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Analysis of the 26 July 2005 heavy rain event over Mumbai, India using the Weather Research and Forecasting (WRF) model

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ABSTRACT: A case-study of the 26 July 2005 Mumbai heavy-rain event that recorded 944 mm rainfall in 24 h with significant spatial variability was carried out using the Weather Research and Forecasting (WRF) model. The event was poorly forecasted by operational models and resulted in large human and economic losses. The present results indicate that the WRF system was able to reproduce the heavy rainfall event and the associated dynamical and thermo- dynamical features. A number of experiments were conducted with the WRF model that suggest the highly localized, heavy rain was the result of an interaction of synoptic-scale weather systems with the mesoscale, coastal land-surface features. These experiments indicate that the large-scale rising motion over the Mumbai region was synoptically forced. Analysis of the model-simulated intense, but short-lived, convective rain cells forming in the large-scale rising motion over Mumbai traces their moisture source to the north and northwesterly flow from the Arabian Sea. Synthetic sensitivity simulations without topography and without a land surface (land replaced with water) show that the large-scale synoptic flow positioned the low-pressure system over the Arabian Sea, while the mesoscale land-surface (including topography and latent heating) feedback modulated the location and intensity of the rain by changes in the winds and regional moisture convergences. Another important feature captured in the high-resolution model analysis is the formation of a mesoscale vortex over Mumbai that appears to have enhanced the conditions for localized, heavy rainfall over Mumbai. Copyright © 2008 Royal Meteorological Society

KEY WORDS Western Ghats; mesoscale model; land surface processes; Indian summer monsoon

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1. Introduction

On 26 July 2005, an official India Meteorological Department (IMD) rain-gauge at Santacruz International Airport (19.11 °N, 72.85 °E) on the north side of the metropolis Mumbai (18 °56′N, 72 °51′E), located on the west coast of India, recorded a 944 mm 24 h accumulated rainfall (0300 UTC 26 July to 0300 UTC 27 July 2005). Mumbai, influenced by the Western Ghats mountains that run parallel to the Indian coast, normally receives heavy rainfall during the summer monsoon; however, several features make the 26 July 2005 event unique. First, the rainfall amount of 944 mm is thus far a record amount for a single-day rain event for a megacity (population over 10 million) such as Mumbai[†]. Second, it exceeds some of the heaviest single-day rainfall amounts over the Western Ghats region and Mumbai (Santacruz) such as 375 mm on 5 July 1975, 318 mm on 23 September 1981, 399 mm on 10 June 1991 and 346 mm on 23 August 1997 (Jenamani et al., 2006). Third, the rainfall was highly localized with the majority of the rain occurring over northern Mumbai with no comparable amounts occurring in the surrounding region. An IMD observatory in northern Mumbai (Santacruz) showed 944 mm of rain, while the other official observatory about 27 km away in southern Mumbai (Colaba) received only 73 mm of rain for the same event. Another feature which makes this event interesting is the availability of observations from *in situ* and satellite sources, such as the Tropical Rainfall Measuring Mission (TRMM). Further, the operational models were unable to simulate the magnitude, location and extent of such heavy rains, making the study of the processes associated with this event additionally important (Bohra et al., 2006; Sikka and Rao, 2008).

Several factors have been identified that can potentially affect the timing, location, and intensity of heavy rains during an Indian monsoon. The strong winds of the southwest monsoon (Somali Jet), carrying the moisture-laden monsoon air from the Arabian Sea, are orographically lifted when they encounter the Western Ghats (Sarker, 1967; Saha, 1974). Grossman and Durran (1984) concluded that the Western Ghats are capable of

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[†] Mumbai is the most populated city and the commercial capital of India; this rain event caused 409 deaths and an unprecedented loss of $1 billion to the socio-economic sector (Jenamani et al., 2006).

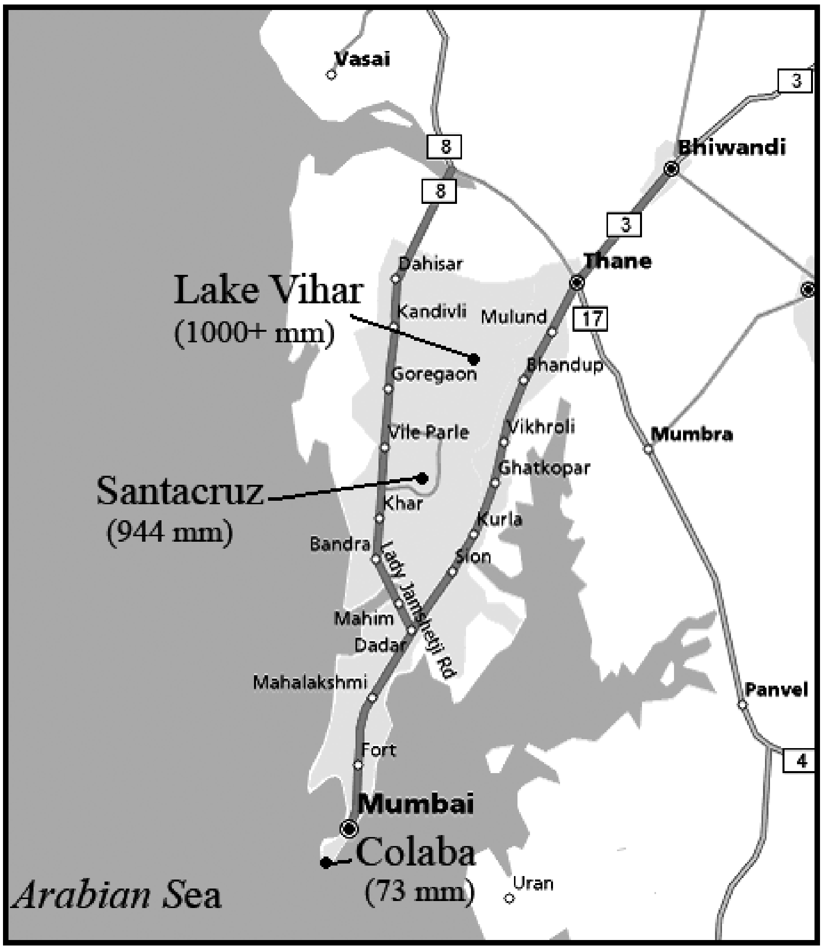

Figure 1. Accumulated 24 h rainfall from rain-gauges across Mumbai and vicinity. Colaba and Santacruz are the official India Meteorological Department observation sites.

producing deep convection far offshore (50–200 km) by lifting potentially unstable air as it approaches the coast. Smith (1985) suggested that the Western Ghats can cause convection initiation due to orographic lifting and due to the differential heating over the mountain slope. The heavy rainfall over Mumbai and other locales in the Western Ghats is a combination of a number of features such as the northwestward movement of low-pressure systems from the Bay of Bengal along the monsoon trough, the increasing southwesterly monsoon strength over the Arabian Sea, and the presence of a northward-moving mesoscale offshore vortex over the northeast Arabian Sea (Asnani, 2005, p. 109). Initial analysis of the mesoscale and synoptic features associated with the 26 July 2005 event suggest that the localized, heavy-rain event was also a product of the various features acting in tandem from the synoptic scale to the mesoscale.

A number of modelling studies have been recently performed for the 26 July 2005 Mumbai heavy-rain case (Sikka and Rao, 2008). For example, Vaidya and Kulkarni (2006) used the non-hydrostatic Advanced Regional Prediction System (ARPS) mesoscale model with a 40 km grid resolution and studied the impact of domain size and boundary conditions. Several features of the rainfall event were successfully captured but the model did not simulate the heavy rain amounts over Mumbai. Another modelling study for the same case was done with the Weather Research Forecasting (WRF) model by Rama Rao et al. (2007) with a 20 km horizontal grid resolution. The model was able to simulate approximately 250 mm of rain with a location error of 50 km north of Santacruz, Mumbai. Chang et al. (2008) also used the WRF model to simulate this event and concluded that the simulation of heavy rains over Mumbai is highly sensitive to the model resolution (grid size), and the amount and location of the rainfall was modulated by land surface feedbacks which affected the formation and intensity of rain-producing convection cells. In a follow-up study, Lei et al. (2008) used an explicit urban energy balance model to simulate the Mumbai urban heat island and the TRMM-prescribed sea-surface-temperature (SST) fields in the Regional Atmospheric Modeling System (RAMS). Their results suggest that the heavy rains were a result of a stationary convergence zone caused by SST gradients just off Mumbai and the sensible-heat flux gradients due to the urban heating over Mumbai.

In this study, we attempt to identify and understand the various small- to large-scale dynamical interactions such as formation of convective cells to large-scale wind

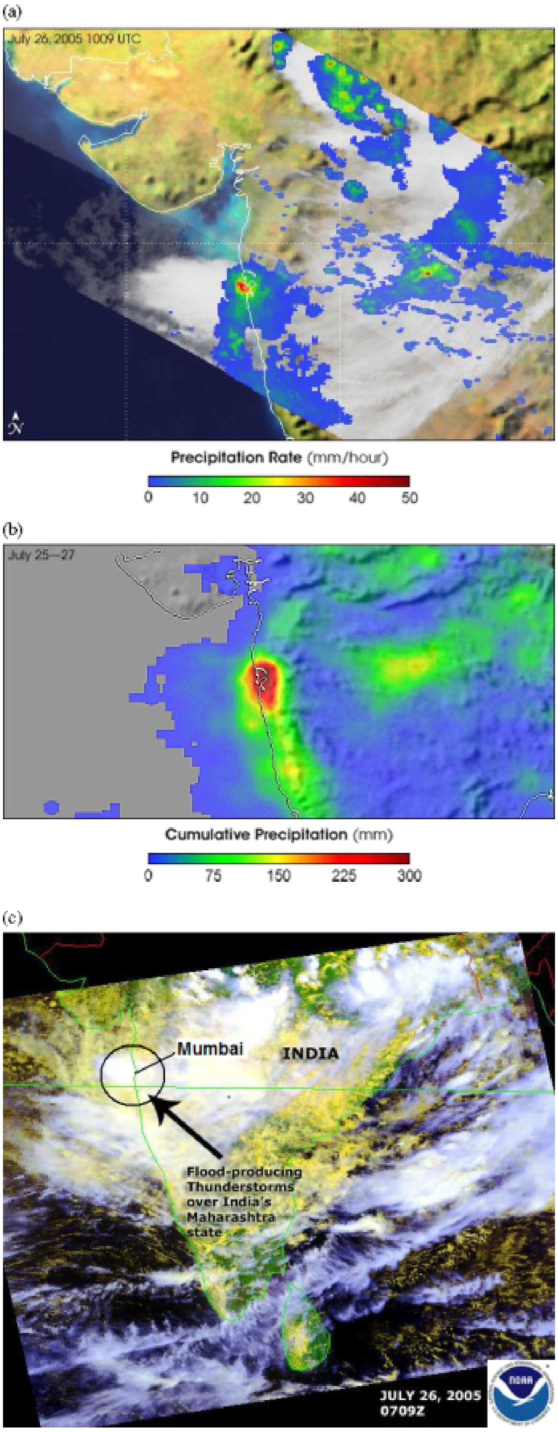

Figure 2. (a) TRMM (Tropical Rainfall Measurement Mission) rainfall rate for 26 July 2005. The rainfall rate in the centre part of the swath is from the TRMM Precipitation Radar, and in the outer swath from the TRMM Microwave Imager. (b) TRMM estimated rainfall accumulated total for 25–27 July 2005. (c) NESDIS satellite imagery at 0709 UTC on 26 July 2005. This figure is available in colour online at www.interscience.wiley.com/journal/qj

circulations that resulted in the localized heavy precipitation over Mumbai. A secondary objective is to test the Weather Research and Forecasting (WRF) model at high resolution (grid spacing of 3.6 km) to simulate this tropical heavy-rain event which the present operational systems failed to predict. The paper is structured as follows: in the following section 2, we summarize the rainfall observations for this event. Section 3 describes the WRF model set-up and its characteristics. Model verification is discussed in section 4. Section 5 describes the model sensitivity tests. Conclusions are presented in section 6.

2. Characteristic features of the 2005 Mumbai rainfall event

The rain-gauge observations compiled from different networks across Mumbai are shown in Figure 1. The 24 h rainfall ending 0300 UTC on 27 July 2005 at India Meteorological Department (IMD) observatories are 944 mm at Santacruz (19.11°N, 72.85°E) in north Mumbai and 73 mm over Colaba (18.93°N, 72.85°E, 27 km south of Santacruz). The non-IMD gauge-recorded rainfall recorded for this event was 1049 mm at Lake Vihar (located about 15 km northeast of Santacruz). Both the measurements as well as the observed accounts indicate that northern Mumbai received torrential rain while southern parts of the city remained relatively dry. On 26 July 2005, the TRMM satellite also captured the rainfall over Mumbai (Figure 2(a)) at 1539 local time (1009 UTC). As seen in Figure 2(a), a dark area representing the heavy precipitation zone is concentrated over Mumbai. Figure 2(b) shows the rainfall accumulation from 25 to 27 July 2005. Both images show the localized and intense nature of this rainfall event. NOAA's National Environmental Satellite, Data, and Information System (NESDIS) satellite imagery (Figure 2(c)) indicated a cloud-cluster over Mumbai at 0709 UTC on 26 July 2005. The existence of a cloud-cluster with possible vortices over Mumbai on 26 July was also inferred by Shyamala and Bhadram (2006) based on analysis of soundings and satellite datasets. The ground-based radar observations (not archived) at 09 UTC 26 July provide evidence of intense convective cells about 40 km north of Santacruz, Mumbai with the formation of a vortex along the Mumbai coast at 16 UTC 26 July (Kumar et al., 2007).

The observed soundings over Mumbai (available from University of Wyoming http://weather.uwyo.edu/upperair/sounding.html) are shown in Figure 3(a)–(c). The sounding at 12 UTC on 25 July shows that the atmosphere is saturated near the surface and relatively dry between 700 and 500 mb (Figure 3). The sounding at 00 UTC on 26 July (Figure 3(b)) shows dryness at mid-levels. However, the later sounding (Figure 3(c)) over Mumbai suggests that the atmosphere is saturated, but no data was recorded above 550 mb at the Santacruz station. Figure 3(d) shows our model-based sounding (discussed below) for 12 UTC on 26 July, which also indicates a saturated atmosphere up to 500 mb.

The surface wind from the National Centers for Environmental Prediction (NCEP) reanalysis data shown in Figure 4(a) suggests a strong low-level westerly flow over Mumbai with 5 m s^{-1} wind speed and a depression forming over the east coast of India at 00 UTC 26 July 2005. The 850 mb and 500 mb wind analyses

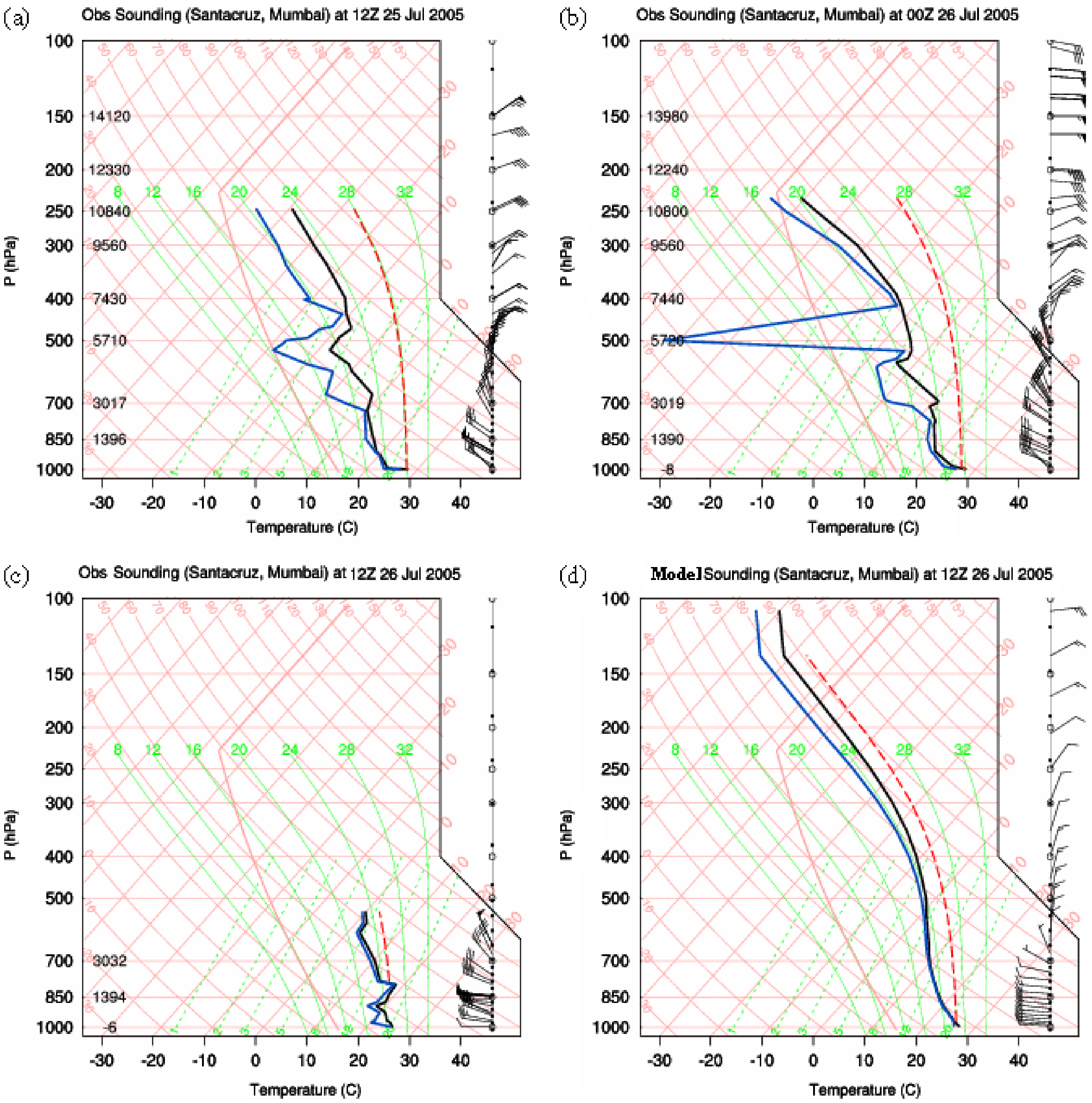

Figure 3. Observed sounding over Mumbai at (a) 1200 UTC 25 July 2005, (b) 0000 UTC 26 July 2005 and (c) 1200 UTC 26 July 2005. (d) Model sounding for 1200 UTC 26 July 2005. This figure is available in colour online at www.interscience.wiley.com/journal/qj

(Figure 4(b)–(c)) obtained from the NCEP global analysis data also show a zone of low-level westerly flow over Mumbai (Figure 4(b)) and strong large-scale upper-level circulation (Figure 4(c)). These features are further investigated using the WRF model simulations and are discussed in the following section.

3. Model description and experimental design

The numerical simulations are carried out using the Weather Research and Forecasting (WRF) model Version 2 (Release 2.1, August 2005). The WRF model is a fully compressible non-hydrostatic, primitive-equation model with multiple-nesting capabilities to enhance resolution over the areas of interest. This version of the WRF model uses the Eulerian mass coordinate and is referred to as the Advanced Research WRF (ARW). For the present study, three nested domains are configured as shown in Figure 5(a). Domain 1 is the coarsest mesh and has 202 × 162 grid points in the north–south and east–west directions, respectively, with a horizontal grid spacing of 33 km. Within Domain 1, Domain 2 is nested with 397 × 319 grid points at 11 km grid spacing. Domains 1 and 2 run together with a two-way nested interaction. The fine-mesh Domain 3 is 397 × 382 points with 3.6 km grid spacing and uses a one-way interaction for computational efficiency. All domains are centred over Mumbai to represent the regional-scale circulations and to resolve the complex flows in this region. The topography, including the location of the Western Ghats in Domain 3, is shown in Figure 5(b).

All the simulations use the same initial and boundary conditions as derived from the NCEP 6-hourly FNL (Final) 1-degree analysis (cf. Vaidya and Kulkarni, 2006). These analyses are interpolated to the WRF-model grid

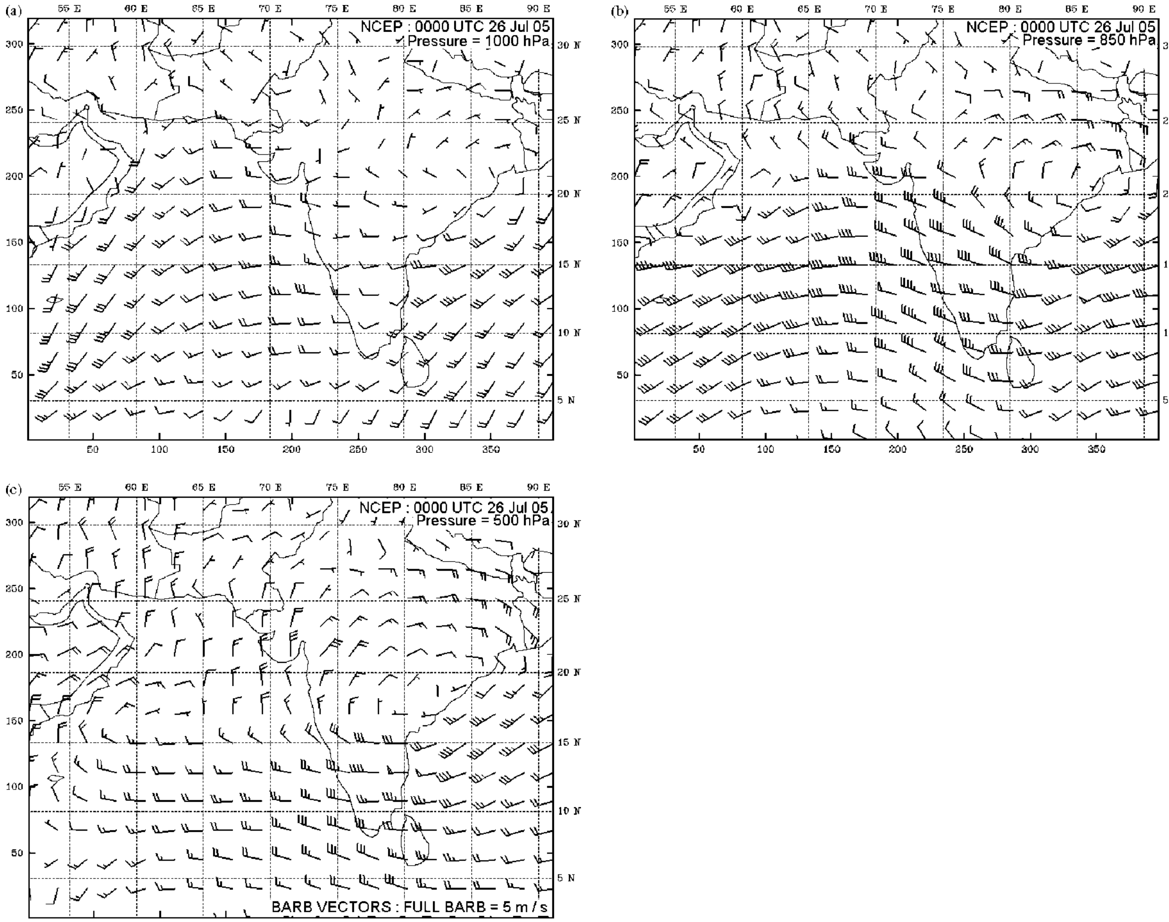

Figure 4. NCEP analysis valid 0000 UTC 26 July 2005 for winds at (a) 1000 mb, (b) 850 mb, and (c) 500 mb.

to provide the initial conditions for 0000 UTC 24 July 2005, as well as 6-hourly lateral boundary conditions for the 33 km domain. The 11 km grid obtained its initial and boundary conditions from the 33 km Domain 1 and provided feedback to the 33 km domain during the nested run. The model simulations over Domains 1 and 2 started at 0000 UTC 24 July 2005 and are integrated for 120 h ending at 0000 UTC 29 July 2005. Model simulation for Domain 3 started from the interpolated Domain 2 output at 1200 UTC 25 July 2005 and ended at 1200 UTC 27 July 2005. This model configuration is referred to as control-run (CTRL).

Numerical experiments are conducted to investigate the relative roles of the large-scale processes and the impact of topography, and land–ocean contrast. To assess the role of topography in this heavy rainfall event, one experiment sets the land surface to a uniform height at sea level. To test the effect of the land–ocean heating contrast, another experiment replaces the land mass with water having a sea surface temperature (SST) set to 301.2 K (representative of the Arabian Sea SST).

3.1. Microphysics and cumulus parametrization

The simulations used the WRF Single-Moment (WSM) 6-class graupel scheme (Hong et al., 2004). This scheme consists of ice, snow, and graupel processes suitable for high-resolution simulations. The Grell–Dévényi (GD) (Grell and Dévényi, 2002) ensemble cumulus parametrization scheme was used for Domain 1 and Domain 2 (in the control simulation). The GD scheme is based on a multi-closure, multi-parameter, ensemble method with the usual 144 subgrid members. The fine-mesh domain is run with the microphysics scheme (WSM6) and without any convection parametrization. The 5-layer thermal diffusion option with prognostic soil temperature and land-use-dependent soil-moisture availability represented the land surface. The Rapid Radiative Transfer Model (RRTM) scheme was chosen for long-wave radiation with the Dudhia (1989) scheme for short-wave radiation.

Sensitivity simulations were performed with different cumulus schemes (for Domains 1 and 2). With the GD scheme, the simulated precipitation was closest to the observed rainfall over Mumbai (as shown in the following section). The Kain–Fritsch (KF) (Kain and Fritsch, 1990, 1993; Kain, 2004) and Betts–Miller–Janjić (BMJ) (Janjić, 1994, 2000) schemes considerably underestimated (by greater than 50%) the rainfall for this case (not shown). This discrepancy highlights the variability in the model results, in particular, the uncertainty associated with the convection parametrizations for simulating such an extreme precipitation event.

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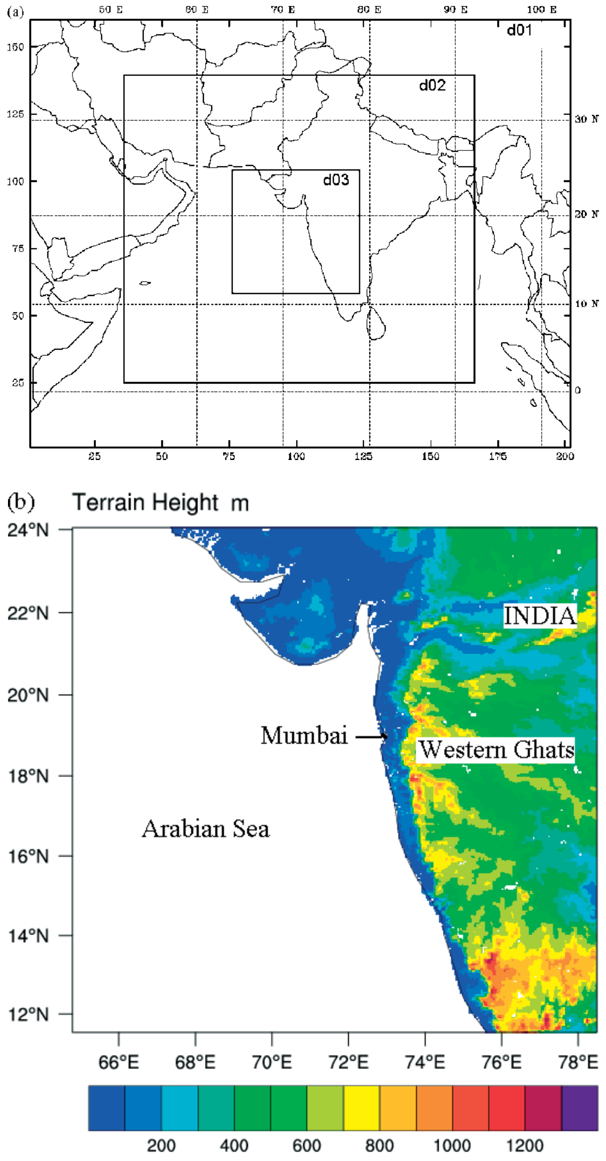

Figure 5. (a) Weather Research and Forecasting (WRF) model domains used in this study. (b) Map showing topography and the location of Mumbai, Arabian Sea and Western Ghats in the innermost Domain 3. This figure is available in colour online at www.interscience.wiley.com/journal/qj

4. Results

4.1. Rainfall

The distribution and amount of model precipitation is a difficult quantity to verify, particularly for this rain event with its extreme spatial heterogeneity and the limited number of available observations. After confirming that the model results showed reasonable precipitation, the discussion centres on the processes related to the model-produced precipitation.

The WRF-model-simulated 24 h rainfall amounts for 26 July 2005 are shown in Figure 6(a)–(c). Figure 6(a) shows model-simulated total 24 h rainfall in Domain 2 at 11 km resolution. In addition to the heavy rain over Mumbai, the model also shows rainfall associated with large-scale processes such as low pressure over the Bay of Bengal region. Figure 6(b) shows the model rainfall in the innermost Domain 3. The simulated rainfall was smoothed to compare with the spatial variability seen in the TRMM image (Figure 2(b)) and is shown in Figure 6(c). A clear similarity exists between the modelled and the TRMM-observed rainfall patterns (i.e. Figures 2(b) and 6(c)). The majority of the heavy rain is offshore and over Mumbai along with a significant spread along the Western Ghats. The rain-gauge observations (Figure 1) showed large spatial variability between north (Santacruz) and south (Colaba) Mumbai. Figure 7(a) shows the temporal evolution of model and observed cumulative rainfall over the Santacruz and Colaba IMD recording stations along 72.5°E. Consistent with the observations, high rainfall values are seen in the vicinity of Santacruz (Figure 7(b)). In particular, the model successfully captured the record-breaking rainfall at Santacruz (which has not been simulated well in prior studies). The distribution and evolution of modelled precipitation are generally consistent with rain-gauge and satellite estimates. The simulations indicate that the rain started in the southern region of the Western Ghats and moved northwards concentrating on Mumbai (not shown).

4.2. Winds

Model-simulated surface winds at 0000 UTC 26 July are shown in Figure 8(a), and are similar to the NCEP surface winds (Figure 4(a)). Figure 8(b)–(c) shows the winds at 0000 UTC 26 July at 850 mb and 500 mb pressure levels. A low-pressure system in the northern Bay of Bengal (eastern India) is visible near 20°N latitude where a confluence of easterly winds with low-level westerly winds from the Arabian Sea occurs over Mumbai. This synoptic-scale feature is similar to that obtained in the NCEP reanalysis data (Figure 4(b)–(c)). The differences are primarily due to the higher resolution configuration of the WRF runs as compared to the analysis. Further review of the control-run (CTRL) precipitation for Domain 2 indicates that in addition to the synoptic pattern and the confluence of moisture-laden low-level westerly and northwesterly winds, the rainfall over Mumbai coincides with strong convective cells that evolved in the mesoscale confluence of air streams from the northwest, north, and northeast directions. Figure 9(a)–(c) shows the 925 mb streamlines at 0600 UTC 26 July, 1200 UTC 26 July and 0000 UTC 27 July, illustrating the development of an offshore vortex. This offshore mesoscale vortex appears to have resulted from a convective latent-heating feedback process. To confirm this we conducted a separate model run in which latent heating was switched off. Results show that there is no mesoscale vortex embedded within the onshore large-scale flow (not shown) when latent heating is turned off. The occurrence of this vortex is significant both in terms of its timing – which corresponds to the heavy-rain events; and its rarity – as Francis and Gadgil (2006) suggest that only 1% of heavy-rain events over western India are associated with a mesoscale offshore vortex.

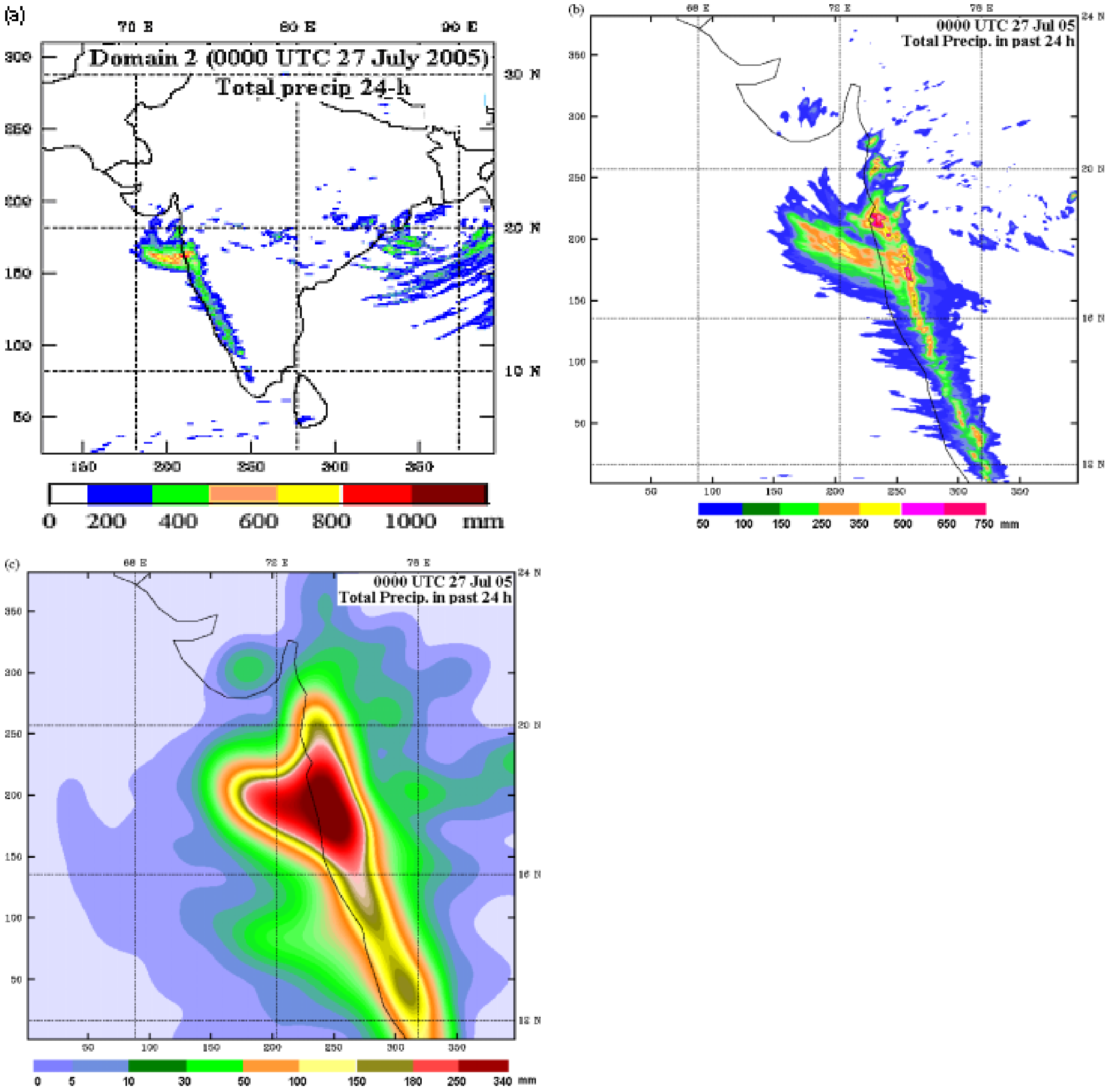

Figure 6. Simulated 24 h accumulated rainfall for 26 July 2005, (a) in Domain 2 at 11 km resolution, (b) at 3.6 km resolution, (c) smoothed version for comparison with the TRMM imagery (Figure 1(a)–(b)). This figure is available in colour online at www.interscience.wiley.com/journal/qj

4.3. Large-scale forcing

Previous studies for heavy rains over Mumbai and along the Western Ghats region suggest that Western Ghats topography, in conjunction with large-scale features such as the Somali Jet and Tropical Easterly Jet, can result in rainfall rates of 100–200 mm d^{-1} during the summer monsoon (Ogura and Yoshizaku, 1988). Here, analysis using the quasi-geostrophic ω-equation and Q-vectors was pursued to understand the large-scale forcing of vertical motion over the Mumbai region

The Q-vector representation of the quasi-geostrophic equation of motion on the β-plane (Hoskins et al., 1978) can be written as

$$\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p}\right)\omega = -2\nabla_p.Q,$$

where

$$Q = \frac{R}{\sigma p}\begin{pmatrix}\frac{\partial V_g}{\partial x}.\nabla_p T\\ \frac{\partial V_g}{\partial y}.\nabla_p T\end{pmatrix} = \begin{pmatrix}Q_1\\ Q_2\end{pmatrix}.$$

Q_1 represents the change in $\partial T/\partial y$ owing to horizontal shear, and Q_2 represents change in $\partial T/\partial y$ due to shrinking in a natural coordinate system in which x and y represent the along- and cross-front directions, respectively (Bluestein, 1992, p.357). Figure 10(a)–(b) shows the geostrophic wind vectors along with geopotential height and potential temperature gradients for the 850 mb pressure levels valid at 2100 UTC 26 July. This analysis is performed for Domain 2. As seen in Figure 10(a), the solution of the omega equation indicates that the area over Mumbai has intense negative ω values (indicative of rising motion) at the 850 mb levels. Figure 10(b) indicates Q-vector convergence and hence a negative ω and a rising motion. The generally westward Q-vector at the

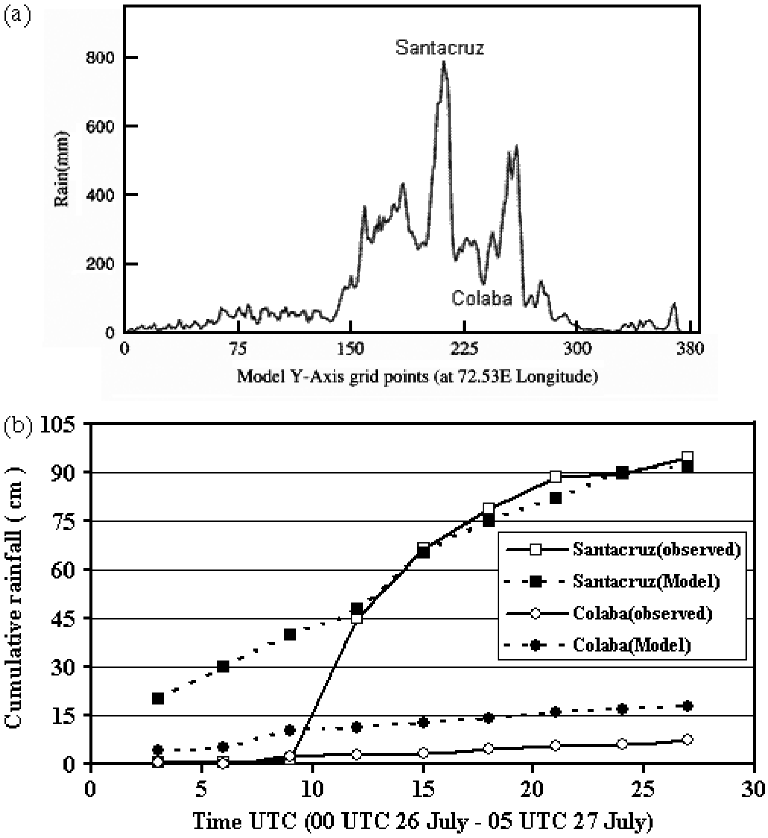

Figure 7. (a) North–south gradient of rainfall distribution over Mumbai (x-axis: grid points) and (b) comparison of observed and simulated 3-hourly interval cumulative rainfall (in mm) over Santacruz and Colaba on 26 and 27 July 2005.

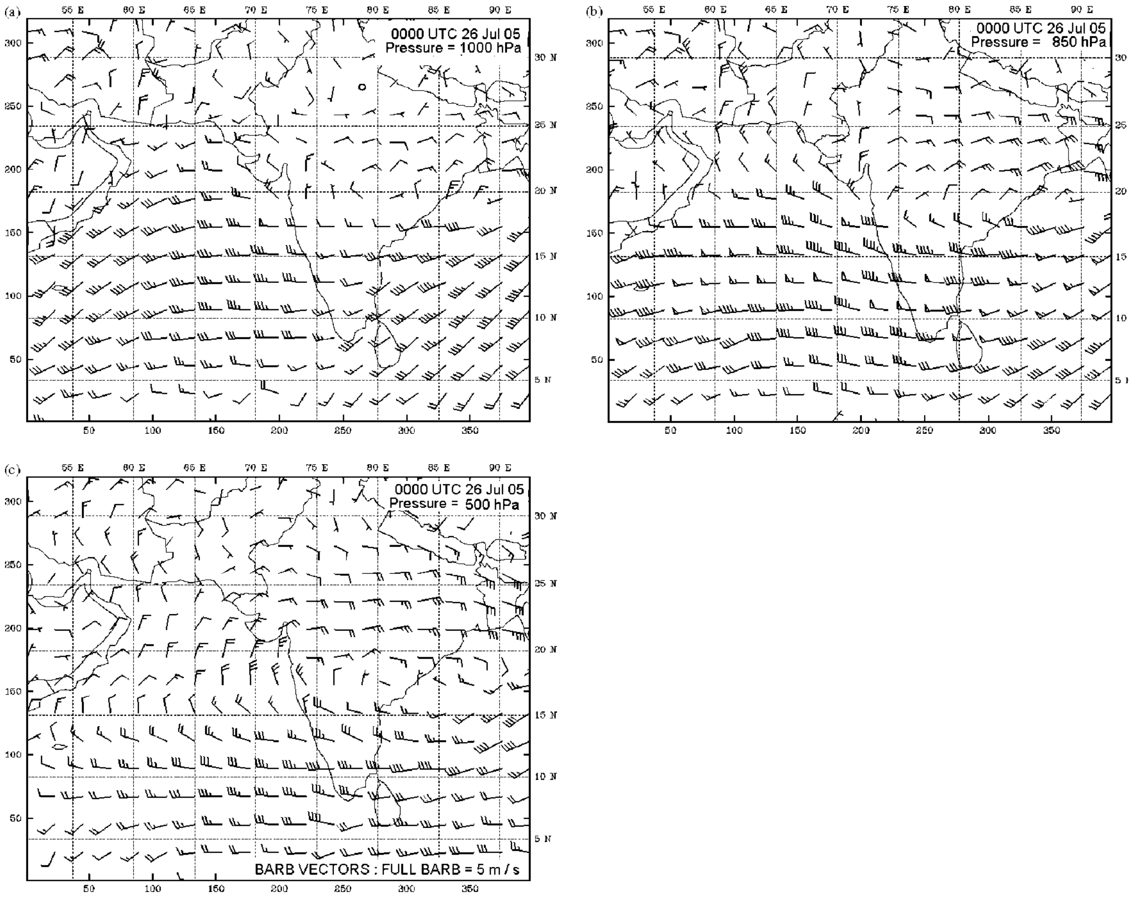

Figure 8. Model-simulated winds for 0000 UTC 26 July 2005 at (a) 1000 mb, (b) 850 mb, and (c) 500 mb.

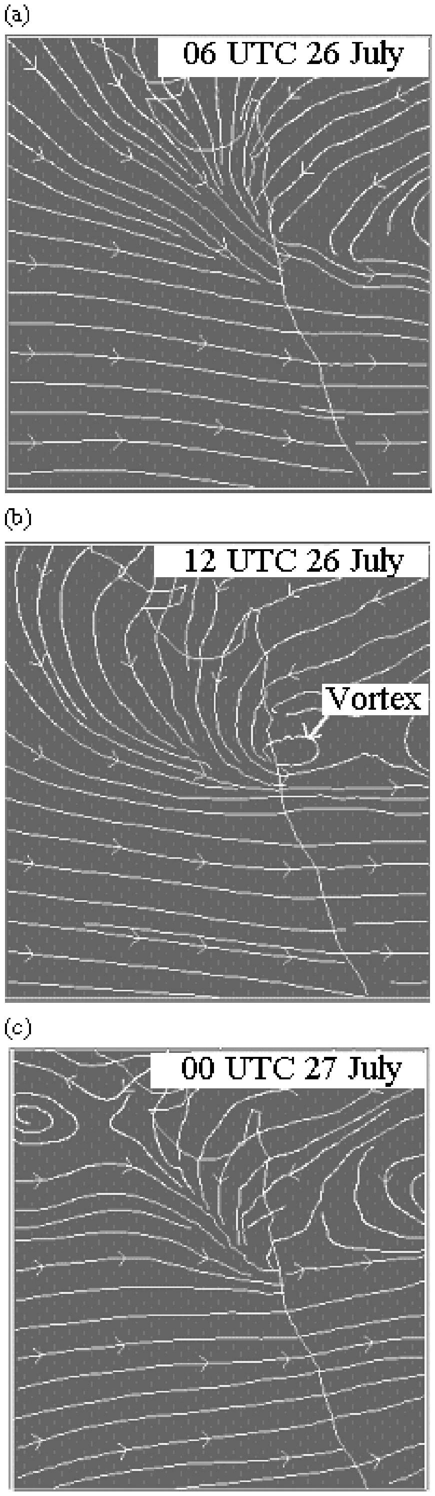

Figure 9. Model horizontal streamlines at 925 mb for (a) 0600 UTC 26 July, (b) 1200 UTC 26 July, (c) 0000 27 July 2005. The streamlines show the evolution of a low-level vortex near Mumbai.

low centre is due to shearing deformation associated with a south to north temperature gradient. The northeasterly Q-vector is due to frontogenesis.

4.4. Analysis of moisture source and wind trajectory

To understand the moisture supply for the intense rainfall periods, we examine in Figure 11(a)–(b) the wind

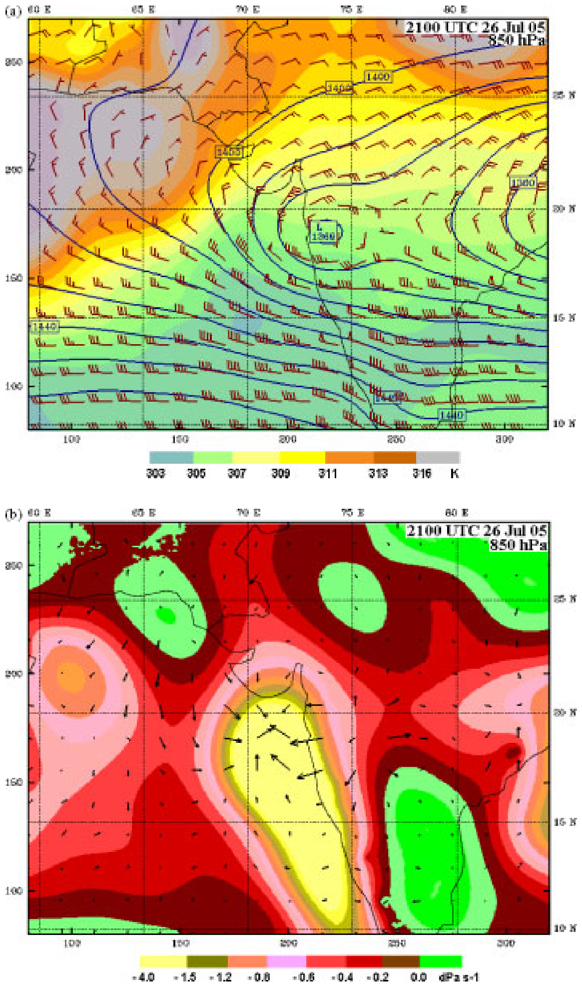

Figure 10. (a) Geostrophic wind vectors V_g (m s^{-1}), geopotential heights Φ, and potential temperature (K) at 850 mb, and (b) quasi-geostrophic omega (dPa s^{-1}) and Q-vectors (m s^{-3} mb^{-1}) at the 850 mb level. This figure is available in colour online at www.interscience.wiley.com/journal/qj

vectors at 1000 and 850 mb together with the hourly rain at 1200 UTC 26 July 2005. These figures indicate that the low-level flow is generally from the north and northwest and veers to northerly with height over Mumbai. The confluence of these two flows near Mumbai helps create the synoptic set-up for the heavy rainfall over Mumbai. Figure 11(a)–(b) also shows that intense rain cells form north of and over Mumbai with rain rates of approximately 85 mm h^{-1}. Figure 11(c)–(d) shows that at the later time (2300 UTC), the low-level winds are northerly towards Mumbai and that a mesoscale vortex is developing (Figure 11(d)) with associated heavy rainfall (150 mm h^{-1}). The final, very localized, rainfall maximum at Mumbai in the simulation resulted from several cells that formed in the same area due to the slow motion of the large-scale system in which the convective cells were embedded.

To determine the rain-cell moisture source supply, we conducted backward trajectory analysis from the core of a typical intense rain cell. Figure 12(a) shows the horizontal path followed by two parcels making the ascent into the updraughts shown in the vertical cross-section indicated

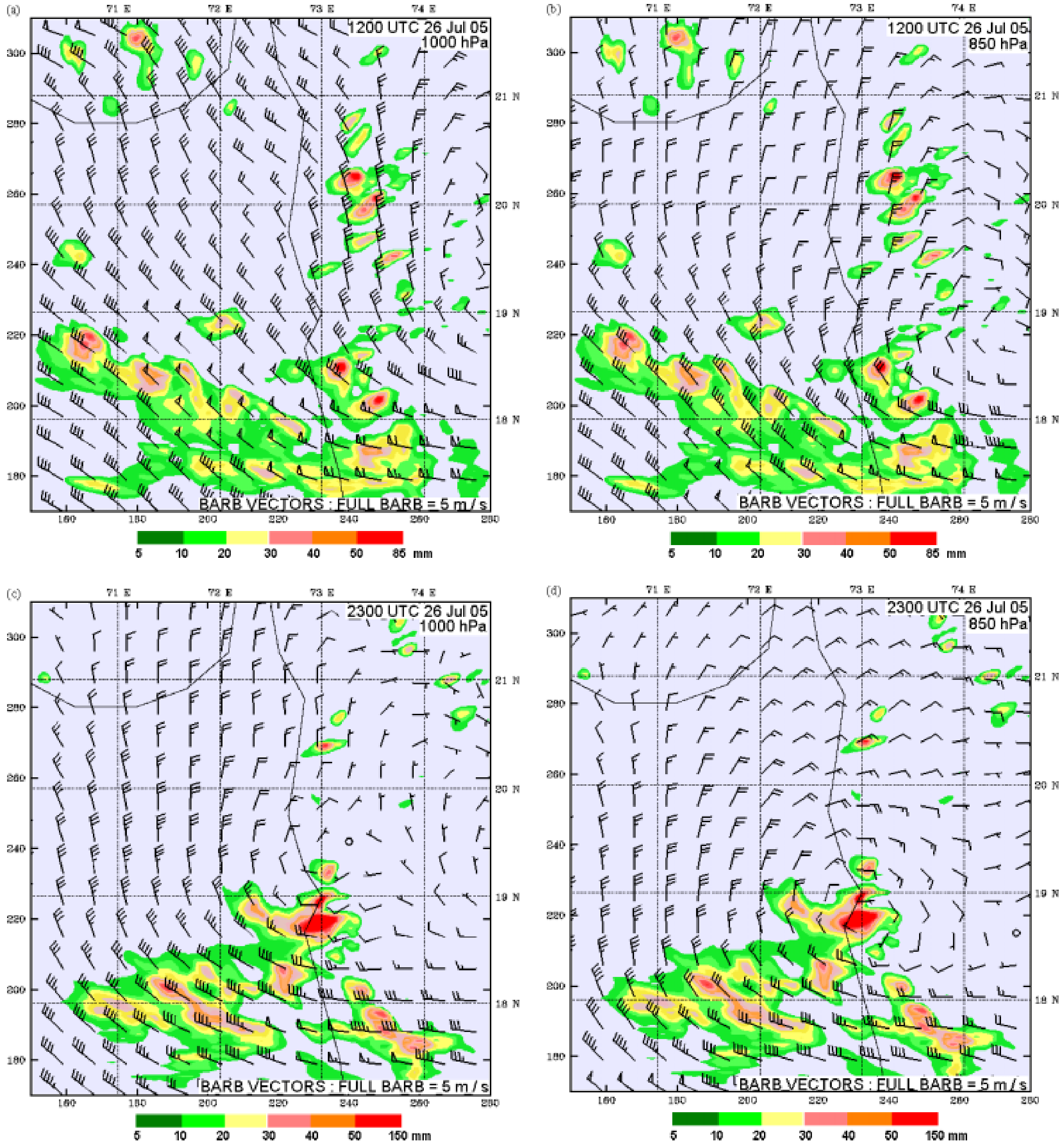

Figure 11. Wind vectors and 1-hourly rain accumulation at 1000 mb and 850 mb levels at (a)–(b) 12 UTC 26 July and (c)–(d) 23 UTC 26 July 2005. This figure is available in colour online at www.interscience.wiley.com/journal/qj

by the line AB, and shown in Figure 12(b). Two backward trajectories are computed (in Figure 12(b)), one from the core region of the cloud (labelled '1') and the other from the periphery of the cloud (labelled '2'). The figure shows that both parcels condensed a large amount of water vapour during their ascent. Tracing these parcels backward in Figure 12(a) shows that these moisture-laden air parcels originated from the northwest direction.

Hence we conclude that the moisture source originates at low-level with confluence of north and northwesterly flow traversing the Arabian Sea. The analysis shown in Figure 11(d) also indicates that the enhanced mesoscale vortex was associated with convective rain cells over the general vicinity of the west coast of India.

One of the intriguing features of this rain event was the high spatial variability in the rainfall intensity and amounts. That is, Santacruz received 944 mm rainfall while Colaba which is 27 km away received only 73 mm. To diagnose this, we investigated the changes in the critical levels – where winds shift from westerly at lower levels to easterly at higher level – over the innermost model domain. A time-varying cross-section of winds over Santacruz and Colaba was analysed. Figure 13(a) is a time cross-section of the wind vector over Santacruz which shows that the critical level has lowered from 600 mb to 900 mb over the heavy-rain region and forms a strong convergence zone with high surface moisture. With passage of time, this convergence intensified and the surface

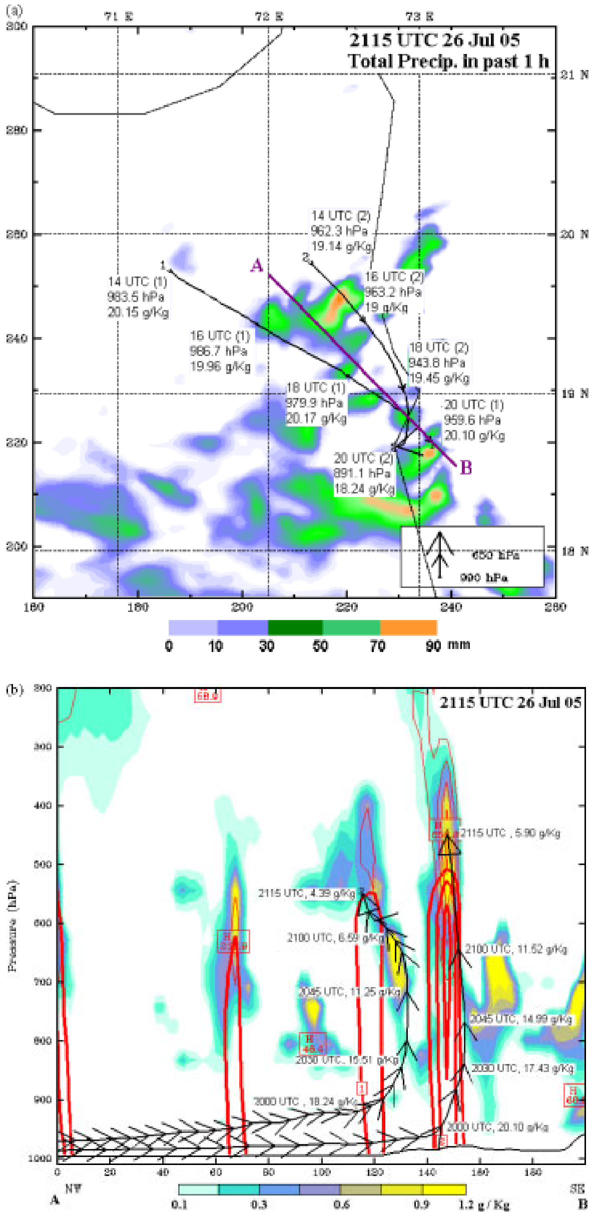

Figure 12. (a) Trajectory and hourly rain at 2115 UTC 26 Jul 05. Trajectories are marked with time (UTC), pressure level (mb) and water vapour mixing ratio (g kg^{-1}) respectively. (b) Vertical cross-section on line AB (marked in Figure 12(a)); colour shades represent cloud mixing ratio (g kg^{-1}), thin red line for high vertical velocity, thick red line for rain water mixing ratio (g kg^{-1}) and trajectories 1 and 2 are marked with time (UTC) and water vapour mixing ratio (g kg^{-1}). This figure is available in colour online at www.interscience.wiley.com/journal/qj

moisture fields also increased (Figure 13(c)). Over Colaba (Figure 13(b)), strong easterly winds are dominant, overlaying low-level westerly winds. There is no significant critical level or convergence zone over Colaba, and the surface moisture values are also smaller as compared to over Santacruz (Figure 13(d)). Figure 13(c)–(d) also shows the temperature distribution, with higher temperature (∼2 K) over Santacruz as compared to Colaba station. Comparing these features, we conclude that lower critical level, larger wind speeds, and the well defined confluence zone all together helped concentrate the heavy rains over Santacruz. The strong easterly winds and the absence of a confluence zone or low-level westerly winds throughout the rain episode led to lowered rainfall over Colaba, even though the two locales were in relative proximity (27 km apart).

5. Sensitivity experiments

The relative roles of topography and the effects of land and ocean heating on regional circulation and the precipitation distribution over Mumbai are investigated next.

5.1. Effect of Western Ghats topography (NOTOPO)

The impact of the Western Ghats topography on the model results is evaluated in this synthetic NOTOPO case. For this run, the model configuration is identical to CTRL, except that the topography is eliminated and replaced by a constant value equal to the mean sea level. In the NOTOPO case, the model produced a 24 h accumulated rainfall of approximately 517 mm day^{-1} on 26 July (Figure 14(a)) at 3.6 km resolution in Domain 3. This is approximately half of the observed (or CTRL) rainfall. Additionally, in the NOTOPO case, the observed rain south of Mumbai along the western coast is poorly reproduced indicating that the rainfall in the southern Western Ghats was largely orographic in nature.

The confluence zone over Mumbai was weakened without the orographic feedback, but the synoptic-scale circulation and the low-level westerlies continued to contribute to the intense rainfall. As shown in Figure 14(b), a synoptic-scale low-pressure system still exists in the NOTOPO run which is similar to that in the CTRL case (Figure 11(a)) at 11 km resolution in model Domain 2. Thus, the large-scale dynamics and latent-heat feedback clearly played an important role in creating the heavy-rain event over the Mumbai region even in the absence of surface feedback due to orography.

5.2. Aqua India experiment (AQUA)

In the Aqua India experiment (AQUA), there is no land (or topography); the land is treated as water with a constant SST of 301.2 K (representative of the Arabian Sea SST). In this case, the model produces rainfall which is more widely distributed over Mumbai (Figure 15(a)) and much weaker than in CTRL (Figure 6(b)) in the innermost domain at 3.6 km resolution. The 24 h accumulated rain is about 239 mm over Mumbai, while the highest rainfall simulated during this case is 465 mm and much farther west than Mumbai. As also in the NOTOPO case, the observed rain features along the west and southern coasts of India are not reproduced in this case, further confirming that these features are likely orographic in nature. This AQUA case shows that the land–sea contrast is an important feature because without it, less than half of the rainfall was produced over Mumbai in this event. The interaction between the mesoscale and large-scale processes is also evident for this AQUA case as evidenced by similarity of the 850 mb fields shown in

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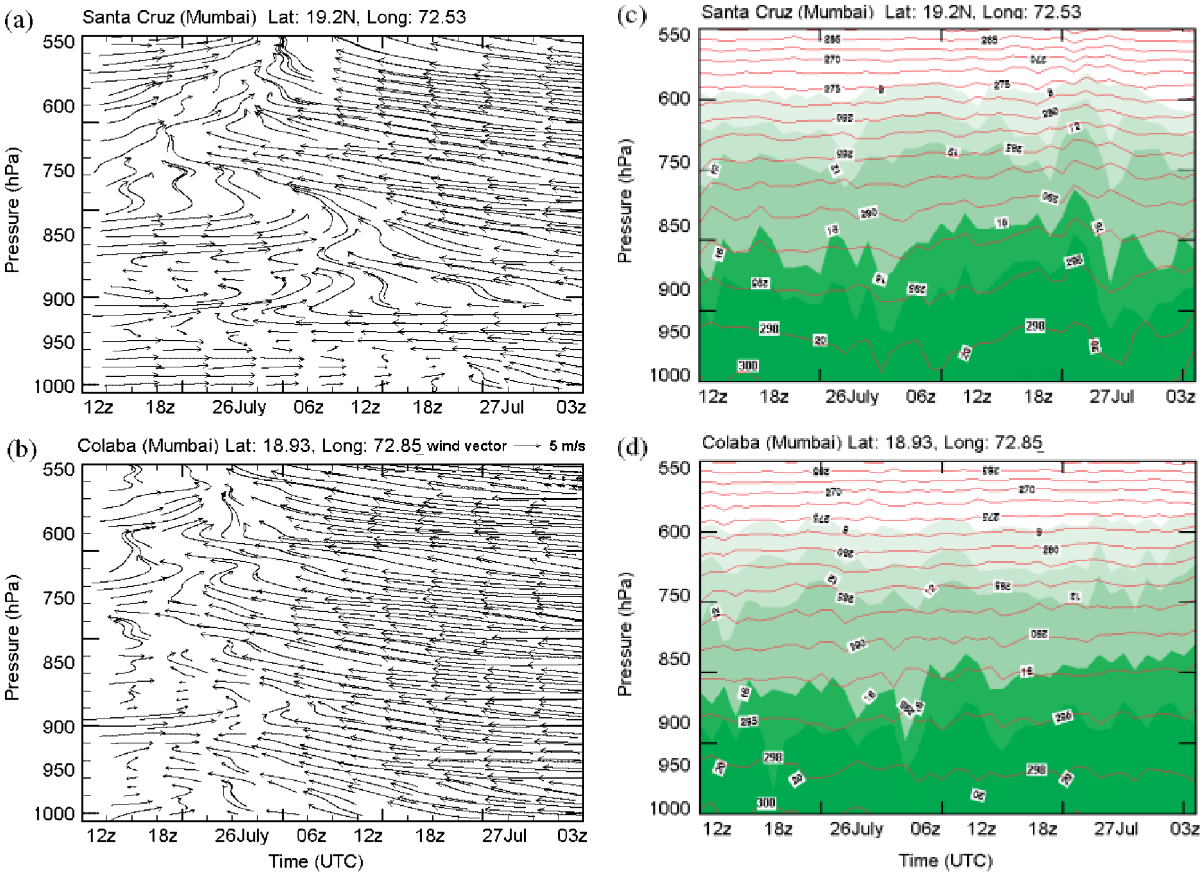

Figure 13. Time cross-section of wind vector (m s^{-1}) over station (a) Santacruz, (b) Colaba. Time cross-section of water vapour mixing ratio (g kg^{-1}) and temperature (K) over station (c) Santacruz and (d) Colaba. This figure is available in colour online at www.interscience.wiley.com/journal/qj

Figure 15(b) to those analysed in Figure 10(a) at 11 km resolution in model Domain 2. Hence, the continued presence of a large-scale rain feature in the absence of the land–sea or topography contrast shows that the *large-scale forcing* was not dependent on these factors and supports the purely dynamical explanation given in section 4.3.

6. Conclusions

This study presents an investigation of the unprecedented 26 July 2005 heavy rainfall event over Mumbai on the western coast of India. Several known meteorological factors contributed to the heavy rain over Mumbai, mainly (1) the development of a low-pressure area over the northwest Bay of Bengal, (2) the confluence of low-level moisture-laden north and northwesterly winds and a synoptic circulation from the northeast direction over Mumbai, (3) an anomalously strong north-to-south temperature gradient and locally high values of precipitable water, (4) a mesoscale offshore vortex near Mumbai, and (5) topography and other land surface feedbacks.

Features of the present study based on a high resolution model are:

1. The WRF-ARW with high resolution (3.6 km) set-up is able to simulate with reasonably good accuracy the amount, intensity, timing and distribution of this unusual rain event. The configuration details included 3.6 km grid spacing, 5-layer slab land surface model for surface energy balance, Grell–Dévényi ensemble scheme for convection (for the outer domain), and one-way nested domain.
2. The synoptic scenario, which created a geostrophic deformation for the temperature gradient, led to a Q-vector convergence suggesting a strong large-scale rising motion over Mumbai.
3. The simulation illustrates that in the region of large-scale rising atmospheric motion, heavy rains developed in the form of intense rain cells with rain rates of 150 mm h^{-1} that sequentially moved over Mumbai and led to high rainfall totals. Moisture was supplied from the Arabian Sea to the northwest.
4. An offshore mesoscale vortex formation over Mumbai is well captured in the model simulation that appears to have resulted from the combination of large-scale and convective-scale interactions off the west coast of India.
5. The present sensitivity experiments show that, in addition to strong large-scale rising atmospheric motion over Mumbai, the topography and the land–ocean differential heating enhanced the rain by over 50%.

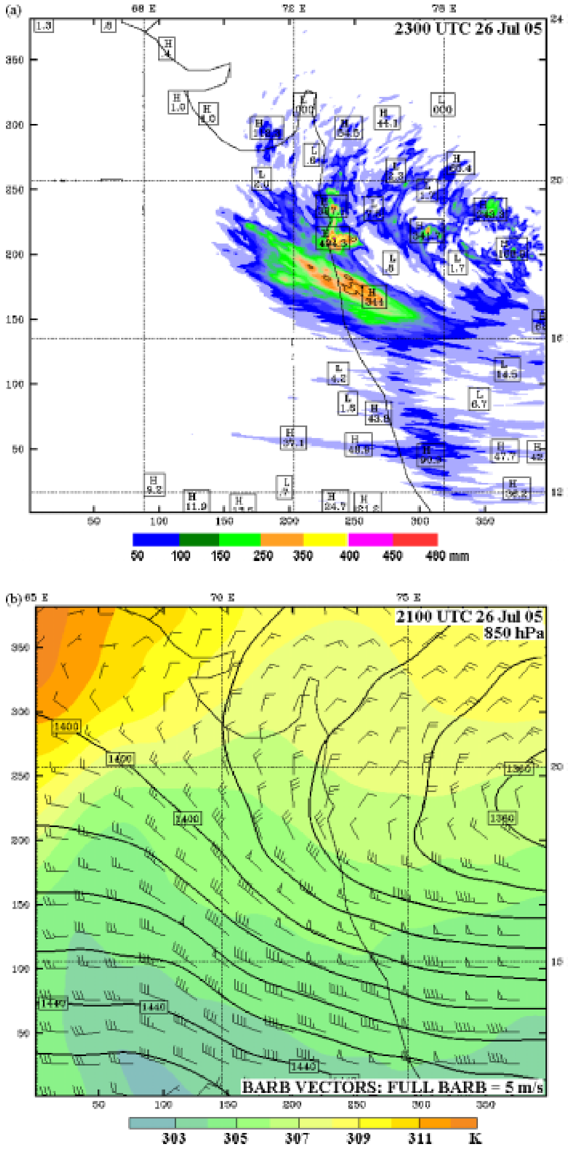

Figure 14. No-topography case (NOTOPO) showing (a) 24 h accumulated precipitation for 26 July 2005 and (b) geostrophic wind, geopotential height contours and potential temperature (K) at 850 mb level. This figure is available in colour online at www.interscience.wiley.com/journal/qj

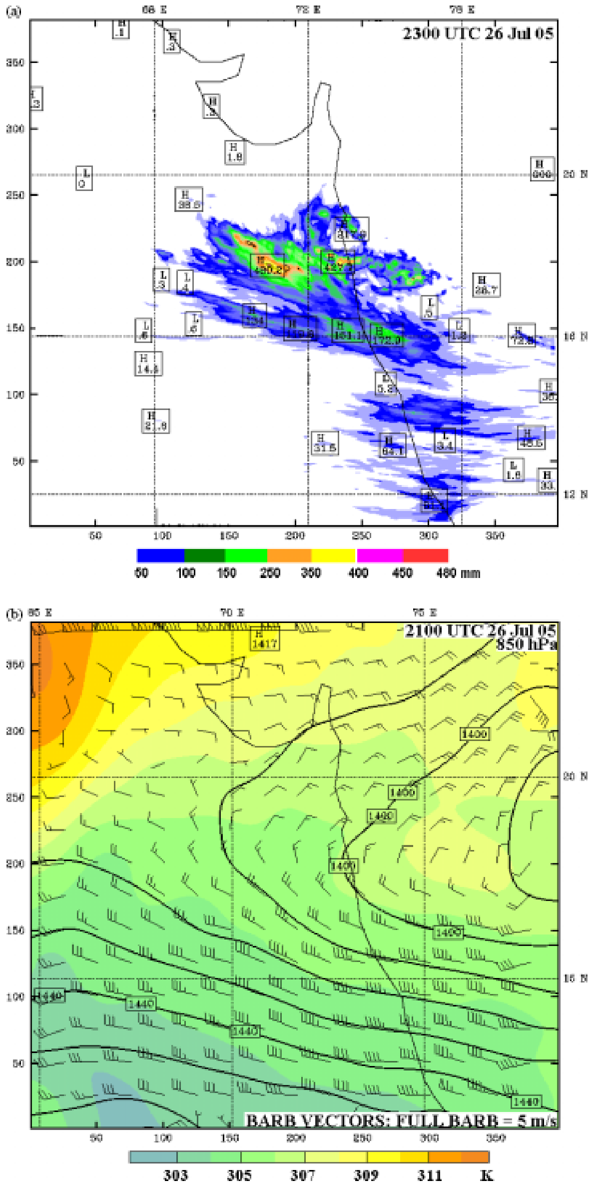

Figure 15. Same as Figure 14, except for the no-land case (AQUA). This figure is available in colour online at www.interscience.wiley.com/journal/qj

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