Weather radar in Nepal: opportunities and challenges in a mountainous region

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Extreme rainfall is one of the major causes of natural hazards in the central Himalayan region, including Nepal. The performance of strategies to manage hazards and related risks relies on the accuracy of quantitative hydro-meteorological prediction. Rain gauges have traditionally been used to measure the rainfall amount. However, point measurements with limited gauge coverage cannot accurately represent spatial precipitation variability in complex topography. Weather radar have shown potential for useful information on accurate areal rainfall estimates. The Department of Hydrology and Meteorology (DHM) in Nepal installed their first weather radar in 2019 in the western region of the country. Two more radars will be added to the planned radar network in the near future, in the country’s central and eastern regions, respectively. We highlight both the opportunities and challenges with radar installation and observation in the mountainous regions. Radar-rainfall estimates across the Himalayas can be useful to inform decision-making in a broad range of infrastructure sectors, including water, energy, construction, transportation, and agriculture.

Introduction

Extreme rainfall-driven hazards such as flash-floods, debris flows, and landslides pose a major risk to life and property in the Himalayan region, including Nepal. Himalayan river basins are characterized by steep slopes and fast runoff processes (DWIDP, 2014). Hence timely and accurate hydrometeorological predictions are sensitive to the spatiotemporal variability of rainfall. Also, numerical modelling of extreme hydrometeorological events is challenging because of observational constraints. Nepal has a diverse climate, ranging from tropical in the southern lowlands to polar across northern mountain peaks and temperate in mid-hills (Talchabhadel and Karki, 2019). It is reported that approximately 8400 weather-related deaths are recorded in Nepal from 1983 to 2013, with an average of 269
deaths per year (DWIDP, 2014). The northern hills (Churia) regions are more prone to landslides, while the southern lowlands (Tarai) are more susceptible to floods such as the 2012 Kharapani flash flood, the 2013 Mahakali flood, the 2014 Jure landslide, the 2016 glacial lake outburst flood (GLOF) in Bhotechosi/Sunkoshi river valley, the 2019 tornado, and the 2020 Kushma debris flow (Qiu, 2016; Cook et al., 2018; DHM, SEN, CIMOD, 2019; Mallapathy, 2019; NDRRMA, 2020). The increasing frequency and severity of extreme events underscore the pressing need for accurate and reliable quantitative rainfall estimates.

To date, Nepal has relied solely on the rain gauge network for surface rainfall measurements. Official monitoring of rainfall started in 1946 with just three rain gauge stations. The Nepalese government added 23 rain gauge stations in 1947, followed by 40 more gauges in 1950. Hydrometeorological services began systematically in 1962. Today, the Department of Hydrology and Meteorology (DHM) currently operates more than 100 automatic and 400 manual rain gauges across the country. However, the station density in the country's mountainous region remains very sparse. The mountainous region covers approximately 50% of the country's area, but only 10% of all stations are located in these remote and rugged areas (Talchabhadel and Karki, 2019).

In general, rainfall variability is monitored using the surface rain gauge network. Two major factors determine the evaluation and design of a rain gauge network: the density of the network and the location of the rain gauges. A high-density network is needed to obtain accurate information about rainfall distribution. There are several challenges associated with rain gauge monitoring in the Himalayas due to the remote location and the complex interactions among the physical environment, the logistical problems, and the cost of maintaining and monitoring the gauges. This means that it is likely that the true spatial and temporal variability of the rainfall field is unknown.

Rain gauges detect the rainfall amount at a particular point and often misrepresent the spatial heterogeneity in basin rainfall estimates. Satellite-based rainfall estimates (SREs) such as PERSIANN-CCS (~4km at 1 hour resolution) and IMERG (~10km at half-hour resolution) exhibit the spatial distribution but demonstrate a poor correlation with ground gauges at a sub-daily level in mountainous regions (Shrestha et al., 2012; Zandler et al., 2019).

A blending of satellite estimates and ground-based gauge rainfall provides a relatively better understanding of the spatial distribution of rainfall (Thapa et al., 2016). However, the reliability of blending entirely depends on the rain gauge density (Berg et al., 2016). Weather radar offer the ability to measure the near-real-time rainfall intensity distribution over the wider region.

Here we summarize the current plan for the installation of a network of three weather radars and provide an overview of a recently installed operational weather radar. We provide an overview of some representative data of the country’s first weather radar installed in the western region of the country. We highlight the possible implications of weather radar output for different stakeholders, including forecasters, decision-makers, and the local public. Importantly, we emphasize the direct use of this information in preparation, early warning, and disaster mitigation to reduce the loss of life and damage to critical infrastructure. We finally summarise the key limitations and challenges in weather radar technology, particularly in mountainous topography.

**Weather radar in Nepal**

Different types of weather radar are used to estimate the amount and intensity of rain over the land surface across the globe. Several options are employed for estimating the spatiotemporal distribution of rainfall. In general, X-band radar has very short wavelengths (2.5–4cm). Therefore, the X-band product has a high spatiotemporal resolution (250m and 1min) and is applicable for localized flood/inundation monitoring, prediction, and analysis. However, the observation range of X-band radar is limited to 80km. Considering demands for a broad range of sectors, including water and energy, construction, transportation, and agriculture, longer-range radars such as C- and S-band radars are more appropriate. The S-band radar necessitates a large antenna and a large motor to power it, resulting in a high initial and operational cost compared to a C-band radar. However, a C-band radar is more financially affordable for a country like Nepal, but at the cost of rain rate retrieval accuracy.

Nepal has plans to install a network of C-band dual-polarized weather radars which will cover the entire country. So far, the first weather radar has been installed in 2019 at Rata Ngandal of Surkhet in western Nepal (Figure 1). Details of the design specification of the installed radar system are available in the supplementary information (Table S1). This radar provides quantitative rainfall estimates for the country’s western region and has the ability to scan over a 200km radius. The DHM monitors the operation and maintenance of the installed radar. Two additional radars will be installed in the near future for the planned three-radar network (see Figure 1). These additional radars are planned to be installed at Ribidikot of Palpa in the central region and Rametar of Udayapur in the eastern region.

The installed radar is of the polarimetric radar system. Polarimetric radars enable the transmission of two types of radio waves: vertical and horizontal polarization, while conventional and Doppler radar can transmit only a single type. Radar moments from the installed system include horizontal polarization reflectivity ($Z_H$), vertical polarization reflectivity ($Z_V$), differential reflectivity ($Z_D$), and the specific differential propagation phase shift ($K_D$). The dual-polarization scheme employed by the Enterprise Electronics Corporation (EEC) C350 system uses algorithms targeted specifically for C-Band radar. Consequently, it results in accurate estimation of radar-rainfall, thereby providing better discrimination between precipitation and non-meteorological signals. The radar has been deployed at the top of a hill cliff to avoid obstructions from adjacent hills; the 4.2m diameter EEC C350 antenna installed in Nepal uses a half-power beamwidth of 0.95° above 5600MHz.

A mountainous country like Nepal has a diverse geography with dynamic weather conditions. The most dominant weather pattern in this region is orographic. The planned radar system is expected to detect hydrometeors such as raindrops, hail, graupel, and snow. However, the primary objective is to estimate the rainfall amount and intensity. The radar technology is useful for short-term forecasting (nowcasting) and provides forecasters with critical real-time information to enhance warning lead-times when a severe weather situation develops. Besides, the DHM uses the radar information to improve the real-time hydrological monitoring and predictions of different hydrometeorological variables (e.g. rainfall, snowfall), which ultimately provide a timely forecast of likely floods, debris flows and landslides in the complex terrain spanning the Himalayas.

Figures 2(a) and (b) show representative data of the radar reflectivity from 5 May 2020, for two time slices (15min each) for light-to-moderate rainfall in the western region of Surkhet, Nepal. The DHM analyses radar reflectivity images using standard retrieval algorithms and produces rainfall estimates at each grid point. Currently, the forecasters from DHM perform hybrid (manual + semi-automated) quality control to the radar-rainfall estimates. Also, the DHM analyses different SREs simultaneously to strengthen the nowcasting. Figures 2(c) and (d) show the quantitative rainfall estimates of PERSIANN-CCS at hourly resolution (Hong et al., 2004) at a short time lag (~1 hour). Similarly, Figures 2(e)–(h) show IMERG Early and Late products at 30-min (Huffman et al., 2019) resolution for the date mentioned above. IMERG Early and Late products are available after ~4 and 14 hours of observation time, respectively.

By visually inspecting the weather radar observations (radar reflectivity) and SREs (Figure 2), we can identify the most salient features. Overall, we find a general tendency of different products to capture the rain-
Figure 1. Location of three weather radars and their areal coverage (thick solid line represents operational radar and thin solid lines represent proposed radar) across Nepal. The coverage areas are shown in three levels: (i) 50km in dark blue, (ii) 100km in light blue, and (iii) 200km in light yellow. Inset at top right shows neighbouring countries, including India, Pakistan, Bangladesh, Bhutan, and China. A typical representation of beam blockage due to the orography, one of the major errors associated with radar observation in mountainous regions, indicates that significant blockage around the northern region of Nepal (not to scale). A location photograph at the bottom left shows the operational weather radar (EEC Defender C350), installed for the first time at Rata Nangala, Surkhet, Nepal.

We present details on the first-ever installed radar-rainfall observation in Nepal, including in situ instrument failure due to power outages, lack of technical expertise for regular maintenance and data collection, data storage processing and dissemination and the financial capability to install, maintain and operate weather radars. On top of that, there is a big challenge of transboundary data sharing in the central Himalayan region (Akanda, 2012; Singh and Thadani, 2015). Furthermore, the end-users presently are not directly connected with the DHM’s network. However, the information generated from DHM is conveyed via the network of government and non-government organizations when issuing early warnings.

Summary

We present details on the first-ever installed weather radar in Nepal. Radar-rainfall estimates across mountainous topography are critical for the issuing of severe weather warnings, floods forecast and landslides, and to inform decision-making across a broad range of sectors, including energy, construction, transportation, and agriculture. There is a huge opportunity to enhance the hydro-meteorological forecasting capabilities in Nepal through integrated observations from currently available systems. The combination of rainfall information from satellite, radar, and weather stations can improve quantitative rainfall estimates. These estimates can be used to enhance the physical realism of real-time watershed monitoring, to improve hazard predictions, to communicate hazard information, and to enhance emergency planning and response. However, several challenges remain associated with radar installation and operation in mountainous regions, such as power outages, the lack of technical expertise, relevant finance, data storage, processing, and dissemination. High-spatiotemporal resolution radar-rainfall estimates in urban areas such as that from X-band polarimetry radar (e.g. Krajewski and Smith, 2002; Berne and Krajewski, 2013) can complement flood preparedness efforts in...
Weather radar in Nepal. Also, the effective implementation of natural hazards risk management strategies requires coordinated efforts among the research, operational, and management communities towards developing a cyberinfrastructure that integrates observations, high-performance computing, early warning systems, transparent information management, and advanced communication services in a networked environment. A network chain between radar sites, central processing units, hydrometeorological services, decision-makers, and end-users can further complement this process.

Acknowledgements

The authors greatly acknowledge the DHM, Nepal, for providing valuable information related to the weather radar. We thank Mr. Bikash Nepal, meteorologist of DHM, for his assistance in data access. The authors are grateful to the anonymous reviewers for their reviews and constructive comments.

Conflicts of interest

The authors declare no conflict of interest.

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Straight-line winds hit parts of Bara and Parsa districts of Nepal

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This study shows that there was a severe thunderstorm leading to an extreme straight-line wind event in some parts of Bara and Parsa districts of Nepal on 31 March 2019. It occurred due to presence of (1) an inversion layer above a lower level of dry deep adiabatic air, (2) moist air at the lower level, (3) a deep dry adiabatic layer above inversion, (4) a veering wind with height, (5) a fairly unidirectional wind from lower mid-levels into upper levels, and (6) wind speed shear at the lower level. As there was no previous history of any analysis of this kind of severe wind system (being of meteorological significance) in Nepal, this study should be quite helpful in improving the understanding of air motion and associated weather and climatic phenomena in Nepal for now and into the future.

Introduction
On 31 March 2019, from about 1300 UTC (1845 local time) onwards, a sudden severe storm hit some parts of Bara and Parsa districts of Nepal¹ and lasted about 30 to 45min in duration, according to local reports. The storm affected areas are about 90km south of Kathmandu International Airport, Nepal (Figures 1 and 2), ranging in altitude from 83 to 109m amsl, and have a hot and humid climate. The extent of the storm damaged area was about 45km long and up to 35km wide (i.e. the distance between parallel lines delineating the storm affected locations). But due to the lack of radiosonde and radar data, as well as skilled/trained weather forecasters in the country, it was not forecast before it hit. In total, the storm killed 28 people, injured hundreds and destroyed a huge amount of public property.² To investigate this event, this study attempts to fill the gap of understanding of atmospheric processes responsible for causing this storm, and hopefully for similar types of events in the future. Here, it is hypothesised that these very strong gusts of wind were due to a severe thunderstorm with extreme straight-line winds.

Data and methods
Satellite images from Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra (EOSDIS Worldview, 2019) were collected and analysed. Reanalysis data sets of geopotential height, wind speed and direction for these areas were also used. High resolution satellite precipitation product, J. Jpn. Soc. Civ. Eng., Ser. G 72(5): 1_27–1_33, 2017. Weather radar rainfall data in urban hydrology. Hydrol. Earth Syst. Sci. 21(3): 1359–1380.

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Supporting Information
Table S1. Specifications of the EEC C-band Defender C350 weather radar installed in Surkhet, Nepal

¹https://www.unicef.org/nepal/stories/bara-and-parsa-storm

²https://myrepublica.nagariknetwork.com/news/10-latest-developments-on-baras-parsa-tragedy-with-photos