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Operational Regional Prediction

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With 14 Figures

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Summary

Regional operational prediction requires the development, implementation and steady improvement of a modelling system which comprises different components like the data assimilation scheme, numerical forecast model, postprocessing and application modules as well as packages for monitoring, diagnostics and verification. The text highlights the impact of some of those components like lateral boundary conditions, data assimilation and statistical postprocessing on the quality of operational regional prediction systems and proposes some important research directions for an improvement of the systems from the operational point of view.

1. Introduction

To meet the growing demand of the public for accurate and detailed weather forecasts, the national meteorological services (NMS) recently introduced high-resolution numerical weather prediction (NWP) models with meshsizes as small as 5 to 20 km. Since current computer resources are too small to allow for a global model with such high a resolution, the fine grid has to be restricted to the area of interest, typically of a size of some 2 to 4 millions km^2. Surveys of current operational models are contained in Bougeault (1992), Wergen and Majewski (1993), and Du Vachat (1994). Since the field is expanding very fast, the annual WMO reports "Progress Report on Numerical Weather Prediction" and "Technical Progress Report on the Global Data Processing Systems" should be consulted too.

This paper deals with the specific problems and challenges in the field of regional operational prediction concentrating not only on the numerical model itself but on the various components of a regional NWP system and their delicate interplay. Most examples presented here have been taken from the system operational at the Deutscher Wetterdienst (DWD) because of the easier availability of the material.

2. Goals of High-Resolution Regional NWP Systems

Some twenty years ago, NWP systems only provided the raw meteorological information which had to be interpreted by the field forecasters in terms of real weather forecasts. Since then, as already foreseen by e.g. Anthes and Warner (1978) high-resolution model results are used for the

- prediction of local weather parameters like temperature and humidity at 2 m, wind at 10 m, clouds and precipitation using the direct model output itself or statistically corrected values (e.g., model output statistics, Kalman filtering),
- provision of meteorological input data for a wide range of application models like air

pollution modelling, hydrological forecasts, sea state and road condition modelling or agro- and bio-meteorological forecasts.

Since nowadays the data produced by high-resolution regional NWP systems provide the basis for many products in the environmental sector a change of name may be appropriate for the NMS like "U.S. National Centers for Environmental Prediction" for the National Meteorological Center (NMC). Because the state of the environment is endangered in many countries the need for accurate predictions of the environment with the atmosphere being a very important part of it will expand rapidly during the next few years. To prepare the necessary meteorological information high-resolution regional NWP systems concentrate on a detailed simulation of the processes in the atmospheric boundary layer (ABL) including the energy exchanges at the surface, and the hydrological cycle in the atmosphere and the ground. To fulfil the needs of the application models, new forecast products like boundary layer height, convective cloud depth, or the photosynthetic active radiation have to be derived.

As an example for the range of applications of the data of a state-of-the-art system some results of the German high-resolution models "Europa-Modell" (EM, 55 km meshsize, 20 layers) and "Deutschland-Modell" (DM, 14 km, 20 layers) are shown. A short summary of this system may be found in the Quarterly Report of the Operational NWP-Models of the Deutscher Wetterdienst (Schrodin, Ed.).

Figure 1 compares a 12-h DM forecast of the wind at 10 m above ground to all synoptic observations in Germany and its surroundings valid at the same time. Obviously, such high-resolution models are not only able to simulate the impact of the topography rather realistically, e.g., land/sea contrasts, orographic channeling and local wind systems but the strong convergence often found at a cold front, too. The model data may be even used to derive detailed weather forecasts (Fig. 2) in form of a meteograph at arbitrary gridpoints. These forecasts include clouds (of stratiform and convective type), rain, snow, freezing precipitation and strong winds for several days ahead with a temporal resolution as high as one hour. While interpreting the meteographs the forecaster has to bear in mind the inherent error growth in the model, e.g. phase errors. Thus an accurate timing of events, like a frontal passage, is impossible two or three days ahead even though the model results are presented at hourly intervals.

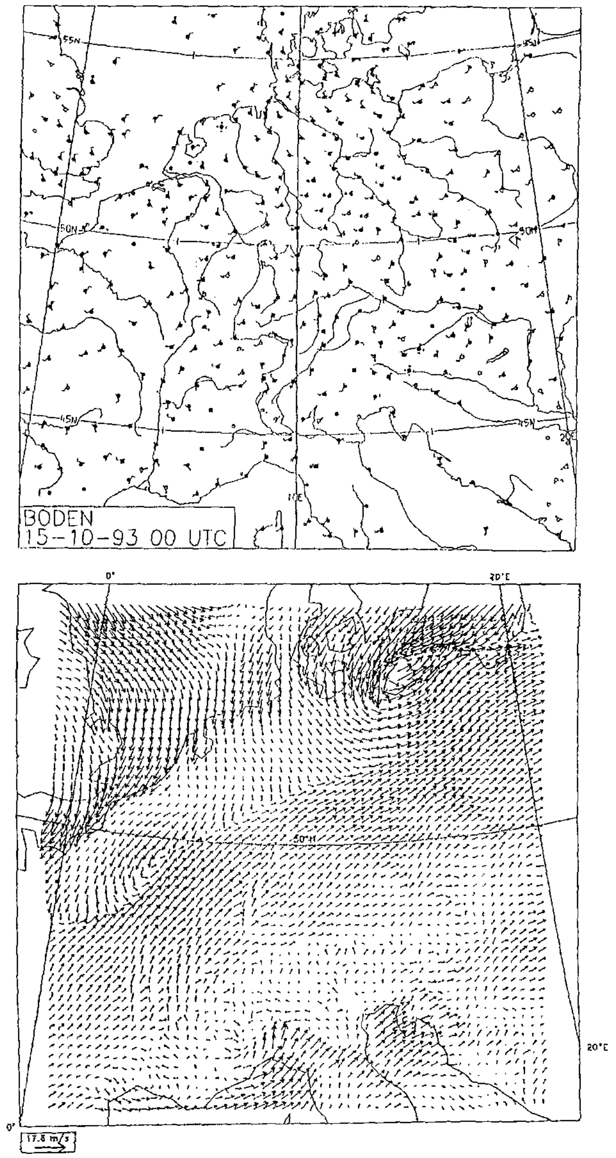


Fig. 1. Wind field at 10 m above the ground for Central Europe. Top: Observation at 00 UTC 15 October 1993. Bottom: 12-h DM forecast valid at the same time; only every other gridpoint is plotted

High-resolution model data output at hourly intervals requires some 300 megabytes of storage for a single 48-h DM forecast. These data are stored at a central database and used as

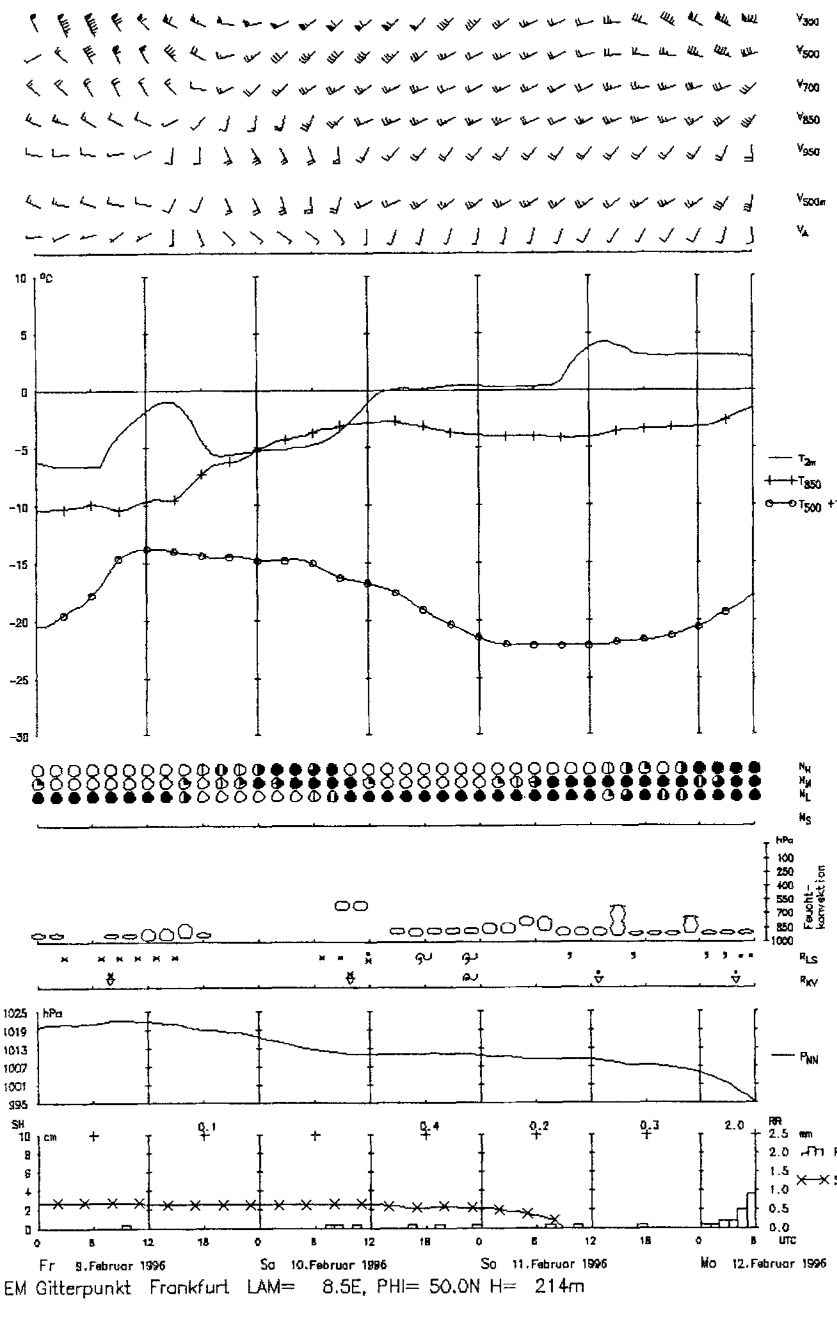


Fig. 2. Meteograph at gridpoint "Frankfurt" based on EM forecast starting at 00 UTC on 9 February 1996

meteorological input by a whole range of application models.

- For TV stations, animated 2-d and 3-d cloud forecasts (Fig. 3) will help the layman to comprehend the temporal evolution of weather systems for his area of interest. Powerful workstations are necessary to process the huge amounts of model data needed for a 3-d view of the cloud evolution.
- Trajectory calculations based on the high-resolution wind field (Fig. 4) provide vital guidance in the case of a nuclear or chemical accident in topographically complex terrain like the Upper Rhine Valley. But for this application the use of a high-resolution model which explicitly resolves at least the major highlands (the Vosges Mountains and the Black Forest for this case) and their impact on the flow is essential. Otherwise the observed channeling is not simulated like in the EM with a 55-km meshsize.
- A better estimate of the transport and dispersion of pollutants may be obtained by a

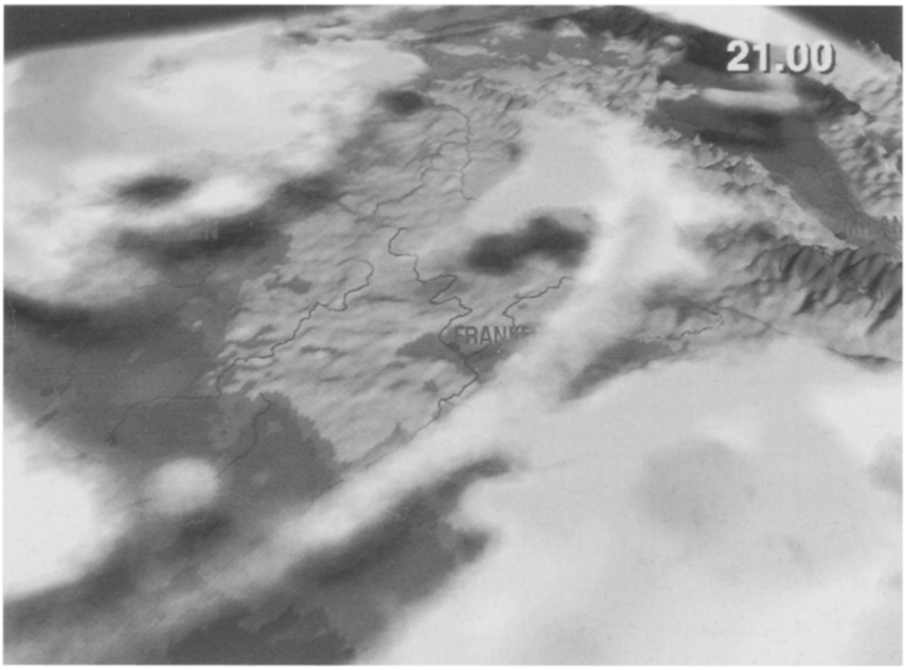


Fig. 3. 3-d graphical representation of the clouds based on a 21-h DM forecast

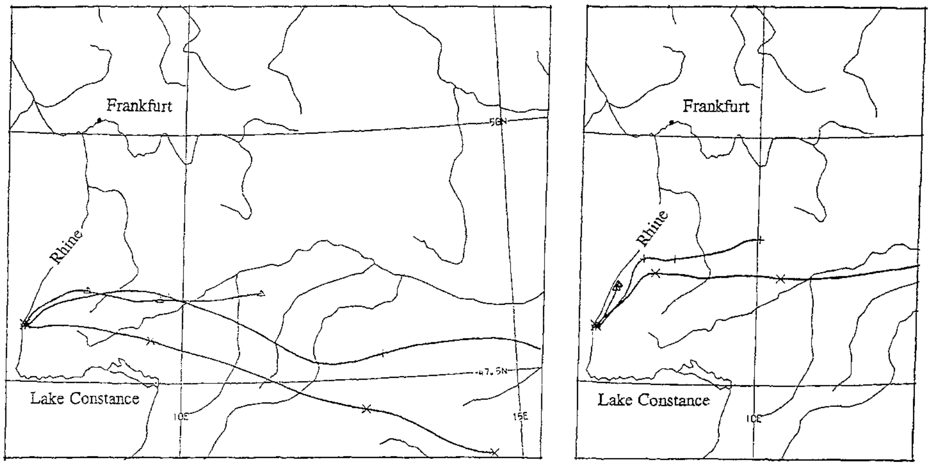


Fig. 4. Comparison of 36-h EM (left) and DM (right) forward trajectories starting at 00 UTC on 23 July 1993 in the Rhine Valley at a height of 50 m (Δ), 250 m ($+$), 500 m (x) above the model orography; symbols $(\Delta, +, x)$ are drawn every 12 hours

Lagrangian particle dispersion model (LPDM, e.g. Fay et al., 1995) but of course for a much higher computational cost. LPDMs need quite detailed meteorological information like the 3-d fields of wind, temperature, humidity, clouds and turbulence at a high temporal resolution. Figure 5 presents the long range dispersion of a passive tracer gas which was released during the European Tracer Experiment (ETEX, Klug et al., 1995) in 1994; the LPDM of the DWD is driven by a 72-h forecast of the EM.

- The correct and timely prediction of heavy precipitation (Fig. 6) fed into hydrological forecast models will save the lives and property of many people hit by a severe flood situation. From the hydrological point of view, the most important parameters for the models are the start and end of periods of intense precipitation as well as the proper distinction between rain and snow, and the storage capacity of the ground. Current regional NWP models allow for the proper timing of heavy precipitation events only in the average

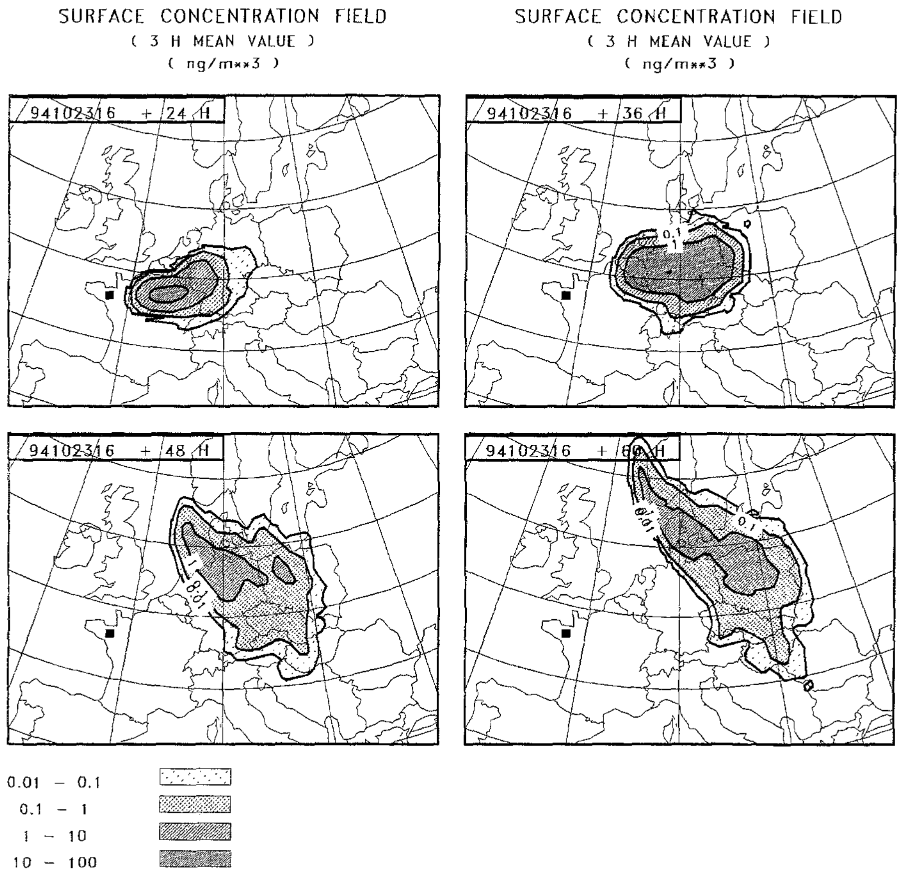


Fig. 5. Dispersion of a tracer plume released at Rennes (France) on 23 October 1994 at 16 UTC (release duration 12 hours) shown 24, 36, 48 and 60 h after start of the release. Calculation based on results of the EM forecast starting at 12 UTC on 23 October 1994. Simulation with Lagrangian particle dispersion model (LPDM), concentrations in ng m^{-3} at ground level

for an area of some 500 km^2; at single stations the correlation between the forecasted and observed precipitation may be even negative in some cases. Of course, this limitation may be partly due to a lack of representativeness of the station observations which are influenced by local details of topography not resolvable by current NWP models. But the poor results at single stations also reflect the limitations of the models in simulating the exact temporal evolution of large convective systems which are responsible for many flood situations.

- Other applications of NWP data include the prediction of road condition as well as agro- and bio-meteorological (e.g. UV-index) forecasts.

The few examples of the use of regional NWP products presented above indicate that huge economic benefits for the society as a whole are being derived from high-resolution NWP data. But the budget of the NMS running the meteorological models often does not reflect these savings since the price of NWP data is not taking the global benefits into account. Even though the regional NWP system still forms the basis of the majority of the products of a regional NMS and needs proper attention.

3. Components of High-Resolution Regional NWP Systems

The data flow in a typical regional NWP system is outlined in Fig. 7. The arrows point into the direction of the main data flow and the different modules of the system are represented by rectangles; the modules typical for regional NWP systems have been shaded.

Observations enter the system via the global telecommunication system (GTS), satellite links or some other communication network. These data form the basis of the regional analysis which is usually closely coupled to the regional model via the 4-d data assimilation. High-resolution topographical and physiographical data like orography, soil parameters and vegetation as well as additional climatological data are needed

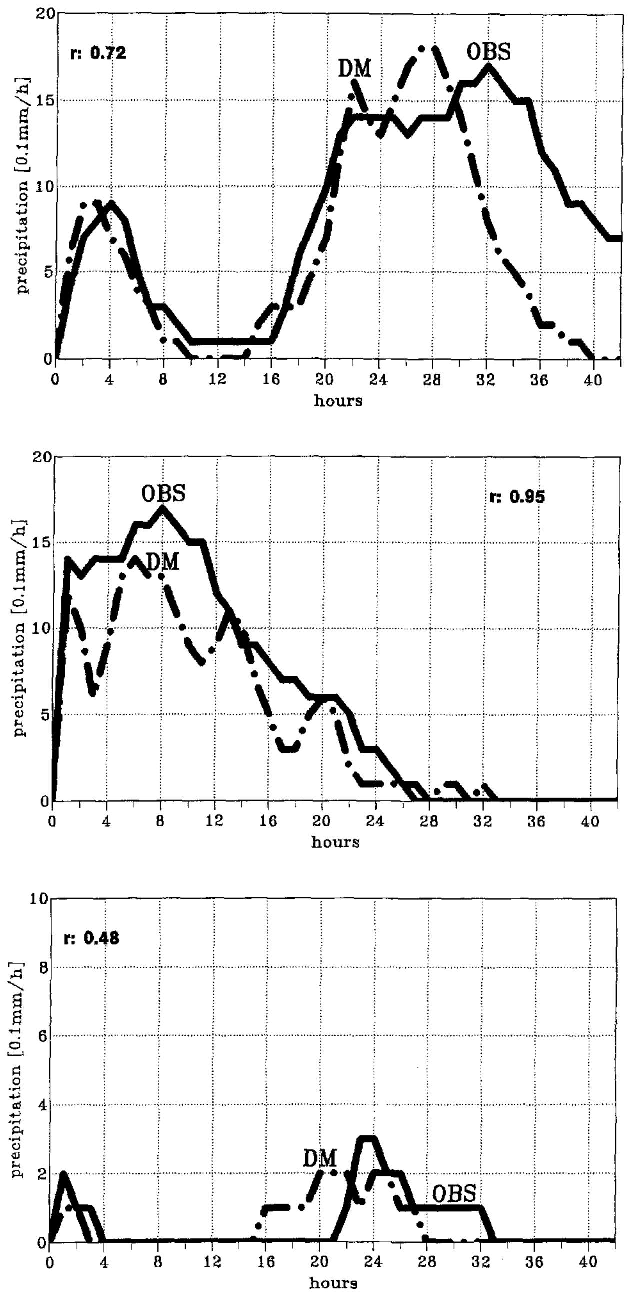


Fig. 6. Time traces of precipitation rate (0.1 mm/h) as observed (solid) and predicted by the DM (dashed) for a flood situation. Mean over 50 stations in southwestern Germany. Top: Period 12–13 April 1994, middle: 13–14, bottom: 14–15. The 42-h DM forecasts started at 00 UTC on each day

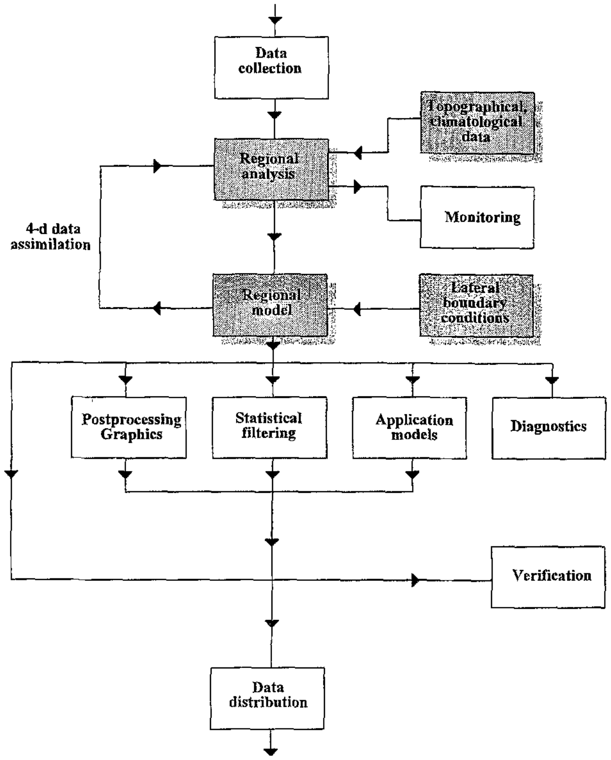


Fig. 7. Mean data flow (arrows) and components (rectangles) of a high-resolution regional NWP system. Components, typical for regional NWP systems, are shaded

to complete the initial state of the model. The necessary lateral boundary data influence the quality of the regional forecast to a large extent, and their impact will be discussed in the next section. The forecasts of the regional NWP model are usually stored in a database and distributed to the different users either directly or in a postprocessed form (e.g., after a statistical filter has removed systematic forecast errors), or used as meteorological input to the application models mentioned in section 2. To control the quality of the NWP system, several modules are needed which monitor the quality of the observations entering the analysis ("Monitoring"), diagnose the mean evolution of the NWP model ("Diagnostics") and finally verify all forecast products of the system ("Verification"). Those three modules are extremly important for the surveillance of the NWP system and the vital basis for any improvement.

One essential task in operational regional NWP is in maintaining a proper balance between the various modules involved while taking care of the strict operational schedule. With the computer resources available today it is for example impossible to include explicit cloud microphysics in operational models which have to provide a 24-h forecast in less than 30 minutes. Reliability and robustness of the NWP system as a whole is another important issue since operational models have to run 24 hours a day, 7 days a week, and 52 weeks a year. Special emphasis has to be placed upon the interfaces between the modules since the overall quality of a NWP system crucially depends on them.

4. Impact of the Lateral Boundary Conditions

The quality of limited-area prediction models is markedly influenced by the driving larger scale model especially if the model domain is not big enough to avoid the quick advection of information from the lateral boundaries into the inner domain of interest. From the operational point of view, five decisions concerning the lateral boundaries have to be taken, namely

- the mathematical method for treating the lateral boundaries of the model; for operational models, the Davies (1976) method or some variant is most popular because of its robustness and accuracy,
- the driving larger scale model, e.g. the ECMWF, DWD, UK, or NMC global models or an in-house larger scale model,
- the initial date and time of the driving forecast, e.g. the same as the regional forecast or 12 hours earlier,
- the update interval, i.e. the time interval between two sets of lateral boundary data written by the larger scale driving model, e.g. 6 hours or less,
- the length of the regional forecast, e.g. 48 hours or less, in relation to the size of the model domain.

The answer to the second question usually depends on the speed of the communication links between the various meteorological centers and the availability of the larger scale forecasts. Concerning the third question, Table 1 may offer some guidance. It compares the root mean square errors (RMSE) of EM forecasts for the period July 1994 until June 1995 and two areas, namely "D" which covers about 90% of the full model domain of 9900*7000 km^2 and "M" with a size of roughly 5500*3000 km^2, i.e. the central area of interest (Fig. 8). The regional forecast "EMV" has a short data cut-off at 2.15 UTC, well before the start of the global model GM of the DWD, which provides the lateral boundary data for the EM. Thus "EMV" is driven by the GM forecast starting 12 hours earlier, whereas for "EMH" with a data cut-off at 3.30 UTC, the regional and driving global model runs start at the same initial time. Strictly speaking, the differences between "EMV" and "EMH" do not only reflect the different lateral boundary values but also, probably to a minor extent, the different data

Table 1. *RMSE of "Europa-Modell" Forecasts for the Period July 1994 until June 1995 for the Areas North Atlantic and Europe (left) and Central Europe (right).* "EMV": Regional model with 12-h old boundary values from a global model, "EMH": Regional and global model start from the same initial date and time

Area "D"	+12 h	+24 h	+36 h		Area "M"	+12 h	+24 h	+36 h
EMV	1.270	1.909	2.578	PS(hPa)	EMV	1.119	1.730	2.371
EMH	1.158	1.771	2.368		EMH	1.070	1.679	2.278
EMH-EMV	−0.112	−0.138	−0.210		EMH-EMV	−0.049	−0.051	−0.093
EMV	8.689	13.394	18.934	FI 850 hPa (m)	EMV	8.074	12.762	17.970
EMH	7.552	12.151	17.075		EMH	7.539	12.223	17.060
EMH-EMV	−1.137	−1.243	−1.859		EMH-EMV	−0.535	−0.529	−0.910
EMV	11.433	16.595	23.722	FI 500 (hPa) (m)	EMV	10.580	15.001	21.394
EMH	10.302	15.011	21.275		EMH	10.124	14.641	20.699
EMH-EMV	−1.131	−1.584	−2.447		EMH-EMV	−0.456	−0.360	−0.695
EMV	1.225	1.520	1.801	T 850 hPa (K)	EMV	1.194	1.463	1.684
EMH	1.195	1.472	1.733		EMH	1.175	1.446	1.669
EMH-EMV	−0.030	−0.048	−0.068		EMH-EMV	−0.019	−0.017	−0.015

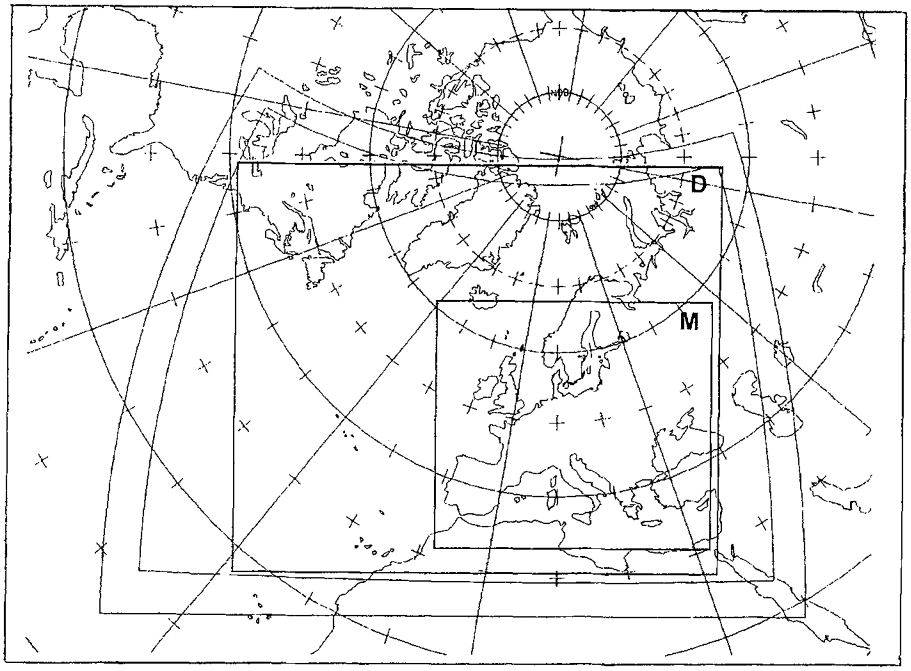


Fig. 8. Domain of the EM and two verification areas "D" and "M"

cut-off times leading to slightly different analyses. Obviously, the regional model driven by the 12 hours old boundary data performs worse in the mean for all seasons even in the inner model domain, but the deterioration is up to a factor of three larger in the large domain and doubles there between +12 and +36 hours. Nevertheless, the 12-h old boundary values are only responsible for an increase of the RMSE by about 10% in the large and 5% in the inner model domain. Thus the quality of the EM forecasts in the inner domain of interest depends much more on the quality of the model itself than on the lateral boundary values. But for very high-resolution models on a small domain, old lateral boundary data severely lower the quality of the regional forecast because large-scale forecast errors at the boundaries spread into the domain of interest in less than 12 hours and contaminate the high-resolution forecast. The selection of the lateral boundary data during the 4-d data assimilation cycle of a regional modelling system deserves proper attention, too. Using boundary data from driving models more than 12 hours old may hamper the analysis quality especially in data void areas like the North Atlantic or Pacific Oceans.

Concerning the update interval of the lateral boundary data, the 6-h cycle used operationally by many NMS clearly has a negative impact on the quality of the regional forecast due to the usual linear interpolation of the boundary data with time. Especially the temporal interpolation of the wind components generally damps the intensity of smaller scale systems simulated by the driving model as is demonstrated in Fig. 9. If the wind veers without a change of the speed in between the update times t_1 and t_2, the linear temporal interpolation results in an underestima-

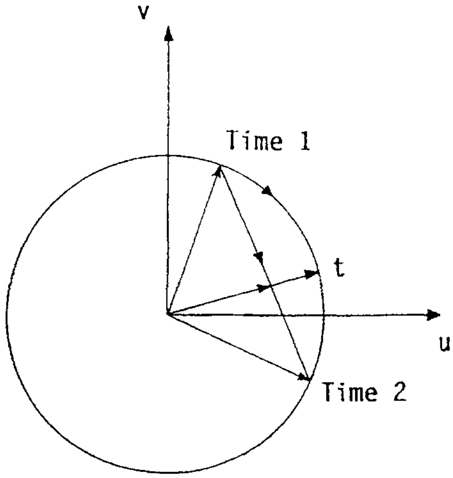


Fig. 9. Impact of the linear temporal interpolation of the wind components used in lateral boundary relaxation schemes. Boundary data are provided at the times t_1 and t_2

tion of the wind speed which is largest just in between t_1 and t_2 leading to a minimum of the kinetic energy in the regional model in the middle of the update interval. Figure 10 presents the time trace of the deviation of the domain averaged kinetic energy from the initial value for a regional model of 41 by 37 gridpoints and a mesh size of 55 km. To highlight the systematic effect, an average over 30 cases has been taken, too. In between each update interval of 6 hours, the mean kinetic energy drops to a minimum due to the linear interpolation of the wind components with time. Especially in strongly baroclinic situations with rapid flow across the lateral boundary, the 6-h update interval is responsible for a severe dampening of smaller scale systems like a secondary cyclone as shown in Fig. 11. To improve the regional simulation in those situations, an update interval of 3 hours or less is mandatory. Interpolating wind speed and direction instead of the wind components with time, as suggested by one of the referees, will not cure the problem since this approach destroys the near-balance between mass and wind fields at the lateral boundaries and may lead to "noisy" boundary values.

Different views prevail concerning the relation between the forecast length and the domain size of the regional model. Some argue that the forecast length should allow a simulation in the inner model domain which is not significantly influenced by the lateral boundary values. But the practical experience in many NMS shows that a useful high-resolution forecast is possible beyond this period as long as the lateral boundary treatment takes care of a proper inflow of larger scale information of the driving model and an outflow of high-resolution flow features out of the regional domain. In this configuration, the regional NWP model merely adapts the larger scale forecast to a high-resolution topography and adds valuable local detail to the driving forecast.

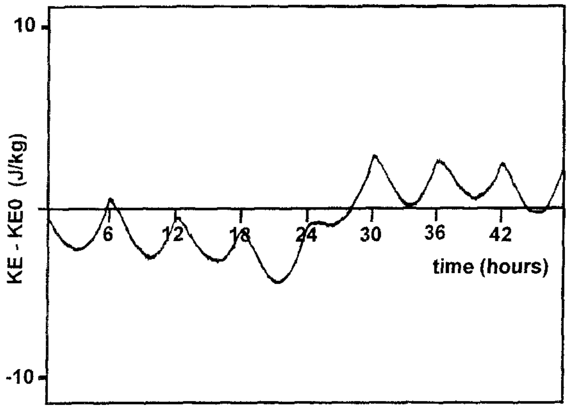


Fig. 10. Time trace of the deviation of the area averaged kinetic energy from the initial value. Mean over 30 forecasts and the whole model domain of 41*37 gridpoints and 20 layers. 6-h update interval of lateral boundary data

5. Impact of the 4-d Data Assimilation

Mesoscale flow features in the atmosphere develop either due to the forcing from the lower boundary or due to scale interaction. If the flow is strongly forced by topography, even a regional model starting from a smooth initial stage, e.g. the interpolated analysis of a larger scale model, will evolve mesoscale systems which compare well to observations. This adaptation process often lasts less than three hours in the ABL depending on the stratification. Thus the goals of regional modelling may be partly realized by initializing the model with an interpolated larger scale analysis without the implementation of a regional data assimilation. On the other hand, scale interaction in the free atmosphere usually needs more time for the evolution of mesoscale structures. To take full advantage of a regional NWP system, a regional data assimilation is essential and reduces the initial adaptation in the spin-up phase of the forecast model.

Current regional data assimilation methods have been mostly derived from their larger scale counterparts (e.g., Lönnberg and Shaw, 1987) modified for the regional extent of the domain. Therefore intermittent 4-dimensional assimilation schemes based on multivariate optimum interpolation are used at many NMS. Nudging (e.g., Lorenc et al., 1991) provides a simple method to benefit from the high temporal resolution of some observing systems. In the future, 3-d and 4-d variational data assimilation systems (e.g., Talagrand and Courtier, 1987) will probably much better take nonconvential data sources like radar and satellite into account than current systems and exploit the intimate relation between different variables of a model.

In principle, all prognostic variables of a regional model plus some external parameters

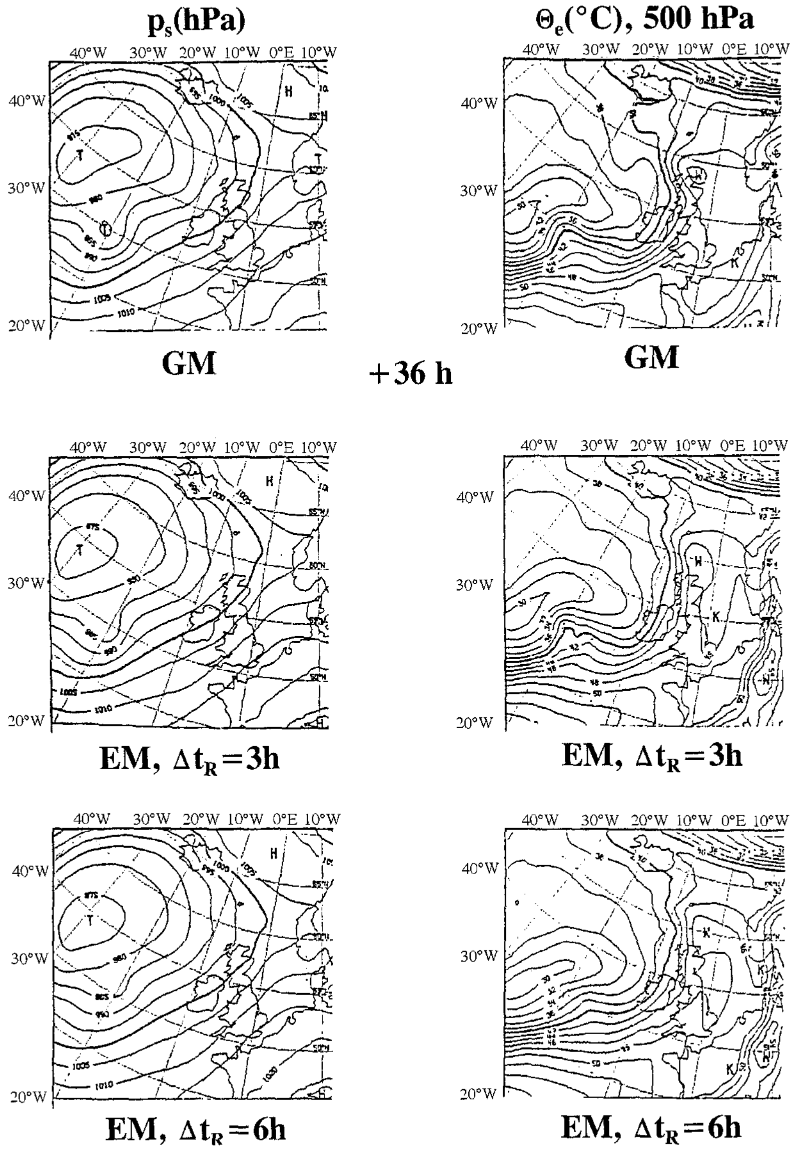


Fig. 11. Surface pressure (left, hPa) and equivalent potential temperature at 500 hPa (right, °C); 36-h forecast by the driving global model (GM, top row), regional model EM with 3-h update interval of lateral boundary data (EM, middle) and regional model EM with 6-h update interval (EM, bottom row)

should be analyzed, but from current operational data assimilation systems only the following variables are usually available

- geopotential height (and/or temperature),
- horizontal wind components,
- humidity,
- surface pressure,
- sea surface temperature (SST),
- temperature and humidity at 2 m,
- snow height.

Because representative observations are missing or too scarce, no analysis is often available for

- cloud water,
- turbulent kinetic energy,
- soil temperature,
- soil water content,
- vegetation parameters like cover, leaf area index, root depth.

A careful monitoring of the quality of the observational data is imperative in regional analysis and assimilation systems since the number of redundant observations is usually very small due to the high-resolution model grids. An example taken from the SST analysis at the DWD highlights this problem. The Lake Vänern in southern Sweden is represented by just

Table 2. *Impact of Erroneous SST of Lake Vänern (Sweden) on EM Forecast. 24-h EM Forecast Starting at 00 UTC on 20 August 1994 at the two lake gridpoints (center) plus surrounding ones.* Surface temperature (T_s), precipitation (RR), sensible (H) and latent (LE) heat fluxes

14	14	15	14	88	1	1	1
14	33	33	14	17	178	125	0
13	13	14	15	3	2	1	0
	T_s[°C]				RR [mm/d]		
6	14	9	−25	−20	−38	−61	−34
7	−194	−272	−5	−15	−648	−934	−37
−2	1	−3	−9	−21	−19	−14	−23
	H [W/m^2] 0–24 h				LE [W/m^2] 0–24 h		

two gridpoints in the EM and the SST analysis has to be performed at those lake points, too. In August 1994, a single wrong ship observation (reporting a SST of 33 °C) passed the quality checks and determined the final analysis at the two gridpoints. Table 2 summerizes the impact of the wrong analysis on the subsequent 24-h EM forecast. Shown are forecasted values at the two lake plus some surrounding gridpoints. Very intense heat (H) and moisture (LE) fluxes are simulated at the two "hot" lake gridpoints. Here, the surface temperature (T_S) is almost 20 K higher than at the surrounding land points. Up to 178 mm of precipitation (RR) are produced during the 24-h forecast period at the lake points.

In general, increased attention has to be paid to the analysis of near surface and soil variables; especially the soil moisture content controls the diurnal cycle of temperature, humidity and cloudiness in the ABL to a large extent, at least in the warm season. Because representative observations of soil moisture are lacking, some NMS reset this variable in the "analysis" to a "climatological" value which may poorly represent the actual moisture content and lead to large errors in near surface weather conditions.

If the initial soil moisture is taken from the first guess of the analysis instead, i.e. typically the 6-h forecast of the model, as is done e.g. in the UK or German data assimilation systems, the systematic errors of the model during those 6-h periods which coincide with the spin-up phase of the model accumulate, and may cause large biases in the near surface weather conditions which persist for days or even weeks. Figure 12 taken from Viterbo (1995) is a nice example of

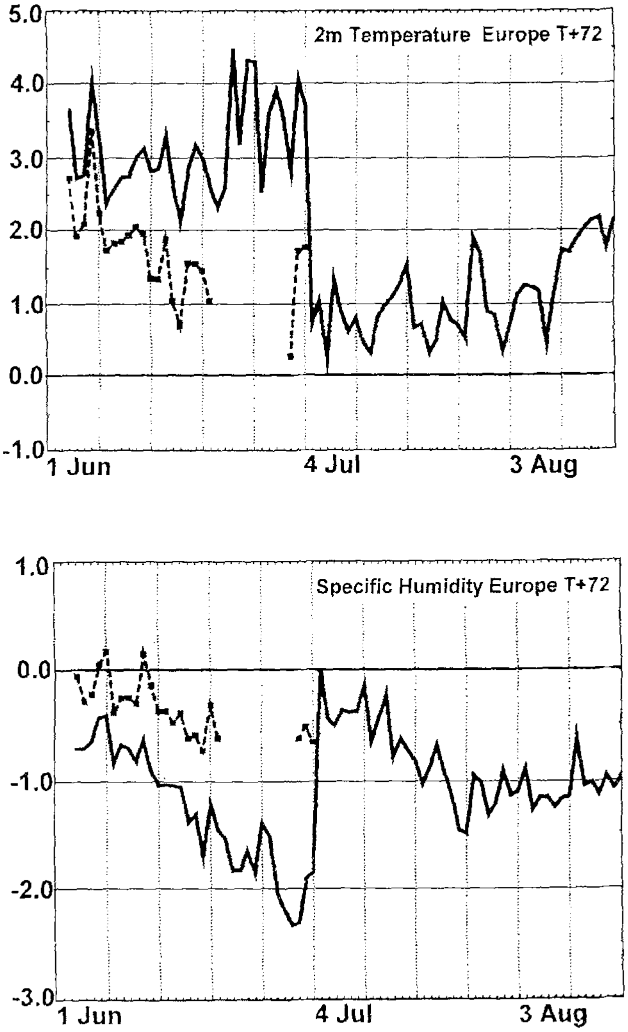


Fig. 12. Top: Mean error of screen level temperature forecasts of ECMWF model verified against SYNOP observations in Europe. Bottom: Same for the specific humidity. 72-h forecasts valid at 12 UTC during June and July 1994. Soil water reset to field capacity on July 4, 1994. Taken from Viterbo, 1995

Table 3. *Impact of Soil Moisture on Precipitation According to Experiments by Luethi and Schär, 1994. Precipitation (Unit: mm) for Selected Areas and Month-long Integrations with the Europa-Modell (Meshsize* $0.5^\circ \sim 55$ *km, 30 layers) using ECMWF Analysis as Initial and Lateral Boundary Data.* Obs: Observation, Ref. EM: reference forecast, 2*WB (0.5*WB): twice (half) the initial soil moisture content of the reference

January 1993

Area/Version	Obs.	Ref. EM	2*WB	0.5*WB
Western Europe	99	131	132	131
Southern Europe	11	12	13	12
Scandinavia	86	121	121	121
Middle Europe	57	66	68	65
France	49	57	60	57
Alpine Area	24	25	26	24

July 1993

Area/Version	Obs.	Ref. EM	2*WB	0.5*WB
Western Europe	65	60	72	58
Southern Europe	7	2	6	2
Scandinavia	85	101	112	82
Middle Europe	125	82	121	59
France	60	21	67	14
Alpine Area	104	68	117	45

the problem. It shows the bias of the temperature and specific humidity at 2m of the ECMWF forecast for Europe at day 3 during the summer of 1994. Since the ECMWF model underestimated the cloudiness during the 6-h data assimilation cycle, too much short wave radiation hit the ground resulting in an overestimation of the evapotranspiration at land gridpoints. Thus by June, the soil got too dry and a large positive temperature bias of up to 4 K and a negative humidity bias of up to 2.5 g/kg at 2 m developed. Since even the forecast of the geopotential at 500 hPa was adversely affected by the wrong near surface values, the soil moisture was reset to field capacity on July 4 with a dramatic reduction of the mean errors at 2 m and in the whole troposphere.

Even the amount of precipitation depends on the initial soil moisture, at least in summer, as shown in Table 3 which compares month-long integrations of the EM for January and July 1993 conducted by Luethi and Schär (1994). The precipitation for selected areas is quantified as observed (Obs) and simulated by the model with the original soil moisture content (Ref.EM) which was taken from the ECMWF analysis, twice (2*WB) and half (0.5*WB) this amount. Whereas the impact of the soil moisture content is negligible in January, the precipitation differs by more than a factor of four in some areas during July probably due to the sensitivity of convective precipitation to the near surface moisture conditions.

Thus a suitable analysis of the soil moisture content is an important milestone for progress in regional NWP. Since direct measurements of this quantity are presently too scarce and not representative enough, the analysis has to be based on indirect methods like the dependency of the diurnal cycle of temperature and dew point on the available moisture as proposed by Mafhouf (1991). A possible disadvantage of this approach is that the derived moisture content reflects all uncertainties of the soil parameterization, too. Thus that value may produce the best forecast of the temperatures and dew points at 2 m but poorly represent the actual soil moisture conditions. As an alternative, an off-line version of the soil parameterization of the regional NWP model driven by observed precipitation and radiative fluxes may be used to assimilate the soil moisture content. Here, the correct parameterization of the vertical turbulent fluxes of heat and moisture as well as the run-off is crucial for a proper assimilation of the soil moisture content.

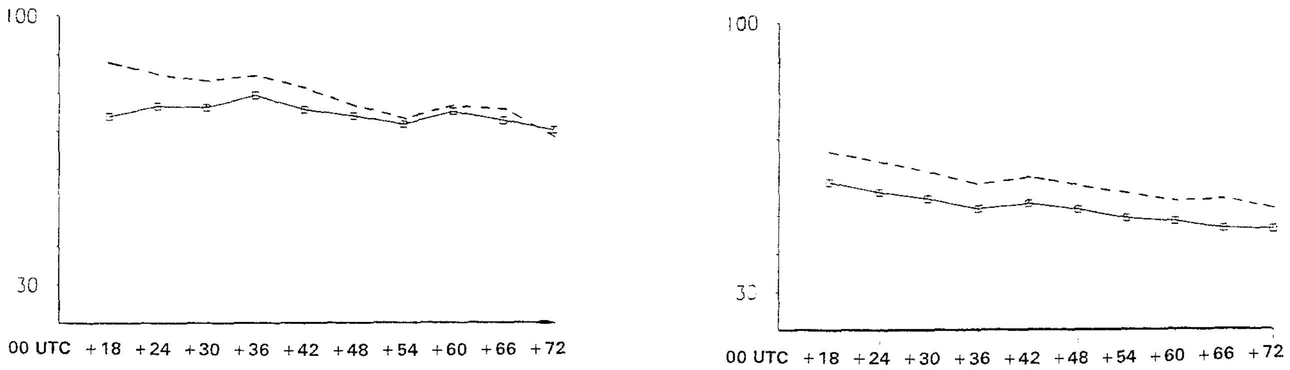
6. Role of the Statistical Postprocessing

Modules for the statistical postprocessing of the direct model output (DMO) form an integral part of regional prediction systems. There are three reasons for this; first of all, the DMO is not free of systematic errors due to an imperfect initial state, e.g. the lack of a suitable analysis of the soil parameters mentioned above, or an imperfect NWP model. Secondly, the local weather is influenced by small-scale features often not resolved by the regional model, e.g. if forecasts for small islands, mountain tops or deep valleys are required. Lastly, statistical postprocessing is helpful in deriving parameters which are not directly forecasted by the regional model but are in some close, yet not strictly mathematical connection to the DMO, e.g. visibility, aircraft icing, or clear air turbulence.

Three statistical methods are widely used,

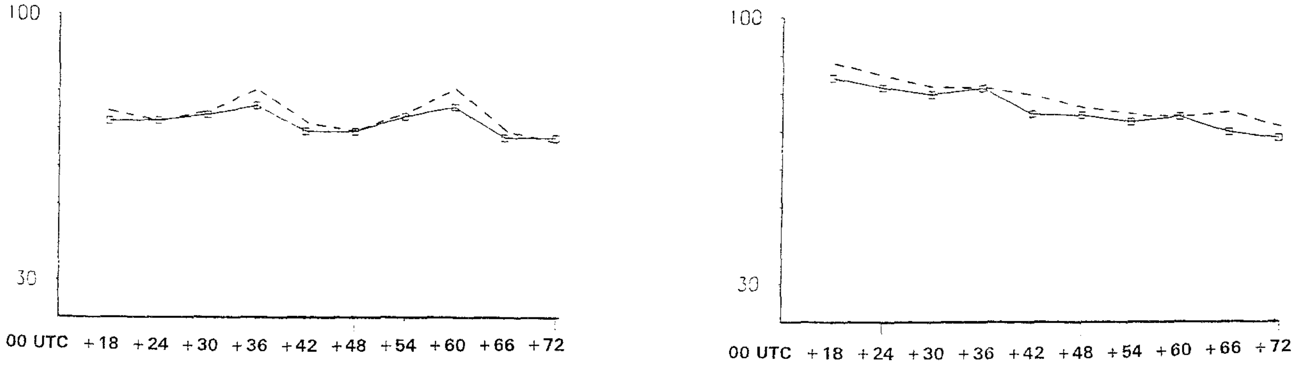
- Model Output Statistics (MOS, Glahn, 1980),
- Perfect Prog Method (PPM, Glahn, 1980) and
- Kalman Filtering (KF, Persson, 1989).

The advantages and disadvantages of the three methods are discussed in Glahn et al. (1991). A combination of MOS and KF probably provides the best correction of systematic errors of the DMO of near surface weather conditions on all time scales. But even a very simple KF which just uses a constant plus a factor times the DMO as filter parameters improves the quality of the DMO of a regional model significantly as shown in Fig. 13 a and b. Here the number of correct forecasts of the EM for 55 stations in Germany and the parameters temperature at 2 m, total cloudiness and wind speed/direction at 10 m is compared for the DMO (solid line) and KF (dashed). A forecasted value is considered to be synoptically correct, if the absolute error is less



a) Temperature (2K)

b) Wind speed (1m/s)

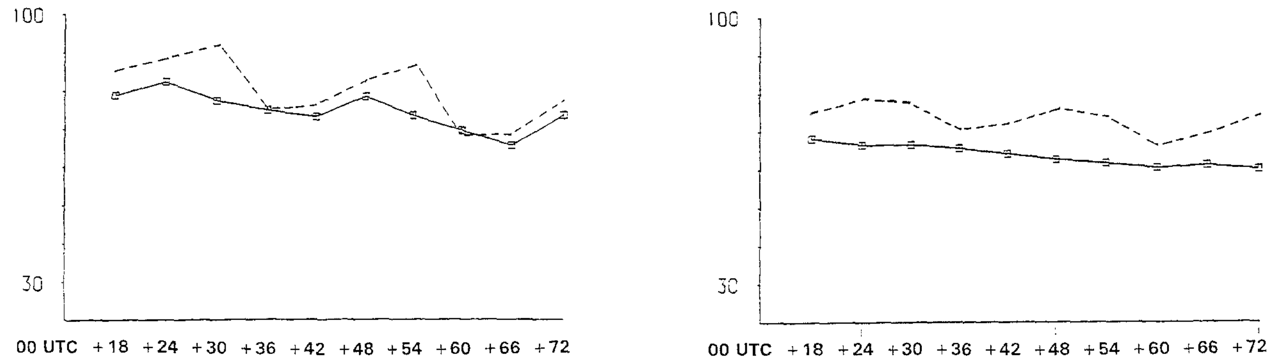


c) Cloudiness (25%)

d) Wind direction (30°)

Fig. 13a. Verification of EM 00 UTC forecasts at 55 stations in Germany. Percentage of correct forecasts, i.e. with absolute error less than the number indicated in brackets. Solid: Direct model output (DMO), dashed: Kalman filtered DMO. December 1994, January and February 1995

a) Temperature (2K) b) Wind speed (1m/s)



c) Cloudiness (25%) d) Wind direction (30°)

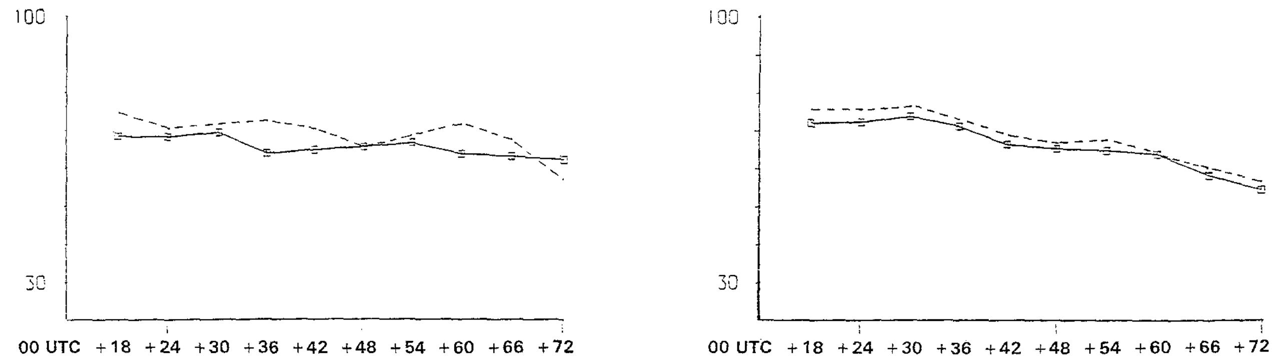


Fig. 13b. Same as Fig. 13a, but for June, July and August 1995

than 2 K for temperature, 25% for cloudiness, 1 m/s for wind speed and 30° for wind direction. The last parameter was only verified for wind speeds above 3 m/s. In winter, Fig. 13a, a marked increase in the number of correct temperature forecasts is possible because the KF removes a persistent negative bias of about 1 K which cannot be corrected by the EM analysis. For the wind speed, the KF yields better forecasts probably because of the local adaptation of the filter coefficients. In summer, Fig. 13b, the KF corrects a positive bias of more than 1 K at 06 UTC and is responsible for a 15% gain of correct temperature forecasts. On the other hand, for the cloud cover and wind direction, only small improvements are realised by the application of the filter probably because the stochastic component of the forecast error prevails for those elements.

The last point to be addressed in this section is the role of the meteorologists in the production of local weather forecasts. To state the problem more precise, is a well-trained meteorologist able to improve the model forecast of near surface weather, corrected by KF to remove systematic errors, on average at least for her/his duty station? To answer this question, the meteorologists at 17 regional centres in Germany are asked to supply a forecast of the following parameters each day in the afternoon (until 16 UTC) to a central verification office

- Maximum temperature for the next day,
- Minimum temperature for the following night,
- Temperature, wind speed/direction and cloudiness for 06, 12, 18 UTC of the next day,
- Precipitation (Yes/No) and precipitation of more than 0.5 mm/12h for the next day. Of course, the DMO of the EM and KF-DMO based on the 00 UTC run, available at about 06 UTC, are presented to the meteorologists. Since the subjective forecasts are prepared in the afternoon, the 12 UTC EM forecast is included in the comparison, too, but not available to the forecasters. As a measure of the ability of the meteorologists to improve the

Table 4. *RMSE of near Surface Weather Forecasts for 17 Regional Meteorological Centres in Germany and the Period January until June 1995.* Parameters: dd-wind direction, ff-wind speed, B-total cloud cover, T-temperature at 2 m, Min-minimum, Max-maximum temperature, TSS-threat score for precipitation

Type of forecast	Following day			Following day		
	06	12	18 UTC	06	12	18 UTC
	dd (°)			ff (m/s)		
Subj. forecast	37.7	41.3	46.3	1.89	2.06	1.97
EM/KF, 00 UTC	30.1	33.5	38.4	1.73	1.91	1.80
EM/KF, 12 UTC	25.7	30.1	36.1	1.58	1.71	1.70
	B (%)			T (K)		
Subj. forecast	29.8	25.3	29.5	1.88	2.16	2.30
EM/KF, 00 UTC	29.7	25.4	29.7	1.69	2.17	2.29
EM/KF, 12 UTC	28.1	24.2	28.3	1.56	1.92	2.12
				TSS (%)		
	Min (K)	Max (K)		N > 0	N > 0.5 mm/12h	
Subj. forecast	1.76	2.18		59.8	52.0	
EM/KF, 00 UTC	1.74	2.31		51.2	53.5	
EM/KF, 12 UTC	1.74	2.08		58.8	57.0	

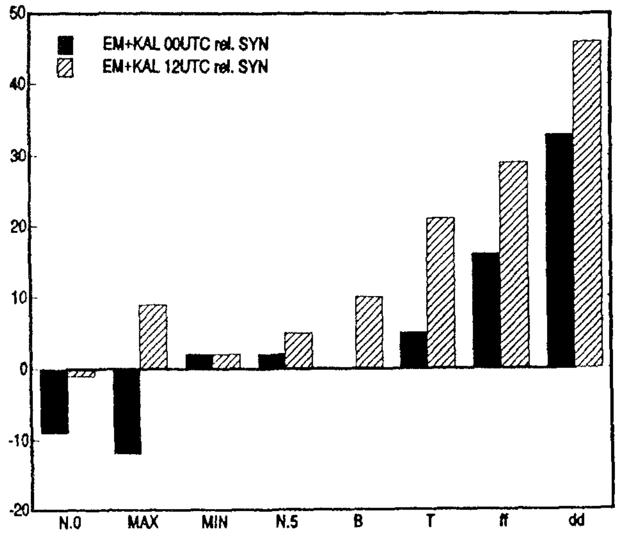


Fig. 14. Comparison of Kalman filtered EM forecasts of weather elements with subjective forecasts issued by 17 regional forecast centres in Germany. The quality is measured by the reduction of variance RV; if RV > 0, the model is better than the subjective forecasts. The following elements are verified: N.0: precipitation > 0.0 mm/12h; N.5: precipitation > 0.5 mm/12h; B: total cloud cover; MAX: maximum temperature of the following day; MIN: minimum temperature of the following night; T: temperature; ff: wind speed at 06, 12, 18 UTC of the next day; dd: direction. EM forecasts are initialized at 00 and 12 UTC each day, the subjective forecasts are based on the 00 UTC forecasts only. Period: January until June 1995

objective products on average, the reduction of variance (RV), defined as RV= 1− RMSE^2(MOD)/RMSE^2(MET) is used. If RV<0, the meteorologists perform better than the KF forecast and vice versa. Table 4 and Fig. 14 taken from Balzer (1995) summerize the results for the period January until June 1995. The meteorologists improved the objective products for the categories "precipitation yes/no" and maximum temperature, at least the ones based on the 00 UTC EM forecasts. On the other hand, the model was clearly superior in predicting the temperature, significant precipitation, and especially wind speed/direction at 06, 12 and 18 UTC. Thus for those parameters, the subjective forecasts deteriorated the quality of the objective ones at least on average.

7. Summary and Outlook

High-resolution meteorological forecasts are needed not only for the purpose of weather prediction but also form the basis of many application models especially in the environmental sector. Operational regional prediction systems are flexible tools for meeting this demand. The quality of regional forecasts depends not only on the numerical model itself, but to a large extent on the other components of the regional prediction system like data assimilation driving larger scale model, postprocessing, diagnostics and verification. The "secret" of successful operational regional prediction is in maintaining a proper balance between those various components. To improve the quality of current operational systems the efforts should be concentrated on the determination of a suitable soil water content and the detailed modelling of the hydrological cycle.

Increasing computer power will, in the near future, allow a significant reduction of the meshsizes of operational regional models. The use of nonhydrostatic models with meshsizes in the order of 1–2 km permitting the explicit numerical simulation of the life cycle of deep convection will be the next quantum leap in regional operational prediction. First steps in developing and implementing those models are taken at several NMS, e.g. Canada (Côté et al., 1994), France (Bubnova et al., 1995), Germany, UK, Australia, Japan (Ikawa and Saito, 1991), and USA (Dudhia, 1993). But to take full advantage of such models, considerable research activities have to be devoted to the derivation of a proper high-resolution initial state for nonhydrostatic models making use of all available observations in space and time by sophisticated assimilation methods.

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