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Journal of Nepal Physical Society
Volume 9, Issue 2, December 2023
ISSN: 2392-473X (Print), 2738-9537 (Online)

JNPS, **9** (2): 69-77 (2023)
DOI: https://doi.org/10.3126/jnphyssoc.v9i2.62407

Published by:
Nepal Physical Society
P.O. Box: 2934
Tri-Chandra Campus
Kathmandu, Nepal
Email: nps.editor@gmail.com

JNPS 9 (2): 69-77 (2023)
ISSN: 2392-473X (Print), 2738-9537 (Online)
***Research Article** © Nepal Physical Society*
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***Received:** 4th May, 2023; **Revised:** 23th December, 2023; **Accepted:** 26th December, 2023*

ABSTRACT

Chaurjahari area of the Rukum West District of the Karnali Province is one of the proposed model cities of the Government of Nepal, being developed to manage the unbalanced, rapid, haphazard, and uncontrolled urbanization in Nepal. While the model city plans to integrate physical, social, economic, and other anticipated urban facilities, no necessary thoughts on the protection of air quality seem to be given. The present study has been conceived to understand the meteorological implications of air pollution transport and the formation of pollutant fields over Chaurjahari City using weather and chemical transport modeling. The meteorological fields and pollution transport were simulated with the Advanced Weather Research and Forecasting (WRF-ARW) modeling system and an Eulerian Chemical Transport Model (CTM), respectively. The WRF simulated fields displayed a strong diurnal pattern with windless conditions throughout the early morning to late morning hours, whereas, strong winds accompanied the significant up and downndrafts in the afternoon. Similarly, the pollution dispersion simulation revealed that the city area remains stagnated blanketing the city area from early morning to noontime deteriorating air quality. However, in the afternoon time, local meteorological flows over the area generally organize pollutants transport towards the northern and northeastern high mountainous region reducing air pollution but risking deposition of pollutants in the mountain glaciers. Such deposition of pollutants over the mountains may accelerate the melting of glaciers and snow enhancing the effects of climate change.

Keywords: Chaurjahari Model City, Himalayan mid-hills, Air pollution, Meteorological modeling, WRF, Chemical Transport Modeling, Fictitious pollutant.

INTRODUCTION

Air pollution has emerged as a major environmental challenge in the urban centers of Nepal risking public health [1]. The air quality of these urban centers is degrading per year due to uncontrolled industrialization, urbanization, commercialization, and increased use of fossil fuel-powered vehicles in line with other cities of developing countries [2, 3]. For example, the Kathmandu Valley and Lumbini regions have experienced record high pollution levels like Delhi and Beijing cities in recent years during the winter months [4, 5, 6, 7, 8, 9]. Though the detailed studies of the other urban areas of Nepal are limited, it is regularly reported that they are catching up with a situation similar to that prevailing in Kathmandu and Lumbini. While the air quality in the unurbanized mid-hills of Nepal Himalaya is still relatively very clean, unplanned urbanization of such places poses a possible risk of air pollution if environmental considerations do not go in tandem with the development. This, however, does not mean to halt infrastructural and other development processes. In this context, the Government of Nepal has proposed to develop ten model cities in the mid-hills of Nepal to reduce the population burden of major cities in the country, but a detailed environmental impact assessment considering meteorology and dispersion of pollutants has not been done. As an initial assessment to demonstrate the importance of a proactive approach in urban development, this study looks into the implication of meteorology of the Chaujahari area for its pollution dispersion.

The air quality over an area depends on the prevailing meteorological conditions and the emission activities. It plays a vital role in the transport, transformation, and removal of air pollutants from an area at the broad spectrum of horizontal length scale [10, 11]. Meteorological factors like wind speed, wind direction, turbulence, and stability [12], etc. affect how the pollutants disperse in the atmosphere. Under adverse meteorological conditions like thermal inversion and low wind speed, vertical dispersion and the horizontal transport of pollutants are, respectively, strongly inhibited [13]. One prominent example is the Kathmandu Valley where pollutants get trapped within a few hundred meters above the ground inhibiting its vertical and horizontal dispersion within a few hundred meters above ground during night and morning time due to the formation of windless nighttime inversion [8]. As a result, the pollutants released over the area are trapped close to the surface and a high pollution level builds up over the area. For the same reason, in the valley, besides the nighttime, the formation of daytime inversion due to the overriding of warm Northwesterly over cooler Southwesterly wind convergence in the late afternoon, causes pollution to rise even during the day [8] showing low pollutant dispersive power. In fact, not only the Kathmandu Valley but also other mountainous valleys of Nepal are highly susceptible to air pollution as they hold adverse meteorological conditions [8].

The Chaurjahari Municipality with 6,837 [14] households and 28,956 people [15] is located mid-hills of Mid-Western Nepal Himalaya (see Figure 1 for location and topography) and shares the similar topographic and meteorological conditions of Kathmandu Valley, its dispersion power can be expected to be poor and may soon suffer from severe air pollution if the area gets urbanized without necessary pro-active thoughts to control air pollution. The lack of knowledge on the characteristics of the meteorological fields, air pollution transport, and formation of pollutant fields have raised serious uncertainties in the development of an effective air pollution system for the Chaurjahari Model City.

In this paper, we present the numerically predicted meteorological flow fields and their implications for air pollution transport and formation of pollutant fields in and around the Chaurjahari to help the development of an air pollution control system for the city based on the prevailing meteorological characteristics, air pollution dispersion and transport patterns and the formation of pollutant fields in and around the area.

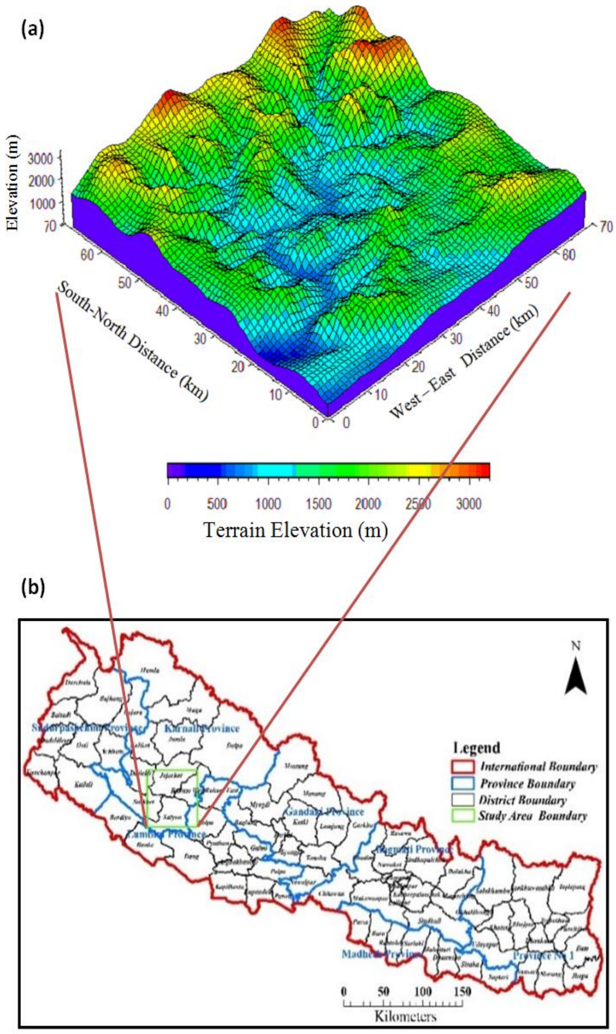

Fig. 1: (a) three-dimensional topographic structural map of the Chaurjahari model city area with surrounding regions, (b) a Map of Nepal with Provinces and Districts.

METHODOLOGY

The meteorological implications for the air pollution and the air pollution transport/ dispersion and formation of pollutant fields over the Chaurjahari Model City have been examined based on the characteristics of the WRF [16] simulated meteorological fields and CTM simulated pollutant fields of inert-tracers released uniformly over the proposed city area and its immediate surroundings. In the following sub-sections, details of the WRF and CTM setup and simulations are discussed.

Meteorological Simulations

The WRF modeling system is one of the successful meteorological systems that has been extensively implemented over the Himalayan complex terrain for various studies such as real-time weather prediction, reconstruction of weather systems [17, 18, 19], air pollution dispersion modeling [8, 20], wind energy assessment [21], flight safety [22, 23, 24, 25], etc. Considering these successful applications of the WRF over the Himalayan complex terrain, this particular meteorological model can also be implemented for the study of the Chaurjahari area.

The WRF-ARW version 3.8.1 was used to reconstruct the three-day weather of Chaurjahari city and its surroundings, selecting a clear winter day without much synoptic activities, from 4 March 2018 to 7 March 2018. On such winter days, air pollution is found to be the highest. The model was initialized with the National Center for Environmental Prediction final reanalysis data at $1° \times 1°$, 24 categories of land use, and 30-second terrain elevation data from the United States Geological Survey.

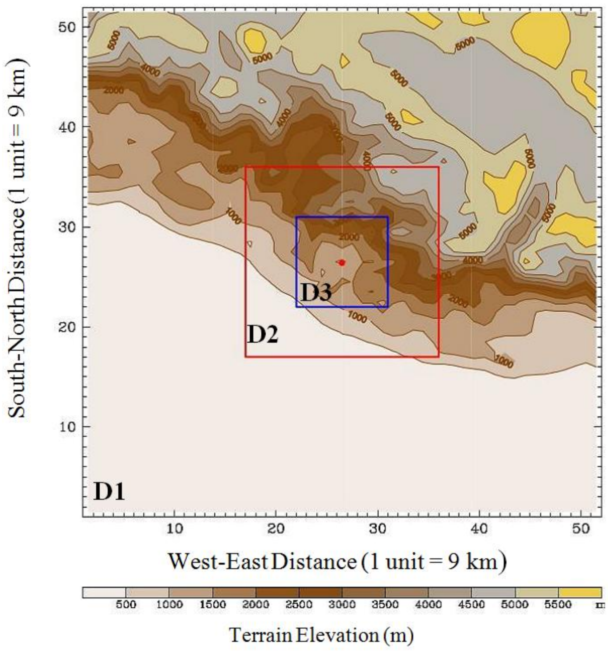

Fig. 2: Triply-nested two-way domain configuration used in the study of meteorological flow system over the study area. The horizontal grid resolution for coarse domain (D1), fine domain (D2) and finest domain (D3) are 9, 3 and 1 km, respectively.

The domain system consisted of triply nested two-way interacting domains. Coarse (D1) and fine (D2) domains consisted of 52 × 52 grid points of 9 km × 9 km and 3 km × 3 km horizontal grid resolution respectively whereas the finest domain (D3) consisted of 70 × 70 grid points at 1 km × 1 km horizontal grid resolution (see Figure 2) and 34 vertical grid points with model top at 100 hPa. All three domains were centered in Chaurjahari (28°36'29.68"N, 82°10'20.36"E).

In physics parameterization, we have adopted Thompson Graupel for microphysics [26], RRTM for longwave radiation [27], Dudhia for shortwave radiation [28], MYJ for planetary boundary layer [29], and the NOAH land-surface model [30].

Air Pollutant Dispersion Simulation

Numerical Chemical transport models are extensively used to simulate the transport, chemistry, and deposition of pollutants released over the study area or the intrusion, stagnation, and channeling of pollutants released beyond the study area, that is, the variability of pollutants in space and time. The CTMs solve the continuity equation for mass conservation of the chemicals in the atmosphere. In this study, an Eulerian CTM developed at the Kitada Laboratory, Toyohashi University of Technology, Japan has been used. This particular CTM has been successfully applied for the study of the dynamics of air pollution over the complex terrain of Nepal Himalaya including the Kathmandu Valley [8, 19].

Fig. 3: Inert tracer (fictitious pollutant) uniformly released area superimposed on the Google earth map.

The CTM simulation domain captures the same region covered by the D3 of the WRF simulation (see Figures 2 and 4). Since inert tracers do not undergo chemical transformation, their dispersion gives a wealth of information on the meteorological implications of air pollution dispersion. Thus, to understand the role of prevailing meteorology for air pollution dynamics and the formation of pollutant fields over the model city area, we performed the CTM calculations by releasing 10 kg day^{-1} km^{-2} inert tracer pollutants, half of the emission strength of the Black Carbon, an inert pollutant, in the Kathmandu Valley [20], over the Chaurjahari model city and its immediate surroundings (see shaded area in Figure 3).

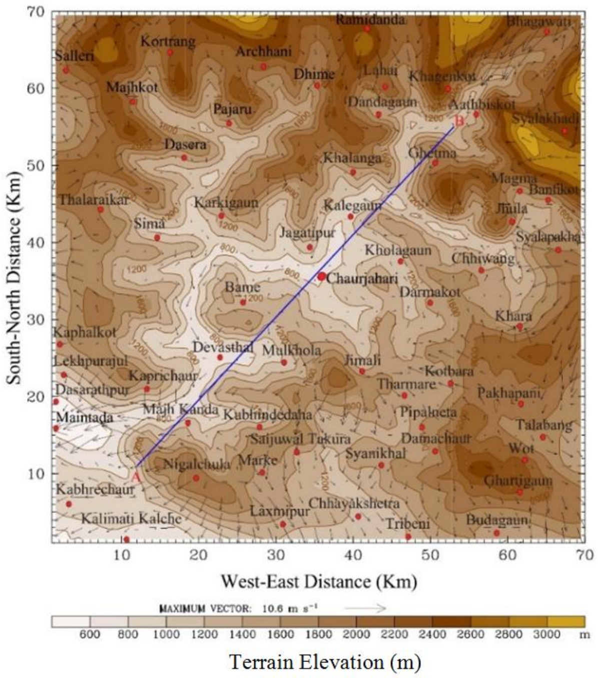

Fig. 4: Geographical coverage of the finest domain of area 70 km × 70 km centered at Chaurjahari (28°36'29.68"N, 82°10'20.36"E). Along the line A-B extending from South-West to North-East.

RESULTS AND DISCUSSION

In this section, we present the near-surface wind characteristics over the Chaurjahari model city as revealed by the WRF simulation, the dynamics, and the formation of pollutant fields in and around the study area.

Characteristics of Near Surface Wind

Analyzing the series of hourly predicted near-surface winds over the study area on 6 March 2018, it can be seen that during the night and early morning hours, the near-surface atmosphere in and around the Chaurjahari city area such as Jagatipur, Kalegau, Darmakot, Bame, Jimali, etc. (see Figure 4 for location) is tranquil as seen in Figure 5a. In the presence of such windless conditions, pollutants are not able to disperse effectively causing increased pollution levels around the emission source area.

The close contour of potential temperature over the Chaurjahari area in the southwest-northeast vertical cross-section of winds and potential contour in Figure 5a', along line AB shown in Figure 4, indicate the atmosphere close to the surface is stratified and stable that could inhibit the vertical dispersion of pollutants. However, downslope winds ranging from less than 1 ms^{-1} to 6 ms^{-1} appear prevalent in the surrounding hilly regions.

Similarly, drainage winds of around 5 ms^{-1} in the lower left region of the Bheri river, around Kabhrechaur, are also evident that can effectively advect pollutants in the region. This wind system may prevail till late morning hours. As the day progresses, the wind patterns shift quickly, with westerly winds beginning to affect the high hill ranges throughout the domain with upslope winds in hill slopes and highly reduced drainage winds by 1045 LST (see Figures 5b and 5b').

By the 13:45 LST, the westerly regional wind remains dominant covering high hills but the lower regions like the Chaurjahari remain unaffected. However, mild southwesterly may prevail as a partial amount of high-speed southwesterly up valley wind speeding up through narrow passes like Kabhrechaur pass, Devasthal along the Bheri gorge encounter hills like Bame on approach to the upper Northeast region (see Figure 5d). During this time the atmosphere is unstable/weakly stratified with increased convective activity indicated by a widely separated potential contour in Figure 5c', allowing a greater vertical mixing of pollutants. Figures 5d and 5d' suggest that in the late afternoon, the up-valley wind further intensifies where the Westerly and south-westerly river valley from the Karkigaun-Jagatipur region and southwesterly from the Devisthan-Bame region affect Chaurjahari. The southwesterly during the time appears to go a hydraulic jump-like phenomenon on interacting with the Bame hill. By early evening after sunset, the upslope and up valley winds quickly cease and are replaced by high-speed downslope wind (see Figure 5e), and atmospheric stability regains ground-up (see Figure 5e'). Similarly, wind gains its calmness as night ripens and until late hours as discussed earlier showing a very clear day-to-day repetition of diurnal variation of wind during winter. The daytime high wind activity and increased convection appear to show higher pollution dispersion capacity over the Chaurjahari but the nighttime atmospheric tranquility and the formation of a stable layer inhibit its dispersive potential. A more detailed discussion on the pollutant dispersion over the area is discussed in the following section.

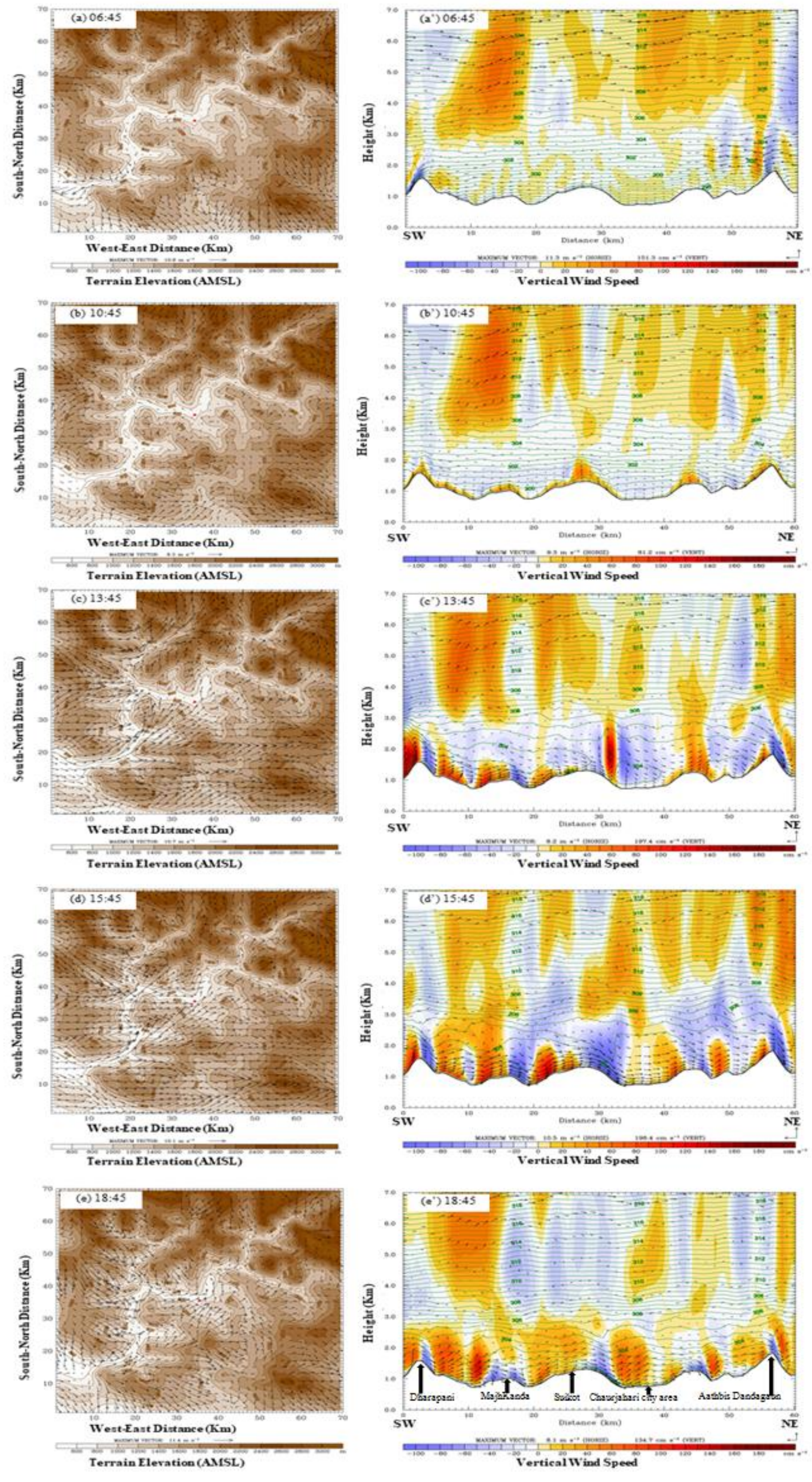

Fig. 5: The WRF simulated spatiotemporal distribution of near-surface wind over the Chaurjahari Model City area and its surroundings (a-e) and the vertical cross-sectional distribution of potential temperature (contour), horizontal wind (vector) and vertical winds (raster color) along the line A – B in Figure 4.

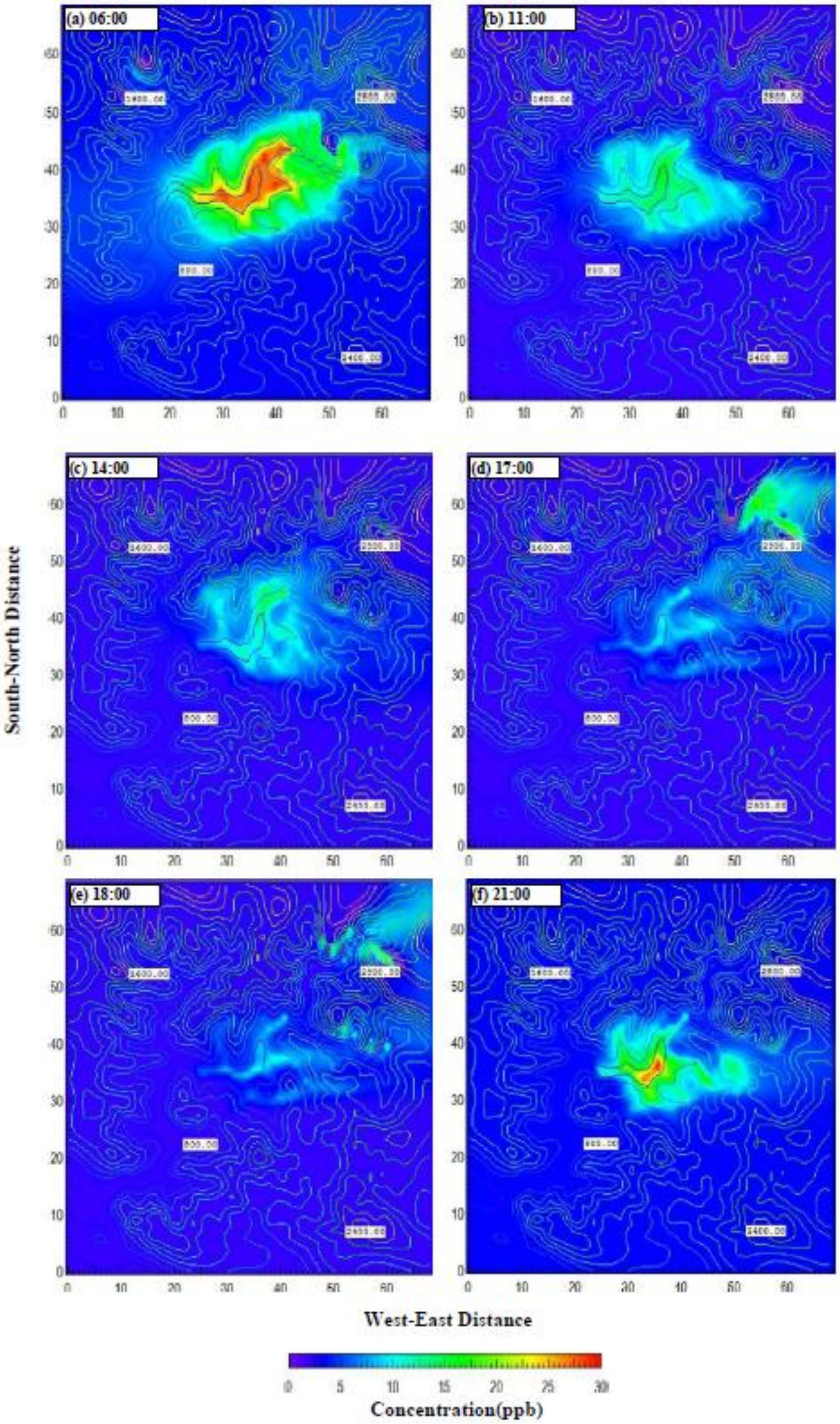

Fig. 6: Spatiotemporal distribution of uniformly released inert pollutants over the Chaurjahari Model City Area.

Dispersion and Formation of Pollutant Fields

In this sub-section, we present the diurnal spatiotemporal distribution of fictitious pollutants in and around the Chaurjahari Model City area on the day of 6 March 2018. The day of 6 March may be considered as the typical day of high air pollution season over the area. Figure 6 represents the spatiotemporal distributions of the pollutants at selected times. Examining the series of hourly predicted spatiotemporal distribution of the pollutant, it can be said that during the early morning, the pollutant is concentrated heavily in the center of the proposed model city and its nearby areas like Jagatipur, Kalegaun, Bame, and Darmakot under very stable atmosphere and calm wind that inhibit the vertical and horizontal dispersion of pollutants respectively. The concentration gradually decreases in the area away from the center. The concentration was recorded at 26.5 parts per billion (ppb) in the city center at 02:00 LST in the model city area which peaked at around 30 ppb at 06:00 LST.

In the late morning, around 1100 LST, with the increased atmospheric instability and vertical mixing, the concentration decreased to around 17 ppb. With the increased dominance of southwesterly up valley winds in the afternoon concentration further decreased as it dispersed radially beyond the city area. During the late afternoon (see Figure 6d) the prevailing wind system organizes general mass transport towards the northeastern areas from the proposed model city affecting areas like Khagenkot, Syalakhadi, etc. In the evening (see Figure 6e), the pollutant dispersed and flushed towards the Sisne Himal. As the nighttime progresses, concentration rapidly builds over the Chaurjahari model city area with increased stability and low wind and gradually resumes the same early morning distribution pattern (see Figure 6f). The dispersion mechanism also shows strong diurnal periodicity and the concentration primarily is affected by the prevalent wind regime and atmospheric stability. Based on the result the newly developed Chaurjahari city should limit pollution emissions during night hours and promote suitable limits during the day to maintain the air quality standard.

CONCLUSION

For the sustainable development of a city, it needs to ensure environmental safety and safe public health. With the extreme levels of air pollution existing in urban areas such as the Kathmandu Valley, it is essential to develop proactive strategies for controlling the air quality to ensure the sustainability of new cities like the Chaurjahari Model City.

As the air quality of a place largely depends on its meteorological conditions, understanding the meteorological flow system becomes important for effective urban planning to reduce air pollution. So, the meteorological flow system of the Chaurjahari model city for a typical winter day was simulated using the WRF model to understand its pollution dispersion mechanism. The simulation shows that the near-surface atmosphere over the model city area remains stably stratified with very light wind during the night and morning time showing poor dispersive power during that time. Whereas, it exhibits a shallow stratification in the afternoon with southwesterly up-valley winds of up to 9 ms^{-1} staying until the late afternoon. This weak stratification, increased mixing due to convective activity combined with the presence of downslope winds and strong afternoon advection, suggests that the area has good air pollution dispersion capabilities during the daytime. The CTM simulations show that pollutants released in the Chaurjahari area could become stagnant in the center of the city and its nearby areas during night and morning time attending peak pollution concentration in the late morning before upslope wind starts to form. The predominant meteorological movements in the region tend to direct the pollutants to northeastern areas, beyond the mountain range that follows the Bheri River basin. This effectively reduces the pollution in the model city area during daytime but the deposition of pollutants like Black carbon in the mountains may accelerate the melting of glaciers and snow.

Considering the pollution accumulation in the valley center during night and morning, and pollution transport to the mountains during the day, while developing the city, emission loading in the city needs to be limited during the night and heavy emission sources need to be avoided in the region to protect mountains from its adverse effects. Similar but long-term studies with realistic emissions need to be done to develop a detailed understanding of it.

ACKNOWLEDGEMENT

The preparation of this paper was partly supported by the Collaborative Research Grant (CRG–75/76–S&T–1) and PhD Research Grant (PhD–75/76–

S&T–16) of the University Grants Commission, Nepal.

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