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Spatial distribution of winter temperatures in Norway related to topography and large-scale atmospheric circulation

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Abstract Reliable estimates of meteorological elements such as temperature and precipitation are key inputs to hydrological models. As hydrological models are improving, moving towards distributed models, the traditional approach in hydrological modelling, i.e. to use observed values from nearby stations, also needs to be improved. An approach using information about large-scale atmospheric circulation and local terrain patterns for describing spatial temperature distribution has been evaluated. Lamb weather types have been used to describe the large-scale atmospheric circulation. These are calculated according to the objective Jenkinson-Collison scheme, which for this purpose was adapted for southern Norway. Local terrain patterns are described by empirical orthogonal functions of the terrain. For each weather type, an analysis is carried out to describe mean temperatures by terrain EOFs and other predictands such as altitude, longitude, latitude, distance to sea, etc. The terrain parameters make a significant contribution to the description of the spatial distribution of winter temperature. The relations between temperature and the set of predictands are different between different weather types, reflecting the differences in the temperature distribution under different circulation conditions.

Key words atmospheric circulation; distributed models; spatial interpolation; temperature

INTRODUCTION

Reliable estimates of meteorological elements like temperature and precipitation are key inputs to hydrological models. The traditional approach in hydrological modelling is to use observed values from nearby stations. Usually they are adjusted by model parameters to make them more representative of the catchment to be modelled. The development of distributed hydrological models also demands a distributed climatology as input. In cold, mountainous regions, like Norway, reliable estimates of temperature are of major importance for modelling of, for example, the snow reservoir. Correct temperature estimates are necessary for both snow accumulation and snowmelt calculations.

Air temperature is strongly related to altitude. On average the temperature decreases by about 0.65–1.0°C per 100 m in the free atmosphere. Close to the surface, this vertical temperature gradient is different due to local and regional characteristics, influenced by the local terrain, distance from the sea, etc. Earlier studies of mean monthly temperatures in the Nordic countries (Tveito *et al.*, 2000) for the normal period, 1961–1990, have shown that that the vertical temperature gradient at the surface varies throughout the year, with the lowest gradient in winter and the highest in spring and autumn. These gradients have been used in a residual kriging approach to establish climatological maps for air temperature for the Nordic countries.

Using models for mean monthly temperature to describe the spatial distribution of mean daily temperatures is, however, not sufficient for describing conditions strongly controlled by local terrain features. In Norway, winter temperatures especially are poorly described by simply using altitude as a predictor since such an approach has difficulties in describing inversions properly. Therefore, an approach using information about large-scale atmospheric circulation and local terrain patterns for describing spatial temperature distribution has been evaluated.

SPATIAL INTERPOLATION

Geostatistical approaches for spatial interpolation have long traditions within hydrology. Such approaches have not been used to the same extent within traditional climatology and meteorology. However, they have been taken into use more and more during the recent years, especially in combination with the introduction of geographical information systems (GIS) for climate mapping purposes.

When using kriging the assumptions of stationarity and unbiasedness should be fulfilled. This is hardly the case of observed phenomena in nature. Another problem in dealing with observations of temperature and precipitation is that the station network is biased. In mountain regions the stations usually are biased towards lower altitudes. In Norway about 85% of the climate stations are located at altitudes of lower than 500 m a.s.l., while 50% of the terrain is above this level (Fig. 1).

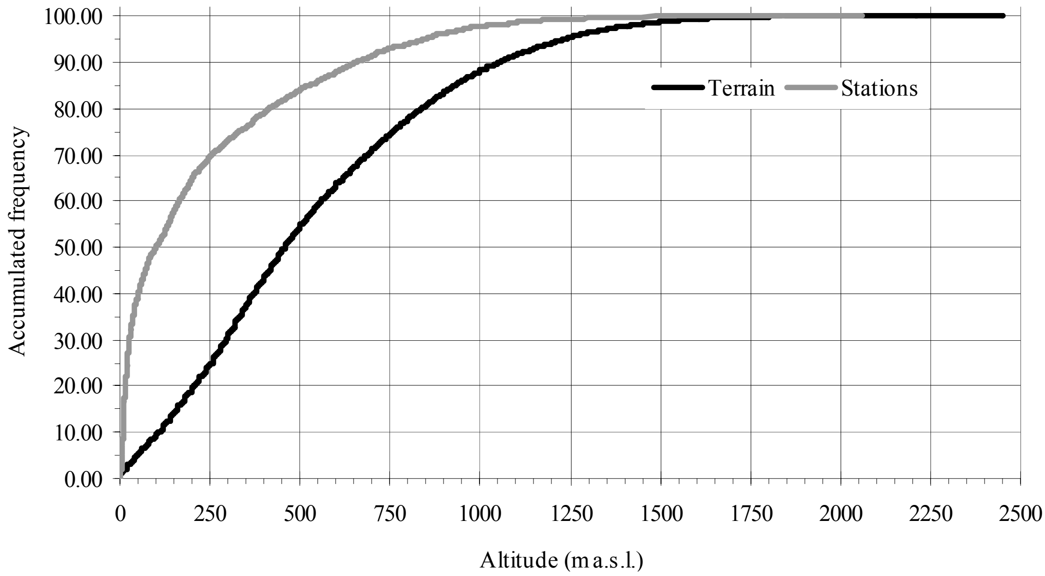

Fig. 1 Cumulative distribution functions of the altitude of the Norwegian meteorological station network and the Norwegian terrain model (100 × 100 m^2).

One way to overcome this problem is to manipulate the data in order to make them stationary and unbiased. A traditional approach in this respect is to reduce the values to a fictitious reference level by deterministic expressions. These expressions relate the climatological variable to physiographical parameters like altitude, distance to sea, etc. This deterministic component describes the large-scale climatological gradients in the area, and is usually established by using linear regression techniques. This large-scale trend is subtracted from the observations, and a spatial interpolation is performed at the "reference level". By adding the trend terms to the estimates, interpolated climatology can be obtained at any point. This method, often called residual kriging, is widely used within climatology, and is found to be one of the preferable methods for establishing climatological maps.

For estimation of mean daily temperatures, which is the most used time resolution in hydrological modelling, expressions for mean monthly temperatures should not be expected to work very well since the conditions controlling the daily temperatures vary considerably from day to day while the deterministic trend component is based on the mean temperatures. Even if the deterministic component varies with the season (Tveito *et al.*, 2000) the error may be considerable. Independent estimation of mean daily temperatures shows, however, that this quite simple approach works remarkably well. However, there are large biases for the colder temperatures (less than –10°C, Fig. 2). During wintertime, the coldest temperatures often are found where inversions are presented. Inversions occur most frequently in sinks in the terrain, since the heavy cold air under stable conditions will flow towards lower levels. A general model cannot describe effects such as the one developed for mean monthly temperatures.

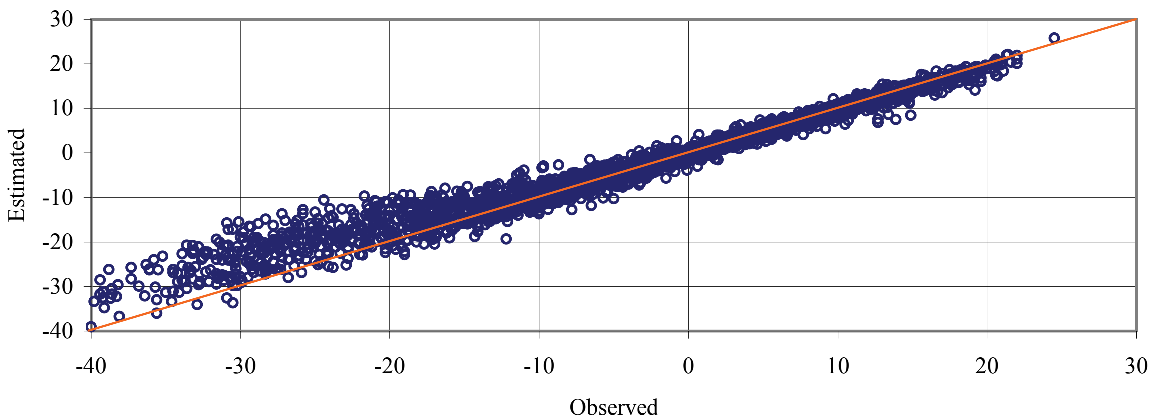

Fig. 2 Observed temperatures *vs* estimates by residual kriging at Karasjok, northern Norway.

WEATHER TYPE CLASSIFICATION

The need for downscaling in climate change studies has given a renewed interest in synoptic climatology, i.e. weather types and circulation indices. Synoptic climatology (Yarnal, 1993) is a description of observed climate related to the large-scale atmospheric circulation. Several studies show that precipitation is especially strongly dependent on the general atmospheric circulation in the area. Temperature variations also show a distinct relationship to the atmospheric circulation. Chen (1999) showed that winter temperature anomalies in southern Sweden vary with different weather types using the Jenkinson-Collison objective classification scheme of the Lamb weather types. Lindersson (2001) has also studied temperature anomalies in southern Sweden using this classification scheme.

Corault & Monestiez (1999) developed a method for interpolation of regional maximum and minimum temperatures utilizing information on large-scale atmospheric circulation, which gave a variation of the vertical temperature gradient of between 0.31 and 0.85°C/100 m. Huth (2001) has shown different variability in temperatures at mountain and lowland stations related to atmospheric circulation.

One method for classification of the atmospheric circulation that can easily be adapted to the Nordic region is the objective scheme of the Lamb weather types by Jenkinson & Collison (1977). The Lamb Catalogue (Lamb, 1972) was developed for the British Isles, and was originally a subjective method. The objective scheme is based on mean sea level pressure at 16 grid nodes that is used to estimate zonal and meridional flow as well as vorticity. It gives 27 weather classes, cyclonic, anticyclonic, 8 direct and 16 hybrid classes, as well as one unclassified. By adjusting the parameters in the flow calculations, this scheme could be adapted to any area. Daily weather types for southern Norway are estimated for the period 1979–1994 using MSLP-values from the NMC gridded data set (NMC, 1996).

Figure 3(a) shows the temperatures at a weather station in the central part of Norway, a valley station where both inversions and föhn situations occur regularly. It can be seen that there are large variations in temperature, and that these seem to be related to the atmospheric circulation pattern. Cyclonic circulation generally gives higher temperatures than anticyclonic circulation. Northerly and easterly winds give lower temperatures than winds from southwest and west. Figure 3(b) show the same information for a station on the western coast. The patterns are generally the same, but the variability is less due to the maritime influence.

The variability within the weather types can be very large. This feature, also addressed by Lindersson (2001), may cause uncertainty for the further analysis. Some weather types are rare, giving very few cases for calculating statistics.

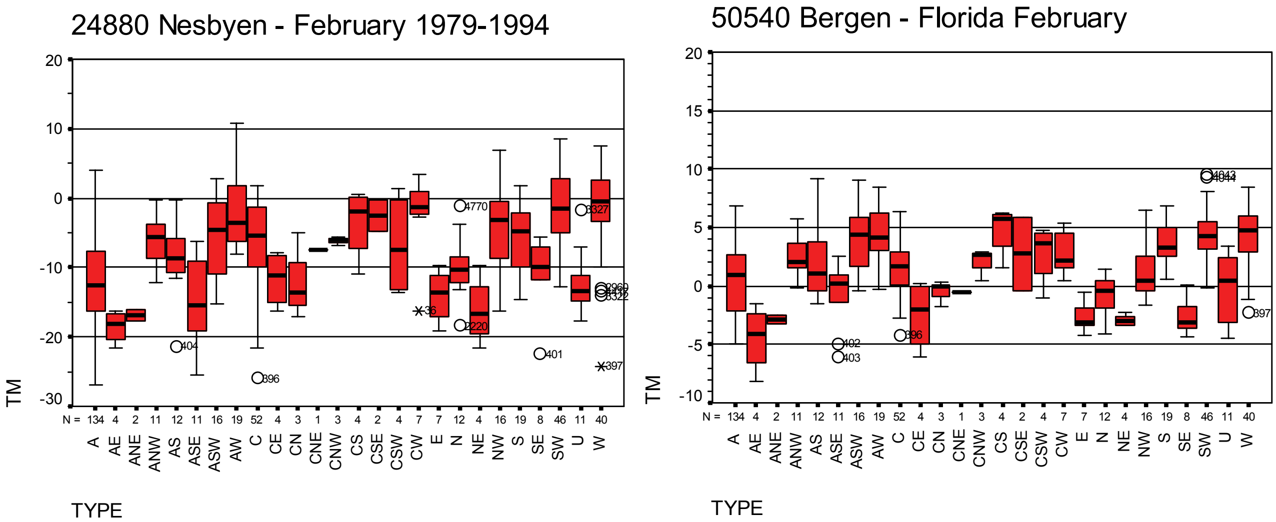

Fig. 3 Box-plots of daily mean temperatures in the winter season grouped in weather types at: (a) Nesbyen, central southern Norway, and (b) Bergen, western Norway.

DETERMINISTIC COMPONENTS

In order to investigate whether information about the atmospheric circulation can be utilized in spatial interpolation of temperatures, and especially in improvement of winter-temperature estimates, deterministic components were derived for each circulation type. These trend expressions are estimated by linear regression. In this study, three different sets of predictors are used in order to find which information is the best.

The model developed by Tveito *et al.* (2000) for deriving mean monthly temperature maps for the Nordic countries is used as a reference method. The variables used as predictors are altitude, mean altitude within a radius of 20 km around the stations, the lowest terrain within the same area, longitude and latitude. In addition to the standard model, the same predictors are used to find deterministic components for each weather type. This model is referred to as model 2.

For this investigation, new information about terrain and terrain characteristics has been calculated. One important feature to consider when modelling temperature is the shape of the terrain. There is a big difference whether the terrain is, for example, concave or convex. One way to derive such information is to use empirical orthogonal functions (EOFs) of the terrain, based on an 11 × 11 node window around each site. This approach is known as the AURELHY method (Benichou, 1985). In this study EOFs from two terrain models are included: one based on a 1 × 1 km^2 terrain model, and one based on a terrain model with 5 × 5 km^2 resolution. The first five EOFs of the 1 × 1 km^2 and the 5 × 5 km^2 model are shown in Fig. 4, showing similar patterns for the two models. The EOFs are based upon the terrain surrounding ~58 000 and ~12 000 locations, respectively. These locations contain both meteorological sites and randomly picked locations across Norway. The first 20 EOFs of each model are included in the regression analysis.

In addition, several other variables are derived, including sea coverage within a 50 km radius around each station, the terrain curvature and slope. The latter two are calculated by the algorithm provided by ArcInfo Geographical Information System. The model including all available variables is called model 1.

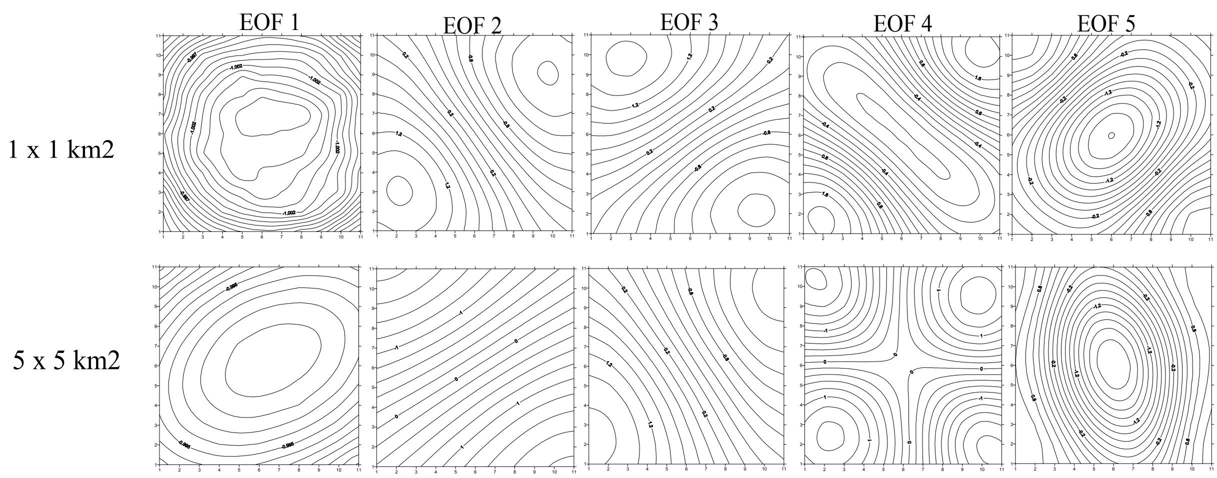

Fig. 4 The first five EOFs for the two terrain models used.

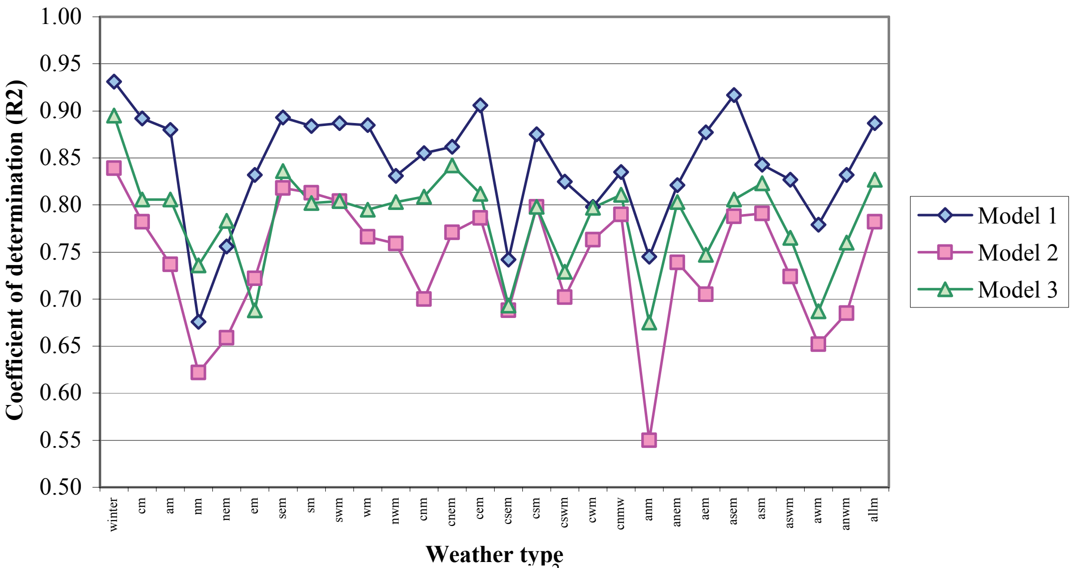

Fig. 5 Coefficient of determination (R^2) for the three models for each weather type.

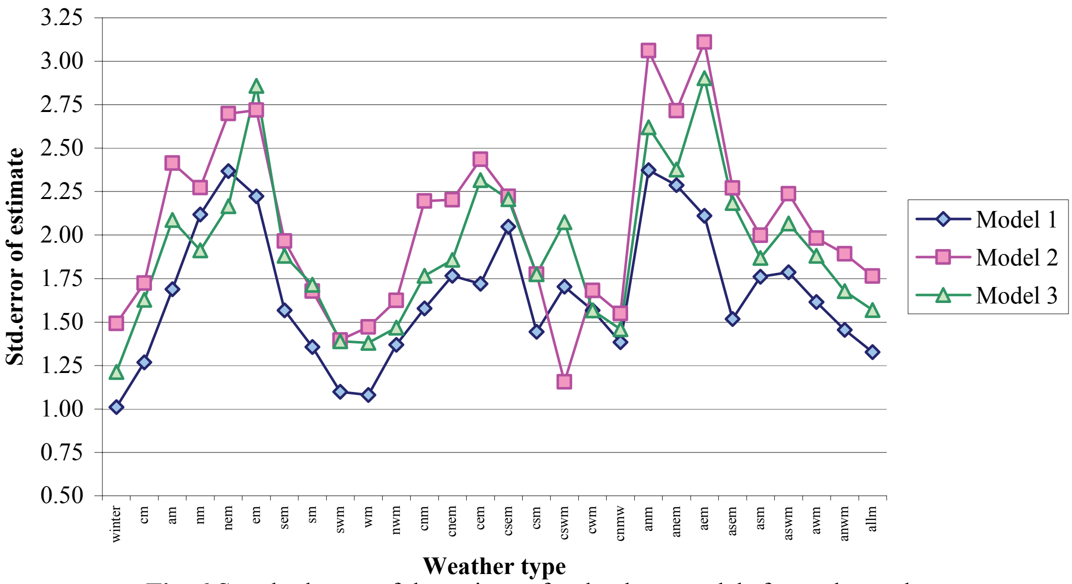

Fig. 6 Standard error of the estimate for the three models for each weather type.

The third model includes the same variables as model 2, and in addition sea coverage, curvature and slope.

Stepwise regression is used to select the best model in each case, which does not necessarily include all variables. The number of selected variables varies from two to eleven. The regression expressions are established for all weather types based on mean daily temperatures 1979–1994, as well as for the mean monthly winter temperature 1961–1990.

Figure 5 shows the performance of the three models with respect to the coefficient of determination (R^2). Figure 6 shows the standard error of the estimate for the models. As seen from the plots the most advanced models (1 and 3) show the best performance, while model 2, including the least parameters, shows the poorest.

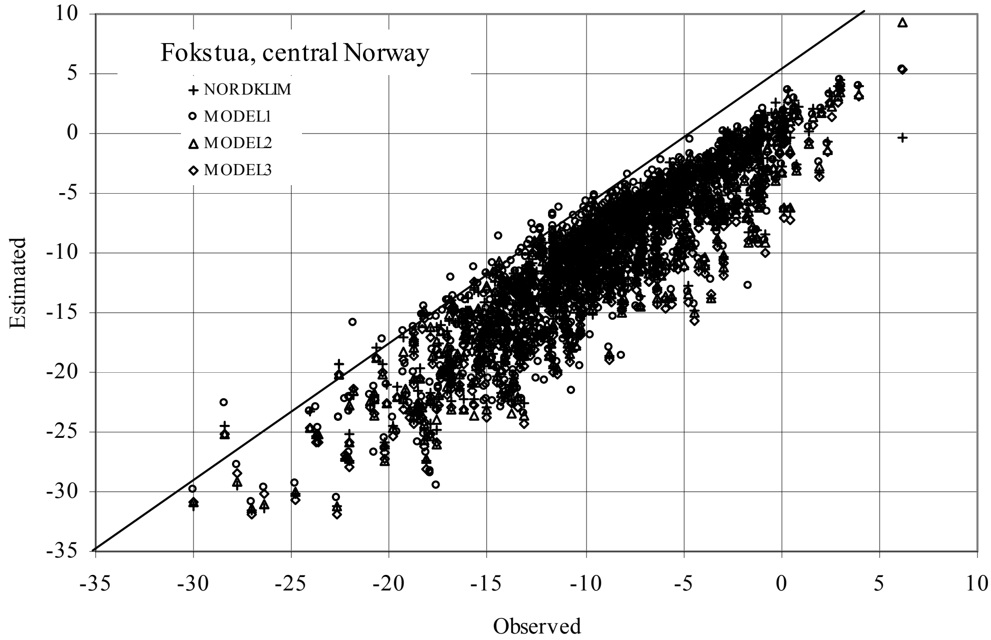

Fig. 7 Observed *vs* estimated temperatures for the three models and reference model at Fokstua, central southern Norway.

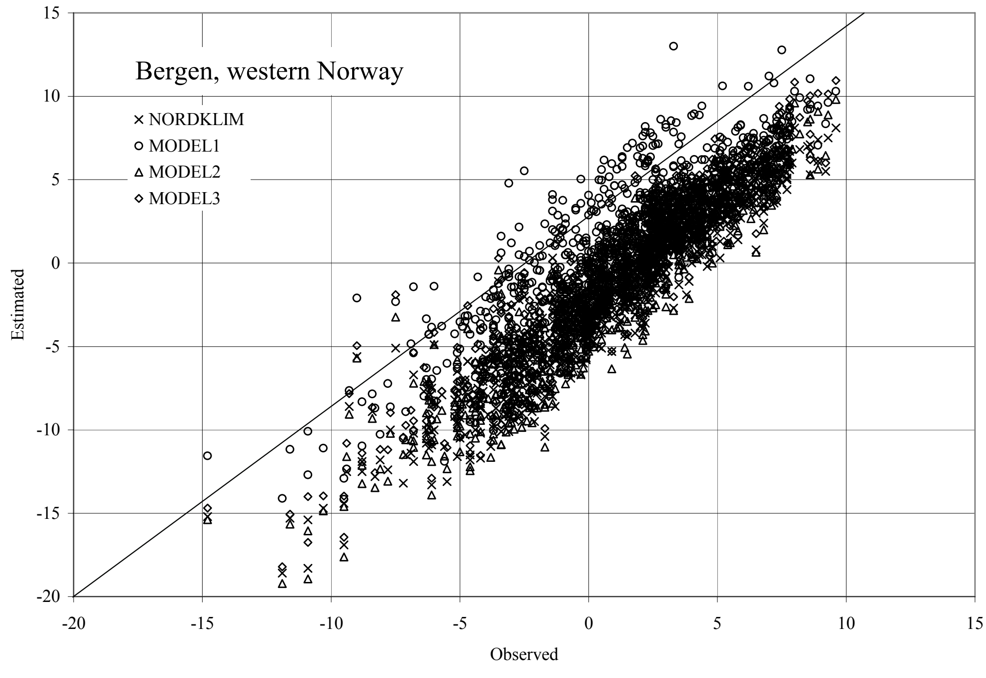

Fig. 8 Observed *vs* estimated temperatures for the three models and reference model at Bergen, western Norway.

SPATIAL INTERPOLATION

Daily mean temperatures are reduced to the reference altitude applying the regression expressions, conditioned according to the weather type. These reduced temperatures are input to the spatial interpolation routine. A few stations are excluded from the input data set, and are instead used as independent verification stations.

Adding the trend expressions to the values in this grid can give estimates at any point. Figure 7 show the performance of the three methods at a mountain station, and Fig. 8 at a station at the western coast. Figures 7 and 8 demonstrate that all three models, as well as the reference method, perform very well at these two locations. The correlation coefficients show values between 0.77 and 0.89 for the coastal station, with the poorest performance for model 1. The reference model performs slightly better than models 2 and 3. For the mountain station, there are small differences between the models and all models have scores above 0.90. Also for this station, model 1 has the lowest score. However, the correlation coefficient is a measure that does not consider the relative differences between two time series. A simple comparison (not shown) of the accumulated error is in favour of model 1. Further verification including more stations is necessary to evaluate which method is the better one overall.

CONCLUSIONS

Weather type classification shows that variations in temperature can be related to the atmospheric circulation. The variability of observed temperatures within each weather type, however, was shown to be large. This may introduce noise into models trying to utilize such information.

Including more terrain characteristics, including terrain shapes in means of EOFs and information about sea coverage has improved the trend expressions used as deterministic components in a residual kriging approach. Three different models utilizing weather type classification have been tested. The terrain parameters give a significant contribution to the description of the spatial distribution of winter temperature. The relations between temperature and the set of predictands are different between different weather types, reflecting the differences in the temperature distribution under different circulation conditions. Even if they are based on different predictor sets, the differences between the estimates at independent verification stations are very small.

All models reproduce the observed mean daily temperatures well, with a correlation coefficient between observed and estimated temperatures greater than 0.8. These preliminary results are based on relatively few years of independent verification at few stations. The models need further verification. Also the spatial interpolation method needs verification; an analysis has yet to be carried out.

However, these results confirm the findings in literature where residual kriging is a robust procedure for climatological mapping. This study shows that the approach also is very useful at timescales applicable for hydrological models. Further studies will be carried out, also including precipitation estimates.

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