On the operational use of a numerical model for prediction of road temperature and ice

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ABSTRACT

A numerical road conditions model is described. The model is supplied with input from an atmospheric forecast model. In addition, cloud cover data and local data from the road station sites are applied. An important feature of the model system is the careful treatment of the initial conditions, including an energy flux correction for each road station site. Verification results from an operational test are presented. The road conditions are forecasted up to 5 hours ahead for 200 road station sites in Denmark. The mean absolute error of the forecasted road surface temperature, and the temperature and dew point at a height of 2 meters is below 1 °C. The forecast accuracy of the road conditions model appears to be limited mainly by the quality of the analysed and forecasted cloud cover.

1. Introduction

A manual now-casting system for the prediction of slippery roads has been operational in Denmark for several years. This forecasting system is based on the monitoring of data from more than 200 road-weather stations throughout the country. New data, e.g. measurements of road surface temperature, air temperature and humidity are submitted approximately every 10 minutes from the road-weather stations to the road masters, and to the weather forecasters at the Danish Meteorological Institute (DMI). A weather forecaster issues every second hour short-range forecasts up to 3 hours ahead. The forecasts are worked out on the basis of road weather data from all stations, together with the latest meteorological information available, e.g. weather maps and satellite images. A number of parameters are forecasted, i.e. road surface temperature, dew point and air temperature (in 2 meters height), cloudiness, precipitation and wind velocity. The manual forecasts have to cover 13 regions of the country. In some weather situation this implies the production of individual forecasts for every region, which is quite a job for the weather forecaster.

Therefore DMI has decided to develop an automatic system for prediction of slippery roads, with financial support from the Danish Road Authorities. A numerical road conditions model (RCM) has been developed and tested since 1992. It is based on the solution of the heat budget equation at the interface between the atmosphere and the road. The equation of heat conduction is solved in the road, and the atmospheric fluxes of radiation, sensible heat, latent heat and precipitation are computed from operational atmospheric forecasts of temperature, humidity, cloud cover, wind and precipitation for the geographical locations of the road stations. The atmospheric model supplying input to the RCM is the High Resolution Limited Area Model (HIRLAM) at DMI (Kållberg 1990). An important feature of the automatic forecasting system is the sophisticated treatment of initial conditions. The involved data-assimilation procedure is described in section 2. The RCM is briefly described in section 3. A first version of the RCM has been described in Sass 1992.

The automatic forecasting system was tested during the winter 1992-93 for 27 road station sites. The results turned out to be rather promising, e.g. the mean absolute error of the surface temperature forecasts was clearly lower than obtained by a corresponding persistency forecast. (Sass 1993). Hence the system has been developed further. During this winter (1993-94) the automatic system has been extended to include almost all (200) road stations throughout the country. In addition an upgraded set-up has been implemented, e.g. forecasts are produced every hour instead of every third hour. Also, the HIRLAM model is run with increased grid point density. The most recent results from the automatic system are presented and evaluated in section 4. Finally, Some concluding remarks are given in section 5.

2. Data-assimilation

The prediction of local road conditions such as road surface temperature and ice requires a careful treatment of initial conditions for the model computations and a realistic forcing from the atmospheric model providing input to the RCM. It appears to be a major problem that the atmospheric models in operational use do not analyse enough local features necessary for precise local predictions. In addition, the models are not run with sufficient horizontal resolution (grid point density) to describe adequately the advection of temperature and humidity. It is well established from observational studies (e.g. Bogren and Gustafsson 1991 among others) that local topography such as terrain and vegetation is responsible for local variations in atmospheric variables affecting the road conditions.

In order to obtain sufficiently accurate local predictions it is thus relevant to include various observational data in a data-assimilation. The data should be used to determine realistic initial conditions for the RCM forecasts. Also the input from the atmospheric model should be corrected if it is inconsistent with observations of important parameters such as cloud cover. The data-assimilation used in the present forecasting system is illustrated in Fig.1 showing that various observational data influence the initial values of the model variables, first computed on the basis of HIRLAM data (see figure text). These data are interpolated horizontally to the positions of the road station sites using simple linear interpolation. It is noted that the fractional cloud cover C(k) is determined from T(k) and q(k) and is therefore not independent from the other variables (see below) The model initial value of road water W_s or ice I_s is computed as a linearly varying function of the precipitation intensity Q. reaching a constant maximum value at Q =0.5 kg/(m2 hour). In case that the road water exceeds 0.5 kg/(m2) during the forecast, runoff is assumed to take place. Road ice, however is allowed to increase above this value. The road temperature profile cannot be initialized properly from the HIRLAM data, and the model system will issue a warning if no road temperature observations are available within a period of 3 hours prior to the forecast initial time.

The first estimate of model variables can be corrected by several observed variables from synoptic stations. However, experience with the model indicates that, apart from the temperature and dew point at 2 meters height, only the observed cloud cover may be easily used with a positive impact in the model. It is important to modify the cloud cover input data from HIRLAM not only at the initial time but also during the forecast. Otherwise the impact of the observed cloud cover will often decrease quickly. The following procedure for correcting the HIRLAM data has been found to work successfully: At initial times no more than 1 hour from observation time, a total cloud cover is estimated for each road station site from an interpolation using all available Danish synoptic observations. The cloud cover obtained in this way may be compared with the total cloud cover from the atmospheric model. The relative humidity correction $(\Delta q)/q$ necessary to change model cloud cover to the observed cloud cover is then applied at the vertical level K where the maximum cloud cover occurs. The cloud cover formula is parabolic shaped in relative humidity. If necessary, humidity and cloud cover at other levels than K are corrected in order not to produce cloud cover in excess of the observed cloud cover. The relative humidity corrections determined in this way are applied at all time levels during the forecast. Finally, the imposed corrections of the atmospheric humidity profile during the forecast corresponds to changes in cloud cover, which is then recomputed.

The initialization of the vertical temperature profile in the road is done by solving the equation of heat conduction during a 3 hour period prior to the forecast initial time. Observed road surface temperatures during this period are imposed as an upper boundary condition at the surface. No input from the atmosphere is used during this phase. The idea is to produce a realistic road temperature profile from observed surface temperatures and a previous temperature profile. Details about the numerical procedure may be found in Sass 1992.

HIRLAM data

↓↓↓↓↓↓↓↓↓↓↓↓

RCM -variables: $T(k), T_{10m}, q(k), q_{10m}, C(k), V_{10m}, Q, p_s, T_s(l), W_s, I_s$

Synoptic data

↓↓↓↓↓↓↓↓↓↓↓↓

RCM -variables: $T(k), T_{10m}, \hat{q}(k), q_{10m}, \hat{C}(k), V_{10m}, Q, p_s, T_s(l), W_s, I_s$

Road station data

↓↓↓↓↓↓↓↓↓↓↓↓

RCM -variables: $T(k), \hat{T}_{10m}, \hat{q}(k), \hat{q}_{10m}, \hat{C}(k), V_{10m}, Q, p_s, \hat{T}_s(l), W_s, I_s$

RCM Forecast

↓↓↓↓↓↓↓↓↓↓↓↓

RCM output: $T_{sF}(j), T_{2mF}(j), T_{d2mF}(j), W_{sF}(j), I_{sF}(j), V_{10mF}(j), C_{totF}(j)$

FIG.1

Modification of model parameters used in the RCM during the data-assimilation and forecast. A symbol (^) indicates that an original model parameter determined from HIRLAM data has been modified from data in the assimilation procedure. Index *F* signifies a forecasted parameter.

HIRLAM data :	$T(k)$ $(k \leq N)$	Temperature at the atmospheric model levels. (°C)
	q(k), $k \leq N$)	Specific humidity at the atmospheric model levels (kg/kg)
	T_{2m}	Temperature at 2 meters height (°C)
	q_{2m}	Specific humidity at 2 meters height (kg/kg)
	V_{10m}	Wind speed (m/s) at 10 meters height.
	Q	Precipitation intensity (kg water/m2)
	p_s	Surface pressure (Pa)
	N	Number of atmospheric model levels.

Synoptic data :	C_{tot}	Observed total fractional cloud cover.
Road station data :	$T_{2m}(j)$	Temperature at 2 meters height valid for time level j
	$T_{d2m}(j)$	Dew point temperature at 2 meters height for time level j.
	$T_s(j)$	Road surface temperature at time level j
Additional variables	T_{10m}	Temperature at 10 meters height from T_{2m} and $T(N)$
	q_{10m}	Specific humidity at 10 meters height from q_{2m} and $q(N)$
	$C(k)$	Fractional cloud cover at atmospheric model levels.
	$T_s(l)\ \ l \leq M,$	Road vertical temperature profile.
	W_s	Road surface water (kg/ m2)
	I_s	Road surface ice.(kg/ m2)
	M	Number of model levels of the RCM.

In order to reduce a possible drift of predicted road surface temperature away from observed values in the early phase of a forecast the following procedure is applied: Prior to the real forecast, a number of short simulations are done for the last 20 minutes of the 3 hour data assimilation, in order to reproduce the observed change of road surface temperature. Constant atmospheric forcing valid at the initial time plus a station dependent atmospheric flux correction is applied. The flux correction necessary to produce the observed surface temperature change during this short period is then applied unchanged during the forecast phase.

Also the observed temperature and dew point in 2 meters height at the road station sites are used to correct the similar data from the HIRLAM model. The correction equals the deviation between observed and model generated temperatures at the initial time. This correction is applied without modification during the forecast period. A necessary security check is made, i.e. the relative humidity at 2 meters height is constrained not to exceed saturation.

3. Forecast

The RCM will be only briefly described. Further details are given in Sass 1992. The basic problem is to carry out an accurate solution of the local energy budget at the road surface, in order to predict the correct road conditions. The included processes contributing to the energetics at the road surface are

i) Solar and longwave radiative heat flux (net radiation)
ii) Sensible heat flux
iii) Latent heat flux from evaporation or sublimation
iv) Energy supply during possible freezing or melting of precipitation.
v) Energy supply during freezing of road surface water, or melting of road surface ice.
vi) Ground heat flux.

The solar and longwave radiation are computed from the radiation scheme used in the HIR-LAM model (Kållberg 1990). This computation requires temperatures T(k) and humidity q(k) of all the vertical atmospheric levels of the HIRLAM model. The shading effects from local topography is taken into account in the following way: The shading angles from the road surface to the top of the shading objects have been estimated through measurements, for 8 equally sized parts of the southern half plane. This information is stored in a physiographic data base. The direct solar radiation is set to zero if the shading condition prevents a direct solar beam from reaching the road surface. The diffuse solar radiation, and also the net long-wave radiation is reduced in proportion to the solid angle covered by the shading objects. Apart from the shading conditions described individually for all station sites, there is at present no site dependent specification of the road physical properties such as for example albedo to solar radiation, longwave emissivity and road heat conductivity.

A few details about the computation of the sensible and latent heat transfer are important: The sensible heat flux (ϕ_s) is computed according to (1) and (2) following Louis (1979) :

$$\phi_s = C_p \times \rho_1 \times C_s \times V_1 \times (\theta_1 - \theta_s) \quad (1)$$

$$C_s = \left(\frac{k}{ln(Z_1/z_0)}\right)^2 \times f(Ri, Z_1/z_0) \quad (2)$$

A similar formula applies to the latent heat flux. - C_p is the specific heat of moist air at constant pressure, ρ_1 is air density at the atmospheric level Z_1 =10 m, and V_1 is the corresponding wind speed. Similarly, θ_1 and θ_s are potential temperatures at the atmospheric level and at the surface, respectively. C_s is a drag coefficient, z_0 is the roughness length for heat and moisture. A small roughness length is needed to describe the road conditions in a realistic way. At present, z_0=2×10^{-5} m. The Richardson number - computed from the variables of temperature, specific humidity and wind speed at Z_1 and at the surface - is denoted by Ri , and $f(Ri, Z_1/z_0)$ is a dimensionless function of the Richardson number and Z_1/z_0 (Louis 1979) . The roughness length to be applied for other types of surfaces is typically much larger (up to several orders of magnitude) than the value applied for the road surface. For this and other reasons, e.g. the increased turbulence caused by traffic, the Richardson number dependence is neglected during stable atmospheric conditions. ($\theta_1 > \theta_s$) - In these situations the wind speed in (1) is constrained to be no less than 3 m/s.

The RCM is run with a rather short time step of 5 min. to assure sufficient accuracy. The HIR-LAM parameters (see section 2) are supplied with a 1 hour frequency. At intermediate time steps a linear time interpolation of the HIRLAM data is applied. The primary output from the RCM is the predicted road surface temperature (T_{sF}) , the road surface water (W_{sF}) and the road surface ice (I_{sF}) . The additional output parameters, i.e. temperature and dew point temperature at a height of 2 meters, the wind speed and the total cloud cover, are determined from the forecasted HIRLAM data corrected by the various observations, as explained in section 2.

4. Operational test

The RCM has been run operationally since late autumn 1993 using the various input data as explained in section2 , i.e. road station data, cloud cover data and HIRLAM data . New forecasts up to 5 hours ahead are produced every hour for 200 road station sites in Denmark. The forecasts are disseminated to the road masters around the country, with a delay of approximately 45 minutes due to the inclusion of observational data and the subsequent dataprocessing at DMI. The computations by the RCM are still considered to be an experimental product. As a consequence the road masters do not formally make decisions based on the RCM output. Also, two of the forecast parameters mentioned in section 2 , i.e. road surface water and ice, have not yet been disseminated. The observations of road surface temperature, 2 meter temperature and dew point temperature up to 3 hours prior to the forecast, and the associated forcasts can be displayed for any road station site by clicking with a 'mouse' on a computer screen at the geographical position of the road station. The output looks similar to Fig.2 showing an example of observations and forecast. (See figure text)

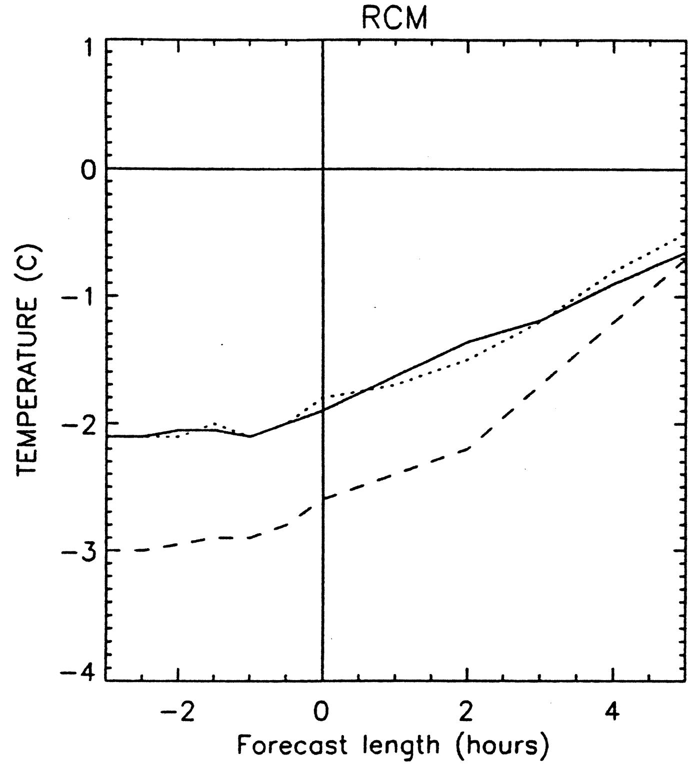

Fig.2 Example of measured and forecasted road weather parameters valid at station 32 (forecast initial time equals 09 UTC, 28 December 1993). This output is displayed to the forecasters and road masters in colours for individual stations. The solid line applies to road surface temperature, the dotted line to 2meter temperature, and the dashed line to dew point temperature.

Only every third forecast has been stored for verification purposes. Synoptic cloud cover data, although not complete, have been available for a set of almost 50 meteorological observing sites. Data were missing for 3 percent of the observation times. Also the supply of HIRLAM data and road station data has been stable. However, data from 37 stations were not fully available to the RCM in the first part of December due to a sorftware problem. Therefore, only data from 163 of the road stations were included in the verifications shown in Fig.3 a-c showing mean error (bias) and mean absolute error (mae) for road surface temperature predictions (Fig.3 a) , 2 meter temperature (Fig.3 b) and dew point temperature (Fig.3 c). the road station data were often available with a high frequency (every 10 minutes), but an interpolation of the data in time has been applied in order to obtain hourly data for the verification.

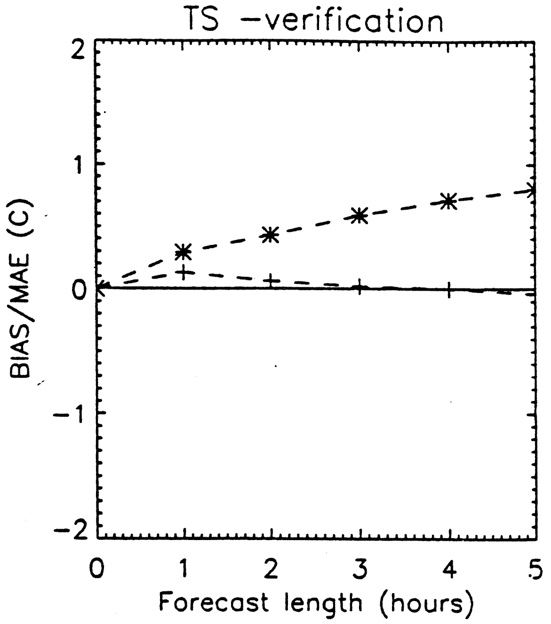

Fig.3a Bias (shown by crosses) and mean absolute error shown by stars for road surface temperature forecasts in December 1993 as an average over 163 road station sites (see text).

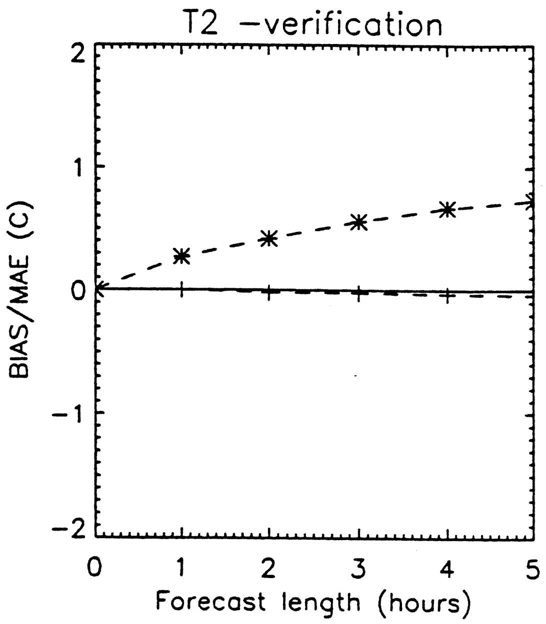

Fig.3b As Fig.3a, but for temperature at 2 meters height.

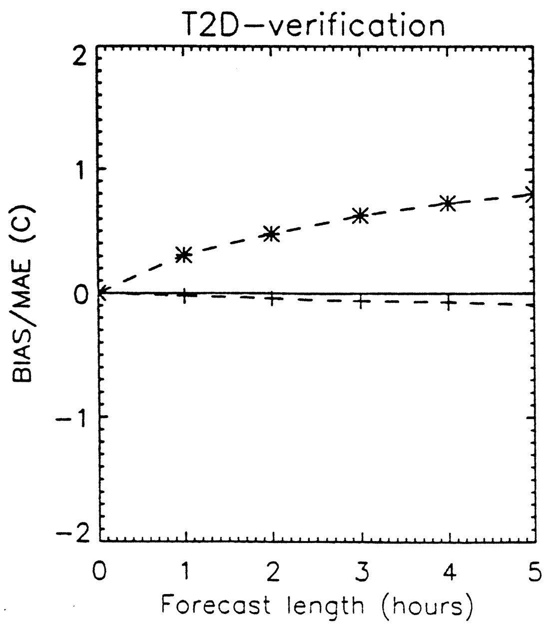

Fig.3c As Fig.3a, but for dew point temperature at 2 meters height.

The weather conditions in December 1993 were quite variable and dominated by several fronts and low pressure systems of a rather small scale crossing Denmark. The precipitation was partly in the form of rain, and partly sleet and snow. The windy conditions offered rather easy conditions for the RCM forecasts, but the passage of small scale lows with rapidly varying cloud cover imposed difficult conditions. The quality of individual 3 hour road surface temperature forecasts (229) for 4 road station sites are illustrated in the scatter diagrams of Fig.4 a-d. Fig.4a applies to a sun-exposed bridge north of Copenhagen, and Fig.4b to a road station site in a wooden area (shaded) in the same part of the country. Fig.4 c-d applies to road station sites (shaded) in the northern, and in the southern part of Jutland, respectively. It is seen that the level of absolute error is quite similar for the different station sites. Mean absolute errors exceeding 2°C occur only in approximately 2 percent of the forecasts. Also the systematic bias is small. Forecast results in the second and in the fourth quadrant of the diagram, representing critical forecasts, cannot be avoided completely. This is partly because the verification is done at precise times. (mentioned further in the last section). Scatter diagrams for other stations (not shown) are rather similar. This may, at least to some extent, be explained by the individual adaptation for the different road station sites.

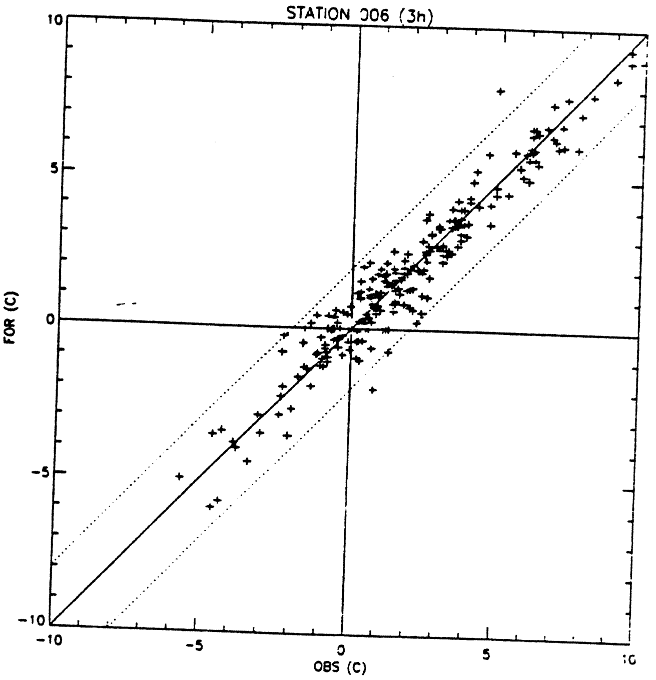

Fig.4a Scatter diagram of forecasted versus observed road surface temperature (°C) for station 006 in December 1993 at a forecast length of 3 hours.

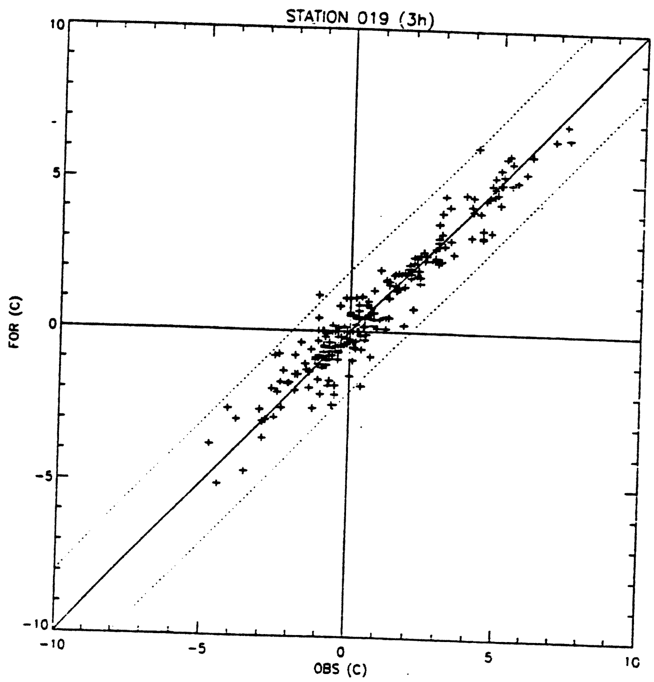

Fig.4b Same as Fig. 4a , but for station 19

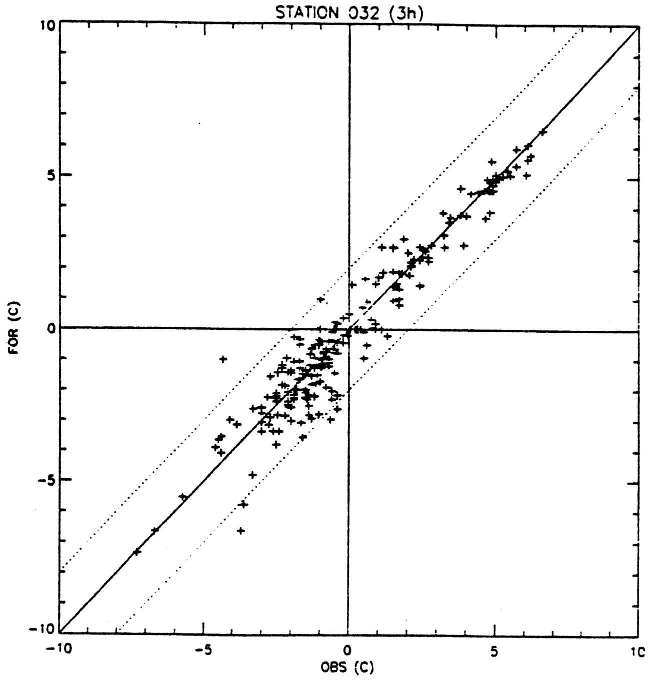

Fig.4c Same as Fig.4a, but for station 32.

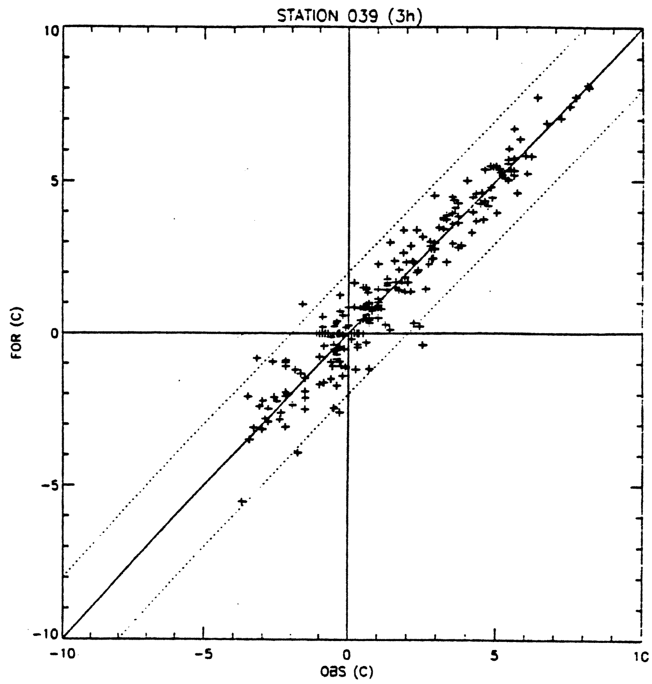

Fig.4d Same as Fig.4a, but for station 39

In addition to the objective verification of the model a more subjective test is carried out during the winter 1993-94, in order to find out whether the model forecasts are sufficiently useful to the road masters. A questionnaire about this has to be fulfilled every time slippery roads are likely to occur due to ice and/or snow. The road masters have to report whether the forecasts in each case have been good or bad guidance for the decisions, if they are available in due time, and so on.

5. Concluding remarks.

The objective verification results of the operational tests of the RCM system during December 1993 are encouraging. The mean absolute error as an average for all stations is below 1℃ for predictions of road surface temperature, 2 meter temperature and dew point temperature up to 5 hours ahead. Also the temperature bias is low, of order 0.1℃ for these parameters.

Both theoretical considerations and practical experimentation with the model indicate that the forecast accuracy is limited mainly by the cloud specification. In order to approach 'exact' predictions of local road conditions including the effect of precipitation, it is necessary to analyse cloud cover properly. This includes a knowledge of the cloud base height. It is also necessary to forecast accurately the cloud cover changes on small time scales. A first step in this direction could possibly be to develop a graphical manual correction procedure for the automatic cloud cover predictions. However, the effect of such a procedure needs to be assessed carefully. A detailed cloud prediction on short time scales is indeed a difficult problem, and the atmospheric models presently available do not fully meet the requirements for high quality cloud cover analyses and forecasts. However, development work in this area is in progress, e.g. fine scale atmospheric models are expected to become operational in the future. The cloud prediction problem is also becoming clear when considering the solar energy input to the road surface. Experience indicates that the mean absolute errors of the surface temperature forecast increase in the late part of the winter season during daytime. This is mainly a result of an insufficient knowledge about cloud distribution (geometry) in the sky, since the main solar energy input to the road surface in these conditions comes from the direct solar beams originating from a narrow solid angle in the sky. Ideally, the radiation scheme of the RCM should include cloud geometry effects in order to describe properly the energy input to the road surface.

Hence, it appears that the further development of high resolution atmospheric models providing the input to the RCM, and refinements of the radiation scheme used in the RCM will lead to further improved forecasts of the local road conditions.

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