

**Response to review comments of Anonymous Referee #2 on the manuscript
"Improved large-scale hydrological modelling through the assimilation of
streamflow and downscaled satellite soil moisture observations"**

**By Lopez Lopez, Wanders, Schellekens, Renzullo, Sutanudjaja and
Bierkens, 2016**

The authors greatly appreciate the time and efforts by Anonymous Referee #2 in carefully reviewing the manuscript. We would like to thank him/her for all the interesting and meaningful comments. We have addressed all issues indicated in the review report in the present document and included them in the manuscript in red colour.

General comments:

Comment 1:

In the analysis of the results in terms of soil moisture simulation at page 17 it reads that after assimilating soil moisture, results of global (PCR-GLOBWB) and local (OSWS) model are closer to each other. It is surely true, but I see that the results of the global model are still significantly lower than the local model (e.g., correlation is around 0.5 for global model and >0.75 for the local model). I believe that this aspect should be clearly underlined, otherwise it seems that after the assimilation the global and the local models give similar results, and it is not true.

Answer:

The authors totally agree with this comment and would like to thank the reviewer for it. The assimilation of soil moisture and discharge observations improves streamflow and soil moisture estimates of the large-scale hydrological model PCR-GLOBWB, but still the local-scale hydrological model, OSWS, performs better. OSWS produces discharges estimates with correlation coefficients higher than 0.7, whereas PCR-GLOBWB with the assimilation of soil moisture and streamflow observations, best obtained scenario, achieves maximum values of around 0.5.

The manuscript has been modified accordingly and this aspect will be clearly underlined in section 3.1. Impact of assimilation on soil moisture estimates as follows:

“... and MAE from 14 % (LOCAL GLOBWB_OL and LOCAL OSWS) to 16 % (LOCAL GLOBWB_SM+Q and LOCAL OSWS). However, the reduction in the differences between PCR-GLOBWB and OSWS performances due to the assimilation of soil moisture and streamflow observations does not mean that both models perform similarly. Maximum r values obtained with PCR-GLOBWB are approx. 0.5, whereas for OSWS maximum r values of 0.7 are reached.

Additionally, boxplots ...”

Comment 2:

It reads in the discussion that discharge data, if available, might be used for the calibration of the global model parameter values, instead as data to be assimilated. The authors are looking for alternative methods for improving global model, not considering the calibration

of parameter values. I understand this point, but if discharge data are assumed to be available, I strongly believe that their use for model parameters calibration will have a much higher beneficial impact on the results with respect to their assimilation. In my opinion, this aspect should be clearly acknowledged in the paper.

Answer:

We really appreciate the comment and have made the following revision accordingly. The main goal of the present study is to investigate the impact of assimilating remotely sensed soil moisture on the streamflow estimates of a large-scale hydrological model. This research may give insight about the usefulness and applicability of a particular type of remotely sensed observations to improve global model estimates, in comparison with locally calibrated model estimates. The here-shown improvement (or perhaps an even larger improvement) may have been also achieved through model parameters calibration. To this end, streamflow observations within the study river basin are needed to calibrate and validate the model, whereas soil moisture observations used via data assimilation are globally available all over the world. This allows reproducing the research methodology in ungauged river basins or with a limited number of gauging stations.

The authors agree with the reviewer that this aspect should be better acknowledged in the manuscript and therefore, section 4. Discussion has been modified as follows:

“... An alternative route to data assimilation to improve model estimates would be to locally calibrate PCR-GLOBWB using discharge observations from in situ gauging stations. The improvement achieved through model parameters calibration would be possibly even higher than when soil moisture and streamflow observations are assimilated into the model (Wanders et al., 2014). However, the present study means to be an attempt of providing hydrological estimations with a global model that could be also used in ungauged river basins where scarce in situ data are available. ...”

Comment 3:

Differently, the use of satellite soil moisture data is fine with me as it is applicable also in ungauged basins, and for me it should deserve much more attention. In other words, instead of underlining the results after the assimilation of both soil moisture and discharge, the results after the use of only soil moisture data should be more discussed, as the only results really applicable everywhere.

Answer:

As the reviewer has commented, we strongly believe that the main finding of the manuscript is the positive impact of assimilating AMSR-E soil moisture observations on streamflow and soil moisture estimates of a large-scale hydrological model. The combined assimilation of discharge and soil moisture observations leads to further improvements, but discharge observations may not be available in all river basins. According with this and following the reviewer comment, the results after assimilating soil moisture observations has been discussed with more details in section 4 Discussion:

“... A major finding of this study is the positive impact of assimilating soil moisture observations on the streamflow estimates, compared to independent discharge assimilation. The estimations of a large-scale hydrological model driven with coarse resolution forcing

data are improved using globally available remotely sensed soil moisture observations. This creates an opportunity for improved global model-based streamflow estimations as a result of the assimilation of remotely sensed soil moisture observations into large-scale hydrological models. Additionally, the adopted methodology has the advantage that it is applicable in river basins all over the world independently of the availability of in situ hydrometeorological information.

The variable effectiveness of soil moisture ...”

Comment 4:

In the previous review I suggested some points that are not considered in the current version, and it reads in the discussion that it will be addressed in “future research studies”. While I understand that performing additional analyses is always difficult, I believe that some of the conclusions are not related to the results and should be better analysed, or removed.

More specifically, it reads that the positive impact of the assimilation of satellite soil moisture data might be due to their fine resolution. I believe that running the model by using the AMSR-E soil moisture product without the downscaling procedure is a small effort, and it will clarify if the benefit should be related (or not) to the fine resolution of the soil moisture data.

Answer:

Following the reviewer’s recommendation, AMSR-E soil moisture observations at the original spatial resolution, hence without applying the downscaling procedure, were assimilated into PCR-GLOBWB hydrological model. The impact was analysed on soil moisture and discharge model estimates.

Non-downscaled AMSR-E soil moisture observations were assimilated independently and in combination with discharge observations. To this end, scenarios GLOBWB_SM and GLOBWB_SM+Q were reproduced with the soil moisture observations at the original spatial resolution (approx. 50 km x 50 km). To compare the new obtained results with the previous ones shown in the manuscript, a new version of Table A1 (Tables 1 and 2) was elaborated and included. Moreover, Figure 1 (similar to Figure 6 in the manuscript) shows the comparison of the impact on soil moisture estimates when downscaled and non-downscaled soil moisture observations are assimilated.

The assimilation of non-downscaled soil moisture observations improves soil moisture model estimates, either using local or global meteorological data. However, the improvement on soil moisture estimates is higher when downscaled soil moisture observations are assimilated. Figure 2 (which exact numerical values are included in Table 2 for clarity) shows that the impact on the correlation, r , the root mean square error, RMSE, and the mean absolute error, MAE, is higher when the fine resolution product is assimilated in comparison with the coarse resolution observations. For example, percent reductions between GLOBAL GLOBWB_OL and GLOBAL GLOBWB_SM in MAE are in the order of 11 % when downscaled soil moisture observations are assimilated and in the order of 4 % when non-downscaled soil moisture observations are assimilated.

The impact of assimilating downscaled and non-downscaled soil moisture observations on streamflow estimates was compared through Figure 2 at multiple gauging locations situated in the Murrumbidgee river basin (similar to Figure 9 in the manuscript).

The assimilation of downscaled and non-downscaled observations, independently or in combination with discharge observations, has a positive impact on streamflow estimates. Assimilating non-downscaled soil moisture observations improves streamflow model estimates, but this improvement is slightly higher when downscaled soil moisture observations are used (see Figure 2 below). The impact on streamflow estimates is lower in comparison with the obtained improvements on soil moisture estimates.

The preliminary analysis here shown indicates that assimilating non-downscaled soil moisture observations improves soil moisture and streamflow estimates to a lesser extent than assimilating downscaled soil moisture observations.

The authors consider that including the previous analysis in the manuscript obscures the understanding of the main purpose of the study and therefore have decided not to incorporate it entirely in the manuscript. However, some clarifications have been introduced in section 4. Discussion relative to this topic as follows:

“... . A specific analysis of the impact on streamflow and soil moisture estimates of assimilating non-downscaled AMSR-E soil moisture observations could be a possible route to further investigate the effect of different spatial resolution soil moisture products. To this end, AMSR-E soil moisture observations at the original spatial resolution were assimilated into PCR-GLOBWB and results analysis presented in this manuscript were reproduced. Results showed that the assimilation of non-downscaled soil moisture observations has a positive impact on soil moisture and discharge estimates, but this improvement is smaller compared to the assimilation of the downscaled soil moisture estimates (Figures 7 and 8 in the supplement).

Moreover, runoff in the Murrumbidgee river basin is mainly dominated by direct runoff processes, with reduced contribution from the groundwater zone (Green et al., 2011). These catchment conditions, together with their representation in the model structure are most likely responsible for the added value of assimilating soil moisture. There may be merit in analysing these scenarios ...”

Comment 5:

Similarly, it reads that the finer resolution of the local meteorological forcing is the reason of the better performances. I expect that local observations have also higher quality with respect to the global data, not only a finer resolution. Therefore, to understand if the better performances are due to the data spatial resolution or data quality, a model run with artificially upscaled local observations (and then downscaled as the global dataset) will be useful to clarify this point.

Answer:

To investigate it, the large-scale hydrological model PCR-GLOBWB was forced with a new version of the local meteorological forcing. This version was generated upscaling the original local meteorological forcing from a spatial resolution of approx. $0.05^{\circ} \times 0.05^{\circ}$ to approx. $0.5^{\circ} \times 0.5^{\circ}$. The temperature and precipitation products obtained in this way were downscaled

from $0.5^{\circ} \times 0.5^{\circ}$ to $0.08^{\circ} \times 0.08^{\circ}$ (model spatial resolution) using the same procedure than with the WFDEI data (Sutanudjaja et al., 2011). The model performances when PCR-GLOBWB was forced with the initial and the new local meteorological forcing were intercompared for the GLOBWB_OL scenario (no observations are assimilated). This comparative analysis of model estimates with the two forcing data introduces more insight about if differences in performance are due to the finer resolution, the higher quality or both of them with respect to the global forcing data.

PCR-GLOBWB forced with the initial local meteorological data estimates similar soil moisture and streamflow values to those estimated when the new version of the local meteorological data is used. Figures 3 and 4 show that the differences in discharge and soil moisture estimates obtained with the two forcing products may be considered almost negligible. For example, in terms of the catchment daily means of soil moisture, MAE varies from 0.058756 to 0.058632 when PCR-GLOBWB is forced with the initial and the new local meteorological data.

Concluding, results show that model performance differences when driven with the global and the local meteorological forcing data are not only due to the finer spatial resolution, but also to the higher quality of the local precipitation and temperature, which is mainly based on in situ observations.

Considering previous results, section 4. Discussion has been modified as follows:

“... The various model and data assimilation options were evaluated under both high- and low-resolution meteorological forcing. In general, the higher spatial resolution and the higher quality of the local forcing data results in better model predictions (PCR-GLOBWB and OSWS) of both soil moisture and streamflow. ...”

Comment 6:

Finally, also the sensitivity analysis related to the assumptions made in the data assimilation method is left to future studies. I could agree, but knowing the large impact of these assumptions in the results, I believe that at least a preliminary sensitivity analysis for one/two case studies should be performed to provide more robust results (not affected by the subjective choices made in the assimilation).

Answer:

We greatly thank the reviewer for his/her comment and suggestion. The authors agree that some assumptions were made in the data assimilation framework that can be further investigated because of their influence in the obtained results. Sections 2.3.2. Soil moisture and 2.4.2. Assimilating soil moisture and discharge observations describe these choices related to model and observations uncertainty. Following the reviewer's suggestion, we explain and discuss them with more detail in the paragraphs below and we include various preliminary sensitivity analyses for some assimilation scenarios.

A total of 100 ensemble members was used based on the results of previous data assimilation experiments within PCR-GLOBWB. These results show that there is no significant improvement with increasing the number of ensembles above 100 (Wanders et al., 2014). A preliminary sensitivity analysis modifying the number of ensemble members (50, 100 and 150) was carried out for the GLOBWB_SM+Q assimilation scenario when the model is

forced with local and global meteorological data. Figures 5 and 6 show the impact of the variation in the number of ensemble members on soil moisture and streamflow estimates. Results indicate that the assumption of 100 ensemble members does not impact the obtained estimates.

To account for model and observations uncertainty, stochastic noise was introduced in model forcing data, soil moisture and discharge observations. Precipitation was perturbed with additive Gaussian white noise with standard deviation of 10 % of the nominal value based on previous studies (Adam and Lettenmaier, 2003; Hijmans et al., 2005). A sensitivity analysis including perturbations of 20 % and 30 % of the nominal value of precipitation for the GLOBWB_SM+Q assimilation scenario was included to further investigate its impact on soil moisture and streamflow estimates. Figures 7 and 8 show the comparison of evaluation results of this analysis. Results indicate that the modifications of the standard deviation to perturb precipitation do not highly impact soil moisture and discharge estimates.

For the assimilation of the satellite soil moisture data, the spatial information on the measurement error covariance R was determined from estimates of Wanders et al. (2012) over Spain. We believe that assuming an R obtained by using high-resolution modelling of the unsaturated zone over a region with diverse climatological and hydrological conditions is a reasonable choice. This choice has been discussed in section 4. Discussion indicating that the determination of AMSR-E observations uncertainty specifically over the Murrumbidgee river basin with physically-based or in-situ soil moisture measurements could be a route for future investigations.

For the assimilation of discharge observations, the standard error was assumed to be 10 % of the discharge. A preliminary sensitivity analysis is included considering standard errors of 20 % and 30 %. Figures 9 and 10 show the comparison in terms of soil moisture and discharge estimates for GLOBWB_SM+Q assimilation scenario. Increasing the standard error of discharge from 10 % to 30 % influence soil moisture and discharge estimates only slightly.

Considering previous results and for the easiness of the manuscript readability, the authors would like not to include a detailed explanation on the data assimilation assumptions made and refer the reader to this document for a more detailed discussion on these choices. However and in the light of the obtained results, a brief description of this preliminary sensitivity analysis has been included in section 2.4.2. Assimilating soil moisture and discharge observations as follows:

“... It was additionally assumed that the covariance between the satellite soil moisture observations and discharge observations equals zero. Some of the assumptions described in this section for data assimilation were investigated through a preliminary sensitivity analysis including the number of ensemble members and the standard errors of precipitation and discharge (Figures 1, 2, 3, 4, 5 and 6 in the supplement). ...”

Specific comments (P: page, L: line or lines):

Comment 7:

P4, L19: Not only the lateral groundwater flow is neglected in global hydrological model, but any lateral flow. I suggest removing “groundwater”

Answer:

The manuscript has been modified according to the reviewer’s comment as follows:

“... in this respect is the neglect of lateral flow, misleading the representation of the complex ...”

Comment 8:

P9, L24: I would specify air temperature

Answer:

According to the reviewer’s suggestion, it has been specified air temperature instead of only temperature:

“... The forcing data required to drive both hydrological models are precipitation and air temperature. Two types of forcing ...”

Comment 9:

P18, L24: specify in the text that results shown in Figure 9 refers to multiple river sections

Answer:

To clarify the interpretation of Figure 9, it has been indicated in the text that the figure refers to multiple river sections or locations as follows:

“... evaluation metrics (RMSE, MAE, r and NSE) were calculated and included for multiple discharge locations in Fig.9 ...”

Tables:

Table 1: Table A1 when downscaled soil moisture observations are assimilated for both the global and the local meteorological data.

| | LOCAL | | | GLOBAL | | |
|------|-----------------|----------------|---------|-----------------|----------------|---------|
| | RMSE [m3/m3] | MAE [m3/m3] | r [-] | RMSE [m3/m3] | MAE [m3/m3] | r [-] |
| w | 0.07571 | 0.05716 | 0.79865 | 0.07854 | 0.06082 | 0.77603 |
| OL | 0.09735 | 0.07520 | 0.43071 | 0.10094 | 0.07662 | 0.40715 |
| Q | 0.09738 | 0.07523 | 0.42041 | 0.10096 | 0.07664 | 0.40652 |
| SM | 0.09085 | 0.06699 | 0.53452 | 0.09372 | 0.06811 | 0.50230 |
| SM_Q | 0.09032 | 0.06609 | 0.52085 | 0.09320 | 0.06845 | 0.49624 |

Table 2: Table A1 when non-downscaled soil moisture observations are assimilated for both the global and the local meteorological data.

| | LOCAL | | | GLOBAL | | |
|------|-----------------|----------------|---------|-----------------|----------------|---------|
| | RMSE [m3/m3] | MAE [m3/m3] | r [-] | RMSE [m3/m3] | MAE [m3/m3] | r [-] |
| w | 0.07571 | 0.05716 | 0.79865 | 0.07854 | 0.06082 | 0.77603 |
| OL | 0.09735 | 0.07520 | 0.43071 | 0.10094 | 0.07662 | 0.40715 |
| Q | 0.09738 | 0.07523 | 0.42041 | 0.10096 | 0.07664 | 0.40652 |
| SM | 0.09188 | 0.07199 | 0.49321 | 0.09773 | 0.07313 | 0.46324 |
| SM_Q | 0.09201 | 0.06994 | 0.51039 | 0.09706 | 0.07400 | 0.46012 |

Figures:

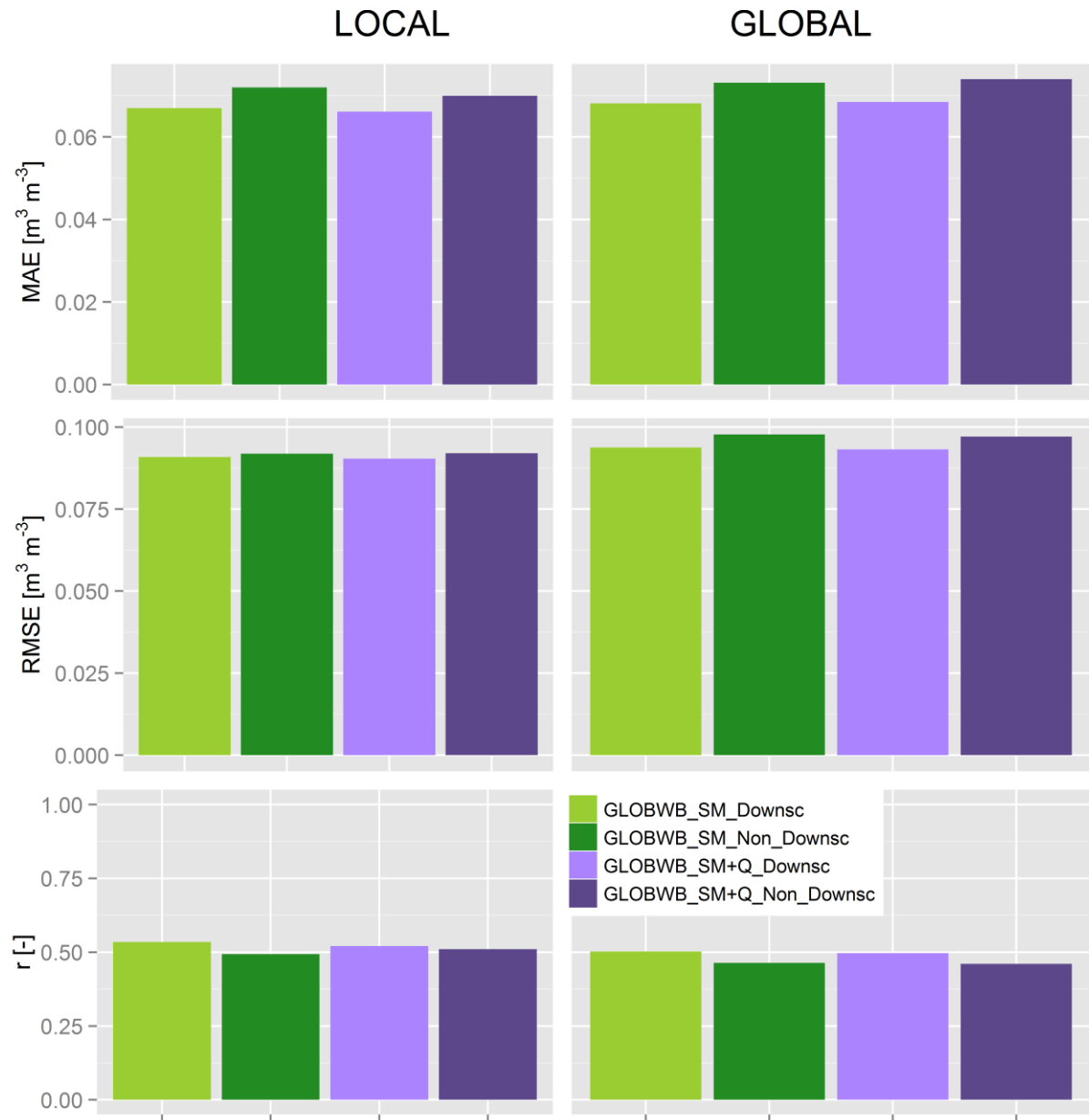


Figure 1: Comparison of evaluation results of the catchment daily means of soil moisture in the Murrumbidgee river basin. Assimilation scenarios GLOBWB_SM (green) and GLOBWB_SM+Q (purple) are shown when downscaled and non-downscaled soil moisture observations are assimilated.

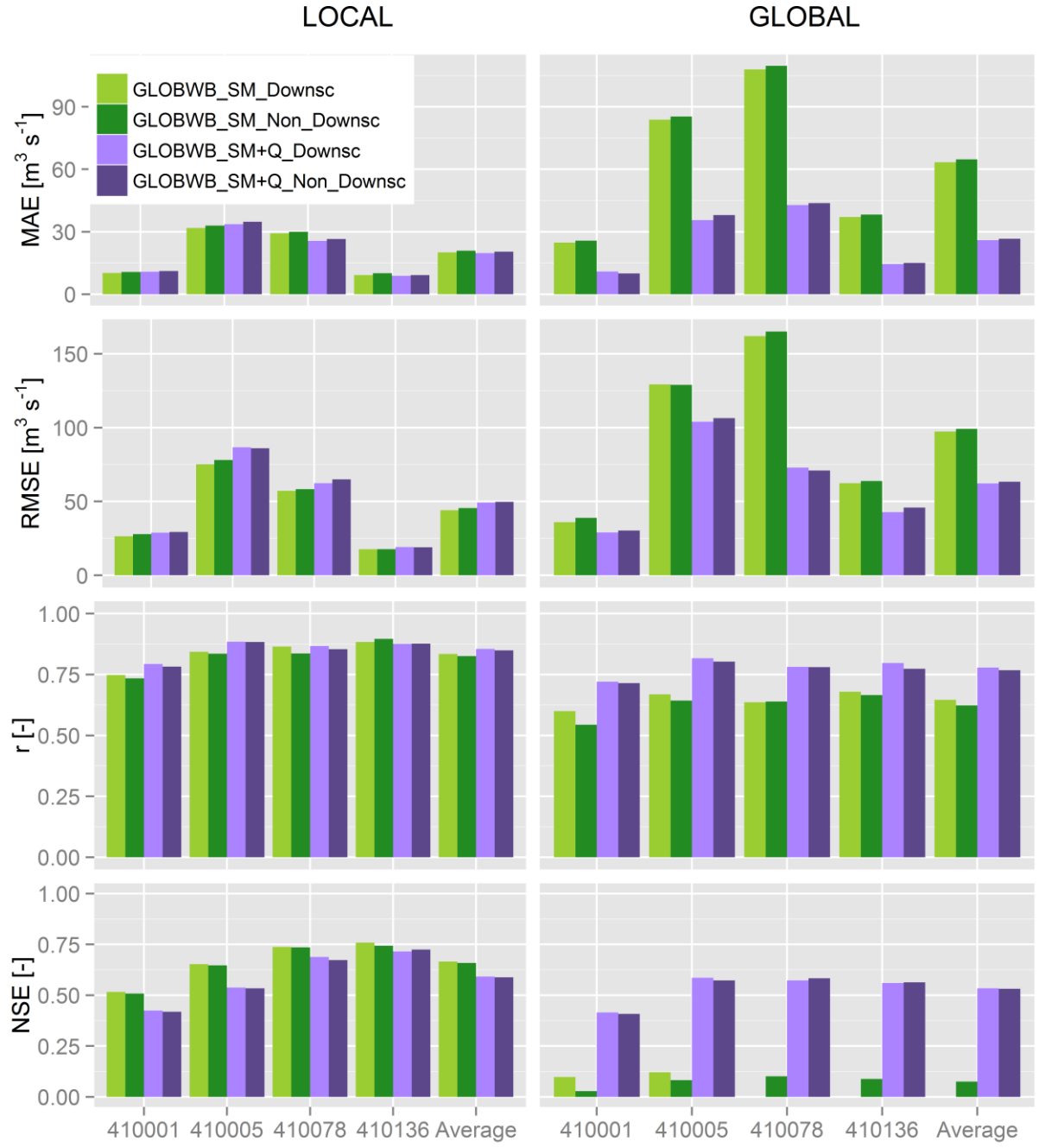


Figure 2: Comparison of evaluation results for streamflow estimates at 410001, 410005, 410078 and 410136 locations in the Murrumbidgee river. Assimilation scenarios GLOBWB_SM (green) and GLOBWB_SM+Q (purple) are shown when downscaled and non-downscaled soil moisture observations are assimilated.

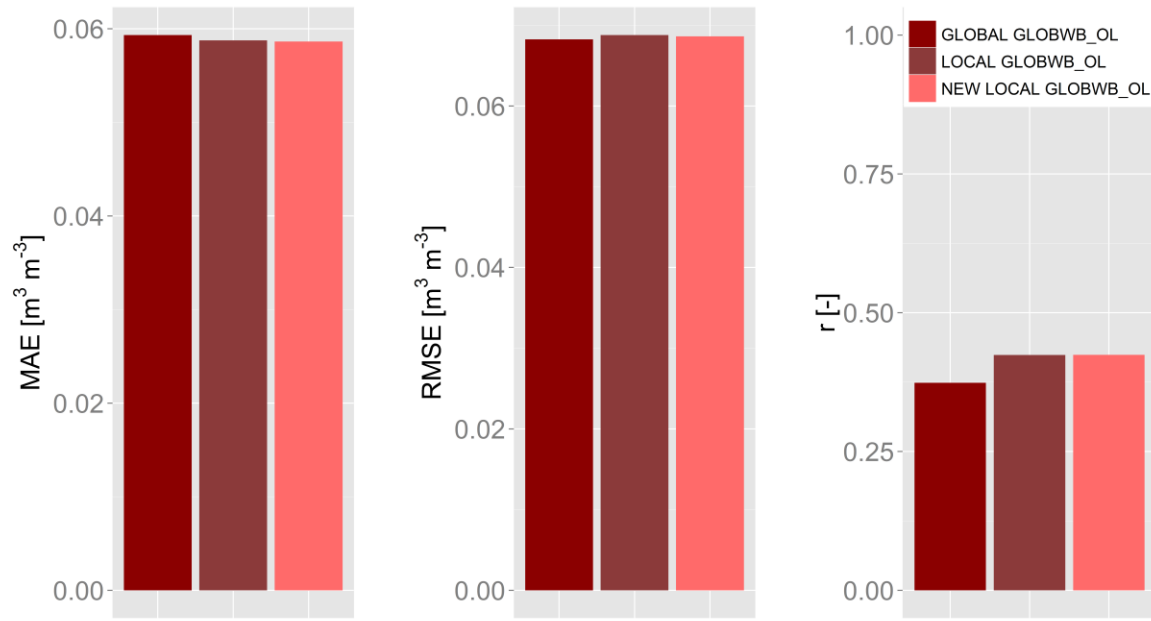


Figure 3: Comparison of evaluation results of the catchment daily means of soil moisture in the Murrumbidgee river basin. Soil moisture estimates when model is forced with global, local and the new version of local meteorological data for the GLOBWB_OL assimilation scenario are included.

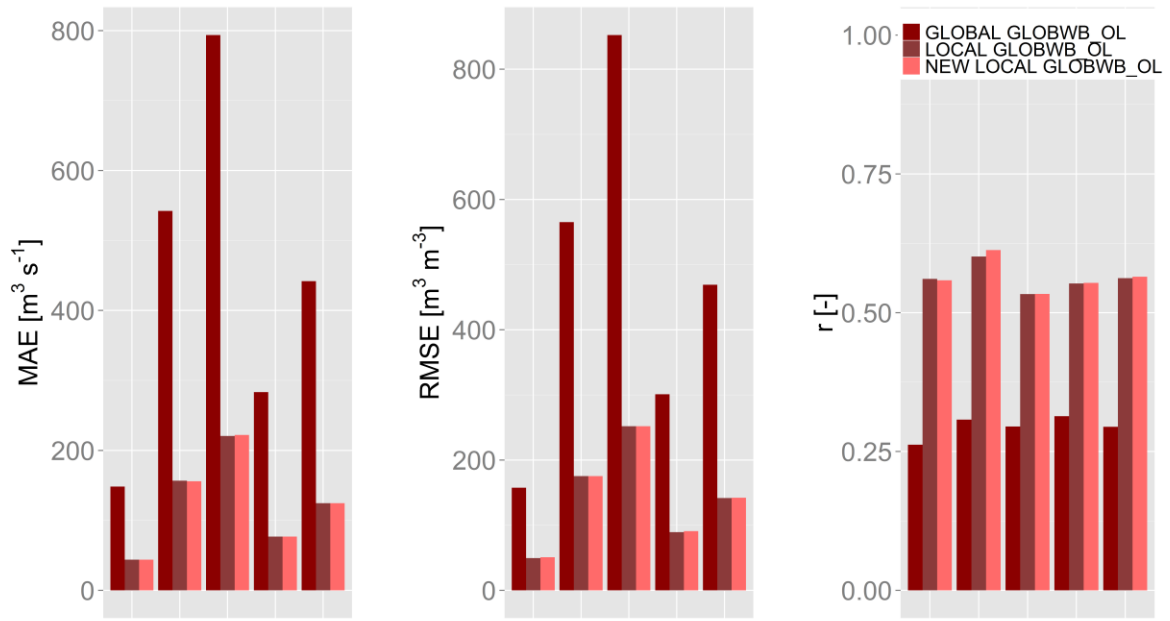


Figure 4: Comparison of evaluation results for streamflow estimates at 410001, 410005, 410078 and 410136 locations in the Murrumbidgee river. Streamflow estimates when model is forced with global, local and the new version of local meteorological data for the GLOBWB_OL assimilation scenario are included.

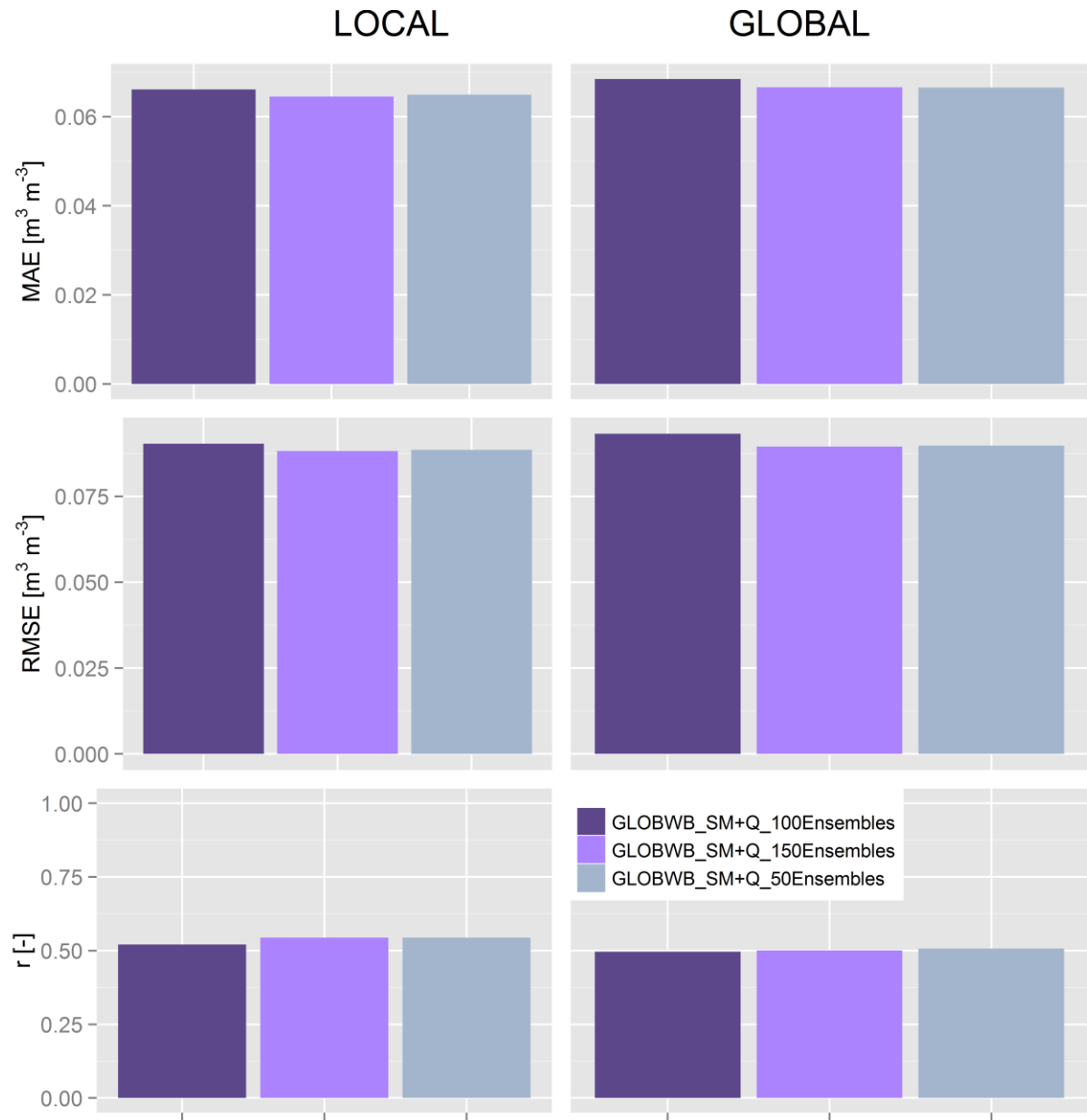


Figure 5: Comparison of evaluation results of the catchment daily means of soil moisture in the Murrumbidgee river basin. Assimilation scenario GLOBWB_SM_Q has been reproduced using 50, 100 and 150 ensemble members.

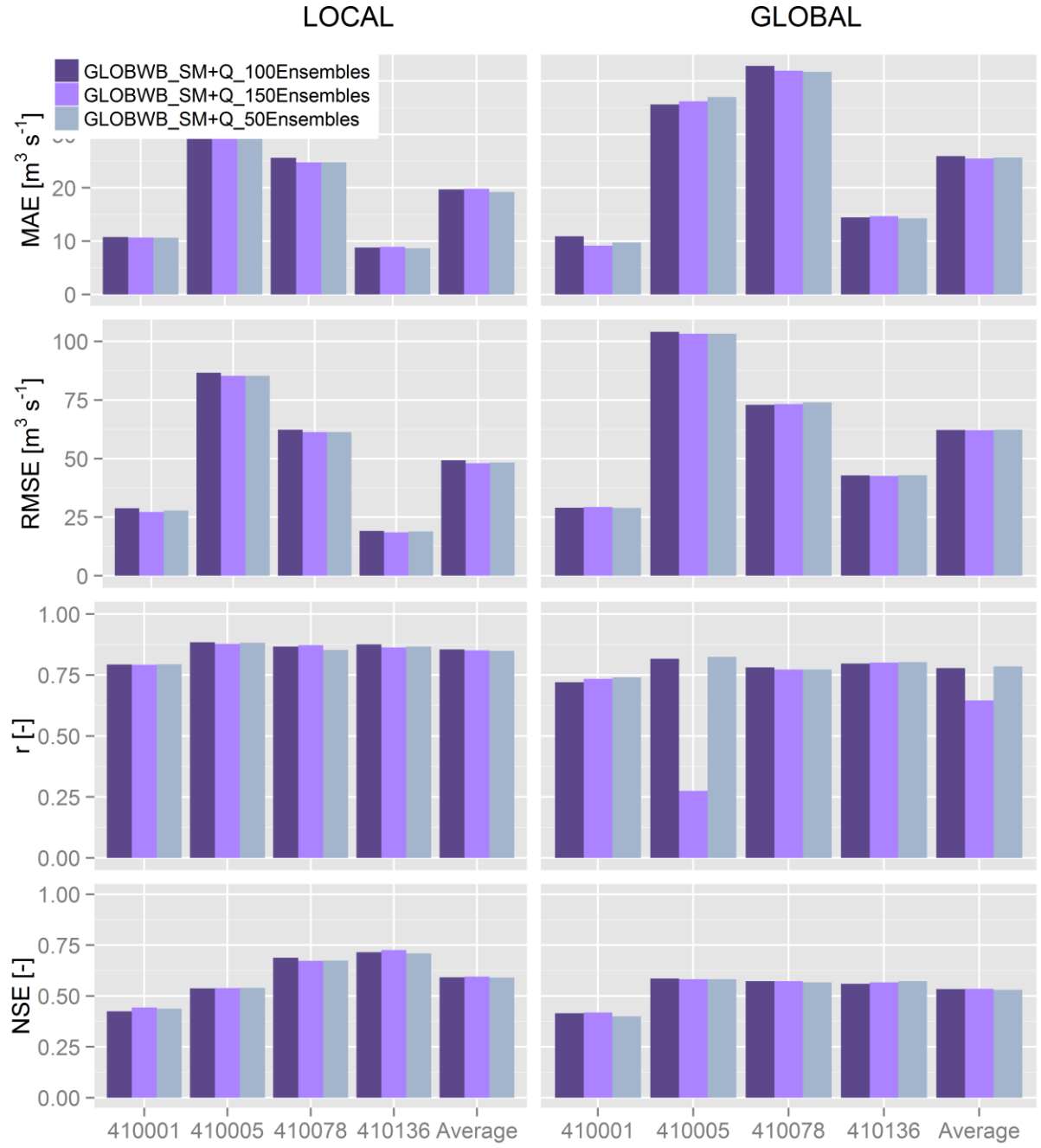


Figure 6: Comparison of evaluation results for streamflow estimates at 410001, 410005, 410078 and 410136 locations in the Murrumbidgee river. Assimilation scenario GLOBWB_SM_Q has been reproduced using 50, 100 and 150 ensemble members.

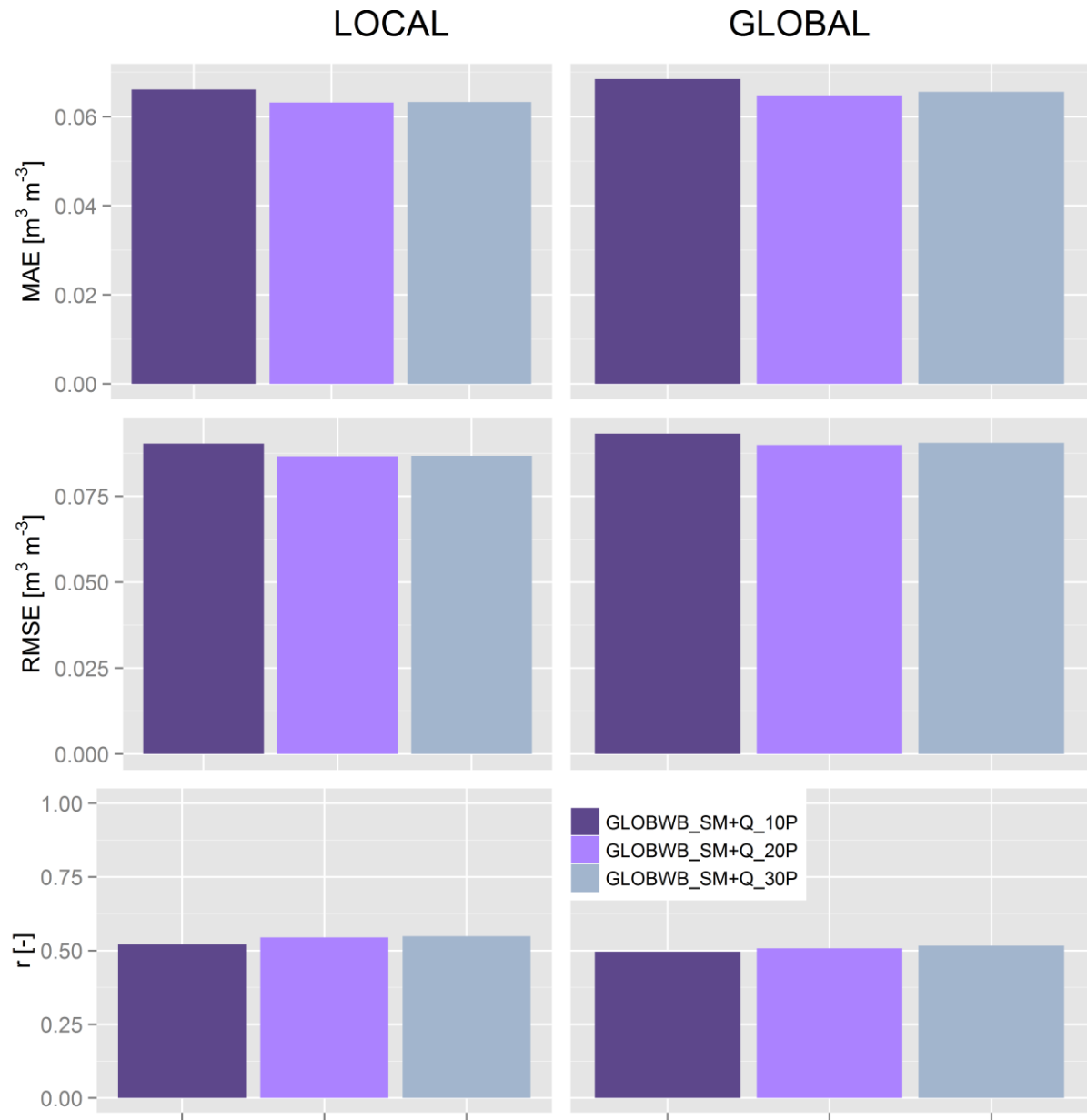


Figure 7: Comparison of evaluation results of the catchment daily means of soil moisture in the Murrumbidgee river basin. Assimilation scenario GLOBWB_SM_Q has been reproduced perturbing the precipitation with additive Gaussian white noise with standard deviation of 10 %, 20 % and 30 % of the nominal value.

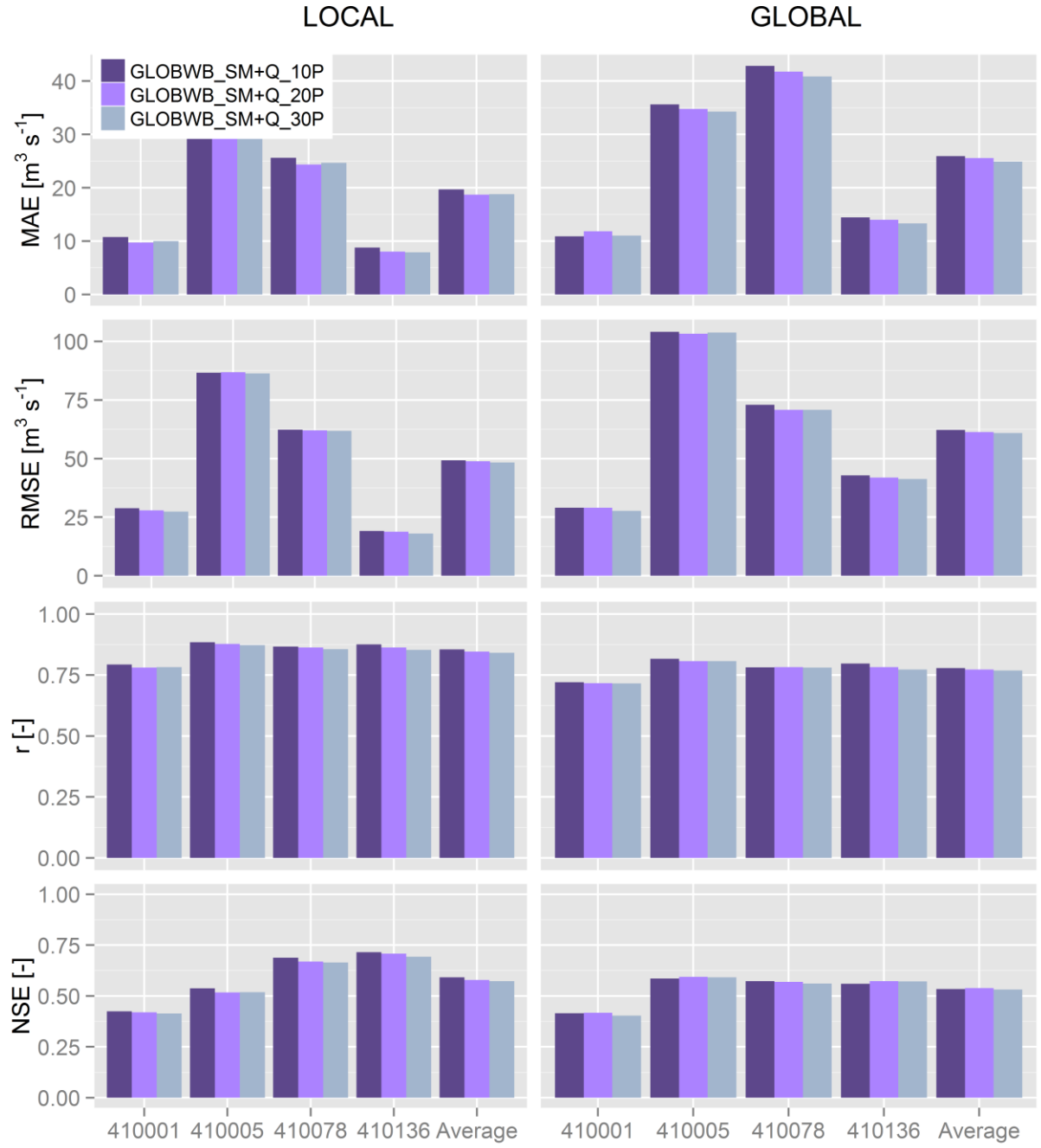


Figure 8: Comparison of evaluation results for streamflow estimates at 410001, 410005, 410078 and 410136 locations in the Murrumbidgee river. Assimilation scenario GLOBWB_SM_Q has been reproduced perturbing the precipitation with additive Gaussian white noise with standard deviation of 10 %, 20 % and 30 % of the nominal value.

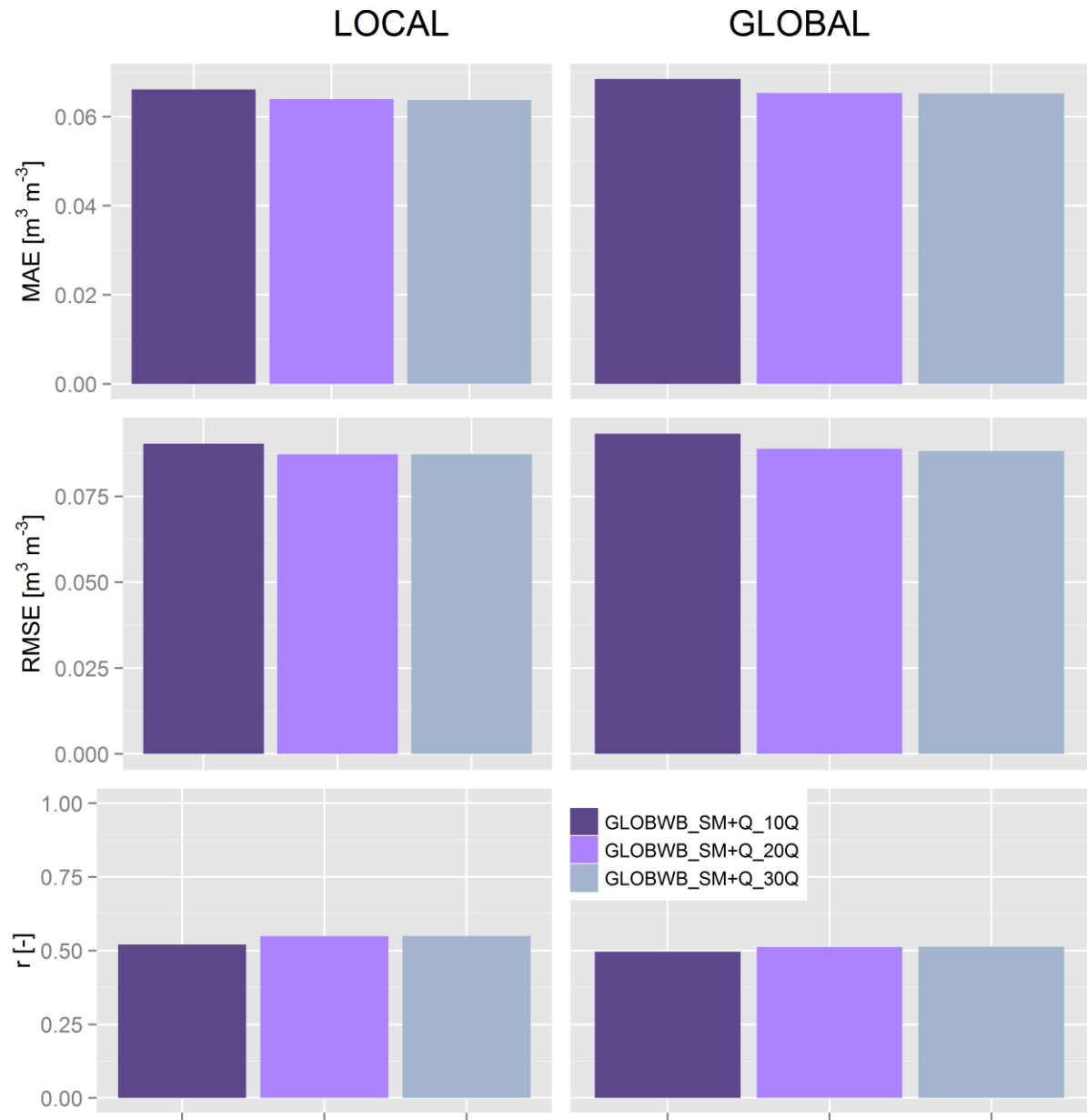


Figure 9: Comparison of evaluation results of the catchment daily means of soil moisture in the Murrumbidgee river basin. Assimilation scenario GLOBWB_SM_Q has been reproduced setting a standard error for the discharge observations of 10 %, 20 % and 30 % of the discharge.

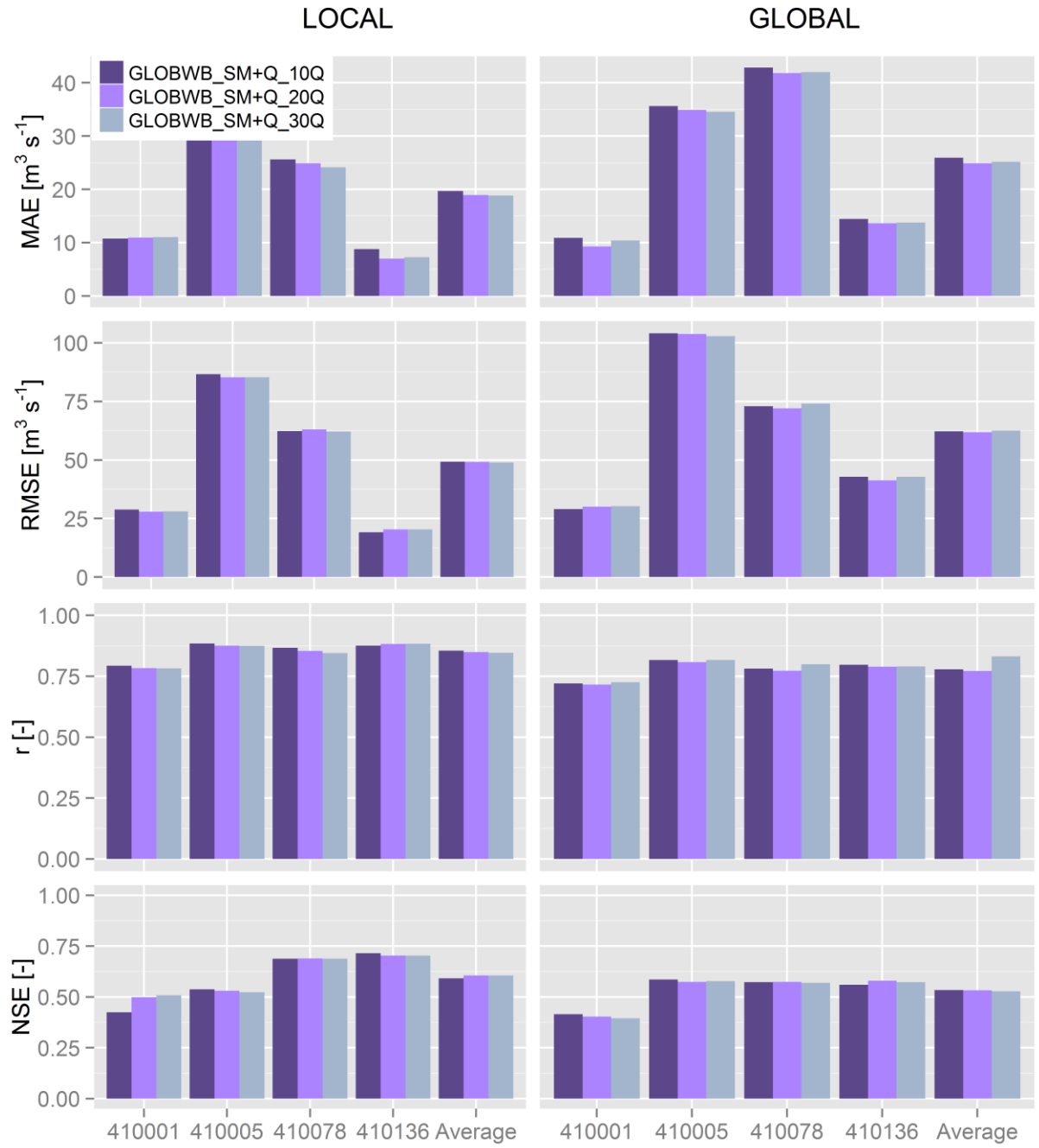


Figure 10: Comparison of evaluation results for streamflow estimates at 410001, 410005, 410078 and 410136 locations in the Murrumbidgee river. Assimilation scenario GLOBWB_SM_Q has been reproduced setting a standard error for the discharge observations of 10 %, 20 % and 30 % of the discharge.

Improved large-scale hydrological modelling through the assimilation of streamflow and downscaled satellite soil moisture observations

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Abstract

The coarse spatial resolution of global hydrological models (typically $> 0.25^\circ$) limits their ability to resolve key water balance processes for many river basins and thus compromises their suitability for water resources management, especially when compared to locally-tuned river models. A possible solution to the problem may be to drive the coarse resolution models with locally available high spatial resolution meteorological data as well as to assimilate ground-based and remotely-sensed observations of key water cycle variables. While this would improve the resolution of the global model, the impact of prediction accuracy remains largely an open question. In this study we investigate the impact of assimilating streamflow and satellite soil moisture observations on the accuracy of global hydrological model estimations, when driven by either coarse- or high-resolution meteorological observations in the Murrumbidgee river basin in Australia.

To this end, a 0.08° resolution version of the PCR-GLOBWB global hydrological model is forced with downscaled global meteorological data (from 0.5° downscaled to 0.08° resolution) obtained from the WATCH Forcing Data methodology applied to ERA-Interim (WFDEI) and a local high resolution gauging station based gridded dataset (0.05°). Downscaled satellite derived soil moisture (from approx. 0.5° downscaled to 0.08° resolution) from AMSR-E and streamflow observations collected from 23 gauging stations are assimilated using an ensemble Kalman filter. Several scenarios are analysed to explore the added value of data assimilation considering both local and global meteorological data.

Results show that the assimilation of soil moisture observations results in the largest improvement of the model estimates of streamflow. The joint assimilation of both streamflow and downscaled soil moisture observations leads to further improvement in streamflow simulations (20 % reduction in RMSE).

Furthermore, results show that the added contribution of data assimilation, for both soil moisture and streamflow, is more pronounced when the global meteorological data are used to force the models. This is caused by the higher uncertainty and coarser resolution of the global forcing.

We conclude that it is possible to improve PCR-GLOBWB simulations forced by coarse resolution meteorological data with assimilation of downscaled spaceborne soil moisture and streamflow observations. These improved model results are close to the ones from a local model forced with local meteorological data. These findings are important in light of the efforts that are currently done to go to global hyper-resolution modelling and can help to advance this research.

1 Introduction

In recent decades, a number of large-scale hydrological and land-surface models have been developed to quantify the global water cycle components, to analyse the human influence on the global water balance, to study climate change impact on water resources and to assess global hydrological extremes, such as drought and flood risk. VIC (Liang et al., 1994, 1996), WaterGAP (Alcamo et al., 2003), ORCHIDEE (d'Orgeval et al., 2008), HTESSEL (Balsamo et al., 2009), JULES (Best et al., 2011), PCR-GLOBWB (Van Beek et al., 2011), SURFEX-TRIP (Decharme et al., 2010, 2013) and W3RA (van Dijk, 2010; van Dijk et al., 2014) are some examples of large-scale hydrological models recently applied to provide water resources assessment over continental to global domains, but their coarse spatial resolution, typically between $0.5\text{--}1^\circ$, limits their ability to resolve key water balance processes for many river basins (Lanza et al., 1997; Wu and Li, 2009) and thus compromises their suitability for water resources management, especially when compared to locally-tuned hydrological models.

A possible solution to the problem may be to drive these original coarse resolution models with high resolution meteorological data. Several meteorological forcing datasets at a global scale are available, including the European Centre for Medium-Range Weather Forecasts – EMCWF ERA-Interim – global atmospheric reanalysis data (Dee et al., 2011), the Climatic Research Unit Time Series – CRU TS – (Mitchell and Jones, 2005), the NASA reanalysis Modern-Era Retrospective Analysis for Research and Applications – MERRA – (Rienecker et al., 2011) and the WATCH Forcing Data methodology applied to ERA-Interim reanalysis

data – WFDEI – (Weedon et al., 2014). They are the result of integrating Bayesian merging of the available earth observations, in situ datasets and models to construct consistent large-scale meteorological time series. Some recent scientific efforts are conducted to improve the quality and availability of these datasets, for example increasing their spatial and temporal resolution (Cannon, 2011; Ebtehaj and Foufoula-Georgiou, 2013; Atkinson, 2013). The use of high spatial resolution meteorological data would indirectly improve the resolution of the large-scale model, producing higher accuracy discharge estimates. However, when models that are designed for coarse spatial resolution are used at smaller spatial scale issues may arise with the representation of field scale processes. One of the major issues in this respect is the neglect of lateral groundwater flow, misleading the representation of the complex interactions between river water and groundwater (surface runoff, subsurface runoff, soil moisture state, etc.). At the moment, more research is required to understand the gain that can be obtained using this higher spatial resolution forcing data for uncalibrated global hydrological models at finer spatial resolutions.

Another approach to bridge the gap between the different spatial scales is to assimilate ground-based and remotely-sensed observations of key water cycle variables. Higher resolution satellite data contain information at finer spatial resolution and could be used to correct for sub-optimal model performance at these finer resolutions. Multiple studies have used data assimilation techniques to obtain the best possible estimate of the hydrological system status, merging the strengths of hydrological modelling and observations and mitigating their respective weaknesses (Moradkhani, 2008; Clark et al., 2008; van Dijk et al., 2014). Among the sequential and variational data assimilation methods, the ensemble Kalman filter (Evensen, 2003) has arguably emerged as the most popular choice for assimilation into land surface and hydrological models. The various individual components of the water cycle, such as surface water (Vrugt et al., 2006; Rakovec et al., 2012), soil moisture (van Dijk et al., 2014; Wanders et al., 2014a), snow water (Sun et al., 2004; Moradkhani, 2008) and groundwater (Zaitchik et al., 2008; Tangdamrongsu et al., 2015), which influence the hydrological system in different ways, can be assimilated into the model.

Soil moisture assimilation has been considered to improve model estimates, due to its key role in the terrestrial water cycle and its responsibility for the partitioning of precipitation between surface water and storage through infiltration. Several studies have assimilated soil moisture data (Draper et al., 2011; Chen et al., 2011; Wanders et al., 2014b; Massari et al., 2015, Alvarez-Garreton et al., 2015; Lievens et al., 2015) both based on ground soil moisture measurements and remotely sensed satellite soil moisture products from remote observation systems, such as ASCAT (Naeimi et al., 2009), SMOS (Kerr et al., 2012) and AMSR-E (Owe et al., 2008). On the other hand, surface water information has often been used for data assimilation frameworks (Vrugt et al., 2006; Rakovec et al., 2012) because discharge provides integrated information of all hydrological states, which is often very effective in improving model simulations. However, the risk of an integrated observation is that in some scenarios accurate simulations could be obtained by adjusting the wrong states variables.

An additional improvement could be made by the assimilation of downscaled or disaggregated satellite soil moisture observations into a particular land surface model (Merlin et al., 2006; Sahoo et al., 2013). Recently, new soil moisture products of higher spatial resolution have been released (Gevaert et al., 2015) but their impact on hydrological model predictions has not yet been explored. For example, they could be used to correct for incorrectly observed (or interpolated) precipitation patterns, which directly affect the input uncertainty into the model.

Moreover, improved results can be obtained by assimilation of multiple observational dataset of different parts of the hydrological cycle into the hydrological model (Barrett and Renzullo, 2009; Reichle et al., 2014). For example, the joint assimilation of discharge and soil moisture could result in an improved understanding of the runoff generation mechanisms and increase the quality and quantity of information incorporated to the model system. However, the added value of this type of joint assimilation procedures is largely unknown and should be further investigated (Aubert et al., 2003; Lee et al., 2011).

Many data assimilation experiments have been set up in conjunction with local-scale hydrological models and the benefit of data assimilation for large-scale models remains

largely an open question. In this context, it is interesting to analyse whether the accuracy of large-scale hydrological models can be improved and become more comparable with locally calibrated model estimates if satellite observations are assimilated. Understanding the potential gain of assimilating satellite observations into large-scale models is a relevant research opportunity and may have potential benefits for water resources management (Van Dijk and Renzullo, 2011). For example, in regions without or low quality meteorological observations the use of large-scale models in combination with satellite data assimilation could improve our understanding of the available water resources. The primary goal of the present study is to investigate the impact of assimilating streamflow and satellite soil moisture observations on the accuracy of global hydrological model estimations, when driven by either coarse- or high-resolution meteorological observations. The Murrumbidgee river basin in the southeast of Australia was chosen as a case study for the investigation because of the variety of land uses in the area, the high level of monitoring available for a large number of relatively unimpaired catchments, and the extensive body of previous studies observing and describing the hydrologic patterns across the basin (Renzullo et al., 2014; van Dijk and Renzullo, 2011). Eight data assimilation scenarios were considered in which discharge and soil moisture observations were either independently or jointly used, and the forcing data were obtained from either local or global data sets. In this context, comparison of the eight scenarios with the locally calibrated model estimates provides insight into how the estimations of global hydrological models driven by global forcing data can come closer to local-scale model predictions.

2 Approach, materials and methods

2.1 Study basin: Murrumbidgee river, Australia

The selected study area was the Murrumbidgee river basin (84 000 km²) located in south-east Australia, specifically in the south west of New South Wales (Fig. 1). The Murrumbidgee river is the second largest river in the Murray–Darling system, flowing for a dis-

tance of approximately 1600 km. Elevations range from over 1900 m in the East to less than 50 m on the Western plain. Forest and woodland coverage dominate in the East, with pasture and cropping in the central region, and increasing grassland to the West. The Western plain is dominated by clay-loam soils and with decreasing clay content in the middle and eastern region (Peischl et al., 2012). The climate in the catchment is one of the most diverse in New South Wales, with an average annual rainfall that ranges from 1700 mm yr⁻¹ in the higher elevations of the Snowy Mountains in the east, to less than 350 mm yr⁻¹ on the Western plain. Average reference evapotranspiration varies from less than 1000 mm yr⁻¹ in the south-east, to over 1800 mm yr⁻¹ in the West. Mean annual flow increases from less than 45 m³ s⁻¹ in the upstream tributaries to approximately 125 m³ s⁻¹ in the mid-Murrumbidgee (Green et al., 2011).

2.2 Hydrological models

The simulations for two distributed hydrological models, i.e. the local OpenStreams wflow_sbm and the global PCR-GLOBWB, were performed for the period 2007–2010. The period 2000–2007 was used to “spin up” the models. The local and large-scale models are described in detail in the following two sub-sections.

2.2.1 Local-scale model: OpenStreams wflow_sbm

The local-scale hydrological model employed in this study was the OpenStreams wflow_sbm model (Schellekens, 2014). This is a distributed model derived from topog_sbm simple bucket model developed by Vertessy and Elsenbeer (1999). The OpenStreams wflow_sbm model (OSWS) is programmed in the PCRaster-Python environment (Weseling et al., 1996; Karssenberget al., 2010) and it is publicly available through the OpenStreams project (<https://github.com/openstreams/wflow>). The defined spatial resolution used in this study was 0.01° × 0.01° (approx. 1 km × 1 km) and the temporal resolution was daily. A schematic representation of OSWS is given in Fig. 2.

OSWS model structure consists of three main routines: (i) rainfall interception (schematized by the Gash model – Gash, 1979), (ii) soil processes (schematized by the topog_sbm model) and (iii) river drainage and overland flow (modelled by the kinematic wave routing over a drainage network).

5 The water enters each model cell from precipitation to the canopy interception storage or snow storage. The remaining liquid water infiltrates into the soil. At the same time, water is taken from the soil through evapotranspiration (based on soil water content and vegetation type). The water exchange into the soil considers two vertical soil layers, the unsaturated zone (UZ) and the saturated zone (SZ), based on topog_sbm structure. Total runoff is the
10 sum of the direct runoff, the melt water that does not infiltrate into the soil and the baseflow (lateral subsurface flow from the saturated zone). This total runoff is conducted along the river network as discharge with kinematic wave routing.

The OSWS model was calibrated for the Murrumbidgee river basin using observations from in situ streamflow gauges (BoM, 2015) for the time period 1990–2010. These gauges
15 are different from those considered in all the data assimilation scenarios to ensure an independent verification.

2.2.2 Large-scale model: PCR-GLOBWB

The large-scale hydrological model employed in this study was PCR-GLOBWB (Van Beek and Bierkens, 2009; Van Beek et al., 2011). Similar to OpenStreams wflow_sbm, PCR-
20 GLOBWB is essentially a leaky-bucket type of model applied on a cell-by-cell basis. PCR-GLOBWB is coded in the PCRaster-Python environment. A spatial resolution of 0.08° (approx. $10\text{ km} \times 10\text{ km}$ at the equator) and a daily temporal resolution were used in this study. A schematic representation of PCR-GLOBWB is given in Fig. 3.

For each time step and cell, PCR-GLOBWB calculates the water balance components,
25 including the water storage in three vertical soil layers (0–5, 5–30 and 30–150 cm) and one underlying groundwater reservoir, as well as the water exchange between the layers (percolation, capillary rise) and between the top layer and the atmosphere (rainfall, evapotranspiration and snowmelt). Sub-grid variability is taken into account considering the variations

of elevation, land cover, vegetation and soil. The total runoff of a cell consists of direct runoff (saturation excess surface runoff), non-infiltrating melt water, interflow (lateral drainage from the soil profile) and baseflow (groundwater runoff from the lowest linear reservoir). The simulated runoff is routed along the river network based on the Simulated Topological Networks (STN30; Vörösmarty et al., 2000). Water abstraction and consumptive water use (domestic, industrial, livestock, irrigation) and reservoir management are included.

In contrast to the local-scale model, PCR-GLOBWB was not calibrated for the study basin. Hydrological model parameters were derived from vegetation, soil properties or geological information and estimated at a global scale.

2.3 Datasets

2.3.1 Meteorological forcing data

The forcing data required to drive both hydrological models are precipitation and air temperature. Two types of forcing data were used in this study: local forcing data, representing the best available data, and global forcing data representing a lower spatial resolution data set but one which is available globally.

Local precipitation and air temperature data were obtained from the gridded datasets generated by the Australian Bureau of Meteorology under the Australian Water Availability Project (AWAP) (Jones et al., 2009). The data are derived from station-level daily precipitation and air temperature, and interpolated on a $0.05^\circ \times 0.05^\circ$ grid covering the Australian continent. These data represent high resolution meteorology in this study which, we argue, will provide the modelling benchmark results.

Global precipitation and air temperature data were obtained from the WATCH Forcing Data methodology applied to ERA-Interim reanalysis data – WFDEI – (Weedon et al., 2014). The daily global precipitation and air temperature data were provided at a spatial resolution of $0.5^\circ \times 0.5^\circ$. To obtain finer spatial resolution climate maps, from $0.5^\circ \times 0.5^\circ$ grid to $0.08^\circ \times 0.08^\circ$ grid, a downscaling procedure was applied based on a linear regression analysis

(Sutanudjaja et al., 2011). It makes use of precipitation and temperature lapse rates derived from the 10' CRU-CL2.0 climatology dataset (New et al., 2002).

Local and global reference evapotranspiration (ET) were obtained through Hamon method (Allen et al., 1998; Lu et al., 2005).

Figure 4 shows the daily mean precipitation, temperature and reference evapotranspiration for the study time period (2007–2010) for both forcing data sets. Aside from the resolution difference, precipitation ranges from higher values in the mountainous regions of the catchment, with increasing variance in elevation and rainfall, to lower values in the western plain. On the contrary, temperature, and subsequently reference evapotranspiration decrease from West to East.

Local and global forcing data show some differences in their spatial distribution and magnitude. Each climate variable shows similar spatial distribution across the various resolutions (rows in Fig. 4), with larger variations in the high elevation areas. However, local temperature magnitude differs in 3–4 °C with the global temperature, which is also reflected in the reference evapotranspiration. The downscaled global forcing data show a similar pattern to the global data with increasing resolution.

Table 1 shows the catchment daily mean values of the climate forcing variables for each year individually. Global temperature deviates from local approximately 3–4 °C, which is also reflected in reference evapotranspiration, but less pronounced. Local and global precipitation, by contrast, is very similar for each year.

2.3.2 Soil moisture data

Soil moisture observations retrieved from AMSR-E (Advanced Microwave Scanning Radiometer – EOS) brightness temperatures were provided by the Vrije Universiteit Amsterdam (VUA) in collaboration with NASA. AMSR-E is a multi-frequency passive microwave radiometer that uses C- (6.9 GHz) and X-band (10.65 and 18.7 GHz) radiance observations to derive near-surface soil moisture via the LPRM radiative transfer model (Owe et al., 2008; De Jeu et al., 2008). In the present study, C-band AMSR-E data reported on a regular ~ 50 km global grid with an observation depth of 2 cm and a revisit time of 1–3 days was

considered (Owe et al., 2008). Brightness temperatures from C-band AMSR-E were down-scaled using the smoothing filter-based modulation technique. In this technique, brightness temperatures from the C-band (approx. $50 \text{ km} \times 50 \text{ km}$) are adjusted based on data from the Ka-band (approx. $10 \text{ km} \times 10 \text{ km}$). From the downscaled C-band AMSR-E brightness temperatures, soil moisture on a $0.08^\circ \times 0.08^\circ$ spatial resolution is estimated. To improve the quality of the final soil moisture products a precipitation mask is applied (Gevaert et al., 2015).

Soil moisture observations from AMSR-E were compared to the unsaturated zone layer of OSWS and the first of the three vertical layers constituting the soil profile in each grid cell of PCR-GLOBWB. To match the remotely sensed soil moisture observations to the statistics of corresponding hydrological model states for soil water, different strategies can be followed, such as linear or minimum–maximum (MM) matching (Brocca et al., 2011), mean-standard deviation (μ - σ) matching (Draper et al., 2009) and cumulative distribution function (CDF) matching (Reichle and Koster, 2004). In this study, a linear rescaling method was used. The converted satellite soil moisture values θ_{new} (in $\text{m}^3 \text{ m}^{-3}$) used for assimilation were calculated as

$$\theta_{\text{new}} = I_{\min} + \left(\frac{I_{\max} - I_{\min}}{\theta_{\max} - \theta_{\min}} \right) (\theta - \theta_{\min}) \quad (1)$$

where I_{\max} and I_{\min} are the field capacity and the wilting point of the modelled soil moisture values at each grid cell [$\text{m}^3 \text{ m}^{-3}$] and θ_{\max} and θ_{\min} are the maximum and minimum of AMSR-E satellite soil moisture values at the respective grid location [–].

In situ soil moisture observations were obtained from the Australian moisture monitoring network, OzNet (www.oznet.org.au; Smith et al., 2012). A total of 28 soil moisture monitoring stations with daily observations was used in this study for the period January 2007 to December 2010 (Table 2). Soil moisture monitoring sites were distributed evenly across 10 different study areas around and in the Murrumbidgee river basin, including the northern and eastern fringe of the catchment and those associated with the Yanco, Kyeamba Creek and Adelong Creek sites. The instrumentation at the sites measures moisture content in soil layers from either 0–8 cm or 0–5 cm depth.

2.3.3 Discharge data

Discharge observations were provided by the Bureau of Meteorology (BoM) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), under the Water Information R+D Alliance (WIRADA). A total of 23 discharge monitoring stations with daily observations in the Murrumbidgee river and its main tributaries was available for the period January 2007 to December 2010. To ensure an independent evaluation of model simulations after the assimilation, a split sample approach of streamflow stations was used (e.g. Lee et al., 2012; Rakovec et al., 2012; Wanders et al., 2014b). The discharge of 10 stations was used for assimilation into the large-scale hydrological model, the remaining 13 stations were used for evaluation. Assimilation and evaluation stations were selected such they are equally distributed over the catchment and are situated both in small tributaries and the main Murrumbidgee river. Figure 1 shows a map with the discharge locations. Table 3 summarizes some key hydrological data.

2.4 Data assimilation

2.4.1 Ensemble Kalman filter

The Ensemble Kalman filter (EnKF) is a sequential data assimilation method evolved from the standard Kalman filter (Evensen, 1994) that has been used previously for assimilation of observations into land surface and hydrological models (Chen et al., 2011; Draper et al., 2011; Wanders et al., 2014a; Tangdamrongsub et al., 2015). It is a Monte Carlo based approach that integrates an ensemble of model states forward in time to represent the error statistics of the model estimate when observations are assimilated (Burgers et al., 1998; Evensen, 2003). The state equation in a discrete form is given as

$$x_{t+1} = f(x_t, F_{t+1}, p, \varepsilon_t) \quad (2)$$

where f are the dynamical model equations that represents the hydrological processes in the system, x_t is the model state at time t , F_t is the forcing at time t (e.g. precipitation and temperature), p are the model parameters and ε_t is the model error.

To assimilate observations into the hydrological model, the already mentioned observations, downscaled remotely sensed AMSR-E soil moisture and discharge, can be linearly described as

$$y_t = H_t x_t + \epsilon \quad (3)$$

where y_t is the observations vector, H is the observation model or operator that relates the model states x_t to the observations y , and ϵ is the random noise with a zero mean and an error given by the observations error covariance matrix R_t .

The EnKF calculates the analysis at each time t , x_t^a , of the model forecast, x_t^f , as

$$x_t^a = x_t^f + K_t \left[y_t - H_t \left(x_t^f \right) \right] \quad (4)$$

where K_t is defined as the Kalman gain

$$K_t = P_t H_t^T \left(R_t + H_t P_t H_t^T \right)^{-1} \quad (5)$$

with H_t^T the transpose matrix of the observation model at time t (which is equal to the identity matrix after linear rescaling) and P_t the state error covariance matrix of the model prediction calculated from the spread between the different ensemble members given as

$$P_t = \frac{\sum_{n=1}^N \left(x_n^f - \overline{x^f} \right) \left(x_n^f - \overline{x^f} \right)^T}{N - 1} \quad (6)$$

where $\overline{x^f}$ the ensemble average of model simulations and N the number of ensemble members considered.

2.4.2 Assimilating soil moisture and discharge observations

In this study, the EnKF was applied to update state variables of the large-scale hydrological model, PCR-GLOBWB, on each daily time step using downscaled remotely sensed AMSR-E soil moisture and discharge observations. We used 100 ensemble members and all the observations were calculated and assimilated at each 0.08° model grid cell for each day that observations are available. The EnKF has been implemented in the PCRaster modelling environment (Karssen et al., 2010).

Eight different data assimilation scenarios with PCR-GLOBWB were inter-compared and compared to the OSWS estimates without any data assimilation. The data assimilation (DA) scenarios are described in Table 3, indicating the meteorological forcing and the observations used in each scenario. Simulations forced with local meteorological data are denoted with **LOCAL** and simulations forced with global meteorological data are denoted with **GLOBAL**. Independent assimilation of discharge (**GLOBWB_Q**) and soil moisture (**GLOBWB_SM**) were investigated, as well as the joint assimilation of both observation types (**GLOBWB_SM+Q**).

In the EnKF, to account for model and observations uncertainty, stochastic noise can be introduced in model forcing data, parameters, soil moisture and discharge observations. For the local and global meteorological forcing, the precipitation was perturbed with additive Gaussian white noise with standard deviation of 10 % of the nominal value (Adam and Lettenmaier, 2003; Hijmans et al., 2005). The errors were assumed to be spatially uncorrelated. For the assimilation of the satellite soil moisture data, spatial information on the measurement error covariance R (Eq. 5) was required. The structure of R was determined from estimates of Wanders et al. (2012) over Spain, obtained by using high-resolution modelling of the unsaturated zone. The average standard error of AMSR-E is $0.049 \text{ m}^3 \text{ m}^{-3}$. The error covariance between the discharge observations was set to zero while the standard error for the discharge observations was assumed to be 10 % of the discharge. It was additionally assumed that the covariance between the satellite soil moisture observations and discharge observations equals zero. **Some of the assumptions described in this section**

for data assimilation were investigated through a preliminary sensitivity analysis including the number of ensemble members and the standard errors of precipitation and discharge (Figures 1, 2, 3, 4, 5 and 6 in the supplement).

2.5 Evaluation

5 The impact of assimilating discharge and soil moisture observations into the large-scale hydrological model PCR-GLOBWB compared with the locally calibrated model OSWS, is separately analysed: firstly, on soil moisture estimates and secondly, on discharge estimates. A common regular $0.08^\circ \times 0.08^\circ$ grid (approx. 10 km) was adopted for the inter-comparison of the two different resolution hydrological models estimates. For this purpose,
10 OSWS estimates were upscaled with a linear resampling from $0.01^\circ \times 0.01^\circ$ (approx. 1 km) to $0.08^\circ \times 0.08^\circ$ (approx. 10 km).

Results were produced for each of the 23 locations listed in Table 3. For practical reasons, the following section includes results for a limited number of evaluation locations only, both in the Murrumbidgee river and its tributaries. This combination thus comprises stations with
15 varying sizes of contributing area.

To understand and inter-compare the performance of the different data assimilation scenarios described in Table 3, an extensive evaluation was carried out, including the calculation of various evaluation metrics, such as Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Pearson's correlation coefficient (r) and Nash Sutcliffe efficiency (NSE –
20 Nash and Sutcliffe, 1970).

3 Results

3.1 Impact of assimilation on soil moisture estimates

The time series of simulated soil moisture for 0–5 cm for each data assimilation scenario and downscaled AMSR-E observations for the time period January 2008–May 2009 at 410057
25 gauging station (mountainous region) are shown in Fig. 5.

The use of global forcing data produces a different dynamic response of soil moisture estimates compared to the local forcing data. This fact is due to the discrepancies between both meteorological datasets, which govern the water exchange processes between the top layer and the atmosphere (precipitation, evapotranspiration and temperature).

Even though global precipitation quite accurately depicts the overall character of the precipitation (daily mean values of the local and global precipitations show similar spatial distributions and magnitudes – see Sect. 2.3.1), the global precipitation misses specific rainfall events at particular days and locations due to its lower resolution. This is especially important for warm season precipitation and regions in mountainous terrain (e.g. 410057 gauging station in Fig. 5), which are dominated by convective storms. The differences in precipitation are reflected in soil moisture estimates of both hydrological models and their impact is higher in PCR-GLOBWB estimates. When PCR-GLOBWB is forced with local data, soil moisture estimates produce patterns with a more accurate description of the small-scale variability of the observations in time. Whereas, when global forcing is used, soil moisture results in a smoother estimation of the observations.

Eight different data assimilation scenarios were investigated, with global and local forcing data (Table 3). In the OL scenario, no data is assimilated into the model to correct intermediate model states. In this first scenario, soil moisture observations are underestimated when local forcing is used. The assimilation of discharge observations, Q scenario, results in similar soil moisture estimates compared to the OL scenario, as expected. This similarity is caused by the assimilation procedure which constrains the model to follow the discharge observations directly affecting on groundwater and routing processes, which are a poor reflection of the upper soil moisture content from 0 to 5 cm. In contrast, the assimilation of soil moisture observations in SM and SM_Q scenarios produces a reduction of the negative bias, improving the soil moisture estimates, especially when local forcing is used.

Figure 6 shows the impact of each data assimilation scenario on the considered evaluation metrics (RMSE, MAE and r). Results of the catchment daily mean values are shown. Each histogram shows the evaluation metric on the vertical axis vs. the data assimilation scenarios on the horizontal axis. Figure 6 consists of a matrix of multiple panels, with rows

showing the three considered evaluation metrics and columns showing local and global forcing data.

From this figure, some general observations can be made. Evaluation results show differences between the results from local and global forcing of the models. For example, the use of local instead of global forcing produces a decrease of 4 and 2 % in RMSE and MAE, respectively and an increase of 6 % in r , when the OL scenario in PCR-GLOBWB is considered.

The large-scale model, PCR-GLOBWB, without data assimilation shows a poorer performance than the locally calibrated model OSWS on soil moisture predictions. Assimilating discharge observations (Q scenario) does not lead to an improvement on soil moisture estimates, whereas downscaled AMSR-E soil moisture observations assimilation (SM scenario) results in an increase of r and a decrease of RMSE and MAE. Therefore, after assimilating soil moisture observations, evaluation results of PCR-GLOBWB and OSWS are closer to each other. For example, percent differences in RMSE between both models are reduced from 22 % (LOCAL GLOBWB_OL and LOCAL OSWS) to 16 % (LOCAL GLOBWB_SM+Q and LOCAL OSWS) and MAE from 14 % (LOCAL GLOBWB_OL and LOCAL OSWS) to 16 % (LOCAL GLOBWB_SM+Q and LOCAL OSWS). However, the reduction in the differences between PCR-GLOBWB and OSWS performances due to the assimilation of soil moisture and streamflow observations does not mean that both models perform similarly. Maximum r values obtained with PCR-GLOBWB are approx. 0.5, whereas for OSWS maximum r values of 0.7 are reached.

Additionally, boxplots of the catchment daily mean values are included in Fig. 7 considering local (upper panel) and global (lower panel) forcing. The assimilation of soil moisture observations leads to an evident improvement in the statistical distribution of PCR-GLOBWB soil moisture estimates, reducing the differences in dispersion with the observations.

Assimilating soil moisture observations and forcing the model with high spatial resolution meteorological datasets impacts the quality of soil moisture estimates with PCR-GLOBWB to a similar extent. Results indicate that the highest improved performance is achieved when

their combination occur, i.e. soil moisture observations are assimilated into a model driven by local forcing data ([LOCAL GLOBWB_SM](#) and [LOCAL GLOBWB_SM+Q](#) scenarios).

3.2 Impact of assimilation on streamflow estimates

The simulated and observed streamflow estimates at [410088](#) gauging station are shown in Fig. 8. From this figure, it is clear that the peaks in streamflow are poorly estimated by PCR-GLOBWB, whereas OSWS is able to capture them with higher accuracy, independently of the forcing data used. This is most probably explained by the higher resolution and the calibration of model parameters for the study.

Differences between local and global forcing data (see Sect. 2.3.1) are reflected in differences in streamflow estimates from both models. When global data is used, evapotranspiration is lower; hence a higher amount of water is introduced into the models, resulting in higher streamflow estimates. By assimilating discharge and soil moisture observations, intermediate hydrological processes, including groundwater state, percolation and surface runoff among others, are corrected and errors in forcing data are reduced to improve streamflow predictions (e.g. November 2008). The best performance is achieved when soil moisture and discharge data are jointly assimilated.

To further analyse and quantify the influence of each data assimilation scenario on streamflow estimates, the evaluation metrics (RMSE, MAE, r and NSE) were calculated and included for multiple discharge locations in Fig. 9.

The highest r and NSE and the lowest RMSEs and MAEs are obtained when models are forced with local meteorological data. The use of global forcing data leads to a reduction in performance, which is more significant for the large-scale than for the local-scale model. Without assimilation, forcing PCR-GLOBWB with local data (L_OL) instead of global data ([GLOBAL GLOBWB_OL](#)) results in an increase of 80 % in r and a decrease of 70 % in RMSE and 72 % in MAE on average. OSWS also improves its streamflow estimates but to a lesser degree, with increases of 7 % in r and decreases of 28 % in RMSE and 43 % in MAE ([LOCAL OSWS](#) and [GLOBAL OSWS](#)).

Both observations assimilation, discharge and soil moisture separately (Q and SM), improve streamflow models estimates. The highest improvement is achieved when both observations are assimilated into the model (GLOBALWB SM+Q), as expected. The improvement is higher when soil moisture observations (SM) are assimilated than the case of discharge assimilation alone (Q). For example, in terms of r GLOBALWB_SM scenario results in an increase of 20 % and G_Q scenario of 5 % relative to GLOBALWB_OL scenario at 410107 gauging station. Some possible explanations could be the finer resolution of AMSR-E soil moisture observations and/or the basin hydrological features, which characterize it as a catchment mainly driven by direct runoff, where the highest contribution to the total runoff comes from the upper soil layer and not from the groundwater zone.

The largest improvements were found at gauging stations in the main channel of the Murrumbidgee river, such as station 410001 where assimilating soil moisture and discharge observations increases r from 0.56 to 0.79 and decreases RMSE and MAE from 49.54 to 28.77 $\text{m}^3 \text{s}^{-1}$ and from 43.85 to 10.76 $\text{m}^3 \text{s}^{-1}$, i.e. comparing the LOCALWB_OL and LOCALWB_SM+Q scenarios. This improvement is more significant when the model is forced with global data than with local data. At station 410001, RMSE varies from 157.62 to 29.01 $\text{m}^3 \text{s}^{-1}$, MAE from 148.29 to 10.88 $\text{m}^3 \text{s}^{-1}$ and r from 0.26 to 0.72 when GLOBALWB_OL and GLOBALWB_SM+Q scenarios are compared.

Boxplots of streamflow estimates are included in Fig. 10. The results clearly show that, compared to the observed streamflow, the median values of PCR-GLOBWB streamflow without data assimilation are very biased. The greatest amount of spread is observed between OL scenarios and observations, across all stations. Every data assimilation scenario (Q, SM and SM+Q) shows improvement in the statistics of streamflow, correcting not only its median value, but also the overestimation.

In contrast with the soil moisture evaluation results, Figs. 8–10 indicate that for streamflow the use of local forcing provides a larger improvement than assimilating soil moisture and discharge observations. Using a global model with local forcing and assimilating satellite soil moisture data yields streamflow predictions comparable to a local model with local forcing along the main river of this catchment. Moreover, also on the main channel, a global model

with global forcing may still yield reasonable results as long as both discharge data and soil moisture data are assimilated.

4 Discussion

PCR-GLOBWB poorly estimates streamflow and soil moisture, when forced either with high- or coarse spatial resolution forcing data, without data assimilation. The derivation of the hydrological model parameters from hydro-geological information at a global scale could be a possible explanation. From the initial scenarios without assimilation, it can be inferred that there is significant space for improvements when discharge and soil moisture observations are assimilated. An alternative route to data assimilation to improve model estimates would be to locally calibrate PCR-GLOBWB using discharge observations from in situ gauging stations. The improvement achieved through model parameters calibration would be possibly even higher than when soil moisture and streamflow observations are assimilated into the model (Wanders et al., 2014b). However, the present study means to be an attempt of providing hydrological estimations with a global model that could be also used in ungauged river basins where scarce in situ data are available.

The joint assimilation of discharge and downscaled satellite soil moisture observations produces the largest improvement on PCR-GLOBWB streamflow estimates (20 % reduction in RMSE). These results agree with the findings made by Wanders et al. (2014a) in the Upper Danube and it is also in line with the expectations, where more observations lead to a better constrained model simulation.

A major finding of this study is the positive impact of assimilating soil moisture observations on the streamflow estimates, compared to the independent discharge assimilation. The estimations of a large-scale hydrological model driven with coarse resolution forcing data are improved using globally available remotely sensed soil moisture observations. This creates an opportunity for improved global model-based streamflow estimations as a result of the assimilation of remotely sensed soil moisture observations into large-scale hydrological models. Additionally, the adopted methodology has the advantage that it is applicable in

river basins all over the world independently of the availability of in situ hydrometeorological information.

The variable effectiveness of soil moisture assimilation has been previously reported in literature. Whereas some studies found improvements (Draper et al., 2011; Wanders et al., 2014b), others obtained mixed or unsatisfactory results (Crow et al., 2005). The scale of soil moisture observations, the dominant runoff processes in the study basin and the model structure and parameters uncertainties may partly explain this variability. In this particular study, the novel use of a finer spatial resolution satellite soil moisture product together with the climate and hydrogeological characteristics of the catchment could be a possible explanation of the positive impact of soil moisture assimilation. Renzullo et al. (2014) assimilated satellite soil moisture observations from multiple sensors (ASCAT and AMSR-E) obtained at scales coarser than the model (AWRA-L) resolution. In the present study, the scale of soil moisture observations coincides with the model scale. A specific analysis of the impact on streamflow and soil moisture estimates of assimilating non-downscaled AMSR-E soil moisture assimilation could be a possible route to further investigate the effect of different spatial resolution soil moisture products. To this end, AMSR-E soil moisture observations at the original spatial resolution were assimilated into PCR-GLOBWB and results analysed presented in this manuscript were reproduced. Results showed that the assimilation of non-downscaled soil moisture observations has a positive impact on soil moisture and discharge estimates, but this improvement is smaller compared to the assimilation of the downscaled soil moisture estimates (Figures 7 and 8 in the supplement). Moreover, runoff in the Murrumbidgee river basin is mainly dominated by direct runoff processes, with reduced contribution from the groundwater zone (Green et al., 2011). These catchment conditions, together with their representation in the model structure are most likely responsible for the added value of assimilating soil moisture. There may be merit in analysing these scenarios in future research studies.

For the assimilation of AMSR-E soil moisture observations, spatial information on the measurement error covariance R (Eq. 5) was based on results from previous studies over Spain (Wanders et al., 2012). Our philosophy was to set the AMSR-E errors to realistic

values determined and validated in previous studies, so that all the required information was already available. The determination of AMSR-E observations uncertainty specifically over the Murrumbidgee river basin with physically-based modelling or in-situ soil moisture measurements (Su et al., 2013) could be further investigated. In addition, a linear rescaling method was used to match AMSR-E soil moisture observations to the statistics of model states related with soil water. Different matching strategies could be applied in future studies. To account for model uncertainty, stochastic noise in precipitation data was introduced. A sensitivity analysis on model parameters could be another possible approach.

Meteorological data play a key role in soil moisture and discharge model estimates. The various model and data assimilation options were evaluated under both high- and low-resolution meteorological forcing. In general, the higher spatial resolution and the higher quality of the local forcing data results in better model predictions (PCR-GLOBWB and OSWS) of both soil moisture and streamflow. The coarse resolution of the global forcing could lead to failures to detect extreme rainfall events or differences at specific regions, such as mountainous areas. Recent studies have developed several downscaling procedures, e.g. geostatistical methods of blending satellite and gauge data (Chappell et al., 2013), that could improve model predictions when global forcing is used.

To improve the representation of the global water cycle using global hydrological models, one could follow multiple strategies. Improve the quality and quantity of ground observation, increase the spatial resolution of the global models or obtain more detailed information on the catchment properties (e.g. soil data). Another way forward is the assimilation of observations and the use of high spatial resolution meteorological data to bridge the gap between the different spatial scales for which large-scale hydrological models are designed and the river basin scale. The advantage of this approach is that it provides a global improvement of the hydrological simulation and the satellite data often have a global coverage. In this study we show the potential gain in model accuracy of using remotely sensed observations. Previous studies on the potential gain of satellite observations for global and continental hydrological models agree with the obtained results in the present manuscript (Andreadis and Lettenmaier, 2006; Lievens et al., 2015).

5 Conclusions

The study investigates the influence of discharge and soil moisture assimilation on the accuracy of large-scale model (PCR-GLOBWB) predictions, when driven by meteorological forcing datasets of high- and coarse-resolution, compared with local-scale model (OSWS) estimations.

Results show poor PCR-GLOBWB streamflow and soil moisture estimates when no observations are assimilated. The assimilation of soil moisture observations results in the largest improvement of the model estimates of streamflow. The joint assimilation of both streamflow and downscaled soil moisture observations leads to further improvement in streamflow simulations (20 % reduction in RMSE).

In general, the higher spatial resolution of the local forcing data results in better models predictions of both soil moisture and streamflow. The added value of using higher spatial resolution forcing data is more significant for PCR-GLOBWB than for OSWS. When the impact on model accuracy of assimilating observations and forcing the models with higher spatial resolution data are compared, the latter leads to a more substantial improvement of streamflow predictions.

Furthermore, results show that the added contribution of data assimilation, for both soil moisture and streamflow, is more pronounced when the global meteorological data are used to force the models. This is caused by the higher uncertainty and coarser resolution of the global forcing.

The greatest benefit is obtained when local coarse resolution forcing data are used in combination with streamflow and soil moisture observations assimilation into the large-scale hydrological model, PCR-GLOBWB.

In conclusion, the present research study shows that data assimilation of high resolution soil moisture succeeds in resolving short-comings that exist nowadays in global hydrological models and can partly overcome the difference in model performance between a large-scale hydrological model driven by coarse resolution forcing data and a local-scale model forced with higher resolution meteorological data. Moreover, it demonstrates that further

investments and improvements in remotely sensed observations, especially in soil moisture products can benefit large-scale hydrological model predictions and bring these closer to those obtained from local-scale hydrological modelling.

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Table 1. Catchment daily mean (μ)/standard deviation (σ) of precipitation (P), temperature (T) and reference evapotranspiration (ET) in the Murrumbidgee river basin for 2007–2010.

| | P (mm day ⁻¹) | | T (°C) | | ET (mm day ⁻¹) | |
|------|-----------------------------|--------------|--------------|--------------|----------------------------|--------------|
| | Local | Global | Local | Global | Local | Global |
| | μ/σ | μ/σ | μ/σ | μ/σ | μ/σ | μ/σ |
| 2007 | 1.38/3.22 | 1.36/3.19 | 19.73/7.05 | 16.02/6.66 | 3.98/2.13 | 3.18/1.62 |
| 2008 | 1.24/3.19 | 1.26/3.32 | 18.89/6.65 | 15.18/6.24 | 3.88/2.06 | 3.00/1.51 |
| 2009 | 1.16/2.48 | 1.15/2.33 | 19.82/7.46 | 16.07/6.76 | 4.08/2.33 | 3.24/1.83 |
| 2010 | 2.35/5.46 | 2.45/5.19 | 18.50/6.91 | 15.03/6.46 | 3.69/2.04 | 2.95/1.56 |

Table 2. Soil moisture monitoring sites information.

| Monitoring site name | Location | | Elevation (m) |
|--------------------------|-----------|----------|---------------|
| | Longitude | Latitude | |
| Adelong Creek 1 | 148.11 | −35.50 | 772 |
| Adelong Creek 3 | 148.10 | −35.40 | 472 |
| Adelong Creek 4 | 148.07 | −35.37 | 457 |
| Kyeamba Creek 1 | 147.56 | −35.49 | 437 |
| Kyeamba Creek 4 | 147.60 | −35.43 | 296 |
| Kyeamba Creek 6 | 147.46 | −35.39 | 317 |
| Kyeamba Creek 9 | 147.44 | −35.32 | 241 |
| Kyeamba Creek 12 | 147.49 | −35.23 | 220 |
| Kyeamba Creek 13 | 147.53 | −35.24 | 261 |
| Murrumbidgee catchment 1 | 148.97 | −36.29 | 937 |
| Murrumbidgee catchment 2 | 149.20 | −35.31 | 639 |
| Murrumbidgee catchment 3 | 148.04 | −34.63 | 333 |
| Murrumbidgee catchment 5 | 143.55 | −34.66 | 62 |
| Murrumbidgee catchment 6 | 144.87 | −34.55 | 90 |
| Murrumbidgee catchment 7 | 146.07 | −34.25 | 137 |
| Yanco 1 | 145.85 | −34.63 | 120 |
| Yanco 2 | 146.11 | −34.65 | 130 |
| Yanco 3 | 146.42 | −34.62 | 144 |
| Yanco 4 | 146.02 | −34.72 | 130 |
| Yanco 5 | 146.29 | −34.73 | 136 |
| Yanco 6 | 145.87 | −34.84 | 121 |
| Yanco 7 | 146.12 | −34.85 | 128 |
| Yanco 8 | 146.41 | −34.85 | 149 |
| Yanco 9 | 146.02 | −34.97 | 122 |
| Yanco 10 | 146.31 | −35.01 | 119 |
| Yanco 11 | 145.94 | −35.11 | 113 |
| Yanco 12 | 146.17 | −35.07 | 120 |
| Yanco 13 | 146.31 | −35.09 | 121 |

Table 3. Hydrometeorological and geographical information of analysed catchments at Murrumbidgee river basin.

| Station number | Station name | Basin area (km ²) | Outlet location | | Mean flow (m ³ s ^{−1}) |
|----------------|--|-------------------------------|-----------------|----------|---|
| | | | Longitude | Latitude | |
| Assimilation | | | | | |
| 410088 | Goodradidgee River at Brindabella | 419.66 | 148.73 | −35.42 | 3.719 |
| 410062 | Numeralla River at Numeralla School | 691.38 | 149.35 | −36.18 | 1.164 |
| 410024 | Goodradigbee River at Wee Jasper (Kashmir) | 1050.60 | 148.69 | −35.17 | 5.805 |
| 410044 | Muttama Creek at Coolac | 1058.49 | 148.16 | −34.93 | 1.072 |
| 410033 | Murrumbidgee River at Mittagang Crossing | 1809.84 | 149.09 | −36.16 | 2.228 |
| 410761 | Murrumbidgee River below Lobbs Hole Creek | 9332.28 | 149.10 | −35.54 | 5.463 |
| 410130 | Murrumbidgee river at D/S Balranald weir | 28 651.21 | 143.49 | −34.67 | 10.113 |
| 410023 | Murrumbidgee river at D/S Berembed weir | 34 133.07 | 146.84 | −34.88 | 38.449 |
| 410021 | Murrumbidgee river at Darlington Point | 37 804.78 | 146.00 | −34.57 | 29.899 |
| 410040 | Murrumbidgee river at D/S Maude weir | 43 110.97 | 144.30 | −34.48 | 16.888 |
| Evaluation | | | | | |
| 410107 | Mountain Creek at Mountain Creek | 140.54 | 148.84 | −35.03 | 1.078 |
| 410705 | Molonglo River at Burbong | 350.22 | 149.31 | −35.34 | 0.591 |
| 410048 | Kyeamba Creek at Ladysmith | 350.30 | 147.53 | −35.20 | 2.41 |
| 410038 | Adjungbilly Creek at Darbalara | 390.89 | 148.25 | −35.02 | 1.494 |
| 410734 | Queanbeyan River at Tinderry | 557.73 | 149.35 | −35.61 | 0.893 |
| 410057 | Goobarragandra River at Lacmalac | 559.77 | 148.35 | −35.33 | 4.964 |
| 410026 | Yass River at Yass | 1226.98 | 148.91 | −34.84 | 1.198 |
| 410091 | Billabong Creek at Walbundrie | 2859.77 | 146.72 | −35.69 | 2.113 |
| 410050 | Murrumbidgee River at Billilgra | 3353.91 | 149.13 | −35.98 | 3.836 |
| 410001 | Murrumbidgee River at Wagga Wagga | 39 856.21 | 147.37 | −35.10 | 59.638 |
| 410005 | Murrumbidgee River at Narrandera | 45 321.40 | 146.55 | −34.76 | 48.074 |
| 410078 | Murrumbidgee River at Carrathool | 69 854.30 | 145.42 | −34.35 | 27.057 |
| 410136 | Murrumbidgee River at D/S Hay Weir | 73 241.50 | 144.71 | −34.52 | 25.243 |

Table 4. Data assimilation scenarios including abbreviations, forcing data, hydrological model and assimilated observations.

| Identifier | DA scenarios | | |
|------------------------------------|----------------|------------------------------|---|
| | Forcing data | Hydrological model | Assimilated observations |
| LOCAL GLOBWB_OL | Local (AWAP) | PCR-GLOBWB | Open Loop (None) |
| LOCAL GLOBWB_Q | | | Discharge stations |
| LOCAL GLOBWB_SM | | | AMSR-E soil moisture |
| LOCAL GLOBWB_SM+Q | | | Discharge stations and AMSR-E soil moisture |
| LOCAL OSWS | Global (WFDEI) | OpenStreams wflow_sbm (OSWS) | None |
| GLOBAL GLOBWB_OL | | PCR-GLOBWB | Open Loop (None) |
| GLOBAL GLOBWB_Q | | | Discharge stations |
| GLOBAL GLOBWB_SM | | | AMSR-E soil moisture |
| GLOBAL GLOBWB_SM+Q | | | Discharge stations and AMSR-E soil moisture |
| GLOBAL OSWS | | OpenStreams wflow_sbm (OSWS) | None |

Table A1. Evaluation results of the catchment daily means of soil moisture estimates.

| | RMSE [m ³ m ⁻³] | Local MAE [m ³ m ⁻³] | r [-] | RMSE [m ³ m ⁻³] | Global MAE [m ³ m ⁻³] | r [-] |
|-------------|--|--|---------|--|---|---------|
| OSWS | 0.07571 | 0.05716 | 0.79865 | 0.07854 | 0.06082 | 0.77603 |
| GLOBWB_OL | 0.09735 | 0.07520 | 0.43071 | 0.10094 | 0.07662 | 0.40715 |
| GLOBWB_Q | 0.09738 | 0.07523 | 0.43041 | 0.10095 | 0.07664 | 0.40652 |
| GLOBWB_SM | 0.09085 | 0.06699 | 0.53452 | 0.09372 | 0.06811 | 0.50230 |
| GLOBWB_SM+Q | 0.09032 | 0.06609 | 0.52085 | 0.09302 | 0.06845 | 0.49623 |

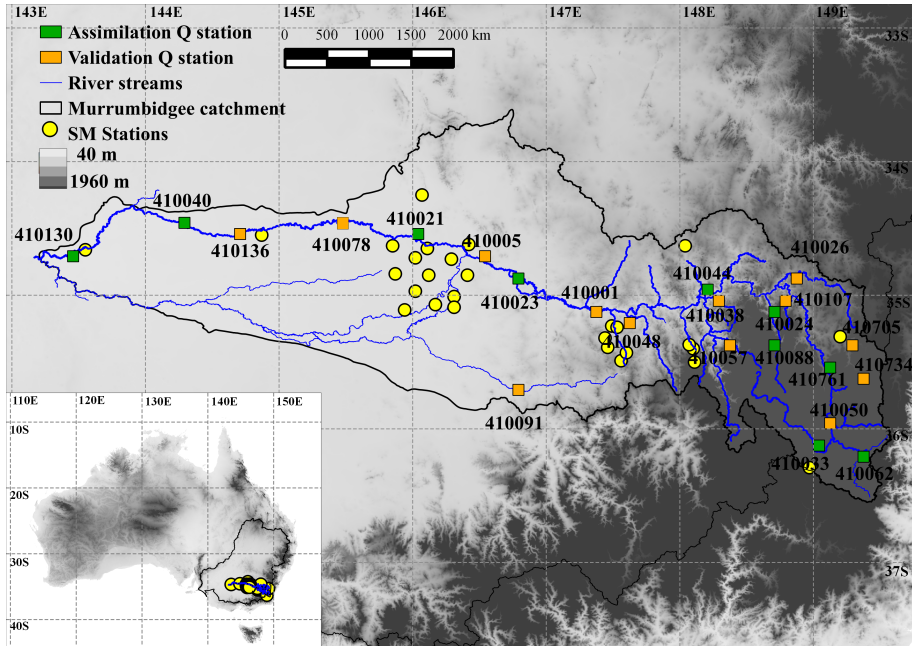


Figure 1. Map of the Murrumbidgee river basin and its location in Australia as part of the Murray–Darling system. Green squares indicate locations for assimilation of streamflow observations and orange squares indicate locations for evaluation of streamflow observations. Each streamflow location is identified with a gauging station number according to BoM (2015). Yellow points indicate locations of field-measured soil moisture observations.

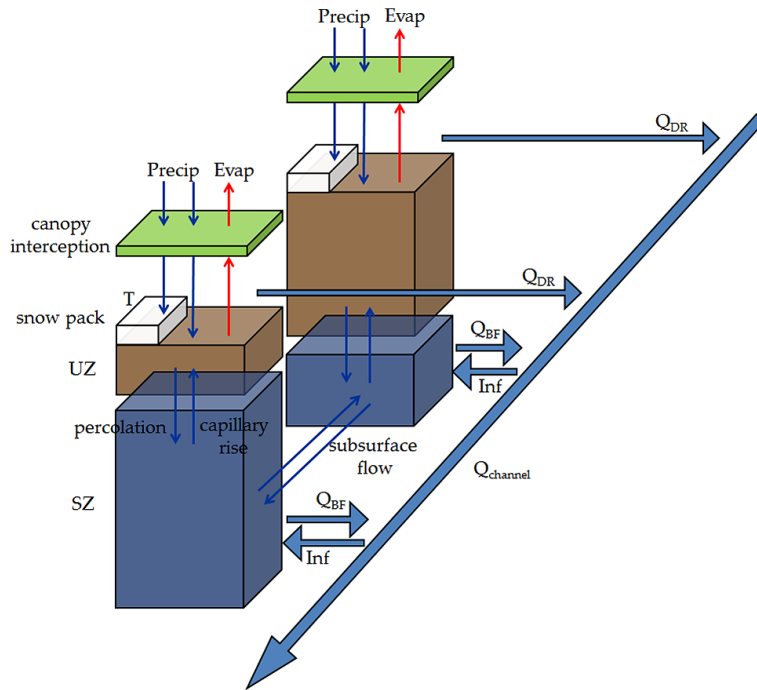


Figure 2. OpenStreams wflow_sbm model structure, adapted from Vertessy and Elsenbeer (1999) and Schellekens (2014). Symbols definition are as follows: Precip, precipitation; Evap, evaporation; T, Temperature; UZ, unsaturated zone; SZ, saturated zone; Q_{channel}, total runoff; Q_{DR}, direct runoff; Q_{BF}, baseflow and Inf, water flow from the river channel to the saturated zone.

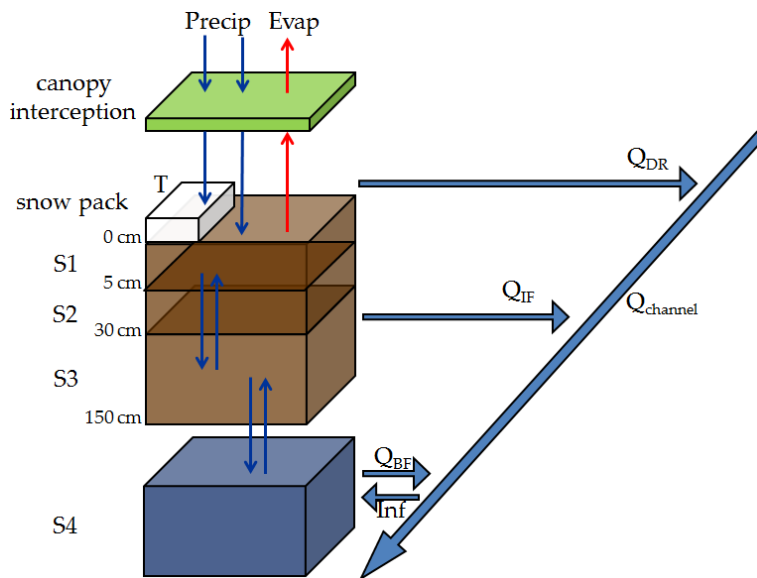


Figure 3. PCR-GLOBWB model structure, adapted from Van Beek et al. (2011). Symbols definition are as follows: Precip, precipitation; Evap, evaporation; T, Temperature; S1, first soil layer; S2, second soil layer; S3 third soil layer; S4, groundwater reservoir; Q_{channel}, total runoff; Q_{DR}, direct runoff; Q_{IF}, intermediate flow; Q_{BF}, baseflow and Inf, water flow from the river channel to the groundwater reservoir.

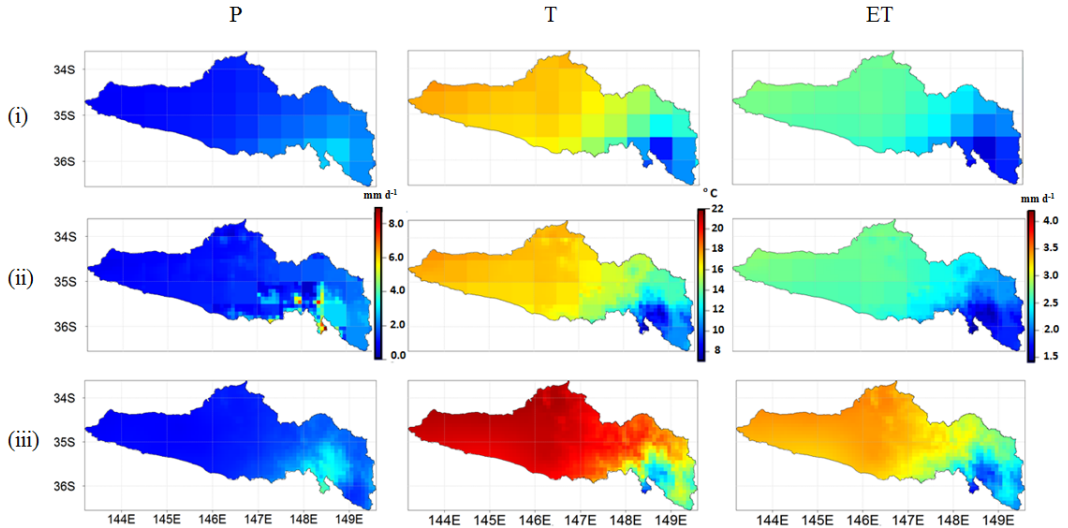


Figure 4. Daily mean precipitation, temperature and reference evapotranspiration for the time period 2007–2010 from the (i) global ($0.5^\circ \times 0.5^\circ$), (ii) downscaled global ($0.08^\circ \times 0.08^\circ$) and (iii) local ($0.05^\circ \times 0.05^\circ$) forcing data sets.

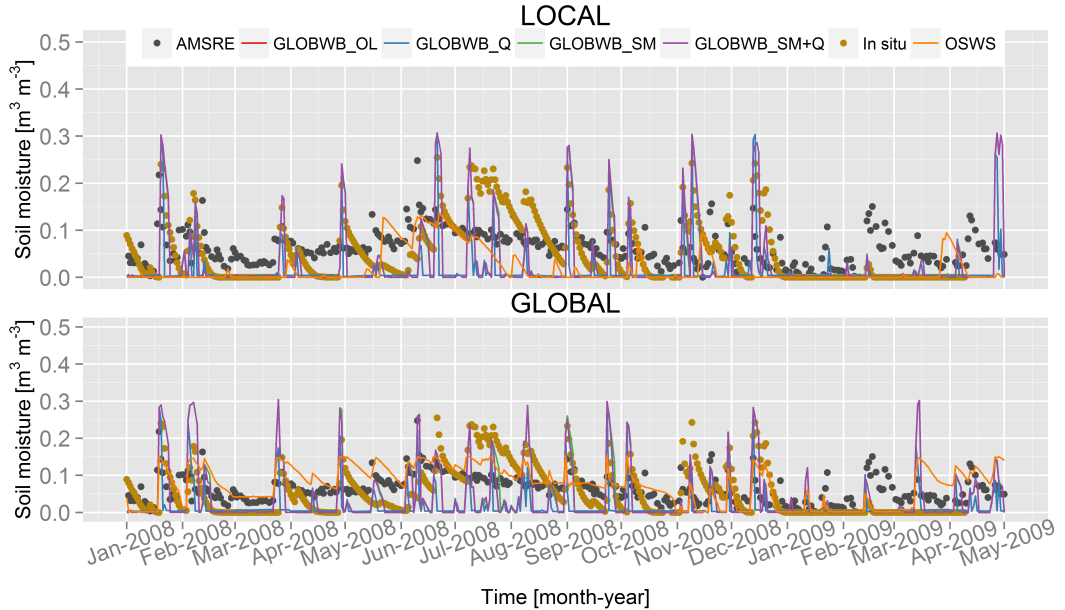


Figure 5. Simulated and observed soil moisture estimates at 410057 gauging station in a tributary of the Murrumbidgee river for the time period January 2008–May 2009. The upper panel shows soil moisture time series when local data is used as model forcing. Soil moisture time series obtained with the global forced models are shown in the lower panel. Each panel contains results for each data assimilation scenario plotted with different colours lines (OSWS – orange, GLOBWB_Q – blue, GLOBWB_SM – green and GLOBWB_SM+Q – purple), downscaled AMSR-E observations with dark grey points and in situ soil moisture observations with dark yellow points.

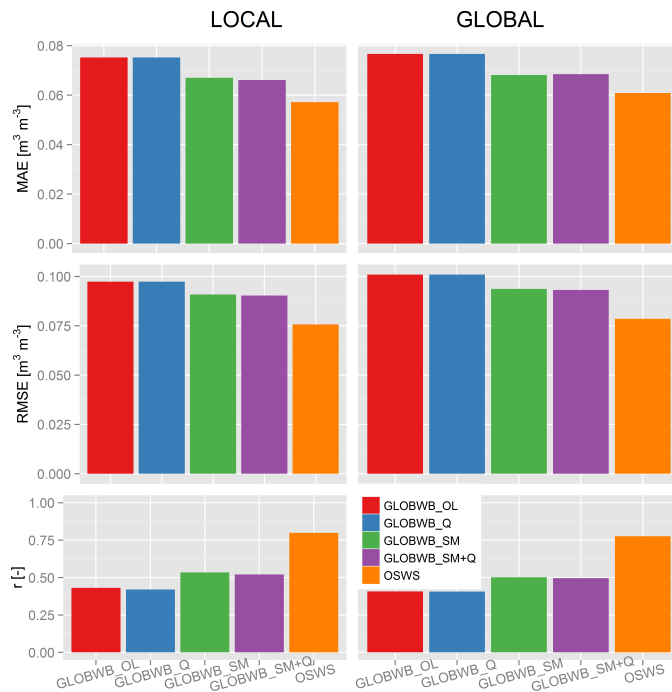


Figure 6. Evaluation results of the catchment daily means of soil moisture in the Murrumbidgee river basin. In the rows, three different evaluation metrics are shown; from top to bottom these are the Mean Absolute Error (MAE), the Root Mean Squared Error (RMSE) and the Pearson's correlation coefficient (r). Columns show various forcing data: local and global. (For clarity, the exact values are included in Table A1.)

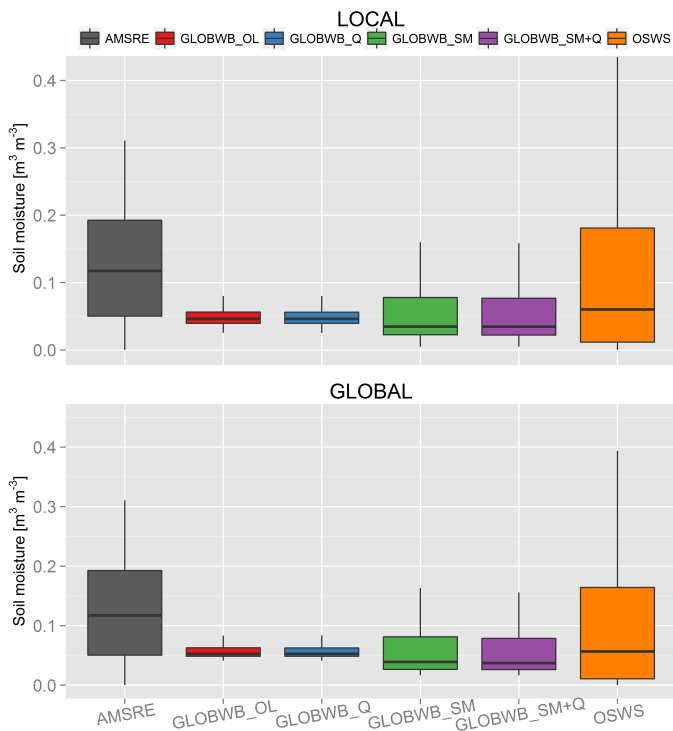


Figure 7. Boxplots of the catchment daily means of soil moisture in the Murrumbidgee river basin. The upper panel shows soil moisture when local data is used as model forcing. Soil moisture obtained with the global forced models is shown in the lower panel. Boxplots of each panel illustrate the first and third quantile ranges (box), the median (dark line) and the maximum–minimum range (whiskers) of soil moisture estimates.

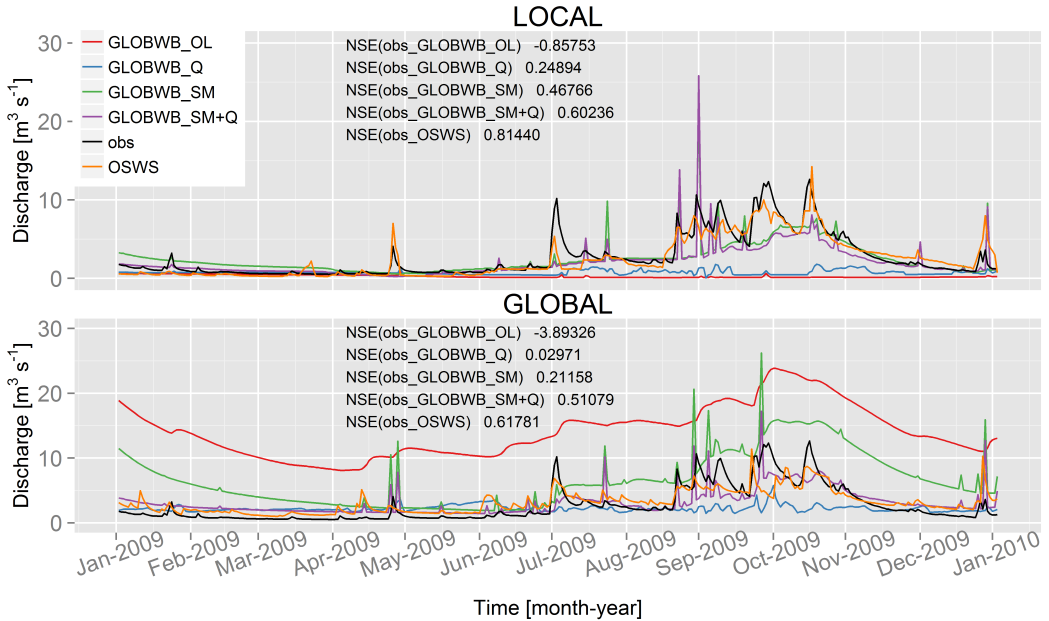


Figure 8. Simulated and observed streamflow estimates at 410088 gauging station in a tributary of the Murrumbidgee river for the time period January 2009-January 2010. The upper panel shows streamflow when local data is used as model forcing. Streamflow obtained with the global forced models is shown in the lower panel. Each panel contains results for each data assimilation scenario and the observed streamflow estimates plotted with different colours lines (OSWS — orange, GLOBWB_OL — red, GLOBWB_Q — blue, GLOBWB_SM — green, GLOBWB_SM+Q — purple and obs — black). The ensemble mean is given for each data assimilation scenario.

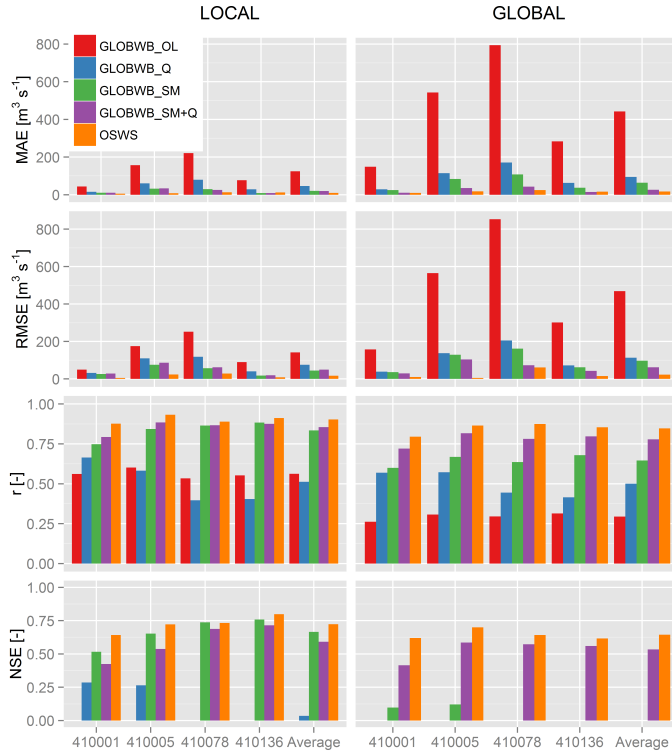


Figure 9. Evaluation results for streamflow estimates at 410001, 410005, 410078 and 410136 locations in the Murrumbidgee river. Average values calculated across those locations are shown in the rightmost bar of each histogram. In the rows, four different evaluation metrics are shown; from top to bottom these are the Mean Absolute Error (MAE), the Root Mean Squared Error (RMSE), the Pearson's correlation coefficient (r) and the Nash Sutcliffe efficiency. Columns show various forcing data: local and global.

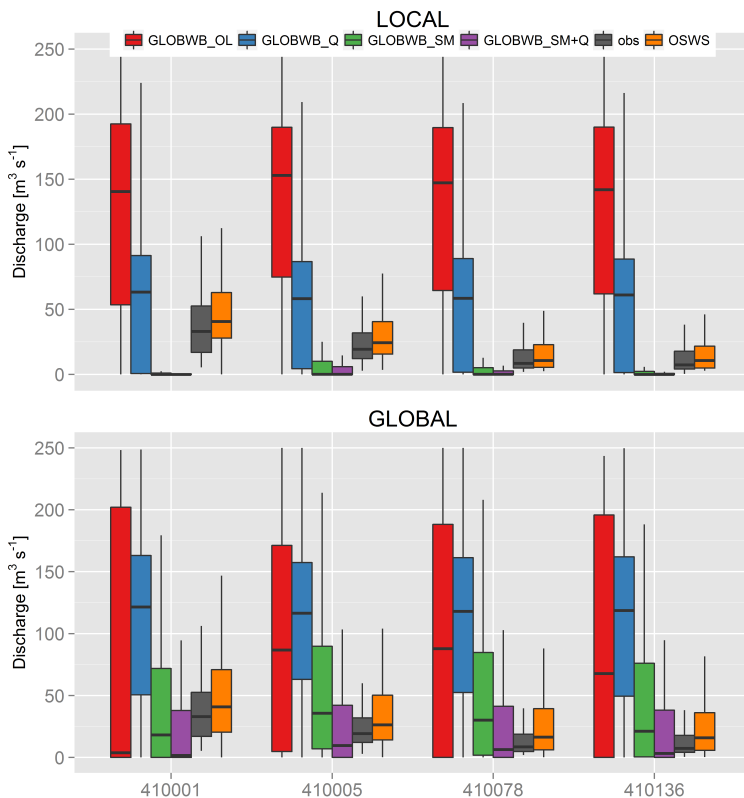


Figure 10. Boxplots of streamflow estimates at 410001, 410005, 410078 and 410136 locations in the Murrumbidgee river. The upper panel shows streamflow when local data is used as model forcing. Streamflow obtained with the global forced models is shown in the lower panel. Boxplots of each panel illustrate the first and third quantile ranges (box), the median (dark line) and the maximum–minimum range (whiskers) of streamflow estimates.