SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	The role of soil moisture and surface- and subsurface water flows on predictability of convection
Computer Project Account:	SPDEARNA
Start Year - End Year :	2015 - 20.17
Principal Investigator(s)	Dr. Joel Arnault
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Other Researchers (Name/Affiliation):	Thomas Rummler, Prof. Harald Kunstmann

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

- Provide soil moisture data for Germany and West Africa using the hydrologically enhanced version of the Weather Research and Forecasting (WRF) model, i.e WRF-Hydro.
- Investigate the sensitivity of simulated precipitation from NWP to this soil moisture dataset.
- Identify meteorological situations when the role of soil moisture, surface and subsurface water flows on precipitation is enhanced.
- Quantify soil moisture-related processes on precipitation with water budgets and water tracking.
- Assess the potential of a stochastic parameterization to account for soil moisture effects on boundary layer processes.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

Despite the extension of computer resources, it was still not sufficient to generate an ensemble of WRF / WRF-Hydro simulations for Germany for the year 2016, as previously planned. A 12-member ensemble could be carried out successfully at the ForHLR1/2 computing facility in Karlsruhe, for the years 2008, 2009, 2010, 2011 and 2016. The available computer resource on the Cray has therefore been used for test simulations related to the project.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

I am satisfied with how my project was handled from an administrative perspective. I particularly appreciated the user support of Dr. Maas for successfully compiling the WRF-Hydro model on the Cray. I am also happy with the fact that the DWD provided me an access to the ECMWF data server after the end of my special project.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

Research overview

The main task of this project is to investigate which improvements in convective precipitation predictability can be achieved by a more sophisticated treatment of terrestrial hydrological processes in Numerical Weather Prediction (NWP) models. The primary test region is Germany. A secondary test region to be addressed in this project is West Africa. So far, the following research tasks have been achieved:

1) An NWP ensemble has been generated with the Weather Research and Forecasting model WRF and its hydrologically enhanced version WRF-Hydro (Gochis et al. 2014), in order to assess the sensitivity of simulated precipitation to terrestrial water flow uncertainty in Central Europe. This research work has been recently accepted for publication in the Journal of Hydrometeorology (Arnault et al. 2018a)
2) A set of 5-year soil moisture ensemble has been generated with WRF / WRF-Hydro, and passed to another project of the CRC 165/1 for sensitivity analysis with the COSMO model.
3) A stochastic boundary layer parameterization has been implemented in WRF / WRF-Hydro. It has been used to generate a forecast ensemble and assess the role of lateral terrestrial water flow on precipitation predictability in a particular case. This research work has been communicated at the European Geosciences Union General Assembly 2018 as a poster presentation (Arnault et al. 2018b).
4) The hydrological component of the WRF-Hydro modelling system has been calibrated for four large river basins in West Africa. WRF and WRF-Hydro-calibrated ensembles have been generated in order to assess the sensitivity of West African precipitation to the uncertainty of lateral terrestrial water flow. This research work has been communicated at the European Geosciences Union General Assembly 2018 as an oral presentation (Arnault et al. 2018c)
5) A precipitation tracking method in the terrestrial and atmospheric compartments of WRF / WRF-Hydro has been developed and further improved. It is used to assess the role of lateral terrestrial water flow on the hydrological cycle at regional scale, which is the topic of a future publication (Arnault et al., in preparation)
6) The above precipitation tracking method has been enhanced with river water tracking in order to estimate river water age in WRF-Hydro. This method has been applied to a small river catchment in Switzerland, and results have been communicated at the European Geosciences Union General Assembly 2018 as a poster presentation (Arnault et al. 2018d)

Selected results

Precipitation sensitivity to the uncertainty of terrestrial water flow in WRF-Hydro – An ensemble analysis for Central Europe (Arnault et al. 2018a)

Precipitation is affected by soil moisture spatial variability. However, this variability is not well represented in atmospheric models that do not consider soil moisture transport as a three-dimensional process. This study investigates the sensitivity of precipitation to the uncertainty in the representation of terrestrial water flow. The tools used for this investigation are the Weather Research and Forecasting (WRF) model and its hydrologically-enhanced version WRF-Hydro, applied over Central Europe during April-October 2008. The model grid is convection permitting, with a horizontal spacing of 2.8 km. The WRF-Hydro sub-grid employs a 280 m resolution to resolve lateral terrestrial water flow. A WRF/WRF-Hydro ensemble is constructed by modifying the parameter controlling the partitioning between surface runoff and infiltration, and by varying the planetary boundary layer (PBL) scheme. This ensemble represents terrestrial water flow uncertainty originating from the consideration of resolved lateral flow, terrestrial water flow uncertainty in the vertical direction, and turbulence parameterization uncertainty. The uncertainty of terrestrial water flow noticeably increases the normalized ensemble spread of daily precipitation where topography is moderate (Fig. 1), surface flux spatial variability is high, and the weather regime is dominated by local processes (Fig. 2).

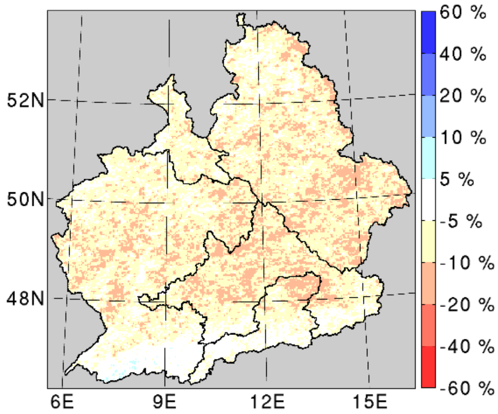


Figure 1. *Difference (%) of normalized ensemble spread of daily precipitation averaged for the period April-October 2008, between the ensemble subset reflecting the turbulence parameterisation uncertainty and the entire ensemble. Negative values indicate areas where the effect of terrestrial water flow uncertainty on simulated precipitation is enhanced.*

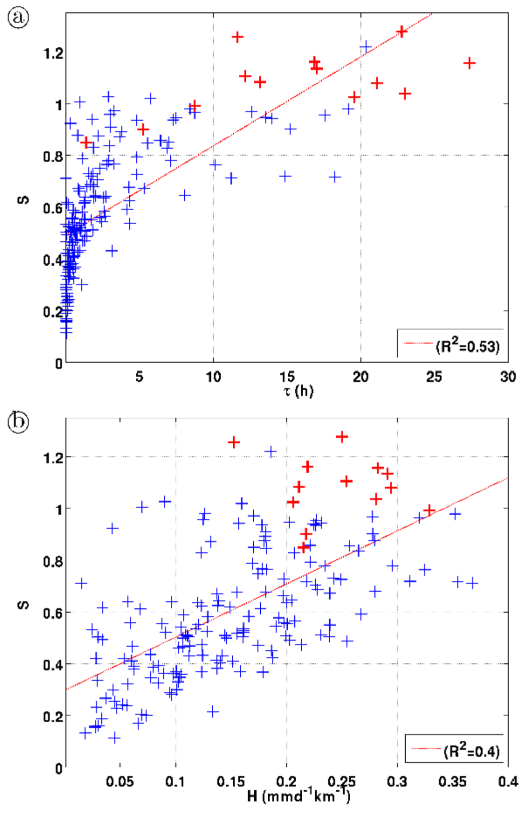


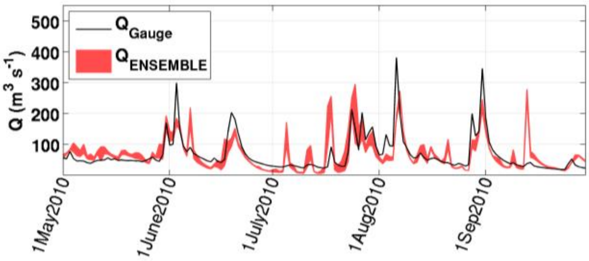
Figure 2. *(a) Scatterplot between daily values of the convective adjustment time-scale τ (x-axis) and the normalized precipitation spread S (y-axis). The red line is the linear fit, with a coefficient of determination R^2 given in the legend in the lower left corner. Red bold plus signs indicate days when the normalized spread from the entire ensemble is 20 % larger than the normalized spread from the ensemble subset reflecting the turbulence parameterization uncertainty, i.e. when the effect of terrestrial water flow uncertainty on simulated precipitation is enhanced. (b) As in (a), except with the surface flux heterogeneity H (mm d^{-1} km^{-1}) for the x-axis.*

Physically-based stochastic perturbations in the PBL to represent the effect of lateral terrestrial water flow on precipitation predictability (Arnault at al. 2018b)

WRF and WRF-Hydro ensemble forecast simulations have been performed with a 2 km horizontal grid-spacing for a 200 km x 200 km area covering the Iller basin in South Germany, for the period from May to September 2010. The regional simulations were forced with the ECMWF deterministic global forecast data. The atmospheric part was re-initialized every day, including a 6-hour spinup time, whereas the soil condition was not re-initialized in order to account for slow processes affecting soil moisture. The ensemble was constructed by randomly varying the stochastic perturbation scheme.

The WRF-Hydro ensemble shows some skill in predicting discharge and precipitation in the Iller basin, as shown in Fig. 3. However, with respect to precipitation, considering the lateral terrestrial water flow in the WRF-Hydro ensemble did not have a remarkable impact of the spread when comparing with a reference WRF ensemble. This is possibly related to the small size of the simulation domain, i.e. 100 x 100 grid points, so that the model results would mainly be driven by the input data. The domain size-dependency of the precipitation sensitivity to lateral terrestrial water flow uncertainty will be investigated in the remaining of this project.

a)



b)

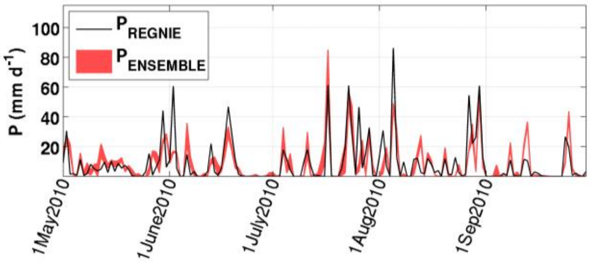


Figure 3. *(a) Daily time series of discharge at Kempten, Iller river basin, 960 km^2, South Germany from gauge station (Gewässerkundlicher Dienst Bayern) and from an ensemble of WRF-Hydro 24-hour forecast runs driven by ECMWF deterministic global forecast data and mutli-year spun-up soil moisture condition. The ensemble contains 10 members constructed with random realisations of the stochastic perturbation scheme. Nash-Suttcliffe efficiency coefficients of 0.30 to 0.49 are obtained, with total biases between -8 and + 12 %. (b) As in (b), except for the basin-averaged precipitation from the REGNIE observation product (Deutsche Wetter Dienst) and from the ensemble members. Root mean squared errors of 9.8 to 10.4 mm d^{-1} are obtained, with total biases between -17 and -1 %.*

Sensitivity of West African precipitation to lateral terrestrial water flow in WRF-Hydro (Arnault et al. 2018c)

Time-lagged ensembles of ten WRF and ten WRF-Hydro simulations have been generated for the period June-July 2000. The impact of resolving lateral terrestrial water flow in WRF-Hydro is assessed with the differential terms of the terrestrial water budget between WRF and WRF-hydro ensemble means (Fig. 4). The significance of this impact is assessed with the Signal to Noise Ratio SNR, computed as the ratio between the ensemble means difference and the sum of ensemble variances (Laux et al. 2016).

In this model case-study, we found that lateral terrestrial water flow mainly had a significant (SNR > 1) impact on surface runoff, and eventually surface evaporation. The impact on 14-day filtered precipitation was not significant, as deduced by the low SNR.

The present result suggests that the sensitivity of West African precipitation to terrestrial water flow is larger at the monthly scale than at the daily scale. On the other hand, Gantner and Kalthoff (2010) found that the triggering of West African convection, a sub-hourly scale process, is highly sensitive to soil moisture conditions. The temporal scale-dependency of the West African precipitation sensitivity to lateral terrestrial water flow uncertainty will be further investigated in the remaining of this project.

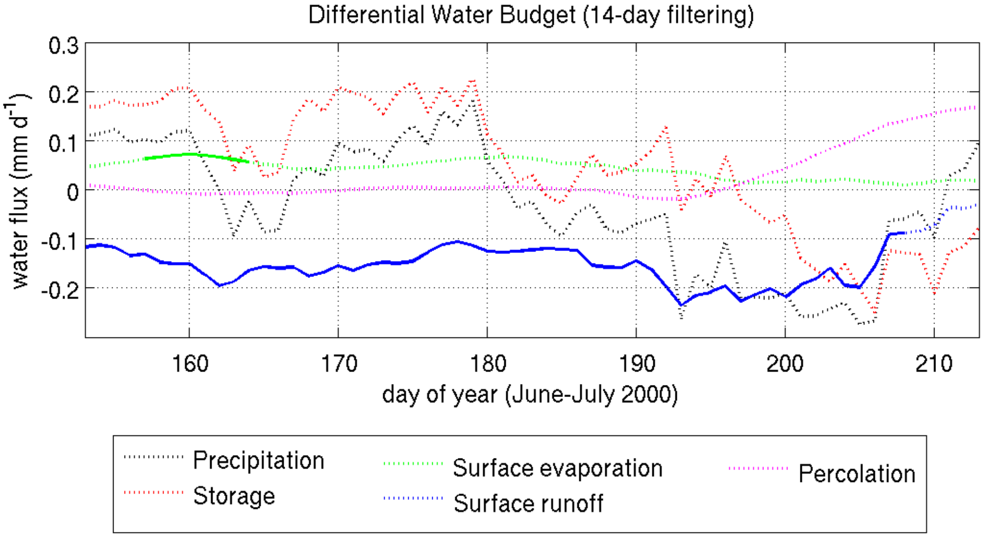


Figure 4. *14-day filtered time series of the terms of the terrestrial water budget, i.e. precipitation, soil storage, surface evaporation, surface runoff and percolation, computed as the difference between WRF and WRF-Hydro ensemble mean results (WRF-Hydro minus WRF), spatially averaged for a 420.000 km² area in West African Sahel encompassing the upper Niger, the Black Volta and the White Volta basins. Dotted (bold) lines correspond to differences between WRF and WRF-Hydro with a Signal to Noise Ratio below (above) one.*

Contribution of lateral terrestrial water flow to the regional hydrological cycle: A joint soil-atmospheric moisture tagging procedure with WRF-Hydro (Arnault et al., in preparation)

Water resources management requires an accurate knowledge of the behavior of the regional hydrological cycle components, including precipitation, evapotranspiration, river discharge and soil water storage. Atmospheric models such as the Weather Research and Forecasting (WRF) model provide a tool to evaluate these components. Recent model developments have focused on coupled atmospheric-hydrological modeling systems, such as WRF-Hydro, in order to account for subsurface, overland and river flow and potentially improve the representation of land-atmosphere interactions. The aim of this study is to investigate the contribution of lateral terrestrial water flow to the regional hydrological cycle, with the help of a newly developed joint soil-atmospheric moisture tagging procedure in WRF and WRF-Hydro. An application to the high precipitation event on 15 August 2008 in the German and Austrian parts of Danube river basin, 94100 km², is presented. The precipitation having fallen in the basin during this event is considered as a source and is tagged for a 40 month-period until December 2011. At the end of the study period, 55 % of the source precipitation has run off, while 42 % has evaporated back to the atmosphere, out of which 2 % has precipitated back in the source region (Fig. 5a). The additionally resolved lateral terrestrial water flow in WRF-Hydro modifies the partitioning between surface and underground runoff in association with an increase of evapotranspiration, and a small enhancement of the recycled precipitation by less than 0.1% (Fig. 5b).

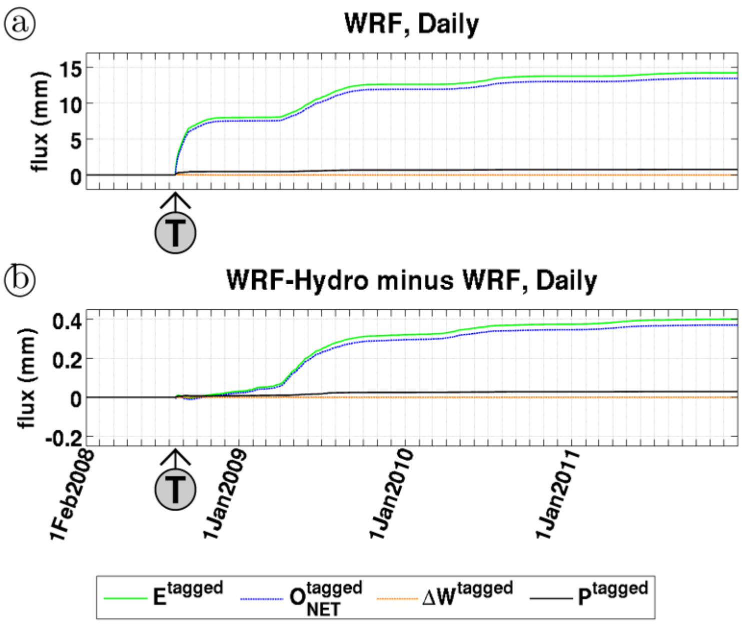


Figure 5. *(a) Water fluxes from the tagged atmospheric water budget in the Danube basin derived from a WRF simulation, displayed as daily accumulated sums [mm] from 1 February 2008 to 31 December 2011. The tagged moisture originates from the source precipitation having fallen in the Danube basin on 15 August 2008,* as indicated by the circled symbol "T". *E^{tagged} is the tagged surface evaporation, O_{NET}^{tagged} the net outflow of tagged atmospheric moisture, ΔW^{tagged} the tagged atmospheric water change and P^{tagged} the tagged precipitation. The graduation of the x-axis indicates the beginning of each month. (b) As in (a), except for the difference between WRF and WRF-Hydro.*

Determining the age of river water with a precipitation tagging method in WRF-Hydro: A case in the Swiss Alptal catchment (Arnault et al. 2018d)

The precipitation tagging method in WRF-Hydro has been enhanced in order to allow tracking moisture from surface precipitation to river discharge at a catchment outlet. Test simulations for the Swiss Alptal catchment showed that water from isolated precipitation events can account for 60 % of isolated summer discharge peaks (see example in Fig. 6). Such model results could be assessed with electric conductivity measurements to estimate event water ratio in river discharge.

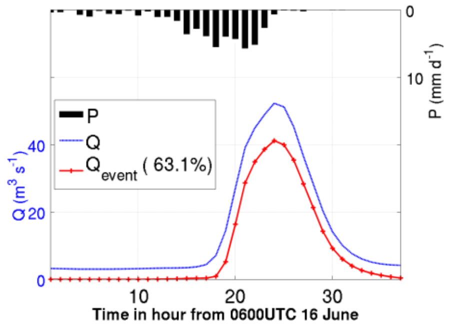


Figure 6. *Simulated hydrograph in the Swiss Alptal catchment, 47 km^2, during the precipitation event on 16 June 2016. The red curve gives the contribution of event water to the discharge, which is about 61. %, as computed by the precipitation tagging method in WRF-hydro.*

Bibliography

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Arnault, J., T. Rummler, F. Baur, S. Lerch, S. Wagner, B. Fersch, Z. Zhang, N. Kerandi, C. Keil, and H. Kunstmann, 2018a: Precipitation sensitivity to the uncertainty of terrestrial water flow in WRF-Hydro – An ensemble analysis for Central Europe. J. Hydrometeor., 0, https://doi.org/10.1175/JHM-D-17-0042.1

Arnault, J., T. Rummler, and H. Kunstmann, 2018b: Physically-based stochastic perturbations in the boundary layer to represent the effect of lateral terrestrial water flow on precipitation predictability, poster presentation, European Geosciences Union general Assembly 2018, Vienna, 8 April 2018.

Arnault, J., T. Rummler, P. Laux, and H. Kunstmann, 2018c: Sensitivity of West African precipitation to lateral terrestrial water flow in WRF-Hydro, oral presentation, European Geosciences Union general Assembly 2018, Vienna, 8 April 2018.

Arnault, J., T. Rummler, J. Von Freyberg, and H. Kunstmann, 2018d: Determining the age of river water with a precipitation tagging method in WRF-Hydro: A case in the Swiss Alptal catchment, poster presentation, European Geosciences Union general Assembly 2018, Vienna, 8 April 2018.

Arnault, J., J. Wei, T. Rummler, B. Fersch, Z. Zhang, S. Wagner, G. Jung, and H. Kunstmann (in preparation) Contribution of lateral terrestrial water flow to the regional hydrological cycle: A joint soil-atmospheric moisture tagging procedure with WRF-Hydro

Gantner, L. and N. Kalthoff, 2010: Sensitivity of a modelled life cycle of a mesoscale convective system to soil conditions over West Africa. Quart. J. Roy. Meteor. Soc., 136, 471–482.

Gochis, D. J., W. Yu, and D. N. Yates, 2014 : The WRF-Hydro model technical description and user's guide, version 2.0. NCAR Technical Document. 120 pages. Available at: WRF-Hydro 2.0 User Guide.

Laux, P., P. N. B. Nguyen, J. Cullmann, T. P. Van, and H. Kunstmann, 2016: How many ensembles provide confidence in the impact of land cover change. Int J Climatol, doi:10.1002/joc.4836

List of publications/reports from the project with complete references

Arnault, J., T. Rummler, F. Baur, S. Lerch, S. Wagner, B. Fersch, Z. Zhang, N. Kerandi, C. Keil, and H. Kunstmann, 2018a: Precipitation sensitivity to the uncertainty of terrestrial water flow in WRF-Hydro – An ensemble analysis for Central Europe. J. Hydrometeor., 0, https://doi.org/10.1175/JHM-D-17-0042.1

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The project will be continued with the computing resource available at the ForHLR1/2 computing facility in Karlsruhe, using the forcing data from the ECMWF data server.