What can a LAM-NWP system tell us about the atmospheric water cycle

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1 Introduction

The BALTEX regional reanalysis project (Fortelius et al., 2002) was carried out jointly by the Finnish (FMI) and Swedish (SMHI) national meteorological services as an ECMWF special project with the objective to carry out high resolution data assimilation around the Baltic drainage basin (Fig. 1) over one year (Sept. 1999-Oct. 2000) during the BALTEX main experiment BRIDGE (Bengtsson 1998), and thereby to promote the use of assimilation products in regional climate system research. A specific objective is to produce gridded fields of all components needed to close the energy and water cycles, with a spatial resolution of approximately 22 km and a temporal resolution of one to six hours. The computational domian is shown in Figure 1 More details are given on the project home page, which is linked to the BALTEX web site http://w3.gkss.de/baltex/.

2 The assimilation system

The forecast model is based on Hirlam level 4, but grid-scale condensation and precipitation are parameterized according to Rasch and Kristjansson (1998), and convection according to Kain and Fritsch (1998), whereas surface and soil processes are treated as in the Rossby Centre climate model as described by Bringfelt et al., (2001).

Boundary conditions at the lateral edges of the domain are specified using analyses from the ECMWF, updated every 3 hours, and interpolated linearly in time to every time step of the forecast model.

The analysis of atmospheric variables is performed using 3DVAR, employing six-hourly cycling. The observations consist of surface data from reporting weather stations, ships and drifting buoys, and upper air data from radio soundings and reporting aircraft. The analyzed atmospheric state is filtered with respect to gravity waves using a diabatic digital filter to get a balanced initial field for the prognostic model.

On land surfaces, only the snow-cover is analysed based on observations, while the temperature and moisture in the soil and vegetation are described by the soil-model. Analogously, the numerous inland lakes in Scandinavia are described with a separate lake model (Ljungemyr et al. 1996). The surface temperature (SST) and ice evolution in the Baltic Sea are described with a coupled ice-ocean model (Gustafsson et al. 1998), forced by the atmosphere-model via fluxes of heat and water vapour, and relaxed towards the observed SST-distribution. Elsewhere, analysed STT and ice distributions from the ECMWF are used.

3 Water balance of the Baltic drainage basin

Barring chemical reactions, the amount of water substance in any volume can change only by fluxes through the boundaries of the volume. For a column of air, these fluxes consist of precipitation (P), phase transitions at the surfcae (evaporation, dew formation et. c., E), and horizontal transports through the lateral boundaries. The net effect of these transports is given by the convergence of the vertically interated horizintal flux of water vapour and cloud condensate (C). In most cases the contribution from the cloud condensate is so small as to be entirely negligible. Symbolically we may write: $W = C + E - P$, where W stands for the rate of change of water substance within the atmospheric column.

All the terms in this equation are easily obtained from the BALTEX reanalysis data. Terms E and P are included in the model output as accumulated within each forecast. Term W is readily computed by taking the difference of appropriate model states. Term C is often evaluated using the state variables of surface pressure, wind and specific humidity, (e.g. Fortelius, 1995). This method is cumbersome and usually inaccurate, since many numerical approximations of derivatives and integrals are involved. A much simpler approach is to evaluate C as a residual term in the budget equation. If this is done in such a way, that all the remaining terms in the equation refer to the same forecast, i.e. the change predicted by the model for a given period is compared to the accumulated precipitation and evaporation during the same period, then the residual is actually equivalent to the accumulated flux convergence as given by the forecast model during the same period.

Fig. 2 illustrates the atmospheric water budget of the Baltic drainage basin from September 1999 through September 2000, as given by the BALTEX reanalysis system. The graphs present 30-day running means based on hours 6 - 12 of four forecast cycles each day. For the basin as a whole (top panel) precipitation (Heavy solid line) dominates over evaporation (dashed line) except for shorter periods during spring and autumn. The deficit (surplus), indicated by the line at the edge of the grey shading, is nearly balanced by convergent (divergent) flux of water vapour flux (the unmarked edge of the same grey shading) so that the rate of change (not shown) is usually small. Averaged throughout the year, the region is clearly one of net imported water vapour.

Comparing the predicted rate of change of the water content to the one that may be deduced from analyses valid at the corresponding times sheds some light on the reliability of these results. The black shaded area shows the difference between these tendencies, which is seen to be small in magnitude compared with either $E - P$ or C. Nevertheless, positive values, indicating excessive accumulation of water in the forecasts, prevail in winter, while the opposite is true in summer. The pattern is consistent with the systematic error of the surface pressure (not shown), reflecting the tendency of the model to spuriously accumulate mass in the region during winter and disperse mass during summer.

Conditions over the land fraction of the drainage basin (middle panel) are similar to those prevailing over the total basin. This is not surprising, as most of the area is covered by land. It is interesting to note, that even the land-part of the basin may serve as a net exporter of water vapour on a monthly time scale. This happens in September 1999 and in May 2000, and again in September 2000.

Over the Baltic Sea itself (Fig. 2, bottom panel), conditions look rather different from those over the continental parts. Precipitation and evaporation both follow a similar annual cycle, but the former is more variable on a monthly time scale. Hence sometimes one and sometimes the other dominates the scene, and periods of net import and export of water vapour follow each other at irregular intervals throughout the year without any obvious annual cycle.

4 Precipitation

The verification of precipitation forecasts in general is made difficult by the huge variability of precipitation in time and space. In general a large number of in situ measurements is needed to estimate the average precipitation over a model grid box. A network of radars provides virtually continuous observations, but obtaining accurate estimates of the precipitation at the surface using radars alone is very problematic. The BALTEX Radar Data Centre combines corrected rain gauge data with radar measurements over the catchment basin of the Baltic Sea. These data were used for verification of the predicted precipitation. Products and methodologies of the BALTEX Radar Data Centre (BALTRAD) are described in Michelson et al. (2000). The data used here consists of gridded consecutive 12-hourly precipitation sums with a horizontal resolution of 2 km. For the purpose of this study, the BALTRAD data are transformed by box-averaging to the HIRLAM-grid having a grid length of 22 km.

Figure 3 shows time series of 7-day running mean precipitation totals over the rectangular area shown in Fig. 1. This area was chosen mainly because the of the high quality of the radar network there. As before, the model output consists of hours 6-12 of four forecast cycles each day. The correspondence between the two totally independent estimates is quite remarkable on all time scales, and the linear correlation coefficient is as high as 0.95. Even for half-daily precipitation sums (not shown), the linear correlation coefficient between the two estimates is as high as 0.91. Annual totals differ by only 6mm for BALTRAD and 788 mm for HIRLAM, so the difference is definitely within the observational uncertainty.

Although important, the total amount is only one aspect of precipitation. It is also important how the precipitation is distributed in space and time. Fig. 4 shows frequency-histograms of semi diurnal precipitation in different seasons for all (22 by 22 km) grid-boxes within the control area. The main features of the observed distributions, including their seasonal changes, are well reproduced by the reanalysis products, especially in spring and summer. In autumn and winter the occurecnce of weak precipitation is overpredicted by the system at the cost of cases with no precipitation at all (note that the leftmost columns in Fig. 4 have been divided by a factor of 10 for greater readability).

5 Conclusions

The BALTEX regional reanalysis project has demonstrated that data assimilation using a modern limited area numerical weather prediction system is a feasible way to determine the essential features of the energy and water cycles of the Baltic drainage basin.

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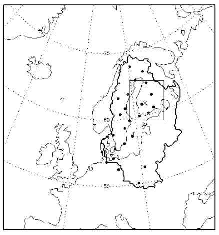

Figure 1: *Domain of the BALTEX regional reanalyses. The black dots and the cross indicate the sites of weather radars.*

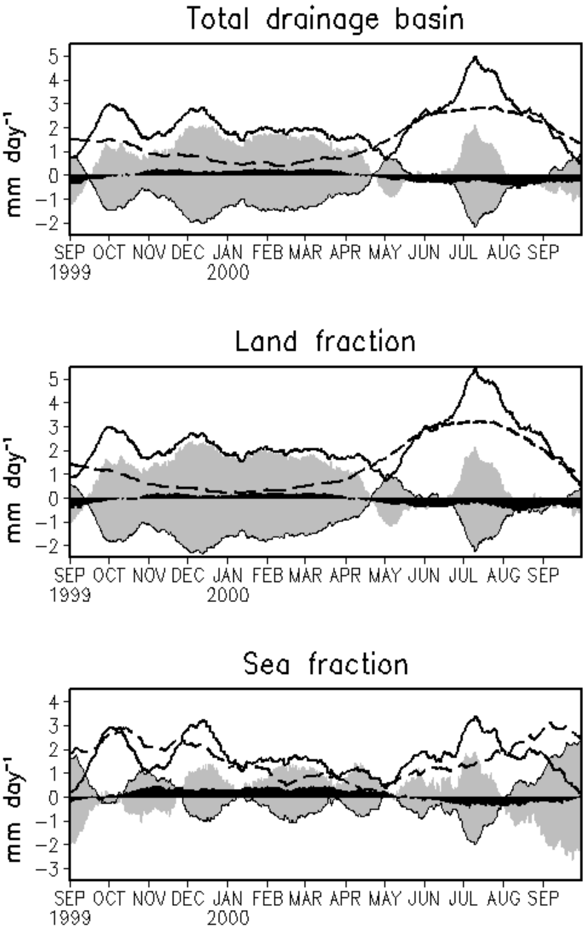

Figure 2: *Terms in the atmospheric water budget over the drainage basin of the Baltic Sea. Graphs represent 30-day running means based on forecast hours 6-12 of four forecast cycles each day. Precipitation and evaporation are shown as heavy solid and dashed lines, respectively, and the difference between evaporation and precipitation is shown by the solid line at the edge of the grey shaded band. The unmarked edge of this band shows the net convergence of lateral water transport in the atmosphere. The black shaded band gives the bias of the predicted rate of change of the atmospheric water content relative to the analysed one.*

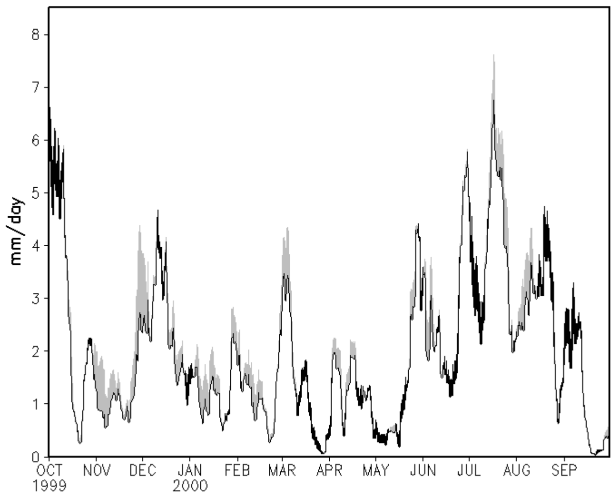

Figure 3: *Areal 7-day running mean precipitation totals for the rectangular area shown in Fig. 1. The solid line shows precipitatoin retrievals from the BALTEX Radar Data Centre. Grey and black shading, respectively indicate positive and negative differences between the BALTEX reanalysis system and the BALTRAD retrieval. Model results refer to hours 6-12 of four forecasts each day.*

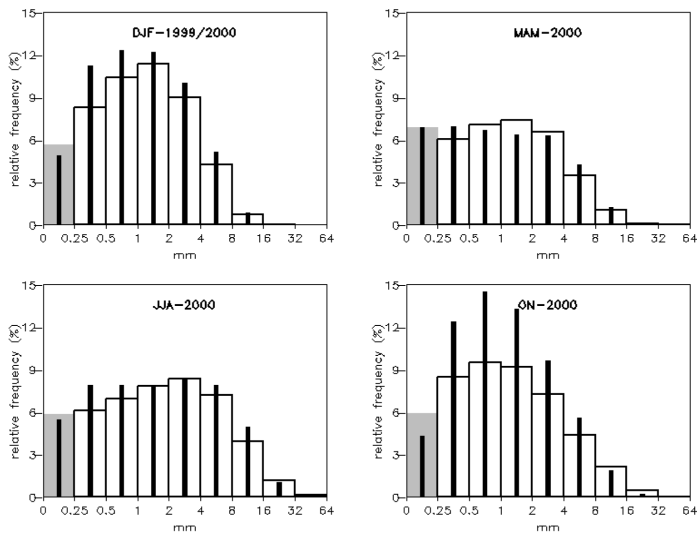

Figure 4: *Relative frequency distributions of semi siurnal precipitation totals for all grid-boxes within the rectangular control area in Fig. 1. The thin black columns refer to the BALTEX reanalysis system, while the wide unfilled columns show precipitation retrievals from the BALTEX Radar Data Centre. Different panels refer to different periopds, as indicated by the letters and numbers. The leftmost columns have been divided by 10 for greater readability.*