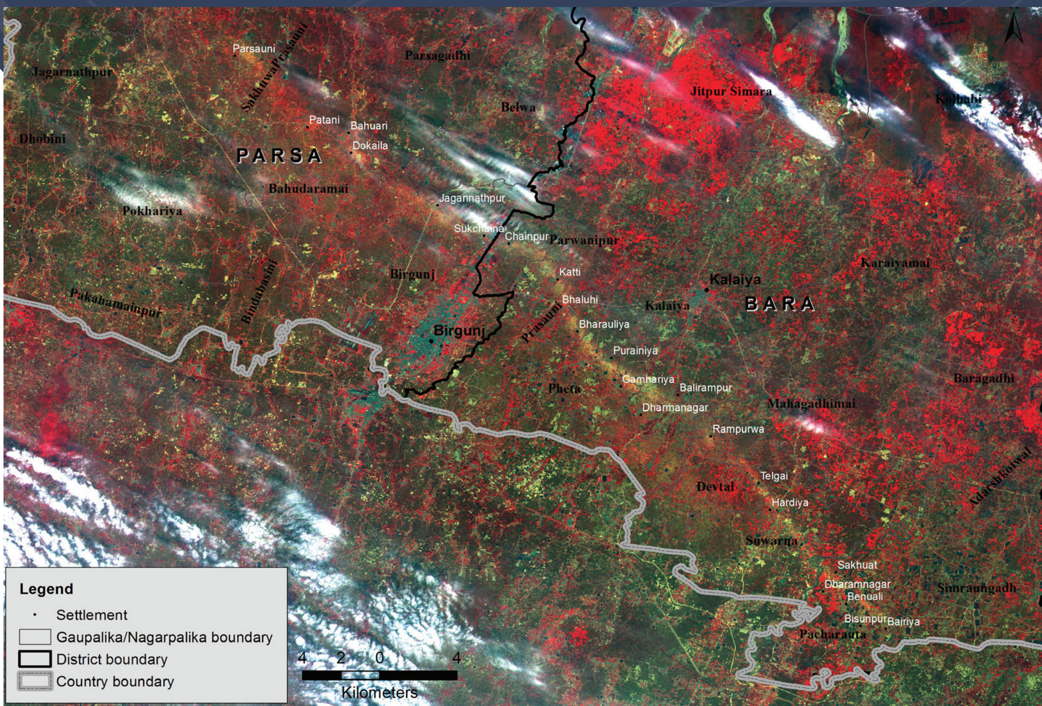
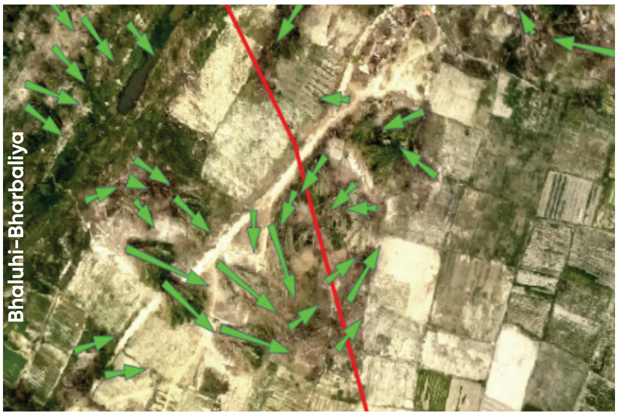
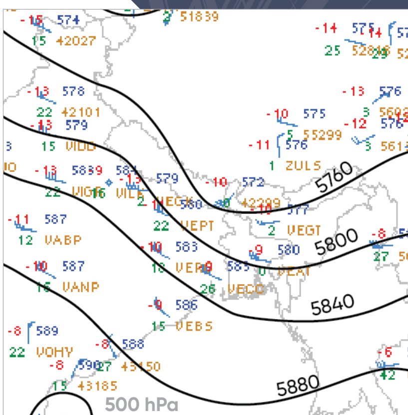
Report on

Bara-Parsa Tornado







June 2019

Government of Nepal
Department of Hydrology and Meteorology

THE SMALL EARTH NEPAL-2001

ICIMOD

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Cover photos: Top inset: Sentinel MSI over Bara-Parsa from Jagannathpur to Bairiya on 1 April 2019. Bottom left: Aerial view of tree fall at Bhaluhi, Bharwaliya; Green arrows are tree fall direction and red line is the tornado path. Bottom right: Analysed upper air map of 500 hPa at 5:45 a.m. on 31 March 2019.

सारांश

चैत्र १७, २०७५ मा नेपालको बारा र पर्सा जिल्लामा आएको विनाशकारी हावाहुरी र असिनापानीले ३० जनाको मृत्यु, ११०० भन्दा बढि घाईते र आठ वटा गाउंका २८०० परिवार घरवार विहीन बनाएको थियो। सो विनाशकारी हुरिवतासले दैनिक उपभोग्य वस्तु, पानी तथा बिद्युत, मस्जिद, स्कुल, उद्योग, कलकारखाना, कृषि लगायत व्यवसायमा समेत ठुलो क्षति पुऱ्याएको थियो भने वसोवास नभएको स्थानमा यसले गरेको क्षतिको विवरण अझै आउन वांकि छ।

यस सम्बन्धमा जल तथा मौसम विज्ञान विभागले द स्मल अर्थ नेपालको सहयोगमा प्रारम्भिक वैज्ञानिक अध्ययन गरी सो असामान्य हुरिवतास टोर्नेडो हुन सक्ने चैत २२, २०७६ मा संयुक्त प्रेश वक्तव्य मार्फत जानकारी गराएको थियो। बारा र पर्सामा आएको हुरिवतासको स्थलगत अध्ययन गर्नका लागि DHM, SEN तथा ICIMOD समेतका ७ जना वैज्ञानिकहरुको एक समूह प्रभावित क्षेत्रहरुमा पठाइएको थियो र स्थलगत अध्ययनवाट प्राप्त जानकारी तथा प्रमाणहरुका आधारमा सो हुरिवतास टोर्नेडो भएको पुष्टि भएको हो। नेपालमा औपचारिक रुपमा पुष्टि भएको यो नै पहिलो टोर्नेडो हो। यस घटनाको स्थलगत र अन्य विश्लेषणहरुको नतिजा विभिन्न संचार माध्यम, र सभा तथा बैठकहरु मार्फत जनसमुदाय र अन्य सरोकारवालाहरुलाई जानकारी दिइएको थियो।

टोर्नेडो सम्बन्धी रिपोर्ट तयार गर्न जल तथा मौसम विज्ञान विभागका महानिर्देशकको अध्यक्षतामा यस विभाग, NAST, SEN र ICIMOD का प्रतिनिधिहरु भएको अध्यक्ष सहितको ८ सदस्यीय समिति गठन गरियो। यस समितिद्वरा टोर्नेडोको नेपाली नामाकरण "घुम्रपात" दिने निर्णय गरियो। यो रिपोर्टमा घुम्रपात आउँदाको वायुमण्डलीय अवस्थालाई मौसमी विष्लेषण, सामाजिक संजाल तथा विभिन्न मिडियाको विश्लेषण, भु-उपग्रह तस्विर र स्थलगत अध्ययनलाई समावेश गरिएको छ। यी विभिन्न माध्ययमहरुवाट गरिएको समष्टिगत अध्ययन/प्रमाणहरुबाट नै सो विनाशकारी हुरिवतास घुम्रपात भएको पुष्टि गरिएको हो। स्थानीय तथा प्रत्यक्षदर्शीहरुसंगको अन्तरकृया/छलफल, फोटो तथा भिडियोहरु, UAV उडानबाट लिइएका तस्वीरहरुको विश्लेषणका साथै भौगोलिक सूचना प्रणाली (GIS) तथा तथ्यांङ्कीय विश्लेषण सफ्टवेयरका आधारमा उक्त घुम्रपातको पहिचान गरिएको थियो। मौसमी विश्लेषण अन्तर्गत सतहि तथा माथिल्लो वायुमण्डलको मौसमी नक्साहरुको विश्लेषण, हिमावारि-८ भु-उपग्रहबाट लिइएको ईन्फ्रा रेड तस्वीरहरु, चट्याङ्ग संजालबाट प्राप्त तथ्यांक, मौसम अवलोकन केन्द्रमा रेकर्ड गरिएको चाप र हावाको विवरणका साथै रेडियोसोण्डको डाटाको समेत अध्ययन गरिएको छ।

वारा र पर्सामा भएको अधिकतम् नोक्सानको आधारमा घुम्रपातको हावाको गति १८० देखि २६५ कि.मि. प्रति घण्टा भएको EF3 समुहको (Enhanced Fujita scale, 3 category) शक्तिको थियो। सो घुम्रपात ३४ कि.मि. प्रति घण्टाको गतिले यात्रा गरेको अनुमान गरिएको छ। विभिन्न भु-उपग्रह र UAV का तस्वीरहरु अध्ययन गर्दा सो घुम्रपात २०० देखि ७५० मिटरसम्मको चौडाईमा रहि पर्साको सखुवा-पर्सौनीमा शुरु भई बाराको बैरीयासम्म ४४ कि.मी. को दुरी तय गरेको देखिन्छ। सो घुम्रपातले पर्सामा भन्दा अघि चितवन राष्ट्रिय निकुन्जको वनक्षेत्रमा समेत क्षति पुऱ्याएको देखिन्छ। यद्दपि त्यसको यकिन विवरण प्राप्त भएको छैन। भु-उपग्रहको तस्वीरहरुले निकुन्जभित्र घुम्रपातले जम्मा ९ कि.मि. को दुरी तय गरेको देखाएको छ।

यो रिपोर्टले घुम्रपात जस्तो अतिजन्य मौसमको कारणले हुने धनजनको क्षति न्युनीकरण गर्न आवश्यक उपकरण र स्रोतहरु सहितको पूर्व सूचना प्रणालीको स्थापना गर्न सुझाव गरेको छ। यो प्रतिवेदनले बारा-पर्सा घुम्रपातको विस्तृत जानकारीको लागि चितवन राष्ट्रिय निकुन्जमा गरेको असरका साथै सो सम्बन्धी थप अध्ययन गर्नु पर्ने सुझाव पनि दिएको छ। यस प्रतिवेदन रिपोर्टद्वारा घुम्रपातको प्रारम्भिक अध्ययन मात्र गरिएको हुनाले र यस घुम्रपातको मौसमी अवस्थाको बिभिन्न दृष्टीकोणहरुबाट विस्तृत र थप अनुसन्धान गर्नुपर्ने सुझाव प्रस्तुत गरेको छ। साथै यस्ता मौसमी गतिविधिहरु हुंदा अपनाउनुपर्ने पद्दतिको विकास गरि लागु गरे मात्र यस्ता अतिजन्य मौसमी घटनाहरुबाट हुने धनजनको क्षति न्यूनिकरण गर्न सहयोग पुग्ने देखिन्छ।

EXECUTIVE SUMMARY

The strong wind and hailstorms that hit Bara and Parsa districts on 31 March 2019 killed 30, injured more than 1150 people and made more than 2890 families homeless. A mosque, schools, industries, agricultural lands, businesses were damaged along with utility services including water supply and electricity. The impact of the severe storm in the non-residential areas is still unknown.

Department of Hydrology and Meteorology (DHM) with the support from the Small Earth Nepal (SEN) carried out a scientific study and declared that most of the damages were due to the tornado formed within the storm system in their joint press release on 5 April 2019 based on the preliminary assessment. This was the first ever officially recorded tornado in Nepal.

To investigate the field situation, a team of seven researchers and experts from DHM, SEN and International Centre for Integrated Mountain Development (ICIMOD) visited the affected areas to gather in-situ information on the impacts of the Bara-Parsa tornado. The evidences gathered during the field study led the researchers to reconfirm that it was a tornado.

The findings from the desk and field studies on this tornado event were shared to general public and stakeholders through various means, including press releases and news media, meetings and workshops by DHM, SEN, and other organizations in several separate occasions.

DHM formed an eight-member committee from DHM, SEN and ICIMOD under chairmanship of the Director General of DHM to prepare this report. The committee in consultation with other experts in meteorology also coined "घुम्रपात" (*Ghumrapaat*) as a Nepali name for tornado.

This report presents the findings of the studies from the four sources: meteorological analysis, social and news media, satellite images, and field studies. This is also the first of its kind of endeavor in Nepal to identify tornadic event by evidences gathered from combination of these sources.

Interviews with tornado affected people, eyewitnesses, photographs and videos, aerial photos from an unmanned aerial vehicle (UAV) flights were collected during the field visit. Geographical information system (GIS), statistical analysis and data analysis software were used to analyze signatures of the tornado. Meteorological analysis included synoptic analysis of surface and upper air weather charts, infrared images of Himawari-8 satellite, lightning data, station pressure and wind observations, and radiosonde point observation data.

Based on the destructions, the strength of Bara-Parsa tornado was estimated to be of EF3 category (Enhanced Fujita scale number 3 category) with the wind speed between 180 to 265 km/h. The tornado travel speed was estimated to be about 34 km/h considering its stretch in Bara-Parsa districts, from Sakhuwa-Parsauni, Parsa to Bairiya, Bara. Based on the satellite images, the length of tornado track in Bara-Parsa districts was estimated to be 44 km and the width ranged between 200 to 750 m.

The tornado also affected forest area inside Chitwan National Park, but the details on the impact inside the park was not investigated for this report. However, based on the satellite images, the path of the tornado inside the park was estimated to be 9 km.

To save lives from such severe weather events in future the report recommends establishing a severe weather warning system (nowcasting) along with resources and tools needed. To better understand the Bara-Parsa tornado event in entirety, the immediate focus should be on the investigation of its impact in Chitwan National Park. This report only presents preliminary analysis of this tornado; therefore, it is necessary to conduct further scientific research along with modeling of the Bara-Parsa tornado and other severe weather events in Nepal.

TABLE OF CONTENTS

LIST OF ACRONYMS AND UNITS

ANAA	Association of Nepalese Alumni from Australia
AWS	Automatic Weather Station
BRCH	Building Resilience to Climate-Related Hazards
CAPE	Convective Available Potential Energy
CCTV	Closed-Circuit Television
CIN	Convective Inhibition
DAO	District Administration Office
DHM	Department of Hydrology and Meteorology
ECMWF	European Centre for Medium-Range Weather Forecasts
EF	Enhanced Fujita
EF3	Enhanced Fujita scale number 3 category
ESA	European Space Agency
FAN	Forester's Association Nepal
FEMA	Federal Emergency Management Agency
FM	Frequency Modulation
GEE	Google Earth Engine
GIS	Geographical Information System
ICIMOD	International Centre for Integrated Mountain Development
INGOs	International Non-governmental Organizations
IR	Infrared images
MFD	Meteorological Forecasting Division
MoEWI	Ministry of Energy, Water Resources and Irrigation
MoHA	Ministry of Home Affairs
MSI	Magnetic Source Imaging
NA	Not Available
NAST	Nepal Academy of Science and Technology
NEOC	National Emergency Operation Centre
NGOs	Non-governmental Organizations
NSSL	National Severe Storms Laboratory
NWP	Numerical Weather Prediction
NWS	National Weather Service
PPCR	Pilot Program for Climate Resilience
RADAR	Radio Detection and Ranging
SCO	Science Coordination Office
SEN	The Small Earth Nepal
SOP	Standard operating procedure
SPC	Storm Prediction Center
USA	United States of America
TOA	Top of Atmosphere
TV	Television
UAV	Unmanned Aerial Vehicle
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting
WSEC	Wind Science and Engineering Center
WSR-88D	Weather Surveillance Radar, 1988, Doppler

Units

hPa	Hectopascal
m/s	Meter per second
km	Kilometer
km/h	Kilometer per hour
g/kg	Gram per kilogram
J/kg	Joule per kilogram
m	Meter
min	Minute
knots	Nautical miles per hour
ton	~ 1000 kilograms

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This report is the result of the concerted efforts of numerous individuals, organizations and government offices whose contributions are acknowledged here. It would not have been possible without their dedicated hard work. We would like to express our deepest appreciation to all those who are involved.

Special gratitude goes to Department of Hydrology and Meteorology (DHM), the Small Earth Nepal (SEN), and International Centre for Integrated Mountain Development (ICIMOD) for supporting this study. We are highly obliged to the District Administration Offices (DAO) of Bara and Parsa districts, and other government offices for their support during the on-site field studies. Special gratitude also goes to CG warehouse, Bara, providing us their CCTV footages and to the people of Bara and Parsa districts who provided valuable information during the field visit.

Special thanks to all the media houses, reporters and social media users for broadcasting news and sharing information on time as per the information received. We are thankful to the Ministry of Energy, Water Resources and Irrigation (MoEWI) for their support and coordination to obtain government approvals for the field visit and their support in preparation of this report. We thank Nepal Academy of Science and Technology (NAST), Association of Nepalese Alumni from Australia (ANAA), Australian Awards, and Forester's Association Nepal (FAN) who have been active in disseminating the information to the stakeholders.

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1. INTRODUCTION

1.1 Synopsis

Sudden onset of strong windstorm accompanied by hailstorms and rain struck villages of Bara and the adjoining Parsa district on the evening of 31 March 2019. Around eight settlements have been ravaged. This devastating windstorm has led to death of 30 people (29 Bara and 1 in Parsa district), injuring 1155 people and affecting 2,889 households according to the National Emergency Operation Centre (NEOC), Ministry of Home Affairs (MoHA, 2019). Many houses have been reduced to rubble; trees, utility poles and even groundwater pumps have been uprooted; and crops ready to harvest have been blown away, threatening people's livelihood. This kind of strong windstorm causing such a huge destruction has never been recorded before in Nepal.

The Meteorological Forecasting Division (MFD) of Department of Hydrology and Meteorology (DHM), forecasted severe thunderstorm for that evening for eastern and central parts of the country. Following the disaster in Bara and Parsa districts, DHM conducted three press briefings to communicate with public. First one immediately after the storm on the following day (1 April), the second during the field visit (5 April) and the third one soon after the field visit. The first press release was about the meteorological synopsis of the event. The second press release was on reporting the event as the first recorded tornado from the preliminary study conducted by DHM and the Small Earth Nepal (SEN). This was based on pre- and post-disaster satellite images obtained from the Sentinel and analysis of social media reporting. The third media briefing was organized to inform public about the findings from the field study (10 April). These three press releases are in Annex 1 (Figure A1.1a-c). A team of seven members from DHM, ICIMOD and SEN conducted field study in Bara and Parsa districts from 3-7 April 2019.

DHM and SEN made a joint presentation to the Minister of Ministry of Energy, Water Resources, and Irrigation about the status of DHM's work about the tornado disaster on 9 April. The presentation was to inform about the tornado to the minister, the secretary, the joint-secretaries and the officials in the ministry. A eight-member committee was formed from DHM, SEN and ICIMOD to prepare this report. Several other interaction workshops were conducted by Nepal Academy of Science and Technology (NAST) and SEN (12 April) (NAST, 2019; SEN, 2019a), Association of Nepalese Alumni from Australia (ANAA), Australian Awards, and Forester's Association Nepal (FAN) (31 May). A dedicated webpage (SEN, 2019b) was also created on 5 April for the Bara-Parsa tornado in the SEN's website to share the photographs, the media releases, and the satellite images.

1.2 Tornado: brief overview

Definition: According to Glossary of Meteorology, a tornado is 'a violently rotating column of air, in contact with the ground, either pendant from a cumuliform cloud or underneath a cumuliform cloud, and often (but not always) visible as a funnel cloud (AMS, 2000). For a vortex to be classified as a tornado, it must be in contact with both the ground and cloud bases. Examples of tornado photos are in Annex 1 (Figure A1.2). Few tornadoes are very distinct to visualize (Figure A1.2a) while others are hard to discern (Figure A1.2b), some are very narrow (Figure A1.2c) while others are wider than a kilometer (Figure A1.2d).

Regions of occurrences: Tornados are most common in USA during Mar-May. Apart from USA, they also occur in many other parts of the world, including Australia, Europe, Africa, Asia, and South America.

Tornadoes are one of the weather hazards in the Bengal region of South Asia (Bangladesh and Eastern India) during the pre-monsoon season (March-May) (Finch and Dewan, 2003; Bikos et al., 2016). The Daulatpir-Saturia, Bangladesh tornado of 26 April 1989 was the deadliest tornado in the recorded history of Bangladesh (Das et al., 2016; Hosen and Jubayer, 2016). It killed more than 1,300 people and injured 12,000 people and 80,000 became homeless (Angwin, 2014). The first documented tornado in the Indian region occurred near Kolkata on 8 April 1838 as documented by Floyd (1839).

1.3 Identification of tornado signature

1.3.1 Social media

Social media (Twitter, Facebook, YouTube) were used as a source of data for collecting people's observation of the event, photo and video of the affected infrastructures and croplands. Social media posts related to the disastrous event were retrieved using R-programming software applying various keywords related to the event. The locational information like affected locations, in need of relief materials, photo taken, video taken were noted and were then geotagged in Google map in order to depict the geographic distribution of the event (Figure 1.1). Sample social media post are presented Box A1.1 in Annex 1.

1.3.2 News media

News media played a vital role in reporting the damages of the settlements and experiences of local people in affected areas. Information regarding destruction of structures, people's observation of the event was collected from all kinds of media (print, online, TV, radio). People in affected areas reported the following signatures of tornado through different social and news media posts:

- It looked like a funnel reaching from clouds down to the ground. The vertical funnel was consisting of rapidly spinning air.
- It uplifted anything that it touched on the ground.
- It occurred 60 to 90 seconds at one place.
- It destroyed in a very narrow area compared to its length.

Additionally, people also reported that they witnessed thunderstorms accompanied by lightning and hailstorm. The locations of the affected area were then geotagged in Google map. Sample news posts are presented in Box A2 of Annex1.

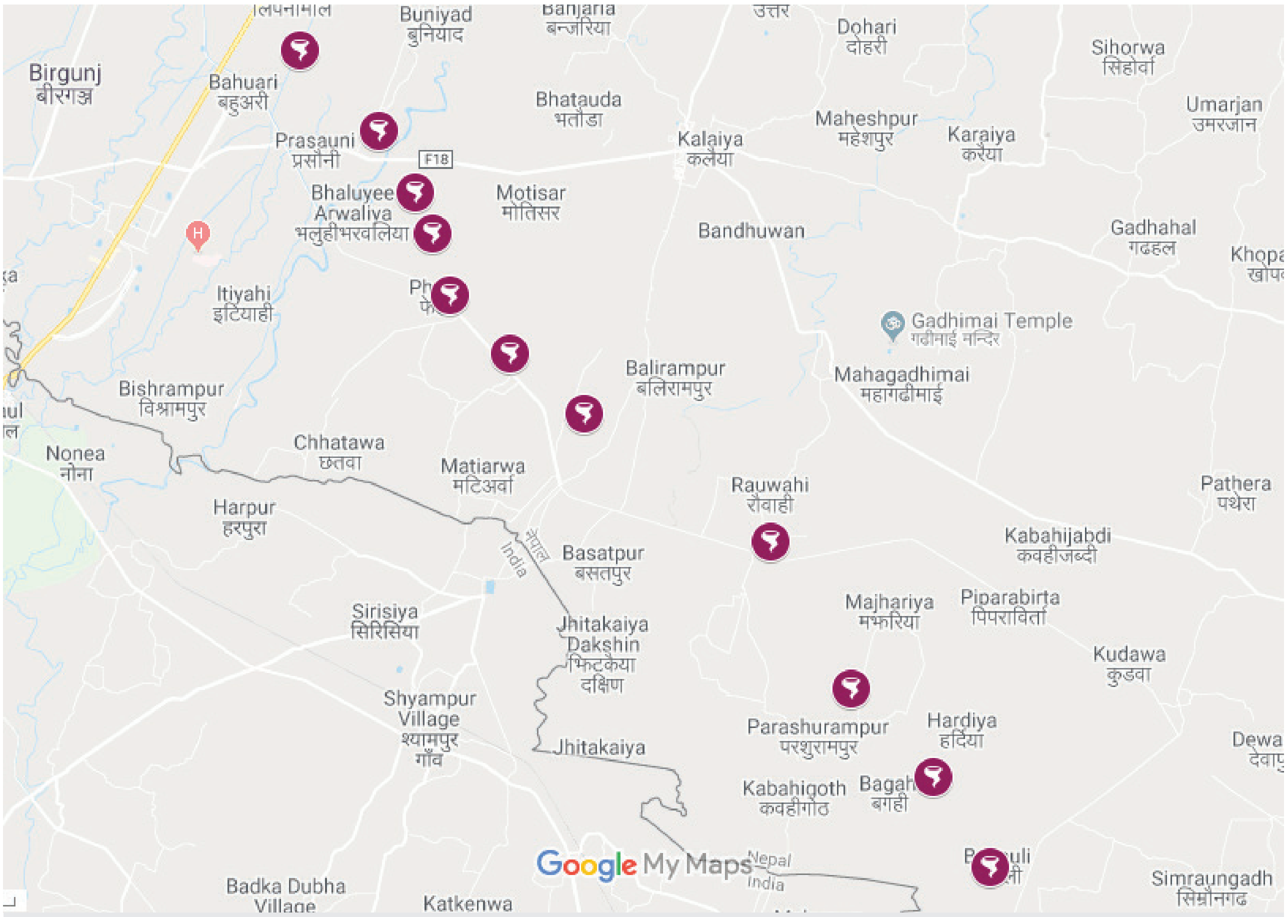

Figure1.1: Google map showing tornado affected areas reported by social and news media.

1.3.3 Sentinel Satellite Images

Sentinel-2 images from European Space Agency were used for analyzing the tornado path. These images contain spectral bands representing Top of Atmosphere (TOA) reflectance from the Sentinel. The Sentinel-2 has a spatial resolution of 10 m with blue, green, red and near-infrared bands. This study was conducted in Google Earth Engine (GEE), a cloud-based computing environment that includes access to the full archive of Sentinel imagery. GEE combines a large data archive of satellite imagery with a computational platform. For the comparison of area before and after events, we used the images of 27 March 2019 and 1 April 2019 (Figure A1.3a and A1.3b satellite images are in Annex 1).

The findings from social and news media posts were subsequently confirmed using the satellite images. The comparison of the satellite images of 27 March and 1 April are presented in Figure A1.3 (a, b) in Annex 1. Figure A1.3b shows the path of destruction made by the tornado. The geotagged locations of reported news and social media in google map were also superimposed over satellite images, which showed that the damages were within the linear path and confirmed that tornado was responsible for the devastation (Figure 1.2). Figure 1.2 shows the linear destruction path/ trail caused by tornado, across Bara and Parsa districts, which is a major feature of tornadoes and Figure 1.2 shows the path of destruction and most affected area reported on news and social media.

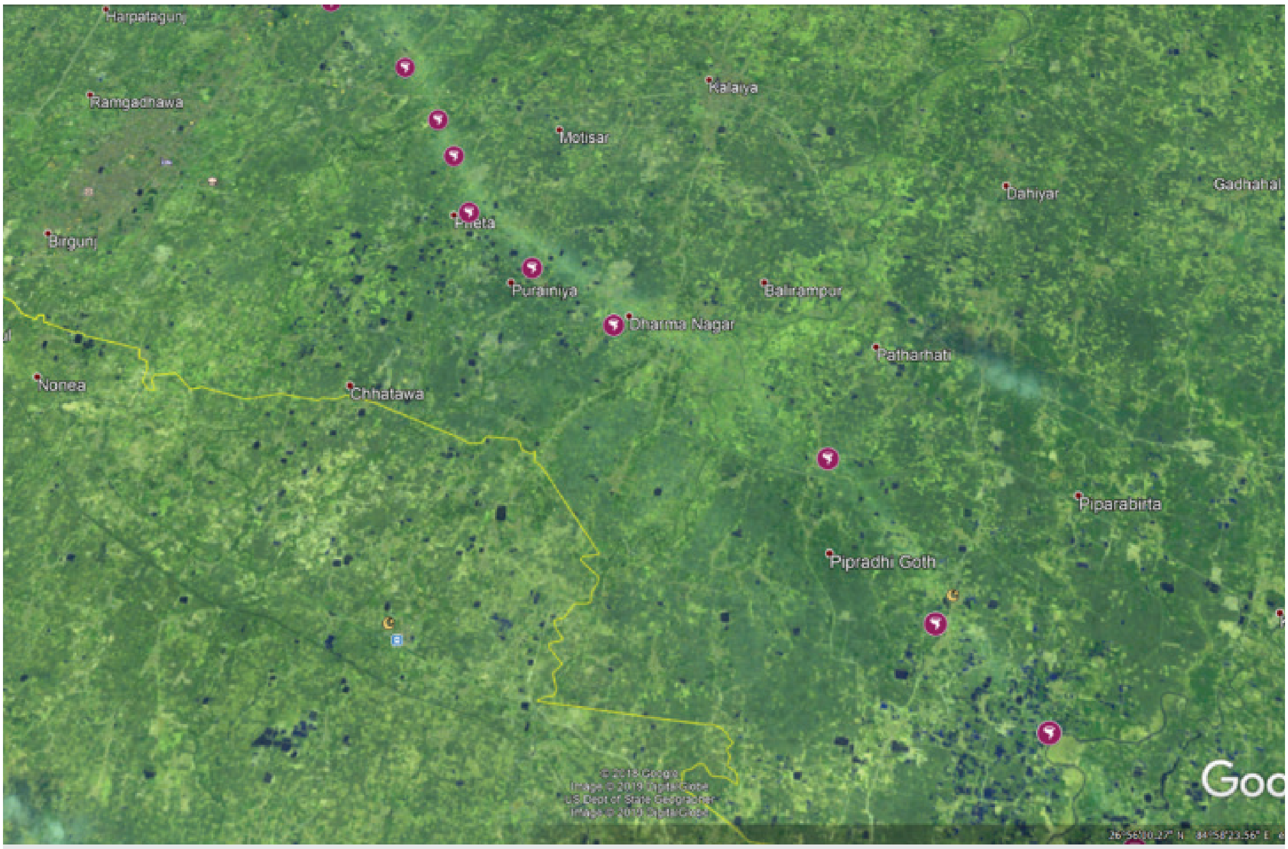

Figure 1.2: *Superimpose of satellite images showing destruction path by the tornado and destructive areas reported in social and news media.*

1.3.4 Nepali name for tornado

To provide a Nepali name for tornado, the committee members and other atmospheric scientists brainstormed the terminology. Several names were discussed along with local names collected during the field visit to Bara and Parsa. The collected local names were: "बंगरेरा", "भुमरी", "घुम्रहवा", but these represent less damaging whirling wind. Therefore, it was decided to come up with a name that represents strong whirling windstorm with a severe damaging capacity. All committee members were requested to send their suggestions. Out of many, the following six names (Table below) were shortlisted considering their appropriate meanings and relevancies. The committee members voted and "घुम्रपात" (*Ghumrapaat*) was chosen as a Nepali name for tornado. "घुम्रपात" is portmanteau word comprised of two Nepali terms "घुम्र" and "पात". "घुम्र" (*Ghumra*) represents rotation of a funnel cloud of tornado in its own axis and the chaos movement of the funnel itself from one place to another on the ground. "पात" represents "उत्पात" (*utpaat*) along with "बज्रपात" (*bajrapaat*) which means catastrophic damage along with thunder and lightning.

१. घुम्रपात	=	घुम्र उत्पात	=	घुमी-घुमी उत्पात/बज्रपात मचाउने हुरी
२. घुम्रहुन्डरी	=	घुम्र हुन्डरी	=	घुमी-घुमी आउने तेज हुरी
३. घुम्रपात हुन्डरी	=	घुम्र उत्पात हुन्डरी	=	घुमी-घुमी उत्पात मचाउने हुन्डरी
४. घुम्रआंधी	=	घुम्र आंधी	=	घुमी-घुमी आउने आंधी
५. घुम्रफान	=	घुम्र तुफान	=	घुमी-घुमी आउने तुफान
६. गोल हुन्डरी	=	गोलाकारमा आउने हुन्डरी		गोलाकारमा आउने हुन्डरी

2. PRELIMINARY METEOROLOGICAL ANALYSIS

This section presents various meteorological aspects of the Bara-Parsa tornado. It mainly covers synoptic features, storm movement, and vertical atmospheric structure using tools and information available at DHM. This section also discusses the weather forecast disseminated by MFD during the Bara-Parsa tornado event.

2.1 Synoptic analysis

MFD receives weather observations from 15 synoptic stations in Nepal at every three-hour interval. In addition, surface meteorological observations from the stations in the neighboring countries (India, Pakistan, Myanmar, Bangladesh, Bhutan) and around are received regularly and are plotted and analyzed in surface map at every three-hour interval, except for 11:45 p.m. and 2:45 a.m. The upper air atmospheric observation maps (5:45 a.m. and 5:45 p.m.) for 31 March 2019 were obtained from University of Wyoming website. Below is a brief description of surface and upper air atmospheric conditions observed on 31 March 2019.

The surface map analysis at 5:45 a.m. shows a large low-pressure area over the north central India and south of western Nepal. The low-pressure system supported the flow of warm and moist air from Bay of Bengal into the region, and southeasterly flow in Nepal (Figure 2.1a). The low-pressure system further intensified and shifted eastward at 5:45 p.m. with center around 85E - south of central Nepal (Figure 2.1b). This low-pressure system supported a flow of warm and moist air from the Bay of Bengal towards eastern and central Nepal. The setup of this low pressure supported a wind flow almost perpendicular to the hills and mountains of central Nepal (in the tornado affected region). The intensified low-pressure system combined with the wind flow pattern against the hills and mountains might have provided an enhanced lift necessary for severe storm, like tornado in the evening of 31 March 2019.

The upper air chart of 850 hPa shows a trough (low pressure region) extending from west Nepal to the Northeastern region of India along the foothills of Central and eastern Himalayas at 5:45 a.m. Upper air data of 5:45 p.m. is missing over much of the South Asia region on that day (Figure A2.1 in Annex 2). Because of the lack of data, analysis at 5:45 p.m. could not be done. The vertical extent of the trough is deep enough i.e. from 850 hPa to 250 hPa (Figure 2.2a, b and c). The location of the trough at 500 hPa (Figure 2.2b) and 250 hPa is responsible for the westerly to northwesterly flow over Nepal. This air flow helped to have dry and cold air advection over Nepal (Figure 2.2b and c) aloft the warm moist surface layer (Figure 2.2a). This synoptic situation supported to increase the instability in the region and giving rise to such disastrous strom. Further details about the formation, intensification and

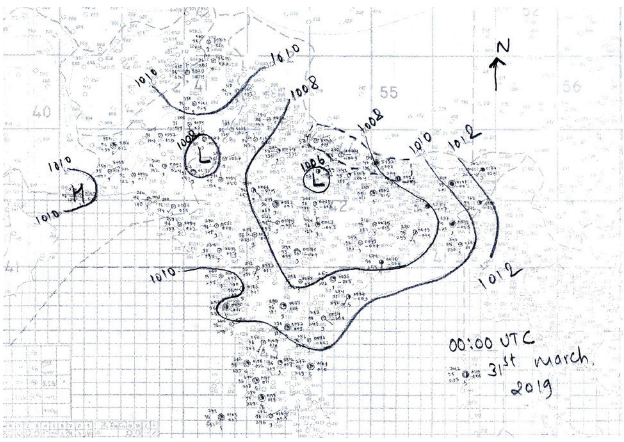

Figure 2.1a: *Surface Map analysis at 05:45 a.m.*

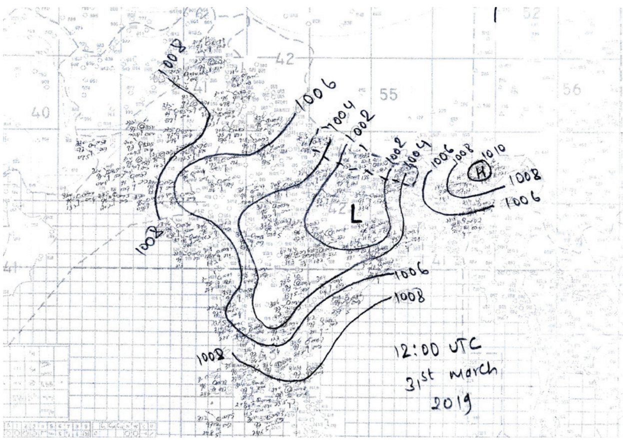

Figure 2.1b: *Surface Map analysis at 05:45 p.m.*

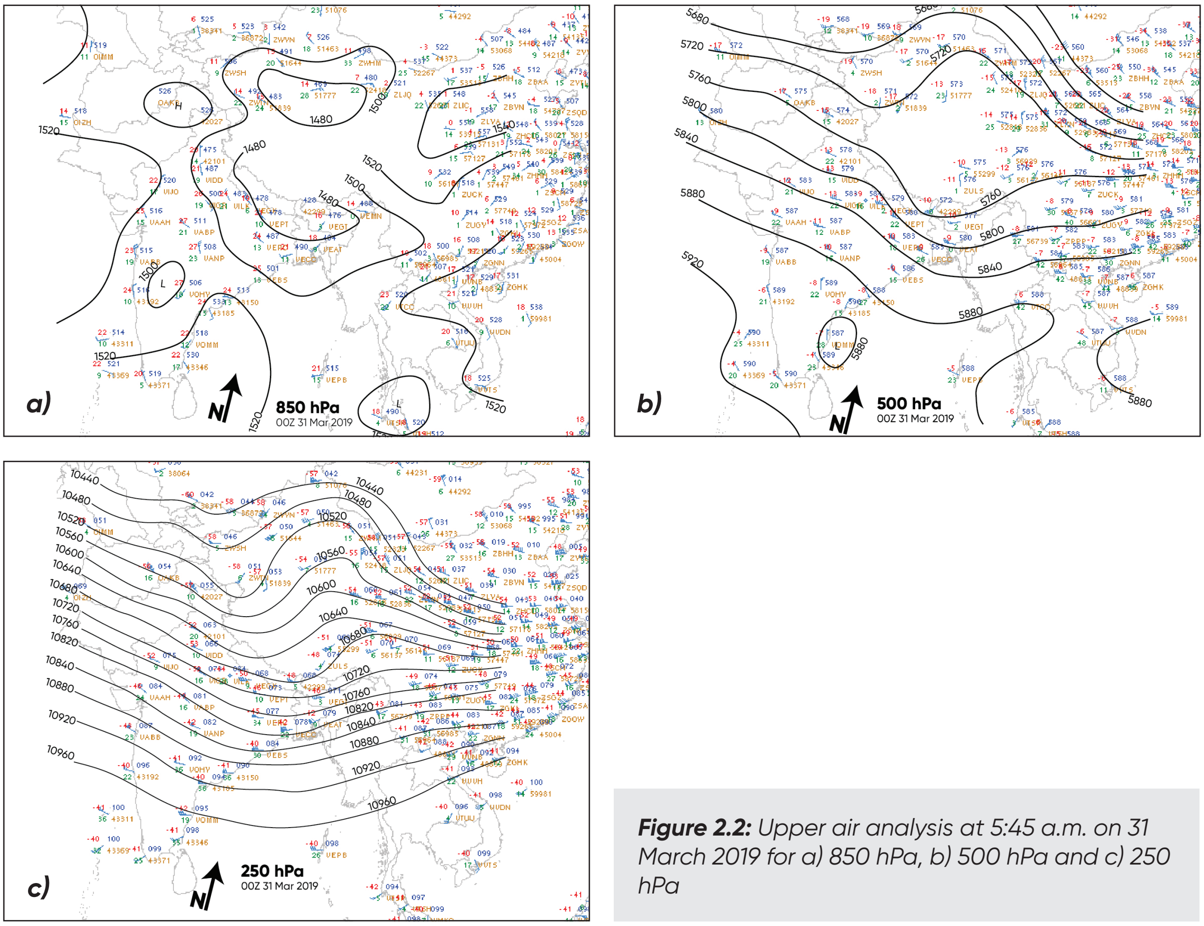

Figure 2.2: *Upper air analysis at 5:45 a.m. on 31 March 2019 for a) 850 hPa, b) 500 hPa and c) 250 hPa*

movement of such devastating storm can be investigated with availability of additional, relevant data – both observations and model simulations.

2.2 Satellite image analysis

The infrared images (IR) of Himawari-8 Satellite from 2 p.m. to 8:35 p.m. were used to track the movement of storm associated with the tornado of 31 March 2019 (Figure 2.3a-Figure 2.3g). These images reveal that the storms system that devastated Bara and Parsa districts was initiated over Myagdi District at around 2 p.m. (Figure 2.3a). The intense updraft, representing high energy, in the storm is represented by the lowest brightness temperature in the satellite images, orange color range inside the black circle (Figure 2.3b-2.3g). This intense part of the storm moved southeastward from Myagdi region and it reached Chitwan district at around 6:35 p.m. (Figure 2.3b). The intense part of the storm reached southern Parsa by 7:25 p.m. (Figure 2.3c) and intensified further and extended to Bara district by 7:35 p.m. (Figure 2.3d). The storm further intensified (very low brightness temperature) in the southern Bara district between 8:05 p.m. (Figure 2.3e) and 8:15 p.m. (Figure 2.3f). By 8:35 p.m. the intense part of the storm system moved southeastward over India. The higher brightness temperature (yellow color range) over southern part of Bara District indicates weakening of the storm in this region (Figure 2.3g).

The satellite images are also useful for understanding storm structure regarding the relation between tornado formation and updraft strength, role of updraft and downdraft, the cloud system and severe weather. However, extensive research is necessary for understanding these aspects of the storm formation.

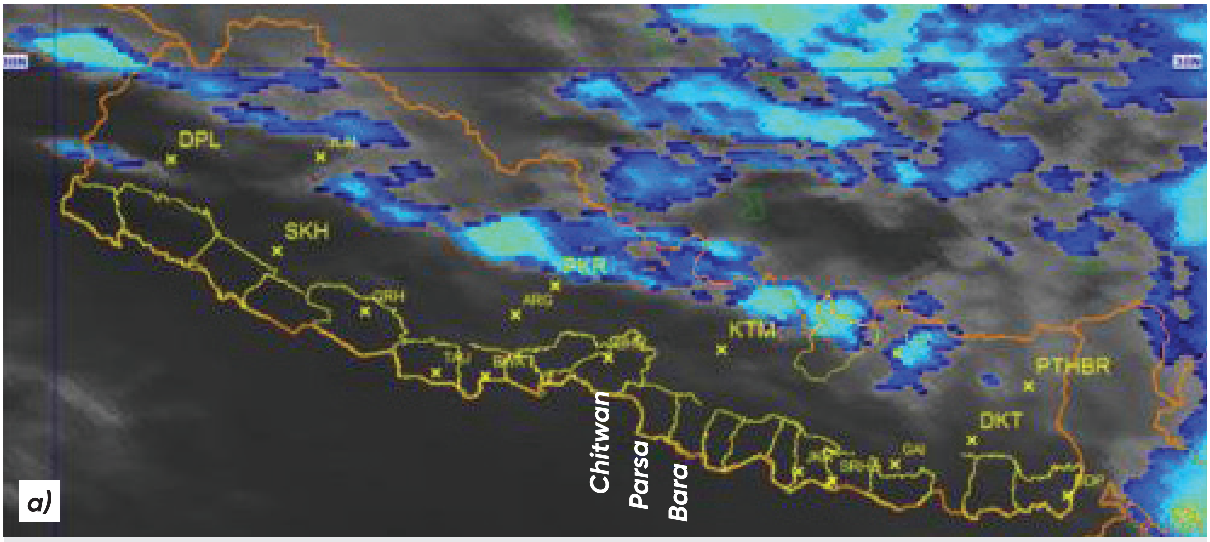

Figure 2.3a: *Himawari IR imagery of 31 March 2019 at 2:05 p.m.*

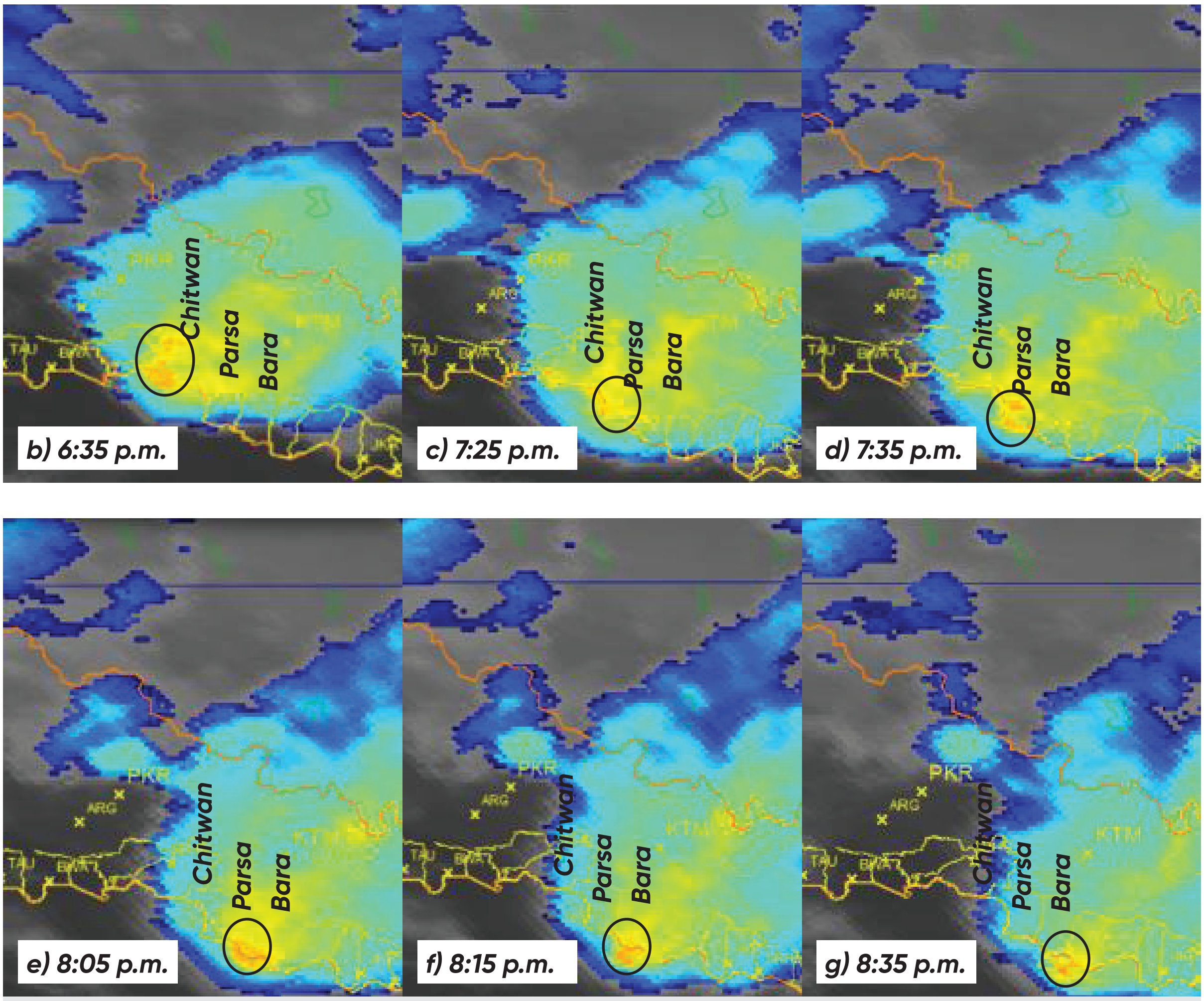

Figure2.3 b-g: *Infrared (IR) images of Himawari-8 showing movement of cloud system from Chitwan district to Bara-Parsa districts. Orange-red color (inside black ovals) represents cooler cloud top temperature and higher cloud top height, indicating strong upward motion and higher storm energy.*

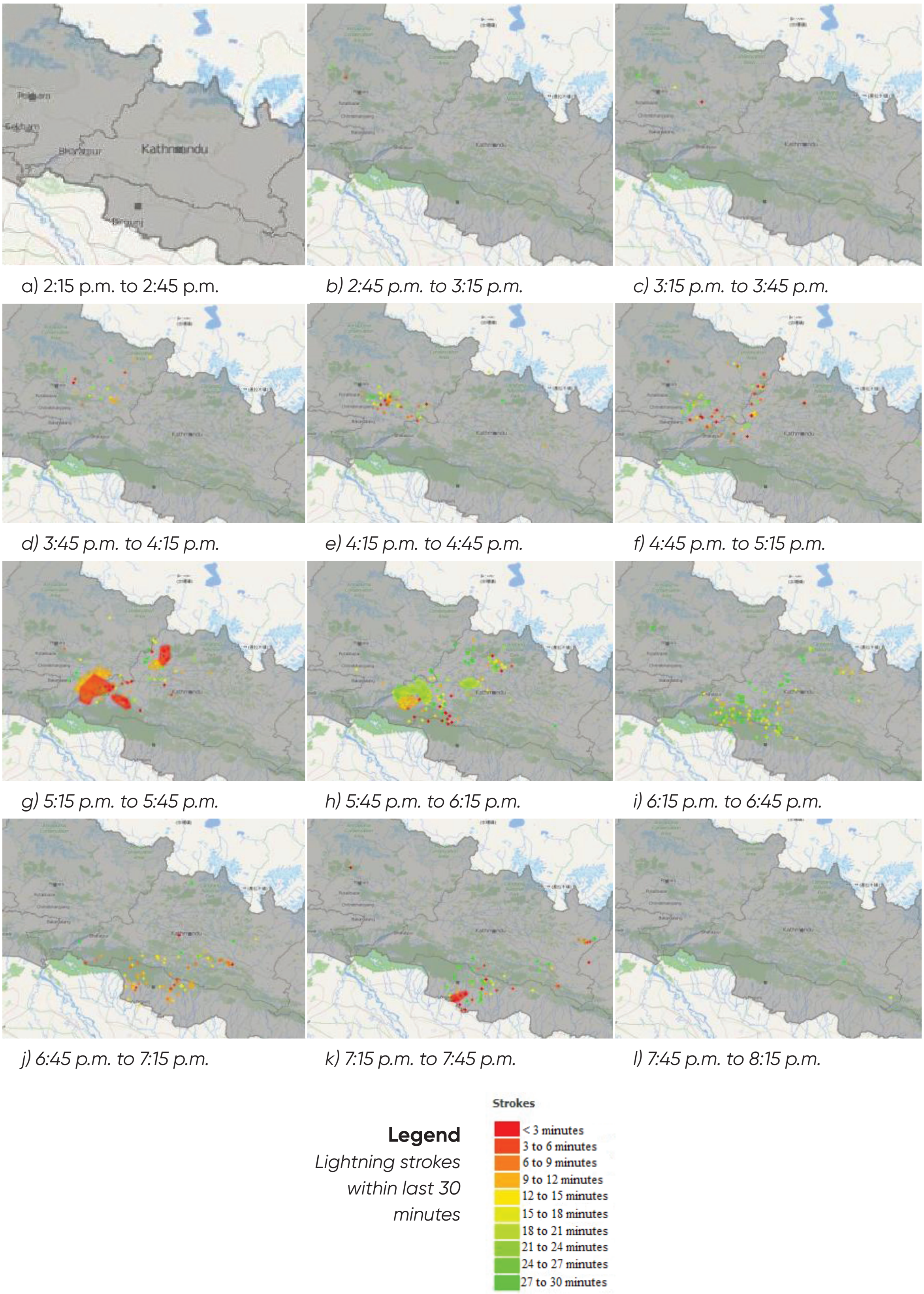

Figure 2.4: *Lightning strokes/cells images from Lightning detection network showing Lightning from Kaski District to Parsa and Bara districts. Each color on the legend map represents the time of lightning incidents in the three-minute period. The time duration in each image shows the total number of lightning strokes occurred within 30 minutes.*

2.3 Lightning data analysis

Lightning strokes are linked to thunderstorm activity. They are useful to detect thunderstorm locations. DHM has installed lightning detection networks at various sites of Nepal. They help to detect lightning strokes and provide the locations of potential storms. The analysis of the lightning events on 31 March 2019 focused on Bara and Parsa districts shows severe storm as shown in Figure 2.4a-Figure 2.4l.

Even though cloud system had already formed before 2:15 p.m. (Figure 2.3a), no lightning strikes were observed in the cloud system until 2:45 p.m. (Figure 2.4a) over Nepal. Lightning strokes started over Pokhara between 2:45 p.m. to 3:15 p.m. (Figure 2.4b). Lightning started over Bara and Parsa districts from 5:45 p.m. (Figure 2.4h) while frequency of lightning strokes was higher from 6:45 p.m. to 7:15 p.m. (Figure 2.4j). Although the frequency of lightning strokes was reduced between 7:15 p.m. to 7:45 p.m., compared to the previous half hour, a huge lightning cell appeared along Bara and Parsa districts at the latter time (Figures 2.4j and 2.4k). To be more specific, they occurred between 7:42 p.m. to 7:45 p.m. (Figure 2.4k). From 7:45 p.m. the lightning stroke reduced (Figure 2.4l). It is thus observed that both Parsa and Bara districts received several strokes between 6:45 p.m. to 7:45 p.m. During this time period, a dense lightning cell was also observed over the area indicating the intensification of the weather system.

2.4 Station pressure and wind measurements

Atmospheric pressure and maximum wind gust were analyzed for two nearby automatic weather stations namely – Rampur in Chitwan and Parwanipur in Parsa. Since these stations are in transitional phase under the Pilot Program for Climate Resilience - Building Resilience to Climate-Related Hazards (PPCR-BRCH) modernization project, wind data was available only for Rampur, Chitwan on 31 March 2019. Figure 2.5 shows one-minute pressure and maximum wind gust variation on 31 March. At Rampur there was a sharp pressure drop of about 5 hPa in about 45 minutes between 4:30 p.m. to 5:15 p.m. and abrupt rise of 6 hPa within a time span of 15 minutes between 5:15 p.m. - 5:30 p.m. The wind gust rose abruptly at Rampur soon after pressure minima and reached maxima (19 m/s) within few minutes, in the meanwhile there was a sharp rise in pressure. This type of barometric pressure drops, and abrupt rises and associated wind gust maxima occurs with the passage of intense localized low-pressure system associated with severe convective system over/near the station. The larger the pressure drop, more severe is the associated storm. The recorded pressure drops in a tornado vortex varied from 5 hPa to 192 hPa (Karstens et al., 2010).

Similar, but smaller pressure drop was observed over Parwanipur, Bara at around 7:15 p.m., about two hours after the sharp pressure drop over

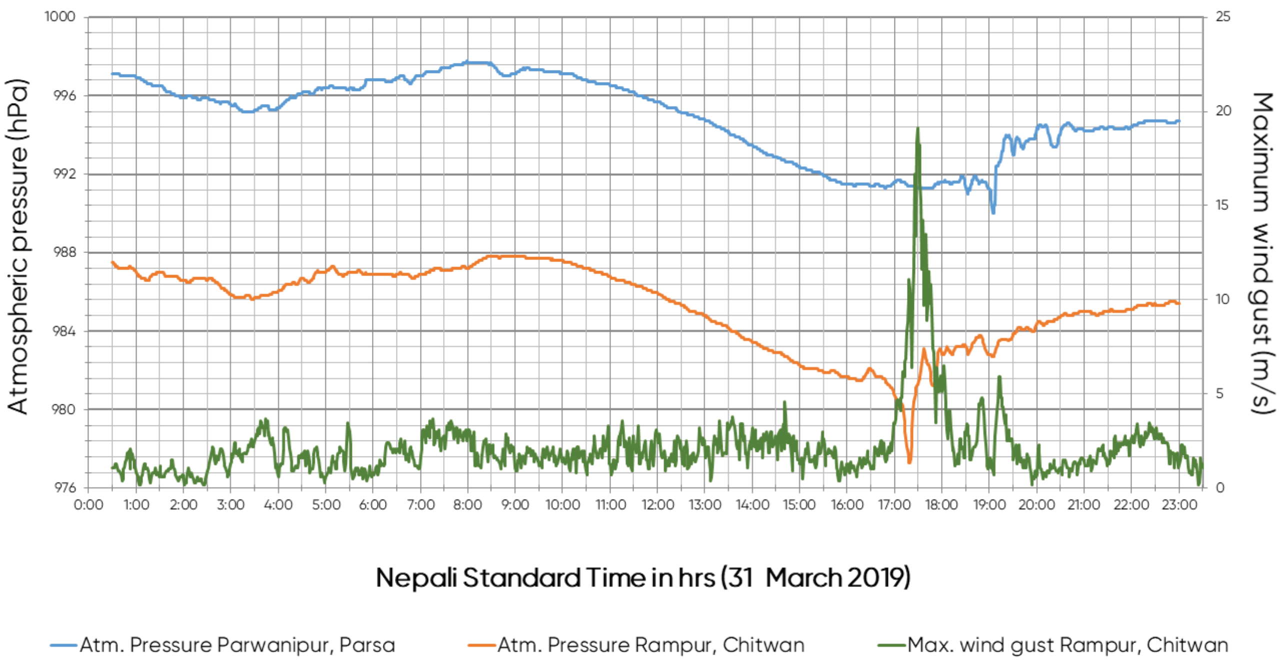

Figure 2.5: *Atmospheric pressure and maximum wind speed (gust) variation in 24-hour period on 31 March 2019 at Parwanipur and Rampur automatic weather stations.*

Rampur. Parwanipur station is close to Chainpur in Bara (an affected area). Areal distance between Rampur station and Parwanipur station is about 85.9 km, so the convective system travelled about 86 km in 2 hours. Hence, the average speed of storm was 43 km/h from Rampur to Parwanipur.

2.5 Analysis of vertical characteristics of atmosphere

Nepal has only one radiosonde station (at Kirtipur, Kathmandu) that takes upper atmospheric measurement once a day at 5:45 a.m. Observed vertical meteorological characteristics of atmosphere at Kirtipur on 31 March 2019 is shown in Figure 2.6a. Due to the differences in terrain, elevation and climate of Kirtipur from that of Bara and Parsa, we assume that the meteorological characteristics of vertical atmosphere measured over Kirtipur may not be representative of that over Bara and Parsa. Sounding station at Patna (25.6 N, 85.10 E), India, about 136 km southeast of Birgunj, Parsa, is the nearest available upper air station that has some similarities in terms of terrain, elevation and climate with Bara and Parsa districts. Therefore, the vertical atmospheric characteristics over Patna might represent that over Bara-Parsa. However, detailed study is necessary to establish the relationships.

The Patna station takes observations twice a day - at 5: 45 a.m. and 5:45 p.m. However, 5:45 p.m. data of Patna is missing for 31 March. Therefore, 5:45 a.m. vertical sounding data of 31 March is used in this report (Figure 2.6b). Since, Kirtipur is in valley at higher elevation than Bara Parsa, we did not use its sounding as reference in this analysis.

Vertical sounding data is used to analyze the status of key basic atmospheric ingredients of tornadic severe storm. There are four major atmospheric ingredients that are necessary for the favorable environment for tornado formation. The first and most critical one is the vertical wind shear – change in wind speed and direction with altitude. Second is warm moist layer at the surface. Third is instability – a measure of available potential energy for convection. Finally, fourth is the forcing or lift, the mechanism that lifts the surface layer upward and help the atmosphere to realize the available potential energy. Detail explanation of these four ingredients is discussed in Box A2.1 in Annex 2.

The wind profile shows mid-atmospheric jet of 23 m/s (45 knots) at about 5 km above the sea level (550 hPa) over Patna (Figure 2.6b). This shows wind speed shear in the lower atmosphere, wind speed increasing with height from the surface to 5 km above the sea level (550 hPa). The wind direction shows wind veering from SW at the surface to WNW at 5 km to NW at 10.7 km above the sea level (250 hPa). Since the surface analysis map (Figure 2.1b) of 5:45 p.m. shows southeasterly flow at 5:45 p.m. directional shear might have increased in the evening compared to in the morning. This wind shear profile suggests the possibility of severe thunderstorm. Higher wind shear condition occurred in Bara and Parsa in the evening that supported tornado formation.

The moisture profile over Patna (Figure 2.6b) shows 16 g/kg of mixing ratio (moisture) at the surface. At mid-level in 500 hPa (>5 km above sea level) moisture was about 0.6 g/kg. This shows steep moisture decrease with a moist layer at the surface and dry layer in the middle atmosphere. Dry layer in the mid-level is one of the factors that leads to increase in the instability. We can assume that the atmosphere over Bara and Parsa might be more unstable with more moisture at the surface and drier layer at mid-atmosphere in the evening than in the morning at Patna.

Convective available potential energy (CAPE), another key ingredient, at Patna was about 1658 j/kg, which was favorable for the formation of moderate severe storm (Gordon and Albert, 2012). Convective inhibition (CIN) was about −310 J/kg; this was a high CIN value which contributed in building more energy. CAPE and CIN values in Patna were high enough to trigger moderate severe storm. The CAPE at Bara-Parsa region might have been higher than in Patna, providing conducive environment for tornado formation.

Combination of above mentioned three favorable key ingredients shown by 5:45 a.m. vertical atmospheric profile of Patna (Figure 2.6b) and the lift (fourth key ingredient) favored by convergence due to surface low formed in the region at 5:45 p.m. (Figure 2.1b in section 2.1) suggests that a conducive environment for the tornado might have developed in Bara-Parsa region. However, a detail study using NWP is required to understand the atmospheric condition in the Bara-Parsa region on 31 March 2019.

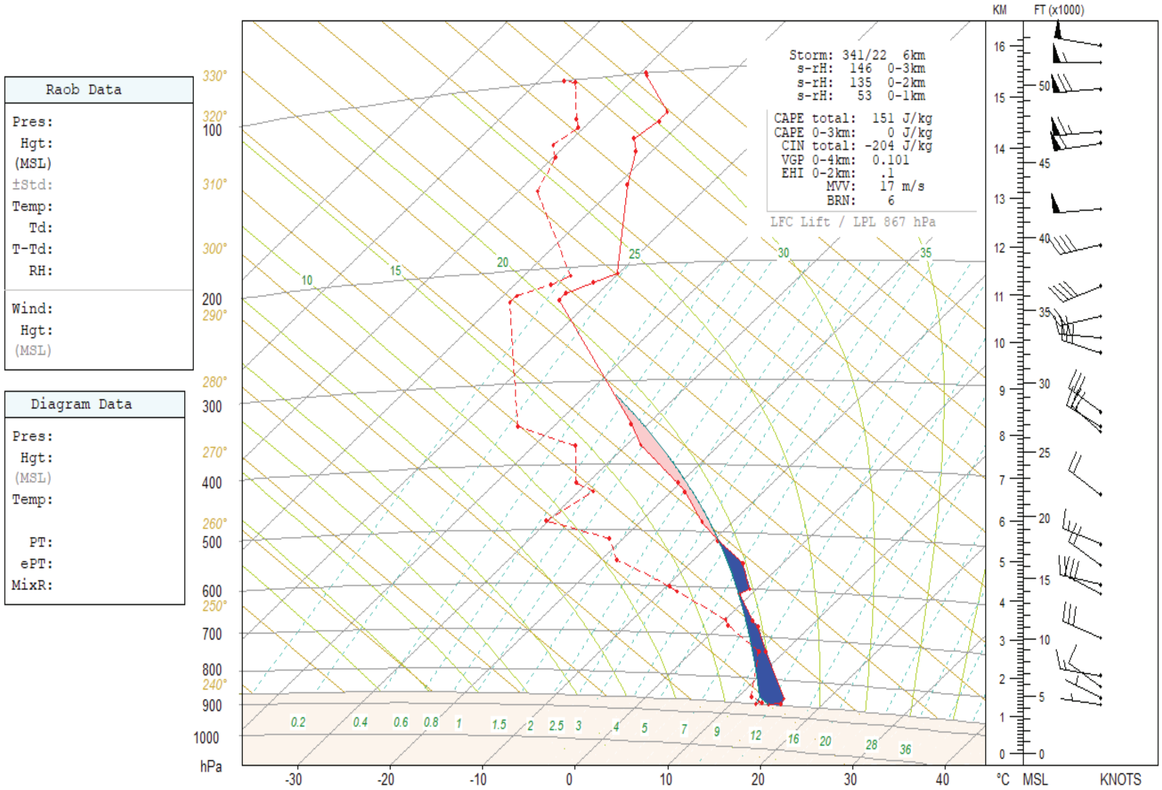

Figure 2.6a: *Skew-T diagram of vertical atmosphere at Kirtipur, Kathmandu at 5:45 a.m. 31 March 2019 (Source: DHM)*

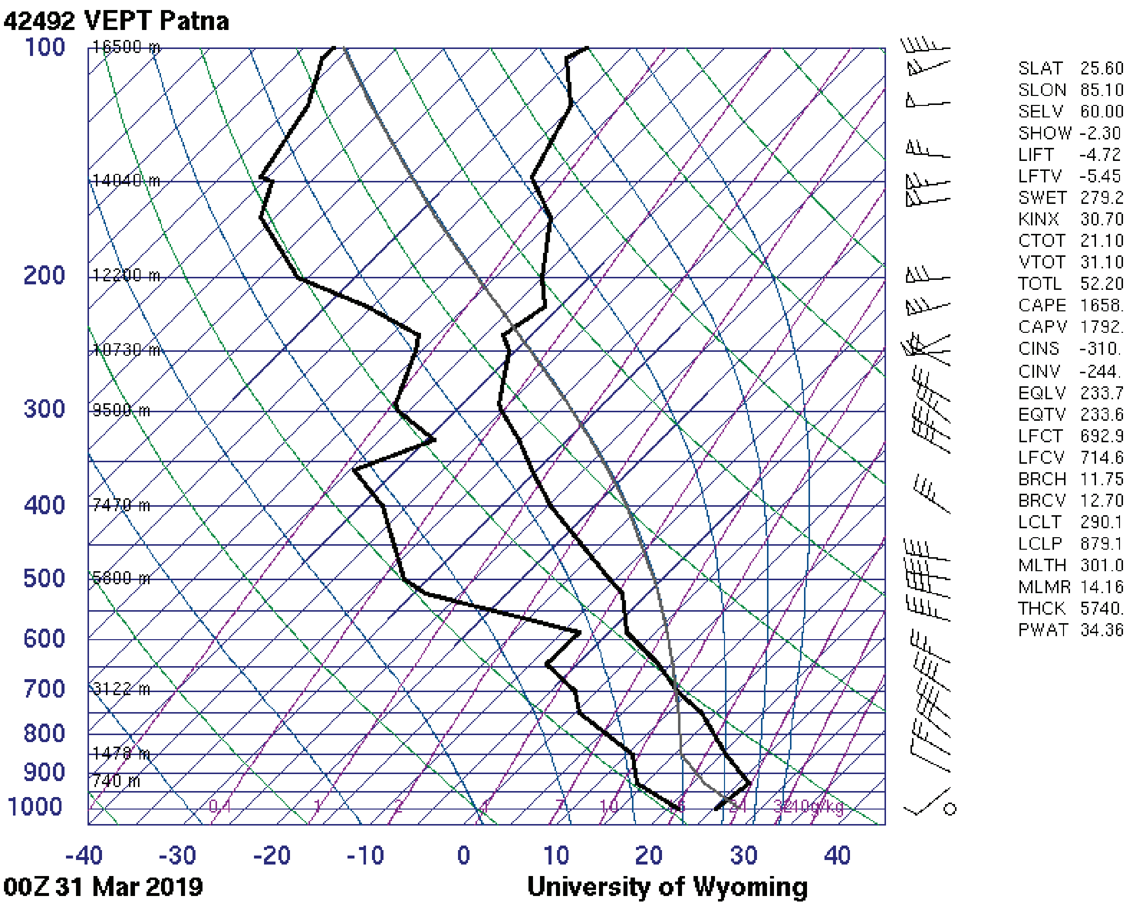

Figure 2.6b: *Skew-T diagram of vertical atmosphere at Patna, India at 5:45 a.m. 31 March 2019.*

2.6 MFD's weather forecast and dissemination on 31 March 2019

Forecast issued by MFD is mainly based on weather observations, weather charts and satellite images. MFD collects weather data from South Asia region whereas, 15 synoptic stations provide every three hourly weather information during the daytime (05:45 a.m. to 5:45 p.m.). MFD is equipped with Himawari satellite and Feng Yun satellite receiving system for receiving satellite imageries.

In addition to this, near real-time lightning activities could be visualized from the LINET system. Moreover, WRF NWP system is also in operation since last few years in MFD. WRF model is running 4 times a day and produces forecast for 72 hours with 12 km and 4 km nested domains. Recently, one Radar in Surkhet and one Radiosonde in Kirtipur is in operation but products are not fully utilized for operational forecasting purposes yet. The incident area is out of range of the Radar in Surkhet.

MFD forecast for the day on 31 March 2019 was: *"chances of being generally cloudy in the eastern and central region along with chances of isolated brief rain or thundershowers at many places of eastern region and some places of central regions"*. This weather forecast was mainly disseminated through its website (www.mfd.gov.np) and media, including social media of Twitter and Facebook. Apart from this, MFD had monitored the weather situation and updated the situation through the social media (Facebook, Twitter). Different numerical models failed to capture the tornado event in Bara and Parsa districts, so the forecasters could not predict and forecast this extreme event.

Weather monitoring and updates posted on twitter:

3. FIELD SURVEY RESULTS

3.1 Background

Seven researchers and experts from DHM, ICIMOD and SEN visited the affected areas of Bara and Parsa districts from 3-8 April 2019. The main purpose of the field survey was to obtain the data on damage pattern from the windstorm and to confirm whether it was a tornado from the ground observation. This chapter discusses various methods and tools used to confirm the tornado on the ground. The second purpose was to obtain the data on the storm characteristics. This chapter also discusses tornado characteristics such as, length and width of the tornado track, strength and speed of the storm and duration of the storm.

During the field visit, information on damage locations was obtained from the District Administration Offices (DAO) of Bara and Parsa. The information of affected areas is summarized in Table 3.1 (the information obtained from the Bara DAO is in Figure A3.1 of Annex 3).

Table 3.1: Locations of damage of properties and lives in Parsa and Bara districts

District	Rural Palikas/ Municipalities	Village (ward no.)
Parsa	Birgunj Metropolitan City	Jagannathpur (22)
		Sukhchaina (18)
Bara	Parwanipur Rural Municipality	Chainpur/Shivapur/Ramtole/Birtatole (4)
	Parsauni Rural Municipality	Khutuwa (4)
		Bhaluhi Chowk North (6)
	Kalaiya Sub-municipality	Dharmanagar (12)
		Managadwa (18)
	Pheta Rural Municipality	Bharawaliya (1)
		Purainiya (6)
		Gamarhaiya (7)
	Devatal Rural Municipality	Rampurwa (7)
	Mahagadhimai Municipality	Telgai (7)
	Suwarna Rural Municipality	Hardiya (4)
		Parshurampur (8)
		Charmohana-Bagahi (1)
		Auraiya (5)
	Pachrauta Municipality	Benauli (7)
		Bairiya (2)

The field team visited most of the villages mentioned in Table 3.1 except in Managadwa (18), Auraiya (5) and Bairiya (2). The visited sites are shown in Figure 3.1. The field team conducted the following tasks in Bara and Parsa districts:

- Took photos of damaged structures in each visited location.
- Measured the tornado path width and of structural damages wherever possible.

- Interviewed locals about the nature of storm, strength of the wind, precipitation type, arrival time of the storm, duration of the disaster, direction of the storm movement etc.
- Took images from UAV.

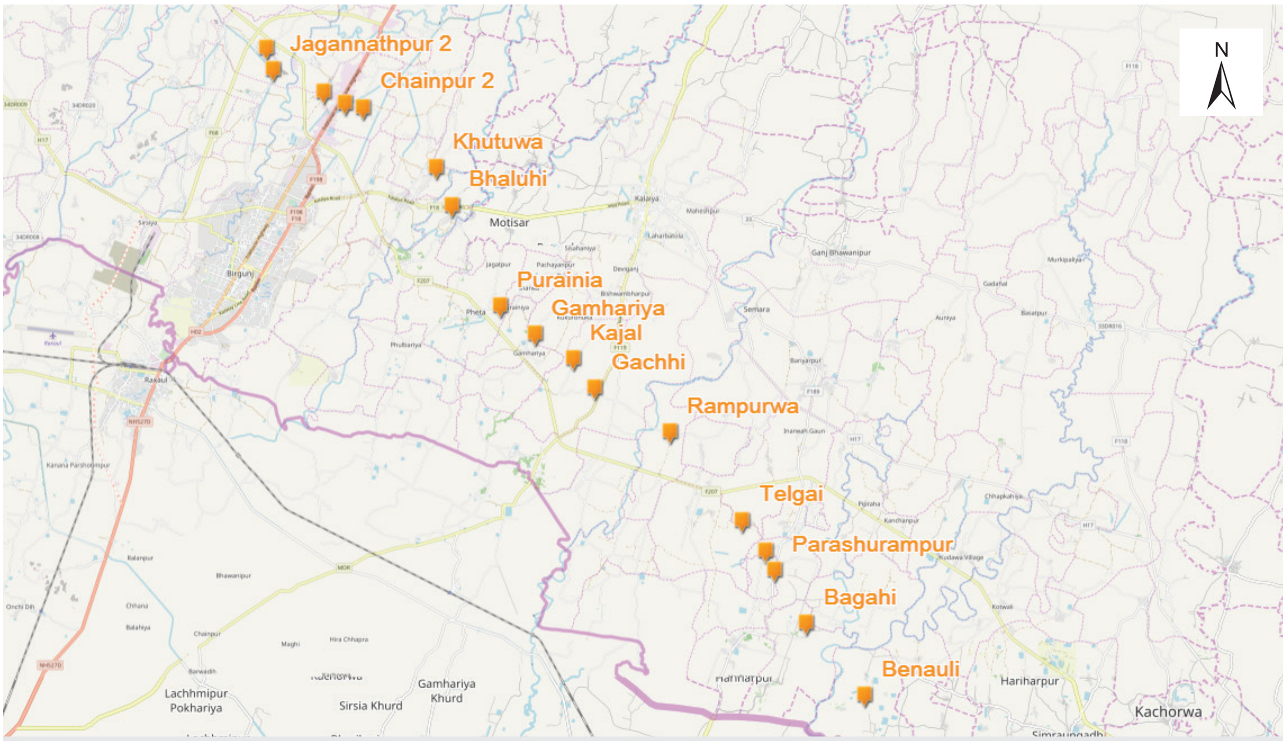

Figure 3.1: *Locations of field assessment in Bara and Parsa districts*

During the survey, the sensFly eBee UAV was used to capture images of the affected areas along the tornado path. Due to windy weather conditions, only nine UAV flights were conducted along the tornado affected areas from Jagannathpur in Parsa to Telgai in Bara. The details of the UAV flight information are given in Table 3.2 and coverage shown in Figure 3.2.

The UAV flight data was used to generate damage patterns, identifying wind directions based on orientation of tree falls and to define widths of damaged areas along the tornado path. All of them are described in the following sections. Before and after storm images of Purainiya, Pheta are shown in Figure 3.3.

Table 3.2: Detail UAV flight information

SN	Flight no	Date and time	Location	Area coverage (km²)	No. of pictures	Flight time (min)
1	EB-03-25336-0066	4 April 2019, 10:40 a.m.	Jagannathpur	2.8	103	21
2	EB-03-25336_0067	4 April 2019, 11:40 a.m.	Sukhchaina	2.8	108	23
3	EB-03-25336_0068	5 April 2019, 08:30 a.m.	Purainiya	Aborted due high wind speed (more than 16 m/s) – it captured 11 pictures.		
4	EB-03-25336_0069	5 April 2019, 12:34 p.m.	Purainiya	2.8	87	19
5	EB-03-25336_0070	5 April 2019, 13:35 p.m.	Bharauliya	3.5	101	21:04
6	EB-03-25336_0071	5 April 2019, 15:35 p.m.	Bhaluhi	3	110	21:36
7	EB-03-25336_0072	5 April 2019, 16:36 p.m.	Katti	2.4	81	16:17
8	EB-03-25336_0073	6 April 2019, 17:02 p.m.	Katti_1	2.2	73	16:17
9	EB-03-25336_0074	6 April 2019, 07:30 a.m	Telgai	1.8	86	21:21

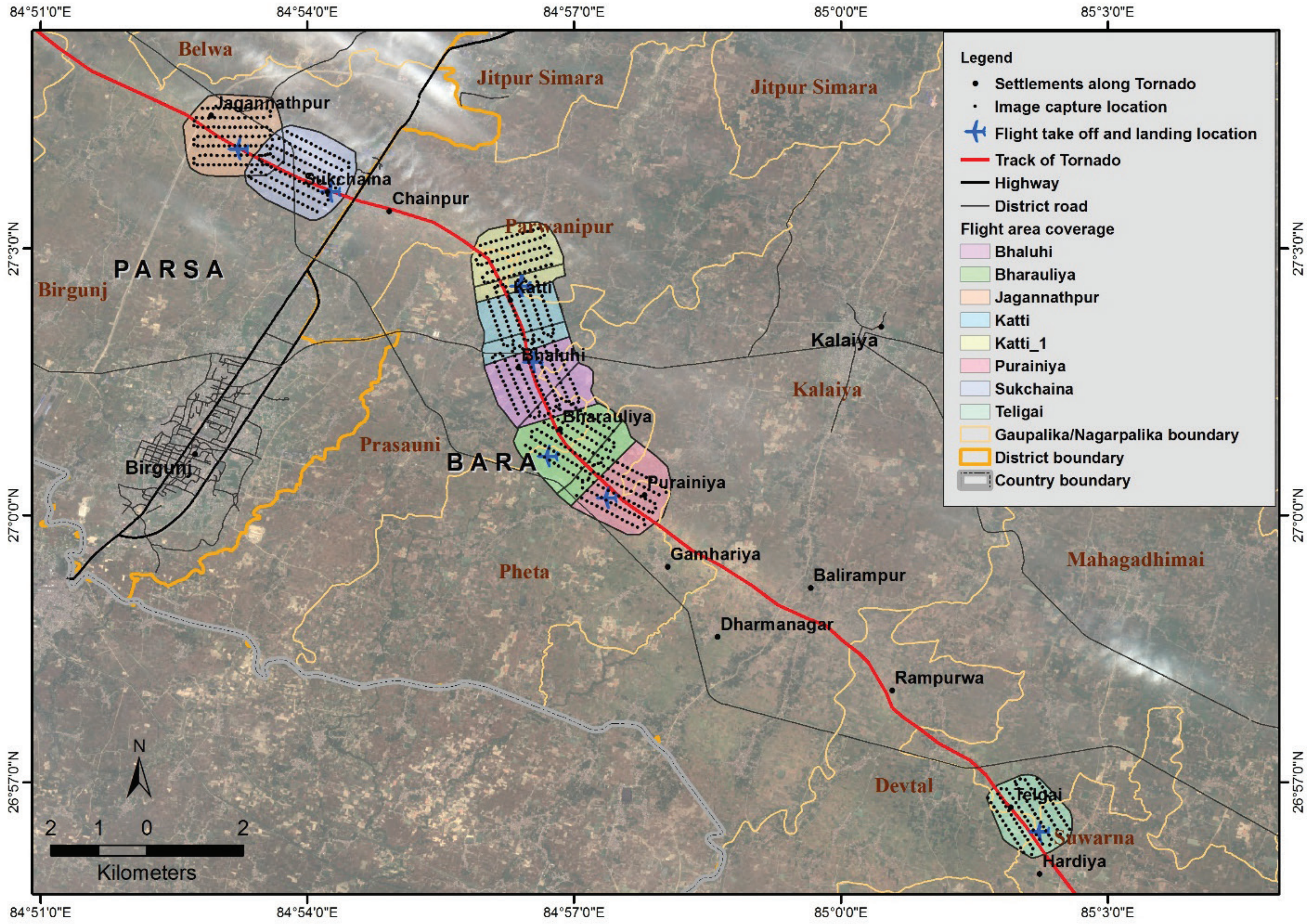

Figure 3.2: *Location and coverage of UAV flights along the tornado path.*

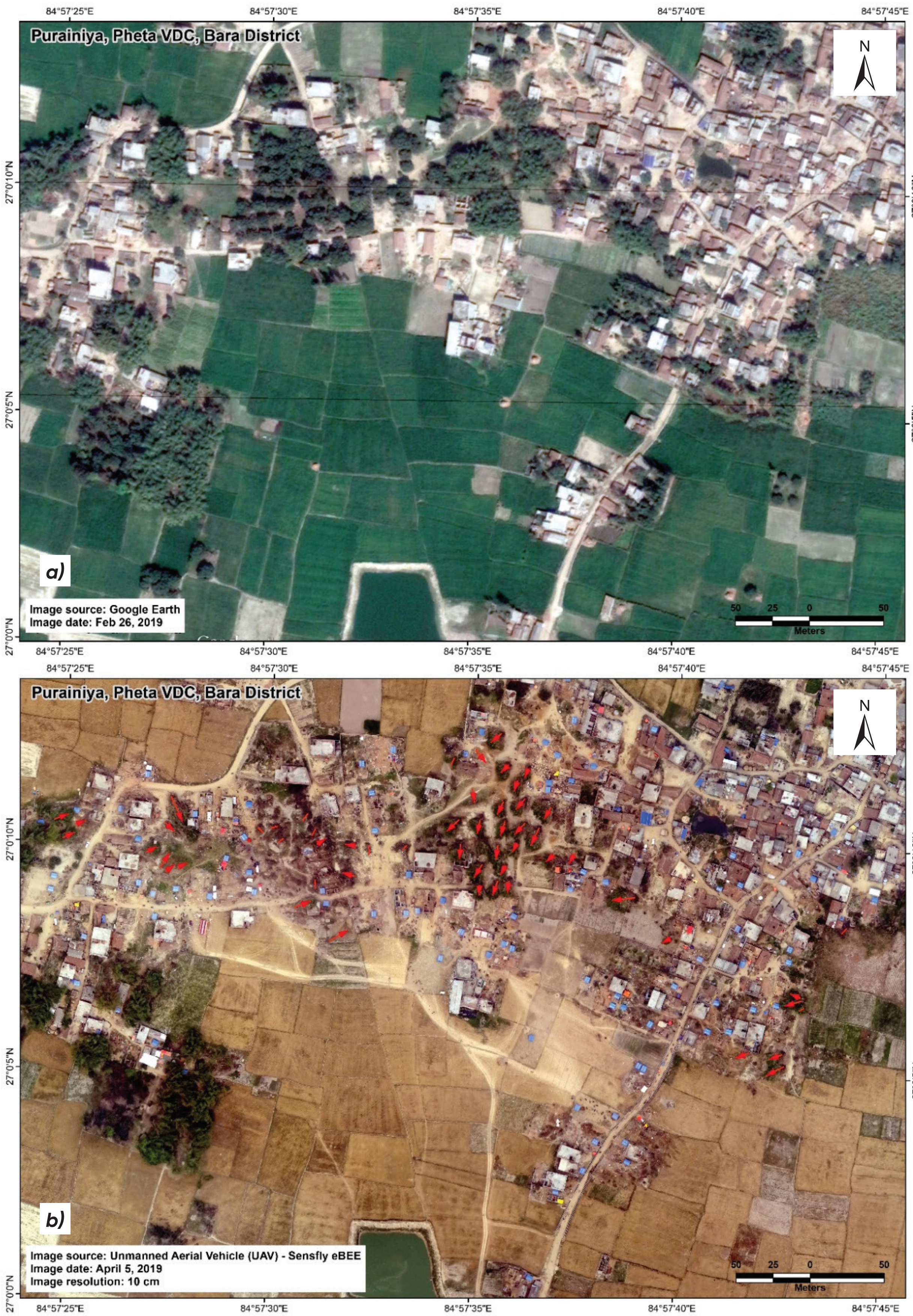

Figure 3.3: *Images of affected area in Pheta. a) Satellite image - before storm (Google Earth) and b) UAV image - after storm*

3.2 Tornado confirmation

3.2.1 Tree fall damage pattern analysis from UAV flights

The wind patterns of storm affected areas of Bara-Parsa districts were reconstructed by analyzing the fallen trees in the images obtained from the UAV flights during the field visit. The wind pattern analysis was done in the areas with patches of tree cover in farmlands and residential areas. Studies conducted on tornado damage assessment in the USA have identified tornado signatures by reconstructing the wind patterns from the damaged forest cover (Hall and Brewer, 1959; Budney, 1965; Beck and Dotzek, 2010; Blanchard, 2013). Various reconstructed wind patterns identified by Hall and Brewer (1959) are shown in Annex 3 (Figure A3.2a-b). Hall and Brewer (1959) presented 3 main types of damage pattern signatures: (a) Trees lay crossed over one another (at **"X"** in Figure A3.2a in Annex 3), (b) "Weak Reverse" flow (at **"Y"** in Figure A3.2a in Annex 3), and (c) "Herringbone" pattern (at **"Z"** in Figure A3.2b in Annex 3). Most recent studies have reconstructed wind patterns based on tree fall by a tornado (Holland et al., 2006; Beck and Dotzek, 2010; Karstens et al., 2013) using mathematical/statistical and computer models, which are shown in Annex 3 (Figure A3.3a-c).

Since, mathematical and computer models do not exist at present in Nepal, we used subjective judgment method to reconstruct wind patterns. Tree fall damage pattern was analyzed at five locations of Bara-Parsa districts, with enough trees to reconstruct wind pattern. These locations are Jagannathpur, Sukhchaina, Purainiya at Pheta, Bharwaliya and Telgai. The results are discussed below:

1. **Jagannathpur:** Tree falls along with associated wind pattern in the farmland and residential areas of Jagannathpur, Parsa is shown in Figure 3.4(a). The tree cover in this location was in very small patches. Wind pattern in the south of center of the tornado track (red line) were reversed from that of the north of the center of the path. This pattern matches with the "reversed" pattern identified by Hall and Brewer (1959), which is the indication of rotational wind. Zoomed view of tree fall pattern in blue box in Figure 3.4(a) is shown in Figure 3.4(b).

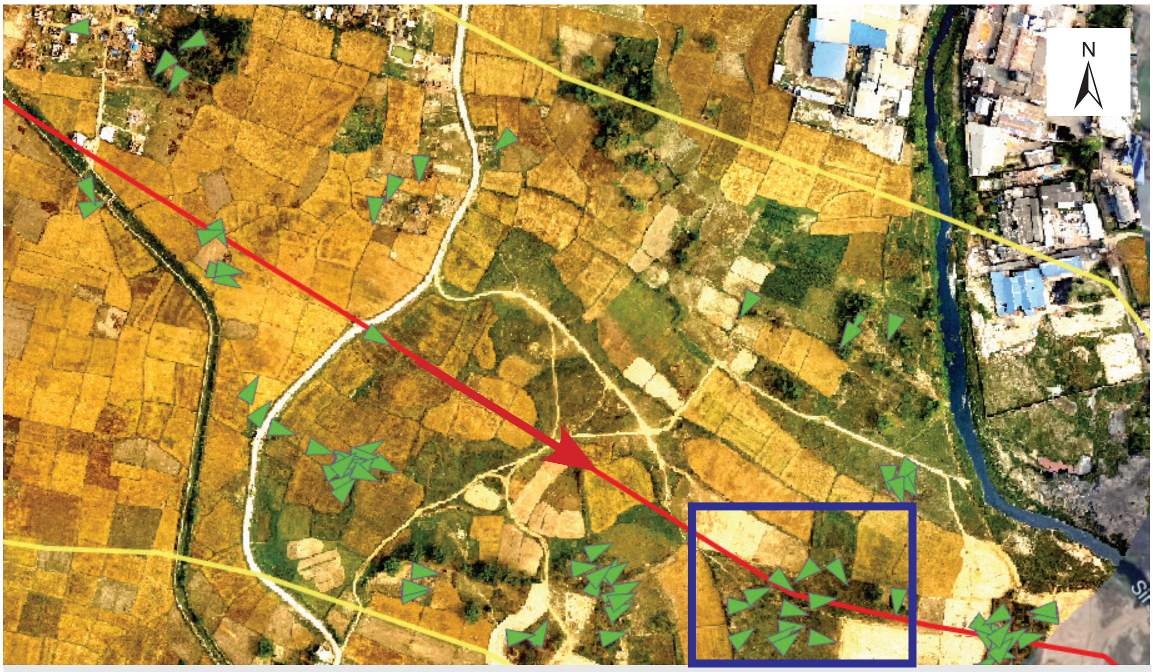

Figure 3.4a: *Aerial view of wind pattern associated with tree fall in Jagannathpur.*
Note: Green arrows indicate direction of the wind but not the magnitude.
Red line: center and direction of tornado path.

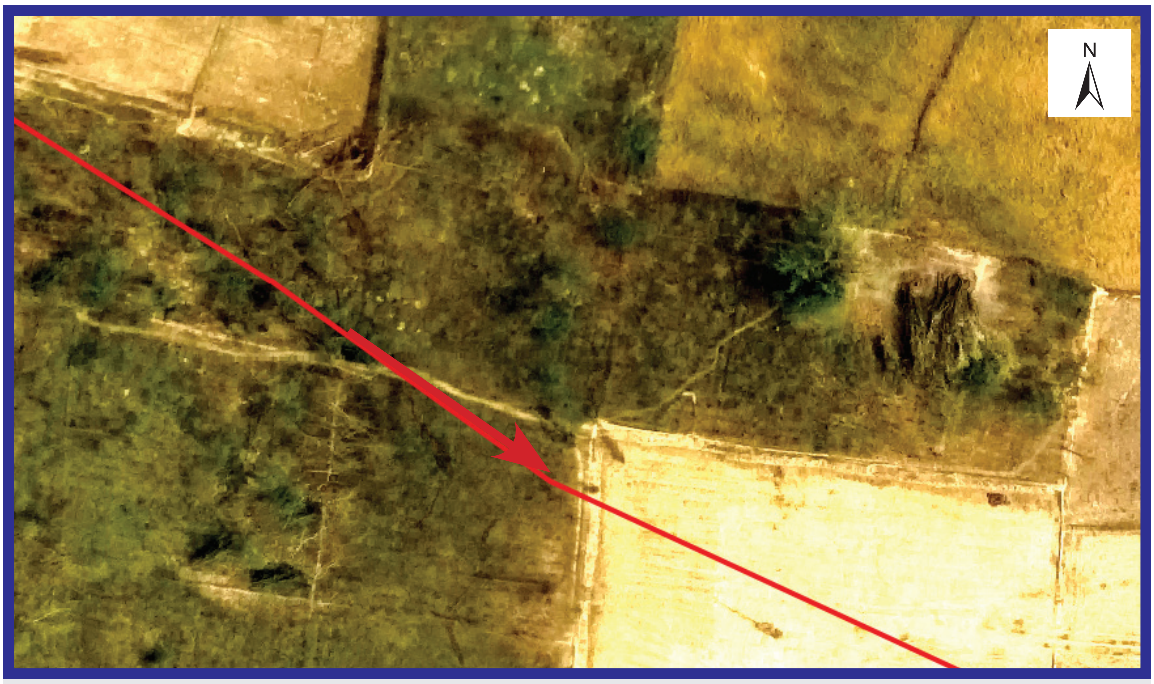

Figure 3.4b: *Zoomed view of damaged trees inside the blue box in Figure 3.4a.*
Red line: center and direction of tornado path.

2. **Sukhchaina:** Aerial view of wind pattern associated with tree fall in Sukhchaina is shown in Figure 3.5(a). Here, the tree cover area was very small. Based on the fallen tree pattern, destructive wind flow direction was generally mirror opposite in northern and southern sides of the center of the tornado track, indicating a circular motion. Figure 3.5(b) shows zoomed view of tree fall in the region in blue box in Figure 3.5(a).

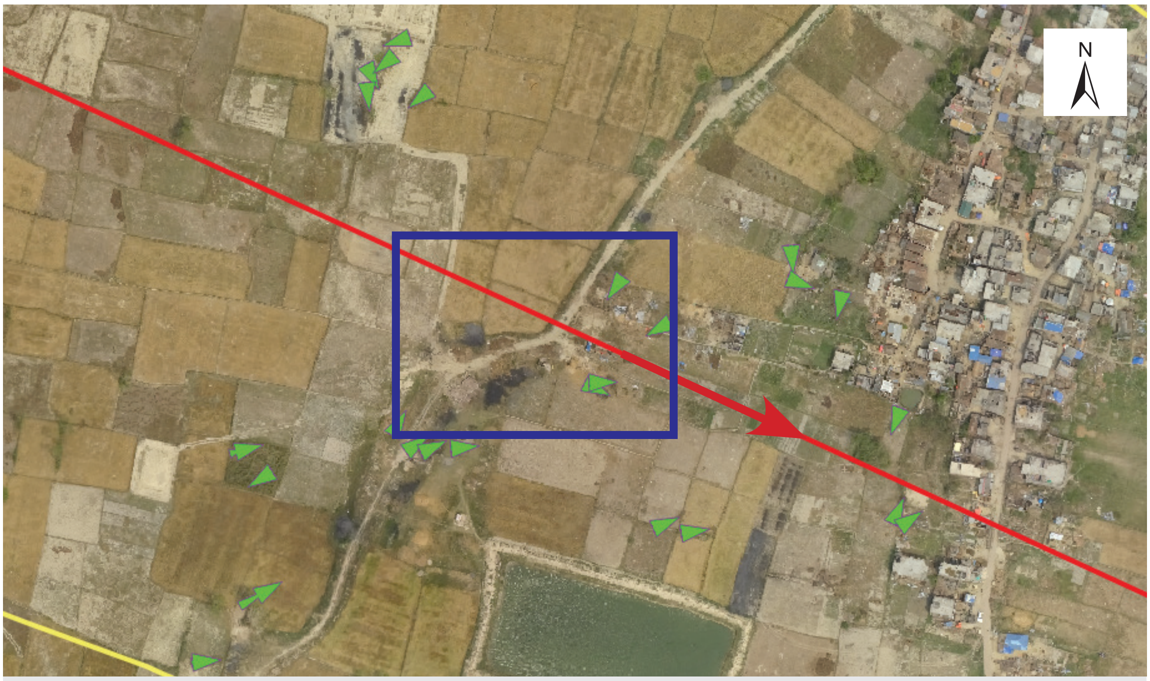

Figure 3.5a: *Aerial view of damaged trees and houses at Sukhchaina.*
Note: Green arrows indicate direction of the wind but not the magnitude. Red line: center and direction of tornado path.

Figure 3.5b *Zoomed view of tree fall in the region in blue box in Figure 3.5a.*
Red line: center and direction of tornado path.

3. **Bhaluhi, Bharwaliya:** Figure 3.6a shows aerial view of tree fall in Bhaluhi, Bharwaliya and Figure 3.6b shows the wind pattern associated with this tree fall in Bhaluhi, Bharwaliya. Close anticlockwise circulation is clearly seen in the region in the blue box in Figure 3.6b. Zoomed view of the region in the blue box in Figure 3.6b is shown Figure 3.6c and Figure 3.6d to show the cyclonic circulation pattern of the tree fall. This close circulation is a clear signature of tornado wind pattern (Figure 3.6c and Figure 3.6d).

***Figure 3.6a:** Aerial view of tree fall at Bhaluhi, Bharwaliya.*
Red line: center and direction of tornado path.

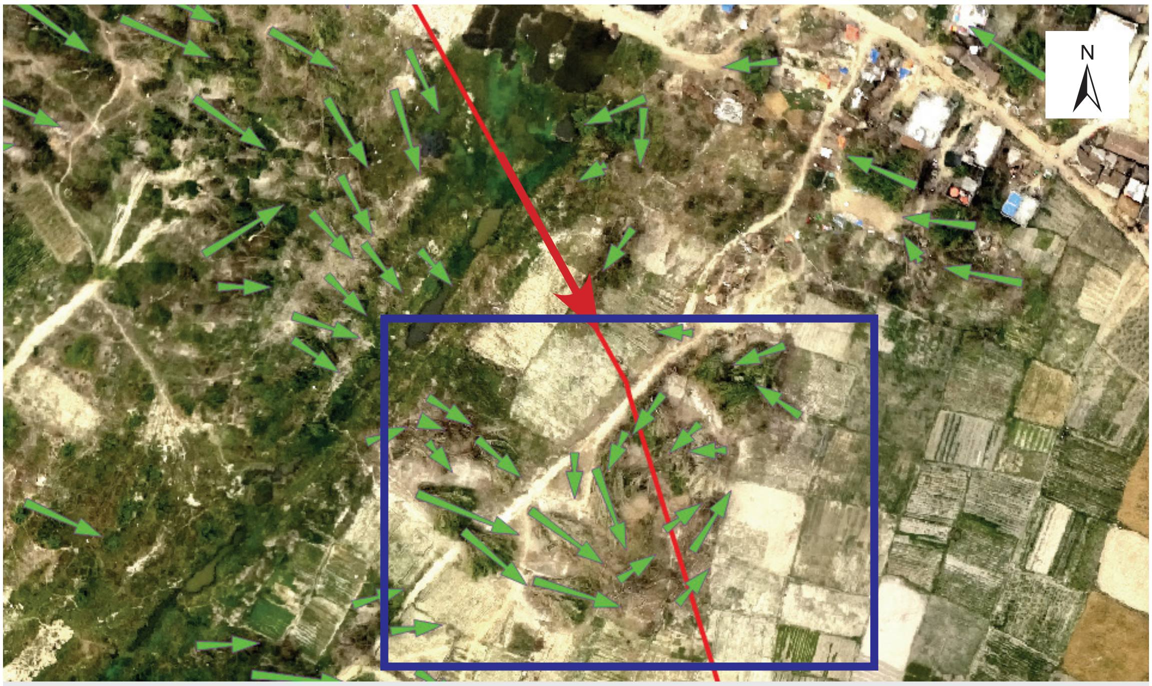

Figure 3.6b: Wind pattern associated with tree fall at Bhaluhi, Bharwaliya shown in Figure 3.6a.
Note: Green arrows indicate direction of the wind but not the magnitude. Red line: center and direction of tornado path.

Figure 3.6c: Zoomed view of the region in blue box in Figure 3.6b, indicating anticlockwise circular wind pattern associated with tree fall. Green arrows indicate direction of the wind but not the magnitude.
Red line: center and direction of tornado path.

Figure 3.6d: *Similar as Figure 3.6c without arrows.*
Red line: center and direction of tornado path.

4. **Purainiya, Pheta:** Figure 3.7a shows wind pattern associated with tree fall at Purainiya, Pheta. Wind direction in the south side of the center of tornado path (red line) is reversed that in north side, suggesting the "reversed" wind pattern. Zoomed view of tree fall in the region in blue box in Figure 3.7a is shown in Figure 3.7b.

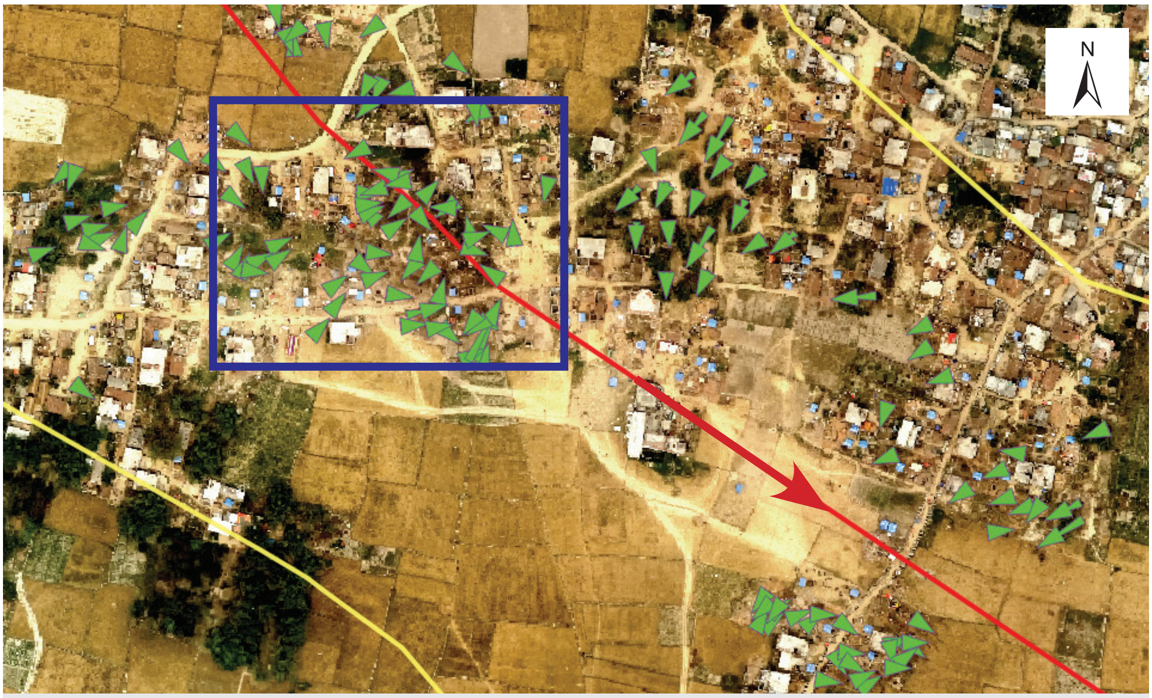

Figure 3.7a: *Wind pattern associated with tree fall at Purainiya, Pheta.*
Note: Green arrows indicate direction of the wind but not the magnitude. Red line: center and direction of tornado path.

Figure 3.7b: *Tree fall in the region in blue box in Figure 3.2.4a.*
Red line: center and direction of tornado path.

5. **Telgai:** Wind patterns associated with tree fall in Telgai-Parshurampur region is shown in Figure 3.8. Wind direction in the south and north of the center of the tornado path (red line) shows coversing pattern as in "herringbone"pattern.

Figure 3.8: *Wind pattern based on tree fall at Telgai.*
Note: Green arrows indicate direction of the wind but not the magnitude. Red line: center of tornado path.

In addition, the wind patterns were also analyzed using photographs of tree tilting. This analysis is shown in Annex 3 (from Figure A3.4 to A3.8). These photos also show example of conversing wind pattern, further confirming a tornado on the ground in Bara and Parsa districts.

In summary, the reconstructed wind patterns in all five locations showed conversing herringbone and reversed patterns, which is indicative of rotational wind. The cyclonic circulation pattern found in the Bhaluhi-Bharwaliya region is the explicit evidence of tornadic wind. These tree-fall damage patterns in Bara-Parsa districts, thus, matched with the criteria of tornadic damage.

3.2.2 Based on interview with eyewitnesses

The team conducted 14 interviews with individuals and in groups at 10 locations. Information gathered from the interviews are summarized in Table 3.3 and associated photos during the interviews are in Figure 3.9. Almost all the interviewees described the storm with horizontally rotating wind in a circular pattern and the rotating storm extended from the ground to the sky, uplifting almost everything in its contact from the ground to the air. Moreover, the team showed photos and YouTube videos of tornado from the USA and asked whether the storm encountered was similar to those photos and videos they confirmed that the windstorm they observed was similar to tornadoes in the audio-visual from the USA. These eyewitness accounts further confirm the storm being a tornado.

According to the locals, convection induced small wind vortices, called "*Bangrera*" in local language, are quite common during the pre-monsoon season in the region. These vortices sometimes lift leaves, dusts and small stones up to about 50 feet above the ground, but they had never witnessed a rotating windstorm of such a large scale before 31 March 2019.

From the interviews, the tentative times of start and end of the storm were also gathered. Most of the interviewees said they did not look at the watch/clock as they were too terrified, so they could tell only a tentative time. When we asked how they knew the time, they told that the storm occurred during the dinner time, which was approximately 7:30-8:00 p.m. According to the interviewees, the storm started between 7:10-7:20 p.m.at Jagannathpur of Parsa district, one of the first residential locations to be hit by this storm. Then the storm moved southeastward from Jagannathpur. The storm might have arrived in Chainpur (first location in Bara district damaged by the storm) at about 7:30 p.m. In the CCTV footage, recorded and obtained from the CG Warehouse office in Chainpur, electricity power went off at about 7:30 p.m. Therefore, tornado must have arrived Chainpur at about 7:30 p.m. Another verified time of arrival of the storm was in Telgai and surrounding locations. A police officer at Telgai informed us that when he called the Mayor of the Telgai Rural Municipality at 7:45 p.m. nothing was reported but at 8:15 p.m. he received a call from the Mayor reporting the damages. Therefore, in Telgai and downstream villages in the southeastern end of the tornado track, the storm hit between 7:45-8:15 p.m. This also matches with the satellite images of 8:05 p.m. and 8:15 p.m. when the storm intensified and by 8:35 p.m., the storm moved to India.

In summary, the eyewitness accounts on rotating wind pattern further confirm the storm being tornado. Also, the tornado might have started at Jagannathpur at 7:20 p.m. (Also looking at satellite image) and ended in Bairiyia at 8:15 p.m. The total duration of the tornado was about 55 minutes.

Table 3.3: Summary of information obtained from interviews in Bara- Parsa affected areas

	Location (No. of interviews)	Approx. Storm time (p.m.)	Approx. Duration (min)	Wind characteristics	Storm Direction	Hydrometeors	Remarks
1	Jagannathpur (1)	Between 7:10-7:20	1 to 2	Strong wind, rotating in circular pattern.	from NW to E	Large hails Lightning	Never seen before
2	Chainpur (3)	7:15-7:30 (Verified with CCTV footage)	1 to 2	Strong wind, rotating for long time (30 min) in the west and then moved to Chainpur Storm width seems more than 200 m	from W	Few but large hails of about 200-250 gm	Tornado video shown to confirm Never seen before
3	Khutuwa (1 group)	After 7:00	< 2	Wind was rotating as if it was dancing	from W	Large hails of 200 gm for short period	Never seen before Tornado video shown to confirm
4	Bhaluhi (1group)	Around 7:00		Strong wind rotating in circular pattern	from W	Large hail and rain after wind	Never seen before
5	Bharwaliya (1group)	After 7:00	1-1.5	Strong wind, sounds like helicopter, uplifting debris About 1 km width	from NW	Large hails for short time Lightning	Never seen before
6	Purainiya, Pheta (1 group)	After 7:30	< 1	Wind was rotating	From NW	Rain after strong wind	Never seen before
	Gamhariya (1 group)	Around 7:00	< 1	Storm was rotating	From NW		Never seen before
7	Rampurwa (1 group)	After 7:00	< 1	Trees falling from all direction, Storm moving in a dancing pattern Rotating faster on land than in cloud Sound of tractor Width of the storm approx. 1 km	From W	Lightning during the storm, Large Hail after storm	Never before of this scale except small vortices or strong gusts
8	Beauli chowk (1)			Wind from all direction. “Bangrera” of large scale		Large hails (200 gm) after wind	Local language “bangrera” for small vortices
9	Telgai (police &1 group)	After 7:45 (Verified with Police)	2	Rotating wind Strong wind - A person was uplifted and blown from home to farm	W to E	Large hails of cricket ball size	Never seen before A person was blown away
10	Charmohaniya	Approx. 8:15	-	-	W to E	Rain and hail	Never seen before

Chainpur | Khutuwa | Gamhariya

Benauli chowk | Telgai police | Telgai village

Purainiya, Pheta | Chainpur | Rampurwa

Figure 3.9: *Interviews at different locations in the affected areas*

3.3 Tornado characteristics

3.3.1 Strength of tornado: maximum wind speed

Strength of a tornado is determined by the estimated maximum wind speed attended. The maximum wind speed of a tornado has never been measured directly by weather stations as it destructs everything on its path (NSSL, 2019). Scientists use Mobile Doppler radars that measure wind speeds in a tornado just above the ground level, and the strongest wind speed 512 km/h was measured on 3 May 1999 near Bridge Creek/Moore, Oklahoma (NWS, 2009).

The maximum wind speed in a tornado is estimated based on the force of destruction. In the USA Enhanced Fujita (EF) scale is developed based on the 28 indicators of destruction to estimate wind speed (WSEC, 2004). Table 3.4 lists the damages in different locations in Bara district (Figure 3.10a-g) along with tentative wind speeds in reference to damage in EF scale as mentioned in WSEC (2004). For some damages the EF reference was not available but for some, it was close to the listed indicators. From this analysis, the maximum wind attended by Bara-Parsa tornado was estimated in between 180 km/h to 265 km/h, which is equivalent to an EF3 tornado.

Table 3.4: List of major damages observed in Bara district and estimated wind speed based on the Enhanced Fujita scale of (WSEC, 2004)

Ref. Figure no.	Description of damage	Estimated wind speed	Reference building in Enhanced Fujita scale indicators in (WSEC, 2004)
3.10a	Concrete roof of 100*12 feet on the top of one-story building uplifted partially (Chainpur)	NA	No reference available
3.10b	Concrete Roof of approx. 20*20ft on top of two-story building blown away 80m far (Gamhariya)	NA	No reference available
3.10c	Brick walls of top floor structure collapsed completely in some one-story houses (Pheta)	182-246 km/h (avg:212 km/h)	One- or two-family residence (indicator 2)
3.10d	Storage building with brick walls and tin roof on metal frame: exterior wall collapsed completely, and roof blown away (Chainpur)	188- 265 km/h (avg:225 km/h)	Strip Mall (indicator 10) Light-frame steel roof support with steel joists or joist girders and Brick or concrete block wall construction
3.10e	Trees snapped (Gamhariya)	180-246 km/h (avg: 211 km/h)	Trees soft wood debarked with only stubs of largest branches remaining
3.10f	Bamboo trees uprooted (Pheta)		No ref available
3.10g	20-ton trucks tussled (Chainpur)		No ref available

Figure 3.10a: *Concrete roof of 100 × 12 feet, one-story building uplifted partially (Chainpur)*

Figure 3.10b: *Concrete roof of approx. 20 × 20 feet one story building blown away 80 m downstream (Gamhariya)*

Figure 3.10c: *Brick walls of top floor structure collapsed completely in some two-story houses (Pheta)*

Figure 3.10d: *Storage building: exterior brick walls with tin roof on metal frame collapse completely in Chainpur*

Figure 3.10e: *Big Trees snapped at Gamhariya*

Figure 3.10f: *Bamboo trees uprooted in Pheta*

Figure 3.3g: *Loaded trucks (20 tons) tussled in Chainpur*

3.3.2 Tornado track length

The Sentinel-2 MSI images (10 m spatial resolution) from the European Space Agency (ESA) was assessed through the GEE and higher resolution PlanetScope (3 m) images were acquired from Planet.com with the support from the SERVIR Science Coordination Office (SCO). Both images were used to trace the path and track direction of the tornado as shown in Figure 3.11a and Figure 3.11b.

The analysis from Sentinel-2 images clearly indicated that the tornado affected the Chitwan National Park area. There was a report of uproot of trees in the Thori region by an observer from a weather station of DHM. However, no field survey was conducted in this section to analyze the damage pattern of impacted trees in the forest. Therefore, this is still an area of investigation. This first track was estimated using satellite image and was stretched by more than 9 km at S22°E[1] direction (Figure 3.11a).

According to the DAO, damages on houses and lives by tornado initiated at Jagannathpur of Parsa district. However, the analysis of the Sentinel-2 images showed this second track (Bara-Parsa track) of the tornado started from Sakhuwa-Parsauni, west of Jagannathpur, in Parsa district. The damaged area between Sakhuwa-Parsauni and Jagannathpur is wheat field, and the damages on crops there were recorded by Parsa Agriculture Knowledge Center (Krishi Gyan Kendra). Evidences from satellite image and from Knowledge Center suggest that the tornado started from Sakhuwa-Parsauni of Parsa district and ended at Bairiya of Bara district.

The total distance of Bara-Parsa part (from Sakhuwa-Parsauni, Parsa to Bairiya, Bara) was 43.6 km and the track orientation was S43oE (Figure 3.11b). The fieldwork along the track from Jagannathpur to Bairiya also indicated the major impact was from Jagannathpur to Bairiya. Based on the direction of its path, the second track (Bara-Parsa track) was divided into fourteen sections (Figure 3.11b) and details of each section

1 *SX°E indicates the direction is X° east from south.*

are in Table 3.5. Pre and post event satellite images of 27 March and 3 April 2019 from PlanetScope are shown in Figure 3.12. The Sentinel-2 images (Figure 3.11b) showed some changes in texture and tone at Sakhuwa-Parsauni area but clear impact was observed from the Jagannathpur onwards, which was also clear in the higher resolution images of planet.com (Figure 3.12).

Table 3.5: Different sections of the tornado path based on its orientation.

Section no (West to East)	From (Location / Coordinates)	To (Location / Coordinates)	Distance covered (km)	Measurement Direction (o) *South to east*	Confirmation Source
1	Sakhuwa-Parsauni (84°47'23.03"E, 27°09'04.04"N)	Patani (84°49'12.32" E, 27°06'55.43" "N)	4.9	S 40 E	Agriculture Knowledge Center (Krishi Gyan Kendra), Parsa
2	Patani (84°49'12.32" E, 27°06'55.43"N)	Bahuari (84°50'04.59"E, 27°06'30.30"N)	1.6	S 64 E	
3	Bahuari (84°50'04.59"E, 27°06'30.30"N)	Dokala (84°50'54.94"E, 27°05'28.93"N)	2.3	S 39 E	Agriculture Knowledge Center, Parsa/ interview at Jagannathpur
4	Dokala (84°50'54.94"E, 27°05'28.93"N)	Jagannathpur (84°52'38.24"E, 27°04'30.37"N)	3.4	S 60 E	Agriculture Knowledge Center, Parsa
5	Jagannathpur (84°52'38.24" E, 27°04'30.37" N)	Sukhchaina (84°54'21.33"E, 27°03'36.79"N)	3.3	S 63 E	Parsa DAO and field verification
6	Sukhchaina (84°54'21.33"E, 27°03'36.79"N)	Chainpur (84°55'32.34"E, 27°03'13.42"N)	2.1	S 72 E	
7	Chainpur (84°55'32.34"E, 27°03'13.42"N)	Katti (84°56'16.44""E, 27°02'24.73" N)	2	S 41 E	Bara DAO and field verification
8	Katti (84°56'16.44"E, 27°02'24.73"N)	Bhaluhi (84°56'31.20"E, 27°01'38.25"N)	1.5	S 18 E	
9	Bhaluhi (84°56'31.20"E, 27°01'38.25"N)	Bharauliya (84°56'58.17"E, 27°00'43.70"N)	1.8	S 26 E	
10	Bharauliya (84°56'58.17"E, 27°00'43.70"N)	Purainiya (84°57'45.23"E, 27°00'01.32"N)	1.8	S 48 E	
11	Purainiya (84°57'45.23"E, 27°00'01.32"N)	Balirampur (84°59'49.96"E, 26°58'45.45"N)	4.2	S 59 E	
12	Balirampur (84°59'49.96"E, 26°58'45.45"N)	Rampurwa (85°00'34.64"E, 26°57'49.95"N)	2.1	S 39 E	
13	Rampurwa (85°00'34.64"E, 26°57'49.95"N)	Telgai (85°01'54.19"E, 26°56'42.51"N)	3	S 50 E	
14	Telgai (85°01'54.19"E, 26°56'42.51"N)	Bairiya (85°05'33.75"E, 26°52'41.49"N)	9.6	S 42 E	

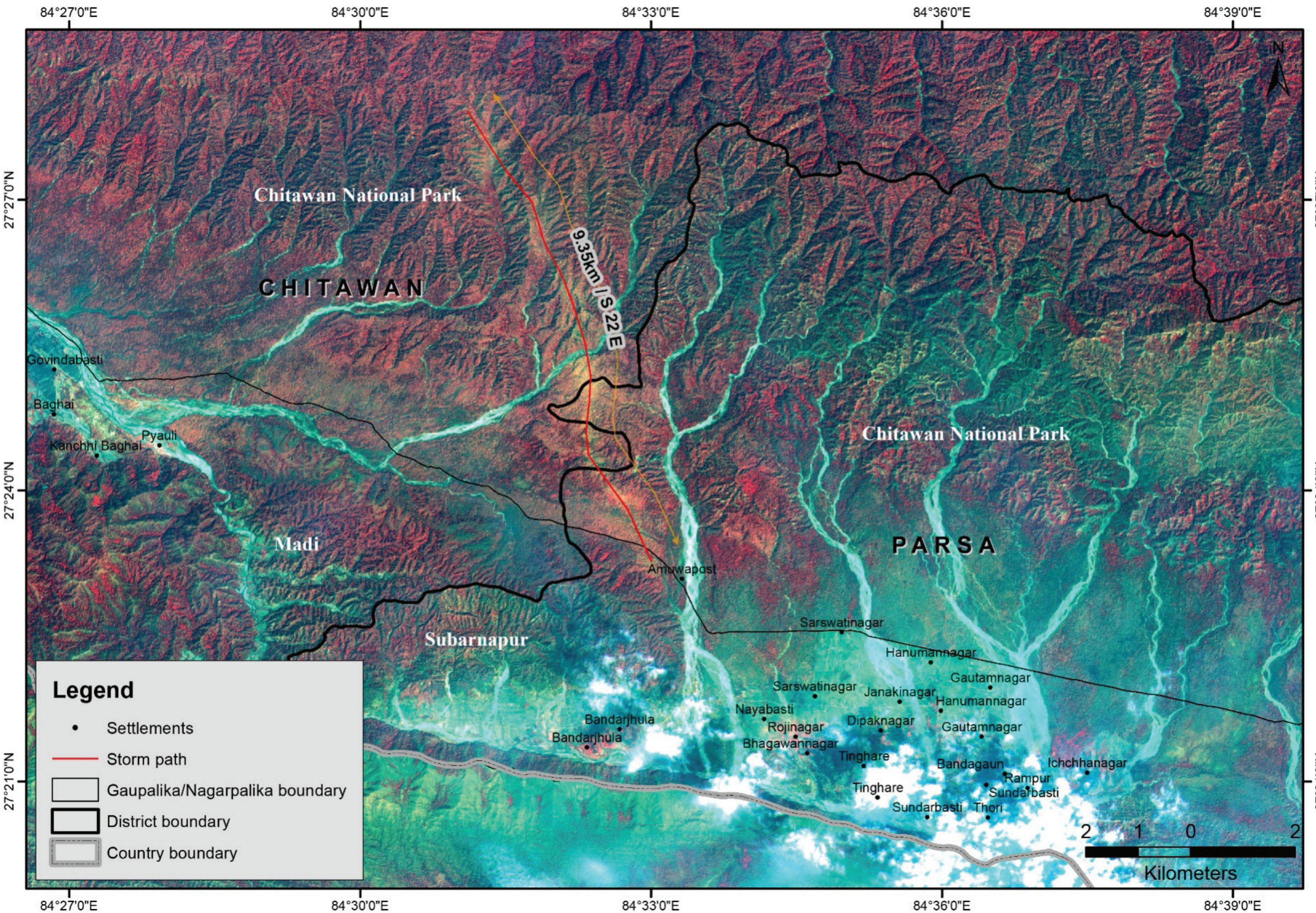

Figure 3.11a: *The redline shows the path of the tornado in Chitwan National Park (center of the affected area).*

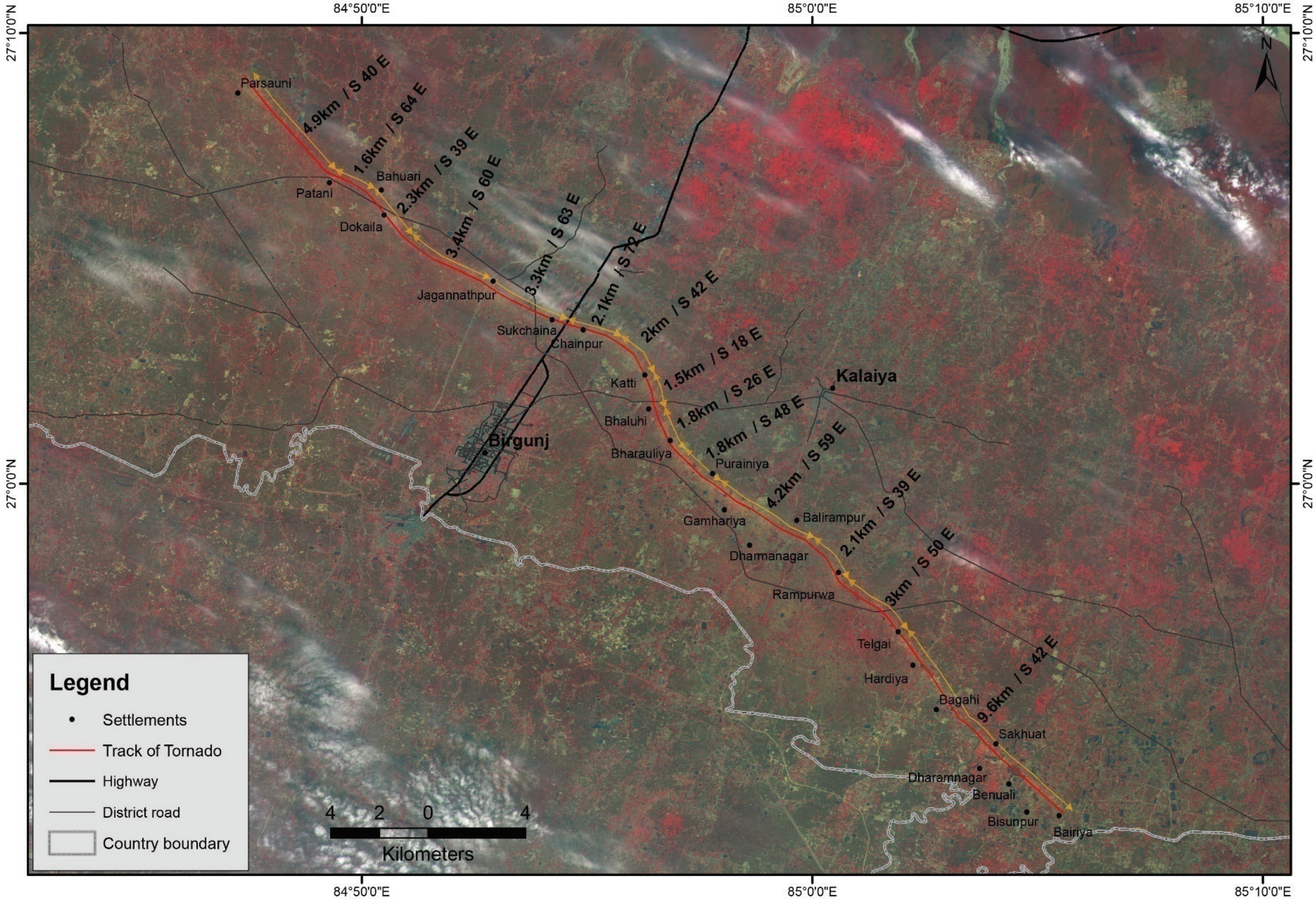

Figure 3.11b: *The redline shows the path of the tornado (center to the affected area) in Parsa and Bara districts. Background image: Sentinel-2 MSI, from1 April 2019.*

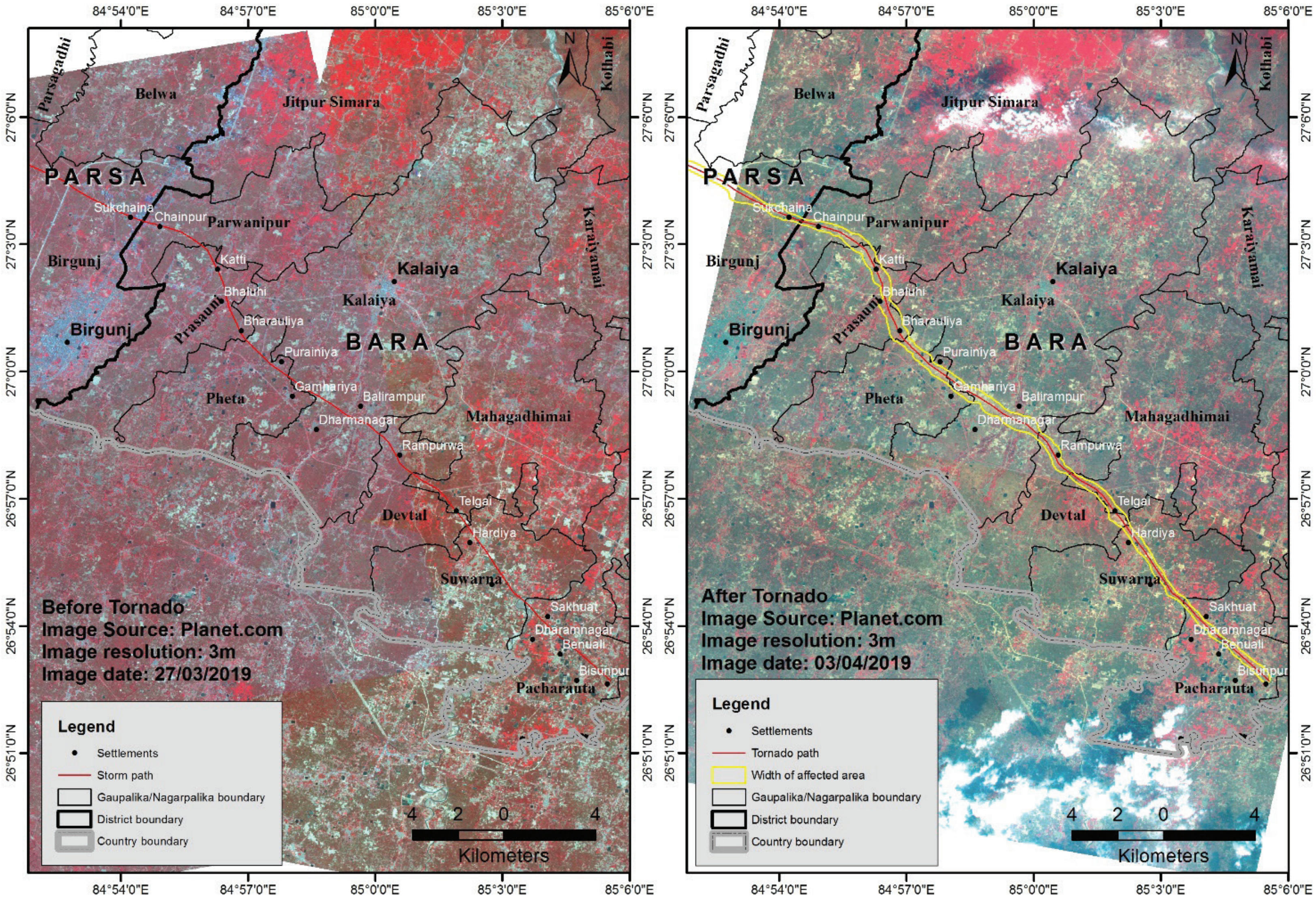

Figure 3.12: *Before and after satellite images showing the path and affected width of the tornado in Bara and Parsa districts.*

3.3.3 Track width

Widths of the affected areas were identified by visual interpretation of pre and post available satellite images and using UAV images wherever they were taken. The boundary of the affected area was traced based on the changes in tone and texture of those (pre and post) images from PlanetScope and further verified using the images from UAV. The images from PlanetScope only cover from Jagannathpur to Bairiya so the upper section from Sakhuwa-Parsauni to Jagannathpur was generated from the sentinel-2 MSI images.

The width of the affected area was calculated by generating perpendicular line at 100 m interval over the central line of the affected boundary (Figure 3.13). The result shows that the width varies from 200 m to 746 m from the Sakhuwa-Parsauni to Bairiya. The highest width is in Sakhuwa-Parsauni area where the damages are mostly in the cultivated land not in any settlement. From Jagannathpur to Bairiya, the width ranges from 200 m to 695 m in which the maximum width is in Bharauliya and near Balirampur. The width ranges in each 100 m interval stretch from Sakhuwa-Parsauni to Bairiya is shown in Figure 3.13 and detail width ranges along the track is given in Table 3.6. The width of the track from Sakhuwa-Parsauni to Jagannathpur was estimated from Sentinel MSI images whereas from the Jagannathpur to Bairiya was traced using the higher resolution images of PlanetScope and UAV images.

Table 3.6: Width ranges in each section of the tornado track from Sakhuwa-Parsauni to Bairiya.

Section no (West – East)	From (Location / Coordinates)	To (Location / Coordinates)	Distance (km)	Direction (o) South to east	Affected width ranges (m)
1	Sakhuwa-Parsauni (84°47'23.03"E, 27°09'04.04"N)	Patani (84°49'12.32" E, 27°06'55.43" "N)	4.9	S 40 E	200 - 746
2	Patani (84°49'12.32" E, 27°06'55.43" "N)	Bahuari (84°50'04.59"E, 27°06'30.30"N)	1.6	S 64 E	218 - 300
3	Bahuari (84°50'04.59"E, 27°06'30.30"N)	Dokala (84°50'54.94"E, 27°05'28.93"N)	2.3	S 39 E	235 - 539
4	Dokala (84°50'54.94"E, 27°05'28.93"N)	Jagannathpur (84°52'38.24" E, 27°04'30.37" N)	3.4	S 60 E	240 - 400
5	Jagannathpur (84°52'38.24" E, 27°04'30.37" N)	Sukhchaina (84°54'21.33"E, 27°03'36.79"N)	3.3	S 63 E	260 - 616
6	Sukhchaina (84°54'21.33"E, 27°03'36.79"N)	Chainpur (84°55'32.34"E, 27°03'13.42"N)	2.1	S 72 E	244 - 433
7	Chainpur (84°55'32.34"E, 27°03'13.42"N)	Katti (84°56'16.44""E, 27°02'24.73" N)	2	S 41 E	431 - 644
8	Katti (84°56'16.44""E, 27°02'24.73" N)	Bhaluhi (84°56'31.20"E, 27°01'38.25"N)	1.5	S 18 E	290 - 620
9	Bhaluhi (84°56'31.20"E, 27°01'38.25"N)	Bharauliya (84°56'58.17"E, 27°00'43.70"N)	1.8	S 26 E	484 - 679
10	Bharauliya (84°56'58.17"E, 27°00'43.70"N)	Purainiya (84°57'45.23"E, 27°00'01.32"N)	1.8	S 48 E	354 - 520
11	Purainiya (84°57'45.23"E, 27°00'01.32"N)	Balirampur (84°59'49.96"E, 26°58'45.45"N)	4.2	S 59 E	446 - 693
12	Balirampur (84°59'49.96"E, 26°58'45.45"N)	Rampurwa (85°00'34.64"E, 26°57'49.95"N)	2.1	S 39 E	315 - 695
13	Rampurwa (85°00'34.64"E, 26°57'49.95"N)	Telgai (85°01'54.19"E, 26°56'42.51"N)	3	S 50 E	239 - 430
14	Telgai (85°01'54.19"E, 26°56'42.51"N)	Bairiya (85°05'33.75"E, 26°52'41.49"N)	9.6	S 42 E	204 - 594

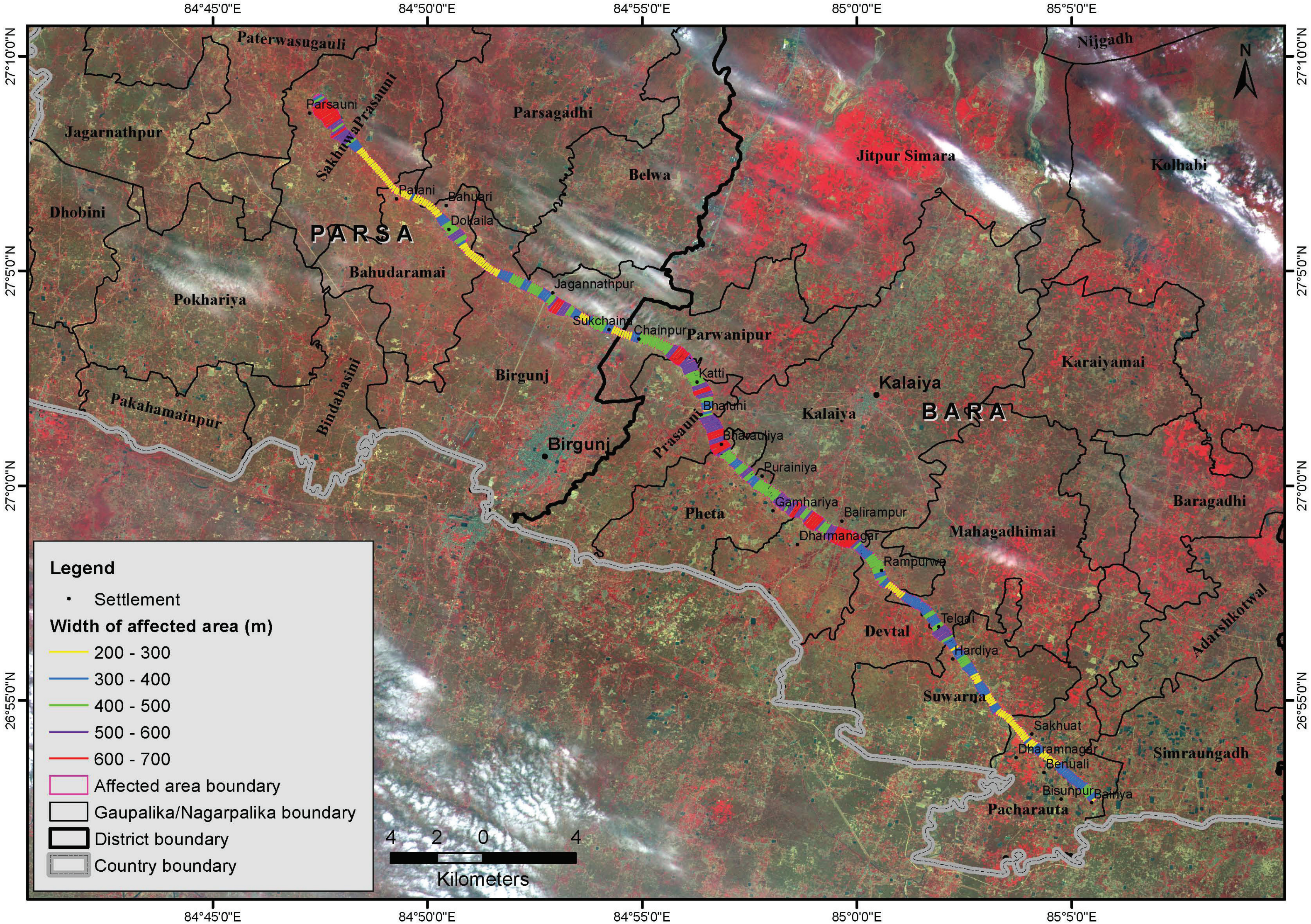

Figure 3.13: *Width of the affected area from Sakhuwa-Parsauni to Bairiya. (Background images: Sentinel MSI; Date: 1 April 2019; PlanetScope and UAV images are used to identify the width of affected area from Jagannathpur to Bairiya)*

The detail methodology used to calculate the track width from satellite images and UAV captured images is explained in Annex 3 (Box A3.1).

3.3.4 Storm speed

The length of the track from Jagannathpur to Bairiya was about 31.4 km. Based on interviews and field evidences as detailed above (and supported by Himawari-8 images), time taken for the tornado to travel 31.4 km distance was tentatively 55 minutes (from 7:20-8:15 p.m.). Therefore, the estimated average storm speed was 34.2 km/h.

3.3.5 Summary of tornado features

Major features of the tornado and its track are summarized in Table 3.7. No information is available for the Chitwan section other than the length of track. Chitwan section is 9 km long while Bara-Parsa section is about 43.6 km. Width of the track was estimated only for Bara-Parsa section and it varied between 200 to750 m. From the data obtained and available references, maximum wind speed of the tornado was between 180 to 265 km/h, which is of EF3 strength. The tornado traveled southeastwards from Jagannathpur to Bairiya with an average speed of 34.2 km/h in about 55 minutes from 7:20 p.m. to 8:15 p.m. on 31 March 2019.

Table 3.7: Summary of the features of the Bara-Parsa tornado on 31 March 2019

Section of Tornado track		Length of track (km)	Width of the track (m)	Maximum Intensity (km/h)	Travel time (min)	Average Storm Speed (km/h)
Bara-Parsa Section	Sakhuwa-Parsauni to Jagannathpur	12.2	200 to 746	-	-	-
	Jagannathpur to Bairiya	31.4	200 to 695	180-265 (EF3 tornado)	55 (7:20-8:15pm)	34.2
	Total Sakhuwa-Parsauni to Bairiya	43.6	200-750	-	-	-

Note: The length of the track in Chitwan National Park is about 9 km as estimated from the satellite images

4. WAY FORWARD: DISASTER PREPAREDNESS

Nepal needs to undertake two strong preparedness actions to reduce the damages from severe storm events including tornado. Firstly, strengthen the capabilities of DHM to make reliable, timely and site-specific alerts and warnings of extreme weather events like tornado. This can be achieved by developing severe weather forecasting system for nowcasting, in DHM. Secondly, build resilience at national to local levels to respond to extreme weather incidents. Among other activities, this includes undertaking of timely and appropriate actions on alerts and warnings issued. The latter can be achieved through close collaboration and coordination among NEOC, local bodies and communities, and other stakeholders.

4.1 Development of severe weather forecasting system for nowcasting

Issuing timely severe weather warning/alert based on identification of such a weather system in the observational data is called nowcasting. According to the World Meteorological Organization (WMO), "nowcasting comprises the detailed description of the current weather along with forecasts obtained by extrapolation for a period of 0 to 6 hours ahead" (WMO, 2019). Nowcasting with reasonable accuracy is a powerful tool to reduce causalities from severe weather events. WMO (2019) also pointed that "The strength of nowcasting lies in the fact that it provides location-specific forecasts of storm initiation, growth, movement and dissipation, which allows for specific preparation for a certain weather event by people in a specific location". Such a specific and detail forecast of extreme weather events is a very challenging task. It gets more difficult when such events are small and of short duration. Hence, like other small-scale extreme weather phenomena, tornado warning is one of the most challenging tasks in the field of meteorology. For initiating nowcasting and issuing an accurate, timely, reliable, specific and detail forecast of such extreme weather events, a well-equipped (with infrastructure and skilled human resources) severe weather forecasting system is necessary.

At present, the National Weather Service (NWS) of the USA provides arguabally the world's best tornado warning system. This tornado warning process is a part of severe weather forecasting system and involves a continuum process of developing 1-8 day convective outlook supported by mesoscale discussions to produce tornado watches and tornado warnings (nowcasting), which are issued by the Storm Prediction Center, under NWS (Figure 4.1). The detail of the steps involved in tornado forecasting and warning is explained in Section A4.1 of Annex 4.

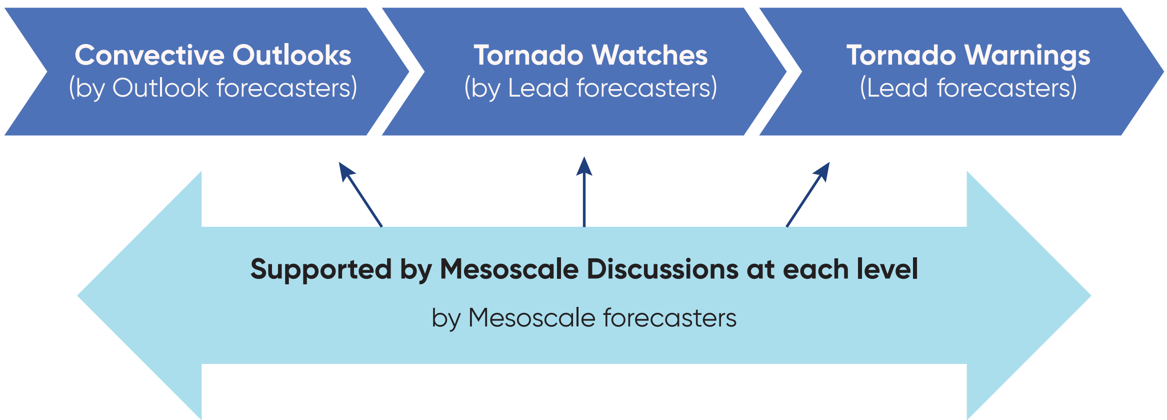

Figure 4.1: *Framework summary of steps involved in tornado warming system of the Storm Prediction Center, National Weather Service of the USA. Arrows represent scientific support using Mesoscale Discussion to each of the three products*

Significant reduction in tornado casualties and injuries were reported in the USA between 1986 and 1999 (Simmons and Sutter, 2005) and between 1950 and 2000 (Boruff et al., 2003) as a result of implementation of WSR-88D Doppler radar network, increased warning lead times, and improved public compliance with warnings. Followings are the four types of resources used for a tornado warning in the Storm Prediction Center (SPC) in NWS and are must for tornado warning anywhere:

1. **Past and present data in real time:** Past and current weather observations allow forecasters to closely monitor changes in the atmosphere that lead to severe weather/ tornado. These observations come from satellite imageries, RADARs, automatic surface weather stations, weather balloon soundings, lightning detection networks, and information from local NWS offices.

2. **Reliable numeric weather models:** High power computing system and numeric weather models are essential for tornado forecasting. These models should be continuously analyzed, calibrated and verified for continuous improvements.

3. **Human resources:** NWS has dedicated center, SPC, for tornado and severe weather warnings. In addition to the support staffs, SPC has dedicated Outlook Forecasters, Mesoscale Forecasters and Lead Forecasters working 24/7 to issue warnings.

4. **Training:** Forecasters have formal training and experience in severe storms forecasting and get trainings regularly.

Therefore, to provide timely and accurate severe weather alerts and warnings including those for tornadoes in Nepal, there is an urgent need to develop severe weather forecasting system equipped with above-mentioned four types of resources. The ongoing World Bank funded project PPCR-BRCH is installing and commissioning some latest equipment and systems to modernize hydrometeorological system in Nepal. These technical infrastructures are the first step towards the modernization of DHM and a complementary strengthening of capabilities of infrastructure and human resources to fill up the current gaps and challenges in MFD (See Section A4.3 in Annex 4). These will lead to a significant improvement in weather forecast system in general. However, those would not be adequate for forecasting small-scale severe weather systems like tornado. As mentioned above, a first rational step towards this would be establishment of a nowcasting cell at MFD/DHM while addressing the current issues and challenges.

Table 4.1 outlines the existing status of resources and capacity of DHM and the necessary resources and capacity for establishing severe weather forecasting system, which will enable DHM to issue forecast/warning of severe weather systems like tornado in future. Those requirements are suggested as minimum requirement with reference to the forecasting practice in the USA. Among those, the most important component is the human resource development listed at the end of the Table. Without additional trained human resources and capacity building of existing staffs, DHM will not be able to fully utilize the modern equipment for improvement of even the general weather services.

4.2 Strengthening disaster risk reduction preparedness

Accurate and timely severe weather forecasting/ warnings alone are not enough to reduce impact of these events. The public should be ready to respond the warnings and arrangements of proper safety measure should be planned and implemented in case of a severe weather event. Tornadoes being one of the most violent severe weather, proper response arrangements should be in place. The details of tornado safety measures used by public and government of the USA to the tornado warnings are discussed in section A4 of Annex 4. Based on those, minimum safety measures that Nepal needs to follow are discussed below:

Safe houses: In tornado prone areas, there should be proper house code to withstand tornadoes. If it is not immediately possible, houses should have at least one room in its inner part as a tornado shelter. Despite timely and accurate issuance of tornado warnings, death tolls can still be high in absence of strengthened infrastructures. In the USA, tornado resilient shelters are built using private as well as government funds to protect people from tornadic winds and debris. For instance, 6,016 safe rooms were installed in 1999 by the Oklahoma Safe Room Initiative and Rebate Program after an EF5 tornado, which saved the lives of the residents during the tornadoes in 2003 (FEMA, 2014).

Public buildings: public buildings like government buildings, schools, hospitals, stadiums should have tornado shelters or "safe rooms"

Table 4.1: Existing and required resources for severe weather forecasting system for nowcasting

	Resources	Existing Status	Immediate plan		Needs	
1	Automatic weather stations	88 stations	-	Basic training on utilization of modern observation network for identification of weather systems and its forecasts including severe thunderstorms.	More in high mountains	Advance training to use observations products in severe weather warning or nowcasting
2	Lightning detection network	9 stations	-		Analysis of data to link with severe weather events	
3	Radiosonde balloon	One in Kirtipur (once a day)	-		Need to measure twice a day and additional stations to cover Nepal	
4	Radar	one in Surkhet	1 each in Palpa & Udayapur		Need short range radars in valleys	
5	Satellite	Himawari	-			
6	High Power Computing (HPC) system	For general forecasting	-		upgrade power of HPC for research	IT and computer personnel
7	Numerical weather model	WRF system for general forecasting	Enhancing of WRF system and provision of forecast verification		• Further model calibration and validation for various weather system including severe weather systems • Data assimilation from satellite, radiosonde and AWS	Training to improve NWP performance for severe weather forecasting
8	Severe weather forecasting system	Does not exist	No plan		• Dedicated section in MFD • Adequate and dedicated forecasters to monitor and issue alerts and warnings and conduct researches	Training for forecasters Development of SOP for issuing warning

Prepare disaster response plan: NEOC of MoHA along with provincial governments, local elected bodies (offices) and communities should prepare disaster response plan for tornado warnings. Technological improvements in timely early warning dissemination protocols and systems, and immediate response and recovery operations should be key considerations at the policy, plan and program levels to reduce impacts of a tornado disaster.

Community awareness: Educational and awareness campaigns should be organized to make communities aware of warning system, respond plans and safety measures. The community should know how to respond in case of tornado/severe weather watches and warnings.

Disaster response and recovery: In case of disaster how well the disaster response and recovery plans implemented matters a lot in saving lives. The key immediate disaster response activities such as temporary shelters, emergency medical camps, rehabilitation services, medicines free of charge, adequate disaster relief (in monetary terms and as food and water), cleanliness and trauma counseling are very important to significantly reduce the impact of disaster. For example, activities undertaken in the recovery period immediately after the Joplin tornado in the USA in 2011 were debris removal, installation of tarps on damaged roofs and property protection, and long-term response were building homes for under insured low-income homeowners (Smith and Sutter, 2013).

4.3 Limitations of the study and research necessities

The tornado of 31 March 2019 not only affected Bara and Parsa districts but also affected Chitwan National Park. This report does not include any field investigation and detail satellite image analysis of the Park damage. Therefore, a field investigation, using high resolution satellite data and aerial photography by UAV is necessary in Chitwan National Park to understand impact to the forest cover. This will help understand the development of the storm in detail.

Second, the wind pattern reconstruction from tree falls is based on subjective analysis. Nowadays, sophisticated mathematic and statistical tools are available to reconstruct wind pattern from tree fall objectively (Holland et al., 2006; Beck and Dotzek, 2010; Karstens et al., 2013). Therefore, a study should be conducted using such tools to understand the movement and wind flow of the Bara-Parsa tornado in detail.

Several aspects on meteorological analysis of Bara-Parsa tornado were presented in this report. However, these analyses were based on assumptions and hypothesis, derived from previous studies in other locations. This report has not yet answered many meteorological questions and some aspects are answered only partially. Some of these outstanding scientific questions are:

1. Why tornadoes are uncommon in Nepal in the past?
2. Bara-Parsa tornado is the officially recorded for the first time in Nepal, while it is common in India and Bangladesh in the Bengal region. There are number of theories how the atmospheric setup brings all the key ingredients of tornado together in this region and in the USA. Therefore, the question is, are all the atmospheric conditions during the formation of Bara-Parsa tornado like those associated tornadoes in Bangladesh, India and the USA?
3. Is Bara-Parsa tornado one of the indicators of climate change? Will this be common in future?
4. Can weather models simulate tornadoes in Nepal?
5. Can tornadoes in Nepal be forecasted?

To answer these questions, detail and dedicated research is necessary. This can be achieved by embedding research in DHM as a collaborative work at various levels. Such collaborative work could be with three types of institutions: 1) With international institutions like leading universities in the USA, NWS of the USA, Bangladesh Meteorological Department (BMD), Indian Meteorological Department (IMD), European Centre for Medium-Range Weather Forecasts (ECMWF). 2) With national universities, NGOs and INGOs. 3) With government organizations like MoHA, Department of Urban Development and Building Construction, provincial and local governments.

In summary, to reduce loss of lives due to severe weather, a resourceful severe weather warning system should be in place at DHM. For reliable severe weather warnings, detail study and research on Bara-Parsa tornado and other severe weather events of Nepal is necessary. Without understanding dynamics of these phenomena reliable warning is not possible. Reliable and timely weather warnings should be accompanied by good coordination of line agencies, local governments and the communities to disseminate the warnings and take appropriate safety measure to reduce the impact of these events. For this, capacity building and awareness of these line institutions and the communities is a must.

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6. ANNEXES

Annex 1

Government of Nepal
Department of Hydrology and Meteorology
Meteorological Forecasting Division

Home Weather NWP Satellite Mountaineering

प्रेस विज्ञप्ति

जल तथा मौसम विज्ञान विभागको प्रेस विज्ञप्ति

मिति: २०७५ चैत्र १८ गते सोमबार

हिजो मिति २०७५ चैत्र १७ गते आइतबार साँझ वर्षासँगै आएको भिषण हावाहुरीका कारणले बारा र पर्सा लगायतका जिल्लामा भएको ठूलो मानवीय क्षतिप्रति जल तथा मौसम विज्ञान विभाग दुःख व्यक्त गर्दै शोकसन्तप्त परिवारमा गहिरो समवेदना प्रकट गर्दछ साथै उक्त घटनाका घाइतेहरु प्रति शिघ्र स्वास्थ्यलाभको कामना गर्दछ।

नेपालमा मनसुन सक्रिय नहुँदा सम्मका मनसुन पूर्वका चैत्र-वैशाख-जेष्ठ महिनामा अपरान्ह वा त्यसपछिको समयमा स्थानिय मौसम प्रणालि विकसित भई साँझ वा रातको समयमा चट्यांग, असिना पानी सहितको हावाहुरिले नेपालको मौसम प्रभावित हुने गर्दछ। मनसुन पूर्वको मौसम प्रणालि छोटो समयमै विकसित भै साधारणतया पश्चिमबाट पूर्व तर्फ लाग्ने गर्दछ। यो नियमित मौसमी प्रक्रिया हो । तर हिजो साझँको मौसम प्रणालि हाल सम्मकै शक्तिशालि मौसम प्रणालि रहेको (९० किलोमीटर प्रति घण्टा भन्दा बढिको गति) देखिन्छ।

नेपाल जस्तो जटिल भू-बनोट भएको देशमा यस्ता मौसम प्रणालिले ल्याउने विपद्को क्षेत्र र ठाउँ तोकेर पूर्वानुमान गर्न अति नै चुनौतिपूर्ण छ। हालको न्यून जनशक्ति र अत्याधुनिक प्रविधि (जस्तै मौसमी राडार नेटवर्क, स्वचालित मौसमी केन्द्रको नेटवर्क, Ensemble numerical model आदि) को कमि हुँदा पनि जल तथा मौसम विज्ञान विभाग अन्तर्गतको मौसम पूर्वानुमान महाशाखाले आफ्नो दैनिक मौसम पूर्वानुमानमा यस्ता मौसमि गतिविधिहरुलाई समेटने कोशिस गर्दै आएको छ। यस प्रकारका मौसम प्रणालिले पार्ने जनधनको क्षति न्यून गर्न हावाहुरी लगायतका अतिजन्य मौसम गतिविधिहरुको मौसम चेतावनी तथा पूर्वानुमान (Weather warning and Nowcasting) का लागि पर्याप्त जनशक्तिको साथै Research and Development सहित अत्याधुनिक प्रविधिको अति नै आवश्यक छ।

Figure A1.1a: *First press release on 1 April 2019*

नेपाल सरकार
ऊर्जा, जलस्रोत तथा सिंचाई मन्त्रालय
जल तथा मौसम विज्ञान विभाग

पत्र संख्या :
च. नं. :

प्रेस विज्ञप्ति

२०७५ चैत्र २२ शुक्रबार

मिति २०७५ साल चैत्र १७ गते आईतवार साँझ पूर्वी नेपालको बारा र पर्सामा भीषण हावाहुरी आई ठूलो धनजनको क्षति भएको सर्वविदितै छ। उक्त मौसमी प्रणाली साधारण हावाहुरी नभई Tornado भएको प्रारम्भिक अध्ययनले देखाएको छ। जल तथा मौसम विज्ञान विभाग र द स्मल अर्थ नेपाल (The Small Earth Nepal) ले संयुक्तरुपमा गरेको अध्ययनबाट उक्त तथ्य पत्ता लागेको हो।

जल तथा मौसम विज्ञान विभाग र द स्मल अर्थ नेपालका वैज्ञानिकहरुको टोलीले Sentinel भू:उपग्रहबाट प्राप्त उच्च रिजोलुसनका तस्विरहरु अध्ययन गरेको थियो। उक्त तस्विरहरुमा क्षतिले बनाएको मार्गको (trail) साथै सार्वजनिक संचार माध्ययमहरुबाट प्रेशित गरिएका तस्विरहरु तथा भिडियोहरुको अध्ययनबाट वैज्ञानिकहरु उक्त विनाशकारी आँधि Tornado नै भएको निश्कर्षमा पुगेका हुन्।

यसअघि नेपालमा Tornado को घटना घटेको जल तथा मौसम विज्ञान विभागको अभिलेख नभएको पनि विदित गराउँन चाहन्छौं । यस्ता प्रकारका अति विनाशकारी मौसमी घटनाको विस्तृत जानकारीका लागी वैज्ञानिक तथा स्थलगत अध्ययन अनुसन्धानको खाँचो रहेको छ ताकि भविष्यमा यस्ता प्रकारका घटनाको पूर्वसुचना प्रवाह गरि उपयुक्त सतर्कता अपनाउन मद्दत पुग्नेछ । सोही सिलसिलामा जल तथा मौसम विज्ञान बिभागको नेतृत्वमा द स्मल अर्थ नेपाल र ICIMOD का एक टोली स्थलगत अध्ययनका लागी प्रभावित क्षेत्रमा परिचालित गरिएको छ ।

नागपोखरी, नक्साल, पो.ब.नं. ४०६, काठमाडौं, नेपाल ।
फोन नं. : ४४३६२७२, ४४२८५३२, ४४४१०९२, ४४२८२२९, ४४३३५६३
फ्याक्स नं.: ४४२९९१९, ४४२६१३६
इमेल: info@dhm.gov.np
वेबसाइट: www.dhm.gov.np, www.mfd.gov.np
www.hydrology.gov.np

Figure A1.1b: *Second press release on 5 April 2019*

नेपाल सरकार
ऊर्जा, जलस्रोत तथा सिंचाई मन्त्रालय
जल तथा मौसम विज्ञान विभाग

पत्र संख्या :
च. नं. :

प्रेस विज्ञप्ति

२०७५ चैत्र २७ बुधवार

मिति २०७५ साल चैत्र १७ गते आईतवार साँझ पूर्वी नेपालको बारा, पर्सा लगायतका जिल्लामा आएको भीषण हावाहुरी Tornado भएको प्रारम्भिक अध्ययनले देखाएको व्यहोरा जल तथा मौसम विज्ञान विभागले २०७५ चैत्र २२ गते प्रेस विज्ञप्ति मार्फत जानकारी गराइ सकेको सबैलाई अवगत नै छ।

जल तथा मौसम विज्ञान विभाग र द स्मल अर्थ नेपालको वैज्ञानिक टोलीले सेन्टिनेल भूउपग्रहबाट प्राप्त उच्च रिजोलुसनका तस्विरको अध्ययन र सञ्चार माध्यम तथा सामाजिक सञ्जालमा राखिएका प्रभावित स्थलको तस्विर, भिडियो लगायत सूचनाको अध्ययनबाट विभाग उक्त निष्कर्षमा पुगेको थियो।

उक्त प्रारम्भिक निष्कर्षलाई थप पुष्टि गर्न स्थलगत अध्ययन अनुसन्धानका लागि जल तथा मौसम विज्ञान विभागको नेतृत्वमा द स्मल अर्थ नेपाल र एकीकृत पर्वतीय विकासका लागि अन्तर्राष्ट्रिय केन्द्र (ICIMOD) का वैज्ञानिकहरुको एक टोलीले चैत्र २० देखि २४ गतेसम्म प्रभावित क्षेत्रको स्थलगत अध्ययन भ्रमण गरेर बिभिन्न तथ्यहरु संकलन गरेको थियो। सो स्थलगत अध्ययनका क्रममा टोलीले प्रभावित क्षेत्रको ड्रोन तथा अन्य उच्च प्रविधियुक्त क्यामेराबाट भिडियो तथा तस्विर खिच्नु र स्थानियहरुसँग अन्तर्वार्ता लिनुका साथै प्रभावित क्षेत्रको सर्वेक्षण समेत गरी सूचना संकलन गरेको थियो। यस टोलीले Tornado पुष्टिको लागि क्षतिको विवरण तथा Tornado को आकार, चौडाई, वेग तथा तिव्रता विश्लेषणका लागी आवश्यक आधारहरुको निरिक्षण गरेको थियो।

स्थलगत सूचनाहरु र अध्ययनको आधारमा विभाग उक्त विनाशकारी हावाहुरी Tornado नै रहेको निष्कर्षमा पुगेको छ। साथै उक्त Tornado चितवन राष्ट्रिय निकुन्जबाट शुरु भएको देखिन्छ । यस मौसम प्रणालीको विस्तृत प्रतिवेदन अध्ययन अनुसन्धान गरेर केहि समय पछि प्रकासित गरिनेछ ।

जल तथा मौसम विज्ञान विभाग यस अनुसन्धान कार्यमा सहयोग गर्ने द स्मल अर्थ नेपाल, एकीकृत पर्वतीय विकासका लागि अन्तर्राष्ट्रिय केन्द्र, बारा तथा पर्साको जिल्ला प्रसाशन कार्यालयहरु, स्थलगत अध्ययनमा सहयोग गर्ने बिभिन्न सरकारी निकाय, सूचनाहरु उपलब्ध गराइदिनु हुने सम्पूर्ण व्यक्तिहरु तथा विभागले बिभिन्न समयमा दिएका जानकारीहरुलाई प्रेषित गरी सहयोग गर्नुहुने सम्पूर्ण पत्रकार तथा संचार संस्थाहरुलाई धन्यवाद ज्ञापन गर्दछ ।

धन्यवाद ।

महानिर्देशक

नागपोखरी, नक्साल, पो.ब.नं. ४०६, काठमाडौं, नेपाल ।
फोन नं. : ४४३६२७२, ४४२८५३२, ४४४१०९२, ४४२८२२९, ४४३३४६३
फ्याक्स नं.: ४४२९९१९, ४४२६१३६
इमेल: info@dhm.gov.np
वेबसाइट: www.dhm.gov.np, www.mfd.gov.np
www.hydrology.gov.np

Figure A1.1c: *Third press release on 10 April 2019*

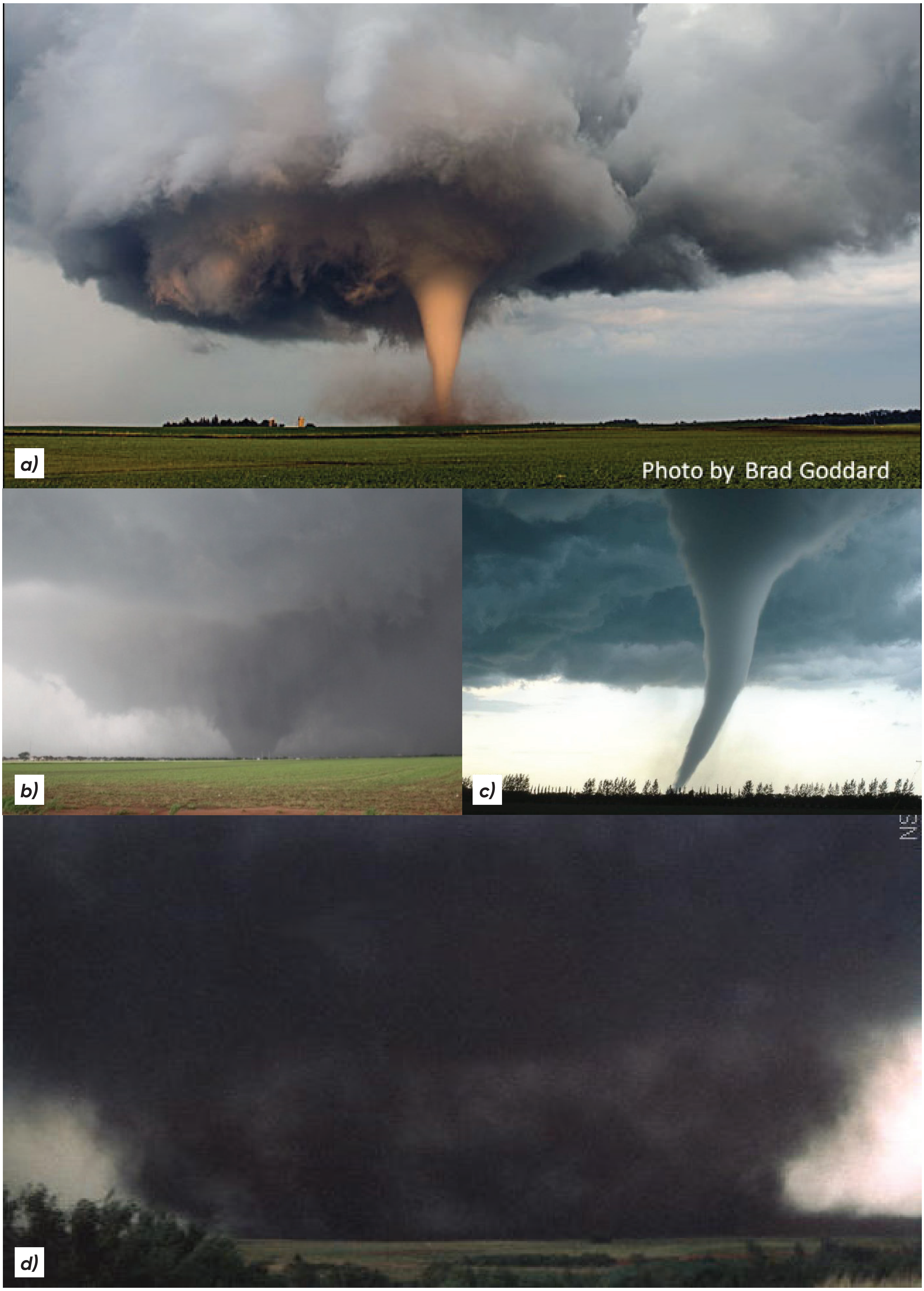


Figure A1.2: *Tornado photos from different parts in the US: a) tornado in the US by Brad Goddard (NWS, n.d.); b) tornado at Moore on 20 May 2013 by Gabriel Garfield/NWS (Thompson, 2016); c) tornado at Johns Creek, Georgia on 19 April 2019 (Sturgeon and Staff, 2019); d) Wedge tornado at Binger Oklahoma on 22 May 1981 (NSSL, 2019).*

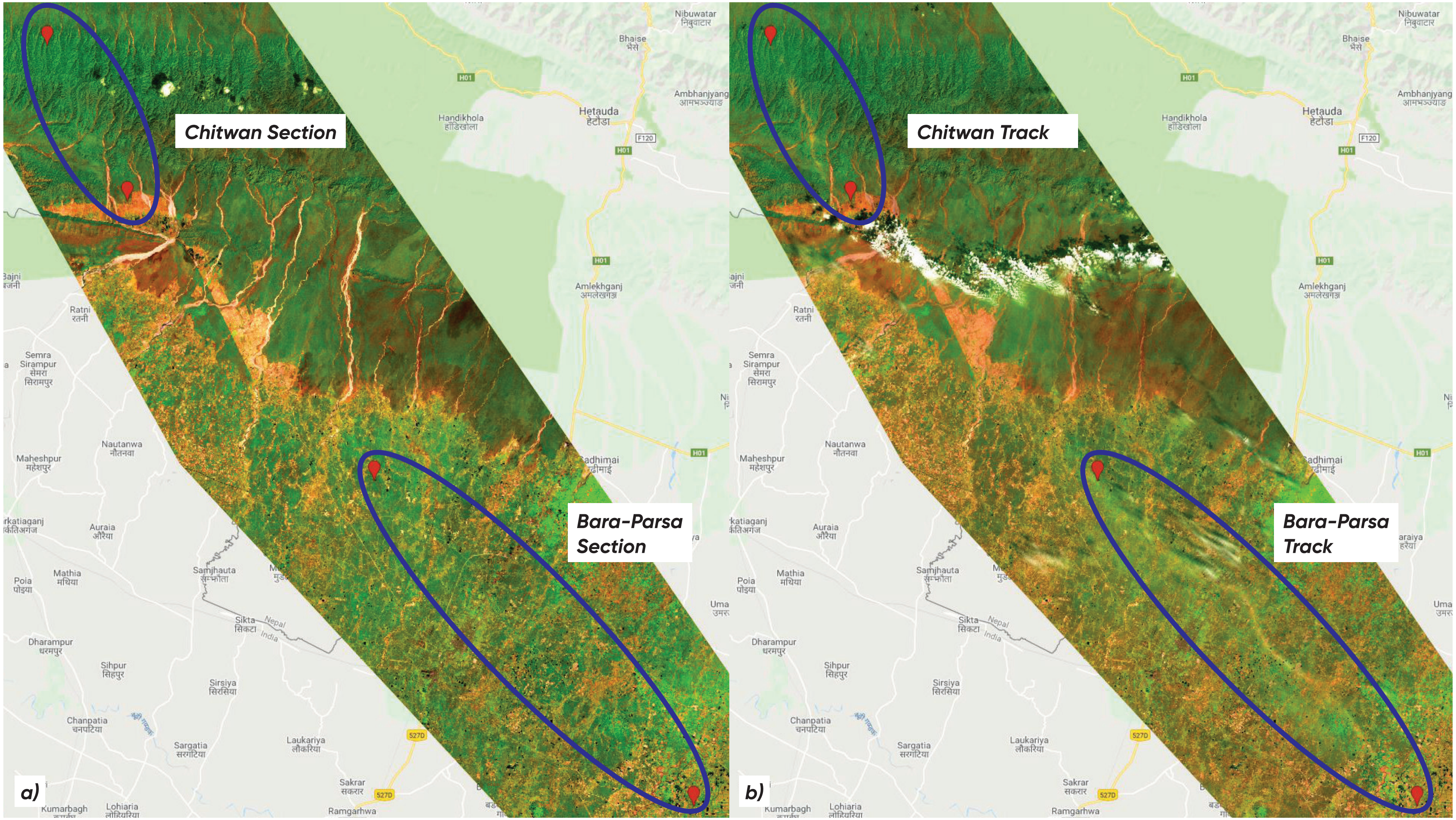
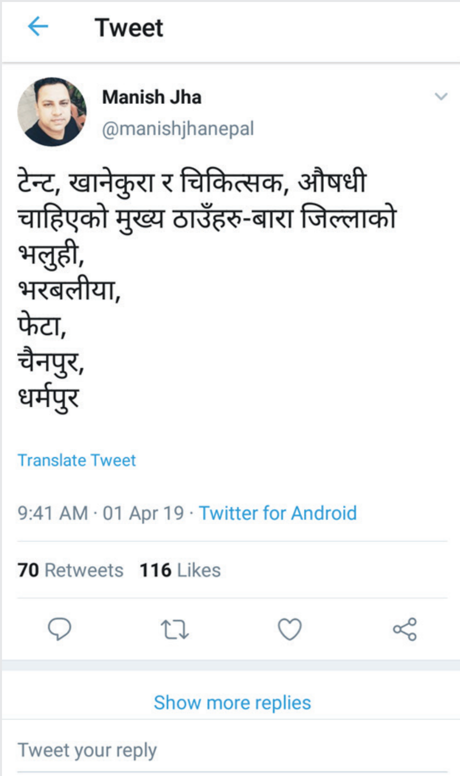


Figure A1.3: *Satellite images (Sentinel 2) covering Chitwan National Park and Bara-Parsa tornado affected areas. a) Before the tornado (27 March 2019); b) After the tornado (1 April 2019).*

Box A1: Social media examples



Box A2: News examples

Annex 2

Figure A2.1: *Upper level maps of 31 March 2019 at 5:45 p.m. showing missing data in the South Asia region (source: University of Wyoming). a) 850 hPa; b) 500 hPa; c) 250 hPa*

Box A2.1 Key atmospheric ingredients for tornado formation (Morrison, 2017)

a) Vertical wind shear:

Vertical wind shear is change in wind speed and/or direction with height. For tornado, speed shear (increasing wind speed height) and wind veering (clockwise change in wind direction with height) is a must condition. Southeasterly at surface, southwesterly or westerly in the mid troposphere and northwesterly wind in the upper troposphere is an example of wind veering (Figure a). Wind shear is the most critical ingredient for a tornadic supercell (cloud systems) as it shapes storm's updraft and gives rotation.

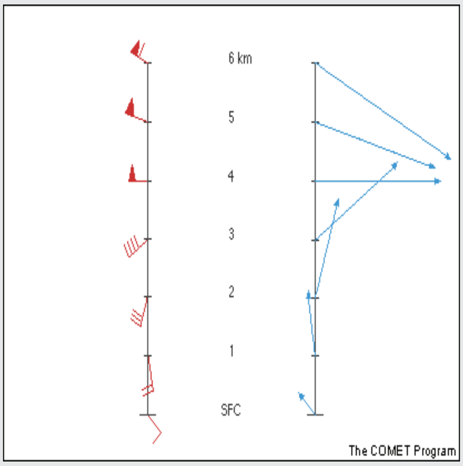


Figure a: *Speed and directional wind shear*

b) Heat and moisture

Warm moist surface layer is one of the energy sources of the storms. To produce an abundance of condensation that drives the tornadic thunderstorms, plenty of heat and moisture is required. During March to May the solar heating earth's surface, which is a source of heat, starts to increase in the Northern Hemisphere. For tornados in the USA, Gulf of Mexico is the main source of moisture.

c) Instability

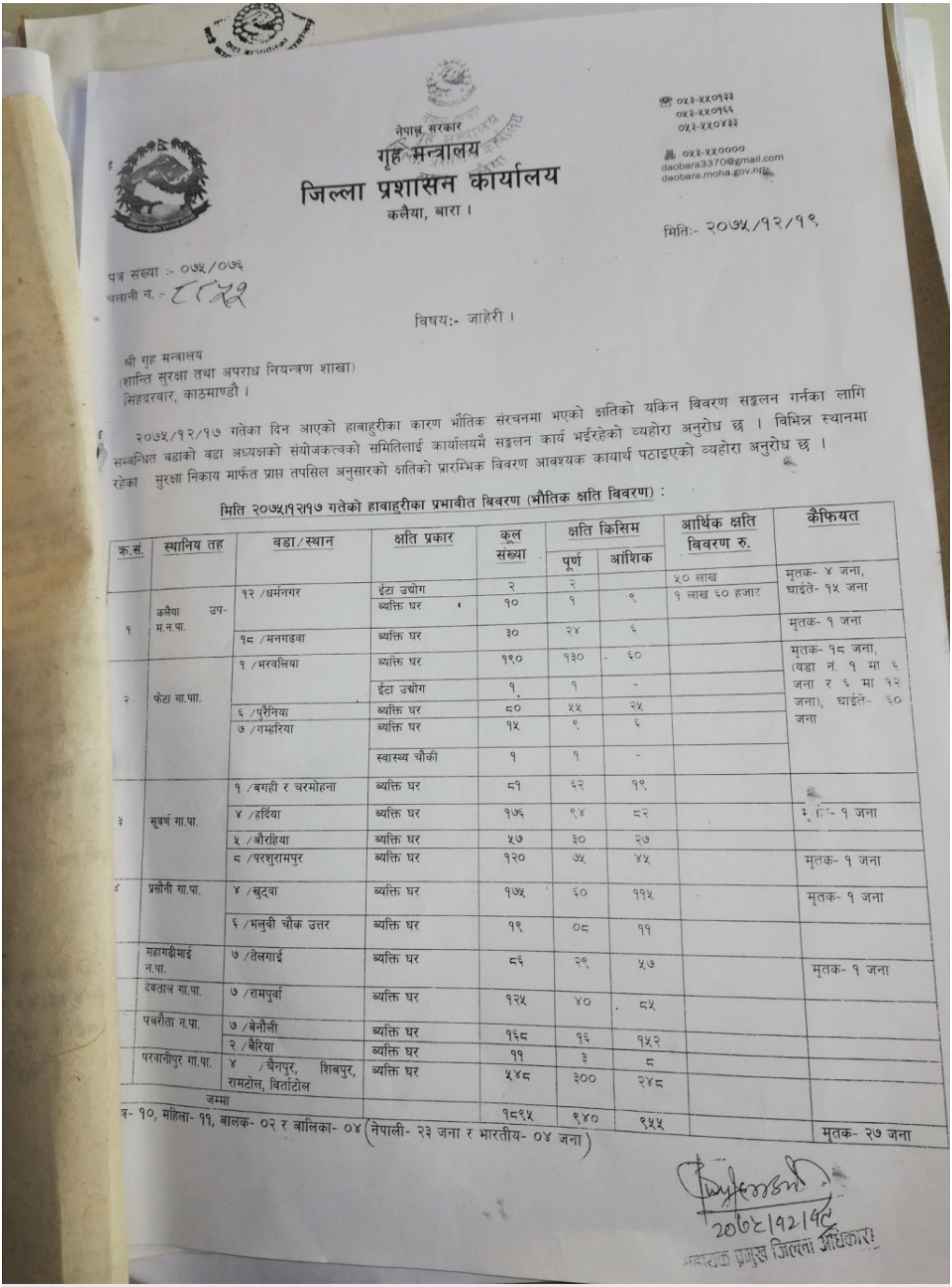
Along with heat and moisture at surface do there should be gradient in heat and moisture with height for storm to form. Instability is a measure of this energy, in the form of vertical heat and moisture gradient, that fuels the storm. It is also known as Convectively Available Potential Energy (CAPE). Greater instability, for storms like tornado, is achieved with temperature and moisture in the environment decreases sharply with height. This occurs when surface is very warm and moist while upper level is very cold and dry.

d) Forcing or lift

Forcing is also known as lift, that helps trigger a storm. Forcing's help to lift moist warm surface air upwards to form a storm cloud system. Sources of lift in the atmosphere are: dry lines (boundary between dry and moist air masses), fronts (boundary between warm and cold air masses), topography, low pressure convergence system, and convection from surface heating.

These ingredients synchronize quite often during March-May in the US in the plains of the East Rockies, known as Tornado Alley. The surface low in these plains brings in warm moist air from Gulf of Mexico northward. In the mid troposphere, warm dry air blow from elevated deserts eastward over the tornado Ally and aloft at upper atmosphere, jet stream brings cold air over the plains. These three synoptic features synchronize in the atmosphere creating a perfect environment-the wind speed shear, wind veering, strong instability and high CAPE for a tornado formation, particularly in the spring season.

Annex 3



नेपाल सरकार
गृह मन्त्रालय
जिल्ला प्रशासन कार्यालय
कलैया, बारा ।

☎ ०५३-५५०१३३
०५३-५५०१६६
०५३-५५०४३३
फ्याक्स ०५३-५५००००
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मितिः- २०७५/१२/१९

पत्र संख्या :- ०७५/०७६
चलानी नं. :- ८८२२

विषयः- जाहेरी ।

श्री गृह मन्त्रालय
(शान्ति सुरक्षा तथा अपराध नियन्त्रण शाखा)
सिंहदरवार, काठमाण्डौ ।

२०७५/१२/१७ गतेका दिन आएको हावाहुरीका कारण भौतिक संरचनमा भएको क्षतिको यकिन विवरण सङ्कलन गर्नका लागि सम्बन्धित वडाको वडा अध्यक्षको संयोजकत्वको समितिलाई कार्यालयमै सङ्कलन कार्य भईरहेको व्यहोरा अनुरोध छ । विभिन्न स्थानमा रहेका सुरक्षा निकाय मार्फत प्राप्त तपसिल अनुसारको क्षतिको प्रारम्भिक विवरण आवश्यक कायार्थ पठाइएको व्यहोरा अनुरोध छ ।

मिति २०७५।१२।१७ गतेको हावाहुरीका प्रभावीत बिवरण (भौतिक क्षति विवरण) :

क्र.सं.	स्थानिय तह	वडा/स्थान	क्षति प्रकार	कूल संख्या	क्षति किसिम		आर्थिक क्षति विवरण रु.	कैफियत
					पूर्ण	आंशिक		
१	कलैया उप-म.न.पा.	१२ /धर्मनगर	ईटा उद्योग	२	२		५० लाख	मृतक- ४ जना, घाईते- १५ जना
			व्यक्ति घर	१०	१	९	१ लाख ६० हजार	
		१८ /मनगढवा	व्यक्ति घर	३०	२४	६		मृतक- १ जना
२	फेटा गा.पा.	१ /भरवलिया	व्यक्ति घर	१९०	१३०	६०		मृतक- १८ जना, (वडा नं. १ मा ६ जना र ६ मा १२ जना), घाईते- ६० जना
			ईटा उद्योग	१	१	-		
		६ /पुरैनिया	व्यक्ति घर	८०	५५	२५		
		७ /गम्हरिया	व्यक्ति घर	१५	९	६		
			स्वास्थ्य चौकी	१	१	-		
३	सूवर्ण गा.पा.	१ /बगही र चरमोहना	व्यक्ति घर	८१	६२	१९		
		४ /हर्दिया	व्यक्ति घर	१७६	९४	८२		[illegible]- १ जना
		५ /औरहिया	व्यक्ति घर	५७	३०	२७		
		८ /परशुरामपुर	व्यक्ति घर	१२०	७५	४५		मृतक- १ जना
४	प्रसौनी गा.पा.	४ /खुद्वा	व्यक्ति घर	१७५	६०	११५		मृतक- १ जना
		६ /भलुवी चौक उत्तर	व्यक्ति घर	१९	०८	११		
	महागढीमाई न.पा.	७ /तेलगाई	व्यक्ति घर	८६	२९	५७		मृतक- १ जना
	देवताल गा.पा.	७ /रामपुर्वा	व्यक्ति घर	१२५	४०	८५		
	पचरौता न.पा.	७ /बेनौली	व्यक्ति घर	१६८	१६	१५२		
		२ /बैरिया	व्यक्ति घर	११	३	८		
	परवानीपुर गा.पा.	४ /चैनपुर, शिबपुर, रामटोल, बिर्तािटोल	व्यक्ति घर	५४८	३००	२४८		
जम्मा				१८९५	९४०	९५५		मृतक- २७ जना

पु- १०, महिला- ११, बालक- ०२ र बालिका- ०४ (नेपाली- २३ जना र भारतीय- ०४ जना)

२०७५/१२/१९
प्रमुख जिल्ला अधिकारी

Figure A3.1: *Damage information in Bara district obtained from DAO*

Box A3.1 Tree fall damage pattern analysis

Signature of wind patterns associated with tornado damage is identified according to Hall and Brewer (1959).

Trees lay crossed over one another: In such cases the sequence of directions in which the trees fell corresponds to passage of a compact, cyclonically rotating vortex ("X" in Figure A3.2a).

"Weak Reverse" flow: Opposite flow along one side of the path become much less prominent as the storm progresses, suggesting that rotation has slowed compared to forward speed. In other words, the forward speed was stronger in countering the backward-moving component (return flow), or that the forward motion was much faster ("Y" in Figure A3.2a).

"Herringbone" pattern: In this pattern fallen trees directed forward and inward toward a line of separation or sometimes crossing: Such patterns suggest the passage of a fast moving center off strong inflow or convergence, with weak reverse flow associated with funnel in one side of the line of separation ("Z" in Figure A3.2b).

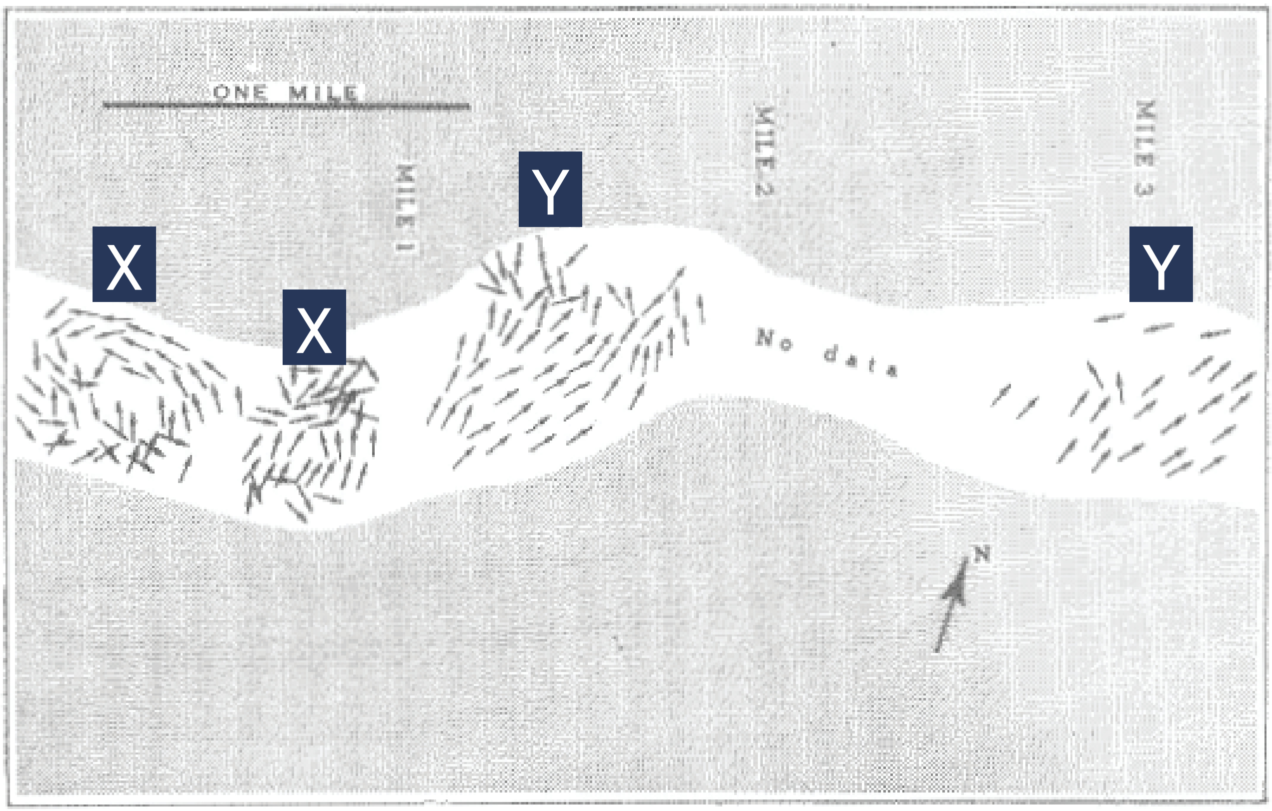


Figure A3.2a: *Wind reconstruction from forest cover damage by tornado (Hall and Brewer, 1959)*

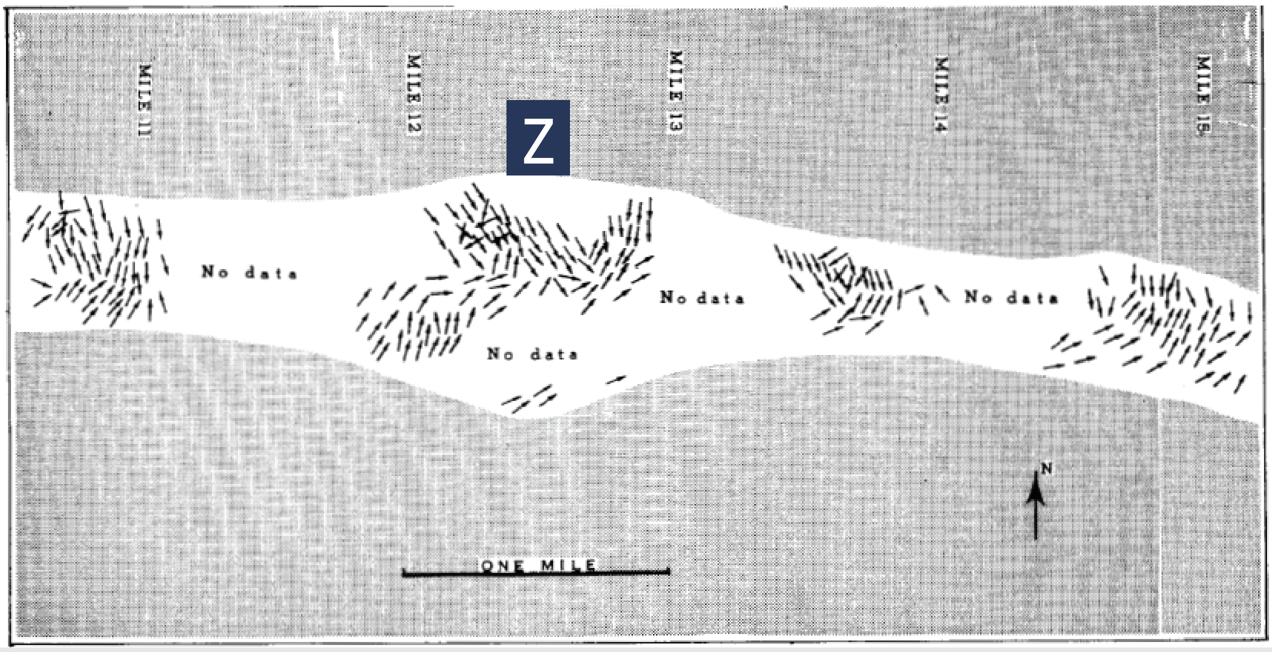


Figure A3.2b: *Herringbone pattern wind reconstruction from forest cover damage by tornado (Hall and Brewer, 1959)*

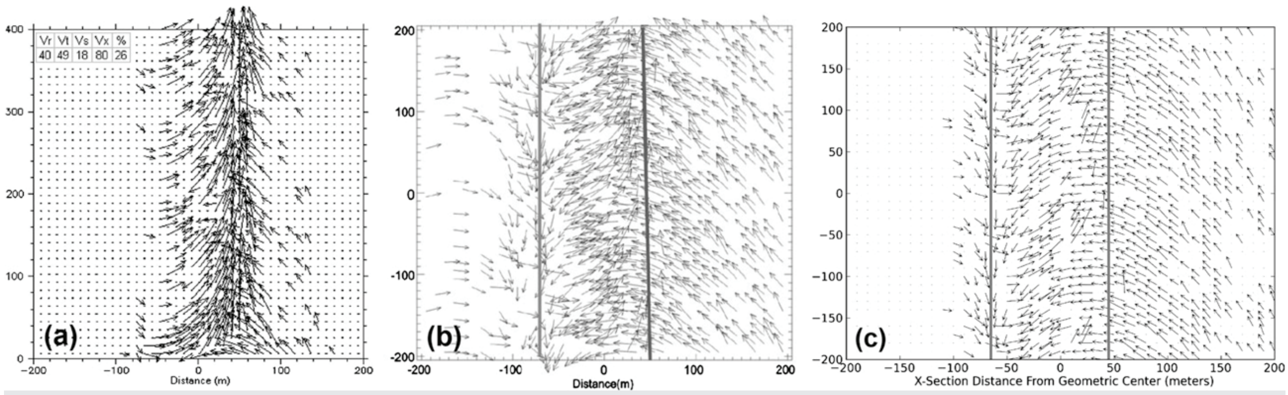


Figure A3.3: *Simulated idealized tornado-induced tree fall from (a) Holland et al. (2006), (b) Beck and Dotzek (2010), and c) Karstens et al. (2013).*

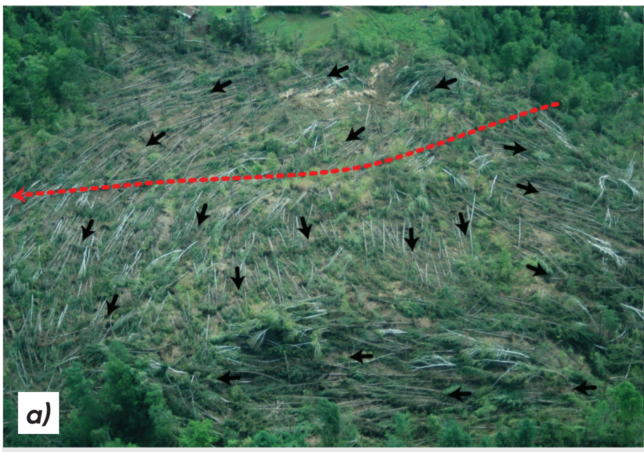


Figure A3.3.a: *The trees are laying in different orientations (Atkins, 2006)*

Figure A3.3b: *Herringbone pattern of tree fall (Godfrey, 2019)*

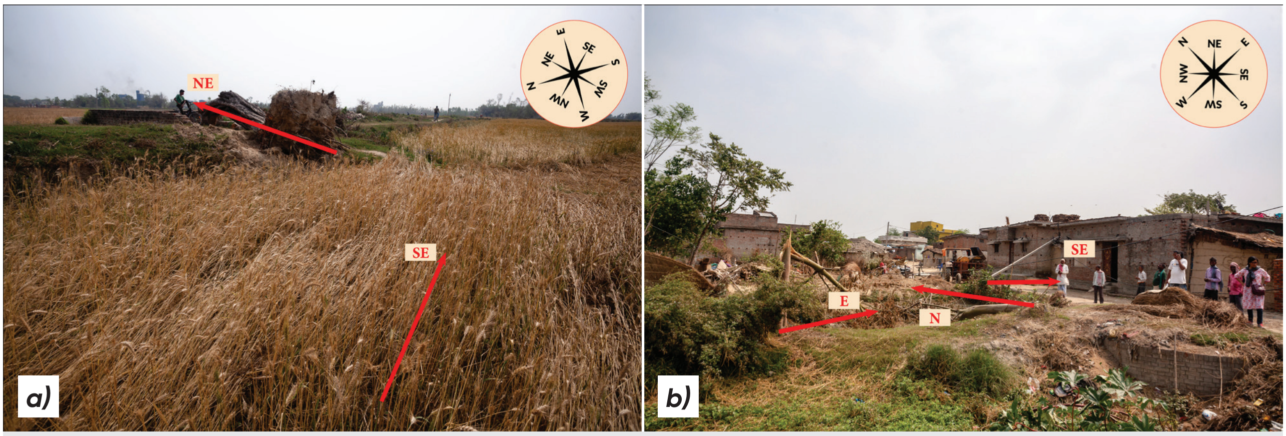


Figure A3.4: *Wind reconstruction based on tree fall orientation using the photos of Jagannathpur. Wind direction showing part of anticlockwise circulation; b) wind direction showing convergence (the red arrows show wind directions)*

Figure A3.5: *Wind reconstruction based on tree fall orientation using the photos of Sukhchaina. Wind direction showing convergence as indicated by the tilting of the trees (the red arrows show wind directions)*

Figure A3.6: *Wind reconstruction based on tree fall and tilting of the trees using photos of Purainiya a) Wind direction showing anticlockwise rotation characterized by the tilting of the trees; b) Wind direction showing convergence by the twisting of the trees (the red arrows show wind directions).*

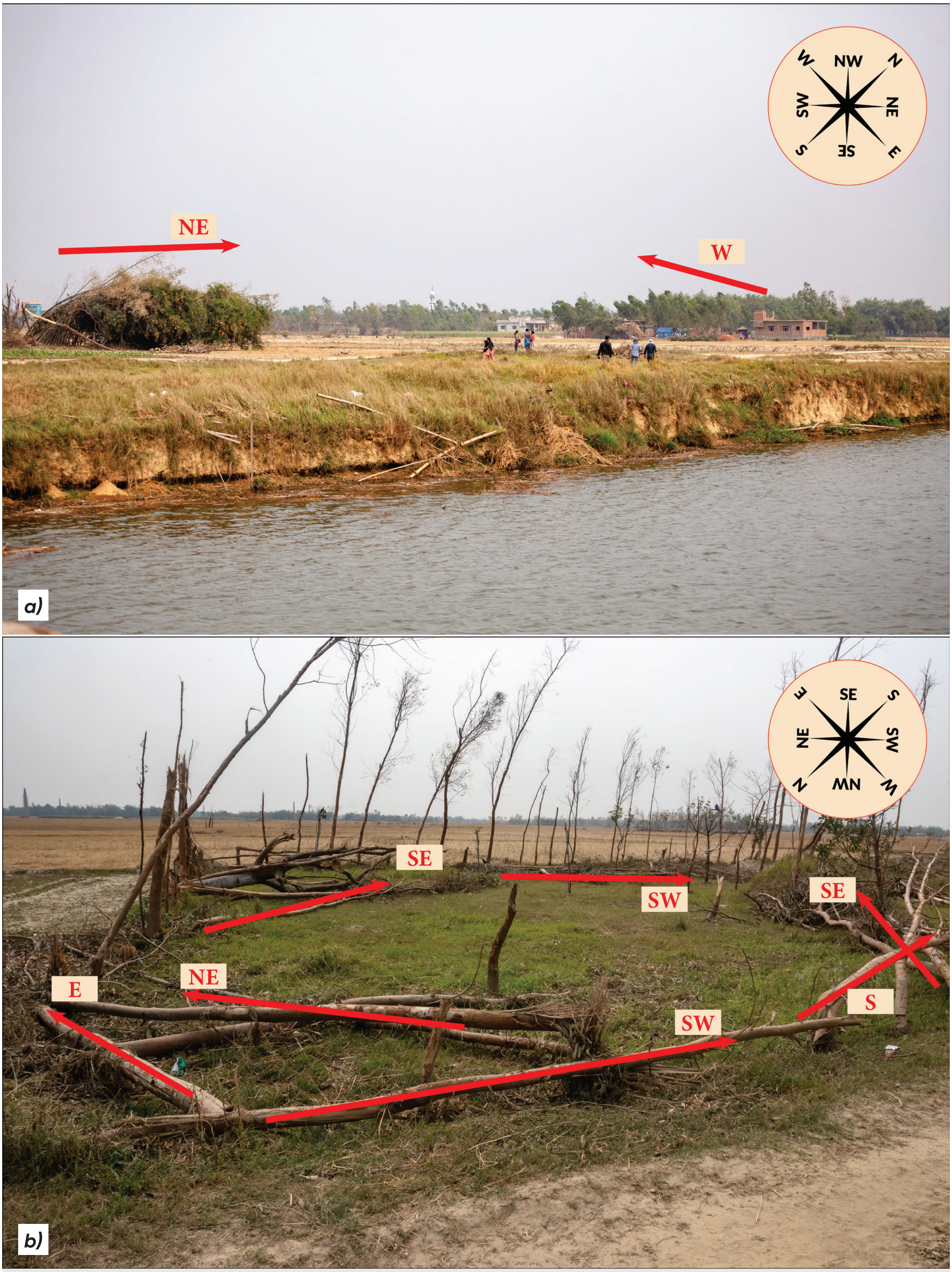


Figure A3.7: *Wind reconstruction based on tree fall and tree orientation using the photos of Gamhariya. a) Wind direction showing convergence of wind; b) Wind direction showing chaotic circular pattern characterized by the tree fall (the red arrows show wind directions)*

Box A1: Methodology of width calculation from UAV images

The width obtained from the satellite was further verified using the UAV captured images. The UAV captured images was ortho-rectified using the Pix4D Software and used for mapping the damages in the area. The houses in the affected area were mapped in the form of point database by visual interpretation using the high-resolution images in the Google Earth and UAV images. All those points were further classified into three classes based on the level of damages comparing with pre event images from Google Earth and post event from UAV images. The three different classes are:

1. Fully damages: Houses completely collapse, half of house was collapse and tiles in rooftop was destroyed.
2. Partially damages: Houses are standing but debris on the rooftop and its surrounding, tiles of the roof was displaced.
3. No Damages: no sign of any debris on the rooftop and its surrounding.

All together 2877 houses were mapped from four most affected villages – Katti, Bhaluhi, Bharauliya and Purainiya. Almost 28% (792) of houses were categories as fully damage and 32% (914) were classified as partially damage. The detail of mapped houses is provided in Table A1 and example from Purainiya is shown in Figure A1.

Table A1: Number of damaged houses mapped from the UAV image analysis.

Villages	Total house mapped	Fully damaged houses	Partially damaged houses	No damages houses
Katti	847	165	230	452
Bhaluhi	814	139	248	427
Bharauliya	698	359	279	60
Purainiya	518	129	157	232

These houses point data was used for hot spot analysis which will help to identify the severely damages zone in the area. This severely damages zone will provide the width of the tornado affected zone in the selected villages.

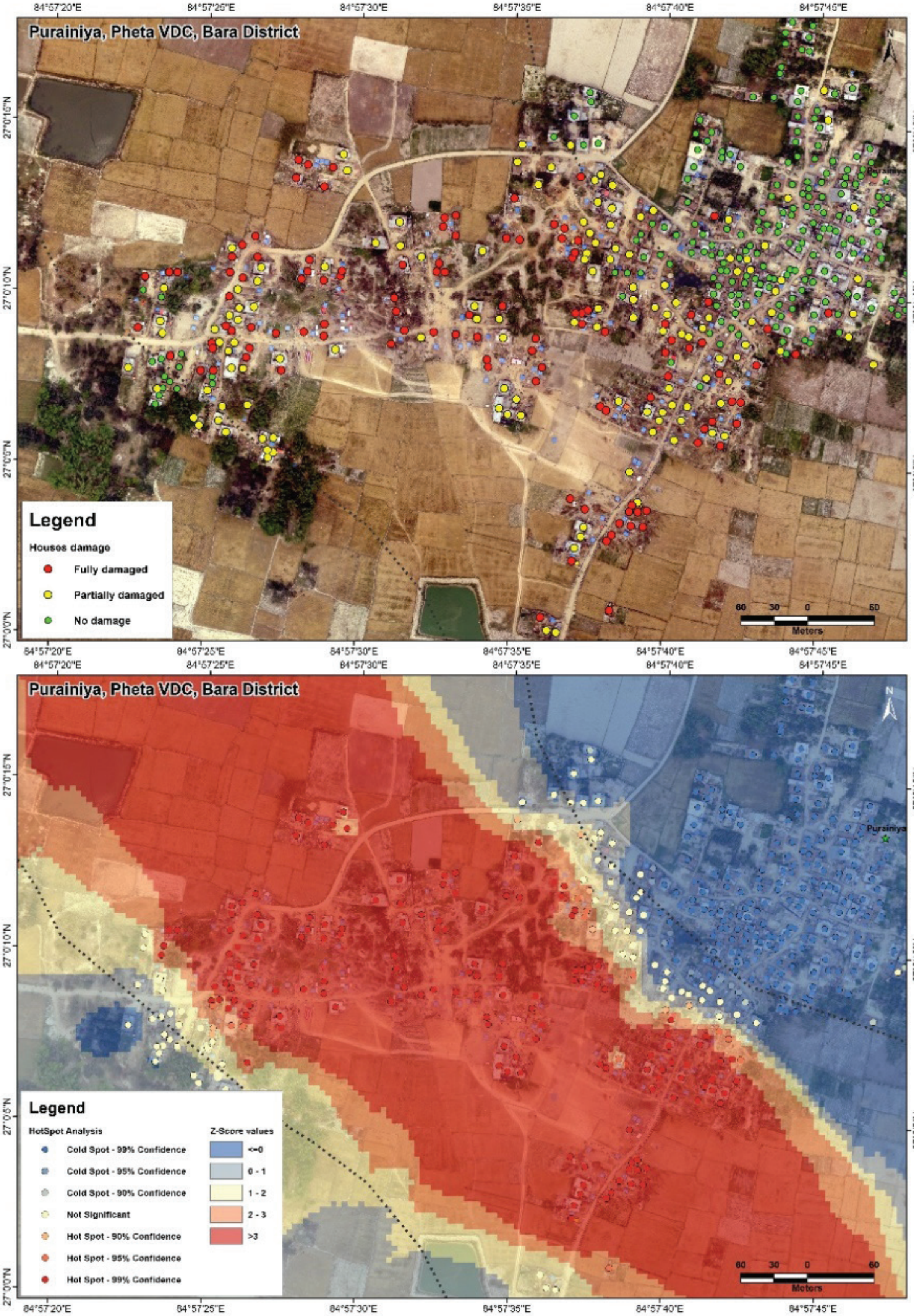


Figure A3.8: *Damaged houses mapped from UAV images and result of hotspot analysis of the damaged houses showing width of the damages in Purainiya village.*

Annex 4

A4.1 Tornado forecasting process in the US

The tornado forcasting in the US begins with preparation 1-8 day Convective Outlooks (Figure A4.1), out of which 1-3-day outlook is more reliable and widely used to analyze the areas of formation of possible severe thunderstorms. Tornado possibilities are produced only in the 1-day convective outlooks (Figure A4.2a). Technology and science have not been developed yet to produce tornado possibilities beyond a day before.

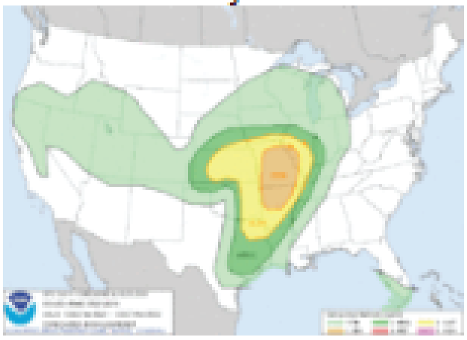
Convective Outlooks are accompanied by Mesoscale Discussions of every severe storm. The severe storms in the Convective Outlooks (Figure A4.2a) are analyzed and monitored continuously based on associated Mesoscale Discussions to prepare Tornado Watches. If development of tornado is likely to occur in the next several hours, the NWS issues Tornado Watch (Figure A4.2b). Tornado watches are also accompanied by Mesoscale Discussions (Figure A4.2c). When a tornado is spotted by a spotter or when a Doppler RADAR indicates a rotation in a thunderstorm that can spawn to a tornado, a Tornado Warning (Figure A4.2d) is issued. Process involved in issuing tornado warning of 2 May 2019 in Oklahoma, the US is shown in Figure A4.2. Brief explanation of the process involved in a tornado warning is presented in Table A4.1.

Today's Convective Outlooks

Updated: Tue May 21 07:39:08 UTC 2019 (5h 12m ago)

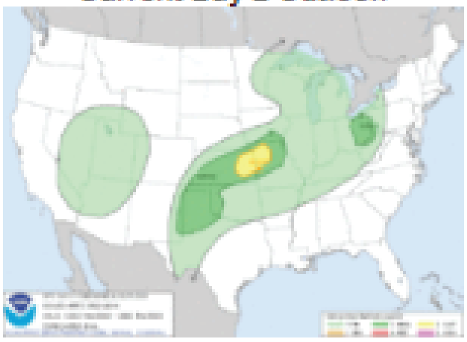
Current Convective Outlooks

Current Day 1 Outlook



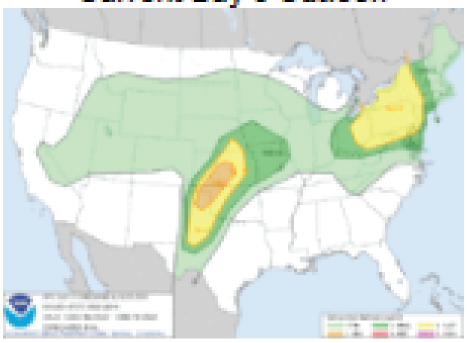
Forecaster: Broyles/Wendt
Issued: 21/0540Z
Valid: 21/1200Z - 22/1200Z
Forecast Risk of Severe Storms: Enhanced Risk

Current Day 2 Outlook



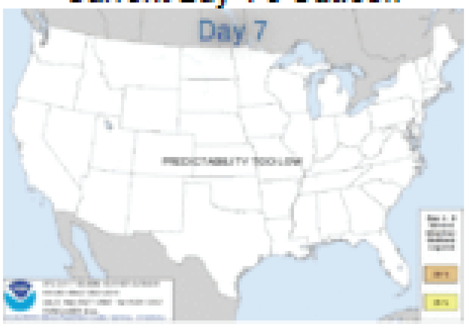
Forecaster: Dial
Issued: 21/0557Z
Valid: 22/1200Z - 23/1200Z
Forecast Risk of Severe Storms: Slight Risk

Current Day 3 Outlook



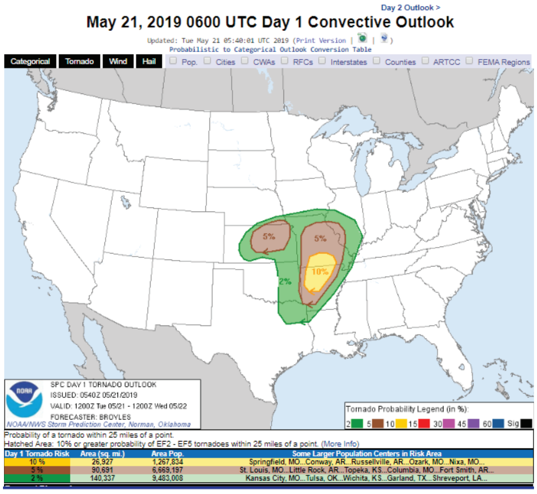
Forecaster: Dial
Issued: 21/0737Z
Valid: 23/1200Z - 24/1200Z
Forecast Risk of Severe Storms: Enhanced Risk

Current Day 4-8 Outlook



Forecaster: Dial
Issued: 21/0842Z
Valid: Fri 05/24 1200Z - Tue 05/28 1200Z
Note: A severe weather area depicted in the Day 4-8 period indicates a 15%, 30% or higher probability for severe thunderstorms (e.g. a 15%, 30% chance that a severe thunderstorm will occur within 25 miles of any point).

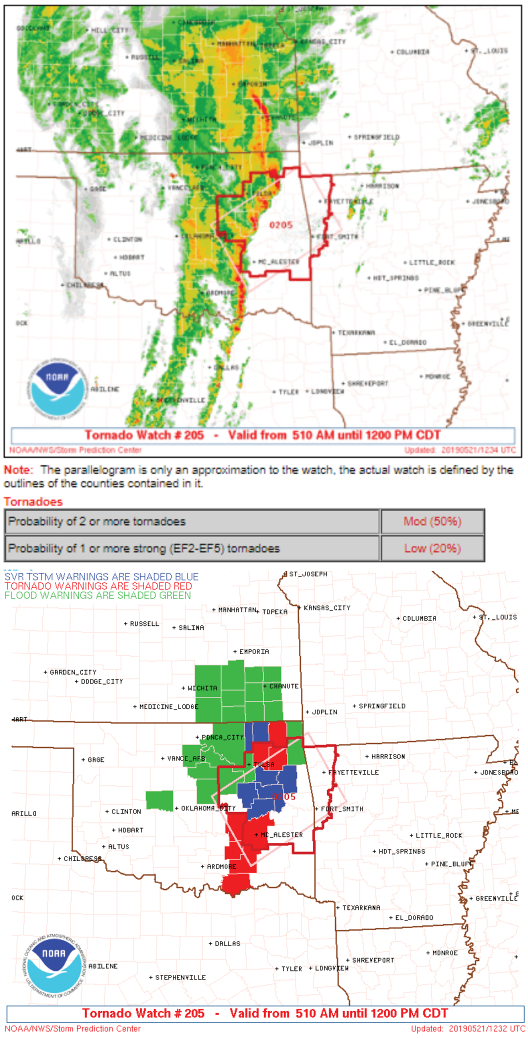
Figure A4.1: *Example of 1-8 day Convective Outlooks for severe thuderstroms and tornados by National Weather Services (NWS).*



Tornado Watch 205 Watch Hazard Probabilities

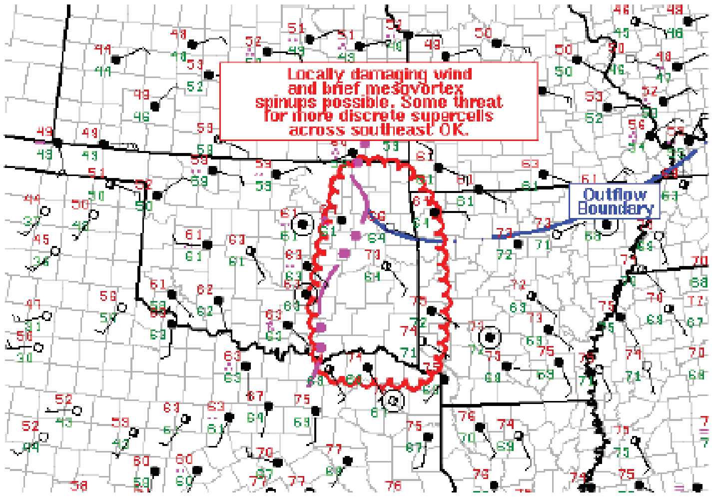
Back to Watch 205

Click for Complete Product Text



Mesoscale Discussion 721

< Previous MD

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Mesoscale Discussion 0721
NWS Storm Prediction Center Norman OK
0726 AM CDT Tue May 21 2019

Areas affected...eastern OK into far nothwest AR

Concerning...Tornado Watch 205...

Valid 211226Z - 211400Z

The severe weather threat for Tornado Watch 205 continues.

SUMMARY...A line of bowing segments stretches north to south across
eastern OK early this morning, posing a threat for locally damaging
winds and a few tornadoes. This threat will continue in the
short-term across northeast OK and may persist through the morning
hours further south across east-central and southeast OK into far
western AR.

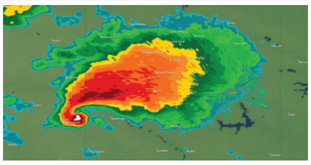
DISCUSSION...A bowing segment just east/northeast of Tulsa will
continue to shift east/northeast across northeast OK this morning.
The bow should be lifting north of the outflow boundary from prior
convection into a cooler and more stable airmass. As this occurs,
the threat for mesovortex tornadoes should diminish as the
convection becomes more elevated and/or weakens as it outpaces any
recovery/northward shift of the outflow boundary.

Further south along the line, locally damaging gusts and mesovortex
tornadoes will continue to be possible as this segment of the line
encounters a better quality airmass untouched by prior convection.
Tornadoes have also been reported early this morning with this
southern portions of the line in Marshall County OK. While
instability is weak downstream (500-1000 J/kg MUCAPE), strong
deep-layer shear and large, curved hodographs, as noted in latest
VWP data from Fort Smith AR 88-D, should continue to support
damaging wind and tornado threat into east-central/southeast OK and
possibly far northwest AR. trends will be monitored for possible
watch issuance across northeast TX into west-central AR this
morning.

..Leitman.. 05/21/2019
```

Figure A4.2: *Process involved in Tornado Warning for May 21 2019: a) Day 1 Convective Outlook with 10% probability of tornado; b) Assocated severe storm upgraded to Tronado Watch 205; c) Mesoscale Discussion associated to Tornado Watch 205; d) Tornado Watch 205 was upgraded to Tornado Warning in the watch area.*

Table A4.1: Brief summury of steps involved in tornado warning process

Product	What it is?	Who does it?	What is the purpose?	How is prepared ?
The forecast process begins with the Convective Outlook				
Convective Outlooks	It is a forecast of if severe thunderstorms are expected to occur. Product is areas of possible severe thunderstorms are labeled depending upon the expected coverage and intensity. (Figure 4.4)	Outlook forecasters of SPC	Many NWS offices use the Outlook to make emergency staffing decisions before severe weather begins. Emergency managers use it to plan for the disaster reposnse	Each outlook involves detailed analysis of recent and current weather data, followed by intensive examination of computer forecast models
Mesoscale Discussions	It is a concise short-term guidance messages consisting of meteorological reasoning of expected severe hazardous weather It addresses areas of current or expected hazardous weather. It is needed to describe an evolving severe weather threat and to advise of possible watch issuance.	Mesoscale forecasters	forecasters at local NWS offices use it to understand causes and prepare for the types of severe weather expected.	Due to the large amount of weather data available in most cases, and the complexity of high-impact weather forecasting, hours of work often go into the preparation of an outlook.
If development of tornado is likely to occur in the next several hours, the SPC issues Tornado Watch.				
Tornado Watch	Tornadoes are possible in and near the watch area. It means be ready to act quickly if a warning is issued or you suspect a tornado is approaching. The watch area is typically large, covering numerous counties or even states.	Lead forecasters	Watches alert the public, aviators and local NWS offices that environmental conditions have become favorable for the development of severe storms or tornadoes. Local storm spotter networks activate Forecasters in the threat area closely monitor radar imagery and spotter reports to issue the appropriate warnings.	This involves a diligent monitoring of current and forecast weather for conditions of violent thunderstorms. The lead forecaster must coordinate with numerous local NWS offices in the threat areas and ensure that the watch process works smoothly.
	When a tornado has been spotted or that Doppler radar indicates a circulation in a thunderstorm that can spawn a tornado, a Tornado Warning is issued.			
Tornado Warning	When severe hail, damaging winds or a tornado appear imminent, Severe Thunderstorm or Tornado Warning is issued	local NWS offices	People in the warning area can find safe shelter to take cover from the storm. .	The warning rapidly disseminated over NOAA Weather radio, mass and social media channels

A4.2 Tornado safety at local level in the US

For the tornado safety, issuing warning is not enough. Public should know the meaning and how to respond. Following are the safety rules in the US:

Tornado Watch Means Be Prepared! Tornadoes are possible in and near the watch area. Review and discuss your emergency plans and check supplies and your safe room. Be ready to act quickly if a warning is issued or you suspect a tornado is approaching. Watches are issued by the Storm Prediction Center, NWS. The watch area is typically large, covering numerous counties or even states.

Tornado Warning Means Take Action! A tornado has been sighted or indicated by weather radar. There is imminent danger to life and property. Move to an interior room on the lowest floor of a sturdy building. Avoid windows. In a vehicle or outdoors one need to move to the closest substantial shelter and to protect from flying debris. Warnings typically issued for a much smaller area.

- ### Before the Tornado

  In US homes are built with basement or with tornado shelters (mainly in tornado alley States). At home, a family should have tornado plan in place, based on the kind of dwelling. One should know where to take shelter in a matter of seconds and practice a family tornado drill at least once a year. All administrators of schools, shopping centers, nursing homes, hospitals, sports arenas, stadiums, mobile home communities and offices in the US should have a tornado safety plan in place, with easy-to-read signs posted to direct everyone to a safe, nearby shelter area. Schools and office building managers should regularly run well-coordinated tornado drills. In the US, especially in the plains east of the Rockies, one should consider a building an underground tornado shelter or an interior "safe room" a building.

- ### During the tornado

  When a tornado watch is issued, one should think about the drill and check to make sure all the safety supplies.

  - **At homes:** Homes with basement one goes in the basement and under sturdy protection (heavy table) or cover with a mattress or sleeping bag. In homes without basement, one avoids windows, go to the lowest floor, small center room (like a bathroom or closet), under a stairwell, or in an interior hallway with no windows.
  - **In an office building, hospital, nursing home or skyscraper:** One go directly to an enclosed, windowless area in the center of the building away from glass and on the lowest floor possible.
  - **At school:** Everybody follows the drill! Go to the interior hall or windowless room in an orderly way as instructed.
  - **In the open outdoors:** Should seek shelter in a sturdy building.

A4.3 Current challenges at MFD

MFD has several challenges for even performing the current regular operational work. Following situation at MFD make the issuance of the severe weather warning a challenging task:

1. MFD still lacks the recent weather observation technologies (radar, radiosonde, AWS, weather camera, fully synoptic weather observatories running 24/7) with good network coverage, so the forecasters are not able to view detail weather situation in the country in real-time.
2. Though the modernization project (PPCR-BRCH) is ongoing in DHM, these modern systems are not fully integrated in the operational system yet. More importantly, MFD personnel are not fully capable of using and operating all the recently installed modern weather technologies due to the lack of hands on training.
3. Currently, numerical weather prediction (NWP) system at MFD lacks the fine-tuned, well validated and multi-model ensemble prediction system.
4. Well managed nowcasting, early warning and communication (including media) system is lacking in DHM.
5. Lack of dedicated Research and Development division with dedicated research areas like verification of different existing system, NWP, RADAR and meteorological phenomenon of various scales.
6. Human resource to operate, monitor, analysis, forecast and communicate the weather observations and weather phenomenon is not enough. Operational staffs (24/7) are over-loaded by daily official work.
7. Lack of enough refresher trainings on advances in meteorology and modern technologies to the forecasters.

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Department of Hydrology and Meteorology

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