Seventh Framework Programme
Theme 6 [SPACE]

Project: 607193 UERRA

Full project title:

Uncertainties in **E**nsembles of **R**egional **R**e-**A**nalyses

Deliverable D4.7

HARMONIE, MO and MESCAN hydrological evaluation report

WP no:	4
WP leader:	KNMI
Lead beneficiary for deliverable :	SMHI
Name of author/contributors:	Peter Berg, Abdulghani Hasan, Wei Yang
Nature:	Report
Dissemination level:	PU
Deliverable month:	45
Submission date: December 19, 2017	Version nr: 1

Report for Deliverable 4.7 (D4.7): HARMONIE, MO and MESCAN hydrological evaluation report

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Precipitation from the UERRA data sets from HARMONIE, MO and MESCAN are analysed from a hydrological perspective. A hydrological evaluation is comparing routed precipitation with long term discharge observations, with an emphasis on water and energy conservation. The method requires time series on the order of ten years and we have therefore focused on evaluating the HARMONIE, MO and MESCAN data sets that were available with sufficient time periods in time for the study. The main findings are a general overestimation of precipitation throughout the domain, except for the coast of Norway and northern UK where there is underestimation.

1   Introduction

Precipitation falling on land can go directly back into the atmosphere through evaporation, into runoff and through river networks to eventually end up in the ocean, or it can go into several different buffers. These buffers are e.g. ground water, taken up by biota, or collected in lakes, wetlands and other freshwater reservoirs. Eventually, the water will continue through these buffers to the ocean, or by evapotranspiration into the atmosphere. Therefore, when observed over a longer time period, precipitation falling within a catchment should at minimum always be larger than the amount of water observed as discharge from the catchment. For most catchments, the measured discharge should rather be a smaller fraction of the accumulated precipitation, due to loss by evapotranspiration in the course of reaching the discharge station.

The advantage of using a discharge station over rain gauges is the complete sampling of all precipitation that reaches the ground and is routed to the gauging station, and no under-catch issues. The disadvantage is delays in form of intermediate storage and routing through the basin, as well as loss terms in the form of evapotranspiration.

In this report, the pan-European hydrological model E-HYPE is used to route precipitation to enable direct comparison to observed discharge. The discharge gauges were quality assessed and collected for the full periods of the UERRA data sets MESCAN, MO and HARMONIE.

2   Model and Data

2.1   The E-HYPE model

The HYPE model (Hydrological Predictions for the Environment; Arheimer et al., 2008) is a semi-distributed, process-based model that simulates hydrology following a multi-basin concept, where multiple catchments are modelled in a consistent way (Figure 1). Here, we make use of the European setup of the model, called E-HYPE (Hundecha et al., 2016). The landscape is divided into different classes according to altitude, soil type and vegetation. In E-HYPE there are over 35'000 catchments with an average size of 250 km^2, see Figure 1.
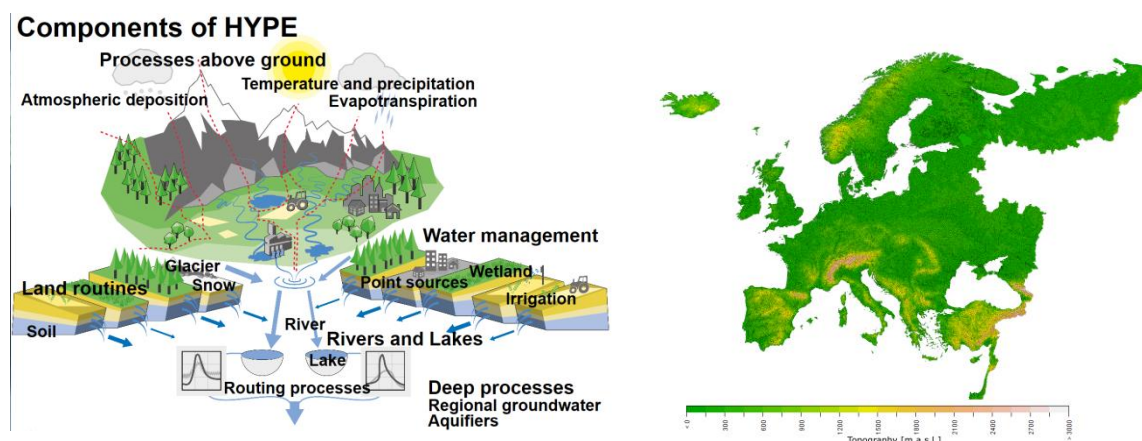
Figure 1: (left) Conceptual image of the HYPE model and its components. (right) Topograghical map of the E-HYPE subbasins (black).

E-HYPE is used for two purposes in this study: (i) to accumulate gridded precipitation over catchments to route all water to the river mouth and (ii) to produce an estimate of the potential evapotranspiration. Evapotranspiration plays an important role, as besides routing of water, this is the only way water can leave the system. Evapotranspiration encompasses direct evaporation (sublimation) of water (snow) from soil moisture and open water, as well as transpiration from plants and trees. In the current set up of E-HYPE, evapotranspiration is calculated using a simple temperature exceedance relationship. This equation estimates the evapotranspiration assuming a linear relationship with the daily mean temperature above a threshold temperature, usually 0. This has been shown to achieve a sufficiently good simulation of evapotranspiration in a large range of catchment scales, climates and physiographies, such that the balance between precipitation, evapotranspiration and discharge is achieved (e.g. Oudin et al. 2005).

Because E-HYPE is working with delineated catchment described as polygons of varying sizes and shapes, it is necessary to map the meteorological forcing data (temperature and precipitation) onto the catchments. This is performed by locating the closest grid point of the forcing data to the centroid point of each catchment. Note that this estimate is only valid for data at approximately the same grid resolution as the catchment areas, and that systematic effects may arise between forcing data sets of different spatial resolution. A first step of remapping all data sets to a common resolution is therefore introduced, see Section 2.2.

2.2 Meteorological forcing data

The goal of this study is to evaluate precipitation estimates produced by the different UERRA model systems. The data requirements of the current analysis are explained in Section 2.3, and for this reason there were only three UERRA data sets that were possible to investigate at the time the work was carried out, namely HARMONIE, MESCAN and MO, see Table 1. As reference data, we use the SMHI produced data set called GFD (Global Forcing Data; Berg et al., 2017), which is also the data set for which E-HYPE was calibrated (Hundecha et al., 2016).

All three model systems are based on ERA-Interim (Dee et al., 2011) reanalysis data at some point in their construction. Briefly:

- GFD is produced by for each single month, scaling the ERA-Interim time series with monthly observations of temperature and precipitation from the CRUts3.21 (Harris and Jones, 2014) and GPCCv7 (Schneider et al., 2015) data sets respectively.

- HARMONIE and MO produce a dynamical downscaling, including assimilation, and takes boundary conditions from the ERA-Interim reanalysis (e.g. Dahlgren and Gustafsson, 2012).
- MESCAN is a statistical model that performs further downscaling of the HARMONIE data and includes station observations (Soci et al., 2016).

Table 1: List of data sets included in the analysis.

Dataset	Resolution	Period(s)
GFD	0.5°	1959-2013
HARMONIE	0.11°	1961-2014
MESCAN	5 km	1981-1990; 2000-2010
MO	0.11°	1981-1990; 2000-2010

As mentioned in Section 2.1, each data set is remapped to a common grid, and here we use the regular 0.5° grid of GFD. The remapping was carried out using conservative methods, such that all grid points were used in the remapping so that water is conserved.

The evaluation presented in Section 3.2, is based on the merged periods 1981-1990 and 2000-2010, which is available for all three models. The GFD and HARMONIE data were also investigated for the long periods, but with no significant differences in the end results and therefore not shown.

2.3   Discharge observations

The discharge observations have been collected from various sources all over Europe. Initial quality checks disqualified some problematic stations. For the hydrological analysis carried out here, we require at least ten years of data, not necessarily consecutive, with no significant data losses during any particular year, as explained in-depth in Section 2.4.

With these criteria in mind, the discharge data are scanned for missing data within any given year. We identify stations that have at least ten years of data with at most 0, 10, 20, and 26% data losses for any particular year, see Figure 2. From the total of 2689 stations available, only little over 500 have problems with missing data during the full period of investigation (1961-2010). In order to remove the uncertainty introduced by the missing measurements of discharge, which might impact significantly on the annual discharge, we decide to use the stations with complete records. Thus, the analysis is performed using 2154 of the discharge stations within the E-HYPE domain.
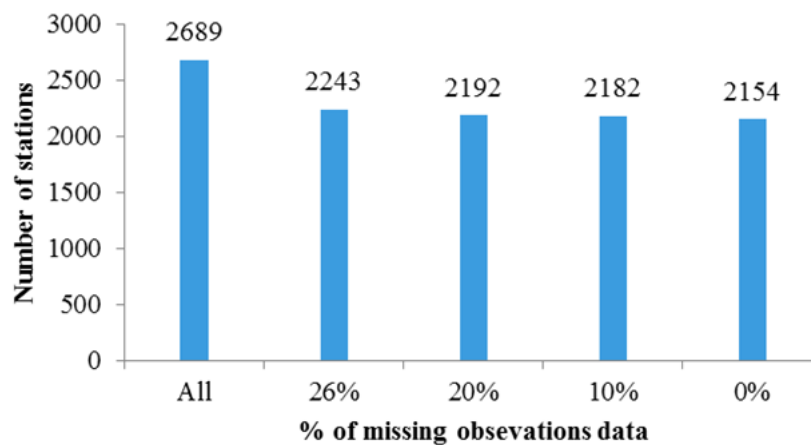

Figure 2: Number of stations out of total 2689 stations. 2154 stations are with no missing data for at least 10 years.

2.4 Metrics and definitions

Discharge is normally described in units of m^3/s, but for direct comparison to the precipitation falling in the upstream catchment it has here been converted to units of mm/day by dividing by the upstream area from the point of the observation.

A catchment's water balance takes the form of:

$$P = E_A + R + \epsilon$$

where P is precipitation, E_A is the actual evapotranspiration, R is the runoff and ϵ is a rest term including various changes in storage, e.g. changes in ground water, lake level or glacier mass. Berg et al. (2014) showed that ϵ can be neglected regarding glaciers, and argued that with longer time series of more than ten years changes in soil and lake storage can be assumed to be in balance, i.e. with no net contribution to the water balance equation.

Further constraints are that there is less runoff than precipitation,

$$R \leq P \quad or\ equivalently\ \ RC = \frac{R}{P} \leq 1$$

(where RC is the *runoff coefficient*), and

$$P - R \ \approx E_A \leq E_P$$

where E_P is the potential evapotranspiration, i.e. the highest rate of evapotranspiration possible.

A violation of the first constraint means that too little water is introduced to the catchment, which we call a *water violation*. The second constraint is that of energy conservation, i.e. water should not be evaporated at a higher rate than allowed by the available energy as estimate using the concept of potential evapotranspiration leading to an *energy violation*. We estimate the actual evapotranspiration using measured discharge and modelled precipitation as described in the equation.

For the concepts described above, observed discharge is aggregated over each year, and then averaged over the time period to produce a climatological annual value. The same calculation is carried out for precipitation in the upstream area. In the analyses, all discharge information is used. For cases where several discharge gauges are available at different points along a particular river network, each gauge is analysed separately using the full upstream area.

3 Results

3.1 Meteorological comparison

We present here a brief comparison of the precipitation data sets. Figure 3 presents the annual mean daily precipitation rate for the period 2001-2010. GFD and MESCAN have similar overall intensity over the land areas, although they differ for some particular regions, such as the Alps. The similarity is due to the inclusion of station observations to adjust the precipitation amounts, but they are not using the same stations throughout the domain.

Over the oceans, there are larger differences as GFD is retaining the original ERA-Interim results when no information is available for the land based GPCCv7 data base. This is also evident in comparison to HARMONIE and MO, which have rather similar precipitation patterns over the ocean where the main contribution over the ocean is due to the model's response to large scale features that are introduced with the boundary information from ERA-Interim. Over land, HARMONIE overestimates the annual precipitation rates throughout the domain. MO also overestimates precipitation, but less so than HARMONIE.
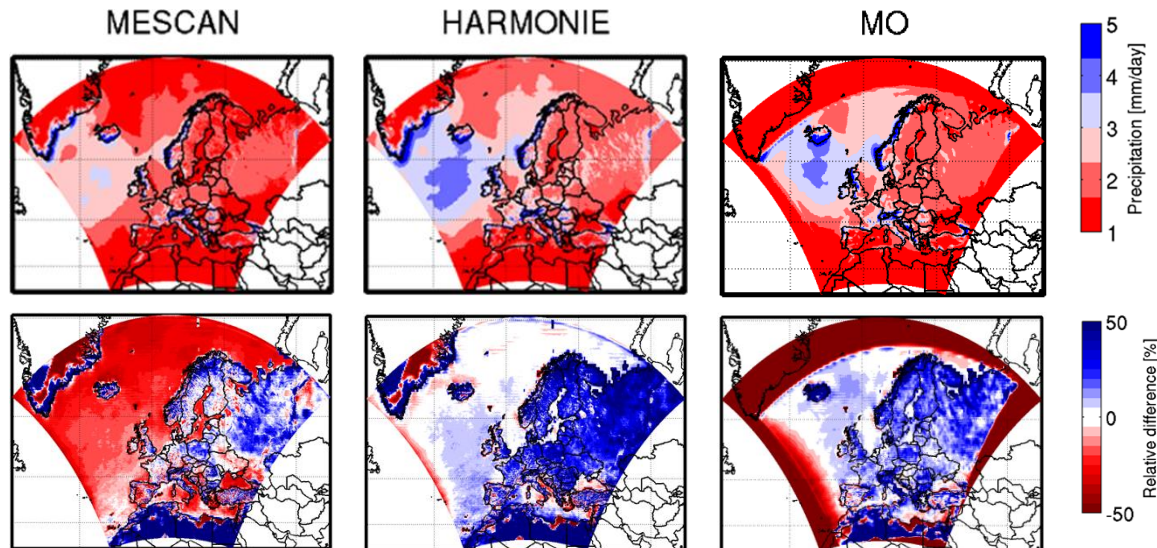

Figure 3: (top) The mean annual precipitation of each analyzed data set for the period 2001-2010. (bottom) Relative difference to GFD for MESCAN, HARMONIE and MO. The red frame around the MO maps is due to the smaller domain and appears as a result of the remapping in this plot. It is outside the E-HYPE domain and does not affect the results.

3.2 Hydrological evaluation

From now on, we study precipitation not at the grid point level, but as accumulations over the upstream area of a discharge gauge. Figure 4 presents scatter plots between each of the UERRA data sets together with GFD data. The higher annual mean precipitation rate of HARMONIE and MO is clear also from this analysis, i.e. with almost all dots above the 1:1 lines in blue. MESCAN is more balanced along the 1:1 line, but also tends to have more precipitation. The differences are similar between catchments with small and large annual precipitation, i.e. the dots align fairly linearly.
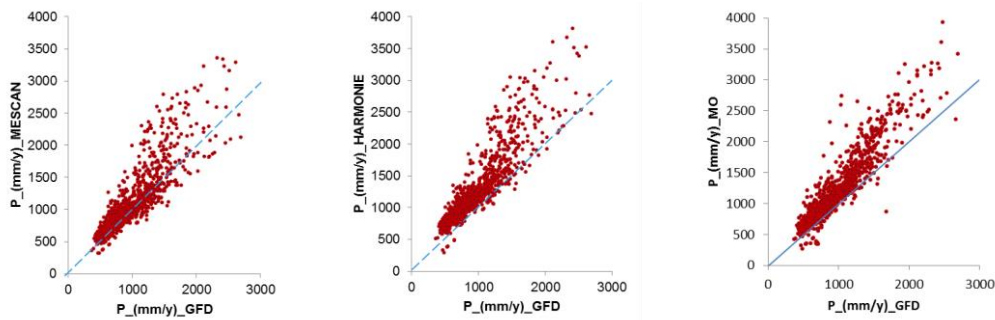
Figure 4: Average upstream precipitation from the GFD data on the x-axis plotted against the average upstream precipitation from MESCAN (left), HARMONIE (middle) and MO (right).

Analysis of the runoff coefficient for GFD (Figure 5) shows a large spread of the coefficient with values generally between 0 and 1. However, RC is larger than one for around 100 gauges, i.e. there is more runoff in the gauge measurements than is introduced by the GFD precipitation data set. In other words, GFD is too dry for these locations. The locations are shown as blue dots in Figure 7, with most of them in Norway. Because GFD is reproducing the precipitation climate of the GPCCv7 data set, this indicates an underestimation from this data set. In this region it is complicated to make accurate gridded measurement products of rainfall due to the large heterogeneity of the precipitation field due to the topography of the Scandic mountains which affects the representativeness of the gauges, but also due to measurement difficulties with windy conditions in combination with frequent precipitation in the form of snow, which causes under-catch issues with the gauges. The method of under-catch adjustments made in GPCCv7 (Schneider et al., 2015) is apparently not sufficient. Due to generally wetter conditions in MESCAN, HARMONIE and MO, there are fewer violations of the RC condition. However, they still have violations primarily in Norway (Figure 7).
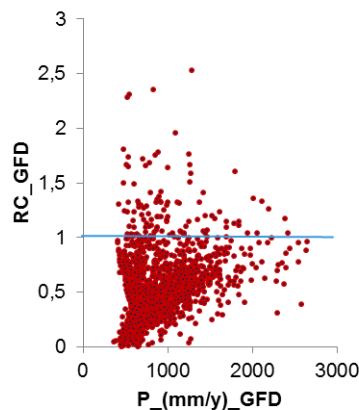

Figure 5: Average upstream precipitation from the GFD data on the x-axis plotted against the average runoff coefficient (RC) estimated for each discharge station and precipitation from GFD data.

Both the water and energy constraints can be evaluated visually using a simplified version of the so-called Budyko curve (Kauffeldt et al., 2013), where the actual evapotranspiration is plotted against the potential evapotranspiration, see Figure 6. The actual evapotranspiration is given by the difference between upstream accumulated precipitation and measured runoff, as discussed in Section 2.4. The potential evapotranspiration is estimate from by E-HYPE using the GFD temperature (which consists of ERA-Interim adjusted by monthly mean temperature from CRUts3.22). The GFD-based estimation of potential evapotranspiration is used for all data sets to have a common reference; however, using the temperature data from each UERRA product does not significantly affect the results. A guide to interpreting the plot is provided by the two blue lines. The 1:1 line marks the point where evapotranspiration is equal the potential evapotranspiration, and points above this line are violating the

energy criterion. The horizontal zero line marks the condition for water violation, i.e. the same as the RC condition. Therefore, a well performing precipitation data set must fall within the wedge of these two lines. We note to the reader that using the actual evapotranspiration calculated in HYPE leads to no violations due to the internal budget conservations in the model, i.e. the actual evapotranspiration increases as a consequence of excessive precipitation, and is therefore not a useful quantity for the analysis presented here. We also note that the method could be used also for evaluations of the evapotranspiration produced by the model systems, but this was not pursued here due to time constraints.
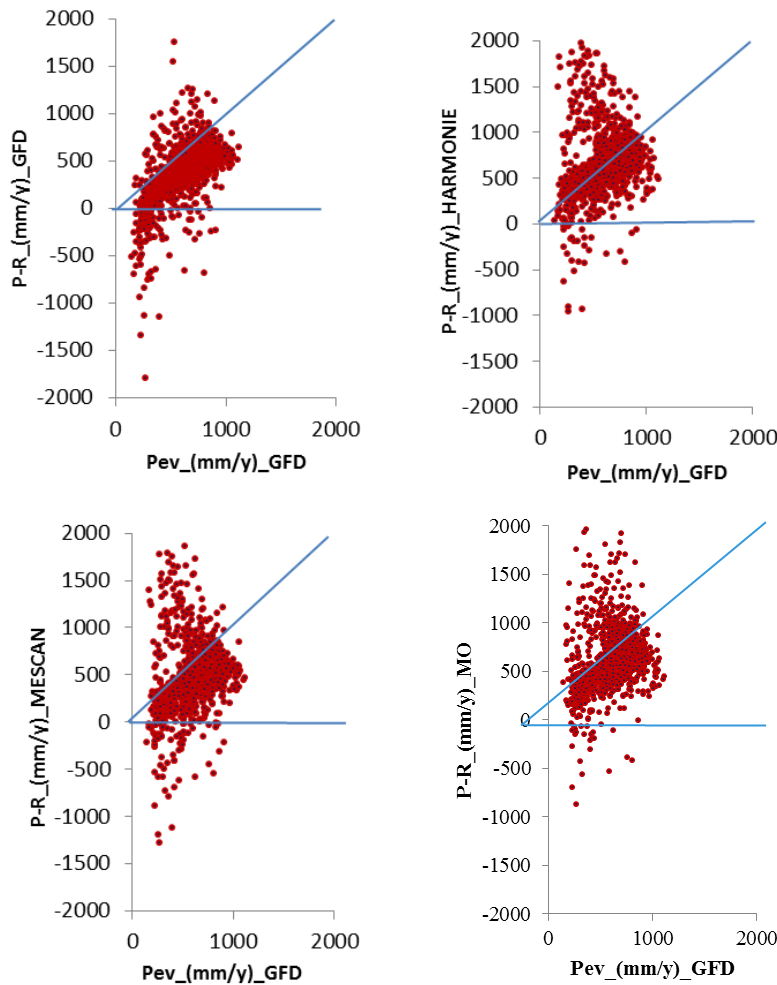

Figure 6: Potential evaporation for the GFD data on the x-axis plotted against the average evaporation as precipitation minus runoff (P-R) calculated from (top, left) GFD, (top, right) HARMONIE, (bottom, left) MESCAN and (bottom, right) MO.

GFD has about equal amounts of water and energy violations, i.e. dots falling above and below, the wedge of the blue lines in Figure 6. The total number of violations is slightly higher for MESAN, but more commonly for energy than water violations. This is an effect of the overall wetter conditions in MESCAN. The same effect, but much amplified, is seen for HARMONIE and MO.

Figure 7 presents the two types of violations on a map. The energy violations tend to occur more frequently in the Alpine region in the GFD data. For MESCAN, the energy violations are similarly distributed, but have a more heterogeneous distribution across the domain. HARMONIE and MO have the same general features, but additional violations throughout the domain. The reason is likely due to generally too wet conditions in the model, however the west side of the Scandic mountains in Norway still have water violations, so this region is clearly still too dry also in HARMONIE and MO. A

tendency toward energy violation in Sweden on the east side of the Scandic mountains indicate that the mainly easterly propagating precipitation systems that affect the region are advancing too far inland, which causes this gradient in the hydrological evaluation.
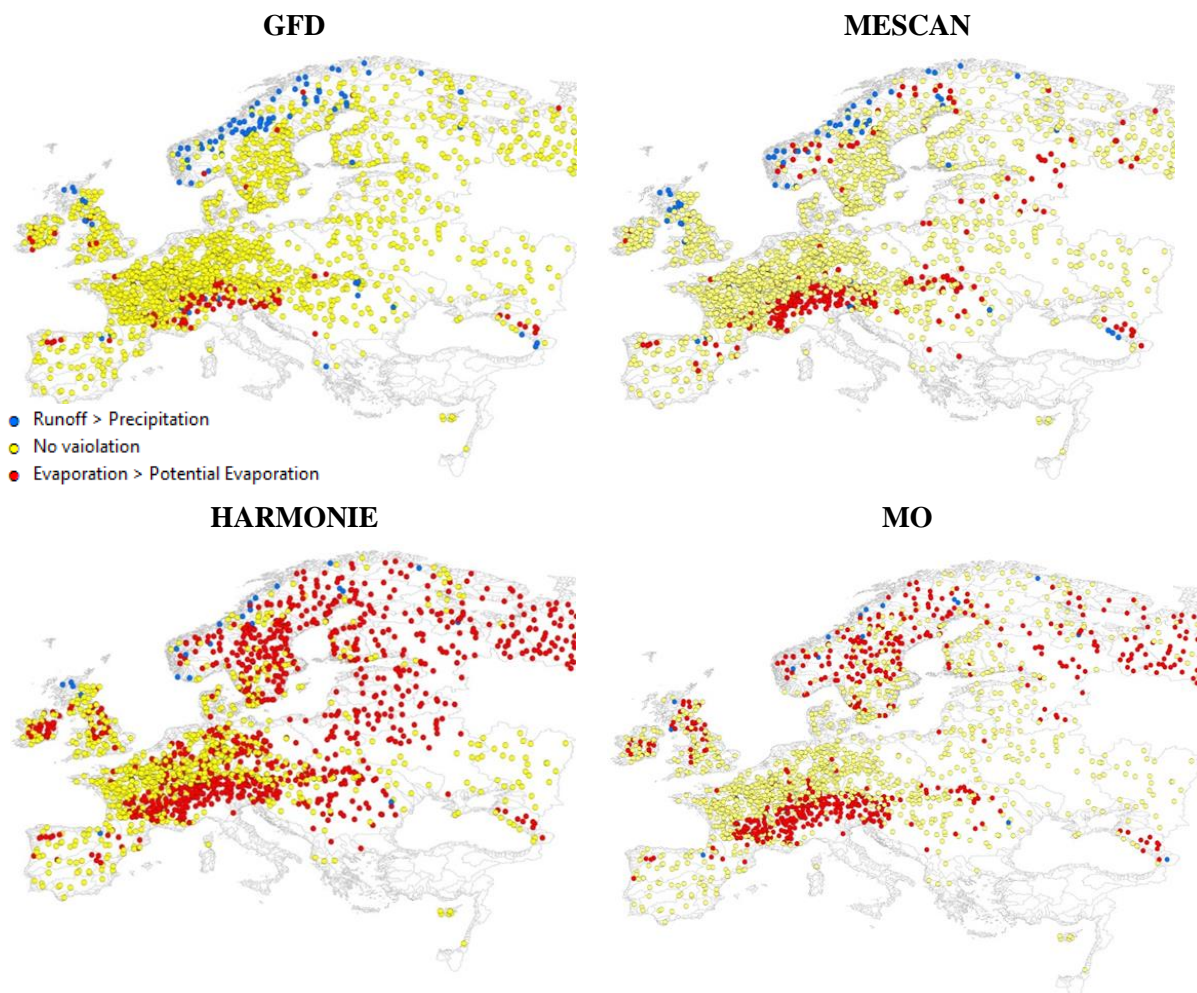
Figure 7: Spatial distribution of water and energy violations for the selected Q stations, calculated from GFD, MESCAN, HARMONIE and MO.

4   Discussion and conclusions

Evaluation of the UERRA data sets HARMONIE, MO and MESCAN against discharge observations has revealed:

- An overestimation of precipitation throughout most of Europe, especially in the HARMONIE and MO data sets.
- An underestimation of precipitation on the western face of the Scandic Mountains, and a potential overestimation on the east side of the mountains.
- An underestimation of precipitation in northern UK is also present for all three data sets

The method of analysing precipitation using discharge measurements is promising as the river basins act as huge rain gauges. However, this has some drawbacks, e.g. due to intermediate storage of water, evapotranspiration losses, and errors in discharge measurements. Net intermediate storage is here assumed to be negligible as we make use of at least ten years of data in the assessments so that snow melt, water management, etc. cancel out. Evapotranspiration losses are a big uncertainty, and few reliable measurements are available. Recent satellite products, e.g. MODIS, are promising for estimations of evapotranspiration, but do not cover the time period of interest for this study. Discharge observations are in themselves uncertain as discharge is not directly measured. Instead the level of the river is measured, and a so-called rating curve is constructed individually for each gauging station to convert the water level to discharge. Because the rating curves are derived individually for each gauging station, we do not foresee systematic bias of the measurements, and the use of multiple gauges in the analysis is valid for making general evaluation across domains as we do here.

Accounting for these uncertainties, the systematic overestimations of the UERRA data sets can be considered significant. Because the current assessment does not separate between seasons or precipitation processes, it is not possible to advice on which component of the models to focus on. However, there are indications from the results over the Scandic Mountains that indicates, given a mainly easterly influence, a too weak response to the orography such that the precipitating systems move too far inland before precipitation falls. The MESCAN and GFD data sets are both adjusted toward rain gauge observations, but still show the same phenomenon. This indicates an underestimation of the rain gauge measurements in this region, or how they are assimilated or gridded for the two data sets respectively. Note that the data set behind GFD, i.e. GPCCv7, includes under-catch corrections, but still underestimates precipitation.

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