Model sensitivity to boundary layer processes for predicting a severe weather event over Mecca, Saudi Arabia

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Abstract:

Sensitivity experiments are performed with a Weather Research and Forecasting (WRF) model to investigate the impact of planetary boundary layer (PBL) processes on prediction of a severe weather event (SWE) that occurred over Mecca, Kingdom of Saudi Arabia on 11 September 2015. This event triggered gale winds and heavy rainfall that caused the collapse of highly elevated crane mounted for construction activities over Mecca grand mosque killing nearly 115 people. We implemented WRF with two nested interactive domains of 3 km and 1 km and four different local and 1.5-order closure turbulent kinetic energy (TKE) PBL schemes. We also conducted two more simulations with non-local, first order closure and another two simulations with hybrid, local-nonlocal closure PBL schemes. The model was nested in the NCEP global forecasting system available at 0.25° horizontal resolution.

Analysis of surface and upper air observations reveals that the SWE is initially associated with synoptic scale conditions and intensified after interaction with the local topography, triggering high convective rainfall with strong winds. The evolution of a well-organized convective cloud associated with SWE is also predicted by the model and well agree with the cloud imageries from EUMETSAT. The model sensitivity analysis with the different PBL schemes showed that the local, 1.5 order TKE closure schemes are more suitable for predicting the characteristics of the SWE rainfall and gale winds. The TKE schemes predicted the maximum wind speeds of 20 - 25 ms^{-1} and sustained for about 2 hours, whereas other non-local first order closure, while the hybrid schemes are not able to generate the gale winds and rainfall. The vertical transport of heat and momentum from the boundary layer are better resolved with TKE schemes. This PBL process allows simulating the sudden burst of winds and a low-level moisture supply from the Red Sea, which, together with the orographic lifting, induced the heavy rainfall.

Keywords: Mecca region; Strong winds; Orography; Red Sea moisture; High-resolution model.

1. Introduction

Severe weather events (SWE) are unique in its nature and can be triggered by various factors, including large-scale atmospheric conditions, local topography and its alignment (Webster et al., 2008; Subyani, 2011; Orr et al., 2014). Extreme weather phenomena usually occur at horizontal length scales of few tens of kilometers, and thus, require very high-resolution (both spatial and vertical) mesoscale models to resolve the involved dynamical/physical features (Webster et al., 2008; Powers, 2007). The use of high-resolution grid and appropriate physics are very important to resolve the land and sea coastal boundaries, different urban properties and orography (Banta, 1990; Chenoli et al. 2013).

The city of Mecca in the Kingdom of Saudi Arabia, the holy city in the religion of Islam, is located in the complex terrain in Hejaz mountains with terrain height ranging between 82 m and 982 m above mean sea level. During the Hajj (annual Islamic pilgrimage in Mecca) season, millions of people gather near Grand Mosque. Just before the eve of Hajj on 11 September 2015, a sudden increase in the wind speed occurred over a short span of time (~1 hour) and was associated with severe rainfall that causes the collapse of a high-elevated crane near the Grand Masque, causing nearly 115 deaths and 394 injuries. Mecca experienced several extreme events in its recent history (Subyani, 2011; Dawod *et al*., 2013), suggesting the need for a forecasting system for the region.

We use the Weather Research and Forecasting (WRF) model to predict the SWE on 11 September 2015 with two-way high-resolution nested domains of 3 and 1km to investigate the model sensitivity on different planetary boundary layer (PBL) processes and ultimately the mechanisms that triggered this event.

2. Model, Data and Methodology

WRF model version 3.8 (Skamarock *et al*., 2008) was used in this study. WRF is a limited area, non-hydrostatic primitive equation model including multiple options for various physical parameterization schemes. The model configuration is composed of two,

two-way interactive nested domains centered over Mecca city with horizontal resolutions of 3 and 1 km respectively. The model topography, land-use and soil types are interpolated from arc 30sec the United States Geological Survey (USGS) data. The model is initialized at 00 UTC 10 September from the National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) analysis fields available at 0.25^{o} x 0.25^{o} grid and then integrated up to 00 UTC 11 September 2015. The boundary conditions were updated every three hours with the GFS forecasts. The model physics included the RRTM scheme for longwave radiation (Mlawer et al., 1997), Dudhia scheme (Dudhia, 1989) for short-wave radiation, WSM6 (Hong et al., 1994) for Cloud Microphysics, and NOAH (Chen and Dudhia, 2001) for land surface physics. A series of eight different simulations were conducted using the various boundary layer processes available in WRF.

Surface and upper air datasets from Presidency of Meteorology and Environment (PME) in Saudi Arabia, University of Wyoming and high temporal resolution cloud imagery from EUMETSAT and Moderate Resolution Imaging Spectro-radiometer (MODIS) satellite are used in the analysis.

3. Synoptic evolution of the event

The synoptic charts from PME between 1200 UTC and 1800 UTC, 11 September shows that a sudden fall in pressure occurred over Mecca (Figure 1) accompanied with an increase of pressure all around the Mecca region induced a sharp pressure gradient which triggered extreme winds. Simultaneously at the 850 hPa level over northern Mecca, a noticeable drop of the geopotential height by about 30 gpm and a sharp zonal gradient of 25 gpm in geopotential between 20 °N - 23 °N, indicating a cold air intrusion from the Red Sea towards Mecca. The skew-T plots from University of Wyoming on 11 September 2015 at Jeddah station (70 km south of Mecca) show (Figure 2) weak winds at 0000 UTC. Six hours after, an abrupt change in wind speeds are observed, indicating passage of a convective storm in the subsequent hours. The sudden abrupt increase in Convective Available Potential Energy (CAPE) on the day of the event from 1300 J/kg to

2800 J/Kg between 0000 UTC to 1200 UTC over Jeddah also suggests the existence of highly unstable conditions.

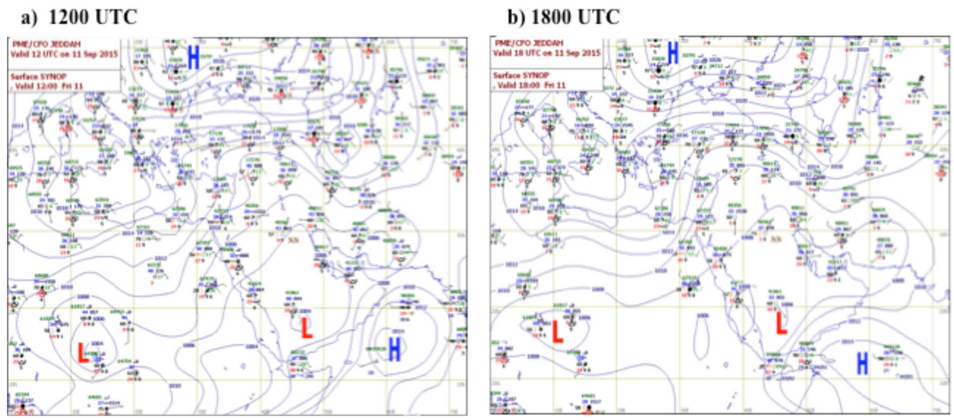

Figure 1: Surface Synoptic charts from PME at different times.

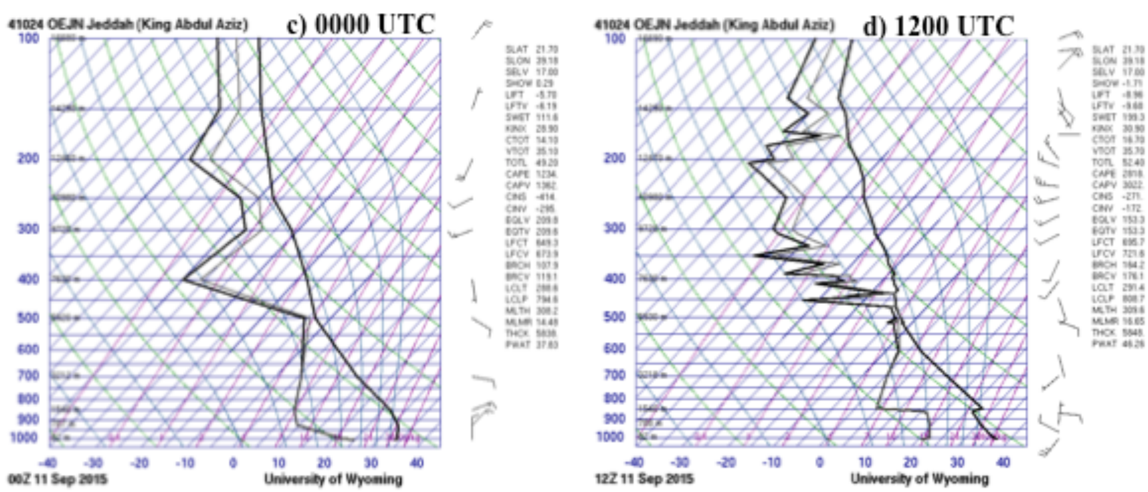

Figure 2: Skew-T gram at Jeddah station from PME at different times.

The precipitable water from radiosonde (~46 kg.m^{-2}) at 1200 UTC between 700 to 300 hPa levels also shows an important amount of mid-tropospheric moisture in the atmosphere. A well-organized convective cloud coverage between 1500 to 1700 UTC over the Mecca region from EUMETSAT (Figure 3 a,b,c,d) and also a clear spiraling structure of massive convective cloud (Figure 3e) passing over Mecca from the near real time MODIS satellite imagery is also clear.

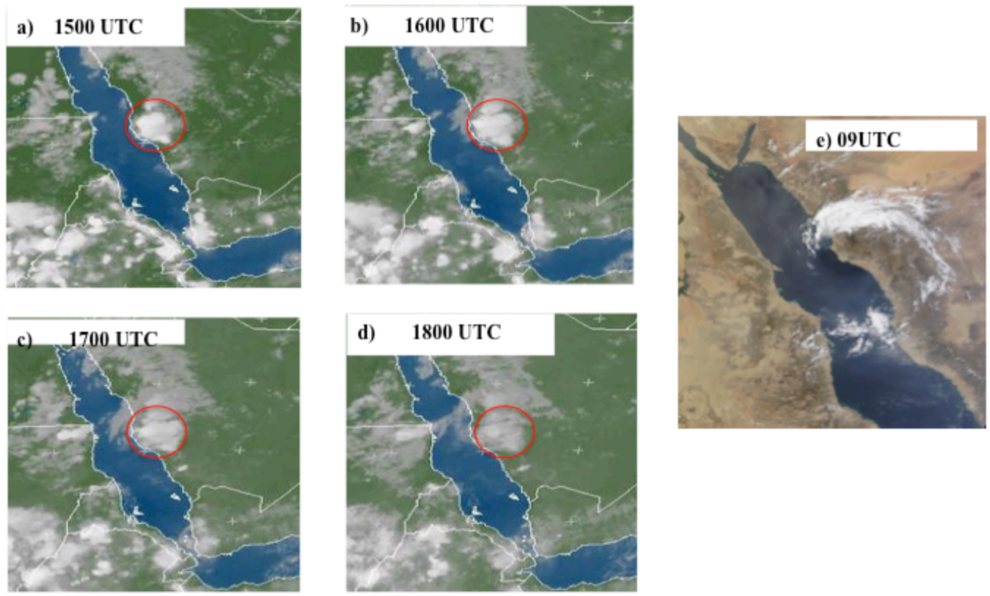

Figure 3: Satellite cloud imagery from EUMETSAT (a, b, c and d) and from MODIS (e) at different times.

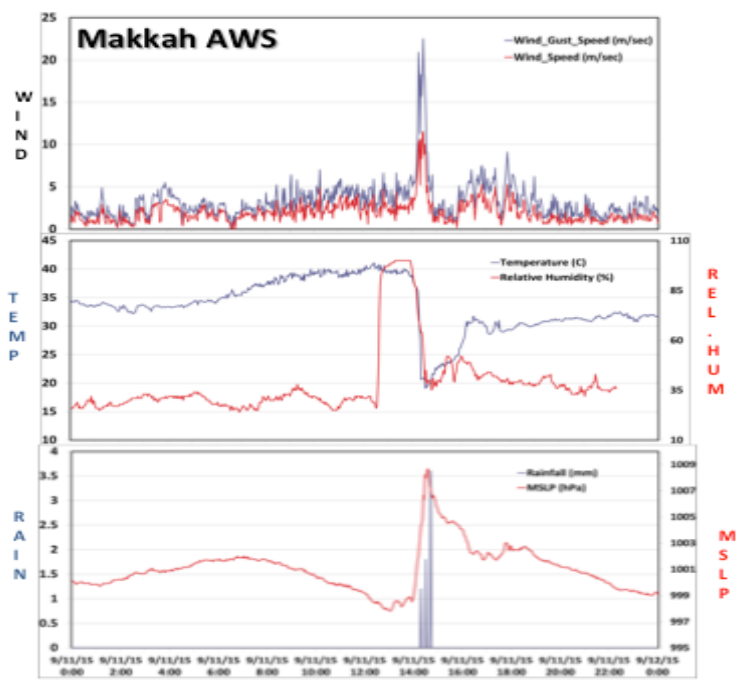

Figure 4: Surface observed features at Mecca (a) Winds (m/sec), (b) Temperature (C) and Rel. Humidity (%) and (d) Rain fall (mm) and Mean sea level pressure (hPa).

The surface observations in Mecca shows (Figure 4) that the sudden fall in surface pressure (around 4 hPa) and temperature (around 20C), and sudden increase in wind speed (around 12 m/sec), wind gusts (around 15 m/sec) and relative humidity (from 20 to 95%) in less than twohour period, suggests that the convective system is very isolated in both space and time. After few minutes of the sudden fall in surface pressure, rapid increase in the surface pressure, temperature, winds and relative humidity was recorded. The high temporal resolution rainfall data indicate that a maximum amount of precipitation of about 20 mm fell with in a 1-hour period over the city of Mecca.

4. Simulation Results

We analyzed the WRF simulations with different PBL schemes to study the evolution the model dynamics and thermodynamics during the event. We focus on analyzing winds, equivalent potential temperature, radar reflectivity and stability of the atmosphere using Skew-T plots to explain the possible mechanism of the SWE on 11 September 2015.

The surface winds as simulated using the four 1.5-order closure turbulent kinetic energy (TKE) PBL schemes (Figure 5) indicate that all four schemes are able to predict the extreme winds and associated interaction with the topography. The height cross-section of winds over Mecca shows that the extreme winds are extended in both horizontal and vertical directions. The horizontal extent in east-west and north-south directions from Mecca are high in all three simulations (QNSE, MYS and UWMT), whereas in BouLac scheme, the extension in both northsouth and eastwest is limited to a small region, suggesting that the event is highly localized. Interestingly, the wind magnitude is high over the foothills of mountain in the simulation using BouLac scheme and weak in the vertical direction, whereas in all other three schemes the magnitude of winds increased in the vertical. The simulations with non-local first-order and hybrid PBL schemes (Figure 6) have not captured the observed wind magnitude and its extension in both vertical and horizontal directions. The wind field features from YSU, non-local first-order scheme, are close to those of the BouLac scheme, but exhibit extremely higher magnitudes.

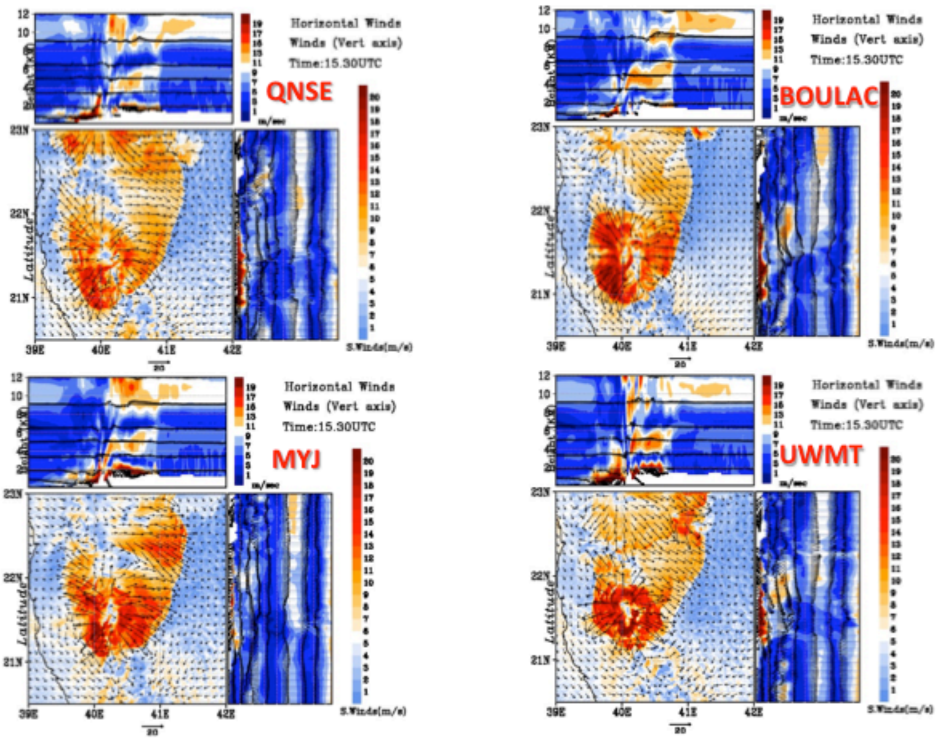

Figure 5: Surface Winds at 15.30 UTC from 1.5-order closure TKE PBL schemes. The height-section plots along Mecca latitude and longitude are presented.

Similarly, the equivalent potential temperature (representation of instability) along Mecca latitude from the different PBL schemes indicate that, except for MRF and ACM2 schemes, all schemes are able to predict the unstable conditions over Mecca. The YSU scheme predicts more intense convection followed by UWMT, and the BouLac scheme predicted an isolated narrow zone of unstable atmosphere over the foothills of mountain (windward side) and extended convective clouds up to around 7km height. The model radar reflectivity clearly show that an isolated maximum value greater than 52 dBz, indicating an isolated strong convection (strong updrafts) over Mecca between 1400 - 1500 UTC. We also plotted Skew-T gram at 1200UTC of 11 September 2015 over Jeddah for different PBL prediction experiments along with the observed radiosonde profile. With all PBL schemes, the simulated height of PBL, inversion, CAPE and level of free convection are slightly weaker than radiosonde observations, in contrast with the BouLac scheme simulation, which is close to the observed values.

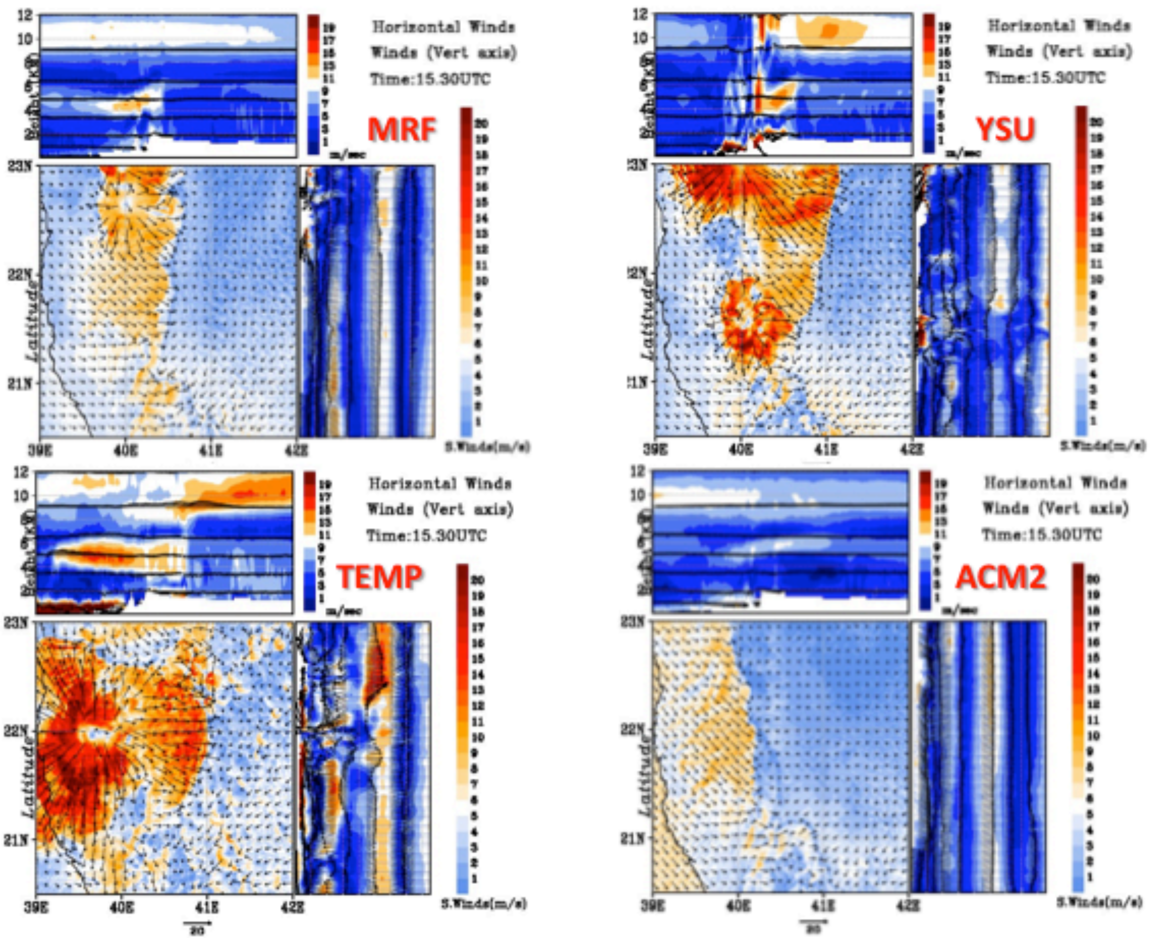

Figure 6: Same as Figure 5 but for non-local first-order and hybrid PBL schemes.

Even though the simulations with non-local, first-order closure schemes performed relatively well compared to observations, the predictions of local, 1.5 order closure schemes were clearly superior. The hybrid schemes did not capture the severe convective features over Mecca. Our results suggest that the BouLac scheme, local, 1.5-order closure, is more suitable for predicting the severe event that devastated the Mecca city on 11 September 2015.

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