SAGA GIS based processing of spatial high resolution temperature data

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Abstract

Many climate change impact studies require surface and near surface temperature data with high spatial and temporal resolution. The resolution of state of the arte climate models and remote sensing data is often by far too coarse to represent the meso- and microscale distinctions of temperatures. This is particularly the case for regions with a huge variability of topoclimates, such as mountainous or urban areas. Statistical downscaling techniques are promising methods to refine gridded temperature data with limited spatial resolution, particularly due to their low demand for computer capacity. This paper presents two downscaling approaches – one for climate model output and one for remote sensing data. Both are methodically based on the FOSS-GIS platform SAGA.

1. Introduction

Provision of adequate data for climate change impact assessment and monitoring tools are elementary tasks in environmental informatics and high performance computing. Besides increasing computing capacity and recent advantages in parallelization of general circulation models (GCM), there is still a large gap between the spatial resolution achieved by the latest GCM generation for global climate scenarios (about 50 by 50 km\(^2\)) and the needed resolution for impact studies (about 1 km or less). Both high mountain regions and urban areas are characterized by a huge variability of local climates within short distances, which cannot be represented by GCMs. While in mountainous terrain differences in solar radiation and local circulation systems, play a crucial role for the spatial and temporal distribution of near surface temperatures, the specific climate of urban areas is mostly determined by alteration of nearly all terms of the urban energy balance which i.e. leads to the development of an urban heat island (UHI). Since near-surface air temperature is one of the main parameters controlling environmental processes, such as glacial, permafrost or timberline dynamics, temporal and spatial high resolution information about its mean values, its variability and change is required for many ecological investigations in

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mountain areas. Furthermore spatial high resolution temperature data is often required for the development of climate change adaption strategies in those climate-sensitive environments. Likewise, in cities temperature data with high spatial resolution is frequently needed for sustainable urban planning. Particularly during summer season many cities suffer from significant increase of hot days with average temperatures of more than 30 °C, which leads to an enhanced health risk for the urban population. Hence the investigation of the intra urban temperature distribution is of great relevance. Due to the fact that meteorological stations are sparsely distributed in high mountain environments, the variability of near surface air temperature is not sufficiently represented by observations. Likewise most urban areas are equipped with only a small number of MetStations, which cannot capture the intra urban distinctions temperatures. Freely available state of the art reanalysis, e.g. ERA-Interim, which is currently developed at the European Center for Medium-Range Weather Forecast (ECMWF), provides 6-hourly estimates of relevant meteorological variables on a spectral T255 resolution (0.7° Lat./Long.). Instruments in the geostationary orbit like the Spinning Enhanced Visible Infra-Red Imager (SEVIRI) aboard Meteosat Second Generation (MSG) satellites with a standard retrieval time of only 15 minutes provide surface temperature fields with a spatial resolution of approximately 5 km depending on the latitude. Both is by far to coarse to adequately represent the spatial variability of high mountain and urban climates, respectively.

Facing the growing demand for spatial and temporal high resolution temperature data we present two GIS based approaches to refine the spatial resolution of reanalysis and remote sensing products by means of predictor based statistical downscaling. For the method development and implementation, we utilized the Application Programming Interface (API) and the Graphical User Interface (GUI) of the System for Automated Geoscientific Analyses (SAGA), a programmable FOSS-GIS platform, explicitly designed to support regional climate and environmental modeling applications (www.saga-gis.org). Due to the computational efficient amalgamation of computer-assisted cartography with database applications within a modular organized object-oriented programming environment, SAGA offers enhanced options for raw data processing (e.g. denoising, filtering, smoothing of digital elevation and remote sensing data), dynamical representation of LU/LC data and numerous geostatistical and numerical up- and downscaling strategies for the adjustment of geodata with respect to the diverse requirements at the climate modeling side.

2. Case study I: Altitude and Bias Correction of Reanalysis Data in complex terrain

High Mountain Regions are considered to be among the most vulnerable ecosystems in the context of climate change (Bolch/Kääb/Huggel 2012; Liu/Chen 2000; Shresth/Mayewski/Dibb 1999). Since meteorological observations in high mountains are sparse, climate model output data with limited spatial resolution are frequently used for climate impact studies. Based on the assumption, that altitude is the main predictor for the near surface micro scale temperature distribution, GIS can be a powerful tool for altitude and bias correction of gridded climate model output data. In this case study temperature fields from different ERA-Interim pressure levels were used to derive local temperature profiles by means of a polynomial regression approach. The specific regression equations can be subsequently used to model free atmospheric temperatures at ground level with high spatial resolution. By comparing the results of the altitude correction approach with in situ observations, a bias correction can be applied. The methods were published in (Gerlitz/Conrad/Thomas/Böhner 2013).
2.1 Data and methods

The target area for this study contains the main mountain ranges of high Asia, the Tibetan Plateau as well as the adjacent Lowlands of India and the Tarim Basin. It extends from 25 °N to 40 °N and 75 °E to 95 °E and covers an area of approximately 2.250.000 km². Thus the target area combines regions, which differ not only in their specific topoclimatic settings, but also in their their large scale atmospheric characteristics. While the large scale atmospheric circulation over High Asia is well represented by freely available reanalysis products, such as ERA-Interim (Bao/Zhang 2012; Wang/Zeng 2012), terrain induced local modifications of near surface temperature can only be considered using appropriate downscaling applications. For the presented approach we used daily temperature and geopotential height fields of the ERA-Interim reanalysis for the levels 1000, 925, 850, 700, 600, 500, 300 and 200 hPa. The fields were resampled to a 1 by 1 km grid and projected to a UTM coordinate system. For the high resolution digital representation of the orography we used the freely available SRTM elevation model published by the US Geological Survey (USGS) with a grid size of 3″ (Reuter/Nelson/Jarvis 2007). The DEM was resampled to a grid size of 1 by 1 km.

Based on the resampled ERA-Interim fields for temperature and geopotential height a third order polynomial regression was applied to estimate local temperature profiles. The curvilinear fit was found to sufficiently represent the ERA-Interim temperature profiles. The coefficient of determination was greater than 95% for every fit. Especially during winter season, when inverse weather conditions occur frequently, the method was found to be superior compared to basic approaches using a fixed lapse rate, such as the often cited environmental lapse rate of 0.65 °C / 100m (Minder/Mote/Lundquist 2010). In conclusion the free atmospheric temperature at ground level (which is given by the high resolution SRTM DEM) was calculated using the local regression functions.

![Temperature profile](image)

**Figure 1**
Resampled temperature fields of different ERA-Interim pressure levels for Jan 2nd 1989 and the derived temperature profile for the location of Kathmandu (27°42'N 85°20'E)

The results of the altitude corrected ERA-Interim data set were subsequently compared with daily in situ observations of 71 MetStations for the period from 1989 to 2010. Since the altitude
correction approach generates free atmospheric temperatures without accounting for surface energy balance processes, residuals were remarkably high, with values up to 6°C. For all stations a seasonal cycle of residuals could be identified. While in winter the in situ observations tend to be colder than the modelled values, a warm bias is characteristic for the summer season. The cycle of residuals was found to be most pronounced on the Tibetan Plateau which is supposed to be due to high rates of incoming solar radiation. For the adjustment of those residuals monthly mean values were calculated and spatially interpolated.

2.2 Results of the Case Study

Using the presented approach the resolution of gridded climate model output data can be significantly improved. The representation of the altitude determined distribution of near surface temperatures in the highly structured target area is well represented by the altitude and bias corrected data set.

![Figure 2](image)

Left: Near surface temperature distribution of the ERA-Interim Reanalysis with a resolution of 0.7 by 0.7 °; Right: result of the altitude and bias correction approach for Jan 2nd 1989.

The presented approach explains 91.01% of the temporal and spatial variability of daily temperatures. This high $r^2$ however is based on the large differences in altitudes. In the mountainous regions with altitudes ranging from 1000 m to above 3000 m asl the RMSE of the reanalysis data decreased by more than 80%. For the high mountain stations where near surface temperatures are mainly influenced by large scale atmospheric patterns (Gao/Bernhardt/Schulz 2012), the added value of the approach is especially high, with decreasing RMSE values of up to 97.7 % at Colle Sud station (27.96 °N / 86.93 °E) at 8000 m asl. In the Lowlands of India with altitudes below 1000 m asl the added value of the approach is less pronounced, but still almost 60 % of the spatial and temporal variability of daily mean temperature values could be explained. Nevertheless high frequency, non predictable residuals remain at all MetStation, which are suggested to be due to mesoscale and local circulation patterns.
3. Case Study II: Downscaling Land Surface Temperature in an Urban Area

Global warming and an increasing frequency and intensity of heat waves also in moderate climates foster the interest in urban climatology. The most prominent effect is the UHI which generally describes an increased air temperature compared to nearby rural areas. However, the UHI is altered by numerous local scale features including buildings, vegetation and impervious surfaces. Hence, the UHI-magnitude shows large micro scale variability which is an important factor for impact assessments. Besides better understanding of the controlling factors an operational monitoring of the intensity and spatial distribution of the UHI in high spatiotemporal resolution has high practical relevance for urban planning and disaster management. While the near-surface (or canopy layer) can only be detected in situ at a few points, the increase in land surface temperature (LST) can be recorded in medium-resolution from satellite thermal sensors. However, these instruments fly on sun-synchronous polar orbit and therefore their temporal resolution is inadequate for UHI monitoring. Sensors on geostationary platforms on the other hand, can represent the diurnal cycle well, but have low spatial resolution (~ 3.5 km) in which urban structures can barely be differentiated. This study shows how both data streams can be combined with the aid of statistical downscaling to a spatially and temporally sufficiently dissolved dataset. The method was first introduced in (Bechtel/Zakšek/Heshyaripour 2012) and improved in (Bechtel/Böhner/Zakšek/Wiesner 2013) and (Bechtel/Böhner/Zakšek 2013). Here a summary of the most relevant findings is presented.

3.1 Data and methods

The area of the case study is located in the southern part of Hamburg, Germany (53.38 - 53.63 °N, 9.75 - 10.38 °E), the date was chosen according to the data availability (2.8.2011, approx. 10:30 UTC).

For geostationary LST the LSA SAF product from the Spinning Visible Infra-Red Imager (SEVIRI) onboard Meteosat-8 was used (spatial resolution: 3.3 km in east-west and 6.7 km north-south in the study area, temporal resolution: 15 minutes). The LST is processed using a generalized split-window algorithm with 10.8 and 12.0 μm bands (Wan/Dozier 1996).

For the 1000 m resolution the Moderate Resolution Imaging Spectroradiometer (MODIS) Level 2 LST product was used in version 5, which is also based on a generalized split-window algorithm. The emissivity for both channels is estimated from land use, the error of LST is < 1 K (Wan/Zhang/Zhang/Li, 2004). The instrument is flying on the Terra satellite, part of NASA's Earth Observing System (EOS).

For ~ 100 m resolution a scene derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument (also on board the Terra satellite) was used. The surface temperature product is calculated from 5 thermal bands using the temperature and emissivity separation algorithm (Gillespie/Rokugawa/Matsunaga/Cothern/Hook/Kahle 1998). The three datasets and their different spatial resolution are illustrated in Figure 3.
Figure 3
LST in K for different resolutions. Right: SEVIRI (~ 5 km), lower left: MODIS (~ 1 km), upper left: ASTER (~ 100 m).

The statistical downscaling was conducted as following. First, suitable predictors were upscaled to the low-resolution grid. For the 1000 m resolution they were simply resampled with an area-weighted average, for SEVIRI, the "irregular" shape of the pixels due to the acquisition geometry and the point spread function was approximated by a Gaussian weight function. Then, an empirical model between the predictors and LST in was calibrated in low-resolution. Eventually, this function was transferred to the higher spatial resolution, assuming a scale-independent relation. The validation was performed with independent measurements in the higher-resolution domain. This method has been widely used in the downscaling of surface temperatures (Kustas/Norman/Anderson/French 2003, Zaksek/Ostir 2011). In this study different predictors were tested for their suitability including annual cycle parameters (Bechtel 2012) and principal components of multitemporal TIR data.

3.2 Results & discussion
The results of the downscaling from SEVIRI to 100 m are shown Figure 4. The left column displays the linear relationships between single predictors and LST in different resolutions. The assumption of a scale independent linear relationship is underpinned but a certain amount of the overall variance cannot be explained. The center column shows the modeled high resolution LST-patterns using three predictor sets, which showed the best performance in the initial study (Bechtel/Zakšek/Hoshyaripour 2012). The right column shows the spatial distribution of the error (= residuals) as compared to the ASTER validation data.
Figure 4: Downscaling of SEVIRI to 100 m. Left: Linear relationship between different predictors and LST in different resolutions: ASTER (100 m) in blue, MODIS (1000 m) in green, SEVIRI (≈ 5 km) in red; Center: Modeled LST pattern in K with respective predictor set (mean annual surface temperature, annual cycle parameters, 1st principal component of multitemporal TIR data). Right: error compared to ASTER validation data in K (adopted from Bechtel/Böhnner/Zakšek 2013).

Table 1 shows the quantitative results for different downscaling experiments. The best model explains 73 % of the spatial variance and has a root-mean-square error (RMSE) of 2.14 K. Surprisingly, the results of the downscaling experiments from SEVIRI to 1000 m (validated with MODIS) and from MODIS to 100 m (ASTER) are not much better or even worse besides the smaller scale factor. This is somewhat contradictory to the former result in (Bechtel/Zakšek/Hoshyarpour 2012) that the performance increases with decreasing scale factor. Reasons might be the simpler upscaling technique using the area weighted approach for the MODIS resolution and the use of upscaled predictors for both calibration and validation in experiment ii.
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Table 1: Downscaling results for different experiments

The most obvious reason however is the large bias in experiment ii. While the positive bias in experiment i. of about 1.3 K (also visible in dominance of red colors in Figure 4 right) might result from the viewing geometry (SEVIRI views from the geostationary orbit above the equator a larger share of south facing surfaces which heat up more quickly), this cannot be the case for the negative bias from MODIS in experiment iii. The relative cool temperatures of MODIS compared to ASTER are also visible in the Figure 4 left (smaller intercept of the MODIS sample) and cannot be explained from the acquisition geometry, since the sensor is flying on the same platform as ASTER.

4. Conclusion and Outlook

Both case studies show that the resolution of temperature fields can be increased using GIS methods. Those methods are promising approaches due to their lower demand for computer capacity.

In high mountain environments the quality of near-surface $T_a$ fields could be significantly improved by considering the terrain altitude as the major predictor. However, non predictable
residuals remain, which are suggested due to local circulation patterns. Currently advanced terrain parameterization schemes are tested to account for those processes.

It the second case study, it was shown that a downscaling of geostationary LST in urban areas is possible. In spite of a scale factor of about 2000, some 70 % of the spatial variance at 100 m resolution were explained, and the mean square error was about 2.2 K. Aggregated parameters from multitemporal thermal data showed to be particularly suitable predictors. The bias accounted for a large share of the overall error and could not be entirely explained by the viewing. Hence, in coming studies the influence of differing atmospheric correction, emissivity and topography will be further investigated.

Bibliography


