Hydrol. Earth Syst. Sci. Discuss., 9, 5931–5953, 2012
www.hydrol-earth-syst-sci-discuss.net/9/5931/2012/
doi:10.5194/hessd-9-5931-2012
© Author(s) 2012. CC Attribution 3.0 License.

Hydrology and Earth System Sciences Discussions

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

Downscaling ERA-Interim temperature data in complex terrain

L. Gao, M. Bernhardt, and K. Schulz

Department of Geography, Ludwig-Maximilians-Universität München, Munich, Germany

Received: 27 March 2012 – Accepted: 6 April 2012 – Published: 9 May 2012

Correspondence to: M. Bernhardt (m.bernhardt@iggf.geo.uni-muenchen.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Air temperature controls a large variety of environmental processes, and is an essential input parameter for land surface models e.g. in hydrology, ecology and climatology. However, meteorological networks, which can provide the necessary information, are commonly sparse in complex terrains, especially in high mountainous regions. In order to provide temperature data in an adequate temporal and spatial resolution for local scale applications, we have developed a new downscaling method able to scale 3-hourly ERA-Interim temperature data. The scheme is based on model internal vertical lapse rates derived from different ERA-Interim pressure levels. The results are validated for three meteorological stations, located within the same ERA-Interim grid element: Zugspitze, Garmisch-Partenkirchen and Zugspitzplatt, in the German Alps; they are also compared with two other statistical, lapse rate based downscaling approaches. The results indicate that the use of model internal ERA-Interim lapse rates can significantly improve the downscaling performance when compared to the standard procedure of using fixed lapse rates.

1 Introduction

The surface air temperature (T_a) is an important control for a large variety of environmental processes and influences the local as well as the global water, energy and matter cycle (Prince et al., 1998; Prihodko and Goward, 1997; Bolstad et al., 1998). Changes in T_a have a distinct influence on biogeochemical processes, the turbulent exchange between surface and atmosphere as well as on plant growth and many other components at the interface between earth surface and atmosphere (Nieto et al., 2011; Regniere, 1996; Bolstad et al., 1998; Stahl et al., 2006). Therefore, historic, current and future temperature time series are needed for analyzing possible changes and impacts on the environment (Barry, 1992; Pepin and Seidel, 2005). They can also provide

HESSD

9, 5931–5953, 2012

reliable data for decision-makers (e.g. tourism planning) and model developers (Dodson and Marks, 1997; Minder et al., 2010; Maurer et al., 2002; Mooney et al., 2011).

The most common sources for T_a time series are meteorological stations. However, meteorological networks are sparse in complex terrains, in particular at high altitudes, such as in mountains. This is mainly due to difficulties with the installation and maintenance of the stations (Kunkel, 1989; Rolland, 2003). Hence, information about T_a has to be calculated on the basis of surrounding stations, which are usually far away from the point of interest. The T_a can also be calculated with the help of climate models, which usually have a limited spatial resolution (Dodson and Marks, 1997; Vicente-Serrano et al., 2003; Ishida and Kawashima, 1993). Both methods tend to work well in homogeneous terrains, but tend to fail in heterogeneous terrains, where changes in the surface temperature can occur over short distances. Reasons for failure are the misrepresentations of key relationships between T_a and elevation (DeGaetano and Belcher, 2007) and the limitations of climate models to consider small-scale variations of the land surface.

Hence, lapse rates (Γ), which display the empirical relationship between T_a and altitude are often used to interpolate measurements or to scale model results of T_a with respect to elevation as well as for generating the required small-scale information of T_a. The most common methods typically assume lapse rates in the range of $-6.0\,^{\circ}\mathrm{C\,km^{-1}}$ (e.g. Dodson and Marks, 1997) to $-6.5\,^{\circ}\mathrm{C\,km^{-1}}$ (e.g. Maurer et al., 2002; Lundquist and Cayan, 2007; Stahl et al., 2006) and assuming some similarity to the theoretical pseudo adiabatic lapse rate (Hamlet and Lettenmaier, 2005) or to the monthly variability of the temperature gradient within the atmosphere (Kunkel, 1989; Liston and Elder, 2006). However, many studies have proven that a fixed lapse rate may be problematic since the values of the lapse rate can vary significantly within short time periods of less than a month (Minder et al., 2010; Lundquist and Cayan, 2007; Rolland, 2003). The reason for these variations can be traced back to topographical characteristics of an area (Mahrt, 2006), the synoptic circulation (Pages and Miro, 2010; Blandford et al., 2008), the activity of the vegetation (Laughlin, 1982), seasonal variations with respect

CC BY

to the incoming radiation (Rolland, 2003; Blandford et al., 2008) and diurnal variations, e.g. due to a changing cloud cover (Minder et al., 2010). This lapse rate variability can only be monitored by dense meteorological station networks or by using alternative strategies that are able to cover the temporal and spatial variability of air temperature.

We here present a newly developed statistical downscaling (SD) approach that is based on the European Centre for Medium Range Weather Forecast (ECMWF) reanalysis product ERA-Interim (Dee et al., 2011; Berrisford et al., 2011). The method accounts for the temporal variability of lapse rates by using model internal temperature profiles and is therefore independent of local station measurements. It allows for a scaling of 0.25° results to the point scale and is tested and validated against two different, standard SD methods (one based on station measurements, and another one that uses fixed data from literature) at three meteorological stations located in a mountainous environment in southern Germany.

2 Data and methods

2.1 ERA-Interim data

We make use of the European Centre for Medium Range Weather Forecast (ECMWF) reanalysis product ERA-Interim, which provides data from 1979 onwards, and continues in real time (Berrisford et al., 2009; Dee et al., 2011). The ERA-Interim project was launched in order to improve key aspects of ERA-40, such as the representation of the hydrological cycle, the quality of the stratospheric circulation, as well as the handling of biases and changes in the observing system (Dee and Uppala, 2009; Simmons et al., 2006; Uppala et al., 2008; Dee et al., 2011). This has been achieved by including many model improvements, as the use of 4-dimensional variation analysis, a revised humidity analysis, the use of variation bias correction for satellite data, and other improvements in data handling (Berrisford et al., 2009; Dee et al., 2011). Cycle 31r2 of ECMWF's Integrated Forecast System (IFS) was used for the ERA-Interim product. The

HESSD
9, 5931–5953, 2012

model in this configuration comprises 60 vertical levels, with the top level at 0.1 hPa; it uses the T255 spectral harmonic representation for the basic dynamical fields and a reduced Gaussian grid (N128) with an approximately uniform spacing of 79 km (Dee et al., 2011; Uppala et al., 2008). The atmospheric component is coupled to an ocean-wave model resolving 30 wave frequencies and 24 wave directions at the nodes of its reduced 1° × 1° latitude/longitude grid. ERA-Interim assimilates four analyses per day at 00:00, 06:00, 12:00 and 18:00 UTC. Furthermore, two 10-day forecasts with a 3-h resolution are initialized on the basis of the 00:00 and 12:00 UTC analyses (Dee et al., 2011; Uppala et al., 2008).

Here, we apply 3-hourly forecast data (03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00 and 24:00 UTC) initialized at 00:00 UTC from 1979–2010 which are projected on a grid of 0.25° × 0.25°. This grid is interpolated from the original reduced Gaussian grid. The used output variables are 2 m temperature, surface pressure, as well as temperature and geopotential height at 925 mb, 850 mb and 700 mb levels. The geopotential height is related to the variation of gravity with latitude and elevation, and is calculated by the normalization of the geopotential over the gravity.

2.2 Test site

The test site is located in the southern part of Germany, at the frontier to Austria. It is centered at about 11.03° E and 47.27° N and stretches from 708 m a.s.l. at Garmisch Partenkirchen to 2962 m a.s.l. at the Zugspitze summit (Fig. 1). The three meteorological stations used in this research are located at the valley bottom (Garmisch-Partenkirchen 719 m a.s.l.), at the crest of the Zugspitze mountain (2964 m a.s.l.) and at the Zugspitzplatt (2250 m a.s.l.). The first two are operated by the German weather service (DWD), the third by the Bavarian Avalanche Warning service (LWD). The DWD provides hourly data, while the LWD is operating at 10-minute resolution (Table 1). The data was aggregated to 3-hourly ($T_{3\,\mathrm{h}}$) and daily (T_{d}) averages for a comparison with the ECMWF model with 0.4 %, 14.9 % and 20 % data gaps for Zugspitze, Garmisch and Zugspitzplatt, respectively. The observed period is 1979–2010 (1999–2010 for

CC BY

Zugspitzplatt). The location of the used ERA-Interim 0.25° grid element is illustrated in Fig. 1.

2.3 Downscaling methods

Lapse rates (Γ) describe the decrease of T_a with elevation. Equation (1) was used for all of the four presented downscaling methods, but the calculation of T_{ref} and Γ varied. T_{ref} was the reference temperature, which was either defined by the ERA-Interim 2 m temperature ($T_{ERA_{2\,m}}$) or the ERA-Interim temperature at the 850 mb pressure level ($T_{ERA_{pl}}$).

$$T_t = T_{ref} + \Gamma \times \Delta h \tag{1}$$

We used three different methods for calculating Γ, Method I specific monthly lapse rates (Γ_S) extracted from literature, Method II measured lapse rates (Γ_M), which were calculated on the basis of the meteorological stations Zugspitze and Garmisch, and Method III ERA-Interim lapse rates (Γ_{E_1} and $\Gamma_{E_{2\,s}}/\Gamma_{E_{2\,fa}}$) which were calculated on the basis of temperatures at different pressure levels. Method I made use of monthly values of Γ_S published by Kunkel (1989) and Liston and Elder (2006) (Table 2). These values are widely applied in earth surface modeling and their temporal resolution of one month can be seen as a standard with respect to generalized lapse rates (Bernhardt and Schulz, 2010; Mernild et al., 2009; Liston et al., 2008).

Method II used measured data from the meteorological stations Zugspitze and Garmisch for calculating 3-hourly lapse rates. Both stations covered a vertical gradient of more than 2000 m and represented an optimal but rather unusual station setup for alpine regions. Therefore, Method II was used as a benchmark to compare the other methods to. Since stations at high elevation that are able to properly represent the meteorology in high mountains are rare, other downscaling methods that are independent of surface measurements have to be developed (Blandford et al., 2008; Pages and Miro, 2010; Rolland, 2003).

HESSD
9, 5931–5953, 2012

CC BY

In the following, we introduce two methods, which are based on ERA-Interim internal temperature gradients for addressing this need. Temperatures as well as the geopotential heights of the 925 mb and 700 mb level were used for calculating Γ_{E_1}. $\Gamma_{E_{2\,s}}$ and $\Gamma_{E_{2\,fa}}$ on the basis of temperature differences between the 925 mb and 850 mb ($\Gamma_{E_{2\,s}}$) level and the 850 mb and 700 mb ($\Gamma_{E_{2\,fa}}$) level (Fig. 2).

A differentiation into $\Gamma_{E_{2\,s}}$ and $\Gamma_{E_{2\,fa}}$ was introduced to accommodate for different atmospheric conditions and therefore dominant controls on surface temperature. While low altitudes are often influenced by local circulation patterns (represented by $\Gamma_{E_{2\,s}}$), temperature conditions at higher elevations (represented by $\Gamma_{E_{2\,fa}}$) are more representative to free air flow conditions (Mahrt et al., 2001). Tabony (1985) noted that the transition from local circulation dominated, to free air dominated temperatures can be found at approximately 1400 m a.s.l. in the Austrian Alps. For our test site, the 850 mb level varying around 1500 m a.s.l., was used as a transition level dividing the local circulation dominated zone, from the free air flow dominated zone. Figure 2 illustrates the different parameters used in Eq. (1). Method III used $T_{\mathrm{ERA}_{2\,m}}$ and Γ_{E_1} for the calculation of the temperature at Garmisch station and $T_{\mathrm{ERA}_{pl}}$ and Γ_{E_1} for Zugspitze and Zugspitzplatt stations. In Method IV, $T_{\mathrm{ERA}_{2\,m}}$ and $\Gamma_{E_{2\,s}}$ are the basis for the calculation of T_a at the Garmisch station and $T_{\mathrm{ERA}_{pl}}$ and $\Gamma_{E_{2\,fa}}$ for Zugspitze and Zugspitzplatt stations.

In order to evaluate the presented downscaling methods, three statistical accuracy measures were used: the root mean square error (RMSE), the mean absolute error (MAE) and the Nash-Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970).

3 Results

3.1 Comparison of ERA-Interim 2 m temperature and local measurements

As a first step, we compared the original 0.25°, 3-hourly results of ERA-Interim with measurements of Garmisch, Zugspitze and Zugspitzplatt stations (Fig. 3, Table 3). A visual analysis and the calculated performance measure indicated a large bias between

HESSD
9, 5931–5953, 2012

cc BY

ERA-Interim and measurements, especially for the higher elevated stations. This is not surprising, given the differences in elevation between sites (see Table 1) and the average pixel elevation (1286.6 m) used by the ERA-Interim model.

The most significant difference between $T_{\mathrm{ERA}_{2\,\mathrm{m}}}$ and T measured was found for Zugspitze station. The relatively small elevation difference between the Garmisch station and ERA-Interim average grid elevation resulted in the smallest bias.

3.2 Temporal variability of the lapse rates

The derived lapse rates (Γ_{S}, Γ_{M}, Γ_{E_1} and $\Gamma_{\mathrm{E}_{2\,\mathrm{s}}}/\Gamma_{\mathrm{E}_{2\,\mathrm{fa}}}$) showed a different annual variability. Figure 4 illustrates the seasonal dynamics of measured and modeled lapse rates as well as those obtained from the literature. The latter ones did not show any inter-monthly variability as they were defined as a single value per month. It can be seen that the negative lapse rates was generally smaller in winter but showed a higher variability during these colder months (October to February). Warmer months were characterized by lapse rates in the range of $-6\,^{\circ}\mathrm{C\,km}^{-1}$ to $-7\,^{\circ}\mathrm{C\,km}^{-1}$ and by a low inter-monthly variability (April–August). March and September represent transition months, where the regime changed from winter to summer or from summer to winter conditions. Γ_{S} generally represented the largest temperature gradient and was significantly different from the measurements especially during the summer months. Γ_{E_1} and $\Gamma_{\mathrm{E}_2\,\mathrm{s}}/\Gamma_{\mathrm{E}_2\,\mathrm{fa}}$ showed larger variations during winter time, similar to the dynamics of the measurements (Γ_{M}). The overall difference between measured and modeled lapse rates was small in summertime (June–August) and showed stronger deviations in winter time (November–February), possibly due to frequent local inversion events during winter months at the Garmisch station that cannot be reproduced by the ERA-Interim model.

3.3 Evaluation of downscaling methods

The overall performance of the four downscaling methods with respect to 3-hourly temperature data is summarized in Fig. 5. Method I only showed moderate improvements

cc BY

and tended to underestimate the temperature at Zugspitze and Zugspitzplatt (Fig. 5a, b, c). The RMSE and MAE for the prediction of Zugspitze data could be reduced by approx. 54 % and 62 % and by approx. 27 % and 36 % with respect to Zugspitzplatt when compared to the original ERA-Interim data (Fig. 3). However, the absolute error values for Method I was still high (Fig. 5b and c). The Nash Sutcliff coefficient could also be improved (0.91 for Garmisch, 0.59 for Zugspitze and 0.71 for Zugspitzplatt), but is still low for the two stations located in higher elevations. Method II outperforms the other methods with respect to Garmisch station (Fig. 5d). However, the original ERA-Interim results for Garmisch still fit very well to the measurements (Fig. 3), and the overall improvement was comparably small for all of the methods used.

The downscaling results for the two high altitude stations could be significantly improved by Methods II, III and IV. Method III performed especially well for Zugspitze station (NSE of 0.96, RMSE of 1.45 and MAE of 1.12) (Fig. 5h), where the RMSE was reduced by 85 % and the MAE by 88 % when compared to the original ERA-Interim results. Methods III and IV performed almost as well as our benchmark method (II), with particular good results for the Zugspitzplatt station. This behavior is extremely encouraging as both methods (III and IV) are independent of local measurement stations and are therefore applicable for wide parts of the world.

Figure 6 illustrates the performance of all 4 methods with respect to daily average temperatures. While the accuracy of the downscaling results is similar when compared to the use of 3-hourly data, some additional interesting aspects can be analyzed for the aggregated data. For example, daily averages as well as daily minima and maxima temperature data are often used for characterizing local sites given current or predicted future climate conditions. The extrapolation of the original ERA-Interim data or of data downscaled using Method I would therefore lead to a systematic misinterpretation of minimum and maximum values. Figure 6 clearly shows that the results at the lower end of the temperature spectrum are overestimated while warmer temperatures are underestimated. This effect can only be eliminated when site specific lapse rates are used. This again is a strong argument against a general application of lapse rates,

HESSD
9, 5931–5953, 2012

cc BY

which are only oriented on a theoretical adiabatic temperature gradient, but which do not factor in the local characteristics of a specific site.

4 Conclusions

3-hourly and daily ERA-Interim 2 m temperature data were first compared with measurements at Zugspitze, Garmisch-Partenkirchen and Zugspitzplatt in the German Alps, all located within the same ERA-interim grid element. This comparison illustrated the necessity to downscale ERA-Interim data based on temperature lapse rates in order to account for elevation driven temperature variations in heterogeneous mountain regions that cannot be represented by a grid average ERA-Interim model prediction.

Four different methods were used to derive lapse rate Γ: (i) a fixed monthly lapse rate (Γ_S) extracted from the literature (Method I); (ii) a measured lapse rate (Γ_M) retrieved from the Zugspitze and the Garmisch stations (Method II); and (iii) ERA-Interim model internal lapse rates (Γ_{E_1} and $\Gamma_{E_{2\,s}}/\Gamma_{E_{2\,fa}}$) derived from predictions at different pressure levels, (Methods III and IV).

Observed changes of lapse rates with elevation and with time, demonstrated that the use of fixed lapse rates (Γ_S) were not satisfactory and led to large biases between downscaled and locally measured temperature values, especially for high elevation stations. Method II represented an almost ideal situation where the complete vertical elevation/temperature gradient is covered by two stations providing continuously measured lapse rates. While this approach provided the best results, it would be interesting to analyze how far these measured lapse rates could be extrapolated in a spatial context. A major disadvantage of Method II is its dependency on the availability of meteorological stations; only very few places in mountainous and high altitude regions worldwide can offer such a station setup.

Method III and Method IV represent novel alternatives for deriving temperature lapse rates by using (global climate) model (here ERA-Interim) internal lapse rates from representative pressure levels. Both methods showed a convincing performance when compared to measured data of the three stations, again especially for those in higher

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

9, 5931–5953, 2012

Downscaling ERA-Interim temperature data in complex terrain

L. Gao et al.

cc BY

elevations. This indicates that the ERA-Interim model structure, including various modules considering sub-grid variability of land surface characteristics and fluxes (e.g. the sub grid scale orographic drag in the Cy33r1 land surface scheme), seems to be well suited to represent the dominant controls on lapse rate variations, at least for this test environment. The additional implementation of an internal baseline at approximately 1500 m and the calculation of separate lapse rates above and below (Method IV), allowed a vertical differentiation and the consideration of local circulation effects (below) and the dominance of free air conditions (above) on the temperature distribution... (Mahrt, 2006; Rolland, 2003; Blandford et al., 2008). However, results only showed minimal differences between Method III and IV for this test site and should be tested further.

So far, our analysis has been limited to a single location in the German Alps with 3 meteorological stations providing calibration/validation data sets for testing developed downscaling methods. While this setup is ideal in that it covers a maximum vertical range of over 2000 m, it will be necessary to extend this analysis to different locations around the world. It should also be investigated whether other global reanalysis products, using different land surface representations in their climate models. Also, the potential of extending our approach to other meteorological variables has to be explored and is a topic of on-going and future research.

Acknowledgements. ERA-Interim data is supported by ECMWF Special Project. We thank Florian Pappenberger, scientist at ECMWF, and Carsten Maaß, expert at the User Support Center of ECMWF, for their valuable contributions regarding ERA-Interim data preparation and processing. The authors appreciate the support by the Deutscher Wetterdienst (DWD) and Lawinenwarndienst Bayern (LWD) for providing the meteorological data.

References

Barry, R. G.: Mountain Climatology and Past and Potential Future Climatic Changes in Mountain Regions – a Review, Mt. Res. Dev., 12, 71–86, 1992.

Bernhardt, M. and Schulz, K.: SnowSlide: A simple routine for calculating gravitational snow transport, Geophys. Res. Lett., 37, L11502, doi:10.1029/2010gl043086, 2010.

Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S., and Uppala, S.: The ERA-Interim archive (version 1.0), ERA Report Series: European Centre for Medium Range Weather Forecasts, 2009.

Berrisford, P., Kallberg, P., Kobayashi, S., Dee, D., Uppala, S., Simmons, A. J., Poli, P., and Sato, H.: Atmospheric conservation properties in ERA-Interim, Q. J. Roy. Meteor. Soc., 137, 1381–1399, doi:10.1002/Qj.864, 2011.

Blandford, T. R., Humes, K. S., Harshburger, B. J., Moore, B. C., Walden, V. P., and Ye, H. C.: Seasonal and synoptic variations in near-surface air temperature lapse rates in a mountainous basin, J. Appl. Meteorol. Clim., 47, 249–261, doi:10.1175/2007jamc1565.1, 2008.

Bolstad, P. V., Swift, L., Collins, F., and Regniere, J.: Measured and predicted air temperatures at basin to regional scales in the southern Appalachian mountains, Agr. Forest. Meteorol., 91, 161–176, 1998.

Dee, D. P. and Uppala, S.: Variational bias correction in ERA-Interim, ECMWF Newsletter, 119, 21–29, 2009.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Holm, E. V., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteor. Soc., 137, 553–597, doi:10.1002/Qj.828, 2011.

DeGaetano, A. T. and Belcher, B. N.: Spatial interpolation of daily maximum and minimum air temperature based on meteorological model analyses and independent observations, J. Appl. Meteorol. Clim., 46, 1981–1992, doi:10.1175/2007JAMC1536.1, 2007.

Dodson, R. and Marks, D.: Daily air temperature interpolated at high spatial resolution over a large mountainous region, Clim. Res., 8, 1–20, 1997.

CC BY

Hamlet, A. F. and Lettenmaier, D. P.: Production of temporally consistent gridded precipitation and temperature fields for the continental United States, J. Hydrometeorol., 6, 330–336, 2005.
Ishida, T. and Kawashima, S.: Use of Cokriging to Estimate Surface Air-Temperature from Elevation, Theor. Appl. Climatol., 47, 147–157, 1993.
Kunkel, E. K.: Simple Procedures for Extrapolation of Humidity Variables in the Mountainous Western United States, J. Climate, 2, 656–669, 1989.
Laughlin, G. P.: Minimum Temperature and Lapse-Rate in Complex Terrain – Influencing Factors and Prediction, Arch. Meteor. Geophy. B, 30, 141–152, 1982.
Liston, G. E. and Elder, K.: A meteorological distribution system for high-resolution terrestrial modeling (MicroMet), J. Hydrometeorol., 7, 217–234, 2006.
Liston, G. E., Hiemstra, C. A., Elder, K., and Cline, D. W.: Mesocell Study Area Snow Distributions for the Cold Land Processes Experiment (CLPX), J. Hydrometeorol., 9, 957–976, doi:10.1175/2008jhm869.1, 2008.
Lundquist, J. D. and Cayan, D. R.: Surface temperature patterns in complex terrain: Daily variations and long-term change in the central Sierra Nevada, California, J. Geophys. Res.-Atmos., 112, D11124, doi:10.1029/2006jd007561, 2007.
Mahrt, L.: Variation of surface air temperature in complex terrain, J. Appl. Meteorol. Clim., 45, 1481–1493, 2006.
Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P., and Nijssen, B.: A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States, J. Climate, 15, 3237–3251, 2002.
Mernild, S. H., Liston, G. E., Hiemstra, C. A., Steffen, K., Hanna, E., and Christensen, J. H.: Greenland Ice Sheet surface mass-balance modelling and freshwater flux for 2007, and in a 1995–2007 perspective, Hydrol. Process., 23, 2470–2484, doi:10.1002/Hyp.7354, 2009.
Minder, J. R., Mote, P. W., and Lundquist, J. D.: Surface temperature lapse rates over complex terrain: Lessons from the Cascade Mountains, J. Geophys. Res.-Atmos., 115, D14122, doi:10.1029/2009jd013493, 2010.
Mooney, P. A., Mulligan, F. J., and Fealy, R.: Comparison of ERA-40, ERA-Interim and NCEP/NCAR reanalysis data with observed surface air temperatures over Ireland, Int. J. Climatol., 31, 545–557, doi:10.1002/Joc.2098, 2011.
Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models part I – A discussion of principles, J. Hydrol., 10, 282–290, 1970.

Nieto, H., Sandholt, I., Aguado, I., Chuvieco, E., and Stisen, S.: Air temperature estimation with MSG-SEVIRI data: Calibration and validation of the TVX algorithm for the Iberian Peninsula, Remote Sens. Environ., 115, 107–116, doi:10.1016/j.rse.2010.08.010, 2011.

Pages, M. and Miro, J. R.: Determining temperature lapse rates over mountain slopes using vertically weighted regression: a case study from the Pyrenees, Meteorol. Appl., 17, 53–63, doi:10.1002/Met.160, 2010.

Pepin, N. C. and Seidel, D. J.: A global comparison of surface and free-air temperatures at high elevations, J. Geophys. Res.-Atmos., 110, doi:10.1029/2004JD005047, 2005.

Prihodko, L. and Goward, S. N.: Estimation of air temperature from remotely sensed surface observations, Remote Sens. Environ., 60, 335–346, 1997.

Prince, S. D., Goetz, S. J., Dubayah, R. O., Czajkowski, K. P., and Thawley, M.: Inference of surface and air temperature, atmospheric precipitable water and vapor pressure deficit using Advanced Very High-Resolution Radiometer satellite observations: comparison with field observations, J. Hydrol., 213, 230–249, 1998.

Regniere, J.: Generalized approach to landscape-wide seasonal forecasting with temperature-driven simulation models, Environ. Entomol., 25, 869–881, 1996.

Rolland, C.: Spatial and seasonal variations of air temperature lapse rates in Alpine regions, J. Climate, 16, 1032–1046, 2003.

Simmons, A., Uppala, S., Dee, D., and Kobayashi, S.: ERA-Interim: New ECMWF reanalysis products from 1989 onwards, ECMWF Newsletter, 110, 25–35, 2006.

Stahl, K., Moore, R. D., Floyer, J. A., Asplin, M. G., and McKendry, I. G.: Comparison of approaches for spatial interpolation of daily air temperature in a large region with complex topography and highly variable station density, Agr. Forest Meteorol., 139, 224–236, 2006.

Tabony, R. C.: The Variation of Surface-Temperature with Altitude, Meteorol. Mag., 114, 37–48, 1985.

Uppala, S., Dee, D., Kobayashi, S., Berrisford, P., and Simmons, A.: Towards a climate data assimilation system: status updata of ERA-Interim, ECMWF Newsletter, 115, 12–18, 2008.

Vicente-Serrano, S. M., Saz-Sanchez, M. A., and Cuadrat, J. M.: Comparative analysis of interpolation methods in the middle Ebro Valley (Spain): application to annual precipitation and temperature, Clim. Res., 24, 161–180, 2003.

Table 1. Test sites information.

Station	Latitude	Longitude	Altitude (m a.s.l.)	Time resolution	Time series	Measured height (m)
Garmisch	47.48	11.07	719	hourly	1979–2010	2
Zugspitze	47.42	10.99	2964	hourly	1979–2010	2
Zugspitzplatt	47.41	11.00	2250	10 minute	1999–2010	4

CC BY

HESSD
9, 5931–5953, 2012

Downscaling ERA-Interim temperature data in complex terrain

L. Gao et al.

CC BY

Table 2. Fixed monthly lapse rates extracted from Kunkel (1989) and Liston and Elder (2006).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse rate (°C km^{-1})	−4.4	−5.9	−7.1	−7.8	−8.1	−8.2	−8.1	−8.1	−7.7	−6.8	−5.5	−4.7

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Table 3. Comparison of the ERA-Interim 2 m temperature with 3-hourly and daily data of the three meteorological stations used. The NSE, RMSE and MAE are also listed.

	Garmisch			Zugspitze			Zugspitzplatt		
	NSE	RMSE	MAE	NSE	RMSE	MAE	NSE	RMSE	MAE
$T_{3\,h}$	0.85	3.45	2.93	−1.00	9.92	9.22	0.45	5.55	4.84
T_d	0.85	3.03	2.76	−0.93	9.52	9.09	0.51	4.95	4.47

HESSD

9, 5931–5953, 2012

HESSD
9, 5931–5953, 2012

Downscaling ERA-Interim temperature data in complex terrain

L. Gao et al.

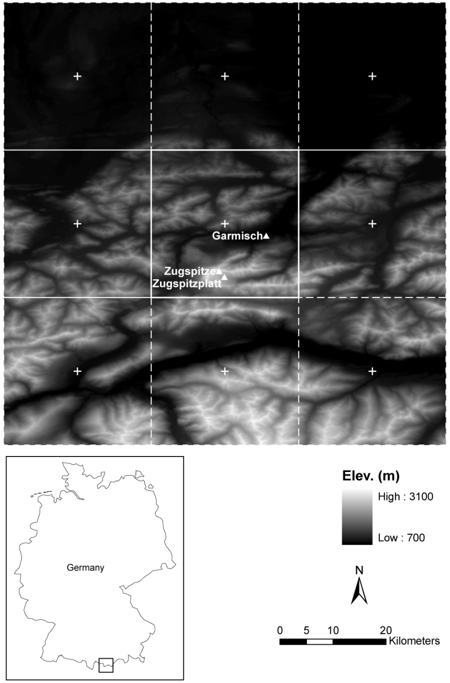

Fig. 1. The locations of the meteorological stations (triangles), and ERA-Interim 0.25° × 0.25° grids (dashed line, cross as grid centre). The middle solid grid covers all meteorological stations and is used in our study. The terrain elevation ranges from 700 m to 3100 m, with a DEM resolution of 90 m.

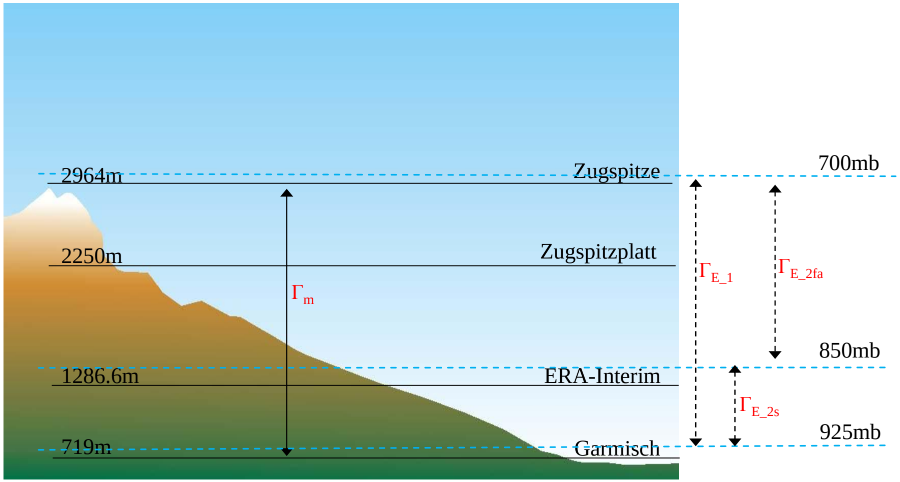

Fig. 2. Schematic illustration of measured lapse rate and ERA-Interim derived lapse rates.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
9, 5931–5953, 2012

Downscaling ERA-Interim temperature data in complex terrain

L. Gao et al.

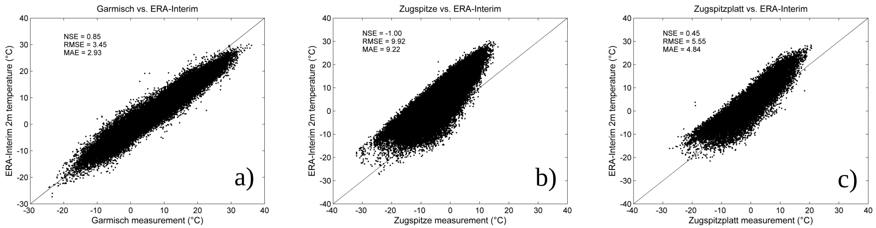

Fig. 3. Scatter plot of 3-hourly ERA-Interim 2 m temperature and measurements, **(a)** Garmisch station, **(b)** Zugspitze station (1979–2010) and **(c)** Zugspitzplatt station from (1999–2010).

HESSD
9, 5931–5953, 2012

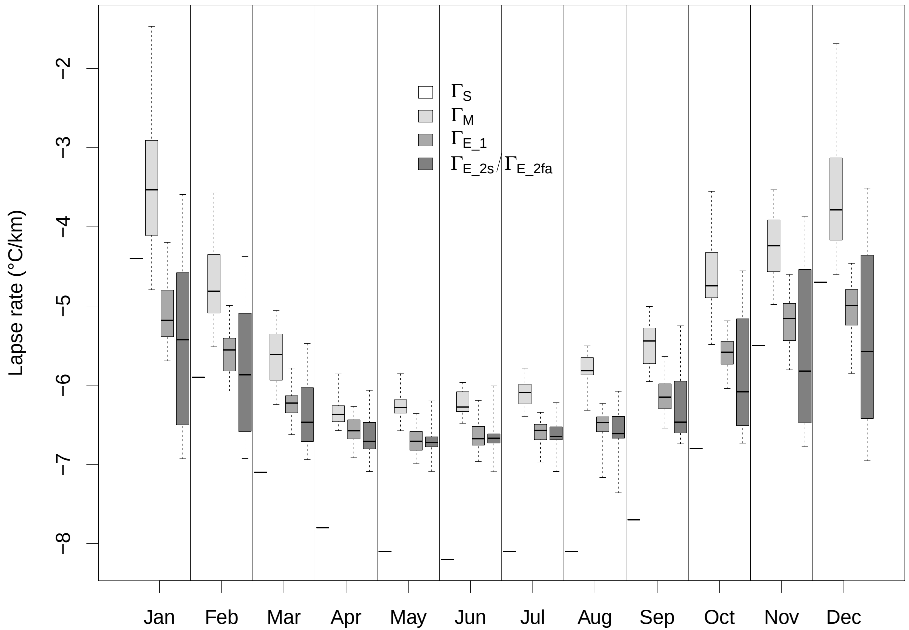

Fig. 4. Boxplot of monthly lapse rates variability in 1979–2010, Γ_S (white), Γ_M (light gray), Γ_{E_1} (medium gray) and $\Gamma_{E_{2s}}/\Gamma_{E_{2fa}}$ (dark gray). Thick horizontal lines show the median values. Boxes indicate the inner-quantile range (25 % to 75 %) and the whiskers show the full range of the values. Note that, because fixed lapse rate is constant for each month in whole period, therefore, only the short dark lines could be seen.

cc BY

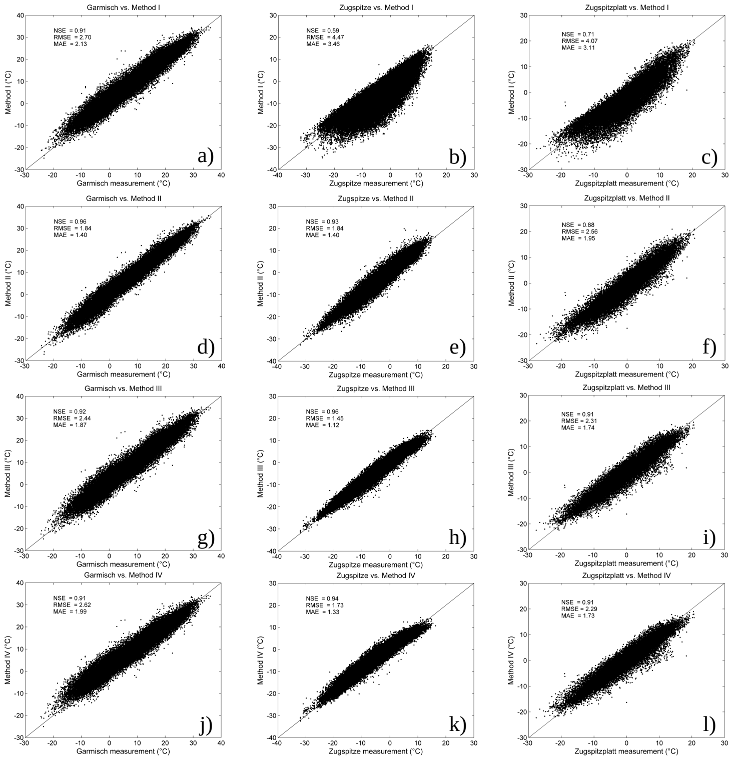

Fig. 5. The scatter plots showing the comparison of measurements and downscaled 3-hourly data and gave information about NSE, RMSE and MAE. **(a–c)** show the results of Method I for Garmisch, Zugspitze (both 1979–2010) and Zugspitzplatt (1999–2010) station. **(d–f)** show the results for Method II, **(g–i)** those for Method III, and **(j–l)** those for Method IV.

HESSD
9, 5931–5953, 2012

Downscaling ERA-Interim temperature data in complex terrain

L. Gao et al.

CC BY

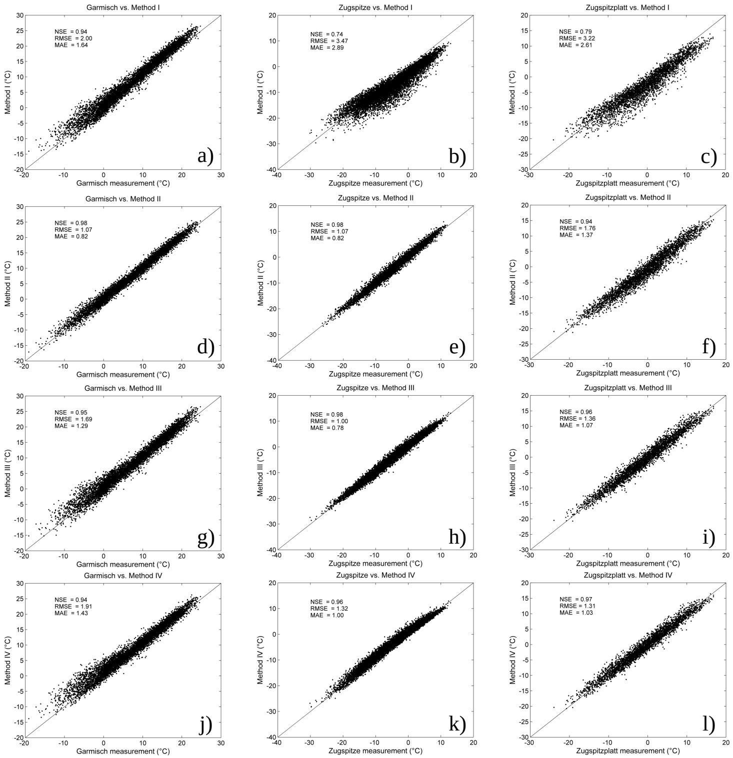

Fig. 6. The scatter plots showing the comparison of measurements and downscaled daily data and gave information about NSE, RMSE and MAE. **(a–c)** show the results of Method I for Garmisch, Zugspitze (both 1979–2010) and Zugspitzplatt (1999–2010) station. **(d–f)** show the results for Method II, **(g–i)** those for Method III, and **(j–l)** those for Method IV.

HESSD
9, 5931–5953, 2012

Downscaling ERA-Interim temperature data in complex terrain

L. Gao et al.

CC BY