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 would like to thank Anonymous Referee #2 for his/her time and constructive and valuable comments on the manuscript. His/her suggestions will help us to improve the quality of our manuscript. We have included detailed responses to his/her comments and suggestions below.

General comments:

Comment 1:

Two different models (global and local) are compared in the paper. However, the differences between the two models (e.g., infiltration equation, lateral flow component ...) are not well specified and, hence, not clear. Theoretically, global models might be more complex and with an improved structure with respect to local models that frequently are quite simple (in the hydrological community). The real difference shown in the paper is not between a global and a local model, but between an uncalibrated (global) and a calibrated (local) model. The differences are in the parameter calibration, and NOT in the models. Therefore, the interpretation of the results is for me misleading.
Why not performing calibration of the global model similarly to the local model? Why not performing the assimilation of soil moisture and discharge into the local model?
These points should be discussed and clarified. I guess that it needs additional work, but results will be more relevant (at least for me).

Answer:

The present study aims to provide streamflow and soil moisture estimates using a global hydrological model driven with coarse spatial resolution forcing data and compared it with a locally calibrated model forced with high spatial resolution data as benchmark. The rationale behind this is as follows: As the reviewer suggested, model calibration could be done to improve model estimates in the case study because of the in situ discharge data availability. However, model parameter calibration according to streamflow observations is not possible in all basins. Despite campaigns to increase the quality and the temporal and spatial availability of ground-based hydro-meteorological data, many river basins around the world still have a limited number of in-situ observations. Using global earth observation products in hydrological modelling, such as AMSR-E soil moisture observations, may be an alternative approach if discharge observations are few or lacking. We investigate if the assimilation of AMSR-E soil moisture observations, globally available, could improve global model estimates in this case. We then use the case of a finer resolution hydrological model that has been subject to calibration as a benchmark. We note that the local model used here has a similar structure and complexity as the global model. We will consider the reviewer's comment and we will include a note on this in section 4. Discussion (comment 6). By using only globally available data (e.g. soil maps), the global model can be deployed even in ungauged basins, that have no data for calibration. If we would have calibrated the model in this study the findings (e.g. increased performance) would be hard to transfer to other catchments and would make the results less generic and more specific for this catchment. Furthermore, we have taken the current status as a starting point and that is that currently most global hydrological models have received little or no calibration while local models are mostly calibrated. Although many global models would also benefit from calibration doing so is a significant undertaking which is beyond the scope of our work and we are investigating an alternative method (assimilation of remotely sensed soil moisture data) to investigate if this can be used to get better streamflow estimates with an uncalibrated model.

Comment 2:

Linked to the comment 1, both models (also the local model) perform very badly in figures 8 and 9. Looking in details at Figure 8, with local meteorological forcings, the open loop (and the assimilation of discharge) simulation does not produce discharge, much lower than the observations. The local model (OSWS) significantly overestimates discharge. Similar considerations can be made for the simulation with global forcings (even worse). I do not like to comment on model results, as it is expected that model fails to reproduce observations. However, in the example of Figure 8 the discrepancies are significant. In figure 9, for several cases the open loop simulations provide negative NS values. In these conditions, I expect that even the assimilation of perfect observations will be not able to improve the performance. More important, the assimilation in a model with a strong bias with respect to observations might have some issues in the specifications of the different comments (see comment 3).

Answer:

According to the reviewer's comment (and comment 17), gauging station 410057 will be substituted with gauging station 410088 in Figure 8, which is a more representative location. Even though PCR-GLOBWB streamflow estimates without data assimilation are poor in comparison with in situ discharge observations, leading to negative NSE values, the assimilation of remotely sensed soil moisture and streamflow data improves the poor initial model estimates. Results show that in spite of the significant bias of PCR-GLOBWB estimates, assimilating discharge and AMSR-E soil moisture observations may partly reduce it and increase model performance. The observed discharge in some of the Australian catchments has proven to be challenging to reproduce for many hydrological models as also shown in other studies. This is also confirmed in other studies (e.g Lievens et. al. 2015) and does increase the potential for SM data assimilation to improve the performance.

Comment 3:

As the authors know very well, the assimilation of any observation in a model has some issues. In data assimilation, the specification of modelling and observation errors, of the model structure (e.g. soil layer in which soil moisture data are assimilated), of the bias correction technique, of the spatial-temporal correlation of errors, etc., has a significant impact on final results (see Massari et al., 2015 for a recent example). The authors mention these issues shortly in the discussion, but no analysis is made to address this issue. Can the authors add some more explanations on the choices made in the data assimilation experiment? Better, a sensitivity analysis on the selected choices is required. Otherwise, the obtained results might be only a random realization of an ensemble of results that might be very different depending on the subjective choices made in the assimilation experiment.

Answer:

In sections 2.3.2. Soil moisture data, 2.4.2. Assimilating soil moisture and discharge observations and 4. Discussion we describe and discuss the choices made for the streamflow and soil moisture assimilation related to model and observations uncertainty. According to the reviewer's suggestion we would like to further explain some of them as follows. Previous data assimilation experiments within PCR-GLOBWB show that there is no significant improvement with increasing the number of ensembles above 100 (Wanders et al., 2014). In addition to this brief explanation and following the reviewer's comment, we will include a note in section 4. Discussion:

"…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 …"

Comment 4:

For me it is obvious that assimilating satellite soil moisture from AMSRE will improve the agreement with AMSR-E observations, as shown in section 3.1 (it happens for any variable, model ...). In the basin, independent in situ observations should be available. Why not using these observations for a more robust assessment of the assimilation results in terms of soil moisture simulation? Can the authors add this analysis?

Answer:

According to the reviewer's suggestion, in situ soil moisture observations will be included for a more robust assessment of the assimilation results in terms of the impact on soil moisture estimates. In situ soil moisture observations from 28 stations will be introduced in the results analysis. In section 2.3.2. Soil moisture data, a description of the field measured soil moisture data and a table with information for each monitoring site will be included:

"…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. …"

Figure 1 will be also modified to incorporate to the map the locations of the soil moisture monitoring sites.

Comment 5:

At page 10578 it reads that the use of finer spatial resolution satellite soil moisture products might be responsible of the good results obtained in the paper. However, the comparison with coarse resolution data is not made. Therefore, it can't be stated that finer resolution data provides improvements. It should be checked with specific analysis.

Answer:

In the second paragraph of section 4. Discussion, we mention possible hypotheses that could explain the positive impact of downscaled AMSR-E soil moisture assimilation on the streamflow estimates. The scale of soil moisture observations, the dominant runoff processes in the study basin and the model structure and parameters uncertainties are stated as possible explanations for this behaviour. We agree with the reviewer's comment that in the manuscript there is no evidences to support the statement of finer spatial resolution AMSR-E soil moisture observations provides higher improvements compared to coarser soil moisture observations. Therefore, a comment will be included to clarify this, following the reviewer suggestion:

"…. 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-dowsncaled AMSR-E soil moisture assimilation could be a possible route to further investigate the effect of different spatial resolution soil moisture products. 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. …"

In future studies, the suggested analysis will be included to check if the finer spatial resolution of the soil moisture observations is actually the explanation of this improvement or not.

Comment 6:

In the discussion and in the conclusions I believe that the authors are over optimistic in the evaluation of the obtained results. With respect to the open loop, an improvement is obtained, and it is good. However, the performance in the open loop is too poor and it seems to me quite easy to obtain a better agreement after the assimilation. I suggest reformulating the text.

Answer:

According to the reviewer's suggestion and in addition to the modifications included in comment 5 to section 4. Discussion, we will include an initial paragraph to state PCR-GLOBWB performances without data assimilation:

" … 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. 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 …"

We will also include a note in section 5. Conclusions:

"…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. …"

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

Comment 7:

P10562, L12: I believe that neglecting lateral fluxes in global hydrological models is the major issue that needs further investigations. Can the author comment on that?

Answer:

We will add a note in the introduction to commenting on the influence of neglecting lateral fluxes in global hydrological models:

"… . 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…"

Comment 8:

P10563, L6: Several recent studies have been published on the assimilation of soil moisture data in hydrological model (Massari et al., 2015), even in Australia (Lievens et al., 2015; Alvarez-Garreton et al., 2015). I believe that these studies should be mentioned and commented here.

Answer:

We will include the reviewer's suggested studies on the assimilation of soil moisture data into hydrological models:

"… . 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 (Dorigo et al., 2010). On the …"

Comment 9:

P10563, L9: The reference to Dorigo et al., 2010 for the AMSR-E soil moisture product is not appropriate. I suggest using Owe et al. (2001).

Answer:

As per the reviewer's suggestion, the reference will be changed:

"… such as ASCAT (Naeimi et al., 2009), SMOS (Kerr et al., 2012) and AMSR-E (Owe et al., 2008). On the …"

Comment 10:

P10563, L28: Also Aubert et al. (2013) assimilated both discharge and soil moisture observations, I suggest mentioning here.

Answer:

We will include the reference to Aubert et al. (2013), as the reviewer suggested:

"…joint assimilation procedures is largely unknown and should be further investigated (Aubert et al., 2003; Lee et al., 2011).

Many data assimilation … "

Comment 11:

P10567, L20-21: Why both air temperature and potential evapotranspiration are used? I believe that only one variable is required. Please specify.

Answer:

As the reviewer commented, only air temperature is needed. Reference evapotranspiration (ET) was obtained through Hamon method using air temperature. We will modify the manuscript according to the reviewer's suggestion:

"… . The forcing data required to drive both hydrological models are precipitation and temperature. Two types …"

Comment 12:

P10569, L17: Here I see two issues. First, the soil layer depth of OSWS model is surely much larger than that of AMSR-E observations. Therefore, their direct comparison might be not appropriate. Second, the depth of the first layer of PCR-GLOBWB model (5 cm) is also larger than that of AMSR-E data (2 cm). More important, it should be clarified how the surface information is propagated with depth through the assimilation procedure. Indeed, it is found that this aspect has a significant impact on the results (Brocca et al., 2012; Chen et al., 2011).

Answer:

We are aware of the differences between the depth of the soil layer representation of OSWS, PCR-GLOBWB and the AMSR-E remotely sensed soil moisture observations, as the reviewer commented. However, when the present study is compared with previous data assimilation experiments, including Lievens et al. (2015), in which SMOS soil moisture observations (5 cm) are assimilated into the Variable Infiltration Capacity (VIC) model (first soil layer represents the top 10 cm) or Renzullo et al. (2014), in which AMSR-E (1-2 cm) and ASCAT (~2cm) soil moisture observations are assimilated into the Australian Water Resources Assessment (AWRA-L) system (first soil layer represents the top 7-9cm); differences in soil depth were not considered highly significant.

As the reviewer suggested and based on previous studies (Brocca et al., 2012; Chen et al., 2011), the propagation of surface information with soil depth through the assimilation procedure was considered on a preliminary analysis. The impact of vertical coupling strength of PCR-GLOBWB soil scheme was analysed to test the effectiveness of the EnKF. The propagation with soil depth of the surface information was assessed by the Pearson's correlation coefficient between the surface layer S1 and layers S2 and S3. The correlations between the surface layer S1 and layer S2 were reasonable (0.45). As expected, coupling strengths between the surface layer S1 and the layer S3 were lower (0.31). Correlations between layers S2 and S3 were greater (0.68). For practical reasons (inclusion of additional figures and tables), these preliminary results were omitted in the manuscript. Furthermore, the use of temporal aggregation algorithms likes the SWI approach by Wagner et. al. 2009, also have their disadvantages. They require local calibration of the T parameter (time-lag), which in turn is another unknown in the simulation. Therefore, the authors would like to use the original data and acknowledge that the penetration depth of AMSR-E has a relatively small mismatch with the SM representation in PCR-GLOBWB (especially, when compared to other studies). Finally, we perform a linear bias correction to ensure that the SM observations to have an identical dynamical range compared to the simulated SM from the model.

Comment 13:

P10571, L18: After linear rescaling, the H matrix is equal to identity matrix. I suggest mentioning here.

Answer:

We will mention the reviewer's suggestion about the observation model or operator that relates model states to the observations:

"… 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 …"

Comment 14:

P10572, L10-17: It is not fully clear from the captions and the legend of figures 5-10 the different scenarios. The figures captions should be self-describing. It should be evident that the assimilation is only performed in the global model, and that the symbol "w" is referred to the local model (it is not specified in the captions). I suggest using symbols more close to the *meaning, e.g. GLOBWB for the global model and OSWS for the local model. The captions should specify all the symbols. The labels should be larger to be read easily.*

Answer:

We will change the abbreviations of the data assimilation scenarios in the manuscript using symbols close to the meaning, as the reviewer suggested. Therefore we will modify lines 10 to 17 on page 10572 as follows:

"… . Eight different data assimilation scenarios with PCR-GLOBWB were inter-compared and compared to the OSWS estimates without any data assimilation (OSWS). The data assimilation 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). …"

We will modify figures 5, 6, 7, 8, 9 and 10 and tables 3 and A1 to include in the captions and in the figures and tables themselves the new abbreviations. We will also increase the size of the labels in figures 5, 6, 7, 8, 9 and 10 to be read easily, according to reviewer suggestions.

Comment 15:

P10573, L25: What is 410057 gauging station? Is it in situ observed soil moisture? Please clarify.

Answer:

410057 is a gauging station considered in the evaluation of the impact of soil moisture and discharge assimilation on streamflow estimates. In accordance with the reviewer's comment and to avoid confusion between in situ soil moisture and in situ discharge observations, Figure 5 will be replaced with a figure corresponding with: Simulated and observed soil moisture estimates at Y8 gauging station in the Yanco site within the Murrumbidgee river for the time period January 2008-May 2009.

Comment 16:

P10575, L1-3: The performance scores were already defined in section 2.5, please avoid repetitions (also at P10576, L18-20).

Answer:

As the reviewer commented, lines 1-3 of page 10575 will be modified to avoid repetition in the description of the evaluation metrics:

"… . Figure 6 shows the impact of each data assimilation scenario on the considered evaluation metrics (RMSE, MAE and r). Results of the catchment …"

Lines 17-20 of page 10576 will be also modified in the same way:

"… . 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 in Fig. 9. …"

Comment 17:

P10577, L16: I would suggest showing the results at station 41001. I believe results will be more meaningful than those given in Figure 8. Please provide also the NS-values.

Answer:

Following the reviewer's suggestion, we will substitute simulated and observed streamflow estimates at station 410057 with station 410088, whose results are more meaningful and representative than those given in Figure 8. We will also provide the NSE values in the same figure. Section 3.2. Impact of assimilation on streamflow estimates will be also adjusted according to this respect:

"… . The simulated and observed streamflow estimates at 410088 gauging station are shown in Fig 8. From this figure, it is clear …"

Comment 18:

P10577, L28: "reasonably good streamflow predictions". As mentioned before, results are quite poor looking at figures 8 and 9.

Answer:

Lines 27-29 will be modified to be consistent with the results showed at figures 8 and 9, as the reviewer suggested:

"… 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, …"

Additional references to be included

Alvarez-Garreton, C.; Ryu, D.; Western, a. W.; Su, C.-H.; Crow, W. T.; Robertson, D. E.; Leahy, C. (2015) Improving operational flood ensemble prediction by the assimilation of satellite soil moisture: comparison between lumped and semi-distributed schemes. Hydrol. Earth Syst. Sci., 19, 1659–1676.

Aubert, D., C. Loumagne, and L. Oudin (2013). Sequential assimilation of soil moisture and streamflow data in a conceptual rainfall runoff model. J. Hydrol., vol. 280, no. 1–4, pp. 145–161.

Brocca, L., Moramarco, T., Melone, F., Wagner, W., Hasenauer, S., Hahn, S. (2012). Assimilation of surface and root-zone ASCAT soil moisture products into rainfall-runoff modelling. IEEE Transactions on Geoscience and Remote Sensing, 50(7), 2542-2555.

Draper, C., Mahfouf, J. F., Calvet, J. C., Martin, E., & Wagner, W. (2011). Assimilation of ASCAT near-surface soil moisture into the SIM hydrological model over France. Hydrology and Earth System Sciences, 15(12), 3829-3841.

Lievens, H.; Tomer, S. K.; Al Bitar, A.; De Lannoy, G. J. M.; Drusch, M.; Dumedah, G.; Hendricks Franssen, H.-J.; Kerr, Y. H.; Martens, B.; Pan, M.; Roundy, J. K.; Vereecken, H.; Walker, J. P.; Wood, E. F.; Verhoest, N. E. C.; Pauwels, V. R. N. (2015). SMOS soil moisture assimilation for improved hydrologic simulation in the Murray Darling Basin, Australia. Remote Sens. Environ., 168, 146–162.

Massari, C., Brocca, L., Tarpanelli, A., Moramarco, T. (2015). Data assimilation of satellite soil moisture into rainfall-runoff modelling: a complex recipe? Remote Sensing, 7(9), 11403-11433.

Smith, A. B., J. P.Walker, A. W.Western, R. I.Young, K. M.Ellett, R. C.Pipunic, R. B.Grayson, L.Siriwardena, F. H. S.Chiew, and H.Richter (2012). The Murrumbidgee soil moisture monitoring network data set, Water Resour. Res., 48, W07701, doi:10.1029/2012WR011976.

Wanders, N., Bierkens, M., Sutanudjaja, E., & van Beek, R. (2014, May). The PCR-GLOBWB global hydrological reanalysis product. In EGU General Assembly Conference Abstracts (Vol. 16, p. 5369).

Additional references to be excluded

Dorigo, W. A., Scipal, K., Parinussa, R. M., Liu, Y. Y., Wagner, W., de Jeu, R. A. M., and Naeimi, V.: Error characterisation of global active and passive microwave soil moisture datasets, Hydrol. Earth Syst. Sci., 14, 2605–2616, doi:10.5194/hess-14-2605-2010, 2010.

Additional modifications in tables and tables to be included

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 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 mo
LOCAL OSWS		OpenStreams wflow_sbm (OSWS)	None
GLOBAL GLOBWB_OL	Global (WFDEI)	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 mo
GLOBAL OSWS		OpenStreams wflow_sbm (OSWS)	None

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

	LOCAL			GLOBAL		
	RMSE [m^3 m^{-3}]	**MAE [m^3 m^{-3}]**	**r [-]**	**RMSE [m^3 m^{-3}]**	**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

Additional modifications in figures and figures to be included

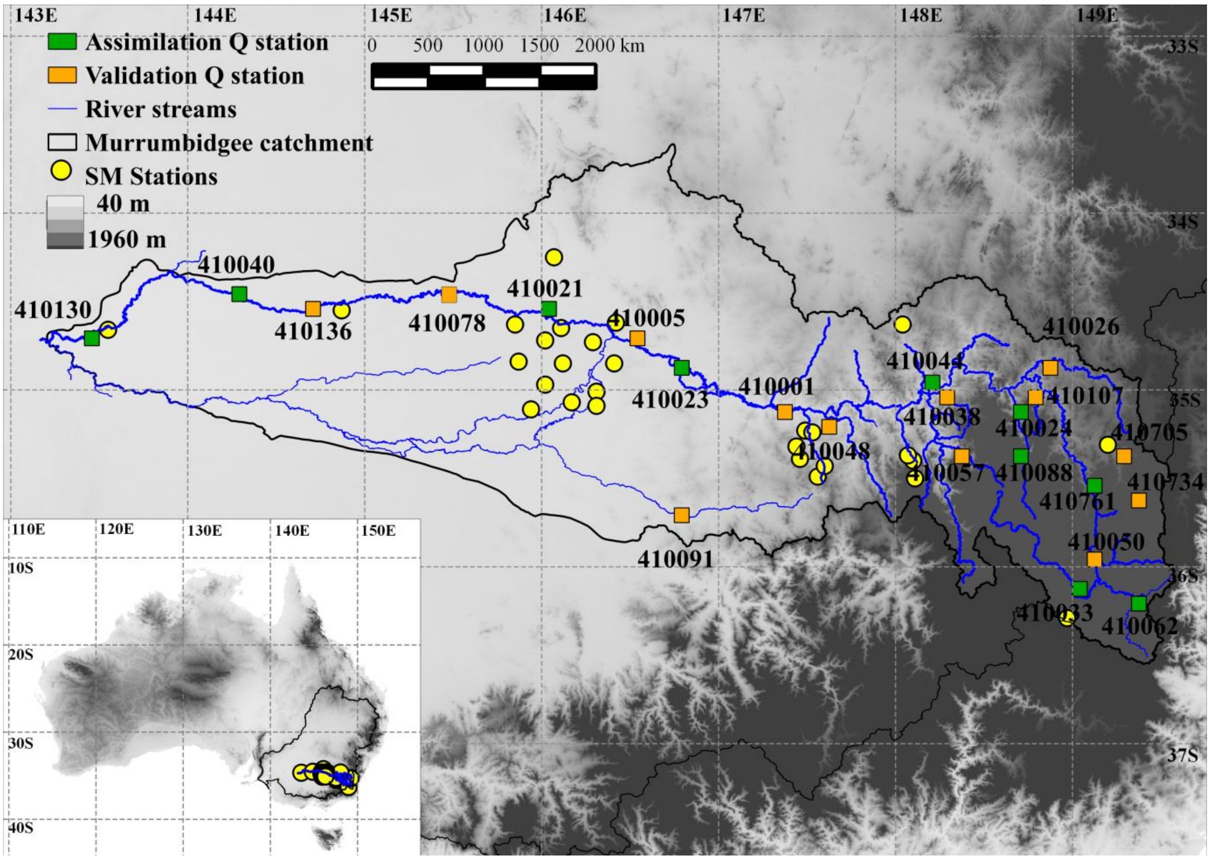

Figure 1. Map of the Murrumbidgee river basin and its location in Australia as part of the Murray–Darling system. Green squares indicate locations for assimilation of streamflow observations and orange squares indicate locations for evaluation of streamflow observations. Each streamflow location is identified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

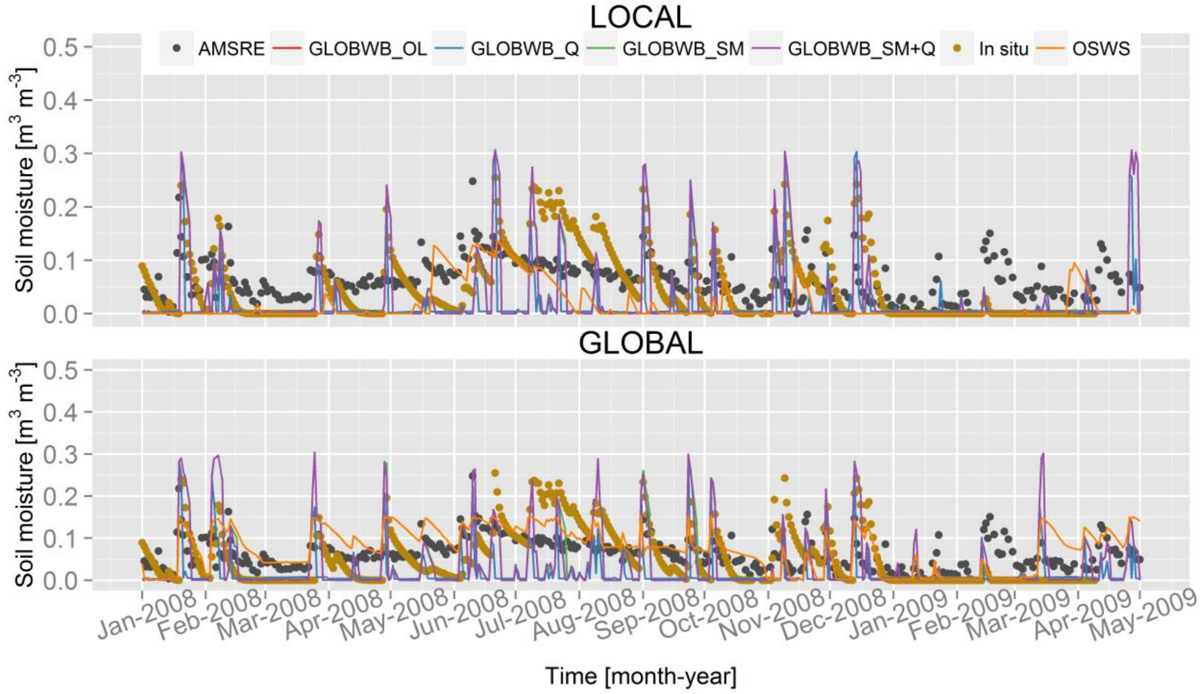

Figure 5. Simulated and observed soil moisture estimates at Y8 soil moisture monitoring site for the time period January 2008–May 2009. The upper panel shows soil moisture time series when local data is used as model forcing. Soil moisture time series obtained with the global forced models are shown in the lower panel. Each panel contains results for each data assimilation scenario plotted with different colours lines (OSWS – orange, GLOBWB_OL – red, GLOBWB_Q – blue, GLOBWB_SM – green, GLOBWB_SM+Q – purple), downscaled AMSR-E observations with dark grey points and in situ soil moisture observations with dark yellow points.

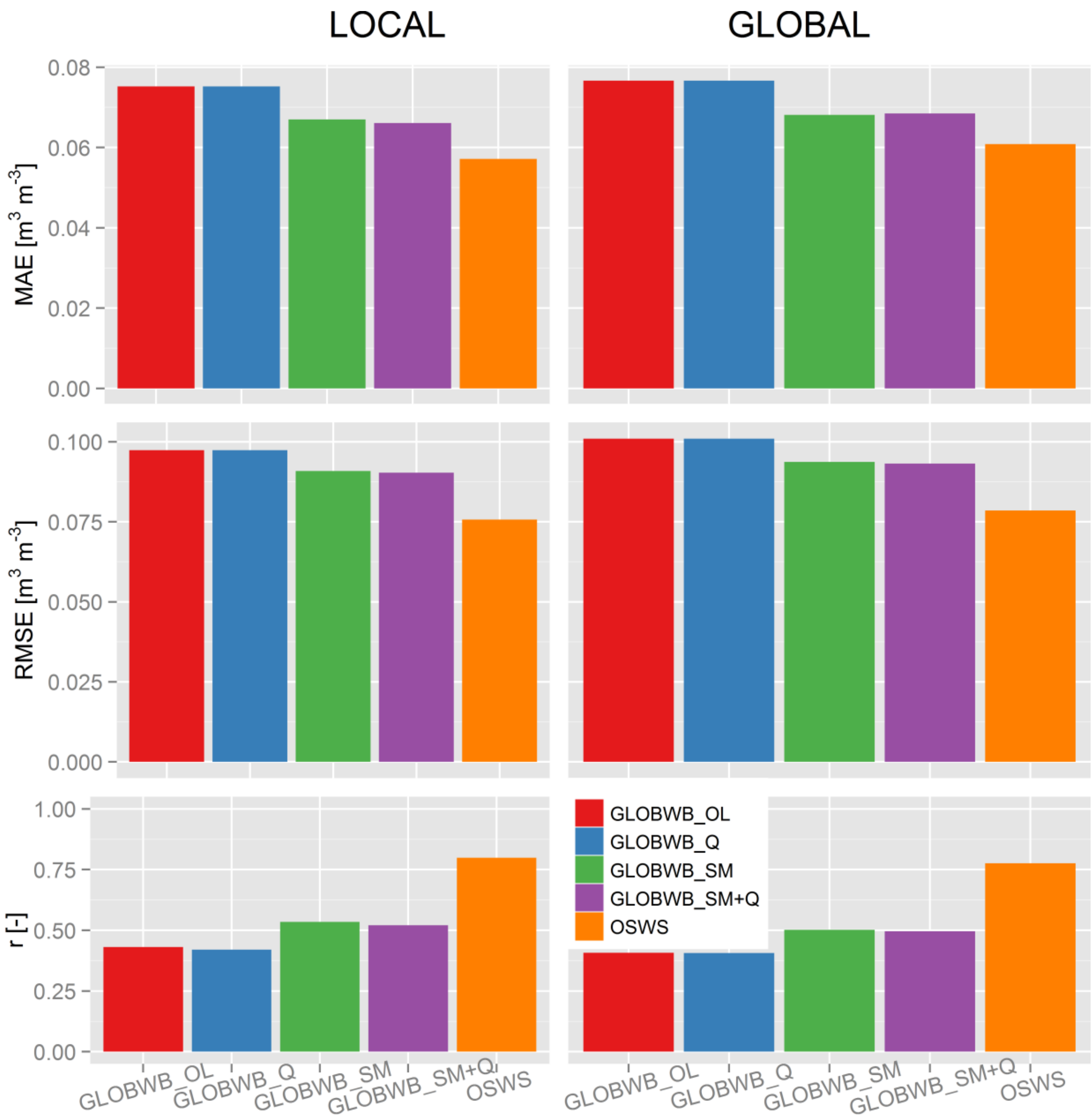

Figure 6. Evaluation results of the catchment daily means of soil moisture in the Murrumbidgee river basin. In the rows, three different evaluation metrics are shown; from top to bottom these are the Mean Absolute Error (MAE), the Root Mean Squared Error (RMSE) and the Pearson's correlation coefficient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

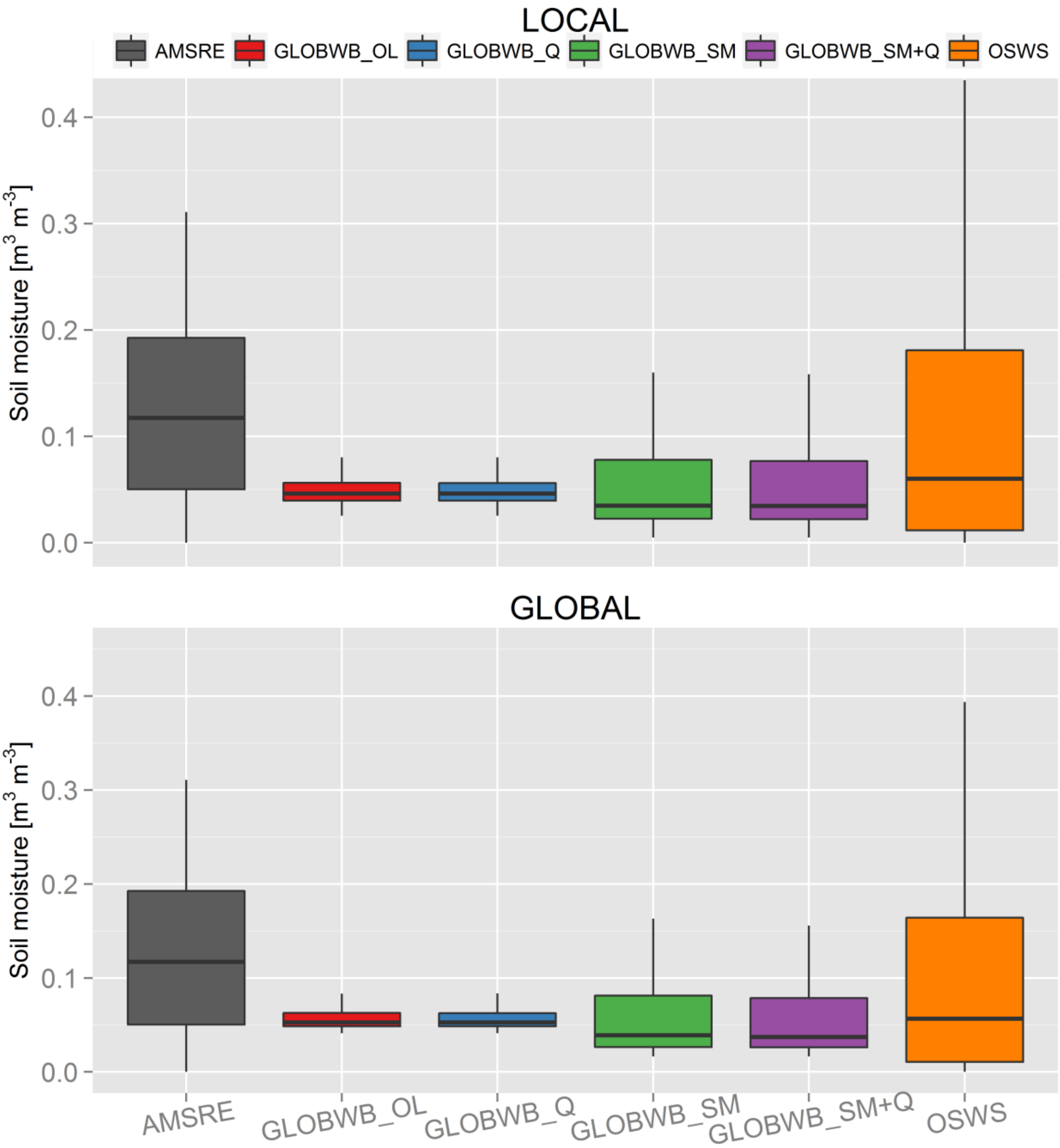

Figure 7. Boxplots of the catchment daily means of soil moisture in the Murrumbidgee river basin. The upper panel shows soil moisture when local data is used as model forcing. Soil moisture obtained with the global forced models is shown in the lower panel. Boxplots of each panel illustrate the first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

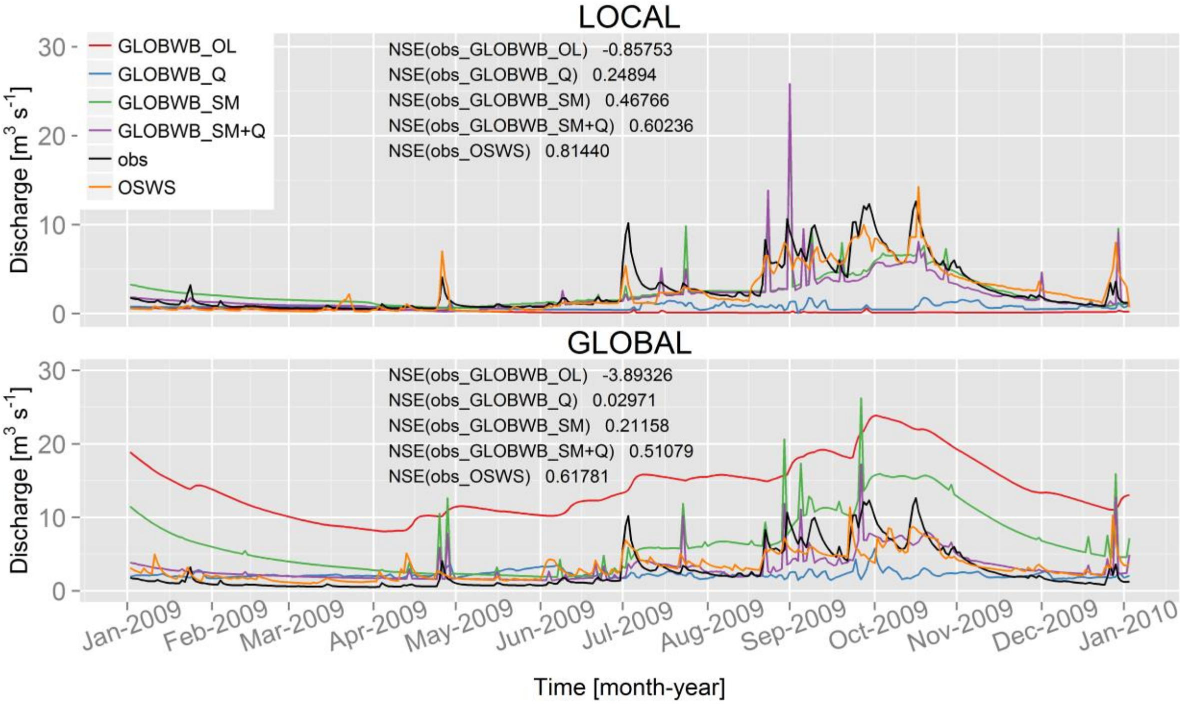

Figure 8. Simulated and observed streamflow estimates at 410088 gauging station in a tributary of the Murrumbidgee river for the time period January 2009 – January 2010. The upper panel shows streamflow when local data is used as model forcing. Streamflow obtained with the global forced models is shown 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.

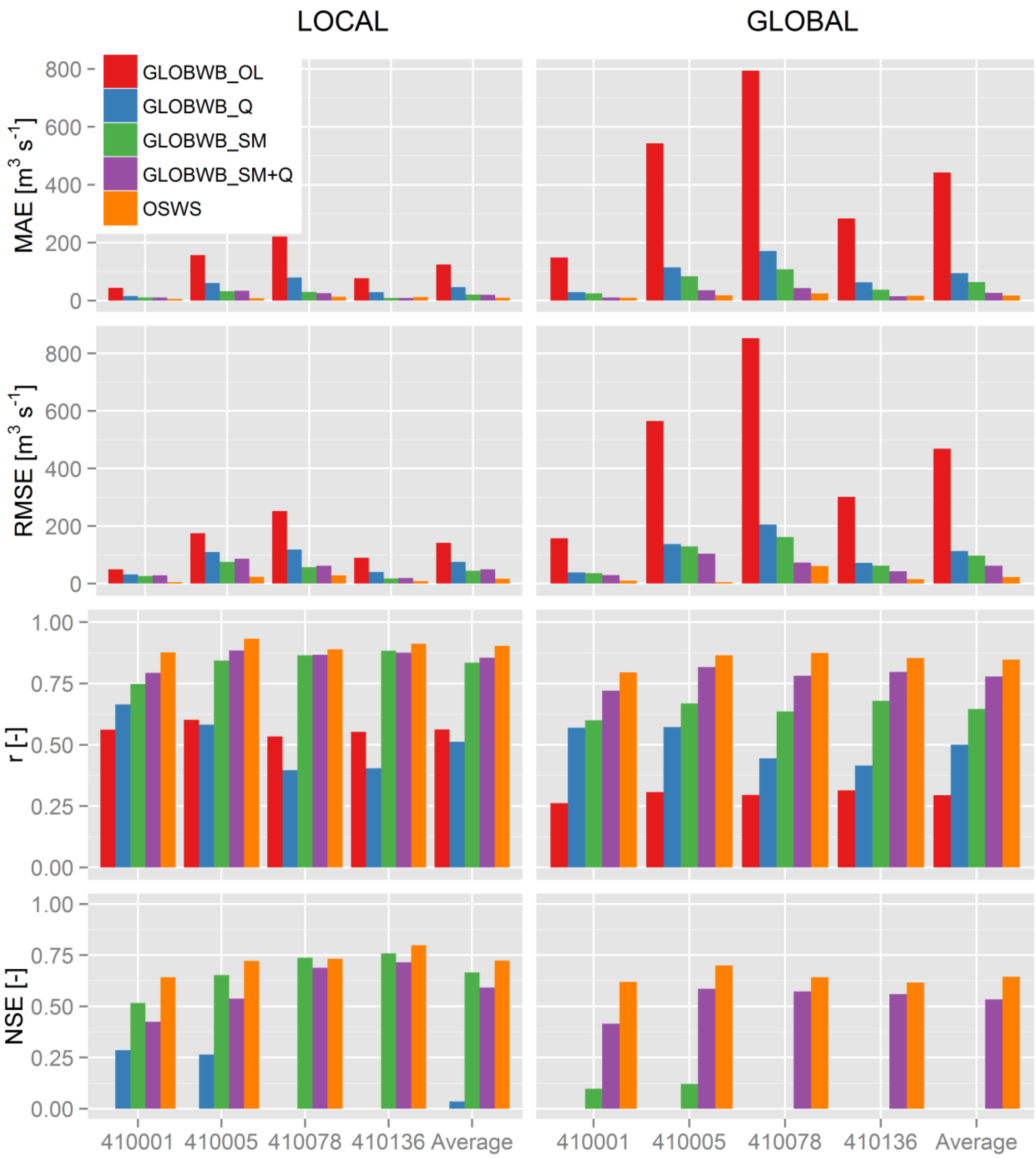

Figure 9. Evaluation results for streamflow estimates at 410001, 410005, 410078 and 410136 locations in the Murrumbidgee river. Average values calculated across those locations are shown in the rightmost bar of each histogram. In the rows, four diferent evaluation metrics are shown; from top to bottom 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.

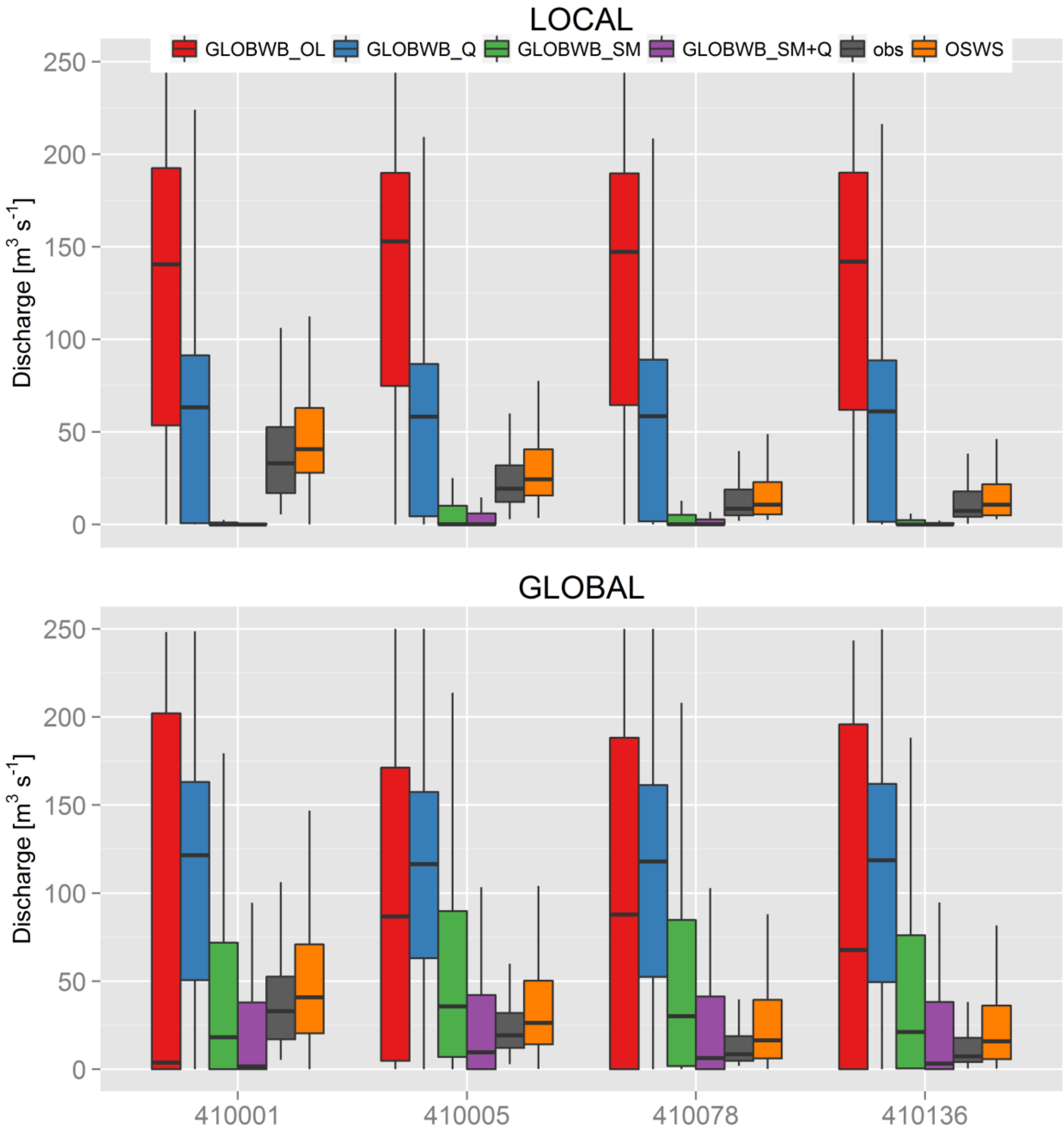

Figure 10. Boxplots of streamflow estimates at 410001, 410005, 410078 and 410136 locations in the Murrumbidgee river. The upper panel shows streamflow when local data is used as model forcing. Streamflow obtained with the global forced models is shown in the lower panel. Boxplots of each panel illustrate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