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ClimCatch

Impact of climate change on the sediment yield of Alpine catchments

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Downscaling Report

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For the assessment of future changes in torrential sediment transport in a small-scale non-glaciated Alpine valley (Schöttlbachtal, Styria) and the related natural hazards, the output of dynamically downscaled regional climate models (RCMs; e.g., Giorgi and Mearns, 1991) with rather large spatial resolutions mostly of about 10-25 km horizontal grid spacing requires further downscaling in order to bridge the gap between the associated space scales. Especially for the small catchment investigated in ClimCatch, localized climate information down to the point scale of single meteorological stations is required. Apart from these scale-discrepancies, RCMs are known to feature systematic errors in the Alpine region, typically amounting up to 2 K to 3 K in air temperature and 50 % to 100 % in daily precipitation sum (e.g., Suklitsch et al, 2010).

In order to account for these discrepancies, empirical-statistical downscaling and error-correction methods (DECMs) such as Quantile Mapping (QM) as described in Themeßl et al. (2010, 2011) are applied, aiming at improving the skill of the RCMs in representing local climate characteristics and to further refine the output of RCMs to more localized scales. In this report we present the evaluation results of QM for daily and sub-daily (3-hourly) precipitation sum and temperature mean applied to selected meteorological stations within the catchment of Schöttelbach.

1. Daily and sub-daily Quantile Mapping

1.1 Error Correction Method

As regional climate models (RCMs) are known to suffer from systematic errors (e.g., Frei et al., 2003; Hagemann et al., 2004; Suklitsch et al., 2008, 2011), an empirical-statistical bias correction and downscaling approach via Quantile Mapping (QM; e.g., Dobler & Ahrens, 2008; Piani et al., 2010; Yang et al., 2010; Themeßl et al., 2011) is applied to adjust and refine RCM results towards the local-scale observations from weather stations.

Compared to other prominent bias correction methods like the delta change or scaling approaches (e.g., Déqué, 2007), QM is able to correct for errors in the entire distribution of a meteorological parameter. Therefore, QM is sensitive to different meteorological situations as they are typically related to the magnitude of a meteorological parameter (e.g., air temperature).

The bias correction of daily temperature and precipitation in ClimCatch is based on an empirical implementation of QM, as described in more detail by Themeßl et al. (2012). Here, we extend the methodological framework of QM to the sub-daily basis. According to Themeßl et al. (2012), QM for sub-daily application can be written as:

$$Y^{cor}_{d,h,i} = X^{raw}_{d,h,i} + CF_{d,h,i}, \qquad (1)$$

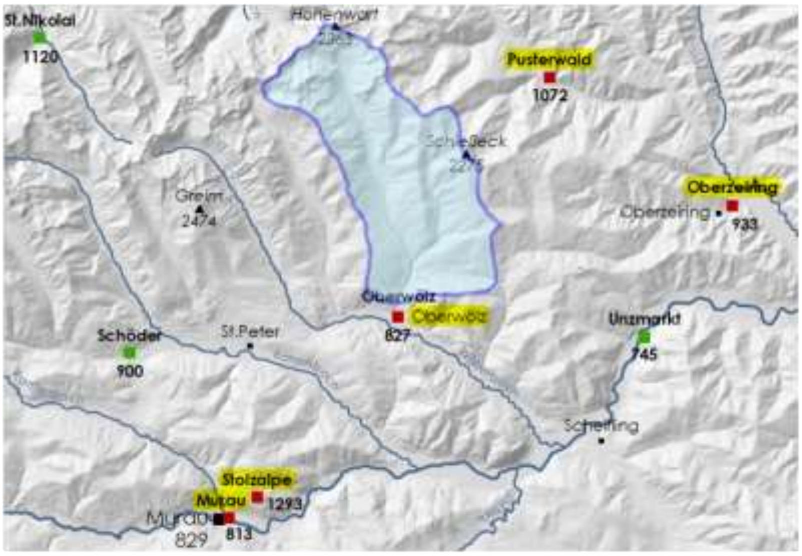

Fig. 1 Location of the catchment of Schöttelbach and the five analyzed stations for daily QM: Oberzeiring (13000), Pusterwald (13010), Oberwölz (15900), Stolzalpe (15910), and Murau (15920).

$$CF_{d,h,i} = ecdf^{obs,cal^{-1}}_{doy,hod,i}(P_{d,h,i}) - ecdf^{\mathrm{mod},cal^{-1}}_{doy,hod,i}(P_{d,h,i}), \tag{2}$$

$$P_{d,h,i} = ecdf^{\mathrm{mod},cal}_{doy,hod,i}(X^{raw}_{d,h,i}). \tag{3}$$

The correction function (*CF*) represents the difference between the observed (*obs*) and the modeled (*mod*) inverse ecdf ($ecdf^{-1}$) for the respective day of the year (*doy*) and hour of day (*hod*) in the calibration period (*cal*) at probability *P*. *P* is obtained by relating the raw climate model output X^{raw} to the corresponding *ecdf* in the calibration period. For the calibration of QM, *doy* is centered within a 31 days moving window, which is used to construct the *ecdf* for each day of the year and hour of the day. The effective resolution of the RCMs (e.g., Denis et al., 2002) is taken into account by considering the four nearest grid cells to the location of the stations.

As can be seen from Eq. 1-3, QM adapts the simulated time series of the raw climate model output by adjusting the empirical cumulative frequency distributions of the selected daily and hourly climate variables to the observed frequency distribution of the calibration period. Consequently, the bias-corrected model output has the same distributional properties as the observed data over the calibration period, but the chronological sequence of weather patterns originates from the raw RCM output. Implicitly, changes in the temporal variability and extremes simulated by the climate model remain in the data after bias correction, although there are only very few evaluation studies available regarding extremes (e.g., very briefly in Themeßl et al., 2012). In addition, some restrictions apply regarding very small scale spatial variability (Maraun, 2013). However, Themeßl et al. (2011) compared several bias correction methods for daily precipitation in the Alpine region and identified QM as being superior, and Gudmundsson et al. (2012) demonstrated that the parameter-free implementation of QM, as applied here, outperforms other parametric implementations. Furthermore, Teutschbein and Seibert (2013) investigated different correction methods to reduce model errors and to cope with non-stationary biases and found that more advanced correction methods such as

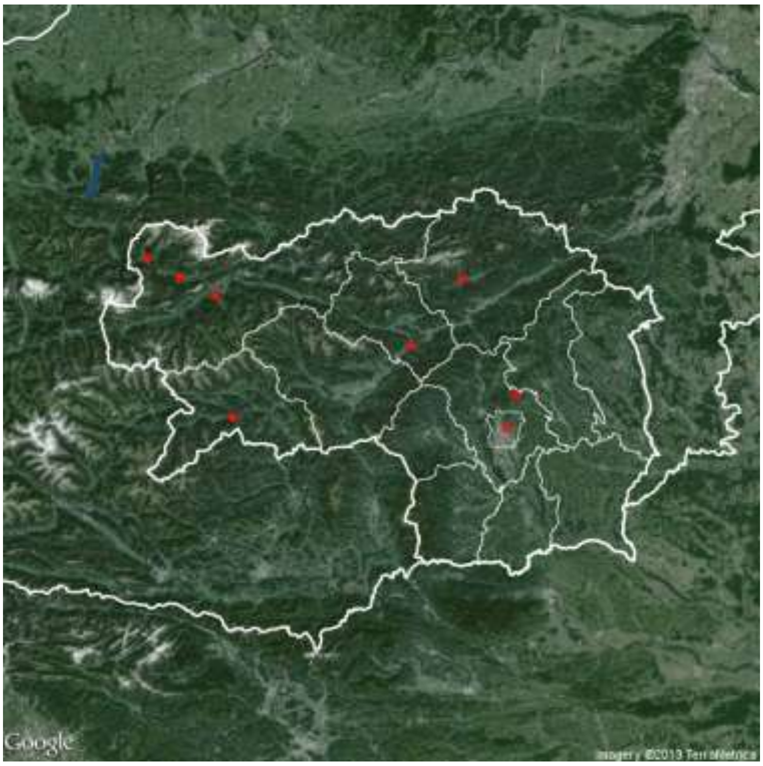

Fig. 2 Location of the eight analyzed stations in Styria for 3-hourly QM: Aflenz (10200), Bad Aussee (9640), Bad Mitterndorf (9700), Graz Universität (16412), Irdning-Gumpenstein (9811), Murau (15920), St. Radegund (16411), St. Michael bei Leoben (13250).

distribution mapping perform better than simple methods such as the delta-change approach or linear transformations.

1.2 Data

As observational basis for QM, station data from the Austrian Central Institute for Meteorology and Geodynamics (ZAMG) are used. For daily temperature and precipitation, data from meteorological stations nearby to the small catchment of Schöttelbach (i.e., Murau, Oberwölz, Oberzeiring, Pusterwald, and Stolzalpe) are used to downscale all 24 RCM simulations used in ClimCatch to the point-scale of the stations (see Fig. 1; further information regarding the utilized RCMs can be found in the ClimCatch uncertainty report).

For the evaluation of sub-daily QM, we select a single RCM simulation of the ENSEMBLES database (SMHI-RCA) for which sub-daily (3-hourly) data is available. Here we apply the hindcast simulation of SMHI-RCA with data from 1961-2008. The associated boundary conditions are from ERA40 (Uppala et al., 2005) for the time period until August 2002. For the remaining time period until 2008, boundary data are taken from the operational analysis provided by the European Centre for Medium-Range Weather Forecast (ECMWF). For the sub-daily scale observations, hourly data from the ZAMG database are extracted and aggregated to the 3-hourly scale. However, stations with a sufficient long measurement period of ~20 years for further evaluation purposes are very sparse in the ZAMG station network

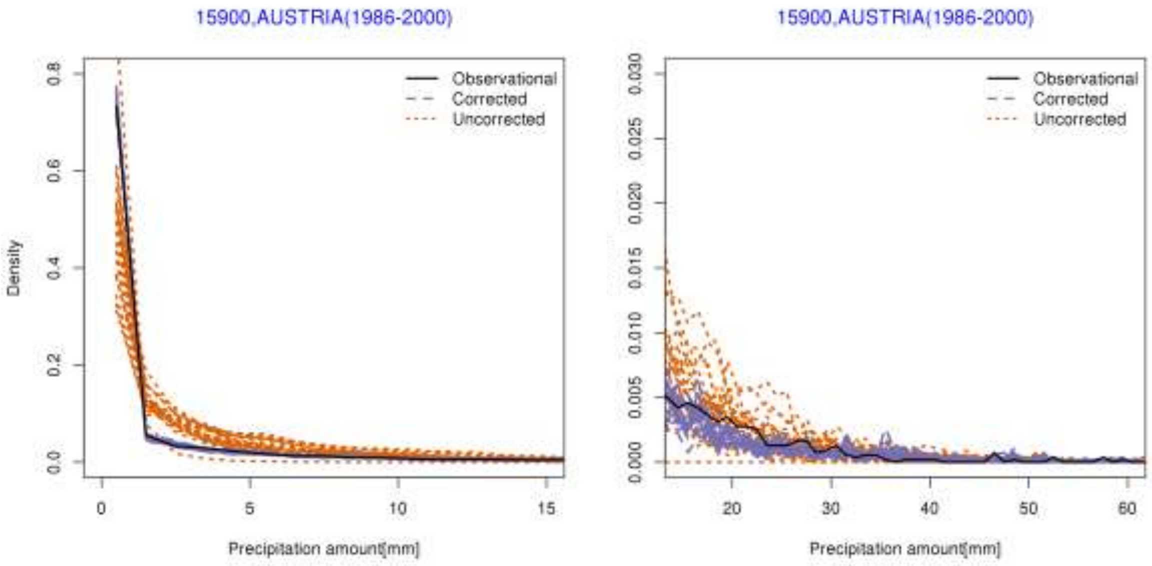

Fig. 3 Uncorrected (orange), corrected (blue), and observed (black) daily precipitation distributions at the station of Oberwölz. Left panel: Light and moderate precipitation. Right panel: Heavy precipitation.

(most of the automatic measurement systems were installed after 1990). We therefore extend our analysis to all stations in Styria which have a common 20 year-long measurement period of hourly data covering the period from 1989 to 2008 (see Fig. 2). In this respect, we note that the station of Murau is located nearest to the catchment of Schöttelbach.

2. Results

2.1 Daily Precipitation

The evaluation of QM regarding daily data has already been carried out in several studies (e.g., Themeßl et al., 2011, 2012; Wilcke et al. 2013) and therefore is only shortly presented here. In order to examine the quality of the generated point-scale time-series we evaluate the results by applying a split-sample approach, using independent 15 year-long evaluation and calibration periods. The calibration period for daily QM is 1971-1985, while the data is evaluated during the independent period of 1986-2000. We apply this split-sample approach to mimic the application of QM to future climate scenarios, where observations in the past are used to calibrate the bias correction of climate projections. The distribution-based evaluation regarding light/medium and heavy precipitation at the station of Oberwölz is exemplarily shown in Figure 3. Distributions of uncorrected model data (24 RCMs), error-corrected model data (24 RCMs) and observations are shown. As it can be seen, error-corrected data (blue lines) match the observed distribution (black line) very well, regardless of the shape of the uncorrected distribution (orange lines). Due to the lack of data concerning heavy/extreme precipitation events, stronger noise is introduced regarding the correction of the upper quantiles of the distribution (see left panel of Fig. 3). However, a clear improvement of the overestimated heavy precipitation frequency of the uncorrected model output is obtained.

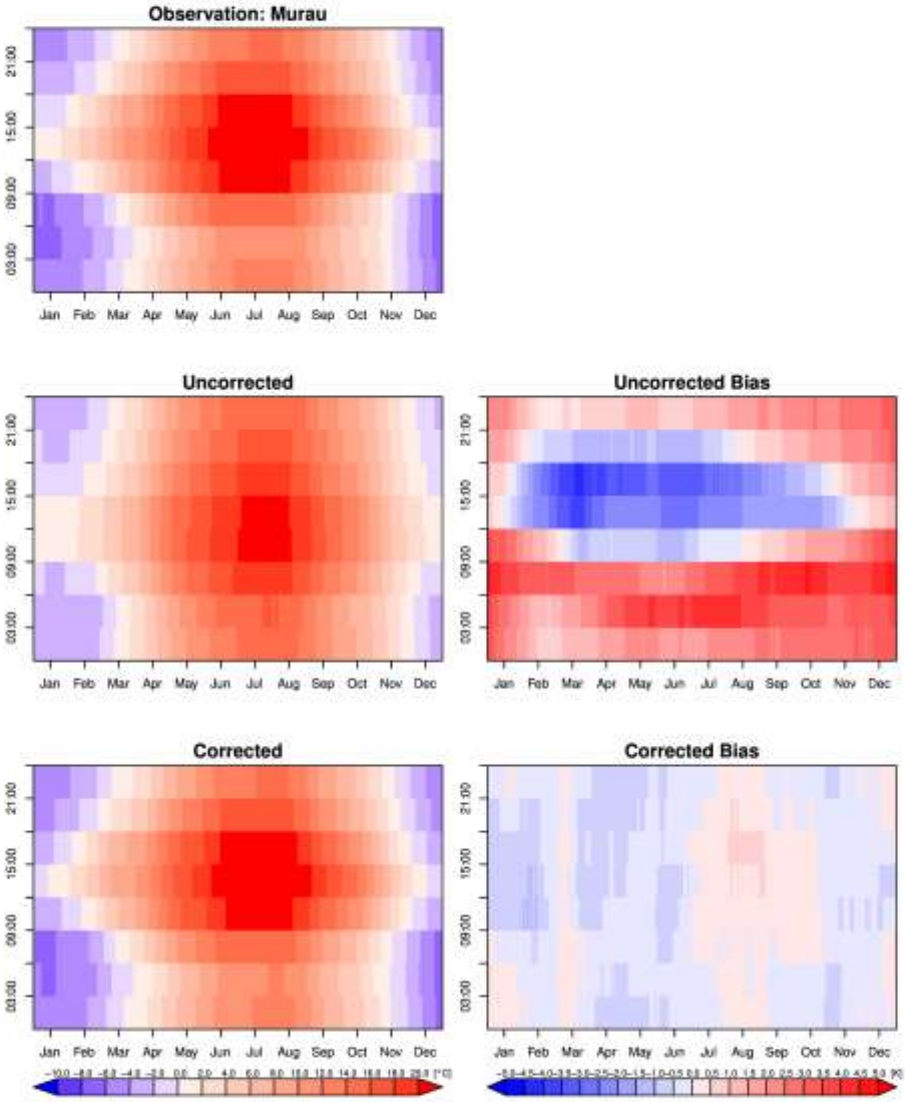

Fig. 4 Left column: Daily temperature cycle in the course of a year (daily increments) for the station of Murau for observed, uncorrected, and corrected temperatures. Right Column: Difference between uncorrected and corrected model output and observations.

Furthermore, most of the uncorrected models overestimate light precipitation frequency (i.e., the "drizzling-effect"; e.g., Gutowski et al, 2003), which is well corrected by QM.

2.1 Sub-daily Temperature

For the evaluation of sub-daily QM, we again apply a split-sample test, using independent 10 year-long evaluation and calibration periods. The calibration period for 3-hourly QM is 1989-1998, whereas the data is validated during the independent period of 1999-2008. Fig 4 shows the bias in the diurnal temperature cycle in the course of a year for the station of Murau. In order to smooth the data, we apply a moving average filter with a length of 30 days centered at the actual day. As can be seen from Fig. 4, the uncorrected SMHI-RCA shows pronounced overestimations in the morning hours between 03:00 and 09:00 while temperatures are underestimated after midday until early evening for most of the year.

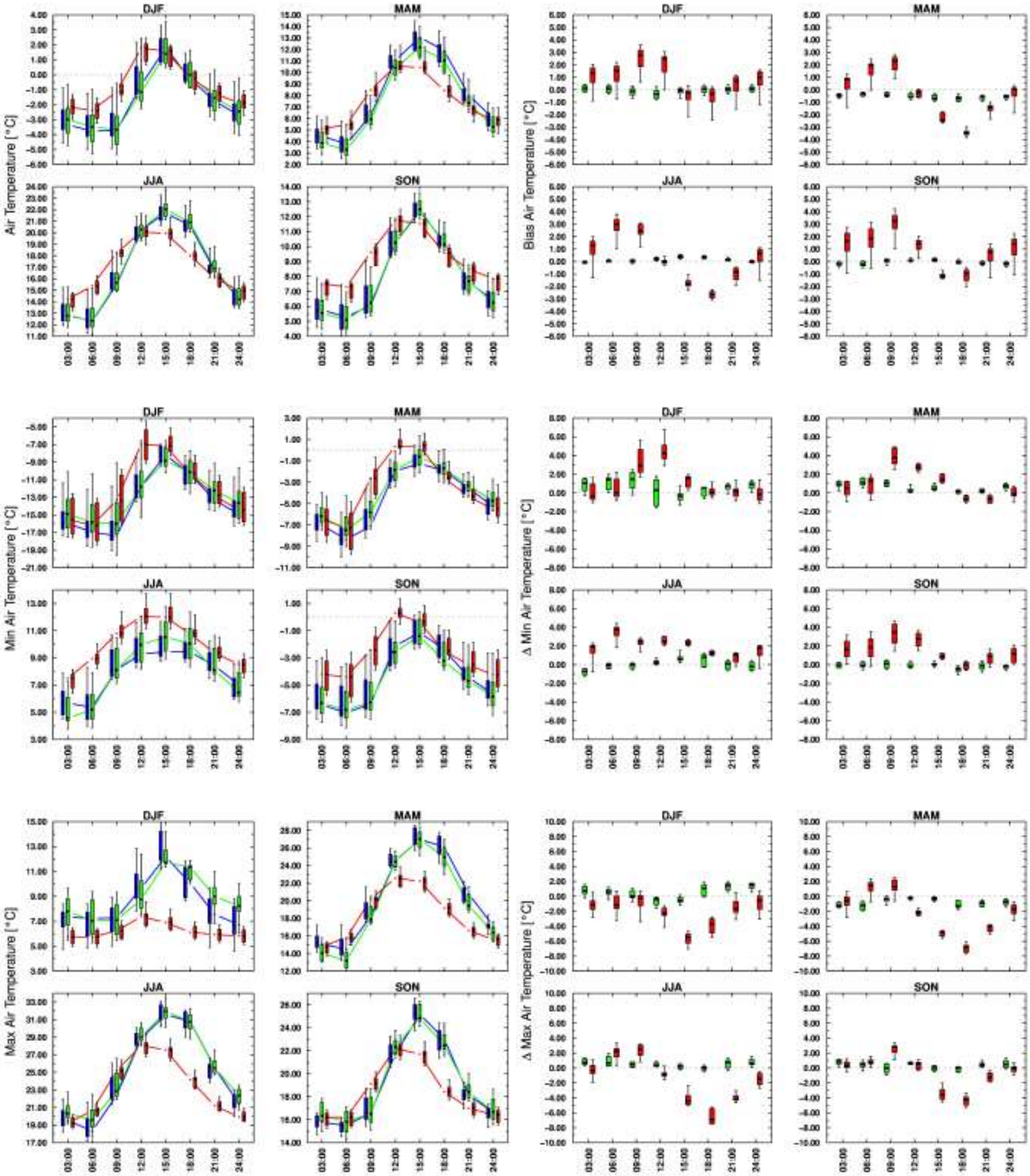

Fig. 5 Diurnal cycle of the observed (blue lines), uncorrected (red lines), and corrected (green lines) temperatures. Left column: Absolute values of the diurnal cycle of 3-hourly mean temperature (upper panel), minimum temperature (middle panel), and maximum temperature (lower panel). Right column: Difference between uncorrected and corrected model output and observations. The box-whisker plots refer to the variability among the eight analyzed stations in Styria and show the 10th, 25th, 50th, 75th, and 90th percentile.

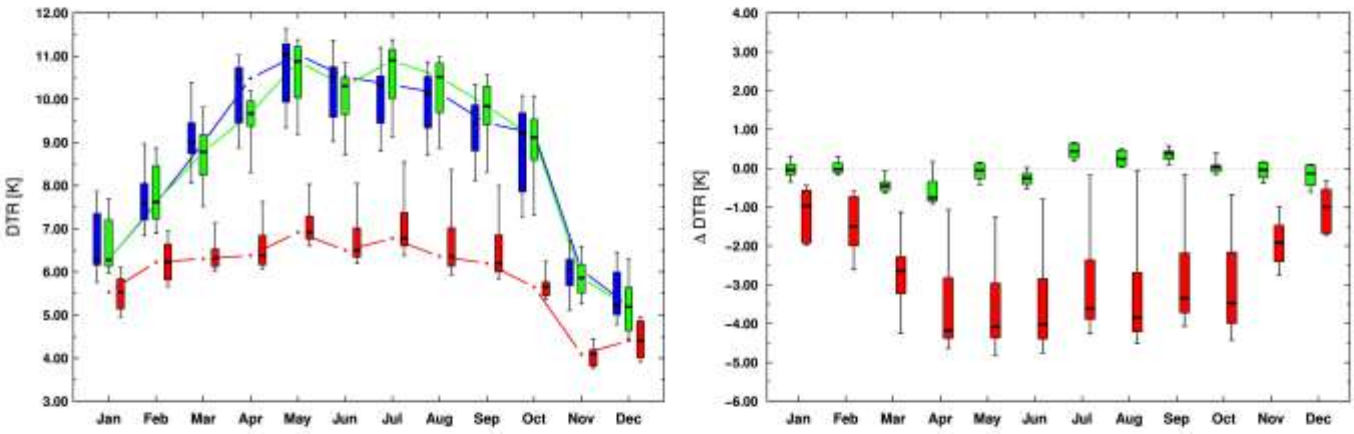

Fig. 6 Left panel: Diurnal temperature range of the observed (blue lines), uncorrected (red lines), and corrected (green lines) temperatures. Right panel: Difference between uncorrected and corrected model output and observations. The box-whisker plots refer to the variability among the eight analyzed stations in Styria and show the 10th, 25th, 50th, 75th, and 90th percentile.

For the corrected SMHI-RCA the biases are drastically reduced by a factor of up to 10 and the corrected diurnal cycles are virtually the same as the observed ones.

Fig. 5 shows the diurnal cycle of observed temperatures (mean, minimum, and maximum) as well as uncorrected and corrected hindcast simulations and the associated errors for the eight analyzed stations in Styria. As can be seen, daily mean temperatures are overestimated during the first half of the day until 12:00 with biases larger than 3 K for single stations. During the second half of the day from 12:00 to 24:00, pronounced negative biases are found in spring (MAM) and summer (JJA) with underestimations up to -3 K between 15:00 and 18:00. Better performance of the uncorrected model with lower biases is found in winter (DJF) and autumn (SON). The large biases are apparently removed by applying QM. However, small errors in the order of 0.5 K remain which can be related to the short calibration period and potential non-stationarities between calibration and validation period. For the 3-hourly minimum temperatures, the uncorrected model mainly shows overestimations which are largest during the first half of the day until 12:00 with errors up to 4 K. Less pronounced underestimations are found in the evening particularly in DJF and MAM. QM improves the diurnal cycle of minimum temperatures. However, larger biases compared to mean temperatures remain which is reasonable as the correction of extremes is generally more challenging, especially for short calibration periods as applied here. The uncorrected diurnal cycle of 3-hourly maximum temperatures is located too early at noon compared to the observations. Furthermore, the daily maximum is strongly dampened in all four seasons. Consequently, the largest biases of the uncorrected model are found in the afternoon and early evening with errors up to -6 K. Again, QM performs astonishingly well and adapts the modeled diurnal cycle to the observed one and consequently strongly reduces the biases. Fig. 6 displays the diurnal temperature range (DTR). The uncorrected model strongly underestimates the DTR in the order of -4 K during spring and summer which can be explained by the under- and overestimation of maximum and minimum temperatures, respectively. QM generally performs well in adjusting the DTR and strongly reduces the bias below 0.5 K.

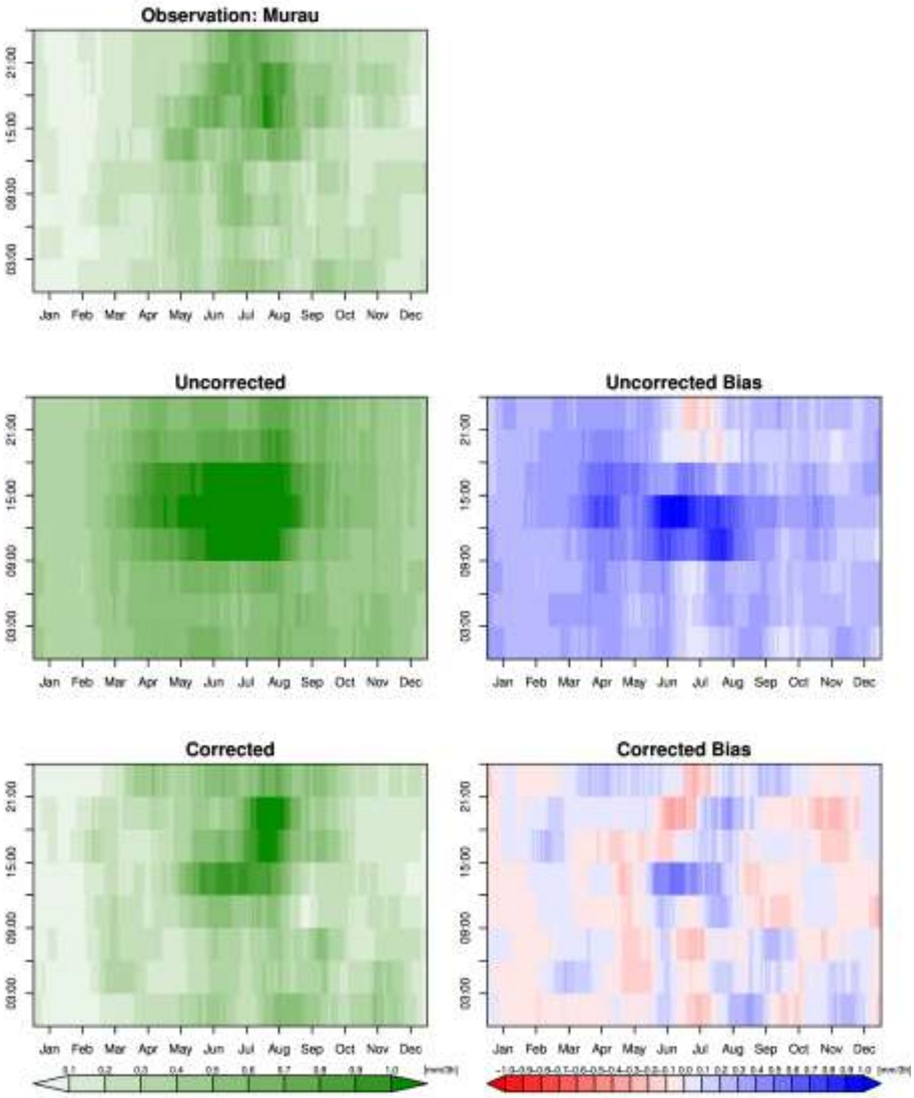

Fig. 7 Left column: Daily precipitation cycle in the course of a year (daily increments) for the station of Murau for observed, uncorrected and corrected precipitation. Right Column: Difference between uncorrected and corrected model output and observations.

2.1 Sub-daily Precipitation

In Fig. 7, the bias in the diurnal precipitation cycle in the course of a year for the station of Murau is displayed. We again apply a moving average filter in order to remove noise in the data. Fig. 7 shows that the uncorrected model mainly overestimates precipitation throughout the day and during the entire year. The most pronounced overestimations of the uncorrected model are obtained from Mai until August between 09:00 and 15:00. QM generally improves the skill of the RCM in representing the diurnal and annual precipitation cycle. Evaluation of the skill of the corrected model under an idealized setup with same calibration and validation periods shows that virtually no error remains (not shown). The biases which remain after correction in Fig. 7 can therefore be related to non-stationarities between independent calibration and validation periods. We further note that possible causes for the non-stationarities are not further investigated in the course of this study.

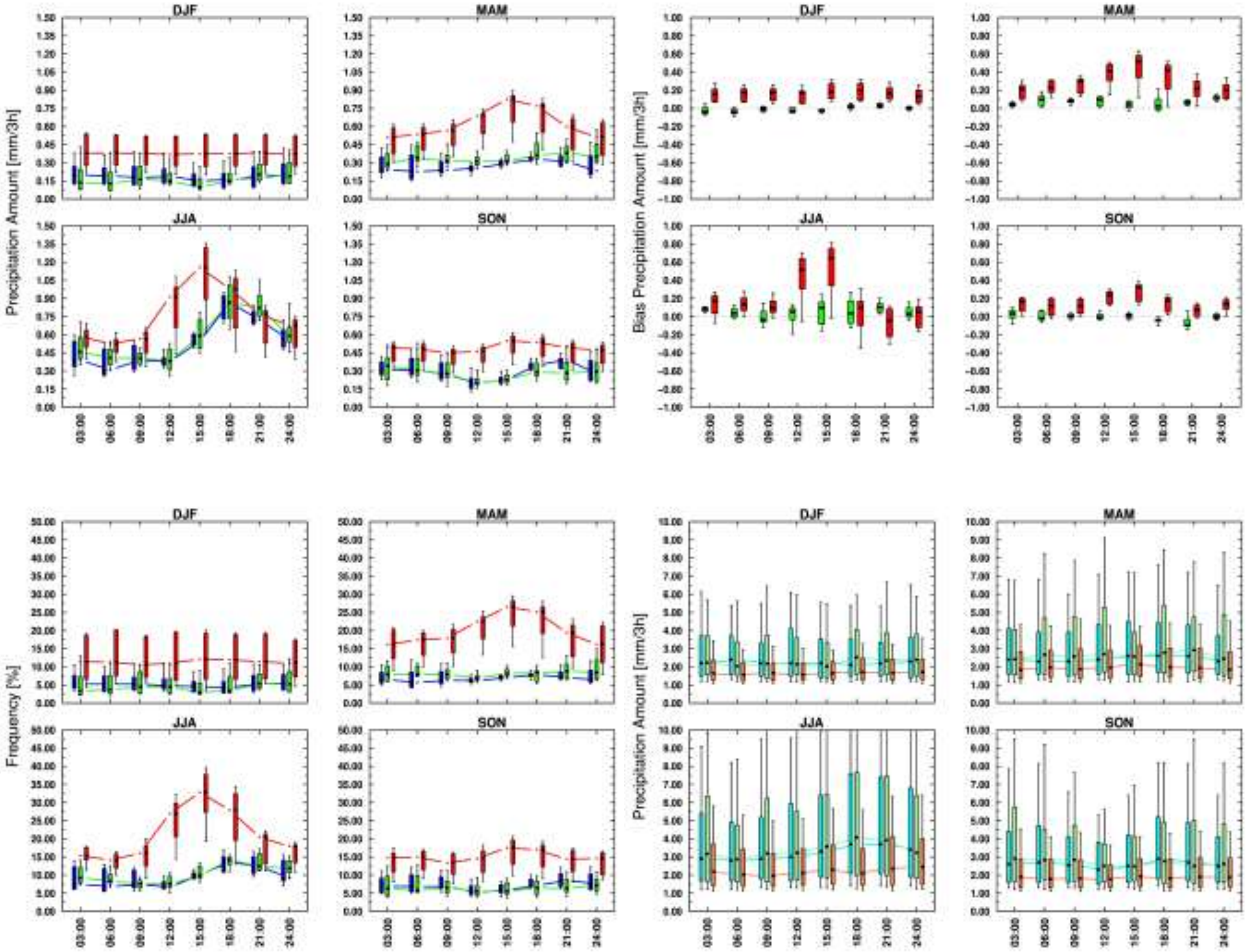

Fig. 8 Upper row: Absolute values of the diurnal cycle of 3-hourly observed (blue lines), uncorrected (red lines), and corrected (green lines) mean precipitation (left panel) and difference between uncorrected and corrected model output and observations (right panel). Lower row: Diurnal cycle of the wet day frequency (left panel) and precipitation distribution for the station of Murau (a threshod of 1 mm/3h is used). The box-whisker plots refer to the variability among the eight analyzed stations in Styria (except lower right panel) and show the 10th, 25th, 50th, 75th, and 90th percentile.

The upper row of Fig. 8 shows the diurnal cycle of 3-hourly observed (blue lines), uncorrected (red lines), and corrected (green lines) mean precipitation and the associated biases. In all four seasons, precipitation is overestimated throughout the day. In summer, a distinct diurnal precipitation cycle is observed, showing a maximum at 18:00 which can be related to convective processes as it also fits well to the observed temperature maximum at 15:00. The uncorrected SMHI-RCA is qualitatively able to reproduce this diurnal cycle. However, the simulated diurnal cycle shows a temporal shift with an earlier precipitation maximum at 15:00. Consequently, large biases are obtained from 12:00 until 15:00 with a magnitude in the order of 0.5 mm/3h to 0.6 mm/3h. QM strongly reduces the errors and both the magnitude as well as the timing are well adjusted. The overestimations in the 3-hourly mean precipitation can be further related to a strong positive bias in the frequency of precipitation events (using a threshold of 1 mm/3h) while the magnitude of precipitation events is underestimated (see lower row of Fig. 8). As can be seen from Fig. 8, QM is able to

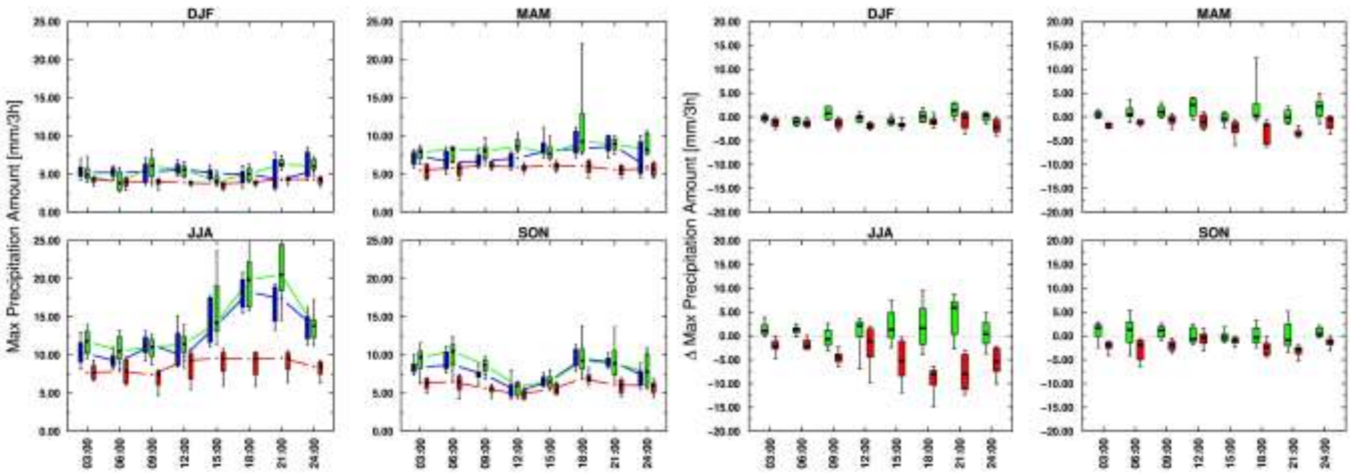

Fig. 9 Absolute values of the diurnal cycle of 3-hourly observed (blue lines), uncorrected (red lines), and corrected (green lines) maximum precipitation (left panel) and difference between uncorrected and corrected model output and observations (right panel). The box-whisker plots refer to the variability among the eight analyzed stations in Styria and show the 10th, 25th, 50th, 75th, and 90th percentile.

correct for errors in the precipitation frequency and also strongly improves the entire precipitation distribution. Finally, Fig. 9 shows the diurnal cycle of precipitaion maximum. The largest errors of the uncorrected model again occur in summer when convective processes play an important role. Here, the shape of the diurnal cycle strongly deviates from the observed one and the magnitude of the maximum precipitation is underestimated throughout the day. Although the correction for maxima is challenging for QM due to the lack of data, QM performs well in adjusting the diurnal cycle of maximum precipitation. Especially in summer, the shape of the diurnal cycle is well adapted and the associated errors are strongly reduced.

3. Summary and Conclusions

In ClimCatch, localized climate information down to the point scale of single meteorological stations is required to assess future changes in torrential sediment transport in a small-scale non-glaciated Alpine valley and the related natural hazards. In order to account the observed local climate information of weather stations and to further improve the skill of RCMs in representing localized present-day climate characteristics, QM is applied to modeled daily and sub-daily temperature and precipitation data. The existing methodology of empirical QM on daily basis is extended to the sub-daily basis and the skill of the correction is investigated. For the evaluation of QM, a split-sample test is applied to daily (3-hourly) model output using independent 15 (10) year-long evaluation and calibration periods.

As already shown in various studies, QM successfully corrects daily precipitation regardless of the shape of the uncorrected distribution and overestimations of light as well as heavy precipitation frequency are well adjusted. For sub-daily temperatures, QM drastically reduces the biases in the diurnal cycles of mean, minimum, and maximum temperature by a factor of up to 10. Furthermore, errors in the DTR due to under- and overestimation of maximum and minimum temperatures are strongly reduced with remaining biases in the order of 0.5 K. For sub-daily precipitation, QM generally improves the skill of the RCM in representing the diurnal and annual precipitation cycle. However, small biases remain after correction which can be related to potential non-stationarities between independent calibration and validation periods. The largest errors of mean and maximum precipitation are obtained in summer during convective processes in the afternoon. QM is able to adjust the timing as well as the magnitude of precipitation and therefore strongly reduces the bias in both cases.

We could demonstrate the succesfull implementation and application of sub-daily QM to produce error-corrected 3-hourly temperature and precipitation data. As extremes play a vital role in ClimCatch, we expect a major benefit from the error-corrected data. However, potential deficiencies of QM related to the spatio-temporal variability of the correted data as well as the temporal sequencing should be investigated in upcoming studies.

References

Denis, B., Côté, J., Laprise, R., 2002. Spectral Decomposition of Two-Dimensional Atmospheric Fields on Limited-Area Domains Using the Discrete Cosine Transform (DCT). Mon. Wea. Rev. 130, 1812–1829. doi:10.1175/1520-0493(2002)130<1812:SDOTDA>2.0.CO;2

Déqué, M., Rowell, D.P., Lüthi, D., Giorgi, F., Christensen, J.H., Rockel, B., Jacob, D., Kjellström, E., Castro, M., Hurk, B., 2007. An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections. Climatic Change 81, 53–70. doi:10.1007/s10584-006-9228-x

Dobler, A., Ahrens, B., 2008. Precipitation by a regional climate model and bias correction in Europe and South Asia. Meteorologische Zeitschrift 17, 499–509. doi:10.1127/0941-2948/2008/0306

Frei, C., Christensen, J.H., Déqué, M., Jacob, D., Jones, R.G., Vidale, P.L., 2003. Daily precipitation statistics in regional climate models: Evaluation and intercomparison for the European Alps. Journal of Geophysical Research: Atmospheres 108, n/a–n/a. doi:10.1029/2002JD002287

Giorgi, F., Mearns, L.O., 1991. Approaches to the simulation of regional climate change: A review. Reviews of Geophysics 29, 191–216. doi:10.1029/90RG02636

Gudmundsson, L., Bremnes, J.B., Haugen, J.E., Engen Skaugen, T., 2012. Technical Note: Downscaling RCM precipitation to the station scale using quantile mapping – a comparison of methods. Hydrology and Earth System Sciences Discussions 9, 6185–6201. doi:10.5194/hessd-9-6185-2012

Hagemann, S., Machenhauer, B., Jones, R., Christensen, O.B., Déqué, M., Jacob, D., Vidale, P.L., 2004. Evaluation of water and energy budgets in regional climate models applied over Europe. Climate Dynamics 23, 547–567. doi:10.1007/s00382-004-0444-7

Maraun, D., 2013. Bias Correction, Quantile Mapping and Downscaling. Revisiting the Inflation Issue. Journal of Climate. doi:10.1175/JCLI-D-12-00821.1

Piani, C., Weedon, G.P., Best, M., Gomes, S.M., Viterbo, P., Hagemann, S., Haerter, J.O., 2010. Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. Journal of Hydrology 395, 199–215. doi:10.1016/j.jhydrol.2010.10.024

Suklitsch, M., Gobiet, A., Leuprecht, A., Frei, C., 2008. High Resolution Sensitivity Studies with the Regional Climate Model CCLM in the Alpine Region. Meteorologische Zeitschrift 17, 467–476. doi:10.1127/0941-2948/2008/0308

Suklitsch, M., Gobiet, A., Truhetz, H., Awan, N.K., Göttel, H., Jacob, D., 2010. Error characteristics of high resolution regional climate models over the Alpine area. Climate Dynamics 37, 377–390. doi:10.1007/s00382-010-0848-5

Teutschbein, C., Seibert, J., 2012. Is bias correction of Regional Climate Model (RCM) simulations possible for non-stationary conditions? Hydrol. Earth Syst. Sci. Discuss. 9, 12765–12795. doi:10.5194/hessd-9-12765-2012

Themeßl, M.J., Gobiet, A., Heinrich, G., 2012. Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal. Climatic Change 112, 449–468. doi:10.1007/s10584-011-0224-4

Themeßl, M.J., Gobiet, A., Leuprecht, A., 2011. Empirical-statistical downscaling and error correction of daily precipitation from regional climate models. International Journal of Climatology 31, 1530–1544. doi:10.1002/joc.2168

Uppala, S.M., KÅllberg, P.W., Simmons, A.J., Andrae, U., Bechtold, V.D.C., Fiorino, M., Gibson, J.K., Haseler, J., Hernandez, A., Kelly, G.A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R.P., Andersson, E., Arpe, K., Balmaseda, M.A., Beljaars, A.C.M., Berg, L.V.D., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B.J., Isaksen, L., Janssen, P. a. E.M., Jenne, R., Mcnally, A.P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N.A., Saunders, R.W., Simon, P., Sterl, A., Trenberth, K.E., Untch, A., Vasiljevic, D., Viterbo, P., Woollen, J., 2005. The ERA-40 re-analysis. Q.J.R. Meteorol. Soc. 131, 2961–3012. doi:10.1256/qj.04.176

Yang, W., Andréasson, J., Phil Graham, L., Olsson, J., Rosberg, J., Wetterhall, F., 2010. Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. Hydrology Research 41, 211. doi:10.2166/nh.2010.004