Convection-permitting modeling of sub-seasonal rainfall over the Kingdom of Saudi Arabia

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1. Introduction and Motivation

The Kingdom of Saudi Arabia (KSA) is one of the driest environments in the world and the availability of fresh water is of major concern. Reliable forecast of convective rainfall events at long lead times are therefore critical. Convection-permitting modeling (CPM) is capable of representing the KSA's organized rainfall activities at sub-seasonal scales (Risanto et al., 2022).

Our objectives are to evaluate the value-added using CPM, identify windows of sub-seasonal forecast opportunities, and synoptic conditions associated with the convective events. Sub-seasonal CPM reforecasts are generated for 20 years of KSA winter. These data will be used to establish a new paradigm for understanding the dynamics and predictability of precipitation over the KSA up to 4 weeks forecast range.

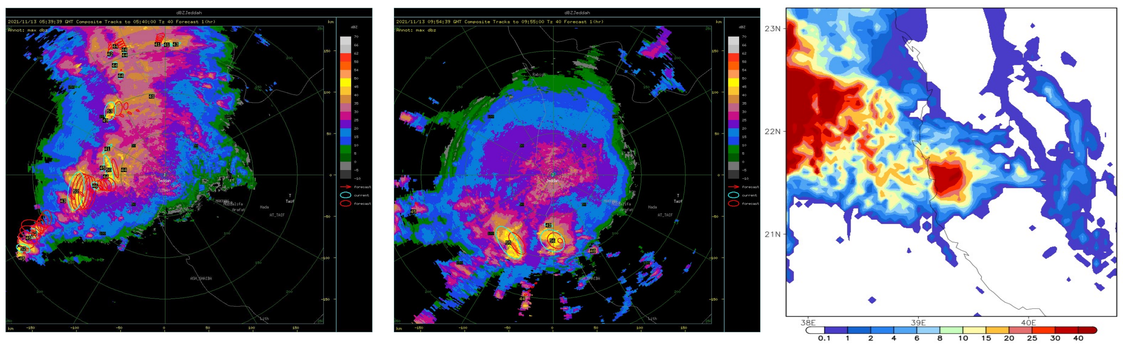


Figure 1. Radar images of a heavy rain event in Jeddah on November 13th, 2021 (left and middle panels). Stations record sustain high wind and rainfall of 20-26 mm. CPM gives a warning rainfall from 10 to 40 mm over the city (right panel). We're aiming to extend the forecast range of these extreme events with a dynamical downscaling system.

2. Experiment design

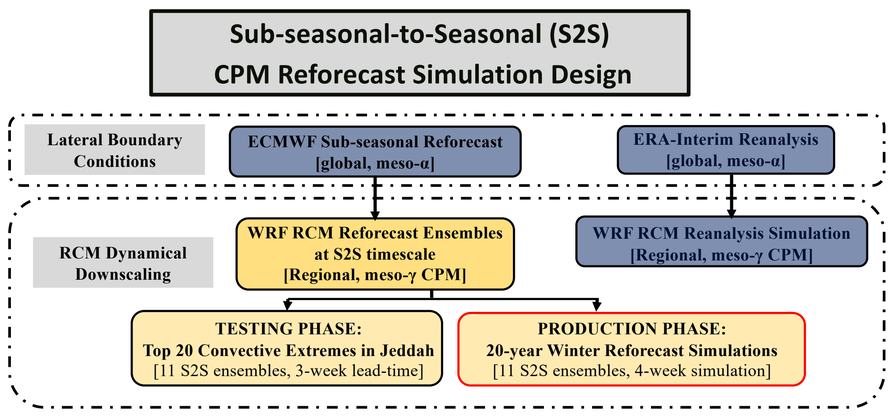
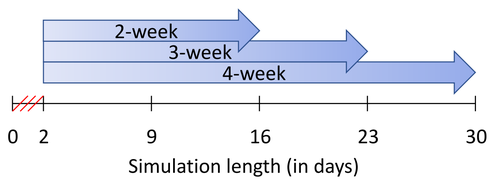


Figure 2. S2S reforecast simulation design: dynamical downscaling of the ECMWF S2S reforecasts at convection-permitting scale (4km) were conducted to study extreme events in Risanto et al. (2022). Here we statistically analyze the 20-year S2S product.

Using the Weather Research and Forecasting Model (WRF) at 4km resolution, we dynamically downscale the ECMWF S2S reforecasts. The simulations are initiated weekly on Mondays from October 8th, 2018, to April 22nd, 2019, for forecast lead times up to 30 days using 11 ensemble members. A total of 191,400 hindcast days have been generated to evaluate the predictability of winter rainfall for KSA over the 20-year period (1998-2018).



The first 2 days period is considered as spin-up time. Analysis of forecast ranges are at weekly basis (e.g., 4-week rainfall is accumulated from day 24 to 30).

3. Saudi Arabia rainfall season

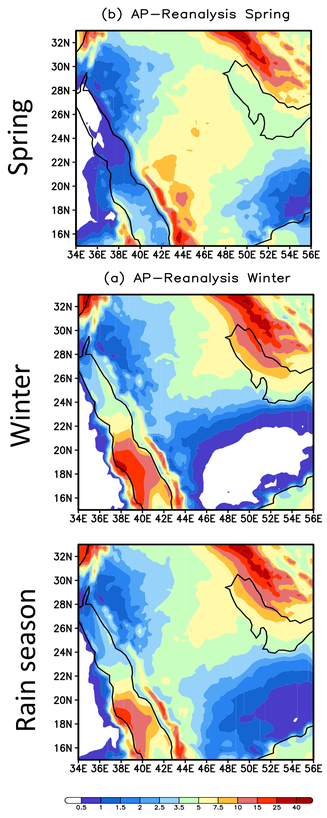


Figure 3. Rainfall climatology from AP-Reanalysis

KSA rain season is from NOV to APR. Winter months are NOV to FEB and Spring are MAR to APR (Fig. 3).

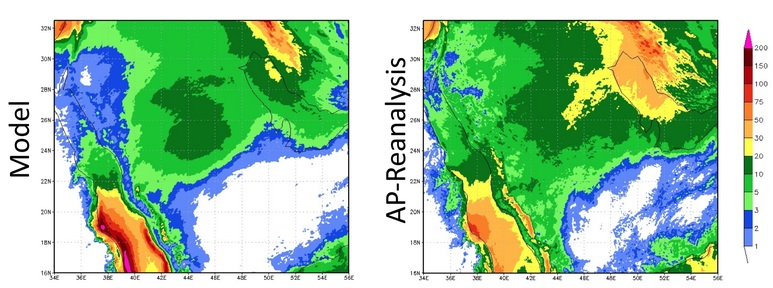


Figure 4. 20-year November precipitation climatology. Left: WRF S2S, Right: AP-Reanalysis

CPM can reproduce precipitation rainfall patterns close to AP-Reanalysis (Arabian Peninsula – Reanalysis generated by KAUST) at 4-week range (Fig. 4)

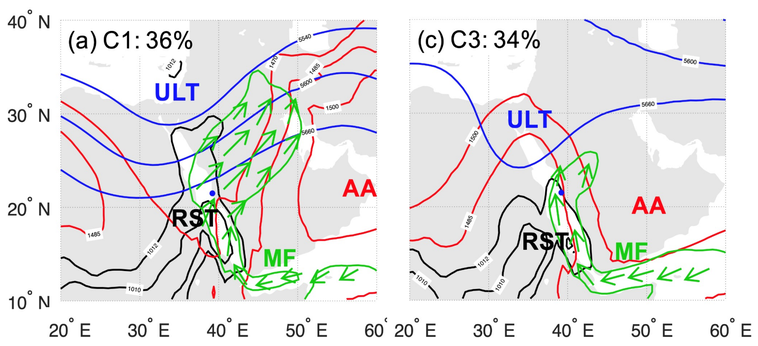


Figure 5. Dominant synoptic patterns that lead to extreme convective events near Jeddah: C1: Extratropical influence / C3: Tropical influence

Most major rainfall events in the winter are associated with extratropical forcing while spring heavy rainfalls are associated with tropical-extratropical interactions (Fig. 5, from Luong et al., 2020).

4. Climatology of ensemble mean: ECMWF versus WRF-S2S

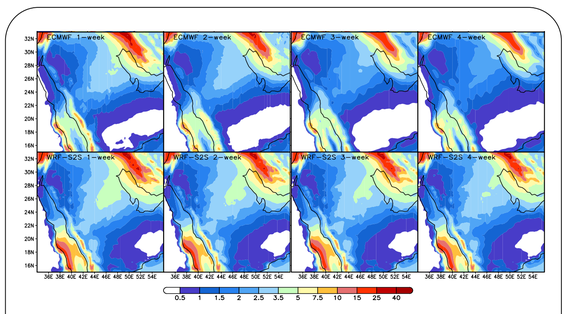


Figure 6. *Ensemble mean precipitation climatology from ECMWF (upper panels) and WRF-S2S (lower panels). Panels from left to right are forecast range from 1 to 4.*

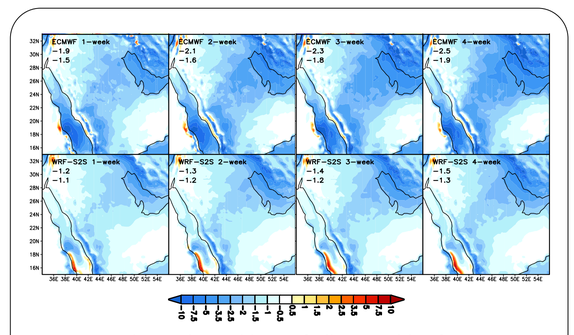


Figure 7. *Climatological bias of all ensembles from ECMWF (upper panels) and WRF-S2S (lower panels). Panels from left to right are forecast range from 1 to 4. Numbers are mean over the domain and the KSA*

Both ECMWF and WRF-S2S capture precipitation rainfall patterns reasonably well at extended range forecast (Fig. 6 comparing to AP-Reanalysis in Fig. 3). ECMWF ensemble mean overall underestimates precipitation, with dry bias overland and wet bias over the southern Red Sea (Fig. 7, upper panel) and the bias increases with longer lead time. S2S downscaling with WRF CPM reduces the bias about 30 to 40% (Fig. 7, lower panel).

5. Model skill assessment

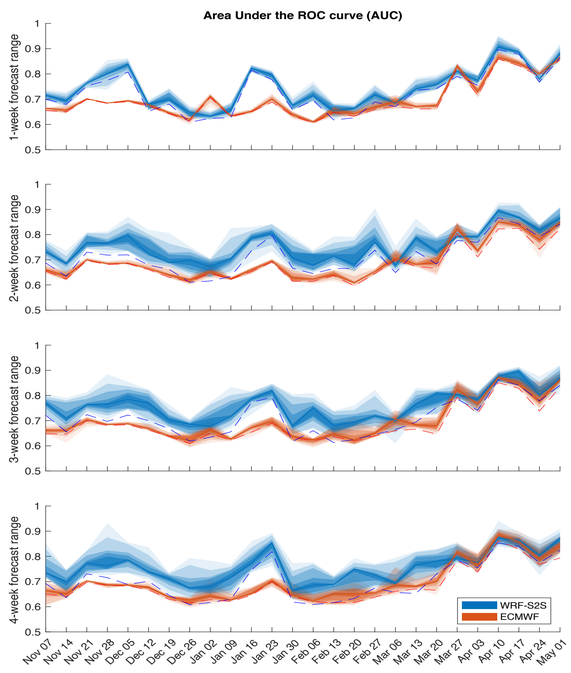


Figure 8. Area under the curve of the receiver operating characteristic for 11 ensembles of WRF and ECMWF

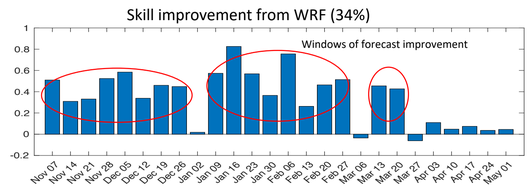


Figure 9. Skill improvement from WRF with respect to ECMWF showing windows of forecast improvement. Improvement = $(AUC_{WRF} - 0.5) / (AUC_{ECMWF} - 0.5) - 1$. AUC = 0.5 is equivalent to no skill forecast.

Receiver Operating Characteristic (ROC) is used to evaluate the ability of the forecast discrimination of rainfall event larger than 5 mm compare with the AP-Reanalysis. Area under the ROC curve (AUC) is used to evaluate forecast skills (Fig. 8):

- Most of ensemble skills are higher than the ensemble mean skills (dash lines).
- The longer the range, the lower the forecast skill, and the larger the forecast uncertainty (more spreading plume).
- Better ECMWF forecast skills in the Spring compared to the Winter, suggesting that large scale signatures are better represented to capture the wide-spread Spring rainfall.
- Overall forecast skill improvements WRF-CPM as compared to driving ECMWF. Largest improvements are found during the Winter where organized convective systems play a major role (Risanto et al., 2022).

There are three windows of forecast improvements where WRF has substantially higher skill than ECMWF (Fig. 9). The average skill improvement is 34%.

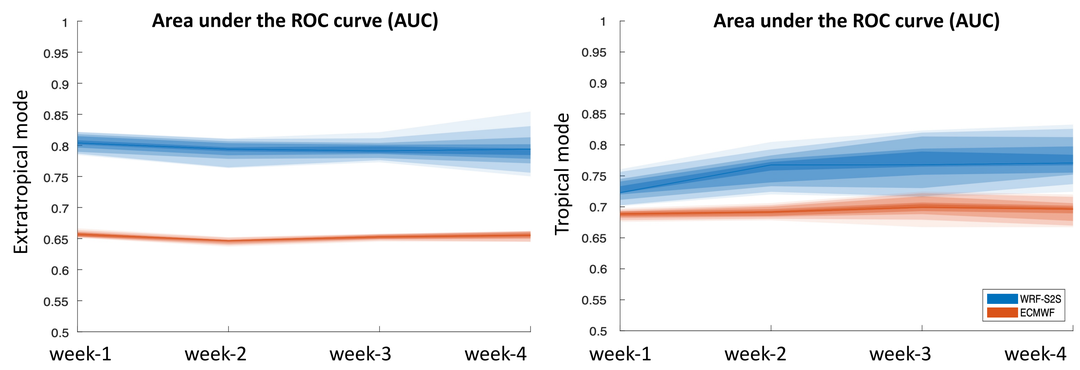


Figure 10. Area under the curve of the receiver operating characteristic for each dominant mode

- Self-organizing map (SOM) identified CPM precipitation reforecast periods under strong synoptic influence: 99 weeks of tropical and 72 weeks of extratropical mode.
- CPM added more value over extratropical mode (WRF = 0.796 / ECMWF = 0.653) than tropical mode (WRF = 0.759 / ECMWF = 0.694) (Fig. 10).

6. SUMMARY AND CONCLUSIONS

- **Over KSA, major rainfall events in November to February are associated with extratropical forcing while March and April heavy rainfalls are associated with tropical-extratropical interactions.**
- **The WRF convective-permitting model adequately describes the precipitation patterns over KSA and statistically improves the S2S forecast skill relative to its driving ECMWF fields.**
- **Periods of forecast improvement are identified for KSA, suggesting higher confidence in forecasting rainfall for the region from November to February and mid March where extratropical influences are dominant.**

Acknowledgements: This work is supported by the competitive research grant from the King Abdullah University of Science and Technology with sub-award agreement OSR-2018-CRG7-3706.2. Computing resources are provided by Shaheen supercomputer.

AP-Reanalysis is a regional reanalysis data over the Arabian Peninsula (AP) at 5 km resolution (Dasari et al., 2019: High-resolution assessment of solar energy resources over the Arabian Peninsula. *Applied Energy)*.
ECMWF: European Centre of Medium-range Weather Forecasts
Luong et al., 2020: Extreme precipitation events are becoming less frequent but more intense over Jeddah, Saudi Arabia. Are shifting weather regimes the cause? *Atmospheric Science Letters*.
Risanto et al., 2022: Retrospective sub-seasonal forecasts of extreme precipitation events in the Arabian Peninsula using convective-permitting modeling. *Climate Dynamics*.