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Forecasting extreme precipitation event over Munsiyari (Uttarakhand) using 3DVAR data assimilation in mesoscale model

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A localized extreme precipitation event occurred over Munsiyari (Uttarakhand, India) on 2nd July 2018 causing flash floods, landslides and damage to the hydropower project. A preliminary study has been carried out by using Weather Research and Forecasting (WRF) model with three-dimensional variation data assimilation technique (3DVAR) to examine the feasibility of the model to predict the localized phenomena. Sensitivity experiments were carried out with two different microphysics in the model. Results show that P3 1-category plus double moment cloud water microphysics scheme with 3DVAR in WRF simulates the quantity of precipitation closer to the observed precipitation over Munsiyari. The vertical velocity and relative humidity were also simulated well during 3DVAR data assimilation as compared to without data assimilation over study region.

Keywords. Extreme precipitation; WRF; WSM6 and P3 microphysics; 3D-Var; Himalaya.

1. Introduction

Extreme precipitation events, now-a-days, have become more concern, particularly over the Indian Himalayan region in the context of present climate change and global warming. Study shows increase in temperature and decrease in precipitation over Western Himalayan region due to global warming and regional climate change (Shekhar *et al.* 2010). The source of many important rivers such as the Ganga and Yamuna, which feeds water to different parts of the country, it becomes necessary to predict the spatial as well as temporal spread of precipitation more accurately. The southern part of the Indian Western Himalaya and Central Himalaya experience enormous amount of rainfall during southwest monsoon season particularly in July and August months. The extreme precipitation events in the form of cloudbursts, squall lines, strong winds, thunderstorms, snowfall, hailstorms and storm surges trigger flash floods, soil erosion, landslides, etc., resulting huge human causalities, loss of properties and affect the economy of the country. The climatology for different categories of extreme events over Western Himalaya during winter has been recently studied by Shekhar *et al.* (2017). By using the observed precipitation data in their study, they have shown that rainy days have decreased and duration of dry spell has increased over the Western Himalayan region. Lack of dense observatory network over Western and Central Himalaya makes it very difficult to understand the climate of these regions which in turn makes it difficult to predict the extreme events more effectively either by using statistical or Numerical Weather Prediction (NWP) models.

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Study of extreme precipitation events over Western Himalayan region has been carried out by using NWP models also (Shekhar *et al.* 2015). Due to lack of observational data over the region, remote sensing promises improvements in forecast accuracy by ingesting various types of gridded satellite data into the NWP models by data assimilation technique which further improves the initial conditions for NWP models. Recent studies show that assimilation of satellite data has significantly improved weather forecasts (Zou *et al.* 2013; Xie *et al.* 2016) especially over some areas with sparse conventional observations (Zapotocny *et al.* 2008). Several studies have reported the benefits of the assimilation of remote sensing data over Indian region (Raju *et al.* 2014, 2015a, b, 2018; Parekh *et al.* 2017). The limited non-hydrostatic models are capable to predict extreme precipitation events but still forecast skill is lagging due to lack of observations and physics and dynamics of NWP models over mountainous regions (Norris *et al.* 2017).

Munsiyari is a hill station situated at an altitude of 2000–2300 m in Pithoragarh district of Uttarakhand in Kumaon hills (figure 1). It is a small town on the slope of the hill and is at a distance of about 130 km from Pithoragarh. The area is landslide prone at some of places. It is surrounded by snowcapped high peaks of the Himalayas. The north and east of Munsiyari having five beautiful and amazing snow loaded peaks together known as Panchachuli. The beautiful valley where Munsiyari is located is known as Johar Valley. This valley is extended in north up to Milan Glacier. The valley is further adorned by Gauriganga River. The Gouriganga originates from Milan Glacier in north of Munsiyari. The climate of Munsiyari is good and temperatures are pleasant with normal wind activity. An extreme precipitation event occurred over Munsiyari (Uttarakhand) on 2nd July 2018 causing flash floods, landslides and damage to the hydropower project. Due to the presence of westerly and monsoonal trough along with cyclonic circulation activity and moisture incursions continuously from the Bay of Bengal and the Arabian Sea, mesoscale convective system was formed over Munsiyari which leads to localize heavy intense precipitation. In this paper, a preliminary study has been carried out to examine the capability of the WRF model for precipitation forecast over Munsiyari using the 3DVAR data assimilation technique. Data and methodology adopted for the study has been depicted in section 2. Results and discussion have been given in section 3. Conclusions have been provided in the last section 4.

2. Data and methodology

NWP models often fail to predict extreme precipitation events over the complex mountains such as the Himalayas due to its coarse observational network and lack of upper air profile data which is very important for the prediction of extreme precipitation events (Norris *et al.* 2017). Remote sensing data of high temporal and spatial resolutions are required to fill up those gaps in the model domain so as to capture the characteristics of the event. In this paper, an effort has been made to simulate the event on 2nd July 2018 by using the WRF model, so as to capture the precipitation associated with this extreme rainfall phenomenon.

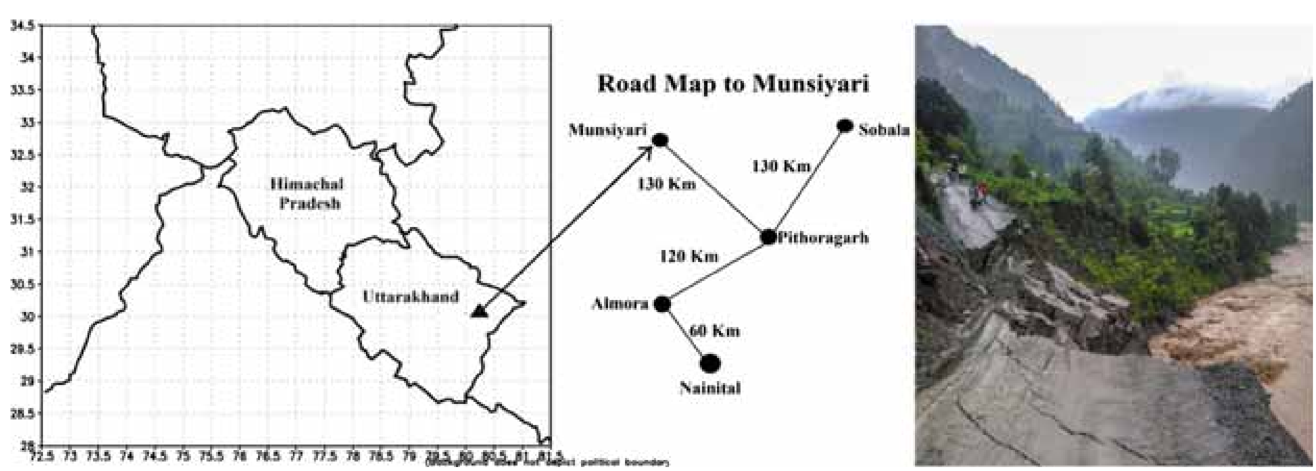

Figure 1. Munsiyari region with a roadmap from Nainital (Uttarakhand) and a damaged road due to flash floods.

Snow and Avalanche Study Establishment (SASE), Chandigarh, has installed an Automatic Weather Station (AWS) in Munsiyari to monitor the atmospheric phenomena and give mountain weather and avalanche forecast to the users, mainly Army and Para-military forces deployed in those areas. The hourly temperature and pressure data of this AWS has been used in this study. Due to non-availability of precipitation sensor at this location, the data with regard to observed precipitation in the area during the extreme precipitation event could not be recorded. The precipitation observation has been taken from National Centre for Medium Range Weather Forecasting's (NCMRWF) gridded IMD-GPM merged precipitation data and rain gauge data (Mitra *et al.* 2009). The high resolution non-hydrostatic Advanced Research WRF (ARW) mesoscale model (version 3.9) developed at National Center for Atmospheric Research (NCAR) is used to simulate the heavy rainfall on 2nd July 2018. In the present study, two-way nested domain with resolution 9 and 3 km, keeping Munsiyari and its adjoining areas as the center has been used. The configuration used to run the model is depicted in table 1. The initial and lateral boundary conditions are obtained from National Centers for Environment and Prediction (NCEP) Global Forecast System (GFS) ($0.25^{o}\times0.25^{o}$) data. Satellite radiances (AMSUA, MHS, HIRS4, and AIRS), GPSRO and NCAR surface and upper-air observations data taken from NCEP archival center have been used in the model for 3DVAR data assimilation. The model is integrated with the initial condition of 1200 UTC 30th June 2018 for a period of 36 hrs. INSAT-3D satellite Thermal Infra-Red (TIR) temperature images have been used to study the synoptic features of the extreme event. ERA5 is the fifth generation European Center for Medium Weather Forecast (ECMWF) atmospheric reanalysis of the global climate Reanalysis. ERA5 data are available in the Climate Data Store on regular latitude–longitude grids at $0.25°\times0.25°$ resolution, with atmospheric parameters on 37 pressure levels (C3S, 2017). ERA5 has been used to verify the model simulated vertical velocity and relative humidity during the extreme precipitation over study location.

3. Results and discussions

3.1 *Synoptic conditions*

An extreme rainfall event occurred in Munsiyari (30.07°N; 80.23°E) of Uttarakhand in early morning of 2nd July 2018 causing devastating flood and landslides. According to print medias, the Motighat/Seranghad Hydro-Power Project in Munsiyari got significantly damaged in the extreme event due to the increase in water level of the Seranghad dam. There were few reports of casualty also. The Munsiyari region was receiving heavy rainfall since Sunday the 1st July 2018. Other parts of Uttarakhand such as Pithoragarh, Champawat and Nainital also received heavy rainfall during last 24-hrs. The details of widespread rainfall in and around Munsiyari as reported in print media has been depicted in figure 2. As seen from the figure, the maximum rainfall of 250 mm was recorded in Munsiyari.

Landsat 8 satellite images (figure 3) show the overflowed areas by the flood water which suggest the possible cause of damage may be due to the flash floods from the river Gauriganga originated from the Milan glacier to the north of Munsiyari. However, the exact cause of damage, whether

Table 1. *WRF model configurations.*

Options	WRF v3.9
Horizontal resolution	9 and 3 km
Microphysics	P3 1-category (Morrison and Milbrandt 2015) WSM6 (Hong and Lim 2006)
Longwave radiation	RRTM
Shortwave radiation	Dhudhia
PBL physics	YSU
Land surface model	Noah land-surface model
Cumulus parameterizations	Kain–Fritsch
Vertical levels	40
Model static fields	USGS
IC and BC	NCEP GFS ($0.25° \times 0.25°$)

linked to the Glacial Lake Outburst Flood (GLOF) of Milan glacier, is yet to be investigated.

The synoptic feature of the event has been studied from the pressure–wind analysis (figure 4a) of India Meteorological Department (IMD). According to IMD analysis, before starting of the event on 30th June 2018 (1200 UTC), conditions were favourable for advancement of southwest monsoon to the northern India. The east–west trough at mean sea level extended up to 0.9 km above was also persisted from Punjab to East Assam across northern parts of Uttar Pradesh, Bihar and Sub-Himalayan West Bengal (shown in dotted lines). The Western Disturbance as a well-marked upper air cyclonic circulation was persisted at 3.1 km above mean sea level over Jammu & Kashmir and adjoining north Pakistan with the trough aloft with its axis at 5.8 km above mean sea level roughly along 74°E and 32°N. Another cyclonic circulation at 1.5 km above mean sea level over south Pakistan and adjoining areas of Kutch and West Rajasthan also persisted. These two low pressure systems along with the monsoon trough were very much favourable for the formation of deep mesoscale convective system over whole Uttarakhand area, which gave widespread rainfall throughout the states with extreme rainfall in the Munsiyari Mountains and adjoining areas on 2nd July 2018.

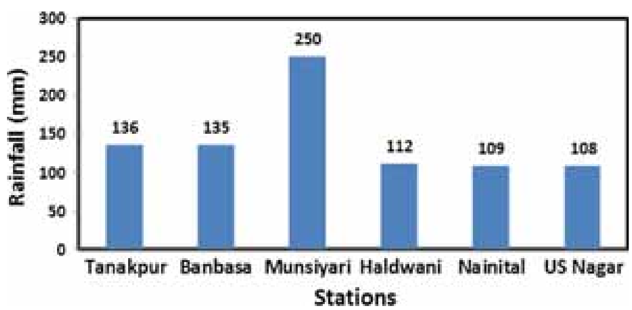

Figure 2. Rainfall (mm) reported at 08:30 hrs (IST) during 2nd July 2018 Munsiyari and adjoining areas in Uttarakhand (source: IMD).

The temporal variations of surface pressure and temperature have also been studied by using SASE AWS data over Munsiyari (figure 4b). There is a sharp decrease in both pressure and temperature at the time of the heavy precipitation event, i.e., 2 July 2018 clearly indicates presence of low-pressure area associated with the event. The actual initiation of the event was at around 23.30 hrs. IST of 1 July 2018 which continued till the morning of 2nd July 2018 at 06.00 hrs IST. Since there was no rainfall sensor available in AWS, the IMD-GPM merged rainfall data over the area has been analyzed for comparison study. The maximum observed rainfall over the region is 240–270 mm since last 24 hrs (figure 7a). This is in complement to the IMD INSAT-3D satellite images (figure 5) which clearly shows advancement of deep convective mesoscale clouds were being stationary position over the Munsiyari region from 23.30 hrs to

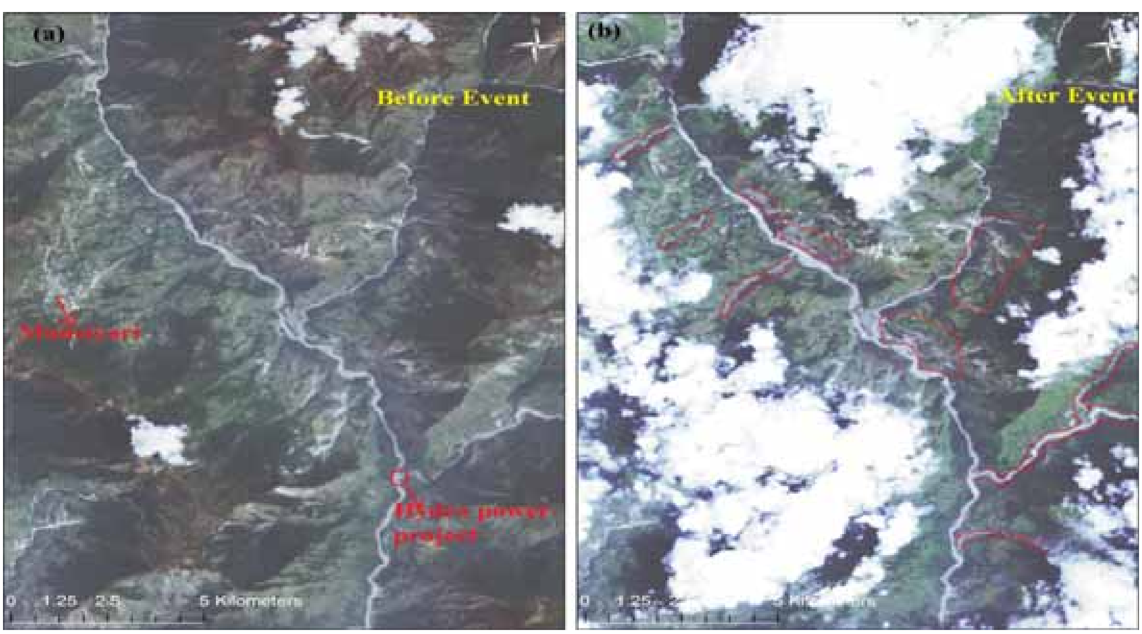

Figure 3. Landsat 8 satellite imageries of **(a)** before event on 22nd June 2018 and **(b)** after event on 7th July 2018 to study the hazard regions over Munsiyari region, Uttarakhand.

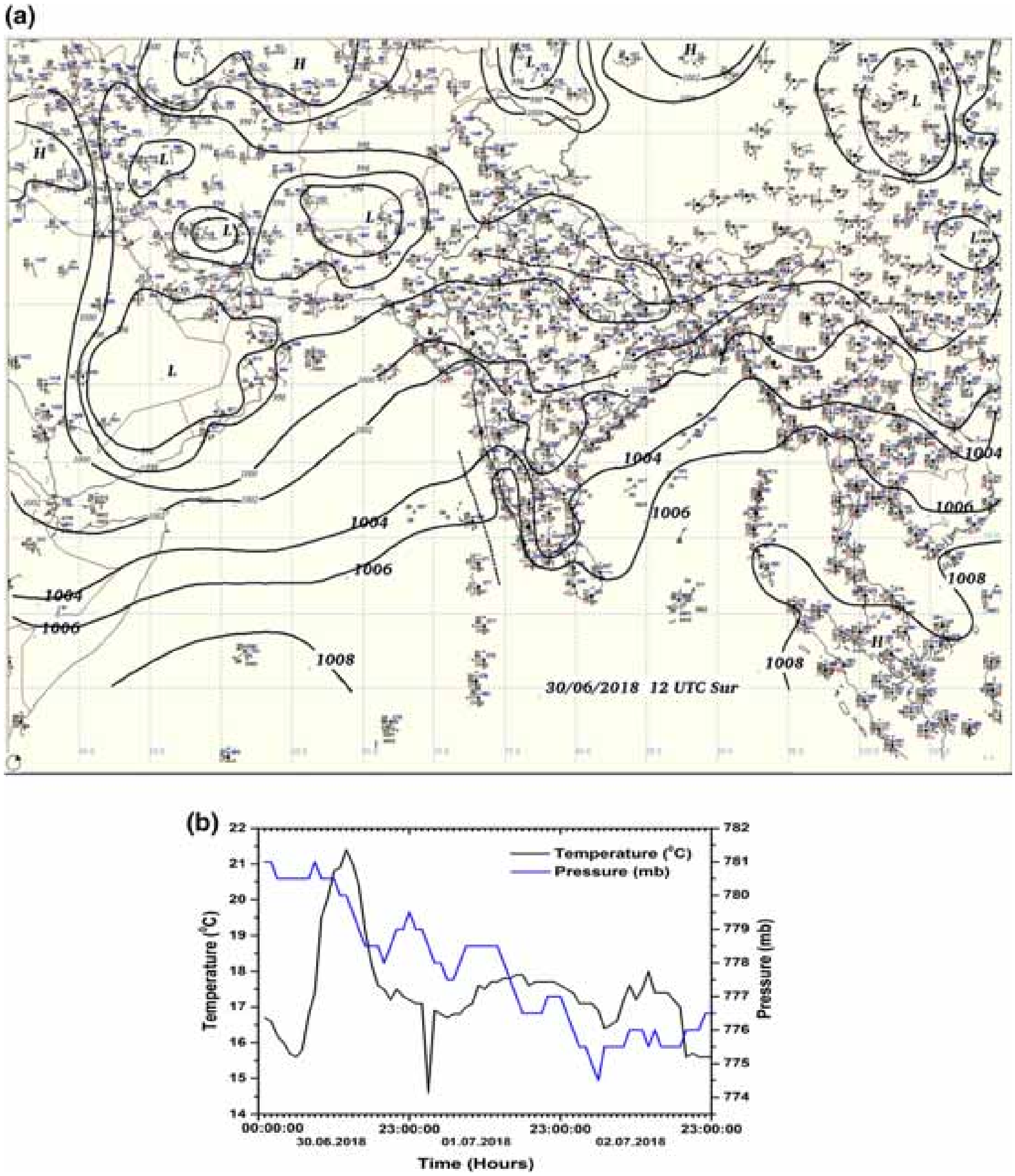

Figure 4. **(a)** Mean sea level pressure (MSLP) analysis chart at 1200 UTC of dated 30th June 2018. **(b)** Automatic weather station's (AWS) hourly pressure and mean temperature data from 0000 IST of 30th June 2018 to 2300 IST of 2nd July 2018.

the complete submerge over the region at around 07.30 hrs of 2nd July 2018.

3.2 *NWP model simulation*

The event was simulated in ARW model. The ARW model is a fully compressible and non-hydrostatic model (Skamarock *et al.* 2008). The details of the configuration of the model to simulate the extreme event have been described in table 1. Figure 6 represents the model domains with two-way nested, mother domain being 9 km and inner domain 3 km. The WRF-3DVAR assimilation technique (Barker *et al.* 2004) was used to ingest satellite radiance data. Sensitivity experiments were carried out for two microphysics schemes in WRF, i.e., P3 1-category plus double moment cloud water, which is newly introduced in WRF version 9 and WSM6 (WRF Single-Moment 6-Class Microphysics Scheme) scheme and also with and without data assimilation to simulate the rainfall event. In total, four sets of experiments were conducted (table 2) so as to simulate the events and to find out the suitable configuration of the model that gives rainfall close to the observed value. The estimated rainfall from the GPM-IMD

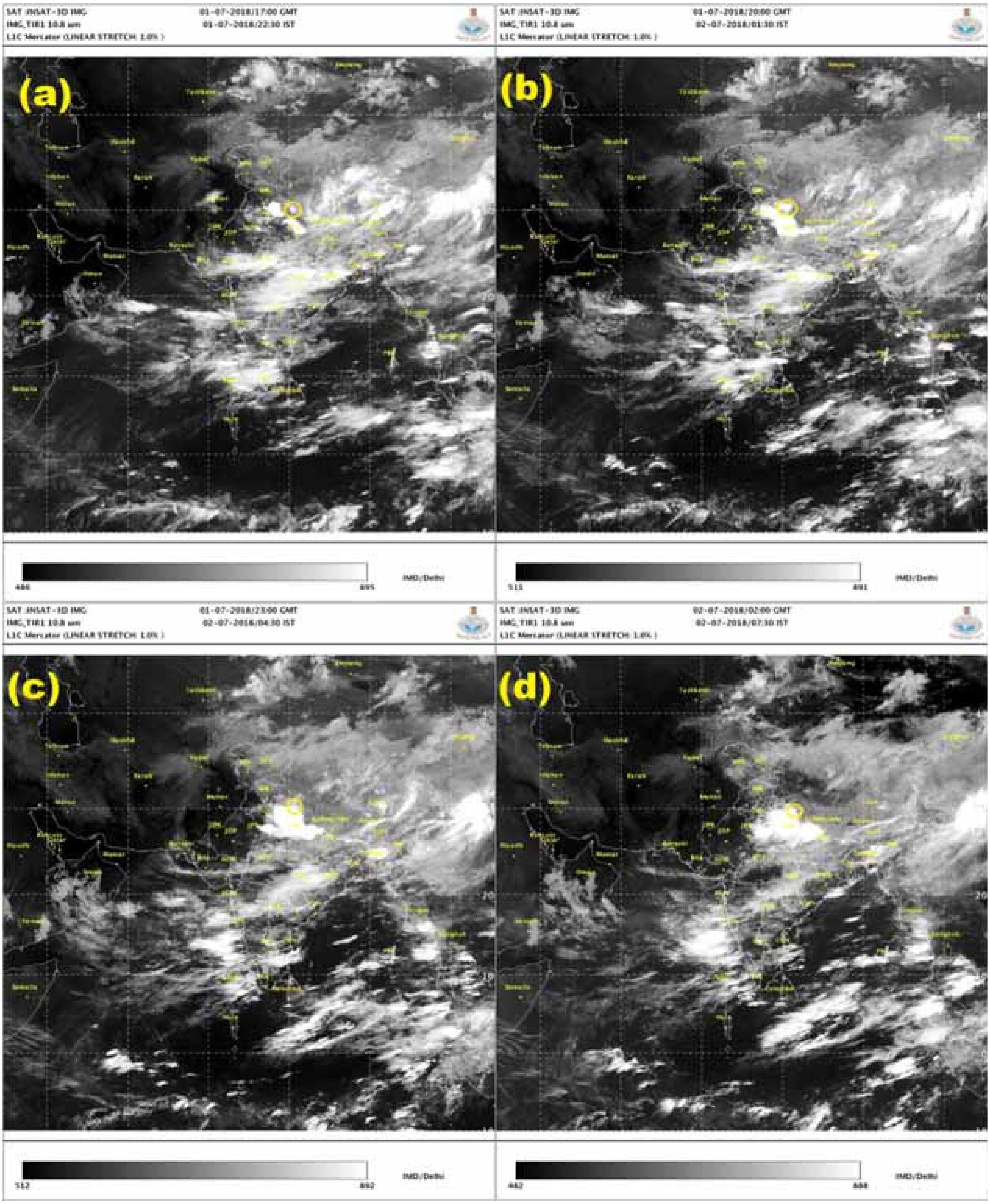

Figure 5. INSAT-3D Thermal Infrared (TIR) satellite images during **(a)** 1700 UTC, **(b)** 2000 UTC, **(c)** 2300 UTC of 1st July 2018, and **(d)** 0200 UTC 2nd July 2018. Circle denotes the study location (yellow).

merged data (Mitra *et al.* 2009) is analyzed and compared with model simulation.

The model was integrated from 1200 UTC of 30th June 2018 up to 0300 UTC of 2nd July 2018. The spinoff for the model was 12-hr and the rainfall simulated by the model was analyzed for next 27-hrs, i.e., up to 0300 UTC of 2nd July 2018. The observed precipitation along with 24-hr accumulated spatial distribution precipitation simulated with four sensitivity experiments are shown in figure 7(a–e). Figure 7(a) shows the observed precipitation from IMD-GPM-merge over Munsiyari region during 2nd July 2018. The maximum precipitation for the Munsiyari region is ∼270 mm

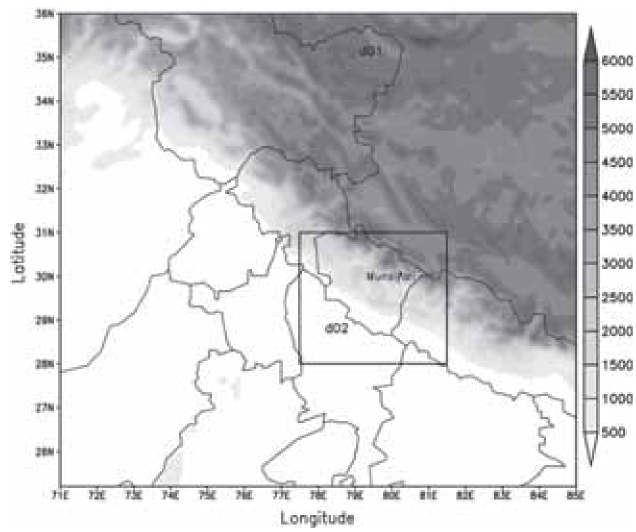

Figure 6. WRF model runs at two-way nested domains 9 and 3 km horizontal domain over Munsiyari region, Uttarakhand. The topography is represented as shaded background.

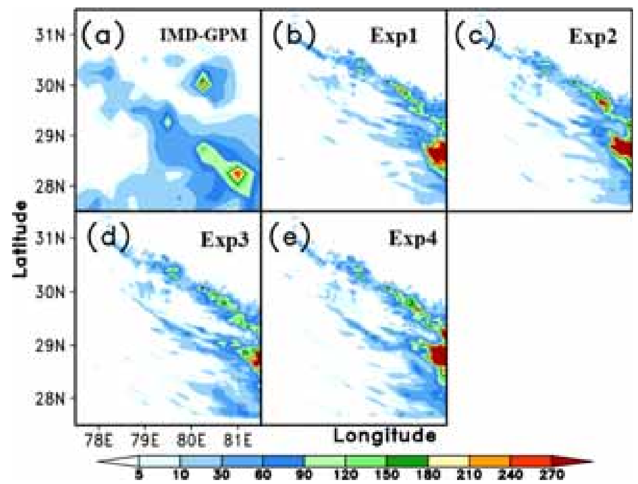

Figure 7. (**a**) Observation and WRF-3DVAR simulations: (**b**) Exp1, (**c**) Exp2, (**d**) Exp3, and (**e**) Exp4 at 3 km horizontal resolution over Munsiyari domain during 2nd July 2018 (24 hr accumulated precipitation (mm)). The triangle (black colour) denotes the Munsiyari location.

Table 2. *Details of experiments with WRF-3DVAR model.*

Experiment	Description
Exp1	Without data assimilation (WSM6)
Exp2	With data assimilation (WSM6)
Exp3	Without data assimilation (P3 1-category plus double moment cloud water)
Exp4	With data assimilation (P3 1-category plus double moment cloud water)

which is close to the ground observation of 250 mm as reported by print media. Figure 7(b–e) shows the four experiments, i.e., Exp1, Exp2, Exp3 and Exp4 as already discussed in table 2. Exp1 (figure 7b) shows model simulated 24-hr accumulated precipitation over Munsiyari region to be 60–90 mm which is highly underestimated in comparison to the observed value of 250–270 mm. The Exp2 (figure 7c) with WSM6 and with data assimilation shows the simulated maximum precipitation to be in the range 150–180 mm. Exp3 (figure 7d) with P3-category microphysics showed the simulated precipitation in the range 180–210 mm which is still underestimated in comparison to the observed precipitation value. Exp4 (figure 7e) shows the maximum simulated rainfall over Munsiyari region in the range of 210–240 mm which is close to observation and also very precisely captured with respect to the location. In Exp4, P3 1-category plus double moment cloud water scheme has been used which is a sophisticated scheme developed recently and very useful in case of intense precipitation rate event. The details of this scheme can be found out in Morrison and Milbrandt (2015) study that used this scheme in WRF model for simulating intense rainfall event. Since the Munsiyari event occurred in data sparse regions, data assimilation with P3-1 category microphysical scheme in WRF could able to simulate the event correctly with respect to spatial and quantitatively.

The vertical cross-section of vertical wind and relative humidity of ERA5 and WRF model experiments at 1200 UTC of 1st July 2018 (mature stage) have been depicted in figure 8. Due to the presence of high topography at study area, all figures have been represented above 700 hPa level. The model simulated vertical winds and relative humidity profiles have been verified against ERA5 reanalysis. Figure 8(a) showed the ERA5 reanalysis products of vertical wind and relative humidity profile. The high relative humidity has been observed in lower to middle atmosphere due to the strong moisture transports from Arabian Sea with south-westerly flow direction (low level jet) towards the Uttarakhand region. The strong updrafts have been observed from 700 to 500 hPa at 12 UTC which is mature stage of storm. Downdrafts have also been occurred at lower atmosphere throughout the day which indicates the favourable conditions for severe rainstorm. The continuous moisture feedbacks from AS and the strong vertical velocity make severe synoptic weather situations, which lead to extreme

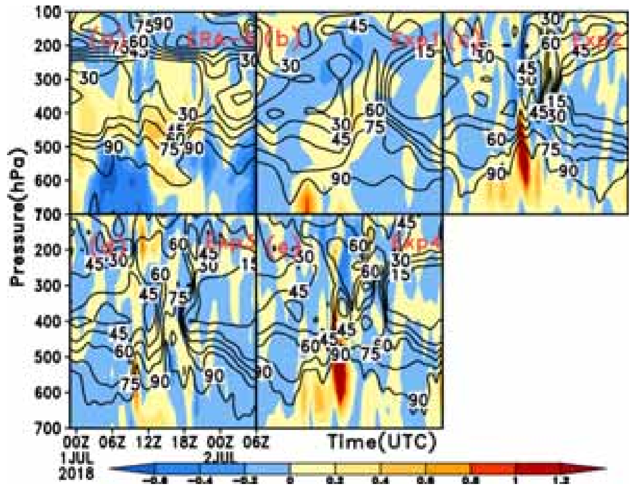

Figure 8. Time–pressure plot (lat.: 30.07; long.: 80.23; Munsiyari location) of vertical wind (m/s; shaded) and relative humidity (%; contour) for (**a**) ERA5; (**b**) Exp1; (**c**) Exp2; (**d**) Exp3, and (**e**) Exp4 at 3 km horizontal model resolution.

precipitation over Munsiyari region. Similar studies were also observed, the same moisture feedback mechanisms which lead to extreme precipitations over Uttarakhand (Shekhar *et al.* 2015; Chevuturi and Dimri 2016). Figure 8(b–e) showed the WRF model four experiments. The high relative humidity has been simulated for all experiments in lower atmosphere from entire time series from 0000 UTC of 1st July to 0600 UTC of 2nd July 2018. The simulated relative humidity profile patterns (figure 8b–e; contour) have been matched well with ERA5 reanalysis entire time series. The strong updrafts have been observed in Exp2 and Exp4, whereas less in Exp1 and Exp3, respectively. The Exp4 better performed than other experiments in the context of vertical velocity in the extreme precipitation over the study location. It is clearly observed that the strong vertical velocity has been simulated after 3DVAR data assimilation as compared to without data assimilation. More experiments need to be designed to study other parameters simulated by WRF such as winds, pressure and moisture, so as to understand the dynamics of the phenomena associated with this unprecedented heavy rainfall. Simulation of WRF model in further high resolution of 1 × 1 km is also being attempted.

4. Conclusions

An extreme precipitation event occurred over Munsiyari on 2 July 2018 causing flash floods, landslides and damage to the hydropower project. The event was simulated in Advanced Weather Research and Forecasting model version 3.9. Four sets of sensitivity experiments were carried out to examine the predictability of the model with two different micro-physical schemes with and without 3DVAR data assimilation. Results shows that P3 1-category plus double moment cloud water microphysics scheme with data assimilation simulates precipitation over Munsiyari closed to the observed precipitation of GPM-Merged. The relative humidity (moisture) and vertical velocity (dynamical) parameters have been improved during 3DVAR data assimilations as compared to without data assimilation over the study area.

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