We thank Reviewer 1 for the many insightful comments and suggestions. Below is our point-by-point responses to the provided comments.

Reviewer Summary: The manuscript presents a case study of mesoscale simulation of a severe cold-season rainstorm in eastern Arabia, where orography and small-scale variability are important factors, compared to ground-based and satellite data. I found it to be well written with a good review of relevant literature, and to make a useful contribution to a societally important concern.

Comment 1 (C1): My main comment is that since the standalone WRF also had the NOAH-MP land model, it is not clear to me why soil moisture feedback would improve precipitation simulations with WRF-Hydro but not standalone WRF. The difference between the two model configurations and its relevance to the simulation performance should be discussed in more detail.

Author's response to C1: We agree with the Reviewer on the need to better highlight the difference between the two model configurations and its relevance to the simulation performance.

The existing Noah-MP land surface model in standalone WRF considers single vertical columns (one-dimensional) of terrain properties at each overland grid cell (Niu et al. 2011, Ek et al. 2003). It fails to account for horizontal interactions between adjacent grid cells to calculate soil moisture, temperature profiles, runoff, and water and energy fluxes at the land surface. Therefore, the runoff–infiltration partitioning in the standalone WRF simulation is described as a purely isolated vertical process with no intake from (or discharge to) neighboring grid cells, as dictated by topography. On the other hand, the WRF-Hydro model utilizes the Noah-MP land surface model 1-D representations and attempts to improve the simulation of terrestrial hydrologic processes at high spatial and temporal resolutions by including lateral redistribution of overland and saturated subsurface flows for runoff prediction (Gochis et al. 2013) – see Fig. 1. More importantly for this study, WRF-Hydro is run in coupled mode with WRF to permit the feedback of land surface fluxes of energy and moisture to the atmosphere, which impacts the simulated precipitation fields (Arnault et al. 2016, Larsen et al. 2016, Senatore et al. 2015, Koster et al. 2004). Hence, the coupled WRF/WRF-Hydro configuration differs from the standalone WRF configuration by its (i) lateral distribution of surface runoff and (ii) feedback of surface fluxes to the atmosphere.

The more physically-realistic conceptualization of terrestrial hydrologic processes in WRF-Hydro compared to the simple vertical column models used in Noah-MP in standalone WRF, along with the coupled land-atmosphere closure of the water and energy balance at each time step (15 minutes for our study), is expected to improve the accuracy of precipitation fields simulated in coupled mode.

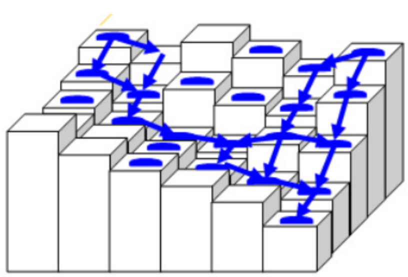

Figure 1. Overland flow routing schematic from Gochis et al. (2013)

To diagnose the processes controlling the improved precipitation fields from the coupled model, we conduct two additional analyses: **(1) verification of soil moisture propagation due to lateral flow from WRF-Hydro**, and **(2) comparison of simulated surface energy balance (SEB) and planetary boundary layer (PBL) heights at the four stations considered in the study.**

(1) Soil Moisture Propagation with Lateral Flow

For a specific area, an individual sensor dedicated to soil moisture measurement fails to capture any change during a short time span in the order of days. The Soil Moisture Operational Products System (SMOPS), provided by the National Oceanic and Atmospheric Administration (NOAA), merges soil moisture retrievals from multi-satellites/sensors to generate a global product at higher spatial and temporal coverage (Liu et al. 2016). Relevant to the current study period, SMOPS now incorporates near-real time SMAP data and includes soil moisture retrievals from the GPM Microwave Imager (GMI). The 6-hourly product mapped at 0.25° x 0.25° spatial resolution is used here to assess the accuracy of the simulated soil moisture.

A comparison of soil moisture evolution at the upstream and downstream of a wadi within the study domain is expected to verify whether soil moisture transport occurs over the storm timescale. A wadi within the coverage of the Saih Al Salem station (24 49 39 N, 55 18 43 E) was selected to conduct this test. Fig. 2 shows the time series of simulated soil moisture from WRF/WRF-Hydro at two locations upstream and downstream of the wadi. SMOPS retrievals are overlaid as data points, along with the hyetograph recorded at the corresponding Saih Al Salem station at the top. Given the short distance (less than 1km) separating the two locations, a lag time of less than 1 hour is observed between the two soil moisture patterns. The first rain of approximately 22 mm at 22 Z 08/03/16 triggers an immediate increase in soil moisture from 0.18 to 0.25 m^3/m^3. The subsequent rainfall then elevates the moisture further to around 0.34 m^3/m^3, with a slight increase in the peak of downstream soil moisture compared to that of the upstream. However, at 18Z 09/03/16 the downstream soil moisture rises again to a sustained peak at around 0.32 m^3/m^3, while the upstream soil moisture continues to dissipate through infiltration and evaporation. In the absence of additional rainfall, this sustained peak in downstream soil moisture is the result of lateral surface flow from the upstream which is resolved by WRF-Hydro and fed back to the soil moisture fields. Despite the SMOPS data gaps during the event, the merged retrievals consistently increase during the event with reasonable accuracy compared to the simulated soil moisture fields.

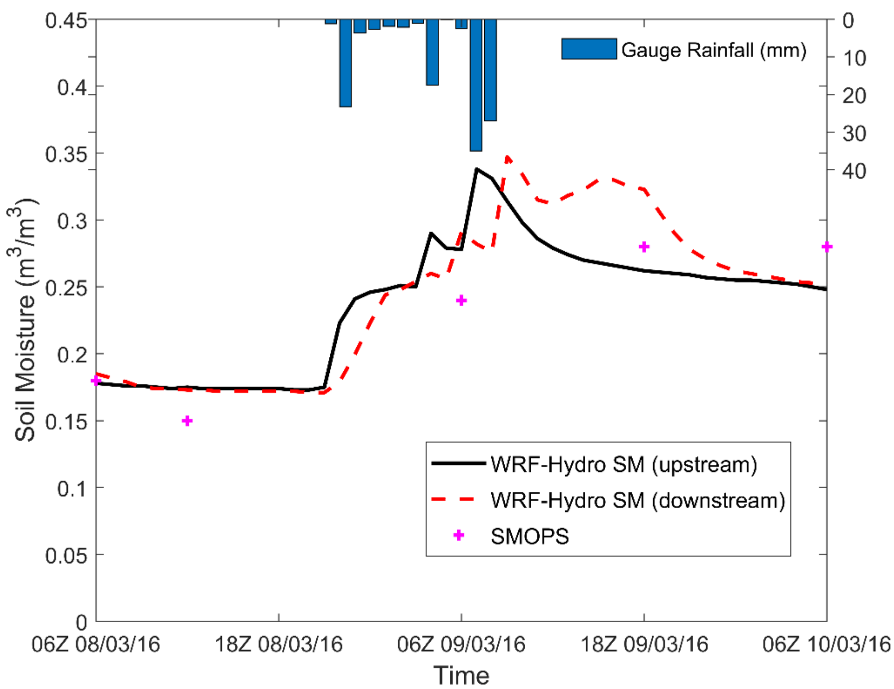

Figure 2. Time series of simulated soil moisture from WRF/WRF-Hydro at the wadi upstream and downstream locations, along with collocated SMOPS retrievals. Hyetograph recorded at the Saih Al Salem station is shown on top.

(2) SEB Analysis:

Following the methodology used by Niu et al. (2011) to evaluate the performance of the Noah-MP hydrological processes at the local scale, the surface energy balance is investigated as follows:

$$\mathrm{SW\ net} + \mathrm{LW\ net} + (\mathrm{Qh} + \mathrm{Qe} + \mathrm{Qg}) \pm \mathrm{RES} = 0$$

, where the net shortwave (SW net) and longwave radiation (LW net) are given as the sum of the positive (outward) component and the negative (downward) components. The Qs, Ql, Qg and RES terms represent the sensible, latent, ground, and residual heat fluxes of the energy balance, respectively. The residual term arises from processes not applicable to the study domain, including energy consumed by snowmelt and rain freezing at the surface.

The Bowen ratio (β), initially proposed by Bowen (1926), describes the contributions of latent (Ql) versus sensible heat (Qs) to net radiation and can be expressed as:

$$\beta = \frac{Qs}{Ql}$$

The physical significance of the Bowen ratio is that it gives an indication of the relative partitioning of net radiation in a region.

Fig. 3 shows the SEB time series and the time-average Bowen ratio for each of the four stations: Abu Dhabi, Al Ain, Jabal Hafeet, and Jabal Mebreh.

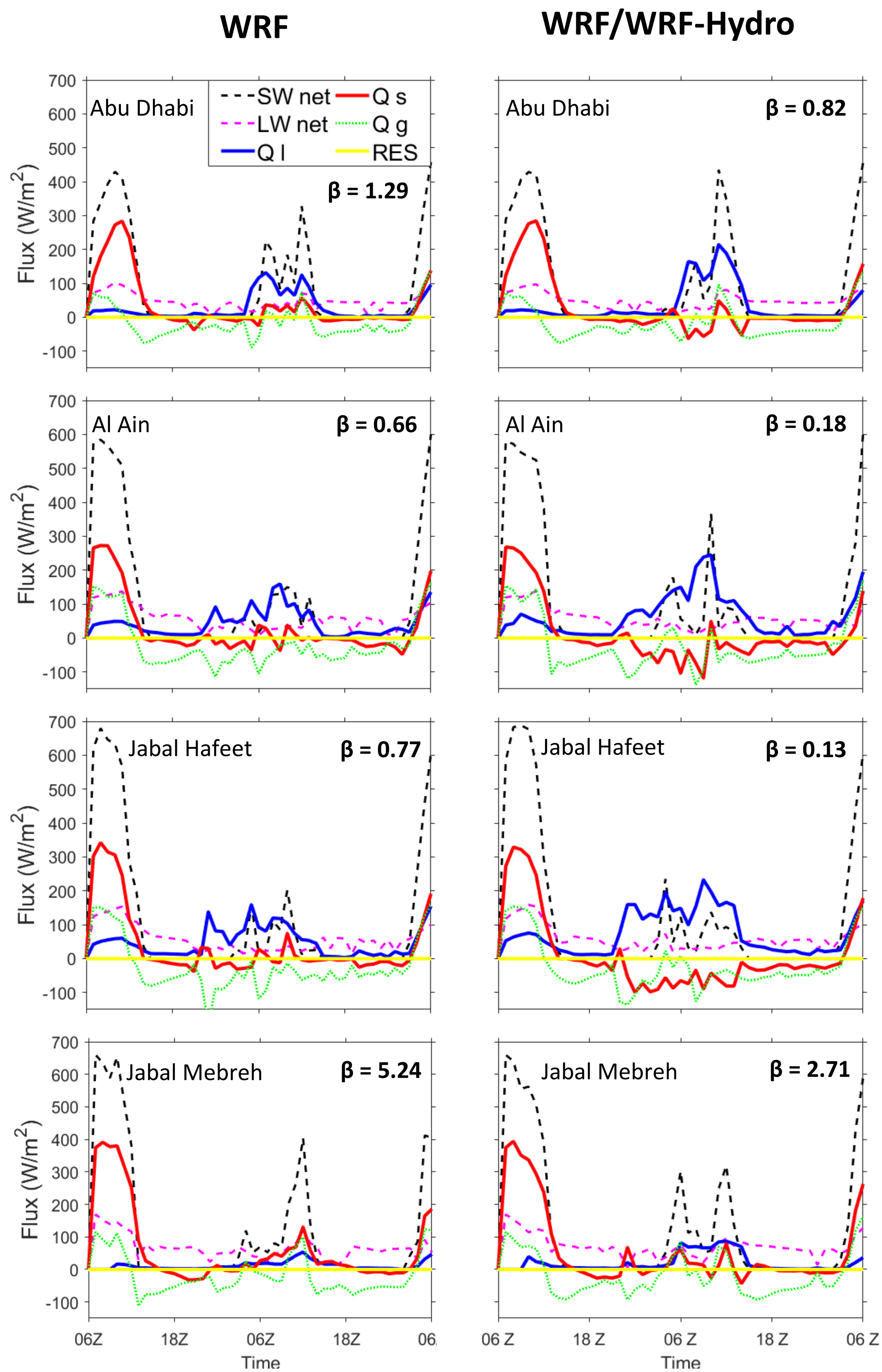

Figure 3. Surface energy budget time series from WRF and WRF/WRF-Hydro simulations at each of the four stations and their corresponding Bowen ratios (β).

The major differences between the SEB from both model configurations are shown midway through the simulation period between 06 and 18 Z. The coupled WRF/WRF-Hydro simulation shows higher (and lower) latent (and sensible) heat fluxes, as well as slightly higher net shortwave radiation, compared to the standalone WRF simulation. The coupled model is also associated with lower Bowen ratios compared to standalone WRF. The results are in line with the soil moisture-rainfall feedback mechanisms explained by Eltahir (1998). An increase in water content of the top soil layer decreases both the surface albedo and the Bowen ratio. A lower surface albedo dictates more absorbance of net radiation, while lower Bowen ratios are a result of higher water vapor content in the boundary layer and more downwards flux of terrestrial radiation at the surface due to the water vapor greenhouse effect. This dual effect amounts to a larger total flux of heat from the surface into the boundary layer.

Furthermore, the cooling of surface temperature accompanied by the moisture should be associated with a reduced sensible heat flux and a smaller PBL height. Fig. 4 shows the PBL heights from both simulations with larger collapses resolved from the WRF/WRF-Hydro. The timings of the reduced PBL heights in Fig. 4 coincide with those of the SEB discrepancies in Fig. 3 between 06 Z and 18 Z, which corroborates the chain of events diagnosed thus far. According to Zheng and Eltahir (1998), the increase of the boundary layer moist static energy is expected to result in additional rainfall from the increase of local convection.

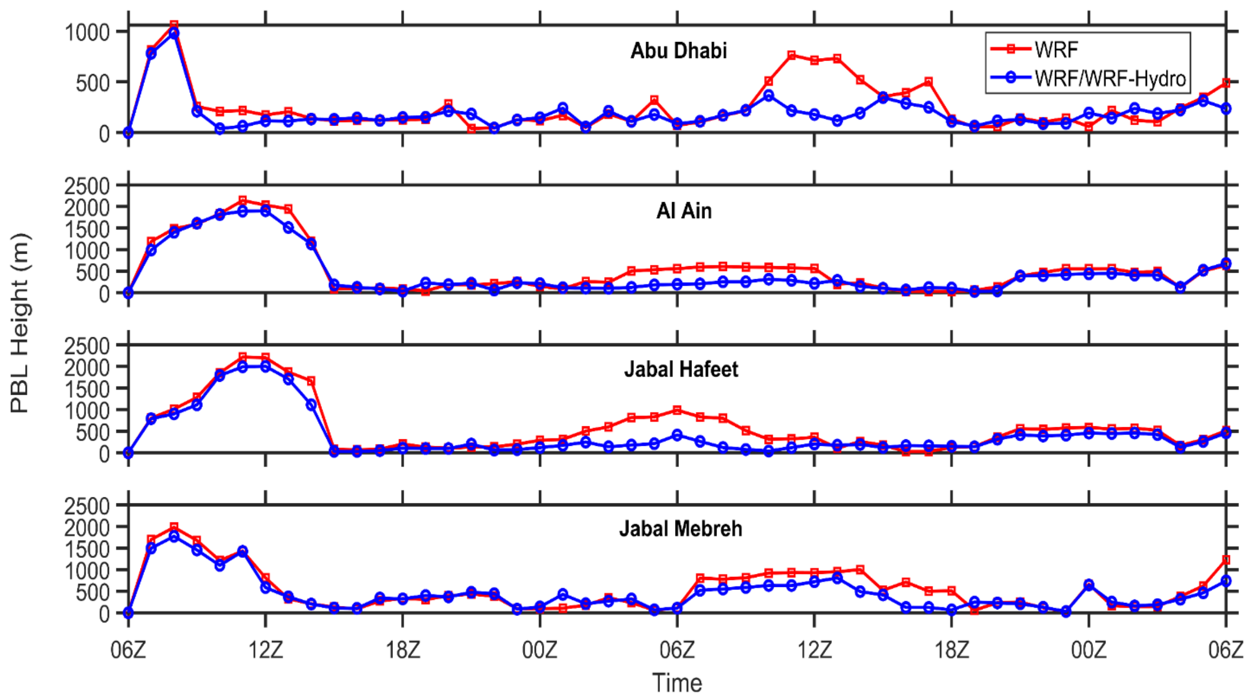

Figure 4. Planetary Boundary Layer (PBL) heights from WRF and WRF/WRF-Hydro simulations at each of the four stations

Author's Changes in Manuscript The analysis of the soil moisture transport due to the lateral flow processes in WRF-Hydro will be added to the revised version of the manuscript.

Minor and technical comments:

Abstract: Use the degree sign instead of "o"
All degree symbols are corrected.

2.7: rain gauges → rain gauge
Corrected.

3.32 And title: hyper arid: hyphenated or one word
All hyper-arid usages are now hyphenated.

4.9: rephrase to "The UAE (22 to 27N) . . . "
Rephrased.

4.22: rephrase to "receives more rainfall compared to the country's 100 mm annual average"
Rephrased.

5.28: clarify to what "Such frequencies" refers – L band?
Frequency range of 6.93 – 89 GHz is now specified.

7.22: "wadis" lowercase
Corrected – Page 7, Line 34.

8.30: does "analysed products" refer to ones interpolating station observations, or those from satellite retrievals or climate models?
We are referring to the remote sensing products (satellite retrievals and merged products). This is now explicitly stated – Page 9, Line 13.

9.10: boarder → border
Corrected – Page 9, Line 21.

13.12: I am not certain that WRF-Hydro includes lateral flow processes that would transport soil moisture. Please verify and give more details. Whether this transport happens in reality over the storm timescale would also need to be verified, which fits in with the authors' call for a soil moisture measurement network.
In our response to C1 and additions on Page 6 (Lines 18 – 29), we explain that indeed soil moisture propagation is impacted by the lateral flow processes resolved by WRF-Hydro. In Section 4.1, we first examine the obtained soil moisture pattern according to the expected runoff direction (dictated by topography). Furthermore, we refer the Reviewer to Figure 10, where narrower soil moisture patterns, indicating lateral drainage, from WRF-Hydro match AMSR2 retrievals more closely than those obtained from standalone WRF.

Table 2 and 4: Specify whether the GPM and model averages are collocated with the stations.
The statistical measures in Table 2 and 4 are obtained from collocated sites between the datasets. Both table captions are now revised accordingly.

Table 3: Specify the time interval and number of data points used for the comparison between products.

Time intervals and sample sizes (n) are now specified in the captions of both Tables 3 and 5.

Author's References

Arnault, J.*, et al.* 2016. Role of runoff–infiltration partitioning and resolved overland flow on land–atmosphere feedbacks: A case study with the WRF-Hydro coupled modeling system for west africa. *Journal of Hydrometeorology,* 17(5), 1489-1516.

Bowen, I. S. 1926. The ratio of heat losses by conduction and by evaporation from any water surface. *Physical review,* 27(6), 779.

Ek, M.*, et al.* 2003. Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *Journal of Geophysical Research: Atmospheres,* 108(D22).

Eltahir, E. A. 1998. A soil moisture–rainfall feedback mechanism: 1. Theory and observations. *Water Resources Research,* 34(4), 765-776.

Gochis, D., Yu, W. and Yates, D. 2013. The WRF-Hydro model technical description and user's guide, version 1.0. *NCAR Tech. Doc*.

Koster, R. D.*, et al.* 2004. Regions of strong coupling between soil moisture and precipitation. *Science,* 305(5687), 1138-1140.

Larsen, M. A.*, et al.* 2016. Local control on precipitation in a fully coupled climate-hydrology model. *Scientific reports,* 6, 22927.

Liu, J.*, et al.*, NOAA Soil Moisture Operational Product System (SMOPS) and its validations. ed. *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 2016, 3477-3480.

Niu, G. Y.*, et al.* 2011. The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *Journal of Geophysical Research: Atmospheres,* 116(D12).

Senatore, A.*, et al.* 2015. Fully coupled atmosphere-hydrology simulations for the central Mediterranean: Impact of enhanced hydrological parameterization for short and long time scales. *Journal of Advances in Modeling Earth Systems,* 7(4), 1693-1715.

Zheng, X. and Eltahir, E. A. 1998. A soil moisture–rainfall feedback mechanism: 2. Numerical experiments. *Water Resources Research,* 34(4), 777-785.