Precipitation Variability and Extremes in Central Europe

New View from STAMMEX Results

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High-quality quantitative information about precipitation characteristics in Europe, including extremes, is crucial for estimating and modeling observed climate variability and trends in European hydroclimate and floods. The recent flood in early June 2013 over Southern and Southeastern Germany exceeded the water levels of the already record-breaking flood of August 2002. This event was followed by very localized and extremely heavy precipitation events in the latter half of June in Western Germany. These two events give a flavor of the strongly localized character of European precipitation, with spatial patterns ranging from a few to several tens of kilometers. The strongest clustering of precipitation patterns is observed in summer when its structure is dominated by convective processes. This poses strong requirements for the spatial resolution of rain gauge networks used for quantification of spatial and temporal variability of rainfall patterns. The sparse rain gauge networks usually used for climate assessments—despite their long and continuous daily records—cannot effectively capture such strongly localized precipitation extremes, especially in regions with complex orography where precipitation patterns are extremely inhomogeneous in space and highly variable in time. Multiannual gridded products based on these sparse network rain gauge collections, although extremely valuable for the assessments of long-term continental-scale changes in precipitation and their further intercomparison with climate model simulations, are hardly useful for the evaluation of experiments with regional high-resolution models targeting case studies of extreme events.

Here we provide a brief overview of the newly developed set of high-resolution daily precipitation grids over Germany, which are derived from the daily-observing precipitation network of the Deutsche Wetterdienst (DWD). High-resolution daily grids covering in different data streams the period from 1931 onward were developed under the STAMMEX (Spatial and Temporal Scales and Mechanisms of Extreme Precipitation Events over Central Europe) project funded by the DFG (Deutsche Forschungsgemeinschaft) and supported by DWD, the Meteorological Institute of the University of Bonn, and the North Rhine Westphalian Academy for Science and Arts.

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DOI:10.1175/BAMS-D-12-00134.1
A supplement to this article is available online (10.1175/BAMS-D-12-00134.2).

NATIONAL DWD RAIN GAUGE NETWORK. The DWD rain gauge network is one of the densest and most properly maintained regional precipitation networks. It consists of 11,617 stations, of which about 7,500 have been digitized, quality-controlled, and included in a digital database. In the last four decades, when sampling was the densest, the typical station-to-station distance was 3–10 km in the southern and central parts of Germany and 5–20 km in the northern and eastern parts (Fig. 1a–c). The number of continuously reporting gauges increased since the late 1940s from about 2,000 to more than

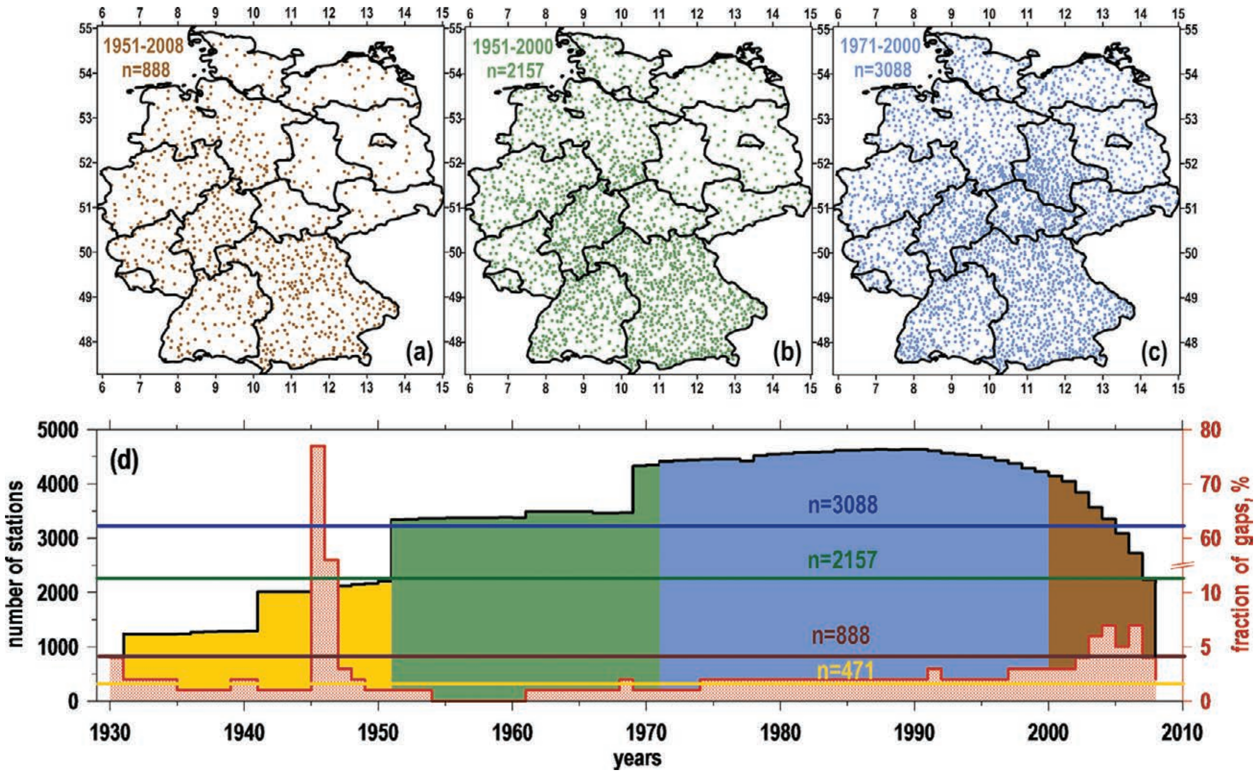

Fig. 1. Maps with the locations of stations used for the production of gridded data for (a) 1951–2008; (b) 1951–2000; and (c) 1971–2000; and (d) time series of changes in the total number of stations (black line, left axis) and the number of gaps (red line, right axis) for different STAMMEX datasets. The total number of stations shown in panel (d) includes only gauges reporting for at least 30 years. The actual total number of gauges (including those reporting for only a few years and which were used for the development of STAMMEX 0.25° dataset based on all available stations) is larger and amounts to 7,561. Horizontal lines mark the numbers of stations for which the number of gaps was less than 10% and which were used for the development of STAMMEX products based on simultaneously reporting stations for different periods.

4,000 stations until about the year 2000, when the collection experienced a decline of about 10%–15% (Fig. 1d). All DWD stations are equipped with Hellmann rain gauges with a 200-cm^2 collecting surface and seasonally activated snow crosses and lids. Since the 1950s, the gauges have been equipped with antifreezing agents. In the 1990s, the Hellmann gauges were replaced at most stations by tipping buckets combined with drop-counting (for low rain rates) rain gauges with the same orifice of 200 cm^2 and a heated funnel controlled by thermostats. In the early 2000s, DWD started to implement the second generation of automatic weighing gauges (the so-called Pluvio devices). Generally, the heated tipping-bucket gauges may imply an uncertainty resulting from evaporation and/or sublimation from the gauge. The new Pluvio systems measure precipitation continuously; thus, this effect is negligible compared to the earlier gauges collecting precipitation over 24 h. The uncertainty associated with the use of heating devices built in different types of instruments is, however, estimated to be much smaller than those related to wind effects.

The measurement precision of the DWD gauges is 0.1 mm. With the installation of the Pluvio devices in the early 2000s, automatic readings started to replace the manual readings. However, this upgrade did not affect the reading time for daily precipitation sums, which remained at 07:30 local time. Every month, the daily records are transmitted to the regional preprocessing offices for quality checks and thereafter transferred to DWD headquarters at Offenbach, where they are repeatedly quality-checked, undergo correction procedures, and are finally archived. Correction procedures include adjustments of the reading time and accounting for instrument exposition (when possible). The main observational error source is the impact of wind on rain gauge measurements. Although most of the DWD rain gauges are still run

Table 1. Overview of the STAMMEX gridded daily precipitation products: setting of methodologies, periods of availability, and spatial resolution.

GRIDDING METHOD				
Kriging			Grid-cell averaging	Distance weighting
Background window: 30 days	Background window: 20 days	Background window: 10 days		

Time period	Resolution
1951–2008	0.25° × 0.25°, 0.5° × 0.5°, 7,561 stations, daily means and uncertainties
1931–2008	0.5° × 0.5°, 471 stations (West Germany only), daily means and uncertainties
1951–2008	0.5° × 0.5°, 888 stations, daily means and uncertainties
1951–2000	0.25° × 0.25°, 0.5° × 0.5°, 2,157 stations, daily means and uncertainties
1971–2000	0.1° × 0.1°, 0.25° × 0.25°, 0. 5° × 0.5°, 3,088 stations, daily means and uncertainties

by volunteers with gauges being placed in their gardens and, thus, to some extent being protected against the wind impact by the surrounding vegetation and buildings, the wind-associated error is present in the daily DWD rain gauge data. Appropriate corrections, which should be based on collocated wind measurements, are hardly applicable due to missing wind information for most of the gauge locations. The total error of the Hellmann gauges, due to evaporation loss and wind effects, is estimated to be in the range of ±10% for the DWD network.

STAMMEX GRIDDED PRODUCTS. *Data selection.* The STAMMEX strategy was to derive different gridded datasets optimized for different purposes. Specifications may range from merging all available observations to using subsampled datasets, in order to guarantee temporal homogeneity of sampling. Some resulting gridded datasets should be exclusively based on stations continuously reporting during the time period for which the respective dataset is built. Products based on the full observational dataset will be suitable for case studies, while products with homogenized sampling will be more applicable to climate variability analyses. Thus, our approach differs from, for example, the ECA (European Climate Assessment) strategy: their E-OBS dataset based on the European collection of rain gauges contains about 500 DWD stations in 1950 and increases to about 800 in the 1990s, with many stations providing data for just a few years. Using all available (and thus, a time-varying number of) stations may result in time-dependent biases and, consequently, impact estimates of trends and variability. To avoid such inhomogeneity, STAMMEX products were made available for four time periods with spatially varying extent (Table 1, Fig. 1):

1) The Western Germany dataset from 1931 onward has a 0.5° spatial resolution and is based on 471 stations;
2) 1951 onward, with 0.25° and 0.5° spatial resolutions (based on all available 7,561 stations) and with 0.5° resolution (based on 888 simultaneously reporting stations);
3) 1951–2000, with 0.25° and 0.5° spatial resolutions based on 2,157 simultaneously reporting stations; and
4) datasets for the best-sampled 30-yr period, 1971–2000, with 0.1°, 0.25°, and 0.5° resolution (3,088 simultaneously reporting stations).

During these periods, the number of gaps in selected subsets of reporting rain gauges was less than 3% except for a 2-yr period (1945–46). Supplement A provides information on data coverage for selected periods and the number of stations per grid cell for different spatial resolutions.

Gridding procedures. Spatial gridding for all STAMMEX gridded products has been provided by several gridding procedures. As a reference, we used kriging, in which semivariogram parameters, influence radii, and weighting coefficients were derived for each individual grid cell and day, accounting for the local arrangement of the available reporting gauges. Kriging was applied to the fractional anomalies around long-term background values. Fractional anomalies were computed by transforming actual anomalies to the anomalies of contributions of daily values to the totals accumulated during the background period. In order to derive the background values we first estimated shape and scale parameters of the gamma distribution for all stations in the grid cell. Averages of the grid-cell parameters of the Gamma distribution were used to derive background values for a given time window (e.g., month). Computations were performed for the background window varying from 10 to 30 days, with a 30-day window applied for the production of the reference datasets and the others used for supplementary gridded datasets. Besides kriging, we also used several alternative gridding procedures (e.g., conventional grid-cell averaging and distance weighting supplemented with a modified method of local procedures for interpolation in fully unsampled cells). This allowed for the development of supplementary gridded products that are equally available for the users and can be used for studying the sensitivity of the method of gridding of long-term tendencies and short term signals. Further details on the gridding procedures are presented in Supplement B.

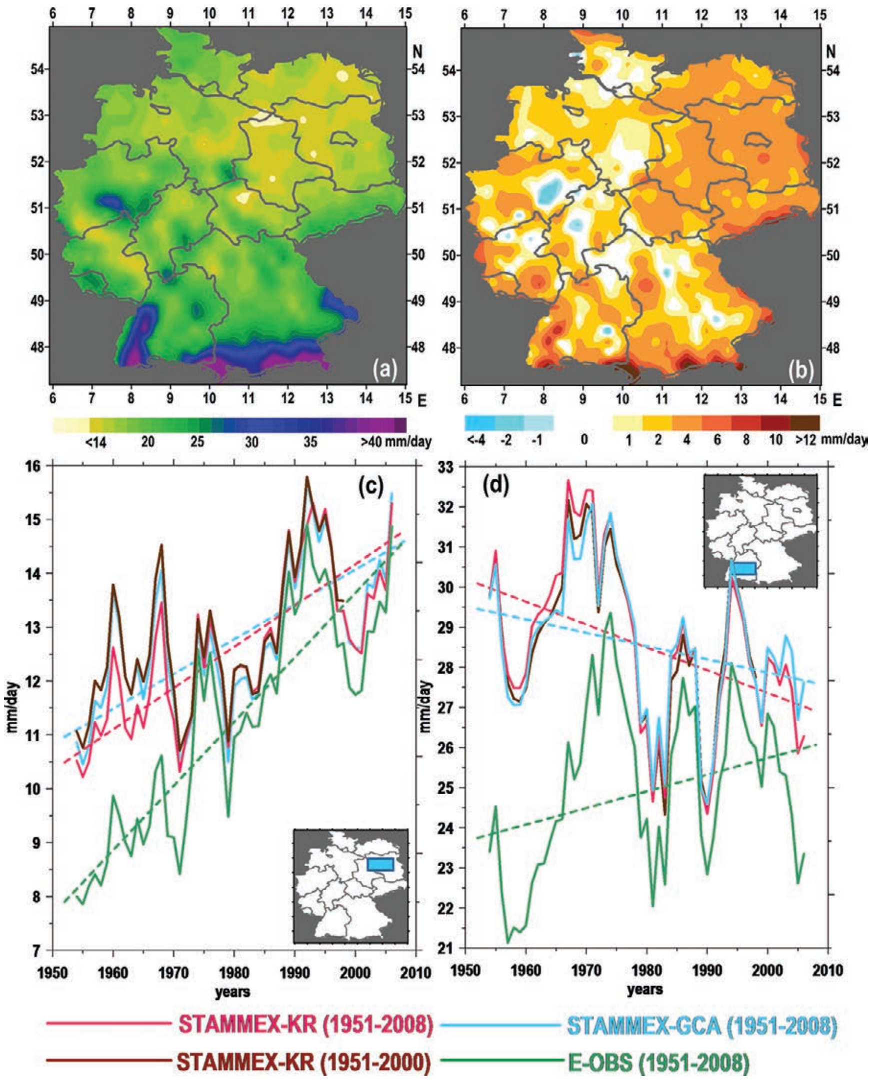

Fig. 2. (a) Long-term annual average of the intensity of very heavy precipitation (99th percentile of daily precipitation) for the period 1950–2000 at 0.25° resolution derived from STAMMEX daily climatology; (b) differences in the 99th percentiles of daily precipitation between STAMMEX and E-OBS datasets, and smoothed 5-yr running mean time series of the 99th percentile of daily precipitation derived from STAMMEX grids using kriging for 1951–2008 (red), 1951–2000 (brown), and using grid-cell averaging for the period 1951–2008 (blue) as well as from E-OBS grids (green) for (c) the winter season over Brandenburg, Saxony-Anhalt, and Berlin and (d) for the summer period over Baden-Württemberg. Regions for which the time series were derived are shown in inlay maps by blue boxes.

Uncertainty estimates. All STAMMEX daily precipitation grid-cell values are accompanied with uncertainty estimates. Besides standard estimates of the kriging uncertainty, we developed error estimates by a bootstrapping algorithm. For each grid cell (0.5°, 0.25°, and 0.1°), we excluded up to half of the randomly selected stations from those falling within the impact radius, and then repeated the gridding procedure without these stations. This procedure was applied several times to every grid cell. Statistics of the differences between values derived from all stations and from the randomly generated subsets were used to characterize uncertainties (see Supplement C for details). These uncertainty estimates were thereafter used to select an optimal setting of the gridding algorithm, including the choice of semivariogram, background window, and interpolation methodology.

Gridded products. Finally, we developed several sets of gridded products for the four periods of data streams with different spatial resolutions (Table 1). Each stream includes daily precipitation grids and uncertainty estimates (derived using kriging with a 30-day background window) as a reference dataset. Furthermore, each stream includes similar daily grids derived using different background windows (grids are provided for 10- and 20-day windows) and two alternative gridding procedures, all of which are accompanied with their uncertainty estimates. For all streams, we also provide files with the number of stations per grid cell. Furthermore, for the grids we also provide supplementary files with blanking fully unsampled grid cells. These additional files can guide users on the actual data coverage in STAMMEX products. The complete STAMMEX database consists of 27 gridded arrays for the periods; all are publically available.

CLIMATOLOGICAL AND SYNOPTIC APPLICATIONS. *Long-term climatology and extremes.* New high-resolution STAMMEX daily precipitation grids allow the development of a large set of climatological characteristics of precipitation relevant for regional climate studies, extreme-event statistics, and the validation of regional climate models. The supplementary datasets provided with the STAMMEX daily grid data include monthly and seasonal precipitation totals, intensities, number of wet days, characteristics of heavy (95th percentile) and very heavy (99th percentile) precipitation, as well as characteristics of relative extremeness derived from standard indices, the distribution of fractional contribution (DFC), and statistics of wet- and dry-spell durations. As an example, Fig. 2a shows the annual climatology of the intensity of very heavy precipitation (99th percentile) for the 1951–2000 period as derived from the STAMMEX 0.25°-resolution product. This figure reveals areas with locally high and very heavy precipitation in central western Germany and in the mountain regions of southern Germany with a climatological intensity reaching 50 mm day^{-1}. Over most of the country, the STAMMEX products reveal very heavy precipitation 10%–25% higher than the E-OBS 0.25° grids based on a limited collection of stations (Fig. 2b), while climatologies of the mean precipitation are generally consistent in the two products, with somewhat better regionalization in the STAMMEX product (See Supplement D). Figure 2b systematically identifies higher estimates of very heavy precipitation over Eastern Germany by 4–7 mm day^{-1} in STAMMEX and the regions in southern Germany where STAMMEX-based estimates indicate an annual very heavy precipitation more than 10 mm day^{-1} higher compared to the E-OBS product (i.e., up to a 25% increase). Although the considerably higher STAMMEX precipitation extremes are persistent in all seasons, the largest differences (up to 40%) are observed in summer, where only very dense observational networks can capture extremes associated with strong convective processes.

Climate variability in precipitation. STAMMEX products allow for detailed regional analyses of the observed climate variability in mean precipitation intensity and in precipitation extremes. Estimation of linear trends for the last six decades from STAMMEX daily grids reveals upward trends in cold seasons with the maxima of more than 6% per decade in northern Germany, and mostly negative trends in summer, with the strongest downward tendencies in central Germany and in Baden-Württemberg, amounting to 5.5%–6% per decade. This seasonality in heavy and extreme precipitation is also evident in the mean intensity and confirms earlier analyses based on individual station data. Spatial structures of linear trends in precipitation characteristics derived from STAMMEX grids are more detailed compared to those revealed by E-OBS. In particular, important local features associated with orography are evident that are not seen in the coarser resolution grids based on a limited collection of rain gauges as well as in reanalyses and satellite (e.g., GPCP, TRMM, CMORPH, PERSIANN) data. Importantly, the homogenized sampling in the STAMMEX daily products results in both quantitative and qualitative differences in trend estimates compared to the E-OBS grids for the same large regions. Figures 2c and 2d show seasonal time series of the 99th percentile of daily precipitation for central eastern (winter) and southwestern (summer) Germany derived from different STAMMEX products and E-OBS data. There is a very close agreement between the time series and linear trend estimates across different

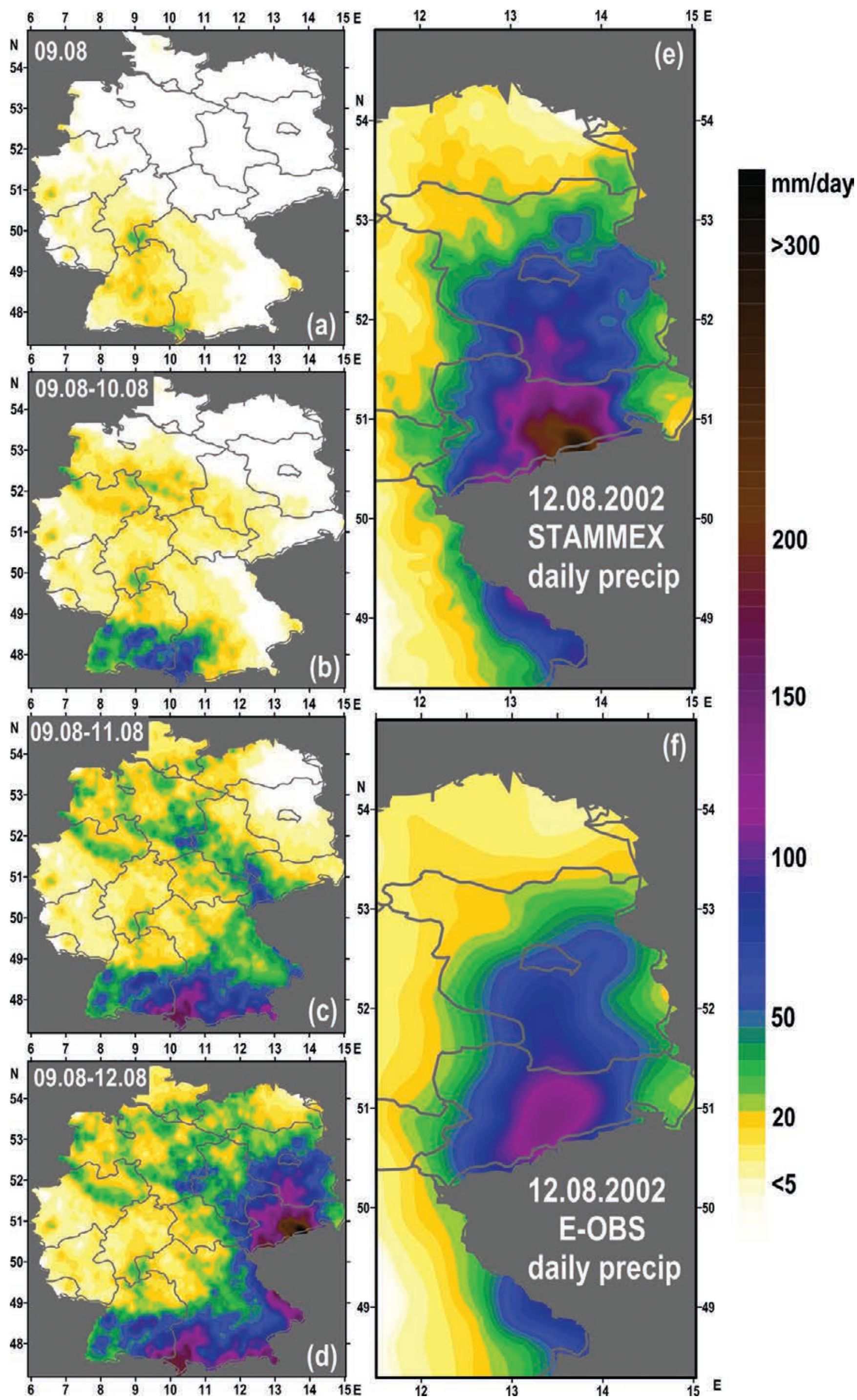

Fig. 3. (a–d) Accumulated daily precipitation over Germany for the period 9–12 Aug 2002 from STAMMEX daily grids, and daily precipitation for 12 Aug 2002 derived from (e) STAMMEX and (f) E-OBS grids.

STAMMEX products based on kriging and grid-cell averages as well as on different subsets of stations (Figs. 2c,d). However, they all reveal both quantitative and qualitative differences in the estimates of linear trends compared to E-OBS data. Thus, in southern Germany—which is known for a strong seasonality in trends of extreme precipitation—STAMMEX data show a negative trend of about −0.54 mm day^{-1} decade^{-1} (about 12% decrease during the observational period), while E-OBS reports alternatively a positive trend of about 8% during the last six decades. Importantly, the major discrepancy in the time series results from the first part of the record, where the differences between STAMMEX and E-OBS estimates are approximately twice as large compared to the latest decades. Similarly, in eastern Germany in winter (Fig. 2c), STAMMEX reports trends twice as small compared to E-OBS, with the difference between the area-averaged time series progressively declining from 2 to 0.3 mm day^{-1}. The most probable cause of the differences in mean precipitation between the two products for the first 20 years of the assessed period [i.e., in the 1951–70 period (Figs. 2c and 2d)] is a changing number of rain gauges used in the E-OBS product.

Synoptic applications and case studies of extreme precipitation. However, the major potential of STAMMEX data is the diagnostics of extreme precipitation events, particularly those leading to disastrous floods in Central Europe. Figure 3 shows the development of precipitation patterns during the disastrous European floods in August 2002 that resulted in unprecedented economic losses exceeding 16 billion Euros and more than 110 fatalities in Austria, the Czech Republic, and Germany. Accumulated precipitation during the 5-day period amounted to more than 250 mm in many regions of southeastern Germany (especially over the Free State of Saxony) and peaked at more than 300 mm south of the city of Dresden. The city was heavily flooded, with the water level in the Elbe River 9.4 m above normal. STAMMEX grids accurately replicate the maximum daily precipitation on 8 December 2002, which amounted to more than 265 mm day^{-1} in the area of Zinnwald-Georgenfösld (Fig. 3e), where the local rain gauge reported just slightly higher values. Based on a coarser resolution network, the E-OBS precipitation grids show for this date only half of the daily precipitation, which peaked at 133 mm day^{-1} (Fig. 3f) and was located about 50 km northwest. Here STAMMEX reports nearly 100 mm day^{-1} higher values. Importantly, the STAMMEX grids also capture the tongues of extreme precipitation higher than 80 mm day^{-1} aligning to the Polish border, which have heavily affected western Poland, while the E-OBS grids report 10–25 mm day^{-1} less precipitation in this region (Fig. 3f). This example shows that STAMMEX products are extremely useful for the validation and further improvement of the regional and local climate estimates and NWP models simulating precipitation and flooding events over other densely populated river valleys, during severe thunderstorms over city areas, and at heads of mountain rivers. They are thus indispensable for accurately monitoring extreme events and impact assessments. Another important realization from analyzing the STAMMEX results for some other regions where dense rain gauge networks similar to those available for Central Europe are absent or are not shared/accessible is that one has to be careful when using coarse resolution grids for assessments of the consequences of extreme rain events. These coarse resolution products may not necessarily accurately reproduce individual rainfall clusters typical for the region and event analyzed. In addition, a spatial resolution of 3–20 km in a terrain as varied as in Germany seems appropriate to quantify small-scale precipitation events.

AVAILABILITY AND UPDATES. Daily gridded data for different time periods, along with the readme files and access codes, are available through the STAMMEX website (www.olgazolina.com/?file=kop10.php). In addition, long-term monthly and seasonal precipitation statistics for different periods as well as a dynamic map environment is now under construction at the same site. STAMMEX products currently cover the period until 2008 and will be regularly updated in the future.

ACKNOWLEDGMENTS. We appreciate comments and suggestions of the two anonymous reviewers, which helped to improve the previous version of this manuscript. Discussions with Klaus Peter Koltermann of MSU (Moscow) are appreciated. We thank the Deutsche Forschungsgemeinschaft for funding the STAMMEX Project under the contract PN-50160119 and the Deutsche Wetterdienst for continuous support of the project and data supply. We also benefited from the support of the Russian Ministry of Education and Science under the contracts 14.B25.31.0026 and 14.577.21.0048, as well as from the support of Université Joseph Fourier and LGGE (Grenoble).

FOR FURTHER READING

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