

Simulation of extreme rainfall event of November 2009 over Jeddah, Saudi Arabia: the explicit role of topography and surface heating

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Abstract In this paper, a nonhydrostatic Weather Research and Forecasting (WRF) model has been used to simulate the extreme precipitation event of 25 November 2009, over Jeddah, Saudi Arabia. The model is integrated in three nested (27, 9, and 3 km) domains with the initial and boundary forcing derived from the NCEP reanalysis datasets. As a control experiment, the model integrated for 48 h initiated at 0000 UTC on 24 November 2009. The simulated rainfall in the control experiment depicts in well agreement with Tropical Rainfall Measurement Mission rainfall estimates in terms of intensity as well as spatio-temporal distribution. Results indicate that a strong low-level (850 hPa) wind over Jeddah and surrounding regions enhanced the moisture and temperature gradient and created a conditionally unstable atmosphere that favored the development of the mesoscale system. The influences of topography and heat exchange process in the atmosphere were investigated on the development of extreme precipitation event; two sensitivity experiments are carried out: one without topography and another without exchange of surface heating to the atmosphere. The results depict that both surface heating and topography played crucial role in determining the spatial distribution and intensity of the extreme rainfall over Jeddah. The topography favored enhanced uplift motion that further strengthened the low-level jet and hence the rainfall over Jeddah and adjacent areas. On the other hand,

the absence of surface heating considerably reduced the simulated rainfall by 30% as compared to the observations.

1 Introduction

The frequency and intensity of the heavy rainfall events over the Saudi Arabia has increased in the recent years (Almazroui 2011). The extreme rainfall events are mainly associated with severe flash floods, loss of lives, and huge economic losses. The classical examples of the heavy rainfall events in the Saudi Arabia occurred during 25 November 2009, 26 January 2011 in Jeddah, 5 May 2010 in Riyadh, and 30 April 2013 in Gizan and Hail (Almazroui 2013). In order to save life and livelihoods and reduce damages from such extreme events, an accurate forecast in terms of occurrence timing and location along with an effective disaster management system is very much essential. However, forecasting severe convective activity and associated heavy rainfall remains a challenging task for national weather service and meteorological researchers (Charles 1993), particularly over the arid and semi-arid region like the Saudi Arabia where the total number of these events in a year is relatively few. The development of such events over the western parts of the Saudi Arabia is mainly associated with the environmental condition of the Red Sea and topographic influence of the Asir Mountain that ranges from southwestern Saudi Arabia to Yemen (Haggag and El-Badry 2013; Hosny and Almazroui 2015).

Climatologically, the Red Sea and surrounding regions receive high rainfall during the wet season from November to April. During this period, unstable synoptic situations are reinforced by warm and moist advection due to southerly winds associated with the developing Sudan monsoon low (e.g., El-Fandy 1948; Kahana et al. 2002). The Sudan monsoon low develops under the influence of the subtropical jet stream position, which is located

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around 28° N in the wet season. This warm upper air trough extending northward along the Red Sea lies under the extended cold upper air trough moving over the Mediterranean, thereby favoring the development of severe convective systems (Sharon and Kutiel 1986), which leads to the heavy rainfall over the western parts of the Arabian Peninsula. Almazroui (2011) mentioned that the convergence over the Red Sea creates favorable conditions for the development of intense convection and heavy rainfall event over the Arabian Peninsula, particularly in the western Saudi Arabia. In addition, the transportation of moisture content from the Arabian Sea enhances the storm intensity associated with active Red Sea trough. Krichak and Alpert (1998) demonstrated with observation and modeling study that the tropical convection over the east Africa intensifies due to the large amounts of moisture availability within the air masses transported from the Arabian Sea. This improved convection contributes to the stronger subtropical jet stream over the Red Sea, thereby triggers the formation of low-level trough.

The Arabian Peninsula is bordered by the Red Sea to the west; the mountain range of Scarp-Hijaz-Asir forms a barrier to the sea and extends the full length of the Arabian Peninsula, running parallel to the Red Sea. The geographical locations of the Arabian Peninsula, particularly the topography along the coastal range of the Red Sea, significantly modulate the development of extreme weather systems. The warm Red Sea acts as a main reservoir of heat and moisture for the development of a strong convective systems causing heavy rainfall over the southwestern part of the Arabian Peninsula during summer, whereas in winter, the middle and northern coastal parts receive maximum rainfall (Abdullah and Al-Mazroui 1998). The mountain ranges along the coast may not only be directly involved by raising warm moist air but may also conserve the low-level flow, thereby favoring explicit mesoscale processes that stimulate the convective weather systems over the region. Though, currently available numerical models can produce more or less realistic mesoscale features, albeit the large errors arise in prediction of mesoscale convective systems and associated precipitation. Therefore, it is important to understand the sub-grid scale processes and its sensitivity to the model. In addition, the initial and boundary forcings are indispensable to regulate the predictability in the forecasting system (Weiss et al. 2004). Understanding of the physical processes associated on the development of severe convective weather systems, it is essential to investigate the relative influence of surface boundary conditions on numerical weather prediction that ascertain the most dominant elements of uncertainty in the system and provide better perception on the role of geographical constrain in the predictability of weather extremes (Martín et al. 2007).

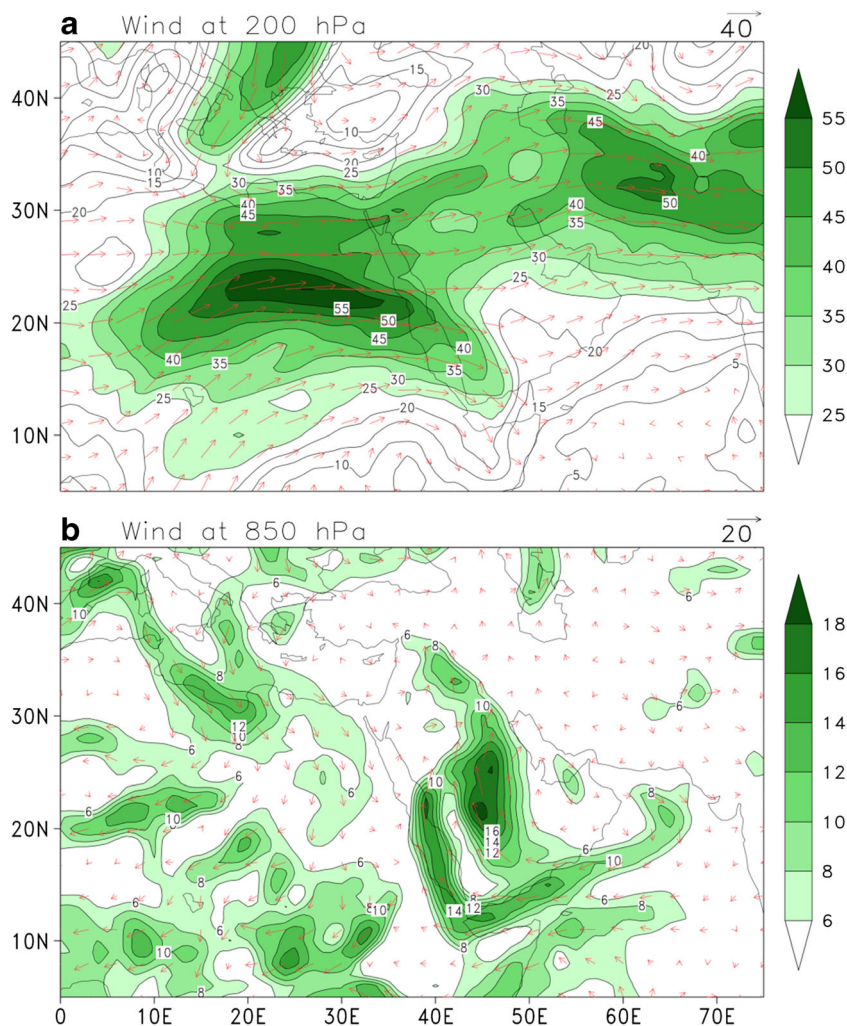
Severe flash floods are not frequent in the Saudi Arabia; as a consequence, very few specific case studies have been available to understand dynamical mechanism of such extreme events in this region. The heavy rainfall event that triggered severe flash flood in Jeddah on 25 November 2009, and caused enormous loss in terms of lives and damage to the property, is an ideal case considered in this study to investigate the synoptic and dynamical processes associated with the heavy rainfall using numerical modeling. The orientation of the orographic barrier along the Red Sea coast makes this region particularly prone to flash floods. By using mesoscale model (MM5) simulations Haggag and El-Badry (2013) reproduced reasonably well the temporal and spatial distribution of the extreme rainfall of November 25, 2009. They showed that convergence at lower levels with enhanced up-slope winds as well as upper-level atmospheric instability influenced by a meso-low (cyclogenesis induced by Al Hejaz escarpments) might be a crucial in enhancing severe convective system. The current study further examined the role of topography and surface heat exchange processes (moisture and latent heat) in the atmosphere on simulation of heavy rainfall over Jeddah. For this purpose, sensitivity experiments are conducted with and without topography and land surface heating (discussed in the next section) to examine their explicit role in the development of the mesoscale system and conditions that favored the extreme rainfall over Jeddah. The paper is structured as follows: the next section describes an overview of the synoptic feature associated with the extreme rainfall event. Sections 3 and 4 illustrated the brief overview of the model and experimental design. The main results are presented in Sect. 5. The discussion and conclusions are given in the last section.

2 Description of the case study

An intense mesoscale convective system occurred on 25 November 2009 over Jeddah, on the eastern part of Red Sea coast and the western region of the Saudi Arabia. This mesoscale system produced 74 mm of rainfall in 4 h over Jeddah, causing a severe flash flood that affected the city and its environs with a death toll of more than 120 people in 2009 and damaged infrastructure and property (Almazroui et al. 2012). Whereas, the floods in January 2011 produces rainfall of 111 mm causing also causing enormous damages to the properties and infrastructure. Both flash flood events of 2009 and 2011 occurred in Jeddah had duration of 3 h.

The observed synoptic conditions during the heavy rainfall event of 25 January 2009 are chosen from the National Centers for Environmental Prediction (NCEP) reanalysis datasets. Figure 1 depicts the wind circulation distribution at 200 and 850 hPa on 0600 UTC of 25 November. It indicates a strong pattern and intensity of the low-level jet (LLJ) over the

Fig. 1 Spatial distribution of wind obtained from NCEP reanalysis datasets at 0600 UTC on 25 November 2009 **a** at 200 hPa (*shaded region* represents the wind above 25 m s^{-1}) and **b** at 850 hPa (*shaded region* represents the wind above 6 m s^{-1})



Red Sea, with a maximum wind of $\sim 16 \text{ m s}^{-1}$. The low-level easterly wind over the Arabian Sea turned to a south easterly when enter to the Red Sea, which is the primary source of locally advected moist air, further enhanced the moisture content in the analysis domain (Fig. 1b). Also, there was a strong low-level convergence at 925 hPa over the Jeddah region at 0600 UTC on 25 November 2009 (figure not shown). The upper-level (i.e., at 200 hPa) features indicate strong cyclonic (anticyclonic) circulation to the northwest (south) of the Arabian Peninsula (Fig. 1a). The concurrence of the upper-level cyclonic and anticyclonic circulation favored strong westerly flow centered over 23° N and 20° E to 30° E . It is noticeable that the upper-level westerly jet, with a core wind speed of about 55 m s^{-1} over the North Africa, extends to the south of the convective system location, and that it is associated with a marked change in the upper-level divergence. The interaction between the low-level jet and upper-level jet is accompanied by the movement of an upper-air cold trough over the Red Sea that facilitates in development of mesoscale convective systems (Whitney 1977; Uccellini and Johnson 1979). The evolution of upper-tropospheric winds (divergence

patterns) is quite similar to that documented in the vicinity of other long-lived convective systems (Maddox 1980; Fritsch and Maddox 1981; Maddox et al. 1981). They also found that severe storms tend to occur north of the subtropical jet and south of the polar jet. McNulty (1978) suggested that the divergence patterns associated with upper-level wind maxima can be used in combination with low-level moisture, instability, and convergence to define areas where severe thunderstorm activity might occur. In addition, southerly momentum in the lower-troposphere supports to produce a favorable environment for growth severe thunderstorm activity, especially when the intersection of the jet axes occurs within the exit region of the upper-level jet (ULJ). The interaction between LLJ with ULJ over Red Sea with association of southerly wind transports the heat and moisture to Jeddah and its surrounding regions, enhancing the convective activity and heavy downpour over this region (Fig. 1b).

The relative humidity, geopotential height, and temperature at 925, 850, and 700 hPa associated with the heavy rainfall event are presented in Fig. 2. The relative humidity values are more than 90% over Jeddah and the surrounding region at 925

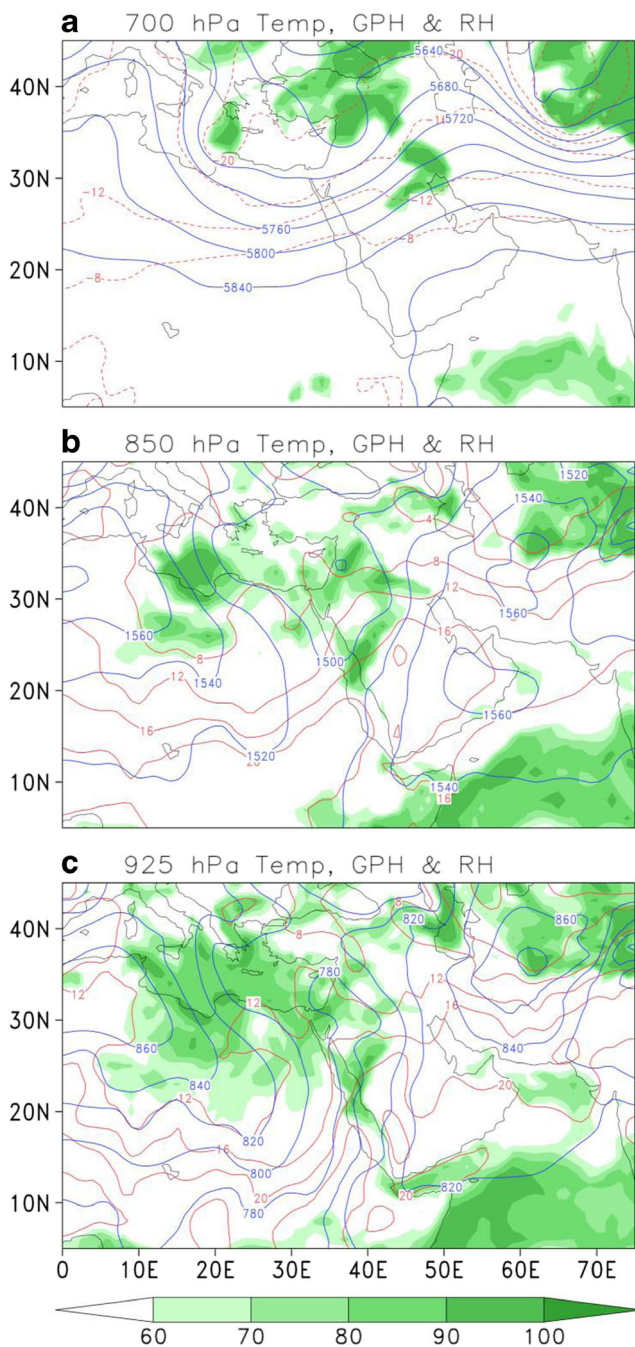


Fig. 2 Spatial distribution of geopotential height (blue), temperature (red), and relative humidity (shaded region) at 925, 850, and 700 hPa obtained from NCEP reanalysis datasets at 0600 UTC on 25 November 2009

and 850 hPa. It is also to be noticed that there are higher values of relative humidity in the low levels over Arabian Sea and the Red Sea, along with a strong low-level flow, suggesting strong intrusion of moisture into the Jeddah and adjacent areas. The temperature distribution depicts cold dry air over the north-western region and warm moist air over the southeast of the Arabian Peninsula at 925 to 700 hPa (Fig. 2). At 850 hPa, it is noticed that an anticyclonic system in the southeast part of the

Arabian Peninsula and the formation of a ridge over the Mediterranean indicates a blocking situation that maintains water vapor passage. The relative influence of the Mediterranean cyclones moving from west to east and anticyclonic circulation centered over the southeastern Arabian Peninsula is key aspect in the development of the intense convective system. The pronounced low-level warm advection that appears over 925 and 850 hPa (Fig. 2) creates a region of strong conditional instability, which subsequent lifting, enabling the production of significant convective activity over Jeddah and the surrounding regions (on 25 November 2009). The vertical sounding at 0600 UTC on 25 November 2009 at Jeddah observed that convective available potential energy (CAPE) amounts to 959 J kg^{-1} and precipitable water reaching 3.3 cm (<http://weather.uwyo.edu/upperair/sounding.html>). The wind shear turned clockwise with warm advection and a strong shear below 700 hPa, and that stratification of dry (wet) air formed at higher (lower) levels. This warm moist weather with the accumulated unstable energy is suitable for the development of heavy rainfall systems. The relative humidity depicted peaks at 850 hPa, along with a low lifting condensation level (LCL), implying strong moisture transport, which typically triggers heavy rainfall over the region.

3 Model description

The simulations of the severe convective system and associated rainfall over Jeddah are carried out using the Weather Research and Forecast Model (WRF) version 3.5 with the dynamic core of the Advanced Research WRF (ARW). The WRF is a nonhydrostatic mesoscale model developed to run at high resolution of a few kilometers or less for the research and operational weather prediction (Skamarock et al. 2005; Michalakes et al. 2005). It also incorporates various physical parameterizations, initialization routines, and assimilation techniques; many operational agencies and research institutes have extensively used and demonstrated its capabilities of the prediction of high impact weather events (e.g., Raju et al. 2012; Das et al. 2015). A series of experiments have been performed with different convection and microphysics for simulation of extreme weather events over this region to choose the appropriate physical schemes in control and sensitivity experiments. In this study, the schemes consisting of the Grell convective scheme, an improved version of the Grell-Devenyi ensemble convection scheme (Grell and Devenyi 2002), and Eta (Ferrier) microphysics scheme are employed on the three domains of 27, 9, and 3 km, respectively. Radiation parameterization is controlled with rapid radiative transfer scheme (RRTM) for long-wave radiation (Mlawer et al. 1997), which represents the influences of the detailed absorption spectrum, considering carbon dioxide, ozone, and

water vapor as well as a scheme for short-wave radiation (Dudhia 1989). The nonlocal parabolic exchange coefficient planetary boundary (PBL) scheme (Hong et al. 2006) of the Yonsei University (YSU) and a four-layer soil diffusion model with a fixed substrate below are also used. In addition, moisture content of the atmosphere adjusts with time, particularly in response to rainfall and evaporation rates (Noah et al. 2003). A brief overview of the ARW model used in this study is illustrated in Table 1.

4 Data and experiment design

The United States Geological Survey (USGS) database on orography, land use, and soil parameters (approximately 15 km for outer domain and 5 km for nested domains) are used. The lateral boundary forcing are updated at every 6 h from the NCEP global reanalysis data (available on a $1^\circ \times 1^\circ$ spatial grid). The 3D meteorological data of pressure, zonal and meridional wind, temperature, relative humidity, geopotential height at 17 standard pressure levels, and four-layer soil data of soil temperature, soil moisture, and surface meteorological data including mean sea level pressure, zonal and meridional wind, temperature, and relative humidity are used for simulations. The constant sea surface temperature data were provided from the NCEP reanalysis throughout the simulation. Vertical hybrid levels are defined such that the model output of 30 levels with attention at the lowest levels to resolve detailed planetary boundary layer structure. The time step of 120 s has been set for iteration of the model run. The model was integrated for 48 h initiated at 0000 UTC

on 24 November 2009 in both control and sensitivity experiments.

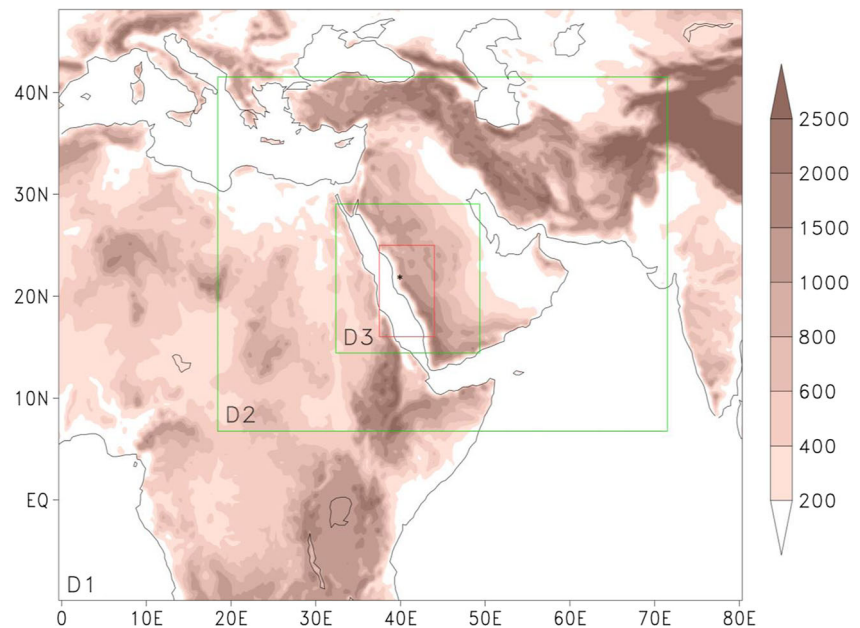
The control run and sensitivity experiments are performed in a nested, two-way interactive way, such that the information in the inner domain can be supplied to the outer domain, and vice versa, with corresponding at the nested boundary. Figure 3 depicts the topography and nested domains used in this study for control and sensitivity experiments. In the southwest, the mountains reach 2500 m in height (see Fig. 3). In the mid-west of the Arabian Peninsula, the coastal plain of Tihama lies where Jeddah is located, at approximately 21.5° N, 39.2° E. These unique orographic features of the Arabian Peninsula (east coast of the Red Sea) interact with the synoptic and mesoscale flows and play a major role in the evolution of convective weather systems associated with heavy rainfall. The outermost domain (D1), with 27-km horizontal resolution, is intended to capture the synoptic-scale characteristics, whereas nested domains of 9 km (D2) and 3 km (D3) are established to resolve sub-grid scale phenomena. To assess the topographic influence in modulating the mesoscale circulation and producing the strong convection, the model topography around Jeddah region (between 18° – 23° N and 37° – 45° E) is flattened to mean sea level (NoTopo experiment). The model is integrated keeping the physical and dynamical options similar to the control experiment. In addition, to assess the effect of the surface heating on the rainfall amount and distribution, an experiment is conducted with the removal of the heat predicted by the model within the surface and PBL (NoHeat experiment).

In addition to the observed rainfall over Jeddah during the severe precipitation event, the Tropical Rainfall Measurement

Table 1 Overview of the ARW model used for the simulation in this study

Model	WRF 3.5
Number of domain	Three; 27, 9, and 3 km
Vertical levels	30
Time step	120 s
Central point of the domain	22° N, 40° E
Map projection	Mercator
Horizontal grid distribution	Arakawa C-grid
Vertical coordinate	Terrain-following hydrostatic-pressure coordinate
Time integration	Third-order Runge-Kutta
Spatial differencing scheme	Sixth-order centered differencing
Initial conditions	3D NCEP analysis
Lateral boundary condition	Periodic, 6 hourly NCEP analysis
Radiation scheme	Dudhia's short-wave radiation RRTM long-wave radiation
Surface layer parameterization	Noah land surface scheme
PBL schemes	YSU
Cumulus schemes	Grell
Microphysics scheme	Ferrier (new Eta)

Fig. 3 Model domain and topography used in the study. The *solid green box* indicates the nested domains of the 9- and 3-km grid resolution. *Red box* depicts the experiment with the removal of topography in the model. The *shaded area* represents surface elevation above 200 m



Mission (TRMM) 3B42 products are utilized for comparison of rainfall distribution as well as intensity of model-derived rainfall. Other meteorological parameters of NCEP reanalysis are used for comparison of model simulations.

5 Results

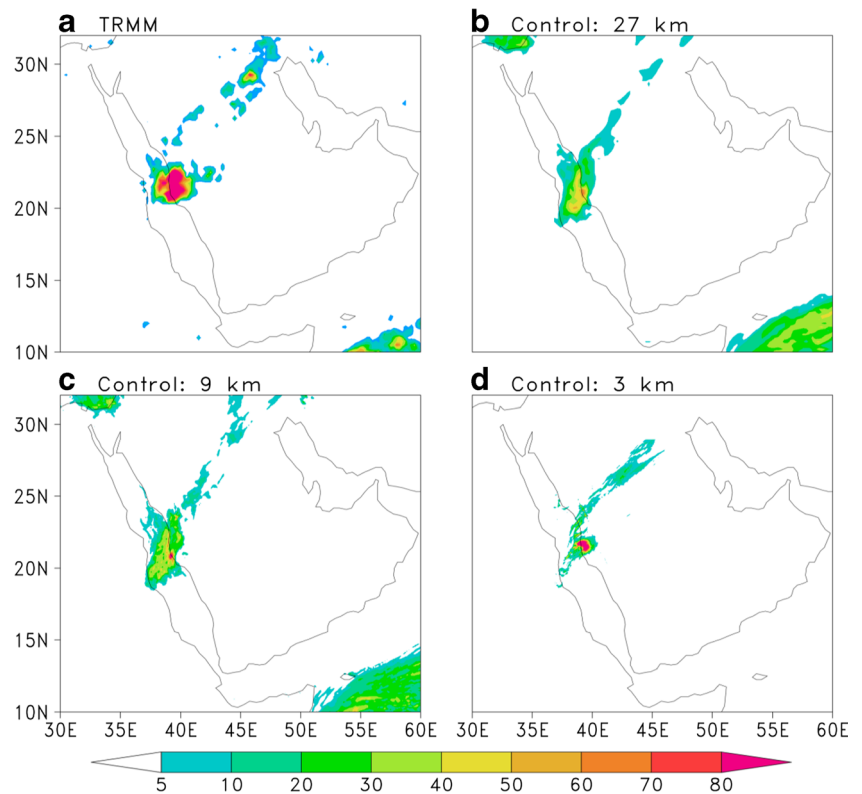
5.1 Control run

The 24-h accumulated rainfall from the WRF control simulation for three different resolutions and the TRMM rainfall estimates are given in Fig. 4. The WRF model reasonably captures the spatial distribution in all three nested domains (Fig. 4). In terms of intensity, the maximum rainfall over the Red Sea coast near Jeddah (approximately 70 mm day^{-1}) is reasonably simulated in the fine resolution (9 and 3 km) simulations, whereas for the course resolution, it is slightly underestimated as compared with the TRMM rainfall. The evolution of 3-h accumulated rainfall from 0000 UTC on 24–26 November 2009 over Jeddah for three domains is displayed in Fig. 5. This illustrates the high-resolution (3 km) model simulation overestimates 00 and 06 UCT and underestimates 09 UTC on 25 November; nevertheless, high-resolution run captures the intensity of the extreme rainfall against the TRMM estimates. Furthermore, the high-resolution simulation also capture well the location and timing of the heavy rainfall that affected Jeddah whereas the coarser resolution (27 km) simulation underestimates the intensity of extreme precipitation. The accumulated rainfall in the

finer grid domain (D3) is around 70 mm , which is in good agreement with observation reported at Jeddah.

The spatial distribution of the wind pattern (at the 850- and 200-hPa levels), the zonal and meridional cross section of vertical velocity (contour lines) and the water vapor mixing ratio (shaded) centered over Jeddah for the control experiment are presented in Fig. 6. The low-level features are well simulated with a strong flow over the Arabian Sea to the Red Sea, further enhancing the LLJ over the Red Sea with a maximum wind of more than 16 m s^{-1} . These results corroborate with the earlier finding that the moisture advected from the Arabian Sea influenced the storm associated with the active Red Sea trough (Krichak and Alpert 1998). The upper-level (200 hPa) circulation features reveal a subtropical jet stream with a core speed of more than 55 m s^{-1} over the North Africa, which moved westerly and exit in the south of the Jeddah region (Fig. 6b). These features resembles to the NCEP reanalysis except the position of core located about 100 km to the west (see Fig. 1). The meridional and zonal cross section of vertical velocity and the water vapor mixing ratio for Jeddah were constructed (Fig. 6c–d). The meridional cross section of zonal averaged vertical velocity indicates a strong rising motion, with a maximum of 18 m s^{-1} at 21° N between 600 and 500 hPa. Moreover, the rising motion over the Red Sea region extends vertically up to 100 hPa. The water vapor mixing ratio over this region depicts higher values centered at 21° N , near Jeddah and extending vertically up to about 500 hPa. The zonal cross section of vertical velocity illustrates strong upward motion (maximum of 12 m s^{-1} between 600 and 500 hPa), centered at 39° E near Jeddah. Another zone of rising motion is centered at 40° E , maximum of 16 m s^{-1} confined at 200 hPa, adjacent to which a strong sinking

Fig. 4 Rainfall accumulated for 24 h obtained from **a** TRMM, model simulations with control experiment, **b** 27 km, **c** 9 km, and **d** 3 km. The unit of rainfall is mm



motion is noticed. The zonal cross section of water vapor mixing ratio depicts the moisture buildup beginning at 36° E and reaching its maximum around 39° E. Figure 6c, d clearly shows high mixing ratio over the Jeddah region through most of the troposphere, giving indirect evidence for large amount of rainfall. It can be seen that the LLJ over 850 hPa significantly increased over the Red Sea (Fig. 6a), where the moisture advected into the region of heavy rainfall occurs. In other words, the LLJ was intensified simultaneously with the maritime wind onto the Red Sea, initiated and sustained the cloud cells as a result of the vertical motion around Jeddah's longitude (39.18° E). These features created a band of rain characterized by convective rainfall. This complex structure is also confirmed by the occurrence of multiple bands of clouds,

which are clearly visible on the satellite image (not shown). The analysis at mesoscale demonstrates that the strengthening of the LLJ advected moisture and thermal fields to create conditional instability over Jeddah and its environment, thereby enabling severe convective activity and associated heavy rainfall event.

5.2 Sensitivity experiments

To study the influence of orography and the surface heating in the development of the convective weather system, we performed two sensitivity experiments with (i) no topography (NoTopo) and (ii) no sensible and latent heat in the PBL (NoHeat). In the following two subsections, the results of

Fig. 5 Three-hourly accumulated rainfall over Jeddah obtained from TRMM and three nested domains (27, 9, and 3 km) of control experiment

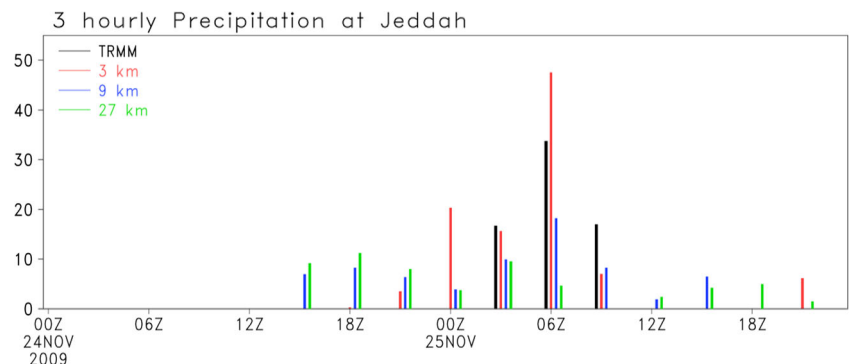
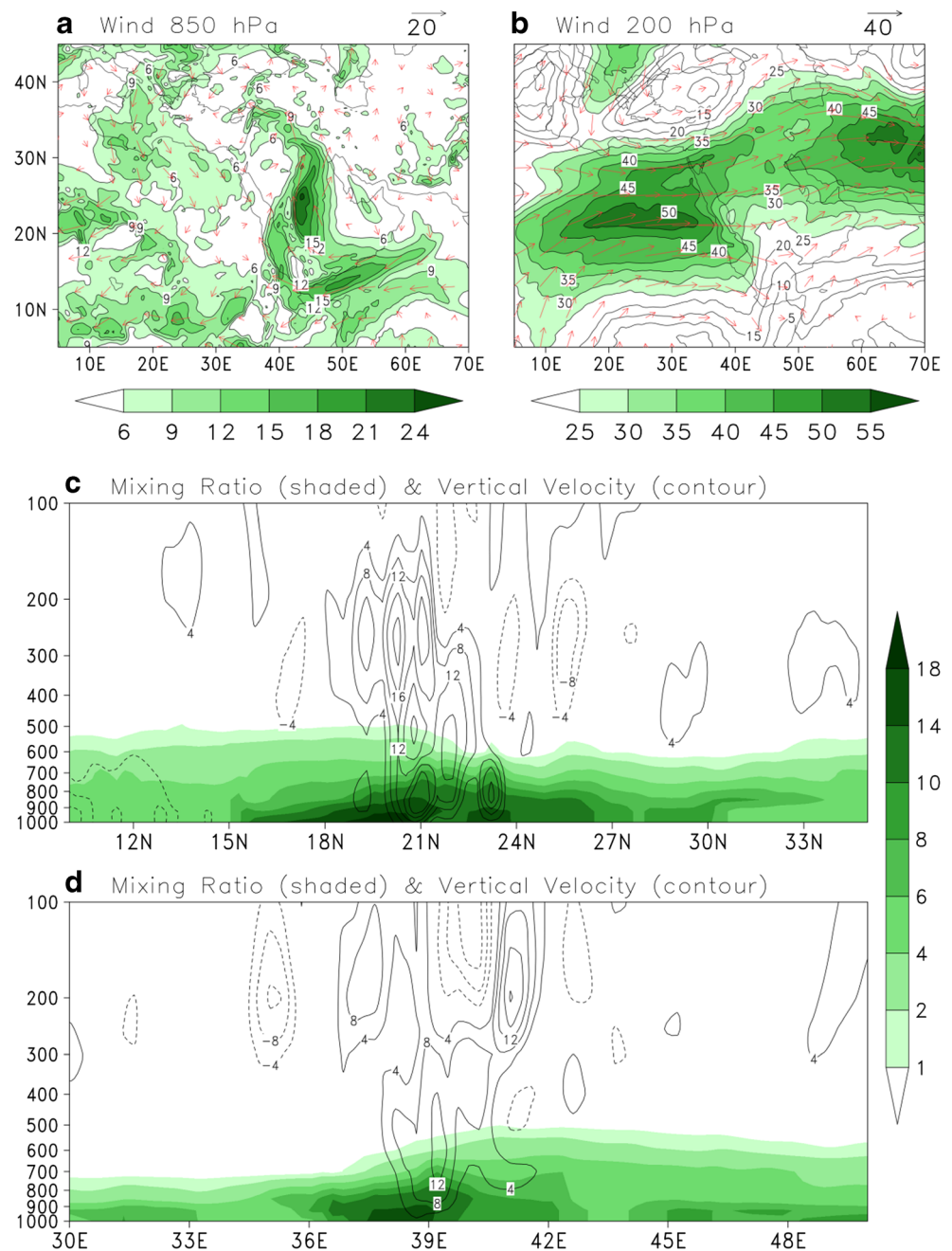


Fig. 6 Control experiment simulation for **a** wind (m s^{-1}) at 850 hPa, **b** wind at 200 hPa, and **c** meridional cross section of vertical velocity (m s^{-1}) (contour) and water vapor mixing ratio (g kg^{-1}) (shaded), **d** zonal cross section of vertical velocity (m s^{-1}) (contour) and water vapor mixing ratio (g kg^{-1}) (shaded)



these sensitivity experiments are presented to understand their individual impact on rainfall distribution and the mesoscale dynamical features (such as circulation patterns) associated with the intense convective event of November 25, 2009, over Jeddah.

5.3 Rainfall

The spatial pattern of the 12-h accumulated rainfall, valid for 0000 to 1200 UTC on 25 November for innermost domain (3 km grid), is depicted in Fig. 7. The finer grid resolution of

rainfall in the control run reveals that the model reproduced reasonably well the rainfall intensity (about 70 mm) associated with extreme event over Jeddah (Fig. 7a). The simulated rainfall intensity is in close agreement with observations as well as the TRMM estimates (Fig. 4a). The heat and moisture transport from the warm Red Sea within the boundary layer act for an effective mechanism for the stabilization of convective activity and further triggering of heavy rainfall (Martín et al. 2007). This heat is very sensitive to the mesoscale system such as the gradient of moisture at comparatively high air temperature in the presence of steep topography, which

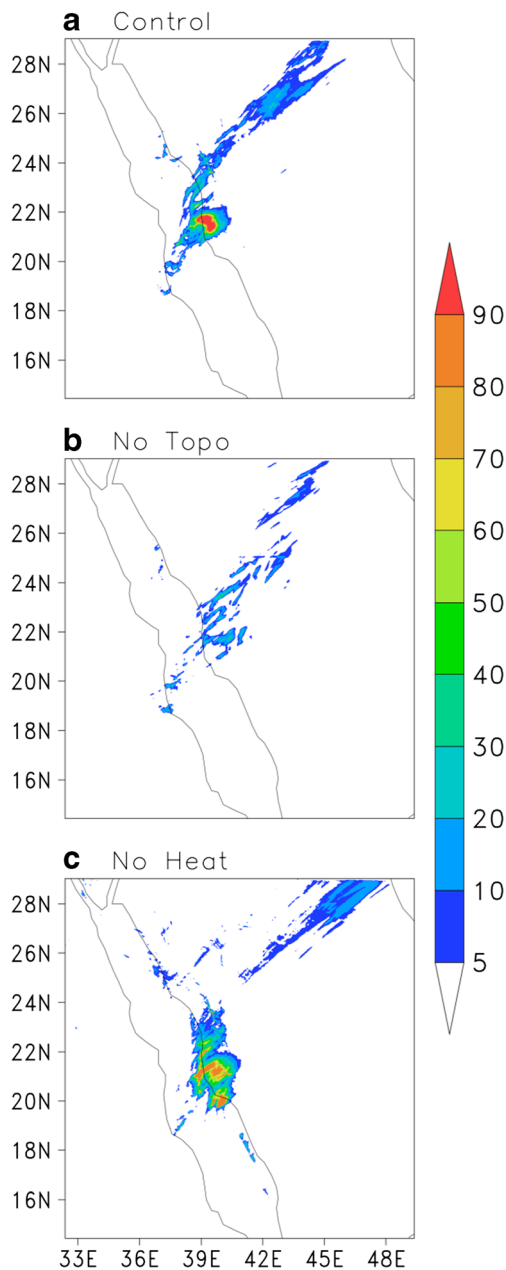


Fig. 7 Model simulated 24-h accumulated rainfall in finer grid resolution (D3) at 0000 UTC to 1200 UTC on 25 November 2009 for **a** control run, **b** no topography, and **c** no surface heating

reinforce large-scale vertical motions (Buzzi et al. 1998). The NoTopo experiment, where the topography is flattened to mean sea level over the region around Jeddah, illustrates that rainfall intensity decreased to 20–30 mm over Jeddah and the surrounding region (Fig. 7b). This could be due to the weak maritime wind and weak orographic ascent during the development of the rainfall system over this region. In the absence of surface heating (NoHeat; Fig. 7c), the model depicts around 30% less rainfall intensity around Jeddah as compared with control experiment.

5.4 Circulation pattern

The lower-level (850 hPa) and upper-level (200 hPa) circulation patterns simulated by the model in the two abovementioned sensitivity experiments are presented in Fig. 8. The enhanced LLJ transports the warm moist air to Jeddah and adjacent areas, creating conditional instability, which further increased the large-scale vertical motion in association with topography and hence cause the heavy rainfall over this region. The lack of topography in the NoTopo experiment clearly indicates the weakening of the uplift branch and LLJ reduced to about less than 10 m s^{-1} over both Red Sea and around Jeddah (Fig. 8a). As a result, the amount of rainfall is considerably reduced in the sensitivity runs compared to the control experiment. This leads to a significant reduction in latent heat, which further decreases the uplift motion and the LLJ. The present case study indicates that the convective activity over this region is sensitive to near surface temperature and humidity.

The strong orographic uplift contributes to build towering clouds by strengthening the vertical motion and LLJ that preserve the supply of moisture and heat into the area. In the NoHeat experiment, the low-level 850-hPa circulation concentrated over the Red Sea indicates decreased wind speed (about 4 m s^{-1}) compared to the control experiment (Fig. 8c). This reduction of convection over Red Sea is due to the weakening of heat and moisture content at the surface layer (Fig. 8c). The considerable dissimilarity in the control run and the NoHeat experiment is evident in terms of the extended subtropical easterly jet with a reduction in speed of the southerly low-level wind fields to 12 m s^{-1} (Fig. 8c, d). In the presence of systematic warming in the atmosphere by the latent heat release, both cold thermal advection and the associated upper air trough are less extended southerly. This creates a temperature gradient under the subtropical jet, and thereby the subtropical jet moves easterly to an exit zone located south of Jeddah. From the control experiment, it is evident that the heat and moisture gradient associated with the LLJ over the Red Sea impinging on the mountains enforces the uplift motion and the conditional instability. In the case of NoHeat, a weak LLJ tends to exhibit lesser flow of heat and moisture at the lower levels. The position of the upward motion is located more in the easterly side and is accompanying with the secondary circulation at the exit of the subtropical jet over the Red Sea and Jeddah (Fig. 8c, d). The strong convergent wind over Jeddah is inferred due to the latent heat release and thereby enhance rainfall amount. The meridional and zonal cross section of vertical velocity and water vapor mixing ratio for the sensitivity experiments are shown in Figs. 9 and 10. The zonally averaged meridional cross section of vertical velocity indicates a weak upward motion in both experiments as compared with control run, with a maximum of 8 and 12 m s^{-1} , respectively, in topography and surface heating experiments (Fig. 9). The maximum water vapor mixing ratio

Fig. 8 Spatial distribution of wind (m s^{-1}) at 850 hPa for **a** no topography and **c** no surface heating, and at 200 hPa for **b** no topography and **d** no surface heating. *Shaded area* represents the magnitude of wind in m s^{-1}

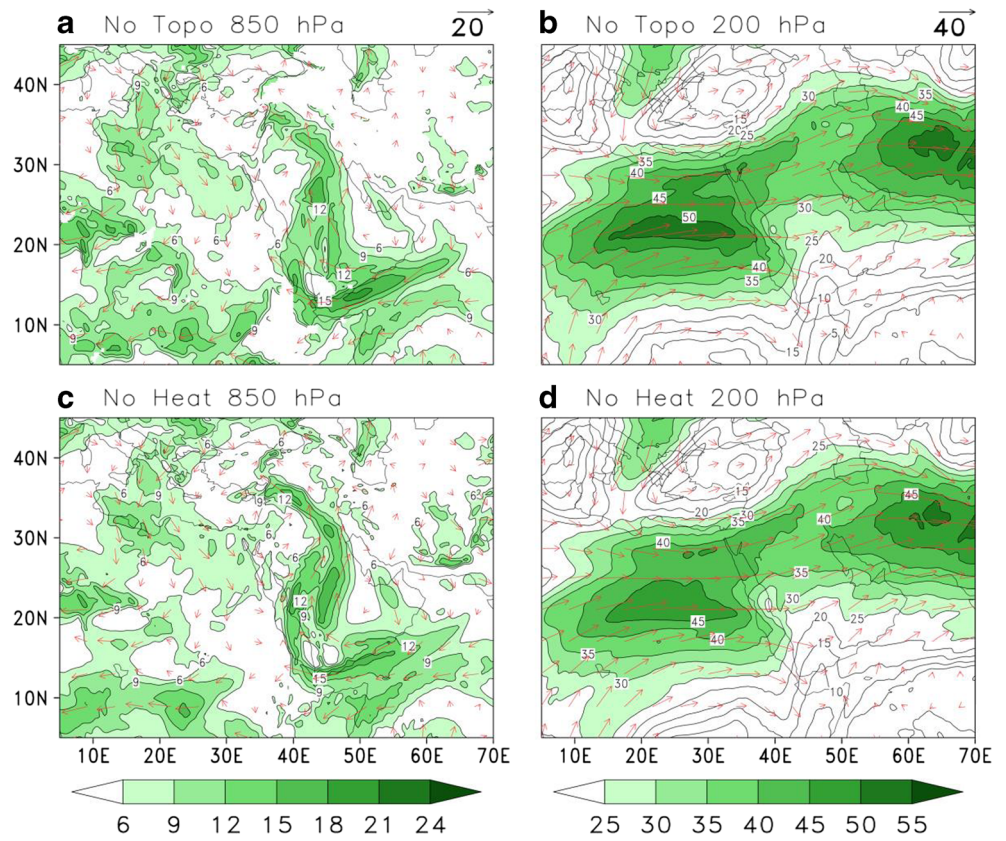


Fig. 9 Meridional cross section of vertical velocity (m s^{-1}) (contour) and water vapor mixing ratio (g kg^{-1}) (*shaded*) for **a** no topography and **b** no heat experiments

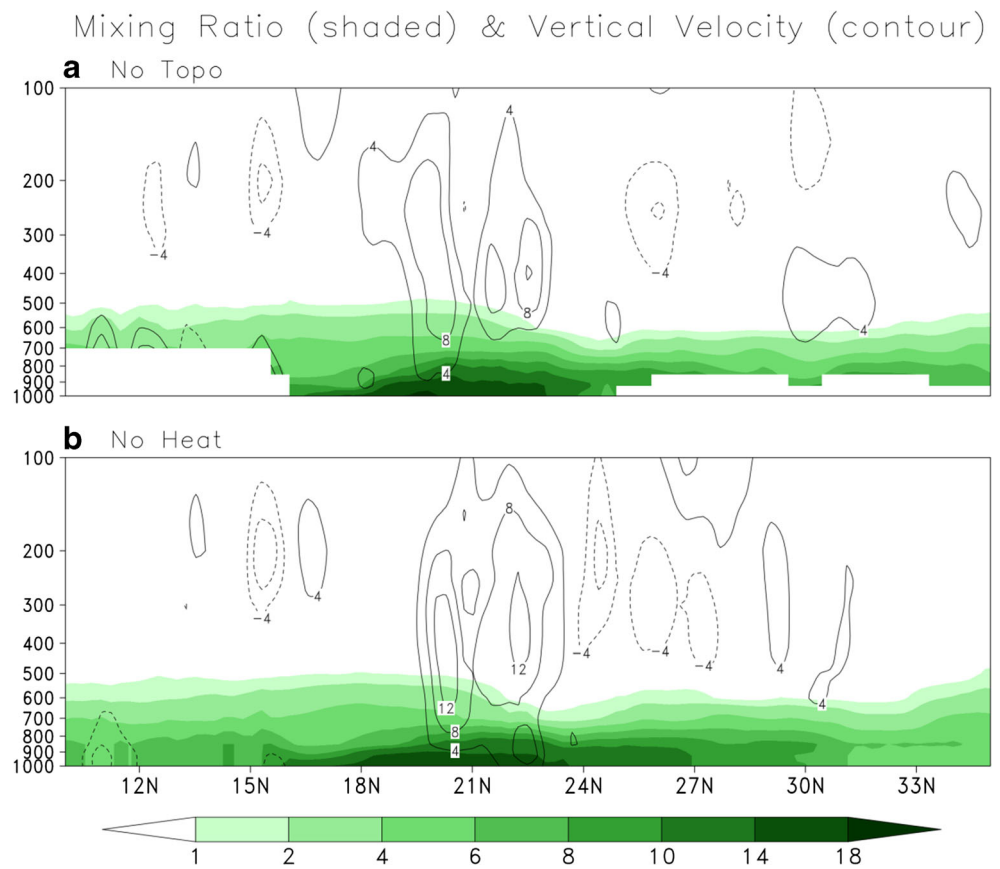
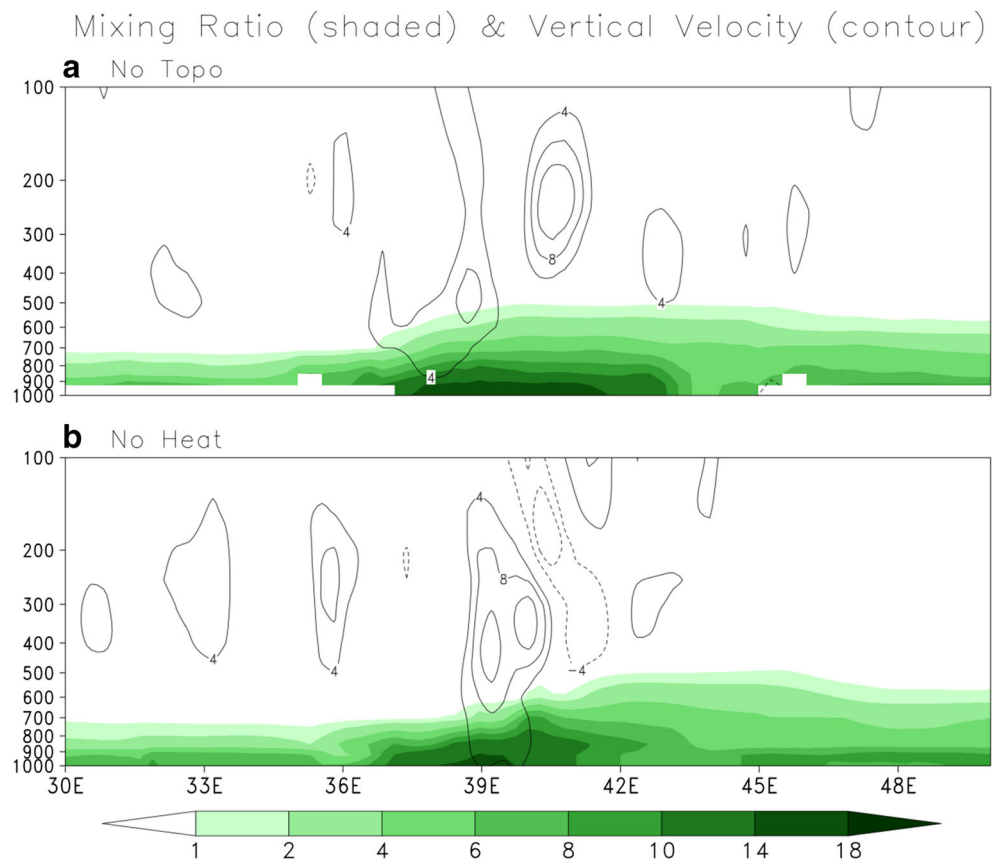


Fig. 10 Zonal cross section of vertical velocity (m s^{-1}) (contour) and water vapor mixing ratio (g kg^{-1}) (shaded) for **a** no topography and **b** no heat experiments



centered Jeddah and extending vertically up to about 500 hPa; however, the intensity is underestimated against control run (Fig. 9). In the absence of topography, the zonal cross section of vertical velocity illustrates that a weak rising motion with a maximum of 8 m s^{-1} between 600 and 500 hPa is centered at 39° E near Jeddah. Whereas in surface heating experiments, the vertical velocity is 12 m s^{-1} centered around 400 hPa. In both sensitivity runs, we found a clear decrease in the vertical velocity compared to control experiment. The zonal cross section of water vapor mixing ratio depicts the moisture reach up to 750 hPa in the absence of heating, and without topography, it extends up to 650 hPa (Fig. 10). It is therefore evident from Figs. 9 and 10 that the surface heating and topography play an important role in the development of convective activity and associated rainfall prediction over Jeddah.

We further examined the vertical velocity averaged over $1.5^\circ \times 1.5^\circ$ grid centered on Jeddah with the three scenarios (Fig. 11). It is evident from the control run that there is a strong vertical motion between 500 and 400 hPa, with a maximum of about 24 m s^{-1} . In the absence of topography (NoTopo), the rising motion drastically declines ($\sim 20 \text{ m s}^{-1}$) compared to control run because of the weak low-level flow and lack of orographic lifting, thereby producing less rainfall over Jeddah in the model sensitivity simulations. On the other hand, in the NoHeat experiment, the vertical velocity has a decline by 40% compared to control experiment with a maximum of 15 m s^{-1}

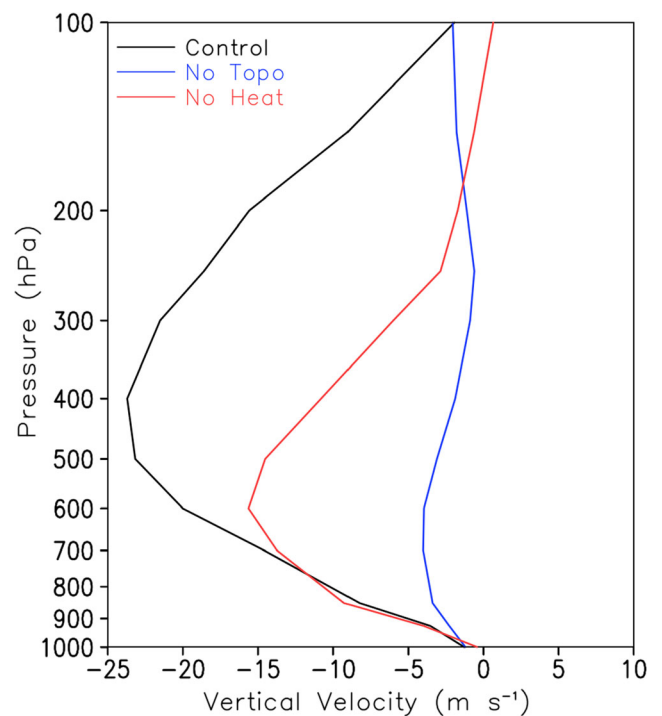


Fig. 11 Vertical profile of vertical velocity averaged over $1.5^\circ \times 1.5^\circ$ grid centered the location of Jeddah for control, without topography and without surface heating experiments at 0006 UTC on 25 November 2009

at 600 hPa and then decreases upward. The decrease in rainfall over the active area was attributed to the reduced buoyancy and upward motion in the entire column of the atmosphere by the weak latent heat release where the condensation takes place. These features are consistent with the rainfall over Jeddah, i.e., in the absence of topography and surface heating produced a weak LLJ and lack of moisture convergence, hence simulate less rainfall over this region. These results indicate that the topography and surface heating played a vital role in creating favorable conditions for mesoscale system that caused extreme convective rainfall over Jeddah and adjacent areas on 25 November 2009.

6 Conclusions

In this paper, heavy rainfall event that affected Jeddah on 25 November 2009 has been examined using the mesoscale model simulations. The performance of WRF model with two-way interactive nested approach in simulation of heavy rainfall event over the Arabian Peninsula was investigated. We found that the high-resolution (3 km) WRF model simulation capture realistically the spatio-temporal distribution of the heavy rainfall that occurred during November 25, 2009, over Jeddah, Saudi Arabia. The simulated rainfall in terms of spatial distribution and intensity are matching well with the TRMM rainfall estimates.

Special emphasis is given to understand the role of topography and surface heating in the heavy rainfall event. For this purpose, two additional sensitivity experiments are performed, one with flattened topography over Jeddah region and other without surface heating. The results of the model simulations and sensitivity experiments reveal that a noteworthy reduction of rainfall intensity associated with the extreme event was modulated by the mesoscale effects induced by the topography and the latent heat on the large-scale synoptic flow. Moreover, the heavy rainfall event was characterized by the upper-level southerly cold trough above Saudi Arabia, which contributed to the strengthening of the southerly LLJ over the Red Sea. The southerly LLJ advected moist southerly air from the Red Sea towards the Jeddah and adjacent areas. Results indicate that the convergence of low-level warm moist southerly air as well as the complex topography of the region has played an important in triggering convection and associated rainfall over Jeddah and adjacent areas. The key findings derived from the sensitivity experiments are as follows:

- The topography of the area (Red Sea and mountains around Jeddah) played a crucial role in intensification of the rainfall over Jeddah and adjacent areas by creating a secondary circulation at the exit of the subtropical jet stream. The removal of the topography reduced the

induced LLJ and the associated warm moisture belt, thereby decreases the intensity of rainfall over the Jeddah region.

- The warming of the boundary layer through the heat and moisture transport from warm Red Sea further enhances the convective system. The removal of heat in the surface layer reduced rainfall amount by more than 30% and changed its distribution, by affecting both the moisture gradient and the dynamics of the upward motion, suggesting that surface fluxes are important in regulate the low-level convergence of the moist air prior to initiate of the development of convection.

For understanding of the mesoscale processes that stimulate heavy rainfall in the context of topography over Saudi Arabia, further theoretical/numerical investigations and more case studies are needed. The prediction of heavy rainfall intensity, its spatial distribution, and time of occurrence is still a challenging task, and ample scope is available for improvement by suitable physical parameterization scheme, increase of model resolution (both horizontal and vertical resolutions), as well as proper representation of the topography may enhance the forecast capabilities. In addition, advanced data assimilation techniques and better initial conditions (inclusion of satellite data and other available observation) could also help to improve the model forecast of such extreme rainfall events.

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