13B.2 EVALUATION OF WRF HIGH RESOLUTION DYNAMICAL DOWNSCALING SIMULATIONS OVER COMPLEX TOPOGRAPHY

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1. INTRODUCTION

One of the expected consequences of climate change and global warming is an increase in extreme weather events such as heat waves, droughts, and floods that can result in adverse effects on agriculture and water resources. This is of critical importance in regions that are already water-stressed, such as the eastern Mediterranean basin which has already been the subject of many global and regional climate studies (Bou-Zeid and El Fadel (2002); Weiss et al. (2007); Giorgi and Lionello (2008); Black et al. (2010)). The entire basin is expected to experience a decrease in winter precipitation and an increase in temperature by the end of the century (Giorgi et al. (2001); Alpert et al. (2008); Kitoh et al. (2008); Evans (2009); Black et al. (2010); El-Fadel (2010)). In this context, simulating the climate of the basin using Global Climate Models (GCMs) is a challenge (Evans et al. (2004)) due to (1) the high natural inter-annual variability, (2) the complex topography of the region that encompasses multiple mountain ranges and inland waters, and (3) the proximity to the sea that increases the influence of land-water contrast on the hydrometeorology (Black et al. (2010)). These characteristics require high-resolution regional to local scale models to capture climate variability. While recent improvements in model simulations relied on a higher resolution at few locations along the eastern Mediterranean (Suppan et al. (2008); Evans (2010); Givati et al. (2012)), such efforts remain scant due to high computational requirements at fine scale simulations.

The present study aims to assess the performance of the Weather Research and Forecasting (WRF) model, and particularly how it improves with increasing grid resolution, for hydrometeorological downscaling over complex terrain. The long-term goal is to use WRF for dynamic downscaling of climate forecasts over the Eastern Mediterranean, though the findings here are of much broader applicability. The focus is on warm and dry years that represent the most adverse conditions under future climate change scenarios.

Located at the northern temperate zone and along the eastern coast of the Mediterranean Sea, Lebanon represents an excellent example of a challenging complex topography that magnifies the effect of orographic precipitation (***Figure 1)***) and generates strong spatial climatological gradients that WRF or other dynamic downscaling models need to capture. For instance, a 50 km east-west cross section shows stark climate variations: a subtropical coastal climate, followed by a Mediterranean climate at low elevations, a cold weather at higher elevations covered with snow during the winter, and reaching a semi-desert inland plain.

2. SUMMARY OF RESEARCH

Climatological dynamic downscaling was examined through high-resolution simulations conducted using the Weather Research and Forecasting (WRF) model, with initial and boundary conditions from the Global Forecast Model (GFS) reanalysis (resolution 1°) historical simulations. Two years were selected to capture the natural variability of the system, with 2003 and 2010 as typical wet and dry years, respectively. The WRF simulations were conducted using three one way nested spatial domains with 9, 3 and 1 km resolution, 35 vertical levels and no nudging. The sea surface temperature (SST) was updated once monthly and the choices for the parameterization schemes are motivated by previous WRF tests (Talbot et al. (2012) and Li et al. (2013)).

In-depth comparisons between simulated and observed precipitation, 2 m temperatures and wind are performed.

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Observational data were obtained from 43 rain gauges, 2 wind and 31 temperature stations located across eight geoclimatic zones (***Figure 2***). These evaluations focused on daily average, maximum and minimum temperatures, precipitation and wind with averages over seasonally to yearly time scales. Several statistics are used to evaluate model performance relative to observational datasets such as the mean bias error (MBE), the root mean square error (RMSE), the coefficient of determination R^2, and an assessment of a set of climate indices (hot and summer days, rainy days, etc.).

The statistical distribution of near-surface average air temperatures related to meso-to-synoptic scale features are captured better in the WRF simulations, compared to the driving GFS-Reanalysis, due to the improved resolution of surface elevation at higher horizontal model resolution (***Figure 3***). The average temperature in WRF-1 (the 1 km resolution run) has an RMSE reduced by 1.1ºC for year 2003 and 1.6 ºC for 2010, relative to the RMSE of GFS-reanalysis. The variability of the average temperature is well represented by WRF-1 at all timescales from daily to monthly and yearly (the coefficient of determination). The largest error were noted in the summer of 2003, and it produces 30% warmer high temperatures (above 25°C) in autumns of both simulated years (not shown). This appears to result from under-prediction of soil moisture, which enhances surface heating during the warmest parts of the day.

WRF-1 also reduces the RMSE of the maximum temperature over all stations by about 40 %, from 3.94°C (GFS-Reanalysis) to 2.22°C in 2010. As for the upper tails of the PDFs of maximum temperature, WRF simulations perform comparably well and the value added by the refinement of the resolution to 1 km is obvious, despite some underpredictions of mid-summer temperatures (Figure 4). Extreme temperature indices were simulated well by WRF, especially by WRF-1, which was able to represent the magnitude as well as the spatial and temporal distribution of summer and hot days. Both GFS-Reanalysis and WRF-1 under-predict the number of summer days for most of the regions in 2003, whereas in 2010, WRF-1 predictions were closer to observations than GFS-Reanalysis in more than half of the climatological sub-regions considered. Regarding hot days, WRF-1 outperformed GFS-Reanalysis in both years, where the latter completely missed these records for 2003 and overpredicted the number in 2010 by more than two folds inland. WRF-1 predictions were the closest to the observations in the majority of sub-regions. Seasonal and regional RMSEs for the maximum 2m temperature are improved in WRF-1 by more than 1°C when compared with GFS-Reanalysis in 2010. Overall, when both years and all regions are considered, WRF downscaling improves significantly on the GFS fields for maximum temperatures.

Regarding minimum temperatures, the performance of WRF-1 is better in 2003 than in 2010: the reduction in RMSE compared to GFS-Reanalysis is 1.03°C for 2003 and 0.77°C for 2010. The RMSE of daily Tmin at the seasonal scale show that WRF-1 has the smallest errors in all seasons of both years. Note that the coefficients of determination of Tmin between the observations and simulations are smaller than those of Tmax. Regarding the frost days extreme index, GFS-Reanalysis exhibited difficulties in capturing this climate index, while WRF in its three resolutions showed lower error in all regions. WRF-1 and WRF-3 were both able to reproduce the observed probability density functions for Tmin well ***(****Error! Reference source not found.* illustrates this for 2003). On another note, the RMSE is relatively consistent (between 1.5º and 2.5ºC) across all seasons in all regions, which signals that the model is able to account for seasonal changes in minimum temperatures rather well.

Precipitation is more sensitive than temperature to regional conditions, hence a relatively high horizontal resolution turned out to be critically important in complex terrain. The orographic lifting in the WRF-1 and WRF-3 simulations was stronger and better resolved than in the WRF-9 simulation that also led to an improvement in the representation of extreme precipitation events, especially in the mountains. The overall distribution of rainfall is simulated well, although WRF tends to overestimate the prevalence of days with moderate precipitation (rainfall between 1 and 5mm) along the coast and in mountainous regions. The overestimation is improved by WRF-1, yielding MDE values less than 10% of the magnitude of observed events even for most extreme conditions (***Table 1***). In fact, the annual WRF-1 bias is 2.0% in 2003 and 6.8% in 2010, which implies that WRF produces adequate results if used for predicting dry year conditions for climate change impact studies. WRF-3 was not far behind, with biases of –9.75% in 2003 and 3.8% in 2010 (in fact it was lower than WRF-1 in 2010).

The simulated wind results confirmed that the wind speed overestimation is a limitation of the model as previously reported (Talbot et al. (2012)). The wind direction is reasonably simulated by the model (Figure 6), especially in wind regimes where there is a marked dominant sector, but a consistent small bias existed at both stations that might be related to errors in the alignment of the wind vanes. The model also revealed significant sensitivity to the local terrain complexity when simulating the wind speed.

In summary, WRF performance was very satisfactory. It captured the complex spatial and seasonal variability that characterize the observed climate in the study area, and reproduced the differences between the mild wet year (2003) and the dry hot year (2010). Most importantly, it markedly improved the accuracy of simulated fields relative to the driving GFS-Reanalysis, supporting its use to downscale future climate change simulations. The improvements were noticeable for maximum temperatures, which are central in climate change impact studies. Accumulated yearly rainfall, another key parameter in impact studies, was reproduced well by WRF; although no GFS data were available for direct comparison, orographic rainfall in general tends to be better simulated by finer models. Rainfall representation over shorter time scales is certainly more challenging, but it is the yearly accumulation that is the most important from a climate-water nexus perspective. These conclusions hold for the 1 and 3 km resolution domain. At a resolution of 9km, deterioration in the simulated fields was evident indicating that a 3 km resolution is sufficient for downscaling climate fields over the complex terrain. The ability to omit the 1 km domain (with its shorter time step) reduces the computational cost of the simulation by about 70 percent.

3. ACKNOWLEDGMENTS

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5. FIGURES AND TABLES

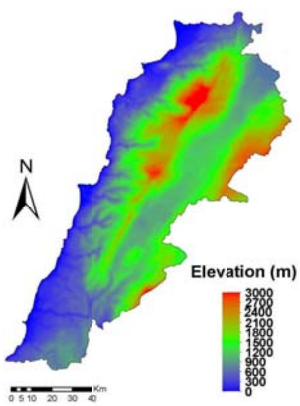

Figure 1. Topographic features of Lebanon

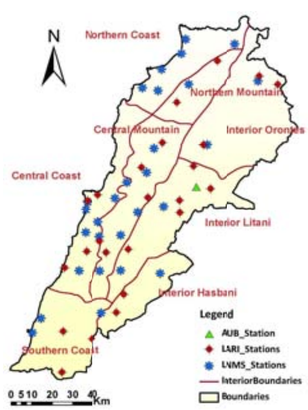

Figure 2. Weather stations location

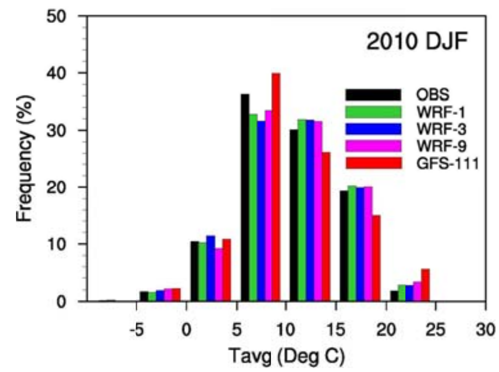

Figure 3. PDFs of the daily average 2m temperature

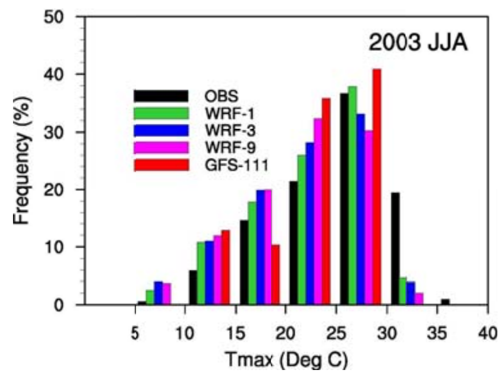

Figure 4. PDFs of summer 2003 Tmax

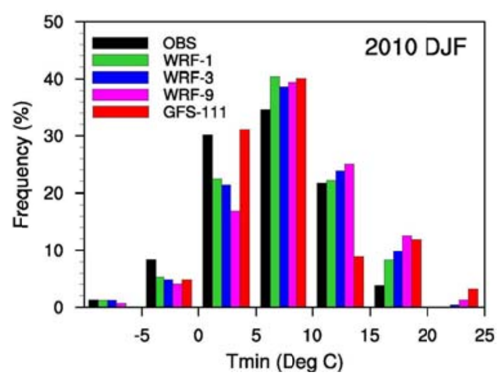

Figure 5. PDFs of winter 2010 Tmin

	2003			2010		
Region	**WRF-1km**	**WRF-3km**	**WRF 9km**	**WRF-1km**	**WRF-3km**	**WRF 9km**
North coast	-7.2%	-42.5%	**0.6%**	16.1%	**15.1%**	38.4%
Central coast	19.4%	**3.9%**	24.3%	14.1%	**6.0%**	15.4%
South coast	**-2.3%**	-15.7%	-9.3%	14.0%	-3.4%	**0.2%**
North mountain	**37.8%**	46.2%	49.7%	**26.0%**	52.9%	47.7%
Central mountain	10.9%	**-3.9%**	-11.1%	4.7%	**4.6%**	6.3%
North inland	-49.2%	-54.5%	**-43.1%**	-37.4%	-37.8%	**-8.4%**
Central inland	-18.3%	-27.9%	**-6.0%**	21.4%	**16.4%**	64.2%
South inland	**19.7%**	37.1%	25.5%	9.3%	**5.4%**	40.0%
Lebanon	**-2.01%**	-9.75%	2.16%	6.8	**3.8**	17.6
R^2	0.64	0.60	**0.66**	**0.70**	0.64	0.57

Table 1. Percentage MBE and R^2 for yearly-averaged precipitation in 2003 and 2010 (lowest errors are in bold).

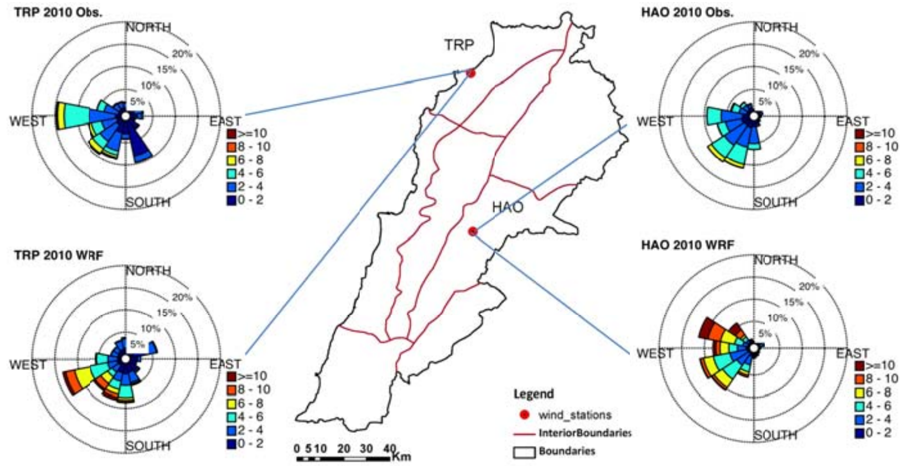

Figure 6 Wind roses for available stations for 2010