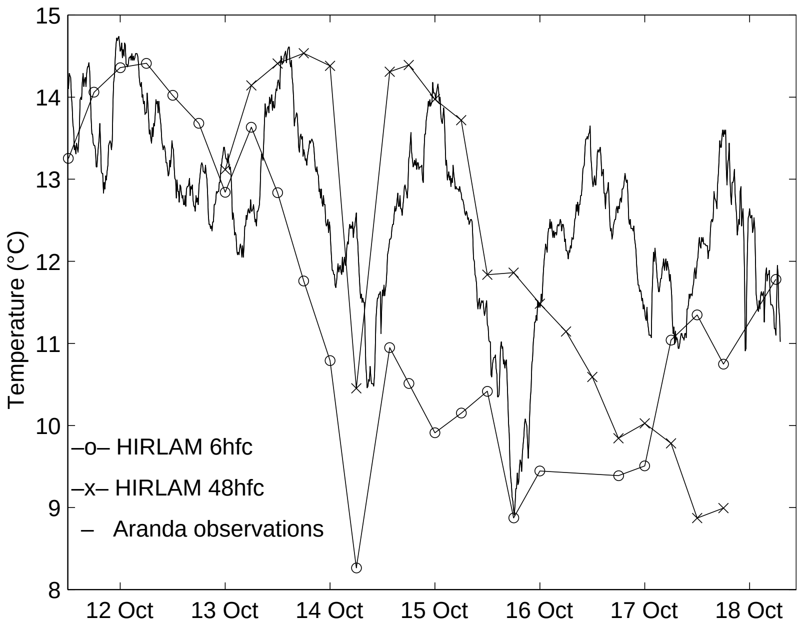

Fig. 6. Time series of the sea surface temperature based on Aranda observations and HIRLAM 6hfc and 48hfc.

Niros *et al*., unpubl.). Because of the different observation heights of the wind speed (19 m) and air temperature and humidity (14 m), an iterative flux-profile scheme was applied (Launiainen and Vihma 1990). Turbulent fluxes based on a bulk-aerodynamic formula are, of course, not the most accurate basis for a validation study. A bulk-formula is, however, applied in HIRLAM as well, and therefore our comparisons mostly reflect the effects of the errors in the input quantities: the sea surface and air temperatures, wind speed, and air humidity. The large errors in the sea surface temperature (Fig. 6) were the most important ones. The comparison showed a low correlation between the calculated H and the HIRLAM results (correlation coefficient $r = 0.39$ for 6hfc and $r = –0.57$ for 48hfc). A better correlation was observed between HIRLAM and the calculated LE ($r = 0.80$ for 6hfc and $r = 0.74$ for 48hfc), but it mostly results from the larger range of variability in LE. The HIRLAM root-mean-square errors were rather high in both sensible and latent heat fluxes, being 24 W m^{-2} for *H* and 50 W m^{-2} for LE in the 6hfc case. Our data did not indicate a systematic overestimation of LE, as observed e.g. by Ganske *et al.* (2001). These comparisons point out the need for more reliable sea surface temperatures in HIRLAM.

Conclusions

The significance of this HIRLAM validation is related to the following points of view:

1. Our data were obtained from the open sea and sea ice, where no regular observations exist,
2. detailed vertical profiles were available, not only data from the standard pressure levels, and
3. the data were independent, not assimilated to HIRLAM.

In general, the HIRLAM temperature, humidity, and wind profiles agreed well with the observations. In March 1999 the main discrepancies were related to the surface and 2-m temperatures: in cold nights the inversions were too weak and delayed. The HIRLAM forecasts could be improved by updating the values of surface albedo and the parameters of the force-restore method on the basis of the snow age and temperature. Problems more difficult to solve were, however, related to the prediction of the cloud cover (too much on 23 March) and fog (too thin a layer in the night of 25 to 26 March). In October 1999, the temperature profiles were accurate on average within 0.5 K, but the boundary layer was too moist. The 6hfc for the wind speed were good, but the analyses over the sea may suffer from the larger shear of the land-based sounding data or from errors caused by the data assimilation scheme. Over the open sea, the surface temperature often differed from the observations causing errors in the latent and sensible heat fluxes.

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